

**STUDIES ON DEHUMIDIFIED AIR DRYING OF  
GREEN CHILLI (*Capsicum annuum* L.)**

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By  
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## CERTIFICATE

This is to certify that the thesis entitled “**STUDIES ON DEHUMIDIFIED AIR DRYING OF GREEN CHILLI (*Capsicum annuum* L.)**” submitted by Sri Uma Sankar Pal for the award of the Degree of **DOCTOR OF PHILOSOPHY IN AGRICULTURAL ENGINEERING (POST HARVEST PROCESSING AND FOOD ENGINEERING)** to the Orissa University of Agriculture and Technology, Bhubaneswar as a record of *bona fide* research work carried out by him under my supervision and guidance.

No part of the thesis has been submitted for any other Degree or Diploma. The help and sources of information as have been availed in course of this investigation have been duly acknowledged.



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**DEDICATED TO MY  
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## ABSTRACT

Mathematical model of a heat pump assisted batch dryer was developed based on the heat and mass balance of refrigerant and drying air. A batch type heat pump assisted dehumidified air dryer was fabricated successfully and a medium range of temperatures (30-41°C) for safe drying of heat sensitive crops were achieved. Dehumidification system of the developed heat pump dryer maintained the relative humidity of air entering the drying chamber below 40%. Specific Moisture Extraction Rate for heat pump dryer for drying sweet pepper at 40°C was found more (1.1 kg/kWh) than hot air dryer (0.93 kg/kWh) while operating at 45°C. Thin-layer drying experiments under controlled conditions were conducted for green chilli and sweet pepper in heat pump dryer at 30, 35 and 40°C and hot air dryer at 45, 55 and 65°C with relative humidities ranging from 19-55%. The moisture content of green chilli and sweet pepper slices reduced exponentially with drying time. As the temperature increased, the drying curve exhibited a steeper slope, thus exhibiting an increase in drying rate. Drying of green chilli and sweet pepper took place mainly under falling-rate period. The treated (blanching in solution containing 0.5% lye and 0.25% magnesium carbonate at 95°C for 2 minutes) and blanched (steam blanched for 2 minutes) samples had higher drying rate and took less drying time as compared to control. The Page equation was found to be better than Lewis equation to describe the thin-layer drying of green chilli and sweet pepper with higher co-efficient of determination and lower root mean square error. The retention of total chlorophyll content, ascorbic acid content and capsaicin content was observed to be more in heat pump dried samples with higher rehydration ratio. Drying air temperature as well as pretreatment both play significant role in influencing the quality parameters of dehydrated chilli and sweet pepper. The sensory scores for colour, texture, flavour and overall acceptability decreased significantly with increase in drying air temperature from 30 to 65°C for all the samples. Keeping in view the energy consumption and quality attributes of dehydrated products, it is proposed to dry green chilli and sweet pepper at 35°C in heat pump dryer. EMC of chilli increased with the increase in the ERH and the sorption isotherms showed the typical sigmoid shaped curve. Chlorophyll content of both dried chilli and sweet pepper decreased with increase in storage period. Quality attributes of treated samples retained well during storage in Metallised Polyester Polyethylene pouches as compared to control samples.

**Key words:** Drying, blanching, heat pump dryer, dehydrated chilli, dehydrated sweet pepper.

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## LIST OF ABBREVIATIONS

atm	Atmospheric
ANOVA	Analysis of Variance
ASTA	American Spice Trade Association
BET	Bruanauer-Emmett-Teller
BIS	Bureau of Indian Standards
cc	Cubic centimetre
°C	Degree centigrade
COP	Coefficient of performance
d.b.	Dry basis
EMC	Equilibrium moisture content
Eq.	Equation
ERH	Equilibrium relative humidity
et al.	et alibi, and others
etc.	et cetra
Fig.	Figure
g	Gram
h	Hour
hp	Horse power
HAD	Hot air dryer
HDPE	High density polyethylene
HPD	Heat pump dryer
HTST	High temperature short time
i.e.	That is
J	Joule
kg	Kilogram
kPa	Kilo Pascal
kWh	Kilowatt-hour
lph	Litre per hour
m	Metre
m.c.	Moisture content

MAP	Modified atmospheric packaging
MER	Moisture extraction rate
mg	Milligram
min	Minute
ml	Millilitre
mm	Millimetre
MPP	Metallised Polyester Polyethylene
nm	Nanometer
PP	Poly propylene
R <sup>2</sup>	Coefficient of determination
RMSE	Root mean square error
rpm	Revolution per minute
Rs.	Rupees
s	Second
SMER	Specific moisture extraction rate
Temp	Temperature
viz	Namely
vs	Versus
w.b.	Wet basis
wt	Weight
W	Watt

## LIST OF SYMBOLS

$a_1 - a_{38}$	= Co-efficients of empirical equations to calculate refrigerant thermodynamic properties
A	= Heat transfer surface area, $m^2$
$A'$	= Empirical constant of Lewis drying equation
$A''$	= Absorbance at specific wavelength
$b_1 - b_4$	= Co-efficients of empirical equations to calculate steam properties
BF	= By pass factor
$c_{pa}$	= Specific heat of dry air, kJ/kg K
$c_{pam}$	= Specific heat of moist air, kJ/kg K
$c_{pf}$	= Specific heat of condensate refrigerant film, kJ/kg K
$c_{pv}$	= Specific heat of water vapour, kJ/kg K
C	= Constant of BET equation
$d_p$	= Diameter of compressor cylinder, m
D	= Diameter of tubes, m
$E_{comp}$	= Compressor power requirement, kW
$E_{fan}$	= Fan power requirement, kW
f	= Friction factor
$f_{dr}$	= Dimensionless drying rate
G	= Mass velocity, $kg/m^2s$
h	= Enthalpy of air, kJ/kg dry air
$h_{fg}$	= Latent heat of vapourisation at reference temperature of $0^\circ C$ , kJ/kg
$h_{we}$	= Enthalpy of condensed water at evaporator surface temperature, kJ/kg
H	= Enthalpy of refrigerant, kJ/kg
$H_{fgr}$	= Latent heat of vapourisation of refrigerant, kJ/kg
$\nabla H$	= Enthalpy change in isentropic compression, kJ/kg
k	= Thermal conductivity, kW/m K
K	= Drying constant, $h^{-1}$
$K_{lf}$	= Load factor
$l_{ad}$	= Length of air duct, m
$l_p$	= Stroke of compressor piston, m
$l_{rs}$	= Tube row spacing, m

$L_t$	= Tube length, m
LMTD	= Log mean temperature difference
$\nabla L$	= Length of capillary element, m
$\dot{m}_a$	= Mass flow rate of dry air, kg/s
$m_p$	= Dry mass of the product, kg
$\dot{m}_r$	= Mass flow rate of refrigerant, kg/s
$\dot{m}_{we}$	= Rate of moisture condensed at the evaporator surface, kg/s
$m_{wd}$	= Mass of moisture removed during drying, kg
$M_{gi}$	= Initial moisture content of product, %d.b.
$M_{gf}$	= Final moisture content of product, %d.b.
$M_{eq}$	= Equilibrium moisture content, %d.b.
$M_m$	= Monolayer moisture content, %d.b.
$M'$	= Moisture content, %w.b.
MR	= Moisture ratio
$n$	= Polytropic index
$n'$	= Empirical constant of Page drying equation
$N_{fin}$	= Number of fins per metre
$N_p$	= Compressor speed, rev/min
$N_s$	= No. of cylinders
$p$	= Partial water vapour pressure, kPa
$p_s$	= Saturated vapour pressure, kPa
$P$	= Absolute pressure of refrigerant, kPa
$Pr$	= Prandtl number
$\nabla P$	= Pressure drop, kPa
$Q$	= Heat transfer rate, kW
$Re$	= Reynold number
RH	= Relative humidity, decimal
$t$	= Temperature of air, K
$T$	= Temperature of Refrigerant, K
$u$	= velocity, m/s
$U$	= Overall heat transfer co-efficient, kW/m <sup>2</sup> K
$v_a$	= Specific volume of air, m <sup>3</sup> /kg dry air
$v_{r1}$	= Specific volume of refrigerant vapour at suction, m <sup>3</sup> /kg
$V_a$	= Volumetric air flow rate, m <sup>3</sup> /s

$V_p$	= Piston displacement, $m^3/s$
$W$	= Humidity ratio of air, kg water/kg dry air
$\nabla x$	= Change of vapour quality
$\alpha$	= Heat transfer co-efficient, $kW/m^2K$
$\rho$	= density, $kg/m^3$
$\theta$	= Drying time
$\theta_{dr}$	= Total drying time, s
$\mu$	= Viscosity, $kg/m s$
$\eta_{mech}$	= Mechanical efficiency of compressor
$\eta_{motor}$	= Compressor motor efficiency
$\eta_v$	= Volumetric efficiency of compressor
$\eta_{sf}$	= Surface fin efficiency of coil

### Subscripts

a	Air
c	Condenser
co	Condenser outlet
cs	Condenser surface
d	At dry bulb temperature
di	Dryer inlet
do	Dryer outlet
dr	Dryer
e	Evaporator
eo	Evaporator outlet
es	Evaporator surface
ext	External
f	Condensate refrigerant film
i	Inside
int	Internal
l	Liquid refrigerant
o	Outside
r	Refrigerant
rc	Refrigerant in condenser
re	Refrigerant in evaporator

s	Saturated
tw	Tube wall
w	At wet bulb temperature
1	Refrigerant vapour at evaporator outlet or compressor suction
2	Refrigerant vapour at compressor delivery or condenser inlet
3	Liquid refrigerant at condenser outlet or capillary inlet
4	Liquid refrigerant at capillary outlet or evaporator inlet

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**CHAPTER I**  
**INTRODUCTION**

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## INTRODUCTION

Chilli (*Capsicum annuum* L.) is a spice-cum-vegetable of commercial importance. It is the most widely used spice all over the world as a condiment, culinary supplement or as a vegetable and virtually an indispensable item in the kitchen. The wide popularity of chilli is due to its wide range of shapes and sizes and sensory attributes such as colour, pungency, taste and distinctive aroma that generally make insipid bulk nutritive flesh and cereal foods more appetizing. Both red and green chillies can be used as fresh but dried chillies are also used extensively.

India is the largest producer and exporter of chilli in the world. Chilli is cultivated in an area of 9.65 lakh ha (2000-01) with a production of 10.75 lakh tonnes (Peter *et al.*, 2004). Around 97% of the total production of chillies is consumed within the country and only 3% is exported (Murthy, 1995).

Chillies belonging to the Solanacea family are grouped into two categories namely sweet pepper and hot pepper. Sweet pepper also called as bell pepper or Paprika is the mild or non-pungent variety of chilli or capsicum. Paprika with mild pungency is cultivated mainly in European countries, viz. Hungary, Spain, Bulgaria, Romania and Poland. Chilli with higher pungency is grown in tropical countries, viz. India, China, Pakistan, Nigeria, Malaysia, Japan and Turkey (Pruthi, 1993).

Green chilli has a delicious capsicum flavour in addition to the hotness, which adds zest to various food preparations. The fresh fruit is also used in salads, pickles and canned products ( Govindarajan *et al.*, 1987). The fruit is eaten fresh or processed, as unripe (green) or ripe (red, yellow, orange, white) pepper. Chilli when taken with food, stimulates our taste bud, thereby, increases the flow of saliva which helps in digestion. When eaten fresh with salads, it being rich in vitamins A and C, serve as a good vitamin supplement in addition to its being an appetizer. Green chilli is more nutritious than ripe, dried chilli as most of the vitamins are lost during drying. Besides, green chilli also contains an anti-cancer compound (Pruthi, 1993). The green Sweet pepper or *Shimla mirch* which is not pungent is used as curried vegetable, salad and dried ripened paprika is valued chiefly for its brilliant red colour and mild flavour. It is one of the richest sources of ascorbic acid.

The prices of chilli are fluctuating during the year. They decline during post harvest season and increase in the off season. Preservation of these seasonal gluts permits seasonal products to become available round the year as well as prevents post harvest losses. As far as preservation of vegetables is concerned, drying is the most widely used method for reducing the water activity of the perishable commodities to the safe storage level to prevent microbial infection. The chief benefits of drying foodstuffs are their prolonged preservation which allows them to be marketed and consumed outside their traditional season, and reduction of their mass and volume, which makes transportation cheaper. Among the various dehydration techniques, hot air circulation around the commodity is commonly used. This technique is energy intensive and characterised by low drying efficiency specially during last phases of drying cycle. Dehydrated green pepper is good source of vitamin C and having anti-cancerous effect. It can find its use in kitchen, fast food stalls and food industries. Dehydrated bell peppers are sold primarily in the form of slices or dices to manufacturers of canned stewed tomatoes and dry soup mixes (Somogyi and Luh, 1988).

Normally drying is carried out in hot air convection dryers. Selection of proper drying conditions is necessary for minimizing thermal stress, over-drying and maintenance of relevant compounds (chlorophyll, vitamin C, capsaicin) which determine the quality of the dried product (Kim *et al.*, 1982). Drying kinetics and parameters are very important for dryer simulation and design. The distinct aromatic odour, colour and pungency are seldom carried over to the processed products (Giridhar *et al.*, 1996). The chemicals responsible for the delicate odours and attractive colours of spice-vegetables are highly heat sensitive and are lost during dehydration (Pezzutti and Crapiste, 1997). The retention of naturally coloured pigments in thermally processed and stored food has been a major challenge in food processing. Several attempts have been made to stabilize the colour but with limited success (Ihl *et al.*, 1998). Colour plays an important role in assessing product quality. The characteristic colour of the dried green chilli or capsicum is considered as one of the essential quality indicator. The most common change that occurs during thermal processing of green vegetables and spices is the conversion of chlorophyll to pheophytins, causing a change of colour from bright green to olive brown (Rocha *et*

*al.*, 1993). Non-enzymatic browning and chlorophyll losses during drying contribute substantially to colour loss in dried green chilli.

Thermal drying often conducted at high temperatures. However many agricultural and food materials (specific crops) are sensitive to high temperatures. Dehydrated products usually suffer distinct losses in quality during processing. It is reported that the pigment and vitamin degradation rate increases as the drying temperature increases (Malchev *et al.*, 1982). Further conventionally air dried products do not rehydrate satisfactorily because of structural changes in the product due to excessive thermal damage (Holdsworth, 1986). Owing to these quality differences compared to other preservation techniques, the demand for dried fruits and vegetables has been almost static. During last few years, emphasis has been laid on improving the rehydration characteristics and quality attributes of hot air dehydrated commodities by changing process variables, using pre-drying treatments and low temperature processes.

Thus drying at low temperature to enhance the quality of food products has been a growing interest in recent years. High value products, which are extremely heat sensitive, are often freeze dried. However, this is an extremely expensive drying process (Baker, 1997). Vacuum drying system is normally used for sensitive materials that can be damaged or decomposed at high temperatures but it is an energy intensive process for maintaining vacuum inside the drying chamber. The dryer has special parts, pumps and hermetical closed circuit and requires frequent inspection. The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput. A drying system that is both energy efficient and preserves product quality is desired (Adapa *et al.*, 2002). This creates challenges for researchers, food industry and dryer manufacturers to develop new technologies to process difficult-sensitive materials and to supply final products with high quality and improved properties.

Heat pumps have been known to be energy efficient when used in conjunction with drying operations. The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust as well as their ability to control independently the drying air temperature and humidity. Many researchers have acknowledged the importance of heat pump dryers in producing a range of precise drying conditions to dry a wide range of products and improve their quality

(Rossi *et al.*, 1992; Strommen and Kramer, 1994; Alves Filho and Strommen, 1996; Prasertsan and Saen-saby, 1998a; Chua *et al.*, 2000a; Sosle *et al.*, 2003). Heat sensitive food products, requiring low-temperature drying, can take advantage of the heat pump drying technology in which the drying temperature can be adjusted from -20°C to 60°C. With proper control, it is also possible for heat pump dryer to produce freeze-drying conditions at atmospheric pressure (Prasertsan and Saen-saby, 1998b). In countries where the level of the air humidity is high, high spoilage rates occur during the rainy season when the drying air is very moist. Heat pump dryer can reduce product spoilage by maintaining low humidity of drying air through the regulation of the latent heat removal at the evaporator.

The literature available on dehydration of green chilli and sweet pepper is meager. Some researchers have studied the effects of pre-treatments and drying conditions on drying characteristics and product quality. But the information pertaining to the effect of dehumidified air drying at near ambient temperature of fruits and vegetables in general and green chilli/sweet pepper in particular and its effect on product quality is scarce.

The main goal of the present investigation was to systematically study the effect of heat pump assisted dehumidified air drying of green chilli and sweet pepper on drying characteristics, energy consumption and quality of dried products. Therefore, the present work was undertaken with the following objectives.

1. To develop a dehumidified air dryer using heat pump system
2. To study the performance of the developed heat pump dryer
3. To study the drying characteristics of green chilli and sweet pepper
4. To develop mathematical expressions for green chilli and sweet pepper dried in heat pump and hot air dryer
5. To compare the quality attributes of dehumidified air dried product with that obtained from hot air dryer
6. To study the storability of dried green chilli and sweet pepper

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**CHAPTER II**  
**REVIEW OF LITERATURE**

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## REVIEW OF LITERATURE

This chapter deals with the review of research work carried out by various workers relating to heat pump dryer, drying of chilli and sweet pepper and effects of different pretreatments and drying parameters on drying characteristics and quality of dried product.

### 2.1 Chilli and Sweet pepper

#### 2.1.1 Composition and quality attributes

Chillies are important well-known commercial crop used as a condiment, culinary supplement or as a vegetable. Chilli was known to Indians about 400 years ago, when this crop was first introduced into India by Portuguese towards the end of the 15<sup>th</sup> century. The varieties of chillies (*Capsicum annuum*) are broadly divided into two groups, (1) the long pungent type, including pickling type, used as a spice and (2) bell-shaped non-pungent or mild and thick fleshed type, popularly known as 'Shimla Mirch' or paprika, also known as sweet pepper which is commonly used as a curried vegetable (Pruthi, 1993). The composition of chilli and sweet pepper are given in Table 2.1. Carbohydrate, protein, fat and fibre are the major components which increase rapidly from the green stage to ripe stage. Capsicums are good sources of many essential nutrients and included as a therapeutic agent for cancer (Indira and Rajan, 1997). One of the paprika's extremely interesting quality attributes is its content of vitamin C (ascorbic acid) even higher than citrus fruit. The Hungarian scientist, Dr. Szent-Gyorgyi, who won the Nobel prize in 1937 for his work on vitamin C, found paprika pods to be one of the richest sources of ascorbic acid.

*Capsicum* is globally so popular because of its pungent nature due to the presence of 'Capsaicin'. *Capsicum* is generally eaten raw, sliced in salads, also used as cooked food. It is commonly used in diet because of their typical colour, pungency and distinct aroma. *Capsicum* also has its anticancerous quality. It has good impact on human heart and liver also (Pruthi, 1993).

Sweet pepper is used for its colouring and flavouring properties. The three functionally important components in the use of chillies as spice are principally the red colour, capsaicinoids- the pungency stimulant and to a lesser degree the

characteristics sweet aroma of sweet pepper and vegetable capsicums or the pungent aroma of chillies. The major red colour in capsicum comes from capsanthin and capsorubin, green colour is from chlorophyll and the yellow-orange colour is from beta-carotene and violaxanthin. Scoville heat units measure the heat or pungency of capsicum powder. One part per million concentration of capsaicinoids is equal to 15 Scoville heat units (Scoville, 1912). The nature of pungency has been established as a mixture of seven capsaicinoids and they are often called capsaicin after the most prevalent one (Hoffman *et al.*, 1983). According to Govindarajan (1985), the group paprika contains less than 0.1% of capsaicinoids, and for the pungent grade, a maximum of 0.5%. But the pungency level of chillies varies from 0.1 to 1.4%. The pericarp is rich in colour whereas pungency is found in veins or placenta. Generally there is a decrease in pungency from chillies to paprika and a parallel increase in colour, pigment concentration and increase in size and fleshy nature of pericarp. The composition of non-volatile compounds influences mainly the sensory perceived taste, while the aroma is affected by volatile compounds (Luning, 1995). Processing methods and storage conditions affect the quality of chillies.

**Table 2.1 Composition of chilli and sweet pepper (per 100g edible portion)**

	Chilli	Sweet pepper
Food energy, kcal	40	25
Moisture, g	87.7	92.8
Protein, g	2.0	0.8
Fat, g	0.2	0.4
Carbohydrates, g	9.5	5.3
Fibre, g	1.8	1.2
Vitamin A, IU	10750	5700
Thiamine, mg	0.09	0.08
Riboflavin, mg	0.09	0.05
Niacin, mg	1.0	0.6
Vitamin C, mg	190	242
Vitamin B <sub>6</sub> , mg	0.28	0.16
Pantothenic acid, mg	0.06	0.04
Folacin, µg	23	17

Source: Agriculture Handbook, 8, U. S. Department of Agriculture

### 2.1.2 Production and variety

India is the largest producer and exporter of chilli in the world. Chilli is cultivated in an area of 9.65 lakh ha (2000-01) with a production of 10.75 lakh tonnes. This contributes 35.5% and 31.6% respectively to the total area and production from all spices (Peter *et al.*, 2004). Chilli export from India during 2004-05 were of the order of 1.3 lakh tonnes valued at Rs.480 crores (Indian Food Industry, 2005).

Arka Mohini, Arka Gaurav, KT-1, KT-2, California wonder and Bharat are some of the released varieties of sweet pepper whereas Pusa Jwala, Sindhu, NP-46A, K-1, K-2, Suryamukhi, Utkal Ava are popular chilli varieties.

### 2.2 Heat Pump Dryer

Drying is one of the most cost-effective means of preservation of grains, crops and foods of all varieties. This technique has been practiced since time immemorial. Drying by dehumidification refers to a process in which moisture is removed from a solid using heat as the energy input. The mechanism of drying is a complex phenomenon involving combined heat and mass transfer and, in most cases, relates to a porous medium. It is apparent that drying itself is an energy-intensive process because the latent heat to be supplied to the material to evaporate the moisture. Drying has found application in a variety of industries such as agricultural, chemical, paper, timber, textile and pharmaceuticals, to name a few (Chua *et al.*, 2002b).

For both energy and environmental view points as well as the global requirement to feed the growing population, it is important that the drying technique and technology be improved to reduce spoilage and enhance quality of the product. Selection of a particular dryer/drying methods depends on the form of raw material and its properties, desired physical form and characteristics of the product, necessary operating conditions and operating costs. Presently most of the dehydrated fruits and vegetables are produced by hot air drying, which is the simplest among the various methods.

Fruits and vegetables are mainly composed of water, carbohydrates, proteins and lipids. Due to modification of chemical and physical bonds of the compounds the material becomes viscous and sticky during processing. Conventional dryers have limitations in handling such sensitive materials (Alves-Filho, 2002).

The retention of naturally coloured pigments in thermally processed and stored foods has been a major challenge in food processing. The most common change that occurs during hot air drying of green vegetables and spices is the conversion of chlorophyll to pheophytins and loss of aroma. If green vegetables and spices can be dried at near ambient temperature with an appreciable drying rate, then quality of dried product which is heat sensitive may be preserved. It is generally observed that for high moisture foods, high drying rate under low temperature gradient may be possible by maintaining a high vapour pressure gradient between the product and drying air. Thus drying of fruits and vegetables with near ambient temperature and low humidity air could be a better proposition as far as the qualities of the dried products are concerned. In a tropical country like India, wherein the relative humidity of ambient air is high in most of the regions, a dehumidified air drying system for agricultural products is a long felt need. Under tropical humid conditions, near ambient temperature drying could be possible with heat pump dryer.

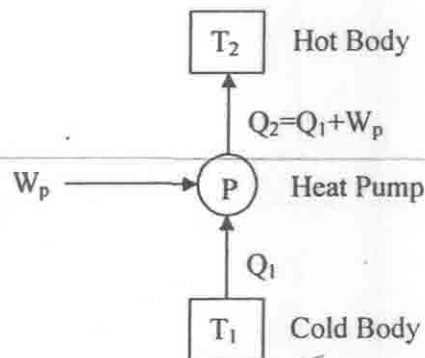
Since drying is an energy intensive process, by average taking energy up to 6% of total processing energy, much attention is given to the development of energy-efficient drying processes. Recently, there has been a significant growth in the potential market for heat pump dryers, aided by the impact of new designs under development or recently introduced into the market. Heat pumps have been known to be energy efficient when used in conjunction with drying operations (Chua *et al.*, 2002b). Heat pump is a device implicitly supplying heat mainly in space heating application and heat recovery. Heat pump application in drying has continuously received attention since it possesses two-fold beneficial characteristic. Through the evaporator, the heat pump recuperates sensible and latent heat from the dryer exhaust, hence the energy is recovered. Condensation occurring at the evaporator reduces the humidity of the working air. Thus increases the driving force for product drying. It is, therefore, anticipated that the heat pump dryer can accelerate the drying process and use energy efficiently. Furthermore, heat pump dryer is suitable for temperature-sensitive products because effective drying can occur at low temperature because of low humidity (Prasertsan *et al.*, 1996). In production of artificially dried food products, direct heated driers operated at 50 to 90°C and vacuum freeze drying operated below -30°C are used. Direct heated dryers have a lower production costs than vacuum freeze dryer but with a much lower quality of the dried product. Vacuum

freeze dryer, on the other side, is so expensive that its use is limited. Heat pump dryers can be used with considerable lower production costs than vacuum freeze dryer but with similar qualities of the dried product (Cardona *et al.*, 2002).

### 2.2.1 Components

Any refrigeration system is a heat pump which extracts heat from a cold body and delivers it to a hot body. Thus there is no difference between cycle of operation of heat pump and a refrigerator. The main difference between the two systems is the operating temperature. A refrigerator works between cold body temperature and atmospheric temperature whereas the heat pump operates between the hot body temperature and atmospheric temperature.

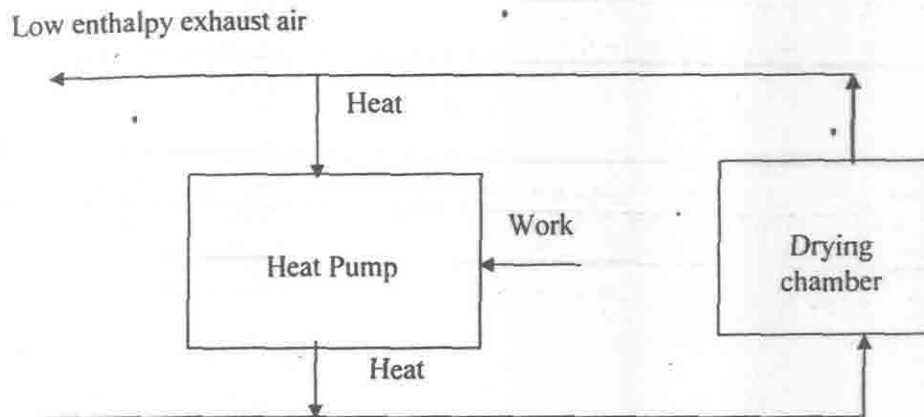
A heat pump is essentially an air conditioning system operated in reverse. Unlike normal air conditioning system, the heat exchanger in focus is the condenser. The schematic diagram representing the operation of heat pump is shown in Fig. 2.1. The basic components of heat pump system are compressor, condenser evaporator and expansion valve (Chua *et al.*, 2000b).



$Q_1$  = Heat absorbed from the cold body,  $Q_2$  = Heat rejected to the hot body  
 $T_1$  = Temperature of cold body,  $T_2$  = Temperature of hot body,  $W_p$  = Work input

**Fig. 2.1 Schematic diagramme of heat pump operation**

Heat pump dryer (HPD) consist of a heat pump in a closed loop configuration integrated with drying chamber (Fig. 2.2). The principal advantages of heat pump dryer is the ability of heat pump to recover energy from the exhaust as well as their ability to control independently the drying air temperature and humidity.



**Fig. 2.2 Recycling of energy in the heat pump dryer**

Heat pump dryer is a co-existence of two engineering systems: the heat pump and the dryer. Heat pump assisted-drying provides a controllable drying environment (temperature and humidity) for better product quality at low energy consumption (cost). In a conventional hot air dryer, substantial energy (heat) loss is not avoidable as the process air at relatively high temperature has to be vented off from the dryer. If the dryer is equipped with a heat pump, the energy at the dryer exhaust is recycled as shown in Fig. 2.2.

### 2.2.2 Operating principle

The low pressure working fluid in the evaporator is vaporized by heat drawn from the dryer exhaust. The compressor raises the enthalpy of the working fluid and discharges it as superheated vapour at high pressure. Heat is removed from the working fluid and returned to the process air at the condenser. The working fluid is then throttled to the lower pressure line and enters the evaporator to complete the cycle. The evaporator and the condenser are, in fact the heat exchangers that recover heat and reduce the energy consumption of the drying process (Prasertsan and Saen-Saby, 1998a).

Refrigerant dehumidification is unique in that it converts the enthalpy or heat content of moist air into sensible heat. By drawing moist air over the surface of the evaporator that is refrigerated to a temperature below dew point of the air, condenses the moisture on the surface, giving up its latent heat of condensation. The cool dry air is then drawn over the hot surface of the refrigerant circuit's condenser. This cycle acts as a heat pump by converting the latent heat of condensation into sensible heat at the hot condenser (Brundrett, 1987).

The state of the process air on the psychrometric chart is shown in Fig. 2.3. If the temperature of the process air passing through the evaporator is below the dew point, moisture condensation occurs at the evaporator (process 1-2-3). In this case, the air returning to the dryer (in a closed cycle) via the condenser (process 3-4) is at reduced moisture content. This system is known as dehumidifying heat pump dryer.

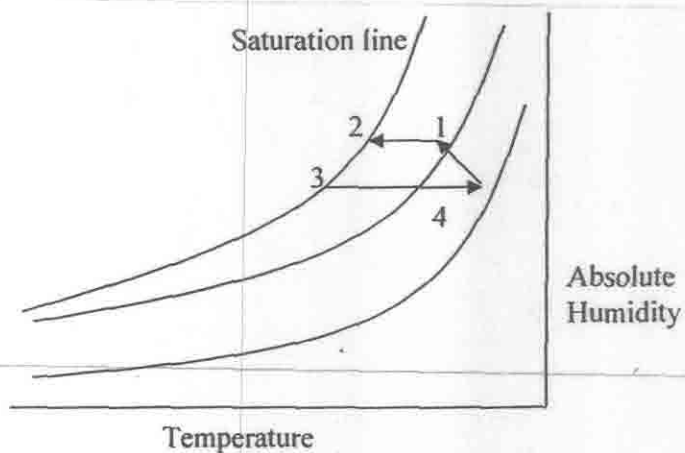


Fig. 2.3 State of processed air in the psychrometric chart

### 2.3 Review of Work on Heat Pump Drying

There has been a growing interest in recent years to apply the heat pump drying technology to foods and biomaterials where low-temperature drying and well-controlled drying conditions are required to enhance the quality of products. High value products, which are extremely heat sensitive often freeze-dried. This is an extremely expensive drying process (Baker, 1997).

Recently, there has been great interest to look at the heat pump drying system as a substitute system to freeze drying. A heat pump dryer can be considered as a 'workhorse' capable of running 24 hour per day. Thus, a consistent product

throughput is ensured. Further, the break-even period for initial capital cost can be significantly reduced through lower operating cost and higher output volume (Chua *et al.*, 2002a).

In plantation forest industry, preservation and control of genetic material is best achieved by drying at low temperature and low humidity to avoid thermal damage which can be met extremely and reliably by the air of dehumidified dryer as reported by Chen *et al.* (2002).

Heat pump dryers have been applied in the production of a diversity of ready-to-eat foods and dried instant products. Besides being energetically efficient and environmentally friendly, the heat pump drying technology provides a wide range of drying conditions as required to produce powders with improved characteristics (Alves-Filho, 2002).

### 2.3.1 Performance of heat pump dryer

The dryer performance can be defined with respect to its capacity or energy effectiveness. Moisture extraction rate (MER) i.e. kilogram of moisture removed per hour indicates the dryer capacity or throughput rate. Specific moisture extraction rate (SMER) i.e. kilogram of moisture removed per kilowatt-hour defines the effectiveness of the energy used in the drying process. The energy efficiency of heat pump is defined by the coefficient of performance (COP) which is the ratio of heat rejected at the condenser to the work used by the compressor (Chua *et al.*, 2002a)

Hodgett (1976) demonstrated that an HPD of average SMER of three kg/kWh would use less primary energy than a steam-heated dryer with a thermal efficiency of 75% or a direct fired dryer of 58% efficiency. Further the system is energy efficient as compared to that of hot air drying. He reported that the thermal efficiency of the dryer was very sensitive to process air leakage; thus the dehumidifier HPD was best suited to a chamber-type dryer.

Air mass flow rate was another factor that affected the heat pump dryer performance. By changing the air flow rate, the specific moisture extraction rate could be either increased (Almeida *et al.*, 1990) or decreased (Pendyala *et al.* 1990b) depending on the range of the air velocity, the HPD configuration and dryer load. The inter-dependence of the process air and heat pump working fluid together with the

time-dependent property of the process air resulted in a dynamic behaviour of the HPD system and complicated control of the system for overall optimum performance.

Rossi *et al.* (1992) compared the performance of an electrical heating dryer with and without heat pump assistance for drying onion slices and reported, save in drying time by 40.7% and electrical energy saving over 40% in heat pump assisted unit for high ambient relative humidity and low evaporator temperature. This implied the beneficial effect of heat pump dehumidification in humid climate.

Aceves-Saborio (1993) presented a comparative performance of a closed cycle heat pump dryer and a conventional dryer in term of relative specific moisture extraction rate and indicated that heat pump dryer consumed less energy, except at operating conditions that resulted in very little moisture extraction. He observed that irrespective to the heat pump dryer configurations, heat pump working fluids and drying materials, the specific moisture extraction rates increased as the relative humidity of the dryer outlet air increased. It seemed that the heat pump was not so attractive if heat recovery was the prime objective and dehumidification ability was the real advantage. Disagreement among many workers regarding the performances of open system, partially closed system and completely closed system was believed to be the effects of different ambient conditions (Prasertsan and Saen-saby, 1998b).

Economic feasibility is always understood as the main barrier of HPD implementations because the high grade energy (electricity) is required while the energy actually used in the drying process is a low grade one (heat). The HPD application is, therefore, suitable for high value products such as biotechnological materials (Strommen and Kramer, 1994).

Heat pump dryers were studied as an alternative to freeze drying for dehydration of lactic acid bacteria. Freeze drying requires energy for freezing the product and subliming the ice. Heat pump dryers consume 60-80% less energy compared with traditional oil fired dryers and freeze dryers as the heat of vaporization is largely recovered (Cardona *et al.*, 2002). There have been documented successes in drying biotechnological products (Strommen and Kramer, 1994). Moreover heat pump dryers represent an environmental friendly technology as no exhaust gases are produced if the electricity is taken from hydro-electric sources.

An open system can also be used and according to many works, was claimed to perform better than the close mode dehumidified HPD. In the open system, the heat recovery, not the dehumidification, is the main purpose. It is possible that condensation does not occur even in the closed-dehumidifying system, especially during the final stage of drying when the process air enters the evaporator at high temperature but low absolute humidity resulted in decreased system performance. The system performance depends on many factors such as ambient condition, drying load, air flow rate and HPD configuration Prasertsan *et al.* (1995) reported that ambient conditions have a strong influence on the HPD performance. In order to avoid control problem due to the ambient fluctuation, he suggested to operate the heat pump dryer as a completely closed system.

Hesse (1995) described a number of energy efficient electric drying system technologies including heat pump dehumidifiers, heat recovery from heated air dryers and microwave assisted drying. He proposed that medium temperature (30 to 55°C) dehumidifier dryers can dry a wide range of food products using only around 20% of the energy used by a fuel fired dryer for the same process and low temperature (1 to 5°C) dehumidified dryers could be a viable alternative to freeze drying with comparable or better product quality and lower capital and operating costs.

Bannister *et al.* (1995) studied the roles of the evaporator economizer and liquid sub-cooler on the heat pump performance and found that specific moisture extraction rate of the test system (open cycle heat pump only) was increased by 50% and rate of condensate formation increased by 65% at optimum evaporator air flow rate and 25% relative humidity.

Prasertsan and Saen-saby (1998b) dried sawn rubber wood and bananas in an experimental heat pump dryer. They observed rapid decrease in moisture extraction rates and specific moisture extraction rates and relatively constant compressor power with drying time both in wood and banana drying. Heat pump drying was reported to be having the lowest operating cost compared to electrically-heated hot air dryer and direct-fired dryer.

Acharyaviriya *et al.* (2000a) developed mathematical models of a heat pump fruit dryer to study the performance and found that simulated results using closed loop heat pump dryer were close to experimental results. The results showed that ambient

conditions affected significantly the performance of the open loop dryer and the partially closed loop dryer. Specific air flow rate and drying air temperature affected the performance of all heat pump dryers.

Regalado *et al.* (2000) dried paddy in an experimental radial-flow, circular bin dryer with a dehumidifier and found that the system was technically feasible, more energy-efficient and safer alternative to electrical resistance heating in the conditioning of ambient air for drying under humid tropical conditions.

Wang and Chang (2001) designed an experimental closed-loop heat pump drying system and evaluated for energy performance while drying shelled corns and grain sorghum. They observed COP of 6.4 for the heat pump including air-to-air thermal transfer and 4.7 excluding air-to-air thermal transfer.

Adapa *et al.* (2002) studied the performance and operating characteristics of a low temperature re-circulating cabinet dryer using a house hold dehumidifier loop for alfalfa drying and observed that medium temperatures (30 to 45°C) for safe drying of heat sensitive crops were achieved experimentally with relative humidity of at or below 30%.

Carrington *et al.* (2002) used dynamic modeling for design of batch-mode dehumidifier dryer and showed that control limits for the evaporating and condensing temperatures must be well matched to maximize the drying speed in the constant rate period. He reported that it was important not to place a lower limit of the relative humidity unnecessarily in the falling rate period.

Saensabai and Prasertsan (2003) studied performances of five HPD configurations covering, fully open, partially open and fully closed systems with external condenser or external cooler and reported that the best operating mode of the heat pump dryer depended on both drying rate and ambient condition. They suggested the partially open system as the optimum operating mode for high drying rate in the tropical climate.

Teeboonma *et al.* (2003) considered recycle air ratio, evaporator bypass air ratio, air flow rates and drying air temperature as the most important factors for examining the optimum conditions of heat pump fruit dryers and minimizing drying cost. He developed mathematical models of papaya and mango glaze drying using HPD and validated experimentally. He also investigated the effects of initial moisture

content, cubic size and effective diffusion co-efficient of products on the optimum conditions of HPD.

### 2.3.2 Quality of heat pump dried product

In most of the research studies conducted, the common conclusion was that the HPD offers products of better quality with reduced energy consumption. This is particularly true of food products that requires precisely controlled drying atmosphere (temperature and humidity). Heat sensitive food products, requiring low-temperature drying, can take advantage of heat pump drying technology since the drying temperature of HPD system can be adjusted from 20 to 60°C with proper control. It is also possible for HPD to produce freeze-drying conditions at atmospheric pressure (Prasertsan and Saen-saby, 1998b). As far as food drying is concerned, HPD offers an alternative to improve product quality through proper regulation of the drying condition.

Besides less energy consumption, Rossi *et al.* (1992) obtained better quality onion slices dried by HPD in comparison to a conventional hot air system.

Strommen and Kramer (1994) investigated heat pumps in combination with fluidized bed driers to achieve good temperature and humidity regulation. They observed that by using a temperature programme, including an initial period of freeze drying, it is possible to regulate the product's physical properties such as rehydration ability, colour and taste of dried fish, meat and vegetable products and improved biological activity of dried bacterial cells and biomolecules/enzymes.

Alves-Filho and Strommen (1996) conducted extensive research on drying of heat sensitive biomaterials such as enzymes, biological active bacteria solutions, fruits, cod fish, fish feed and shrimps in fluidized and shelf heat pump dryers and observed improvements on survival rate, rehydration, colour and hardness in dried samples.

Vazquez *et al.* (1997) described a pilot-scale drying plant comprising a closed-circuit, hot air convection chamber with a heat pump for drying food and forest products with lower energy consumption and over a wider range of air speeds, temperatures and relative humidities than in conventional dryers. The colour and texture of grapes dried in the dryer were reported to be qualitatively satisfactory.

Chua *et al.* (2000b) summarised that when the quality of dried food products was paramount, heat pump drying offered an attractive option to enhance product quality and reduced spoilage through better regulation of the drying conditions. Chua *et al.* (2001) studied the effect of time-varying drying air temperature for batch drying of banana slices in a two-stage heat pump dryer on drying kinetics and colour of the dried products. The results showed that stepping the air temperature up from an initial value of 20°C to finish drying at 35°C reduced colour degradation in the order of 40% as compared to 23% in case of stepped down temperature profile. Saving in drying time up to 180 minutes was also observed when air temperature was stepped down.

Preservation and control of genetic material in order to facilitate the fertilization process can be best achieved by drying at low temperature and low humidity prior to extraction of seeds and pollen. Chen *et al.* (2002) studied the use of a dehumidifier dryer for drying pine cones and pollen catkins and found the system to be effective and reliable with increased speed of drying and the quality of the product.

Alves-Filho (2002) reported that heat pump dryers could be applied in the production of a diversity of ready-to-eat foods and dried instant foods being energetically efficient, environmentally friendly and providing wide range of drying conditions as required to produce powders with improved characteristics.

Cardona *et al.* (2002) studied heat pump dryers as an alternative to freeze drying for dehydration of lactic acid bacteria for starter cultures. Results indicated that suitable combinations gave products at least equal to freeze drying and nitrogen purging gave significant improvement in activity.

Sosle *et al.* (2003) reported that apple dried in heat pump dryer exhibited better rehydration properties and lower water activity than hot air dried samples whereas, heat pump dryer assisted drying was more expensive as, much of the energy input was rejected at the secondary condenser as excess heat.

## 2.4 Drying of Chilli

Dehydration is one of the oldest methods of food preservation as well as an important food processing stage (Lima *et al.*, 2002). Dehydration of foods is aimed at producing a high density product, which when adequately packaged has a long shelf life, after which the food can be rapidly reconstituted without substantial loss of flavour, taste.

Drying of agricultural products under direct sunlight is the traditional way of preservation of a large number of fruits and vegetables. In most producing areas, weather conditions during harvest are not favourable for complete sun drying of fruits and vegetables to safe storage conditions. In addition to this, sun drying has many disadvantages such as dust, insects, likelihood of microbial cross contamination and spoilage resulting from rain during drying. All these factors call for artificial drying of agricultural products after harvesting to allow safe storage and retail distribution. Hot air drying is one of the usual unit operations in food processing which decreases drying time and is able to substantially preserve quality of the dried product (Maskan *et al.*, 2002)

To prevent loss of harvested green chillies during seasonal gluts and to assure returns to farmers and processors, it is important to preserve them by adopting suitable value-adding processing methods. This permits seasonal product to become available round the year. In most Asian countries, dehydrated vegetables are popularly used as ingredients in soups and are usually included in foods such as instant noodles. This means that a large market exists for dehydrated product. Green chillies and sweet pepper have a delicious capsicum flavour in addition to the hotness, which adds zest to various food preparations. Both red and green chillies can be used as fresh but dried chillies are also used extensively.

As far as preservation of vegetables is concerned, drying is the most widely used method for reducing water activity and microbial infection. Several workers have described the influence of pre-treatment and drying parameters on the quality of dried chilli and paprika. Colour plays an important role in assessing product quality. Rocha *et al.* (1993) reported that during thermal processing of green vegetables most common change that occurred, was the conversion of chlorophyll to pheophytins, causing a change of colour from bright green to olive brown. The retention of naturally coloured pigments in thermally processed and stored foods has been a major challenge in food processing. Several attempts have been made to stabilize the colour but with limited success (Ihl *et al.*, 1998).

#### 2.4.1 Effect of drying parameters

Air velocity and relative humidity were having very little influence on the drying conditions (Madamba *et al.*, 1996) and in thin layer drying, resistance to moisture movement at the surface is negligible compared to the internal resistance (Henderson and Pabis, 1962).

Ramesh *et al.* (2001) studied drying of paprika at 60°C and influence of various pre-processing steps. He suggested an optimum process of cutting and blanching the product for 3 minutes to facilitate higher retention of vitamin C, tocopherol, carotenoids and a higher ASTA value. He concluded that higher air velocities and lower relative humidities were desirable for reducing drying time in paprika due to relatively high diffusivities.

Nindo *et al.* (2003) evaluated five drying methods namely tray drying, spouted bed drying, combined microwave and spouted bed drying, refractive window drying and freeze drying to add value to green asparagus. He observed that tray dried asparagus were least green and retention of ascorbic acid was also least. The colour of the freeze dried product deviated the least whereas retention of ascorbic acid was highest in refractive window drying.

Chilli is generally harvested at very high moisture content ranging from 700 to 800%(d.b.) and dried to very low moisture content of 8-10%(d.b.) for storage and 4-5%(d.b.) for grinding purposes (Pruthi, 1993; Miaruddin *et al.*, 1995). It is essential to dry the chilli in a suitable environment to produce good quality (colour and pungency) dried product.

Lantz (1946) reported that slicing and slitting pods reduced the drying time by half and that there was no loss of initial colour on drying for 72 hours at 60-75°C. Lease and Lease (1962) carried out a more comprehensive study of effects of forced air-drying on Carolina hot pepper. Drying of sliced pods was found to have considerable advantages over whole pods; drying time was much reduced (50%) and a superior initial colour was obtained. The optimum drying temperature for a good quality product was found to be 65°C; single layers of succulent whole fruits dried to 8% moisture content in 12 hours, and in 6 hours when in sliced form. Extended drying was considered permissible at 50°C and at 65°C, but at 80°C a lowering of pungency, of initial colour and colour-retention properties was encountered. Rama Rao and Ojha

(1972) stated that freshly harvested chillies should be dried on the same day in thin layers at lower temperatures. Mishra (1972) reported that chillies dried at 60°C turned black and lost part of their pungency and glossiness; and recommended a range of temperatures, 45-50°C, as suitable. Drying operations of chillies could be made economical if drying time can be reduced by punching chillies.

#### **2.4.2 Effect of pre-treatment**

Considering the limitations associated with hot air drying, emphasis has been laid on the application of pre-drying treatments as a means to improve drying characteristics and minimise adverse structural and quality variations. Pre-treatment technique of surfactant impregnation, osmotic concentration and blanching are commonly employed within vegetable systems (Mazza, 1983).

Blanching constitutes a partial cooking process, most commonly in hot water or steam. Blanching of vegetable tissue is commonly implemented to denature enzymes responsible for undesirable reactions such as enzymatic browning and oxidation. Vegetables are typically blanched by subjecting them to steam or hot water (70-105°C) for a prescribed time to inactivate enzymes known to reduce quality. The effectiveness of this pre-drying treatment is adjudged in terms of the degree of enzyme inactivation, namely peroxidase activity in vegetables. Peroxidase, the most heat resistant enzyme in many plant-derived foods, is often used as an indicator of blanching process adequately (Anthon and Barrett, 2002). Further to promote quality enhancement, blanching is also beneficial in terms of a reduction in drying time, removal of intercellular air from the tissues, softening of texture and retention of ascorbic acid.

Alzamora and Chirife (1980) confirmed that moisture transport characteristics are dependent on the chemical composition of the blanched food systems. The authors reported a reduction in the rate of potato drying due to starch gelatinization, a significant enhancement in the drying behaviour of sugar beet, and only a slight increase in the drying rate of avocado. Thus it could be concluded that blanching rendered a variable influence on drying kinetics, reflecting the dissimilar tissue properties within food systems.

### 2.4.3 Drying characteristic

Drying is a complex thermo physical and biochemical process comprising simultaneous heat and mass transfer between the surface of the material and the surrounding media, and a transfer of heat and moisture within the material. The transfer of moisture from the interior pores of the material to its surface depends on the structure and the properties of the material. In the initial stages, the moisture removal is rapid since the excess moisture on the surface of the products presents a wet surface to the drying air. Subsequently drying depends upon the rate at which the moisture within the product moves to the surface by a diffusion process, depending upon the material to be dried (Hossain and Bala, 2002).

Modern methods for designing air drying operations require the mathematical description of food moisture movement during the process, known as drying kinetics (Hernandez *et al.*, 2000). Among the wide range of mathematical models, thin layer drying models have found wide application due to their easy of use. They do not require evaluation of many model parameters as is common in more complex representations (Madamba *et al.*, 1996).

Thin layer drying modeling contributes to the understanding of the drying characteristics of agricultural materials. Investigators developed theoretical, semi theoretical and empirical equations to express and explain the thin-layer drying of agricultural products. The theoretical approach concerns with either the diffusion equations or simultaneous heat and mass transfer equations. The empirical equations give satisfactory fit to all experimental data and take less computing time in comparison to the theoretical equations. The semi-theoretical equations are analogous to Newton's law of cooling which assumes that the drying rate is proportional to the difference between actual and equilibrium moisture content. Among these models, the theoretical approaches take into account only the internal resistance to moisture transfer while the semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air.

Many researchers have proposed numerous mathematical models for thin-layer drying of agricultural products.

Lewis (1921) introduced an equation analogous to Newton's law of cooling, of the form:

$$\frac{dM}{d\theta} = -K(M - M_{eq}) \quad (2.1)$$

Integrating Eq. (2.1), yields

$$\frac{M - M_{eq}}{M_0 - M_{eq}} = A' \exp(-K\theta) \quad (2.2)$$

Page (1949) proposed the following empirical equation that has been used successfully to describe drying behaviour of a variety of biological materials.

$$\frac{M - M_{eq}}{M_0 - M_{eq}} = \exp(-K\theta^{n'}) \quad (2.3)$$

Linear form of Eq. (2.3) is:

$$\ln[-\ln(MR)] = \ln(K) + n' \ln(\theta) \quad (2.4)$$

where,

$M$  = Moisture content at time  $t$ , %(d.b.)

$M_{0i}$  = Initial moisture content, %(d.b.)

$M_{eq}$  = Equilibrium moisture content, %(d.b.)

$MR$  = Moisture ratio

$K$  = Drying constant,  $h^{-1}$

$A'$ ,  $n'$  = Empirical coefficients

Linear regression of Eq. (2.2) and (2.4) was carried out using the least square's technique and the coefficients were determined.

Using Van Meel's concept (1958) of the characteristic drying curve, it is possible to present the drying rate curves of a given product, obtained under different air conditions, by a single normalized drying rate curve. This curve can be used to generalize data for drying kinetics of chilli and sweet pepper in heat pump and hot air dryer.

Several authors, based on the Van Meel transformation, have used simply the initial moisture content ( $M_{0i}$ ) and the equilibrium moisture content ( $M_{eq}$ ) to obtain moisture ratio  $MR$  and initial drying rate ( $-dM/d\theta$ ), to normalize the drying rate as follows:

$$MR = \frac{M - M_{eq}}{M_0 - M_{eq}} \quad (2.5)$$

$$f_{dr} = \frac{\left(-\frac{dM}{d\theta}\right)_\theta}{\left(-\frac{dM}{d\theta}\right)_i} \quad (2.6)$$

where,  $f_{dr}$  the dimensionless drying rate.

The drying process is mainly influenced by internal mechanisms of moisture flow caused by diffusion, shrinkage and external mechanisms like drying air temperature, velocity and humidity. During drying, heat is transferred to the surface of the product, part of it propagates to the interior and the remaining is utilized in evaporation of moisture from the surface. Similarly, the moisture from the interior diffuses to replace the evaporated moisture at the surface. It is generally assumed that the mechanism of moisture movement during thin layer drying of biological materials is governed by diffusion as described by Fick's second law of diffusion (Saravacos, 1995).

Hossain and Bala (2002) studied thin layer drying of green chilli under overflow-underflow and through flow conditions with air temperature ranging from 40-55°C, relative humidity ranging from 10-60% and air velocity ranging from 0.1 to 1.0 m/s. He observed that Page equation described the drying characteristics of chilli better than single exponential equation and expressed the parameters of both the equations as a function of drying air temperature, relative humidity and air velocity.

Erenturk *et al.* (2004) studied the influence of air temperature range of 50-80°C, air velocity range of 1.67-3.10 m/s and air absolute relative humidity range of 0.005-0.08 kg vapour per kg dry air on the thin-layer drying of rosehip. They fitted six mathematical models available in the literature to the experimental data and concluded that the logarithmic model represented the drying characteristics better than the other equations.

Lahsasni *et al.* (2004) observed that experimental drying curves in thin-layer solar drying of prickly pear cladode showed a falling rate period and drying air temperature was the main factor in controlling the drying rate. From the eight different drying models studied, the Page model satisfactorily described the solar drying curves with an  $R^2$  of 0.9995.

## 2.5 Quality of dehydrated chilli

Selection of proper drying conditions is necessary for minimizing thermal stress, over-drying and maintenance of relevant compounds (carotenoids, vitamin C, tocopherols, capsaicin), which determine the quality of the product (Kim *et al.*, 1982; David, 1982). It was reported that drying at low temperature did not alter the properties of the product significantly and drying at higher temperature drastically reduced the vitamin content (Tong and Lund, 1990).

### 2.5.1 Rehydration behaviour

The time taken to reconstitute a dried vegetable and its appearance are two important physical factors that need special attention, when designing, selecting or evaluating a given drying process. The ability of food products to reconstitute in piece form, such as sliced or diced vegetables, depends primarily on the internal structure of the dried pieces and the extent to which the water holding components (proteins and starch) have been damaged during drying (Brennan *et al.*, 1990). With hot air drying, higher drying rate at the initial stage may cause hardening of the product surface and result in loss of ability for fast reconstitution.

Somogyi and Luh (1988) reported a study on the effect of drying methods on quality of dehydrated green asparagus in which it was observed that freeze-dried green asparagus with hot water blanching was faster in reconstitution and more tender in texture than the hot-air dried product. Drying of vegetables with hot air usually results in considerable shrinkage and formation of dense structure.

### 2.5.2 Chlorophyll content

The colour of green vegetable is contributed primarily by chlorophyll. Chlorophyll is a coordination compound between magnesium and the tetrapyrrole ring. The stability of the coordination complex is directly related to the stability of the green colour of vegetables. The blanching of vegetables help to maintain their green colour by inactivating enzymes, such as peroxidases, lipases and lipoxygenases, that convert chlorophyll to pheophytins. The replacement by hydrogen of the magnesium atom in chlorophyll results in pheophytins, which appear brownish-green. One way to help stabilize chlorophyll in processed vegetables is to maintain an alkaline pH during blanching and to reduce the loss of magnesium by maintaining a high concentration of magnesium in the environment (Chin and Dudek, 1988).

Luhadiya and Kulkarni (1978) investigated the effect of pre-treatment and hot air drying on chlorophyll retention and rehydration characteristics of green chilli. They reported that the pre-treatment with 2% lye solution, washing and drying at 60°C gave the best product.

Giridhar *et al.* (1996) reported that the distinct aromatic odour, colour and pungency were seldom carried over to the dehydrated spice-vegetable (chilli, onion, garlic, coriander) products. The chemicals responsible for the delicate odours and attractive colours of spice-vegetables are highly heat sensitive and are lost during dehydration (Pezzutti and Crapiste, 1997). The chlorophyll degradation involves the loss of phytol to form chlorophyllide, loss of  $Mg^{2+}$  to form pheophytin, the loss of  $Mg^{2+}$  and phytol to form pheophorbide, and the loss of  $Mg^{2+}$  and carbomethoxy group to form pyropheophytin (Von Elbe, 1986). Ahmed *et al.* (2000) used the colour loss during thermal processing as a basis to evaluate the quality of green chilli puree.

Strahm and Flores (1994) also studied drying and colour kinetics of low-grade green asparagus during heated air-drying and observed similar trends. Krokida *et al.* (2001) reviewed the effect of hot air, vacuum, microwave, freeze and osmotic drying on the colour of dehydrated agricultural commodities and stated that the browning of fruits and vegetables during drying is due to both enzymatic and non-enzymatic browning reactions. Browning is usually a negative quality attribute, but other studies show that overall antioxidant properties of certain foods may be enhanced due to formation of melanoidins during the advance steps of the Maillard reaction (Anese *et al.*, 1999a and b).

### 2.5.3 Ascorbic acid content

Ascorbic acid, one of the most labile nutrients in vegetables, is water soluble, pH-, light and heat sensitive, readily oxidized and affected by the naturally occurring enzyme system, ascorbic acid oxidase (Klein, 1992). Preservation of ascorbic acid in vegetables, particularly those which are good sources, is important in preserving food quality. Ascorbic acid acts as a chemical reductant due to its quinone-reducing capacity and prevent the formation of coloured polymers.

Important components of vegetables include vitamins, particularly those which act as antioxidant. Of the antioxidant compounds, ascorbic acid and  $\beta$ -carotene have been identified as potential anticarcinogen as well as antioxidant. The processing

and storage condition greatly affect, the antioxidant activity of many processed products. Loss of ascorbic acid and carotenoids are also one of the main limiting factors of nutritional quality (Kaur and Kapoor, 2001).

Ascorbic acid is an important nutrient in vegetables. It is more sensitive to heat, oxygen and light than most other components in asparagus such as vitamin A, E or some phenolic compounds. Ascorbic acid can also act as a synergist with tocopherols by regenerating or restoring their antioxidant properties (Yanishlieva-Maslarova, 2001). Depending on the type of process, product physical properties and the time-temperature regimes used, thermal energy can cause varying degrees of loss of vitamin C during drying of green vegetables. Generally, if a process for drying vegetables takes place at a low temperature and within a short time, relatively high retention of the heat-labile vitamin C is expected (Nindo *et al.*, 2003).

Because vitamin C is relatively unstable to heat, oxygen and light, the retention of vitamin C is used often as an indicator of the quality of processed foods. If ascorbic acid is retained well, other nutrients also will be retained well (Bender, 1966). Blanching inactivates ascorbic acid oxidase and stabilizes vitamin C (Benterud, 1977). Odland and Eheart (1975) reported that total ascorbic acid was more adversely affected by water blanching than by steam blanching and 17 to 25% loss of vitamin C was reported due to blanching.

Vitamin C is highly water soluble and as there is no contact with water most of the vitamin C is retained. It is also observed that blanched product retain higher vitamin C because of increased tocopherol which acts as antioxidant during blanching. However, by washing much of the vitamin C is lost (Ramesh *et al.*, 2001).

Ade-Omowaye *et al.* (2002) reported that air drying reduced vitamin C to approximately 5% of initial concentration while increasing temperature (25-55°C) during osmotic dehydration decreased residual vitamin C concentration after osmotic dehydration from 20% to 4% of initial value.

#### **2.5.4 Pungency and flavour**

Pordesimo *et al.* (2004) observed that drying temperature ranging from ambient (27°C) to 85°C and physical state of the pepper when dried (whole or cut) did not affect the concentration of total capsaicinoids in dried peppers.

Luning (1995) described the flavour compounds of fresh and hot air dried bell peppers as well as the behaviour of volatile compounds during hot air drying. He reported that the levels of glucose, fructose, ascorbic, citric and oxalic acid decreased, while the levels of sucrose, malic, fumaric and cis-aconitic acid increased. Hot air drying decreased the intensity of scores of several characteristic fresh aroma attributes. In the green and white fruits, mainly 'green' attributes like herbal, grassy, green bell pepper and cucumber decreased after drying.

## 2.6 Storage Characteristics

### 2.6.1 Moisture sorption study

All food contain water, and it is well recognized that those most susceptible to physical and chemical degradations are of high water content. During long term storage of food, important physico-chemical and biological changes take place with a strong impact on the nutrient properties. To a large extent these changes depend on the moisture content of food. (Hentges *et al.*, 1991). A hygroscopic food stuff contains water in both bound and unbound forms that can influence its structure and texture. The unbound water can also affect the stability of the food stuff, by determining the extent to which bacteria thrive and degradation reactions occur within it. The relationship between water activity and the moisture content in food at a constant temperature is often expressed as sorption isotherm. For food materials these isotherms give information about the sorption mechanism and the interaction of food biopolymers with water. The moisture sorption isotherms are extremely important in modeling the drying process, in design and optimization of drying equipment, in predicting shelf-life stability, in calculating moisture changes which may occur during storage and in selecting appropriate packaging materials (Gal, 1987). These are also used to predict energy requirements and determine proper storage conditions (Myhara *et al.* 1998).

If the storage environment has a partial pressure of water vapour above or below the vapour pressure of water at the food stuff surface, water is adsorbed or desorbed, respectively. Up to water activity of about 0.3 it is considered that water is held on polar sites of relatively high energies. This is called the monolayer. The water activity in the range of 0.30 to 0.70 is referred to multilayer water. It consists of layers of water which are adsorbed onto the first layer hydrogen bonds. There is a capillary

sorption region above a water activity of 0.7 and water is relatively free water (Lahsasni *et al.*, 2002). The monolayer moisture content has a significant importance for the physical and chemical stability of dehydrated materials (Menkov, 2000).

Thermodynamic properties of food are crucial in the analysis of heat and mass transfer phenomenon during dehydration. They determine the end point to which food must be dehydrated in order to achieve a stable product with optimal moisture content and yield a figure for the theoretical minimum amount of energy required to remove a given amount of water from food. The properties also provide insight into the microstructure associated with the food-water interface (Rizvi, 1986).

In studying the behavior of food or agricultural commodities during storage and processing, it is important to have information on equilibrium moisture constant (EMC) which is defined as the moisture content of a hygroscopic material in equilibrium with a particular environment (Temperature and RH). The hysteresis effect is the difference between desorption and adsorption EMC values for the same equilibrium relative humidity (ERH). Sorption isotherms for a food product over the full range of water activity form a hysteresis loop in which the desorption curve lies above the adsorption curve (Shatadal and Jayas, 1992).

Kaleemullah and Kailappan (2004) studied the equilibrium moisture contents for red chillies using the static method at 25, 35 and 45°C over the range of relative humidities from 0.115 to 0.865. They found that sorption capacity of chillies decreased with an increase in temperature at constant relative humidity, sorption isotherms exhibited the phenomenon of hysteresis and Kaleemullah model could be used with good predictive accuracy.

Arslan and Togrul (2005) examined the moisture isotherms of crushed chillies at 25, 35 and 45°C and within the range of 0.1 to 0.8 water activity and analysed the data to fit different models. They determined the water activities corresponding to the monolayer values and found that the isosteric heats of desorption were higher than the isosteric heats of adsorption.

#### **2.6.2 Storage under different conditions**

Gonzalez-Aguilar *et al.* (2004) stored fresh-cut peppers under modified atmospheric packaging (MAP) and vacuum packages at 10 and 5°C and observed that ascorbic acid did not change apparently at 10°C and highest values were showed

during storage at 5°C. He concluded that storage temperature was a detrimental factor that significantly affected ascorbic acid retention. It is reported that the stability of the main carotenoids of paprika during storage is dependent on drying conditions and the degradation rate increases as the drying temperature increases. (Malchev *et al.*, 1982).

Pura Naik *et al.* (2001) studied the storage behaviour of 'Guntur' and 'Byadigi' varieties of chillies in high density polyethylene (HDPE) and metallised polyester polyethylene (MPP) and revealed that MPP stored samples retained higher colour than HDPE. The discolouration of the red pigments of chillies during storage was greatly influenced by moisture and temperature. The capsaicin content showed a decreasing trend irrespective of storage conditions, packages and varieties.

From the literature reviewed, it was observed that the information available on effect of dehumidified air drying of green chilli and sweet pepper at near ambient temperature on the drying characteristics and quality aspects is meager. As the research work on effect of pretreatment and dehumidified air drying of green chilli on product quality is lacking, the present research was undertaken in this direction.

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**CHAPTER III**  
**THEORITICAL**  
**CONSIDERATIONS AND DESIGN**

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## THEORITICAL CONSIDERATIONS AND DESIGN

This chapter describes the basic definitions, principle of heat pump assisted dehumidified air dryer and various processes involved in this system using psychrometric chart and pressure-enthalpy chart. It also describes the detailed mathematical models and design procedure of a heat pump assisted batch type dryer. The model takes into account the heat and mass transfer phenomena taking place in all components of the system.

### 3.1 Basic Definitions

Dehumidification	: Removal of moisture from air
Isenthalpic process	: Constant enthalpy process
Isentropic process	: Reversible adiabatic process during which entropy remains constant
Isothermal process	: Constant temperature process
Refrigerant	: Working substance used in a refrigerating system
Evaporator	: Heat exchanger that provides heat transfer surface through which heat can pass from the refrigerated space into the vaporising refrigerant
Condenser	: Heat exchanger that provides heat transfer surface through which heat passes from the condensing refrigerant to the surrounding medium
Compressor	: Device which draws refrigerant vapour from the evaporator and raises its temperature and pressure and maintains continuous flow of the refrigerant through the system
Expansion device	: Device which supplies refrigerant to the evaporator after reducing its pressure

### 3.2 Heat Pump Assisted Dehumidified Air Dryer

Drying, one of the oldest forms of food preservation is an energy-intensive process. Conventional hot air dryers being simple are widely used for fruit and vegetable drying. In these dryers, the exhaust humid air is vented to the atmosphere, which results in loss of both the sensible and latent heat of vaporization of its moisture content. However, the high drying temperature usually causes low quality of products due to excess thermal damage and structural changes in the product. Heat pump assisted dryers are an alternative method for drying food products with lower energy consumption, less relative humidity, and lower temperature.

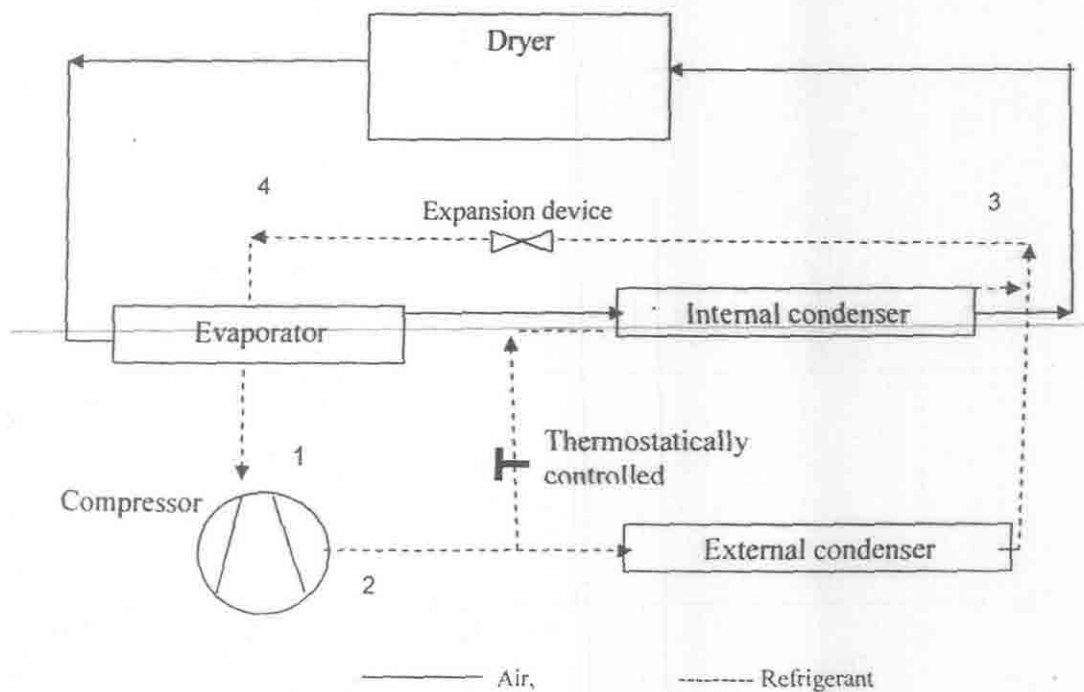
Heat pump application in drying possesses two-fold beneficial characteristics. Through the evaporator, the heat pump recuperates sensible and latent heat from the dryer exhaust, hence the energy is recovered. Condensation of moisture occurring at the evaporator reduces the humidity of the working air, thus increases the driving force for product drying. For specialty crops the optimum drying temperature at which no structural damage and nutrient losses occurs lies between 30 to 45°C (Adapa *et al.*, 2002). The heat pump drying technology can be used to dry heat sensitive food products requiring low temperature drying and in tropical countries where the level of air humidity is high. Many researchers have acknowledged the importance of heat pump drying in producing a range of precise drying conditions to dry a wide range of heat-sensitive products.

#### 3.2.1 Working principle

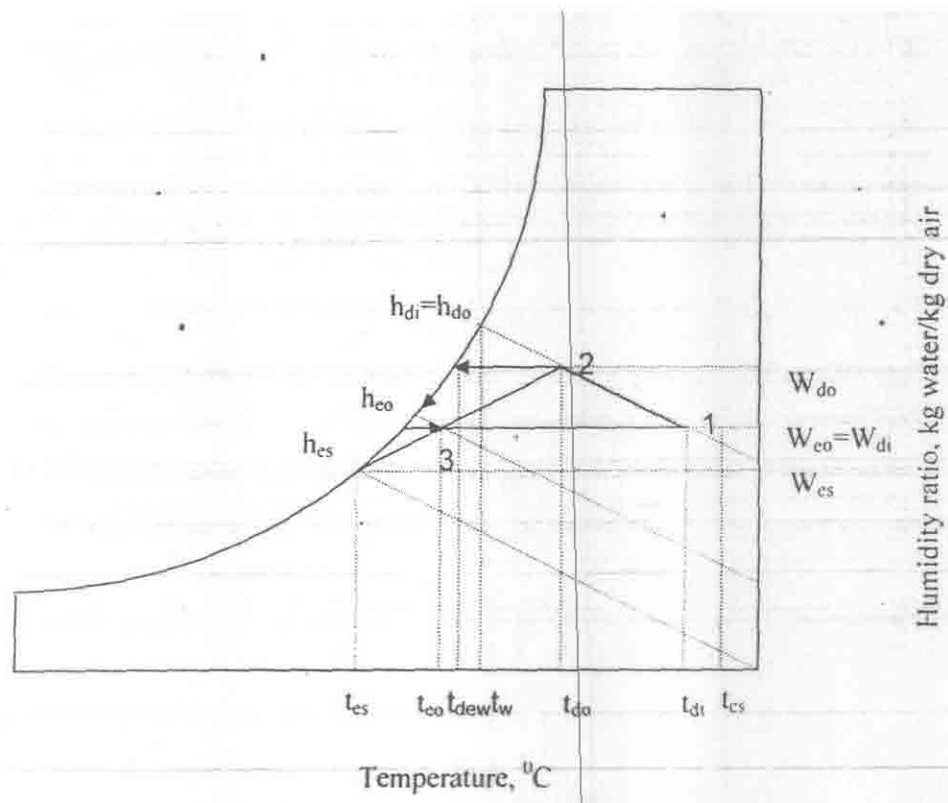
A heat pump assisted batch dryer consisting of air and refrigerant circuit is modeled for the study as shown in Fig. 3.1. The air cycle on psychrometric chart is given in Fig. 3.2. The inlet drying air passes through the drying chamber at point 1 and picks up moisture from the product. The moisture-laden air at point 2 is then directed to the evaporator coil. During the dehumidification process from point 2 to 3, the air is first cooled sensibly to its dew point. Further cooling results in water being condensed from the air. Latent heat of vaporisation is then absorbed by the evaporator for boiling of the refrigerant. The recovered heat is “pumped” to the condenser. The cooled and dehumidified air then absorbed the heat at internal condenser moving from point 3 to 1 for sensible heating to the desired temperature.

In the air circuit the moist hot air leaving the dryer is directed to pass through the evaporator, where dehumidification takes place. The air leaving the evaporator is heated in the condenser and then passed to the dryer for drying the product. The temperature profile of air and refrigerant in the evaporator and condenser is shown in Fig. 3.3.

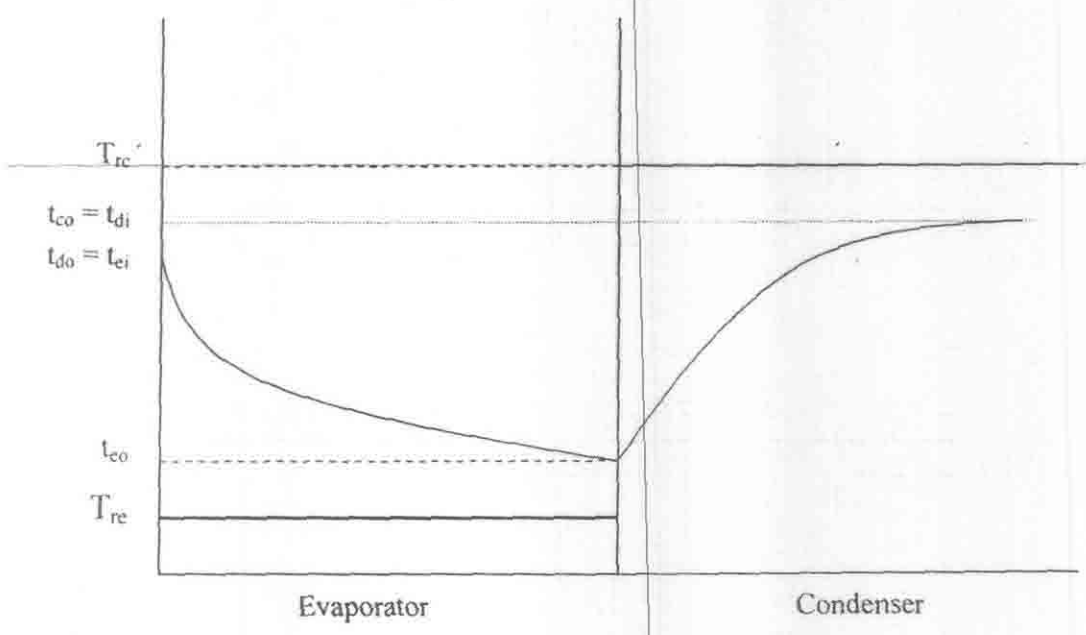
The pressure-enthalpy and temperature-entropy diagram of the refrigerant cycle is shown in Figs. 3.4 and 3.5. In the refrigerant circuit, the working fluid is evaporated (4-1) in the evaporator on gaining both latent and sensible heat from the air, and is then compressed (1-2) to give up heat in the condenser (2-3) to the circulating air. The high-pressure and high-temperature liquid is then expanded (3-4) through an expansion device into a mixture of vapour and liquid at low pressure and temperature.



**Fig. 3.1 Schematic diagram of heat pump dryer configuration with air and refrigerant circuit**



**Fig. 3.2 Psychrometric chart showing air cycle in the heat pump dryer**



**Fig. 3.3 Temperature profile of air and refrigerant in evaporator and condenser**

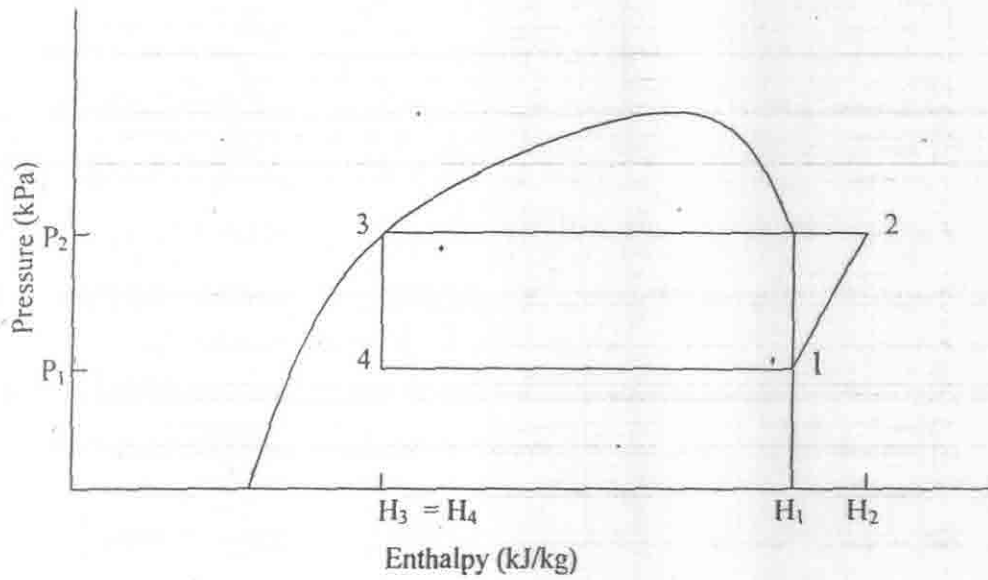


Fig. 3.4 Pressure-enthalpy diagram of the refrigerant cycle in the heat pump

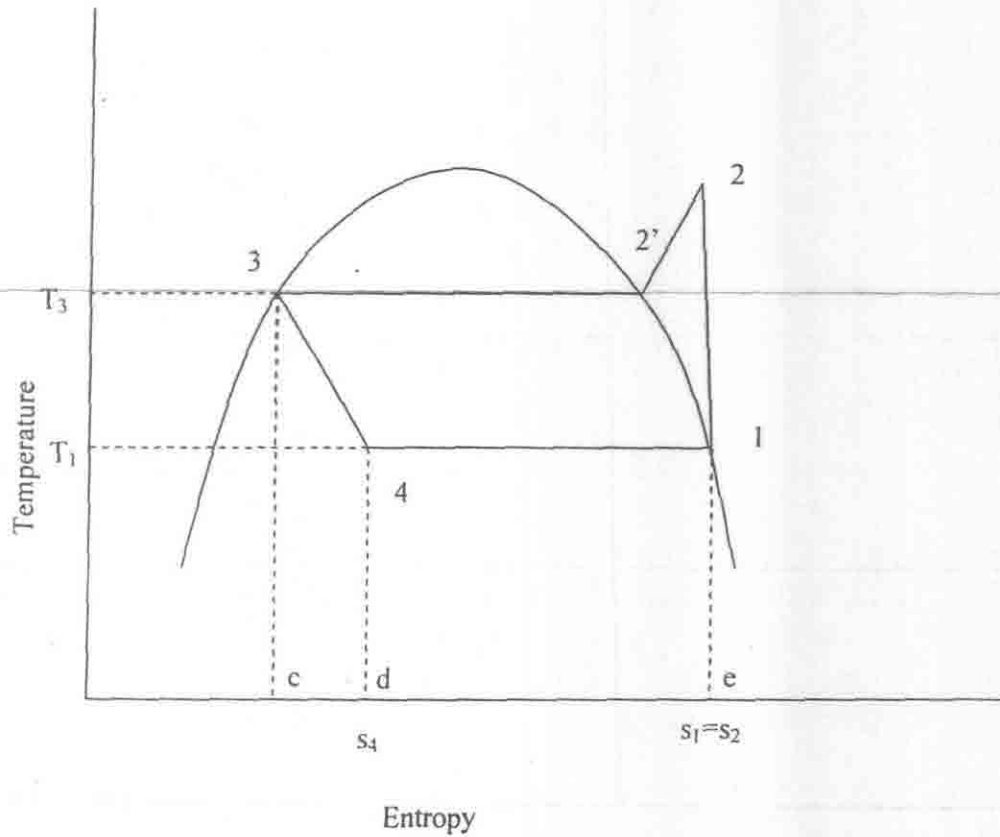


Fig. 3.5 Temperature-entropy diagram of the refrigerant cycle in the heat pump

### 3.2.2 Review on mathematical modelling of heat pump dryer

Heat pump air dehumidifier coupled with a dryer is a complex system since all components are interdependent. Jolly *et al.* (1990) reported a mathematical model of a heat pump assisted continuous dryer. This model was used by Jia *et al.* (1990) to investigate the performance of a heat pump assisted continuous dryer. Clements *et al.* (1993) used the model developed by Jolly *et al.* (1990) to predict the performance of a heat pump assisted continuous dryer. Prasertsan *et al.* (1996) developed a detailed mathematical model and used the model to simulate the results (Prasertsan *et al.*, 1997). Achariyaviriya *et al.* (2000a) had developed an empirical model of heat pump dryer to study the performance. Teeboonma *et al.* (2003) developed mathematical models for papaya and mango glaze drying using heat pump dryer and optimized the conditions to minimise annual total cost per unit of evaporated water. Saensabai and Prasertsan (2003) studied the effects of component arrangement and ambient and drying conditions on the performance of heat pump dryers.

### 3.3 Mathematical Models

The following assumptions are made for modeling of the heat pump assisted batch dryer.

#### *Heat pump unit*

1. The refrigerant at outlet of evaporator and condenser are saturated vapour and saturated liquid, respectively.
2. The compression and the expansion of the refrigerant are isentropic and isenthalpic processes, respectively.
3. The tubes connecting the heat pump components are insulated and the pressure drop in the pipe system is negligible.
4. The wall of the component housing is adiabatic.
5. Heat pump is operated at steady state.

#### *Dryer unit*

1. The air duct and drying chamber are thermally insulated.
2. Ambient conditions and specific heat capacity of air are constant.
3. The dryer is in a steady state condition.
4. Pressure of air in the system is constant at 1atm and mass flow rate of circulating dry air is constant.

5. Drying process is under constant rate period and working air in this period follows the constant wet bulb temperature line in the psychrometric chart.
6. Thermal equilibrium exists between the drying air and product.
7. The condition of air entering the evaporator is same as that leaving the dryer and air entering the dryer is same as that leaving the condenser.

The mathematical model of a heat pump dryer consists of three submodels, namely, drying models, heat pump models and performance models. Heat and mass balance of both refrigerant and air circuits are used for development of mathematical models.

### 3.3.1 Drying model

$$\theta_{dr} m_a (W_{do} - W_{di}) = m_p (M_{\theta i} - M_{\theta f})/100 \quad (3.1)$$

$$c_{pa} t_{di} + W_{di} (h_{fg} + c_{pv} t_{di}) = c_{pa} t_{do} + W_{do} (h_{fg} + c_{pv} t_{do}) \quad (3.2)$$

During drying, moisture content decreased with drying time. As moisture content of product is a function of drying time ( $\theta$ ), it can be predicted from the drying equations at a particular time for a given drying air temperature.

$$MR = A \exp(-K\theta) \quad \text{and} \quad K = f(t) \quad (3.3)$$

The final moisture content of the product after drying is the desorption equilibrium moisture content of the product corresponding to the drying air condition. The final moisture content under the given drying air condition can be predicted from equilibrium moisture content equation for the concerned product as expressed in the form of BET model.

$$\frac{RH}{(1-RH)M_{eq}} = \frac{1}{CM_m} + \frac{(C-1)}{CM_m} RH \quad (3.4)$$

where,  $M_m$  and  $C$  are function of temperature.

The properties of moist air leaving the drying chamber at different time intervals can be calculated using above equations for dynamic modeling of the system.

### 3.3.2 Heat pump model

The basic heat pump model includes component models for evaporator, compressor, condenser and capillary tube. For given system geometries, bypass factor

and conditions of air entering the evaporator, the model can predict the air conditions leaving the condenser to the dryer and performance of the heat pump system.

### Evaporator model

The mass and energy balance on evaporator can be used for the development of mathematical model.

$$m_{we} = m_a (1-BF) (W_{do} - W_{es}) \quad (3.5)$$

$$Q_e = m_a (1-BF) (h_{do} - h_{es}) - m_{we} h_{we} = m_r (H_1 - H_4) \quad (3.6)$$

The forced convection heat transfer co-efficient on the air side of a flat finned tube coil is calculated by the correlation proposed by Rich (1973).

$$\alpha_a = 0.195 G_a c_{pam} Pr_a^{-2/3} Re_a^{-0.35} \quad (3.7)$$

$$Re_a = \frac{G_a l_r}{\mu_a} \quad (3.8)$$

$$Pr_a = \frac{c_{pam} \mu_a}{k_a} \quad (3.9)$$

This correlation is suitable for the range of  $118 < N_{fin} < 787$  fins per metre.

For forced convection evaporation, the heat transfer co-efficient of refrigerant is evaluated by Pierre's (1955) correlation.

$$\alpha_{re} = 9.1825 \frac{k_l}{D_i} \cdot \left( \frac{D_i G_f}{\mu_l} \right)^{0.8} K_f^{0.4} \quad (3.10)$$

$$K_{if} = \frac{\nabla x H_{fg}}{L_i} \quad (3.11)$$

$$U = \frac{1}{\frac{1}{\alpha_a \eta_f} + \frac{A_o}{A_i \alpha_r} + \frac{A_o \ln(D_o/D_i)}{2\pi k_m L_i}} \quad (3.12)$$

$$LMTD_e = \frac{(t_{do} - t_{eo})}{\ln \left( \frac{t_{do} - T_{re}}{t_{eo} - T_{re}} \right)} \quad (3.13)$$

$$Q_e = U_e A_e (LMTD)_e \quad (3.14)$$

### Compressor model

$$E_{\text{comp}} = m_r (H_2 - H_1) / (\eta_{\text{mech}} \eta_{\text{motor}}) \quad (3.15)$$

$$\nabla H = \frac{P_1 v_{r1}}{3600} \left( \frac{n}{n-1} \right) \left\{ \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right\} \quad (3.16)$$

$$n = a_{31} + a_{32} T_1 + a_{33} T_1^2 + a_{34} T_1 (T_2 - T_1) + a_{35} T_1^2 (T_2 - T_1) + a_{36} T_1 (T_2 - T_1)^2 + a_{37} T_1^2 (T_2 - T_1) + a_{38} (T_2 - T_1) \quad (3.17)$$

$$m_r = \frac{\pi d_r^2 l_p N_p \eta_c N_s}{240 v_{r1}} \quad (3.18)$$

$$\eta_v = 1 + n - n \left( \frac{P_2}{P_1} \right)^{\frac{1}{n}} \quad (3.19)$$

### Condenser model

$$Q_c = m_r (H_2 - H_3) \quad (3.20)$$

$$Q_{c,\text{int}} = m_a (c_{pa} + W_{d1} c_{pv}) (t_{co} - t_{eo}) \quad (3.21)$$

Finally, the energy balance of the heat pump dryer system is given by Eq.(3.22)

$$Q_c = Q_e + \nabla H = Q_{c,\text{int}} + Q_{c,\text{ext}} \quad (3.22)$$

The heat transfer co-efficients of the refrigerant side of the condenser for single-phase are calculated as follows (ASHRAE, 1981).

$$\alpha_{rc} = 0.023 \frac{k_f}{D_i} \left( \frac{G_f D_i}{\mu_f} \right)^{0.8} \left( \frac{\mu_f c_{pf}}{k_f} \right)^{0.4} \quad (3.23)$$

The air side forced convection heat transfer coefficient is calculated from Eq. 3.7 and overall heat transfer co-efficient can be calculated using Eq.(3.12).

$$LMTD_c = \frac{(t_{ca} - t_{eo})}{\ln \left( \frac{T_{rc} - t_{eo}}{T_{rc} - t_{ca}} \right)} \quad (3.24)$$

$$Q_c = U_c A_c (LMTD)_c \quad (3.25)$$

### Capillary tube model

In this model, capillary tube is used as the expansion device for pressure reduction. The expansion process is assumed to be isenthalpic, i.e.

$$H_3 = H_4 \quad (3.26)$$

The temperature drop in the capillary tube is divided into a number of parts. The frictional pressure drop and friction factor of each part is calculated and the required length of capillary tube is determined using Eq. (3.27) and (3.28) as solved by Arora (1981).

$$\Delta P_r = \frac{\rho_r f_r \nabla L u_r^2}{2D} \quad (3.27)$$

$$f_r = \frac{0.32}{Re_r^{0.25}} \quad \text{for turbulent flow} \quad (3.28)$$

### Fan power

The air side pressure drops are calculated using the following equation

$$\Delta P_a = \frac{2f_a l_{ad} G_a^2}{D \rho_a} \quad (3.29)$$

The friction factor,  $f_a$  of air in the evaporator, condenser and air duct is determined by the correlations of Turaga *et al.* (1988) and ASHARE (1981). Dynamic pressure losses in ducts due to change in direction and velocity are also calculated to determine fan total pressure.

$$\text{Fan power requirement } (E_{fan}) = \text{Fan total pressure} \times \text{Volumetric air flow rate} \quad (3.30)$$

### 3.3.3 Performance model

The drying and dehumidification performance of the system is evaluated by the co-efficient of performance (COP) of the heat pump and the specific moisture extraction rate (SMER) and moisture extraction rate (MER) of the dryer.

$$\text{COP} = \frac{\text{Heat delivered in internal condenser}}{\text{Power input to compressor}} \quad (3.31)$$

$$\text{SMER} = \frac{\text{Water evaporated from product}}{\text{Total energy input}} \quad (3.32)$$

$$\text{MER} = \frac{\text{Water evaporated from product}}{\text{Drying time}} \quad (3.33)$$

### 3.4 Design of Heat Pump Dryer

#### Design data and assumptions

1. Required drying air temperature and relative humidity
2. Amount of material to be dried per batch
3. Initial and final moisture content of the product
4. Required drying time
5. Assumption of bypass factor to be 0.2 for evaporator and condenser coil
6. Assumption of temperature difference of 5°C between refrigerant and heat exchanger surface
7. Fin efficiency of 90% is assumed.
8. Mechanical and motor efficiency of compressor is assumed to be 95 and 85%, respectively.

#### Design calculations

Step 1: Calculation of rate of moisture removal from the product during drying

$$m_{wd} = \frac{m_p (M_a - M_{af})}{100 \theta_{dr}} \quad (3.34)$$

Step 2: Calculation of the humidity ratio, specific heat, enthalpy, specific volume and wet bulb temperature of drying air using following empirical expressions developed for steam table by Martin (1961) and Steltz <sup>Silvestri</sup> and (1958) and as shown in an example solved through MS EXCEL spread sheet by Singh and Heldman (2001).

$$p_{sd} = 6.895 \exp \left( 8.0728362 + \frac{X_d (b_1 + b_2 X_d + b_3 X_d^2)}{(1 + b_4 X_d)((t_d \times 1.8 + 32) + 459.688)} \right) \quad (3.35)$$

$$\text{where, } X_d = (t_d \times 1.8 + 32) - 705.398 \quad (3.36)$$

$$p_d = RH \times p_{sd} \quad (3.37)$$

$$W_{di} = \frac{0.622 p_d}{101.325 - p_d} \quad (3.38)$$

The wet bulb temperature is assumed to be less than the dry bulb temperature of drying air. Saturation vapour pressure at assumed wet bulb temperature is

calculated using Carrier equation (Eq. 3.39) and corresponding saturation temperature from Eq.(3.40) by successive iteration method to obtain the wet bulb temperature.

$$p_{sw} = \frac{p_d(1555.56 - 0.722t_w) + 101.325(t_d - t_w)}{1555.56 + t_d - 1.722t_w} \quad (3.39)$$

$$t_s = \frac{6687.848}{50.10987 - \ln(p_s) - 4.655564 \ln(t_s + 273.15)} - 273.15 \quad (3.40)$$

$$v_a = (0.082t_d + 22.4) \times \left( \frac{1}{29} + \frac{0.023}{18} \right) \quad (3.41)$$

$$c_{pam} = 1.005 + 1.88W_{di} \quad (3.42)$$

Step 3: Calculation of the heat requirement for drying, mass and volumetric flow rate of drying air required

$$Q_{dr} = m_{wd} \times h_{fgw} \quad (3.43)$$

$$m_a = \frac{Q_{dr}}{c_{pam}(t_d - t_w)\theta_d} \quad (3.44)$$

$$V_a = v_a \times m_a \quad (3.45)$$

Step 4: Calculation of the humidity ratio and temperature of air at dryer outlet using Eqs. (3.1) and (3.2), respectively.

Step 5: Determination of the partial water vapour pressure of dryer exhaust air and the dew point temperature

Partial water vapour pressure of dryer exhaust air is calculated from  $W_{do}$  using Eq. (3.38). Dew point temperature is assumed less than the dry bulb temperature of exhaust air. At dew point temperature,  $p_d$  is saturated pressure and corresponding saturated temperature can be calculated from the assumed value of dew point temperature using Eq.(3.40) by iteration till two consecutive readings are approximately same.

Step 6: Calculation of the humidity ratio, saturated vapour pressure of air in close contact with evaporator surface and evaporator surface temperature from the bypass factor.

$$W_{es} = \frac{W_{di} - BF \times W_{db}}{1 - BF} \quad (3.46)$$

$$P_{re} = \frac{W_{es} \times 101.325}{0.622 + W_{es}} \quad (3.47)$$

Evaporator surface temperature ( $t_{es}$ ) is assumed to be less than the dew point temperature of exhaust air from dryer and find out the corrected value by successive iteration method using Eq. (3.40).

Step 6: Calculation of the refrigerant temperature inside evaporator and air temperature at evaporator outlet.

$$T_{re} = t_{es} - 5 \quad (3.48)$$

$$t_{e0} = t_{es} + BF (t_{d0} - t_{es}) \quad (3.49)$$

Step 7: Calculation of condenser surface temperature and refrigerant temperature inside condenser

$$t_{cs} = \frac{(t_{d1} - BF \times t_{e0})}{(1 - BF)} \quad (3.50)$$

$$T_{rc} = t_{cs} + 5 \quad (3.51)$$

Step 8: Calculation of saturated suction and delivery pressure corresponding to refrigerant temperature inside evaporator and condenser, enthalpy of refrigerant at point 1,2,3 and 4 using empirical correlations given by Cleland(1988) and as shown in an example solved through MS EXCEL spread sheet by Singh and Heldman (2001).

$$P_s = \frac{\exp\left(a_1 + \frac{a_2}{T_s + a_3}\right)}{1000} \quad (3.52)$$

$$H_3 = (a_4 + a_5 T_{rc} + a_6 T_{rc}^2 + a_7 T_{rc}^3) / 1000 \quad (3.53)$$

$$H_1 = (a_8 + a_9 T_{re} + a_{10} T_{re}^2 + a_{11} T_{re}^3 + a_{12}) / 1000 \quad (3.54)$$

$$v_{r1} = \exp\left(a_{19} + \frac{a_{20}}{T_{re} + 273.15}\right) (a_{21} + a_{22} T_{re} + a_{23} T_{re}^2 + a_{24} T_{re}^3) \quad (3.55)$$

$$H_2 = H_1 + \nabla H \quad (3.56)$$

$$H_3 = H_4 \quad (3.57)$$

$\nabla H$  is calculated from Eqs. (3.16) and (3.17).

Step 9: Calculation of the enthalpy of air at dryer, evaporator and condenser outlet using following equation.

$$h = c_{pa}t + W (h_{fg} + c_{pv}t) \quad (3.58)$$

Step 10: Calculation of the cooling load on the evaporator and required refrigerant flow rate

$$\text{Cooling load} = m_a(h_{do} - h_{eo}) \quad (3.59)$$

$$m_r = \text{cooling load} / (H_1 - H_4) \quad (3.60)$$

Step 11: Calculation of power requirement of compressor using Eq.(3.15) and piston displacement using following equation.

$$V_p = m_r \times v_{r1} / \eta_v \quad (3.61)$$

Step 12: Calculation of the heating load on internal condenser and refrigerant flow rate in internal and external condenser

$$\text{Heating load} = m_a(h_{di} - h_{eo}) \quad (3.62)$$

$$m_{r,intc} = \text{Heating load} / (H_2 - H_3) \quad (3.63)$$

$$m_{r,extc} = m_r - m_{r,intc} \quad (3.64)$$

Step 13: Calculation of SMER, COP and dryer efficiency

$$\text{SMER} = \frac{m_{wd}}{E_{comp} + E_{fan}} \quad (3.65)$$

$$\text{COP} = \text{Heating load} / E_{comp} \quad (3.66)$$

$$\eta_d = \frac{t_{di} - t_{do}}{t_{di} - t_w} \quad (3.67)$$

Step 14: Calculation of the air side and refrigerant side heat transfer co-efficient for evaporator and condenser using empirical Eqs. (3.7), (3.10) and (3.23). Calculation of the overall heat transfer co-efficient and LMTD value for both evaporator and condenser and determination of the required evaporator and condenser finned surface area from equations (3.12), (3.13), (3.14), (3.24) and (3.25).

Step 15: Calculation of the length of capillary tube required for desired pressure drop using Eqs. (3.27) and (3.28) and determination of the fan total pressure and required fan power from Eqs. (3.29) and (3.30).

Step 16: Selection of the compressor, evaporator, condenser, capillary tube and fan of proper size and capacity from manufacturer's hand book matching the calculated values.

The above mathematical model of different components of heat pump assisted dryer will be helpful for simulation of results and performance evaluation of the dryer. The design procedure presented for heat pump assisted batch type dryer may be adopted within the limitation of the assumptions.

### 3.5 Design Data

Based on the above modeling, design calculations were carried out in MS Excel spread sheet and presented in Appendix B. The summary of the design data and calculated values is given in Table 3.1.

**Table 3.1 Design data and calculated values of the heat pump dryer**

Drying air temp	40°C
Drying air RH	15%
Amount to be dried per batch	4 kg
Initial MC	92% (w.b.)
Final MC	10% (w.b.)
Drying time	12 h
By pass factor	0.2
Volumetric air flow rate	0.0214 m <sup>3</sup> /s
Evaporator surface temperature	6.6°C
Condenser surface temperature	47°C
Suction pressure	525 kPa
Delivery pressure	2035 kPa
Cooling load	0.676 kJ/s
Refrigerant flow rate	17 kg/h
Compressor power requirement	165 W
SMER	1.84 kg/kWh
COP	4.1

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**CHAPTER IV**  
**MATERIALS AND METHODS**

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## MATERIALS AND METHODS

This chapter deals with development, fabrication and instrumentation of a laboratory model dehumidified air dryer using heat pump system and to study its performance. The details of the experimental procedure for drying of chilli and sweet pepper, quality analysis and storage of the dehydrated products have also been presented.

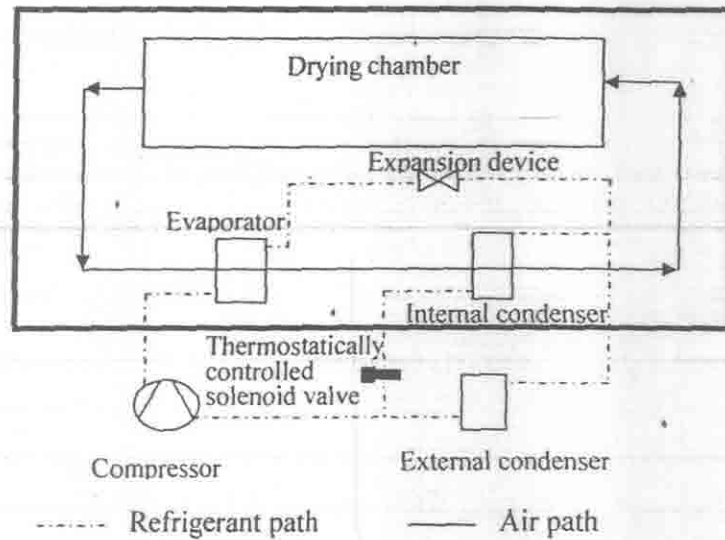
### 4.1 Laboratory Model Dryer

#### 4.1.1 Development of heat pump dryer

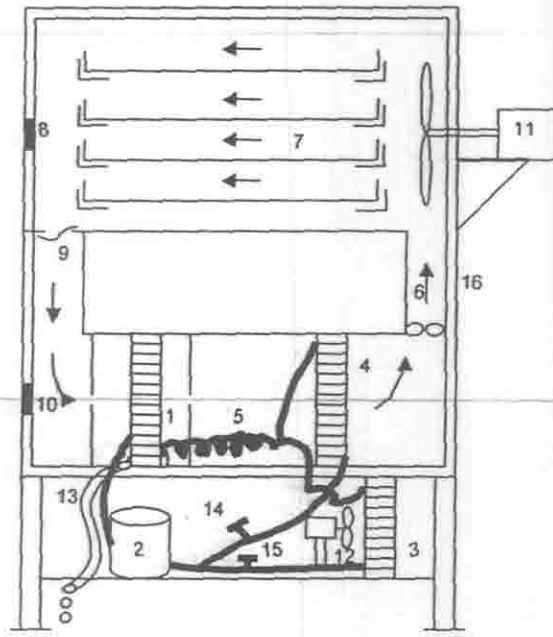
Because of the possibility of providing hermetically closed drying environments while drying with high energy efficiency, a suitably designed heat pump dehumidifier would be the best option to provide the required low temperature and low humidity condition. A laboratory model heat pump dryer with special features of variable drying air temperature and mode of operation (open and close) was fabricated. The line and schematic diagrammes of the dryer are shown in Figs. 4.1 and 4.2. The developed dryer consists of dehumidifier unit and the drying chamber. The dryer is a closed insulated chamber consisting of a dehumidifier unit with evaporator and condenser at its lower portion and a drying chamber at its upper portion. The compressor and external condenser are located at the bottom of the chamber.

#### **Dehumidifier unit**

The dehumidifier unit consists of compressor, evaporator, condenser, capillary and fan. A reciprocating compressor with a swept volume of 7.8 cc has been used. The condenser and evaporator coil provide the required heating and cooling/dehumidification operation for the process air in the dryer. In order to maintain low relative humidity conditions and prevent air exchange with outside, an external condenser has been employed to remove excess heat.



**Fig. 4.1 Line diagramme of the heat pump dryer showing refrigerant and air path**



- |                        |                      |                                |
|------------------------|----------------------|--------------------------------|
| 1 - Evaporator         | 6 - Fan              | 11 - Circulation fan           |
| 2 - Compressor         | 7 - Drying tray      | 12 - Fan to external condenser |
| 3 - External condenser | 8 - Exhaust air port | 13 - Drain pipe                |
| 4 - Internal condenser | 9 - Damper           | 14, 15 - Solenoid valve        |
| 5 - Capillary tube     | 10 - Inlet air port  |                                |

**Fig. 4.2 Schematic diagram of the dehumidified air dryer using heat pump system**

The evaporator and condenser are finned tube designs consisting of copper pipes of 9.5 mm external diameter and face dimension of 28 cm X 25 cm. The fins are continuous aluminium lamellas 0.3mm thick with longitudinal and transverse tube spacing of 22 mm and 25 mm, respectively. Two heat exchangers (each 0.254 m high, 0.279 m wide and with 0.07 m<sup>2</sup> surface area with finned tubes) are installed inside the unit across the air path. Another air-cooled heat exchanger is also installed outside the air circuit that acts as a secondary condenser. The two heat exchanger units in the machine are adjacent to one another and the arrangement does not allow for establishing a by pass between the two coils. Additional valves have also been provided to protect and prevent possible damage and liquid return to the compressor. A fan with 0.09 m<sup>3</sup>/s capacity is connected into the dehumidifier. It is used to drive the air through the coils. R22 refrigerant is used in the unit. The entire dehumidifier unit is located at the bottom of the drying chamber. The walls of the chamber are insulated with 3.5 cm thick thermocool insulation.

#### **Dryer unit**

The design of the dryer includes drying chamber, air circulation system, tray and other ancillary components. An insulated drying chamber of 66 cm length, 57 cm width and 33 cm height was constructed using aluminium sheets of 1.4 mm thickness. The door of the drying chamber was made of two layer glass with air spacing in between for insulation and better vision of the drying chamber during operation. Rubber strips were used in the door for proper air tight sealing. The air circulation in the dryer is provided by an axial flow fan. Four aluminium trays are stacked with the help of aluminium angles to support the drying materials. Two air ports, one for inlet air to the dehumidifier and the other for exhaust air from the drying chamber were made to operate the system in open, partially closed and closed mode. A damper was also provided in the air path between the drying chamber and dehumidifier unit. It opens for the recirculation mode and remains closed when exhaust port is open. Dimensional and other data of the dehumidified air dryer is listed in Table 4.1.

**Table 4.1 Dimensions of different components of the heat pump dryer**

Overall dimension of the dryer	92 cm X 66 cm X 137 cm
Material of construction	Outside M.S. sheet and inside Aluminium sheet
Evaporator and internal condenser housing	66 cm X 57 cm X 28 cm
Drying chamber dimension	66 cm X 57 cm X 33 cm
Number of trays	4
Compressor and external condenser housing	66 cm X 57 cm X 31cm
Clearance for air passage	8 cm
Thermocool insulation thickness	3.5 cm
Evaporator face area	28 cm X 25 cm
Compressor swept volume and power input	7.8 cc, 470 W
Capillary tube	Diameter = 0.78 mm , Length = 3.05 m
Condenser Fan power	9 W
Dryer air circulation fan	20 W
Solenoid valve	8 W
Refrigerant flow rate	7 lph

### **Control system**

Because of the tight requirements for the drying air conditions, precise control of the dryer operation is essential. Control devices in the refrigerant circuit enable distribution of the refrigerant (on the high pressure side) between the two condensers for heating the process air. The temperature of the drying air is controlled by a thermostat, which operates the solenoid valve connected to internal condenser line and allow the refrigerant to flow. When the desired drying air temperature is achieved, the flow of refrigerant to the internal condenser is cut off. Thus the flow is diverted through the external condenser.

## Measuring system

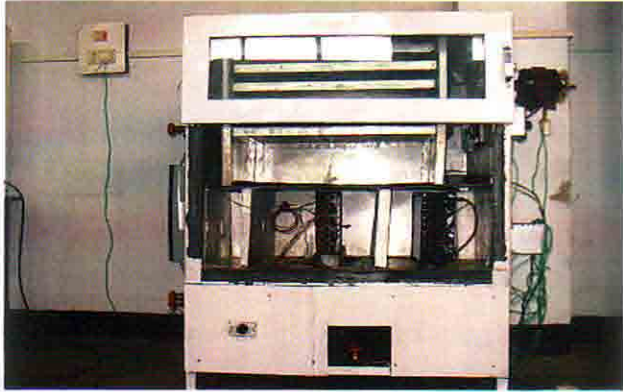
Temperatures and relative humidities were measured at the entrance and exit of the stacked trays and between the condenser and evaporator coils. The relative humidity readings were recorded using digital hygrometer. The thermocouples were installed at the entrance and exit of the stacked trays, in the space between the condenser and evaporator coils to measure the air temperatures. Thermocouples were also mounted on the evaporator and condenser coils for measuring pipe surface temperatures. Atmospheric temperatures and relative humidities were also measured using these instruments. A digital anemometer was used to measure the velocity of process air. The mass of moisture condensed at the evaporator and material being dried was measured using electronic weighing balance. Power consumption was measured by a watt meter. A rotameter is connected in the liquid line to measure flow rate of refrigerant. The fabricated dehumidified air dryer using heat pump system is shown in Figs. 4.3(a) and (b).

### 4.1.2 Hot air dryer

The hot air tray dryer consists of insulated drying chamber with trays, fan, electrical heater and digital temperature indicator cum controller to maintain the desired drying air temperature (Fig. 4.4). The drying air temperature, relative humidity and energy consumption were also measured during the experiment.

## 4.2 Performance of Heat Pump Dryer

In heat pump drying system, COP represents performance of heat pump. Moisture extraction rate and specific moisture extraction rate are the dryer performance indicator. The dryer was operated using R22 refrigerant to study the drying air condition with closed and open mode of operation (Fig. 4.5 (a) and (b)). The inlet and outlet drying air temperatures and relative humidities, evaporator and condenser surface temperatures, suction and delivery pressures were recorded to study the variation with drying time. The energy consumption and mass of moisture evaporated during drying of chilli were measured to study the performance of the dryer.



(a) Front view



Dryer unit

Dehumidifier unit  
(Evaporator and  
internal condenser)

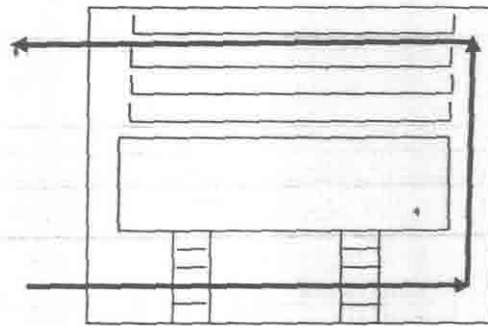
Compressor and  
external condenser

(b) Side view

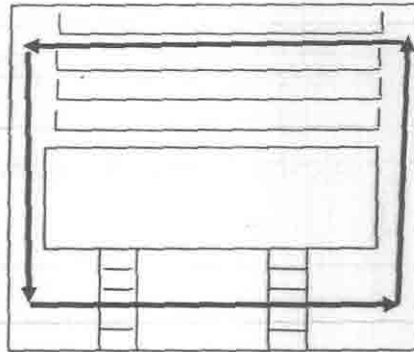
**Fig. 4.3 Laboratory model heat pump dryer**



**Fig. 4.4 Hot air dryer**



(a) Open air cycle operation



(b) Closed air cycle operation

**Fig. 4.5 Open and closed air cycle operation of the heat pump dryer**

### 4.3 Drying Experiment

Various experiments were planned to optimize the drying air conditions and compare dehumidified air dryer with hot air dryer based on the energy consumption and quality of the final dried product.

#### 4.3.1 Preparation of sample

Fresh green chilli and sweet pepper used for the experiment were procured from the local market in Bhubaneswar on daily basis. The discoloured, diseased or damaged ones were sorted out. These samples were washed properly in running water to remove the adhering impurities and spread on a plastic filter tray to drain out excess water.

Green chillies were destalked manually and the cups, seeds and stems of sweet pepper were separated. These were then sliced into 0.5cm thick slices using stainless steel knives. The whole and cut slices of green chilli and sweet pepper are shown in

Figs. 4.6 and 4.7. The samples were divided into three lots, one lot was steam blanched, second lot was given required pretreatment and the third one was used as control.

For blanching, the cut samples were placed into a stainless steel wire mesh basket and steam blanched for 2 minutes at 100°C under atmospheric pressure by direct steam injection. Blanched samples were immediately cooled in cold water to prevent further thermal stress. Some samples were blanched in solution containing 0.5% lye and 0.25% magnesium carbonate at 95°C for 2 minutes. After treatments, samples were washed in potable water to remove lye adhering to the surface. The water adhering on the surfaces of blanched and treated samples was removed with tissue paper prior to drying. Spot test for peroxidase activity was conducted to determine adequacy of the steam or water blanching process.

#### 4.3.2 Drying of sample

Thin-layer drying experiments under controlled conditions were conducted in two different types of tray dryer; (1) hot air dryer and (2) dehumidified air dryer. Different combinations of air temperature and relative humidity were considered in both the dryers. Before starting any experimental run, the instrumentation system was checked carefully and the dryers were started 1 hour before experiments in order to reach steady state. After stabilizing the whole system, samples were loaded on to the drying trays (Fig. 4.8). Sample of about  $25 \pm 2$  g was placed evenly as thin layer (at single piece thickness) in a small aluminium wire mesh tray (3cm x 3cm) of known weight (loading density of  $2.0 \text{ kg/m}^2$  for chilli and  $3.6 \text{ kg/m}^2$  for sweet pepper) and placed at the centre of the drying tray of the dryer which was also previously loaded with same sample. The initial weight of the tray with sample was recorded. The aluminium tray was removed from the dryer and weighed regularly at 30 minutes interval. As the weighing operation took only a few seconds, no significant disturbances were imposed on the steady-state drying operation. When the weight of the sample became constant, the experiment was stopped. At the completion of each experiment, the final moisture content of dried sample was determined. All the experiments were carried out at  $1.5 \pm 0.2$  m/s air velocity. The drying experiments were repeated twice to have enough data for statistical analysis. The experimental plan for drying parameters and quality attributes are given in Table 4.2.



**Fig. 4.6 Whole and sliced chili**



**Fig. 4.7 Whole and sliced sweet pepper**



**Fig. 4.8 Trays with samples inside the dryer**

**Table 4.2 Experimental plan for drying parameters and quality attributes**

Drying parameters	Levels	Values
Design of experiment		Completely Randomized Design (CRD)
Replications	2	
<b>Independent variable</b>		
Variety	2	Chilli Sweet pepper
Drying method	2	Hot air dryer (HAD) Heat pump dryer (HPD)
Drying air temperature and relative humidity	HAD HPD	30°C (40%), 35°C (27%), 40°C(19%) 45°C(55%), 55°C(35%), 65°C(20%)
Treatment	3	Control, Blanched, Treated
Air flow rate	1	1.5 m/s
Tray load	1	2.0 kg/m <sup>2</sup> (chilli) 3.6 kg/m <sup>2</sup> (sweet pepper)
Replications	2	
<b>Dependent variable</b>		
Drying characteristics		Moisture ratio Total drying time Drying rate Drying constant
Quality attributes		Dehydration ratio Rehydration ratio Total chlorophyll content Capsaicin content (chilli) Ascorbic acid content (sweet pepper)

### 4.3.3 Drying characteristics and equation fitting

The drying mechanism depends on simultaneous heat and mass transfer phenomena and factors dominating each process determine the drying behaviour of the product. The drying rates were computed from the experimental data and drying characteristics curves i.e. Moisture content (d.b.) vs time, drying rate vs moisture content(d.b.) were plotted. The single exponential Lewis equation and Page's power equation were fitted to the experimental data. Linear regression of these equations were carried out using least square method and co-efficients were determined. The fitting of the equations were evaluated on the basis of co-efficient of determination ( $R^2$ ) and root mean square error (RMSE). The drying characteristics curve for green chilli and sweet pepper are fitted by plotting dimensionless drying rate and moisture ratio.

### 4.4 Product Quality Analysis

Experiments were planned to evaluate the quality parameters of dehydrated green chilli and sweet pepper obtained from different drying conditions in order to optimize the drying process. The dried green sweet pepper was analysed for total chlorophyll and ascorbic acid content and dried chilli for total chlorophyll and capsaicin content as the quality indicator.

#### 4.4.1 Determination of moisture content

The moisture content of chilli and sweet pepper was determined by vacuum oven method. Sample of 2 to 5g was taken into a covered dish of predetermined dry weight. The dish and cover were placed in the vacuum oven separately and dried for 6 hours at 70°C under a pressure of not more than 100mm of mercury. After 6 hours, the dish was removed from the oven, covered, cooled in desiccator and the final weight was taken (ASTA, 1985; Ranganna, 1986). The moisture content of sample was calculated as follows.

$$\text{Moisture content, \% (w.b.)} = \frac{W'_2 - W'_3}{W'_2 - W'_1} \times 100$$

$W'_1$  = Weight of the empty moisture dish along with its cover

$W'_2$  = Weight of the moisture dish along with the sample

$W'_3$  = Final weight of the dish along with the dried sample

#### 4.4.2 Dehydration ratio and Rehydration ratio

Dehydration ratio was determined from the drying experiment by measuring the initial weight of the sample before drying and final weight of the dried product and calculated as follows.

$$\text{Dehydration ratio} = \frac{\text{Mass of the sample before drying}}{\text{Mass of the dried sample}}$$

The rehydration ratio of the dried chilli was determined by mixing 2g of sample with 20ml of distilled water in a beaker. The beaker was left for 2h at room temperature (Yang and Atallah, 1985). The sample was taken out and surface water was removed by blotting paper. The rehydration ratio was calculated as follows (Kim and Toledo, 1987).

$$\text{Rehydration ratio} = \frac{\text{Mass of the rehydrated sample}}{\text{Mass of the dried sample}}$$

#### 4.4.3 Estimation of total chlorophyll content

The chlorophylls are the essential components for photosynthesis and occur in chloroplasts as green pigments in all photosynthetic plant tissues. They are bound loosely to proteins but are readily extracted in organic solvents such as acetone or ether.

Representative sample (0.1 to 1g depending on the product) was taken, ground and mixed thoroughly. The sample was extracted with 80% acetone in a mortar and pestle using purified quartz sand. The supernatant liquid was decanted after centrifuging at 5000 rpm for 5 minutes. The extraction procedure was repeated with acetone till the residue is colourless. The volume was made up to 100ml with 80% acetone. Absorbance of the solution was taken at 645 and 663nm in a spectrophotometer against the solvent (80% acetone) as blank (Thimmaiah, 1999).

Total chlorophyll content present in the extract (mg chlorophyll per 100g d.b.) was calculated using the following equation.

$$\text{Total chlorophyll, mg/100g d.b.} = \frac{(20.2 \times A''_{645} + 8.02 \times A''_{663}) \times V' \times 100}{W' \left(1 - \frac{M'}{100}\right) \times 1000}$$

where,  $A''$  = Absorbance at specific wavelengths

$V'$  = Final volume of chlorophyll extract in 80% acetone, ml

$W'$  = Fresh weight of the tissue extracted, g

$M'$  = Moisture content of sample used for estimation, %(w.b.)

#### 4.4.4 Estimation of Vitamin C (Ascorbic Acid) content

The titration method which is used for measurement of ascorbic acid is based on the extent to which a 2, 6-dichlorophenol indophenol solution is decolorised by ascorbic acid in sample extracts and in standard ascorbic acid solutions.

Ascorbic acid in sweet pepper was determined according to AOAC official method (AOAC, 1995; Ranganna, 1986). Half a gram of dried sample was blended with 50ml of 3% metaphosphoric-acetic acid solution (15g of meta phosphoric acid dissolved in a mixture of 50ml glacial acetic acid and 450ml of water) to extract ascorbic acid. The mixture was centrifuged and then supernatant was taken and transferred to a volumetric flask. This was rapidly titrated with 2, 6-dichlorophenol indophenol solution until light distinct rose pink colour persisted for more than 5 s ( $V'_2$  ml). Two replicates of each sample were analysed. The working standard solution of ascorbic acid (1ml = 0.1mg of ascorbic acid) was also titrated against the dye ( $V'_1$  ml). The ascorbic acid was determined using the following formulae.

Ascorbic acid content (mg of ascorbic acid per 100g d.b.)

$$\frac{0.5 \times V'_2 \times \text{Volume made up} \times 100}{V'_1 \times \text{Aliquot of extract taken for estimation} \times \text{Weight of sample taken} \left(1 - \frac{M'}{100}\right)}$$

where,  $M'$  = Moisture content of sample used for estimation, %(w.b.)

#### 4.4.5 Capsaicin content

Capsaicin is a protoalkaloid which is responsible for the pungency of chilli. The phenolic group in capsaicin reduces phosphomolybdic acid to lower acids of molybdenum. The resulting component is blue in colour and is read at 650nm. The colour intensity is directly proportional to the concentration of capsaicin.

Dry chilli powder of 0.5g was mixed with 10 ml dry acetone in a volumetric flask and shaken in a mechanical shaker for 3 h. One ml of the clear supernatant was taken into a test tube after centrifuging at 10000 rpm for 10 minutes and evaporated to dryness in a hot water bath. The residue was dissolved in 5ml of 0.4% sodium hydroxide solution and 3 ml of 3% phosphomolybdic acid was added to it. After 1

hour, the solution was filtered followed by centrifuging at about 5000 rpm for 10-15 minutes. Absorbance of the solution was measured at 650nm with the help of spectrophotometer. The sample with the highest optical density was considered to be containing more capsaicin and hence more pungent (Thimmaiah, 1999).

#### **4.4.6 Sensory evaluation**

Sensory evaluation was carried out by a panel of ten judges of different age groups, having different eating habits. Different attributes viz. colour, texture, flavour and overall acceptability were rated on the basis of a 9-point Hedonic scale (BIS 1972), ranging from 1 (most undesirable) to 9 (most desirable).

#### **4.5 Storage Experiment**

##### **4.5.1 Moisture sorption study**

Fresh and dried slices of both green chilli and sweet pepper were exposed to seven levels of relative humidities (10.8 to 74.3%) using static method. Various super saturated salt solutions of different relative humidities viz. Lithium chloride (10.8%), Potassium acetate (21.6%), Magnesium chloride (31.8%), Potassium carbonate (43.6%), Sodium nitrite (62.8%), Sodium chloride (74.3%) were taken in glass desiccators and placed in an incubator at 35°C constant temperature to provide required constant relative humidities.

Samples of known weight and moisture content were placed in petridishes and these dishes were placed on a plastic platform inside the desiccators to avoid direct contact between samples and salt solutions. The weight of the samples were taken periodically until constant weight. The moisture content of samples were determined. All the experiments were replicated two times and the average of two values were taken. The equilibrium moisture contents were determined both in desorption and absorption conditions at 35°C and isotherms were plotted using the experimental data.



**Fig. 4.9 Spectrophotometer**



**Fig. 4.10 Desiccators with sample inside the incubator**

#### **4.5.2 Packaging and storage of dehydrated product**

Dehydrated green chilli and sweet pepper were put in pouches (12 x 10 cm) made from Poly Propylene (PP) of 37 $\mu$ m and Metallised Polyester Polyethylene (MPP) of 12 $\mu$ m and heat sealed. The sealed packs were stored under ambient condition (27 $\pm$ 5°C, 65 $\pm$ 8% RH,) for 6 months. The stored packs were visually evaluated for surface colour, texture and mould attack and analysed for rehydration ratio, moisture, chlorophyll and ascorbic acid (in case of sweet pepper) or capsaicin content (in case of chilli) after every 2 months storage interval.

#### **4.6 Data Analysis**

In order to conduct the experiments in a systematic and efficient manner and keeping in view the levels of independent and dependent variables, the experiments were planned on two factorial completely randomised design (CRD). Data obtained from the experiments were analysed by using computer software 'MS Excel' and 'Curve Expert'. The effects of drying air temperature and pre-treatment on quality of the dehydrated product were analysed statistically through two way analysis of variance (ANOVA).

**CHAPTER V**  
**RESULTS AND DISCUSSION**

## RESULTS AND DISCUSSION

This chapter deals with the results obtained from different experiments conducted during this investigation. The results were analysed to study the performance of heat pump dryer (HPD) as compared to hot air dryer (HAD) based on energy consumption. The drying characteristics of green chilli and sweet pepper were studied. The effect of drying and storage conditions on quality parameters of the dehydrated products were also determined to optimize the drying conditions.

### 5.1 Performance of Heat Pump Dryer

#### 5.1.1 No load condition

The change in air temperature and relative humidity for heat pump (refrigerant flow in the internal condenser) and refrigeration mode (refrigerant flow in the external condenser) of operation with recirculation of drying air (closed air circuit) under no load condition is shown in Fig. 5.1. Initially, the relative humidity of air decreased rapidly due to dehumidification of air at the evaporator surface in both the mode of operation. After 20 minutes of operation, the relative humidity of air in refrigeration mode increased gradually due to the lowering of drying air temperature and attained a constant value of 46%. But in the closed air circuit heat pump mode, the relative humidity continued to decrease at a slower rate and attained a constant value of 19%. The temperature of air decreased continuously to a constant value of 22°C in refrigeration mode, whereas increased to 41°C in heat pump mode of operation. So, the drying air temperature and relative humidity in the closed air circuit heat pump mode attained a value of 41°C and 19% from an ambient value of 32°C and 72%, respectively under no load condition after 90 minutes of the dryer operation.

Medium range of temperatures (30-41°C) for safe drying of heat sensitive crops were achieved experimentally in the heat pump dryer. Dehumidification system of the heat pump dryer maintained the relative humidity of air entering the drying chamber below 40%.

The achieved drying air temperature, relative humidity, suction and delivery pressure in the heat pump dryer under different operating conditions and mode of operation is given in Table 5.1.

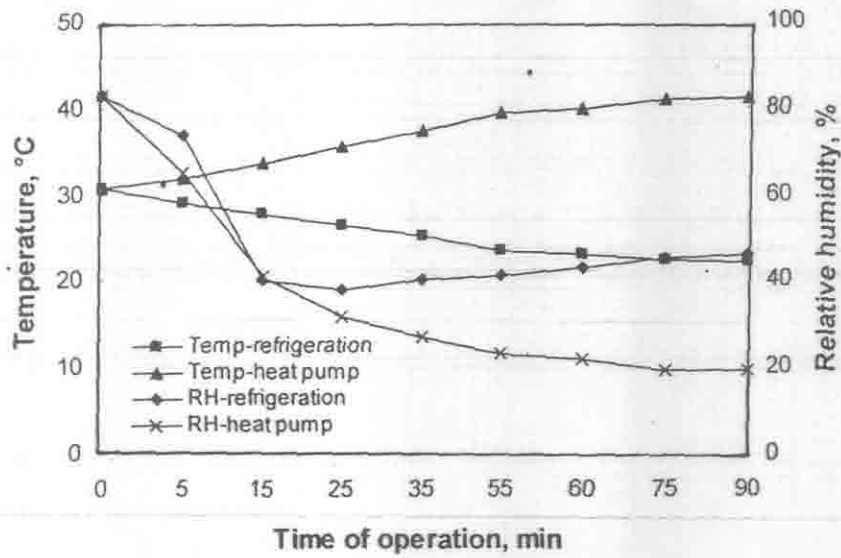


Fig. 5.1 Variation in drying air temperature and relative humidity with time in the heat pump dryer under no load condition at different modes of operation

Table 5.1 Achieved drying air temperature, relative humidity, suction and delivery pressure in the heat pump dryer under different operating conditions

Refrigerant	Mode of operation	Operating condition	Achieved drying air condition		Suction pressure (kPa)	Delivery pressure (kPa)
			Temperature (°C)	RH (%)		
R22	Refrigeration	Closed air	22	46	138	1545
	Refrigeration	Open air	25	42	151	1720
	Heat pump	Closed air	41	19	179	1999
	Heat pump	Open air	35	43	198	2084

The suction and delivery pressure in case of heat pump mode were found to be 179 and 1999 kPa in closed air circuit (with recirculation of drying air) and 198 and 2084 kPa for open air circuit operation (ambient air entering the dehumidifier unit and leaving at dryer outlet without recirculation), respectively. The higher suction pressure in open air circuit operation as compared to closed air circuit may be due to higher cooling load of ambient air on the evaporator leading to superheating of refrigerant vapour and this increases the load on condenser. Both the suction and delivery pressure were higher when operated under heat pump mode as compared to refrigeration mode which might be due to improper condensation at the internal condenser.

### 5.1.2 Loaded condition

#### Temperature profile

The temperature profile of dryer inlet and outlet air in closed circuit heat pump mode under loaded condition is shown in Fig. 5.2. The initial phase is marked by a drop in temperature during the early hours followed by rapid rise between the 2<sup>nd</sup> and 10<sup>th</sup> hours, after which the temperature was almost stable. Initially the material was wet and cool. The decrease in inlet air temperature at the initial stage of drying might be due to the utilization of most of the heat transferred at the evaporator surface for dehumidification purpose. The air temperature at the inlet and outlet of the drying chamber decreased initially, after which increased and reached an asymptote at 41°C. The temperature varied between 35 and 40°C for the first 10 hours during which period almost 40% of the drying took place. Most of the latent heat recovered during the early stages of the process was rejected at the secondary condenser. As the drying progressed, most of the heat exchanged at the evaporator is sensible heat and the temperature of the air entering the drying chamber increased gradually. The results were similar to the findings of Sosle *et al.* (2003).

The exhaust drying air temperature was less than that of the inlet air temperature as part of the heat was utilized for raising the temperature of product and its associated water. As the product became drier with less water content at the later part of drying, the difference between inlet and exhaust drying air temperature decreased.

### Relative humidity profile

The relative humidity of inlet and exhaust drying air increased initially to 48 and 61%, respectively from an initial value of 19% after 2h of drying and decreased subsequently, with drying time as product became drier (Fig. 5.3). The difference between exhaust and inlet air relative humidity was more initially due to loss of water from the wet product. The relative humidity of drying air at the exit of the drying chamber decreased almost exponentially from an initial value of 61% down to 25% by the end of drying. The initial high moisture content of the material and low temperature of drying air resulted in higher initial relative humidity of the drying air. The air became drier due to the onset of falling drying rate period as reported by Adapa *et al.* (2002). The ambient relative humidity value ranged from 55-80%.

The air temperatures at the evaporator outlet were ranged from 15 to 18.5°C. The evaporator and condenser surface temperatures were ranged from -16 to -20°C and 45 to 49°C, respectively. The variation of these temperatures might be due to variation of exhaust and ambient air conditions with drying time. The variation in evaporator and condenser surface temperature with drying time is shown in Fig. 5.4.

#### 5.1.3 Specific moisture extraction rate

The energy consumption and specific moisture extraction rates (SMER) calculated for different drying air temperatures are given in Table 5.2. The SMER value increased with increase in drying air temperature due to more drying potential of high temperature air (Fig. 5.5). Specific moisture extraction rate for heat pump dryer for drying sweet pepper at 40°C was found more (1.1 kg/kWh) than hot air dryer (0.93 kg/kWh) while operating at 45°C. This might be due to lesser energy requirement and higher drying potential of low relative humidity air in heat pump dryer. The heat pump dryer was found to have a specific moisture extraction rate between 0.55 and 1.10 kg/kWh. The SMER generated agrees with works by Adapa *et al.* (2002).

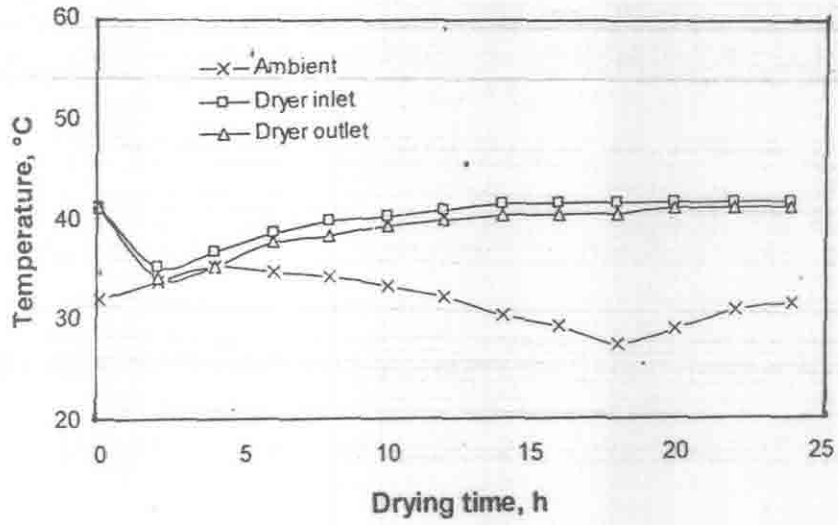


Fig. 5.2 Variation in ambient, dryer inlet and outlet temperature with drying time

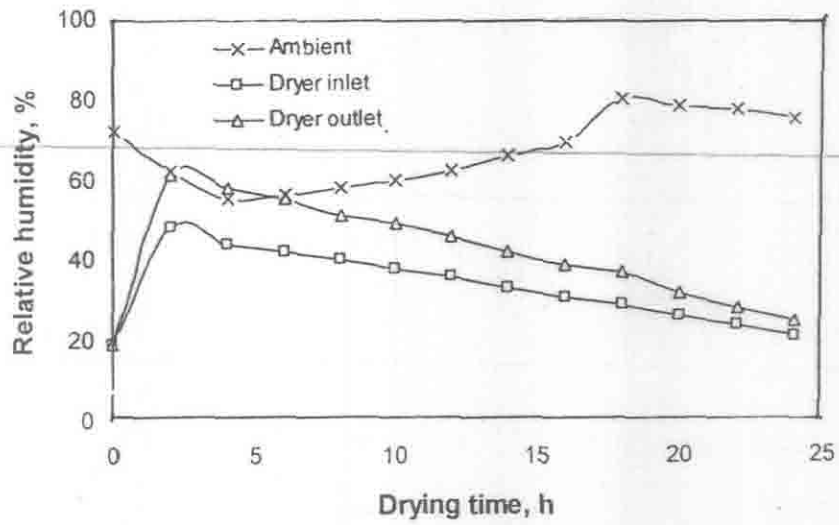


Fig. 5.3 Variation in ambient, dryer inlet and outlet relative humidity with drying time

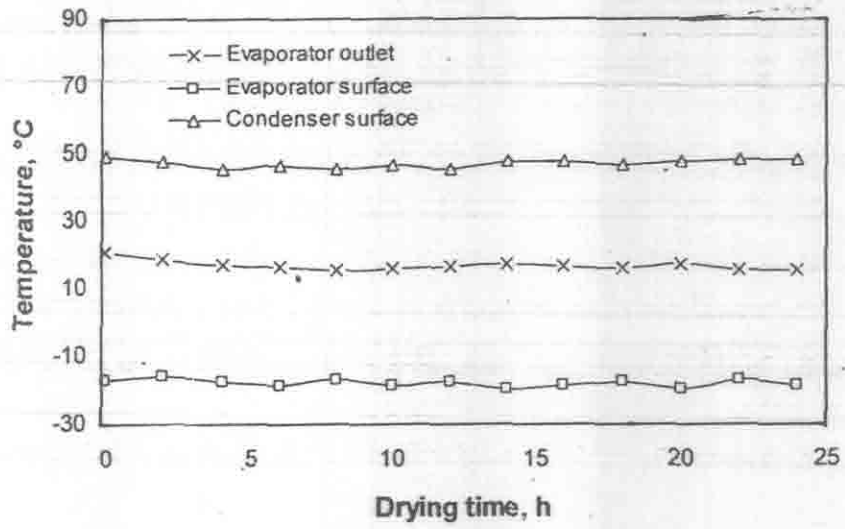


Fig. 5.4 Variation in evaporator outlet, evaporator and condenser surface temperature with drying time

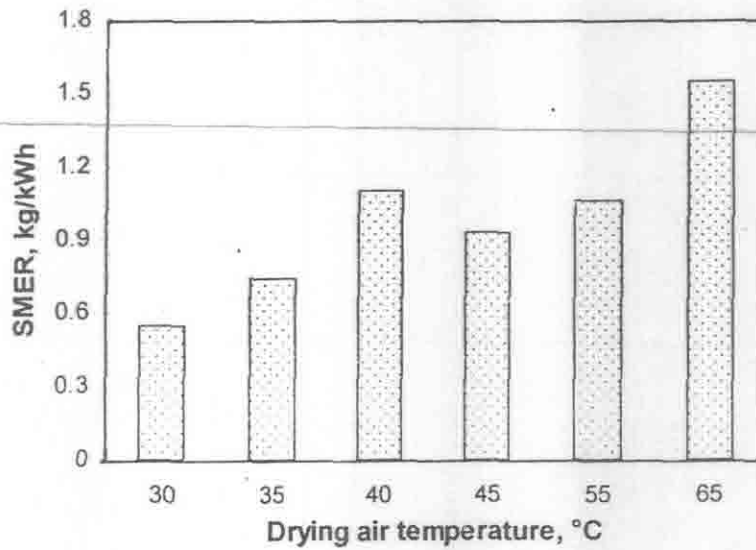


Fig. 5.5 Variation in specific moisture extraction rate with drying air temperature

Energy consumption for heat pump dryer for 24 hours of operation was found less (4.48-5.05 kWh) than the hot air dryer (5.65-9.6 kWh) while operating under different drying conditions. It was also observed that the variation of energy requirement (for 24h of operation) in heat pump dryer at different drying air temperatures was not much (at low drying air temperatures) as the compressor was to operate for same duration of time leading to almost equal energy consumption and the excess heat was rejected at the external condenser. The higher energy requirement at 65°C in hot air dryer might be due to more time of operation of the heater controlled by thermostat to maintain the high drying air temperature in the drying chamber.

**Table 5.2 Comparison of energy consumption, MER and SMER at different temperatures in hot air dryer and heat pump dryer**

Dryer	Drying air temperature (°C)	Energy consumption for 24h of operation (kWh)	MER (kg/h)	SMER (kg/kWh)
HPD	30	4.48	0.103	0.55
	35	4.84	0.148	0.74
	40	5.05	0.232	1.10
HAD	45	5.65	0.218	0.93
	55	8.4	0.37	1.06
	65	9.6	0.618	1.55

## 5.2 Drying Characteristics

The main aim of this investigation was to determine the effect of drying air condition and pre-treatment on total drying time, drying rate, moisture ratio and quality parameters such as chlorophyll, ascorbic acid and capsaicin content. Drying experiments were conducted on green chilli and sweet pepper in the fabricated heat pump dryer (HPD) at 30, 35 and 40°C and hot air dryer (HAD) at 45, 55 and 65°C. The experimental data were fitted to drying equations.

### 5.2.1 Effect of drying air temperature

#### Moisture content vs drying time

Air temperature has an important effect on the drying of chilli. Increase in drying air temperature was observed to increase the drying rates, which decreased total drying times.

Variation in moisture content with drying time at each of the drying air temperatures of 30, 35 and 40°C in HPD and 45, 55 and 65°C in HAD for green chilli and sweet pepper control samples are shown in Figs 5.6 through 5.9. From the plot of moisture content against drying time, it is clearly evident that drying time decreases with increase in drying air temperature from 30 to 65°C.

It was observed from all the figures that the moisture content of green chilli and sweet pepper slices reduced exponentially with drying time. These curves followed the general trend of drying curves as reported for many food materials (Ahmed and Shivare, 2001). As the temperature increased, the drying curve exhibited a steeper slope, thus exhibiting an increase in drying rate. Total drying time required to dehydrate chilli and sweet pepper under different drying conditions and pretreatments are given in Table 5.3.

The HPD when operated with drying air temperature at 30°C took 34 hours to reduce the moisture content of green chilli from 521.1 to 6%(d.b.) while HAD at 65°C took only 5 hours. Heat pump drying of chilli at 30°C took the longest time with lower drying rates. Similarly it took 36, 25 and 16h at 30, 35 and 40°C in HPD and 17, 10 and 6h at 45, 55 and 65°C in HAD, respectively to dry sweet pepper from 1452.8 to 10% m.c.(d.b.). This shows a significant reduction in drying time with increase in drying air temperature which is stated by many researchers for different agricultural commodities. Similar trends were also observed with treated and blanched samples dried in different drying air temperatures (Table 5.3).

The declining trend of total drying time with increase in temperature is due to (i) increase in vapour pressure within the product with increase in temperature which results in faster migration of moisture to the surface and (ii) decrease in relative humidity of drying air with increase in temperature that enhances the moisture removal rate from the product surface. It was also evident from the results that for

10°C rise in air temperature in heat pump dryer from 30 to 40°C (at lower temperature range), the total drying time for chilli reduced drastically by 19 hours. However, this reduction was much less (3 hours only) when air temperature was raised from 55 to 65°C in HAD (at higher temperature range)! It was also evident from the results that the increase in air temperature from 30 to 40°C reduced the drying time from 30 to 13h\*for treated sample, whereas this reduction was from 32 to 14h in steam blanched green chilli samples. Hence, it shows a pronounced reduction in total drying time with rise in temperature at lower levels. Case hardening and shrinkage of the slices due to initial higher drying rate at higher temperature may be the reasons for the same.

**Table 5.3 Total time (hours) required to dry up to EMC for both chilli and sweet pepper at different temperatures of drying**

Product	Sample	HPD			HAD		
		30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	34	24	15	16	8	5
	Treated	30	22	13	14	7	5
	Blanched	32	22	14	14	7	5
Sweet pepper	Control	36	25	16	17	10	6
	Treated	32	22	14	15	9	5
	Blanched	34	23	15	16	10	6

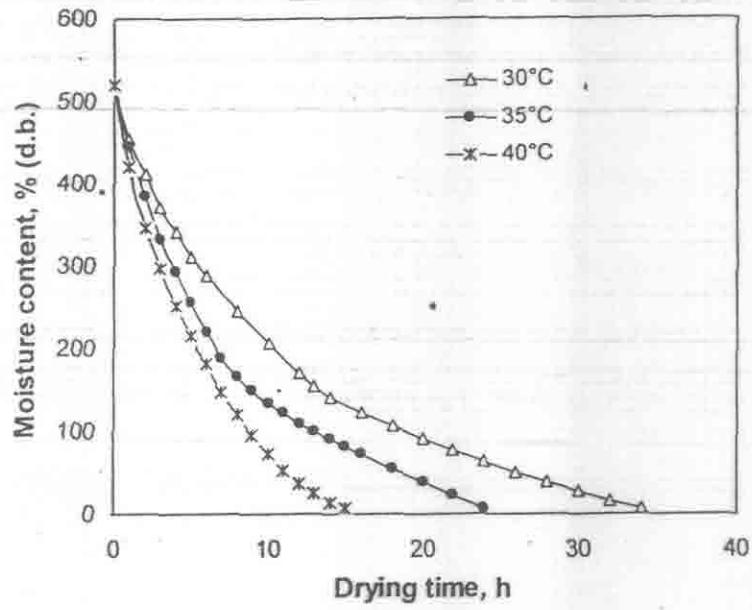


Fig. 5.6 Variation in moisture content with drying time of chilli dried in heat pump dryer at different temperatures

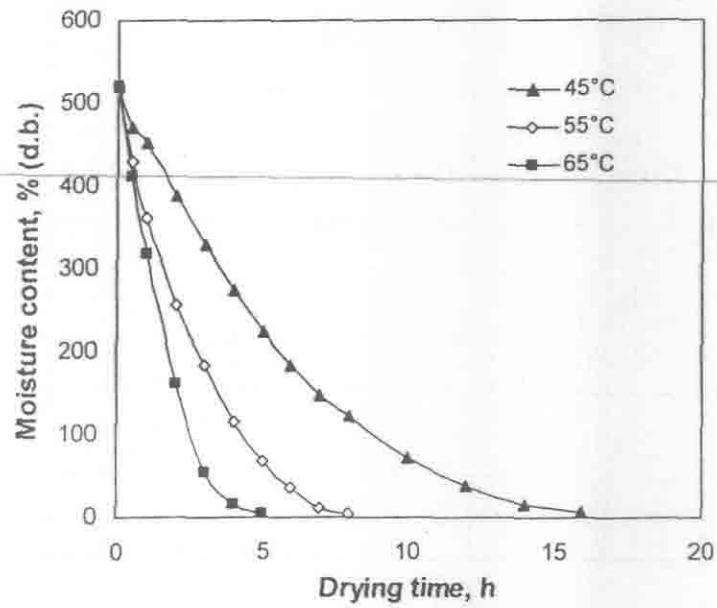


Fig. 5.7 Variation in moisture content with drying time of chilli dried in hot air dryer at different temperatures

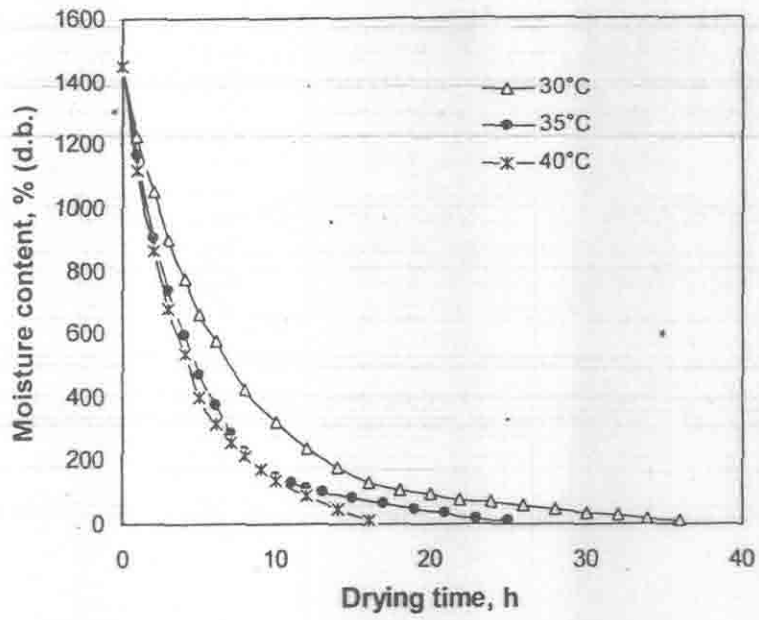


Fig. 5.8 Variation in moisture content with drying time of sweet pepper dried in heat pump dryer at different temperatures

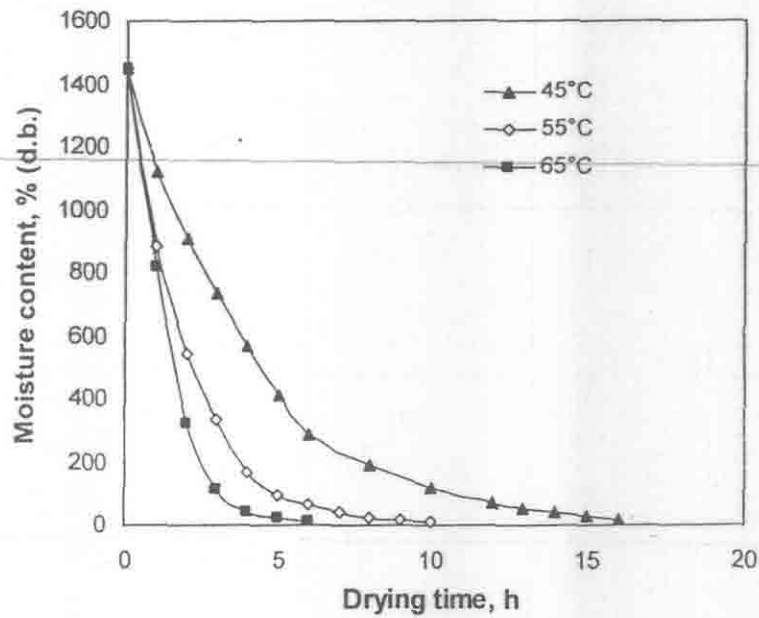


Fig. 5.9 Variation in moisture content with drying time of sweet pepper dried in hot air dryer at different temperatures

### Drying rate vs moisture content

Variation of drying rate as a function of moisture content at different drying air temperatures and pretreatments for both chilli and sweet pepper samples are shown in Figs. 5.10 through 5.13.

Drying of green chilli and sweet pepper took place mainly under falling-rate period. During this period the migration of moisture occurred through the mechanism of diffusion. These results are in agreement with the observations of earlier researchers (Lahsasni *et al.*, 2004). As the drying of chilli and sweet pepper slices occurred at relatively faster rate, amount of water available at the surface soon became inadequate to maintain the supply and the rate rapidly declined to a value controlled by liquid diffusion within the slices. These results are in agreement with the observations of earlier researchers.

The peak drying rates of chilli and sweet pepper for different drying conditions is given in Table 5.4 . The peak drying rates of 221.4, 182.1 and 99.8% m.c.(d.b.)/h at 465.8, 475.6 and 496.2% m.c.(d.b.) were found while drying chilli at 65, 55 and 45°C, respectively. Similarly the peak drying rate for sweet pepper was found to be 637.3% m.c.(d.b.)/h at a moisture content of 1134.2% d.b. with 65°C drying air temperature in HAD as compared to 229.7% m.c.(d.b.)/h at 1337.9% m.c.(d.b.) in HPD at 30°C. The drying rate increases considerably with increase in drying air temperature. Thus, a higher drying air temperature produced a higher drying rate and consequently faster reduction in moisture content.

It was noted that by increasing the temperature from 30 to 65°C, the increase in peak drying rate was 155.2% m.c.(d.b.)/h for chilli, whereas 407.6% m.c.(d.b.)/h for control sample of sweet pepper.

The final moisture content attained by control samples under different drying air temperatures were ranged from 5.18 to 6.87% d.b. for green chilli, whereas 9.79 to 10.96% d.b. for sweet pepper with the higher value for lower drying air temperature (Table 5.5). The final moisture content was observed to be less at higher drying air temperature which might be due to lower relative humidity of drying air at higher temperature since the absolute humidity of drying air was maintained relatively constant for all the drying experiments.

**Table 5.4 Peak drying rates for chilli and sweet pepper at different temperatures of drying**

Sample	Drying Temp (°C)	Chilli		Sweet pepper	
		M. C. (% d.b.)	Drying rate (%m.c.(d.b.)/h)	M. C. (% d.b.)	Drying rate (%m.c.(d.b.)/h)
Control	30	488.0	66.2	1337.9	229.7
	35	483.5	75.1	1309.9	285.8
	40	470.3	101.6	1285.5	334.7
	45	496.2	99.8	1288.3	328.9
	55	475.6	182.1	1169.5	566.6
	65	465.8	221.4	1134.2	637.3
Treated	30	611.3	84.5	1562.3	184.2
	35	588.9	129.4	1547.6	213.5
	40	558.3	190.6	1381.9	545.0
	45	586.1	134.9	1473.3	362.2
	55	539.4	228.3	1315.3	678.2
	65	564.5	356.3	1191.5	925.8
Blanched	30	516.9	63.3	1365.3	284.8
	35	503.4	90.2	1308.1	399.3
	40	483.4	130.1	1273.1	469.3
	45	501.9	93.3	1318.9	377.7
	55	462.0	172.9	1222.6	570.2
	65	444.7	207.7	1173.7	668.0

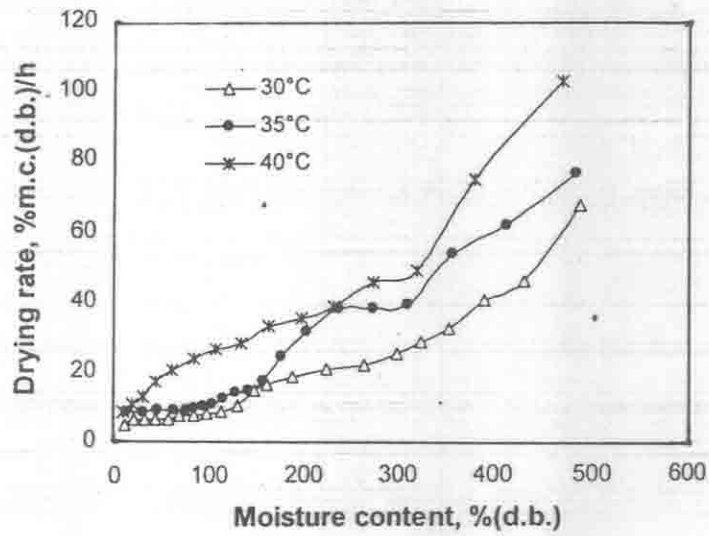


Fig. 5.10 Variation in drying rate with moisture content of chilli dried in heat pump dryer at different temperatures

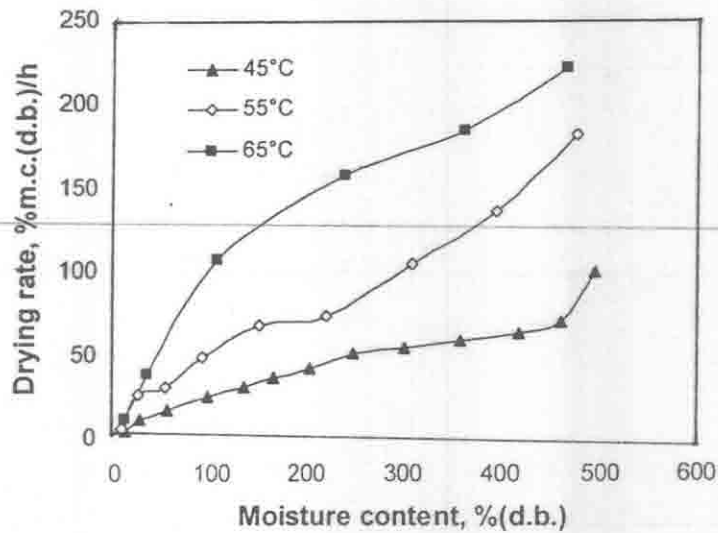


Fig. 5.11 Variation in drying rate with moisture content of chilli dried in hot air dryer at different temperatures

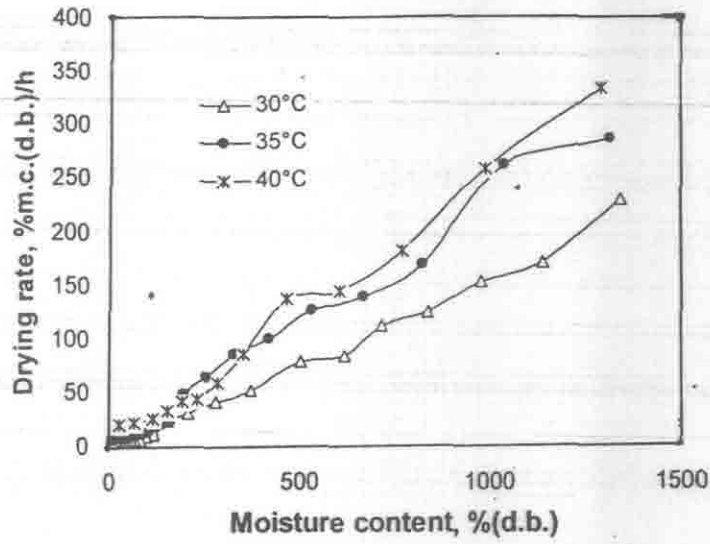


Fig. 5.12 Variation in drying rate with moisture content of sweet pepper dried in heat pump dryer at different temperatures

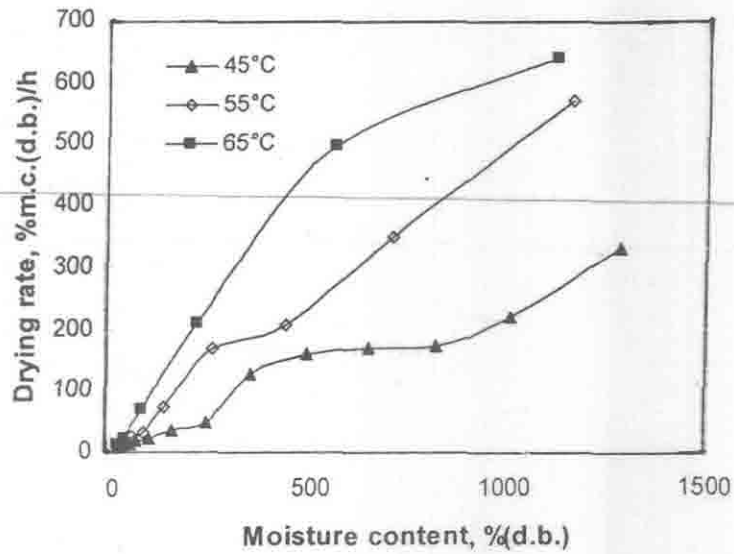


Fig. 5.13 Variation in drying rate with moisture content of sweet pepper dried in hot air dryer at different temperatures

**Table 5.5 Final moisture contents of both chilli and sweet pepper at different temperatures of drying**

Product	Sample	Initial	HAD			HPD		
			30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	521.1	6.87	6.1	5.92	5.87	5.60	5.18
	Treated	653.58	6.27	6.02	5.54	6.01	5.16	4.98
	Blanched	548.51	5.73	5.56	5.27	5.92	5.59	4.92
Sweet pepper	Control	1452.79	10.96	10.71	10.59	10.49	10.09	9.79
	Treated	1654.38	10.79	10.13	9.02	10.07	9.27	10.12
	Blanched	1507.72	10.99	10.61	10.22	10.51	10.37	9.82

### 5.2.2 Effect of pretreatment

The average initial moisture content of control, treated and blanched samples were 521.1, 653.6 and 548.5% d.b. for green chilli and 1452.8, 1654.4 and 1507.7% d.b. for sweet pepper samples, respectively. It can be observed from Table 5.3 that the total drying time required for complete drying of treated and blanched samples is less as compared to control. The decrease in total drying time due to treatment is more at lower temperature level, but at higher temperature level the difference is not significant.

Variation in drying rate with moisture content in case of pretreated samples for chilli and sweet pepper dried at 65 and 40°C is shown in Figs 5.14 through 5.17. The peak drying rates were found to be 221.4% m.c.(d.b.)/h at 465.8% m.c.(d.b.), 356.3% m.c.(d.b.)/h at 564.5% m.c.(d.b.) and 207.7% m.c.(d.b.)/h at 444.7% m.c.(d.b.) for control, treated and blanched chilli samples dried at 65°C, respectively.

The treated samples had higher drying rates and faster moisture removal due to disruption of its matrix and possible loss of soluble solids during blanching, resulting in the easier diffusion of moisture from the core of the product (McMinn and Magee, 1999). Same results were also obtained by Ahmed and Shivare (2001) during drying of green chilli. Though the treated samples had more drying rates initially at higher temperature level of 65°C in hot air dryer, the drying rates were more or less

same for all the samples at the later part of drying. This might be due to case hardening in all the samples at higher drying air temperature limiting the movement of moisture from inside.

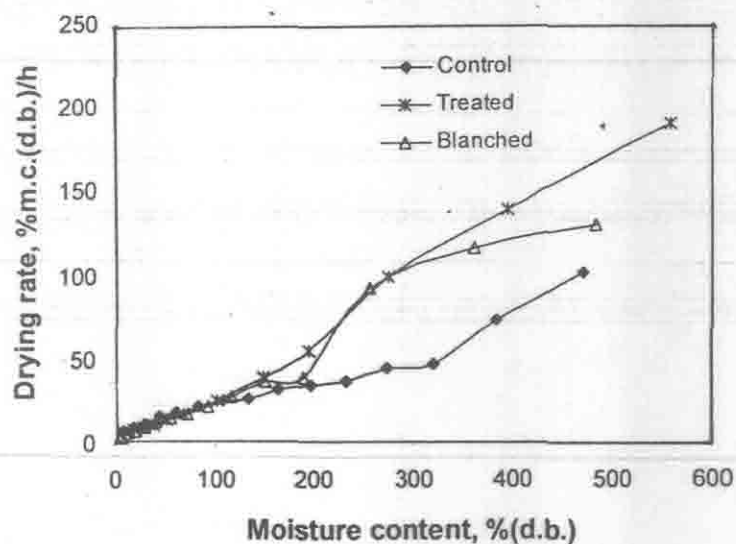


Fig. 5.14 Effect of pre-treatment on drying rate of chilli dried in heat pump dryer at 40°C

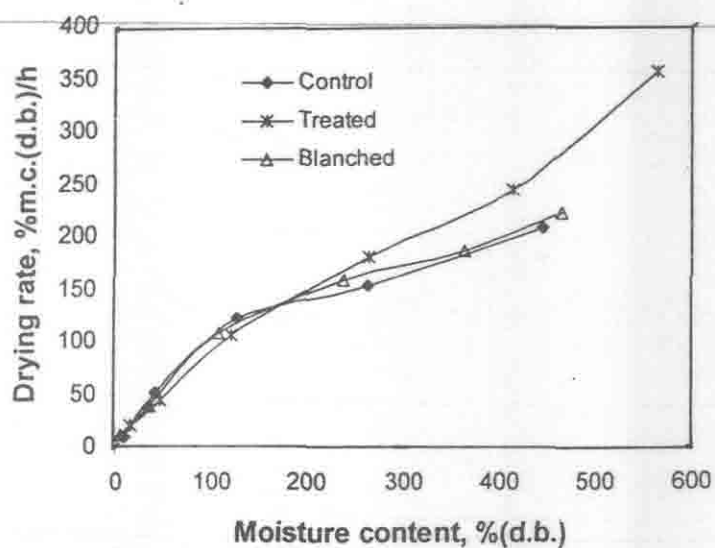


Fig. 5.15 Effect of pre-treatment on drying rate of chilli dried in hot air dryer at 65°C

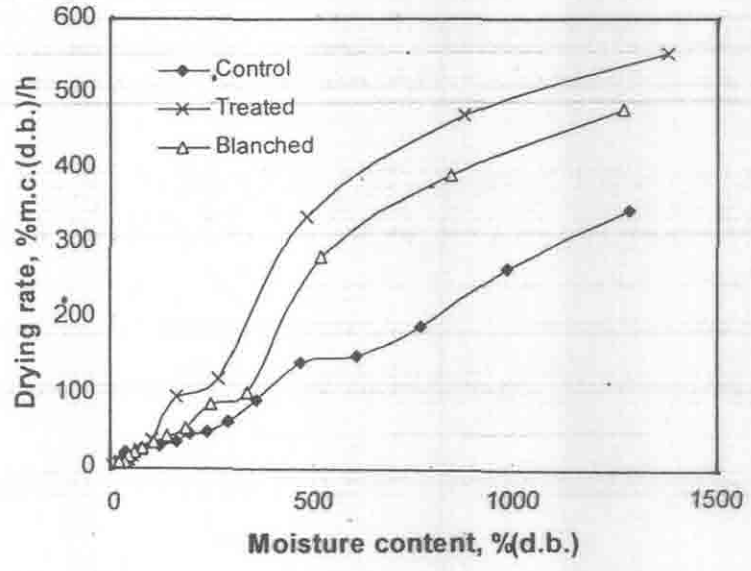


Fig. 5.16 Effect of pre-treatment on drying rate of sweet pepper dried in heat pump dryer at 40°C

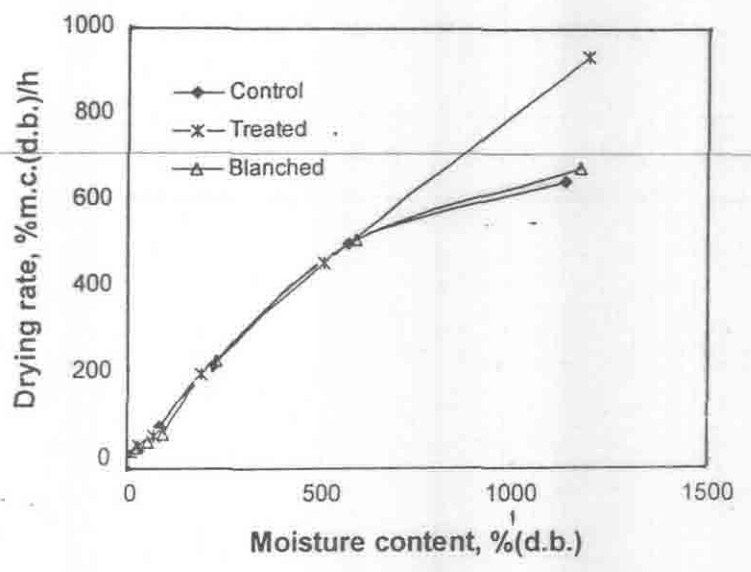


Fig. 5.17 Effect of pre-treatment on drying rate of sweet pepper dried in hot air dryer at 65°C

better than Lewis equation to describe the thin-layer drying of green chilli and sweet pepper. Similar findings were also reported by Hossain and Bala (2002).

The rate constant,  $K$ , which is a measure of the drying rate, significantly increased ( $P=0.05$ ) with the drying air temperature resulting in substantial reduction in total drying time. Pre-treatment, in general, resulted in enhancing the drying rate as indicated by greater values of the rate constant,  $K$  (Tables 5.6 and 5.7).

**Table 5.6 Drying parameters of Lewis and Page model for chilli under different drying conditions**

Sample	Dryer	Drying Temp (°C)	Lewis				Page			
			K	A'	R <sup>2</sup>	RM SE	K	n'	R <sup>2</sup>	RM SE
Control	HPD	30	0.17	1.94	0.74	1.70	0.11	1.00	0.96	0.30
		35	0.24	2.08	0.75	1.52	0.14	1.04	0.96	0.27
		40	0.43	2.92	0.75	1.82	0.16	1.19	0.94	0.34
	HAD	45	0.47	2.90	0.81	1.77	0.15	1.22	0.96	0.36
		55	1.03	3.48	0.81	2.20	0.35	1.28	0.95	0.4
		65	2.11	5.05	0.84	2.73	0.55	1.58	0.96	0.42
Treated	HPD	30	0.17	1.55	0.85	1.03	0.12	1.01	0.97	0.23
		35	0.29	2.18	0.76	1.76	0.18	1.00	0.94	0.32
		40	0.53	2.10	0.80	1.77	0.32	1.08	0.95	0.28
	HAD	45	0.52	2.95	0.81	1.94	0.16	1.27	0.95	0.37
		55	1.26	4.98	0.81	2.45	0.31	1.49	0.93	0.43
		65	1.78	3.35	0.86	2.16	0.66	1.38	0.96	0.39
Blanched	HPD	30	0.19	2.19	0.71	2.00	0.09	1.06	0.95	0.34
		35	0.35	3.26	0.74	2.15	0.13	1.14	0.95	0.34
		40	0.57	3.25	0.75	2.33	0.24	1.16	0.94	0.32
	HAD	45	0.51	3.40	0.73	2.43	0.12	1.29	0.93	0.47
		55	1.16	4.62	0.77	2.57	0.28	1.46	0.91	0.49
		65	2.26	8.29	0.83	3.15	0.91	0.22	0.91	0.62

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**Table 5.7 Drying parameters of Lewis and Page model for sweet pepper under different drying conditions**

Sample	Dryer	Drying Temp (°C)	Lewis				Page			
			K	A'	R <sup>2</sup>	RM SE	K	n'	R <sup>2</sup>	RM SE
Control	HPD	30	0.20	1.69	0.78	1.94	0.16	0.99	0.97	0.24
		35	0.33	2.10	0.79	1.96	0.22	1.04	0.97	0.24
		40	0.64	5.64	0.72	3.14	0.21	1.16	0.93	0.40
	HAD	45	0.49	2.94	0.75	2.62	0.20	1.18	0.96	0.32
		55	0.94	3.26	0.85	2.02	0.42	1.22	0.97	0.25
		65	1.76	4.68	0.87	2.37	0.53	1.54	0.97	0.28
Treated	HPD	30	0.23	2.15	0.84	1.59	0.10	1.15	0.98	0.23
		35	0.42	3.97	0.79	2.31	0.11	1.30	0.97	0.29
		40	0.74	2.56	0.87	1.85	0.42	1.13	0.97	0.21
	HAD	45	0.69	4.46	0.77	3.00	0.21	1.25	0.95	0.39
		55	1.29	4.95	0.88	2.16	0.44	1.37	0.98	0.23
		65	2.29	5.99	0.85	3.03	0.69	1.54	0.94	0.40
Blanched	HPD	30	0.20	1.60	0.82	1.62	0.18	0.96	0.97	0.23
		35	0.37	2.43	0.77	2.11	0.25	0.99	0.95	0.27
		40	0.65	3.00	0.82	2.10	0.37	1.08	0.96	0.26
	HAD	45	0.51	2.55	0.77	2.39	0.25	1.14	0.96	0.30
		55	0.94	4.28	0.79	2.54	0.36	1.23	0.94	0.34
		65	2.06	8.13	0.80	3.59	0.51	1.57	0.94	0.41

The Page model can be used to estimate the moisture content of chilli and sweet pepper at any time during the drying process at different temperatures with an acceptable accuracy. Validation of the selected model was made by comparing the computed and measured values of moisture contents in all drying runs as shown in Figs. 5.26 and 5.27. It is observed that consistency of fitting the drying data into this model is very good for all the experimental drying air temperatures.

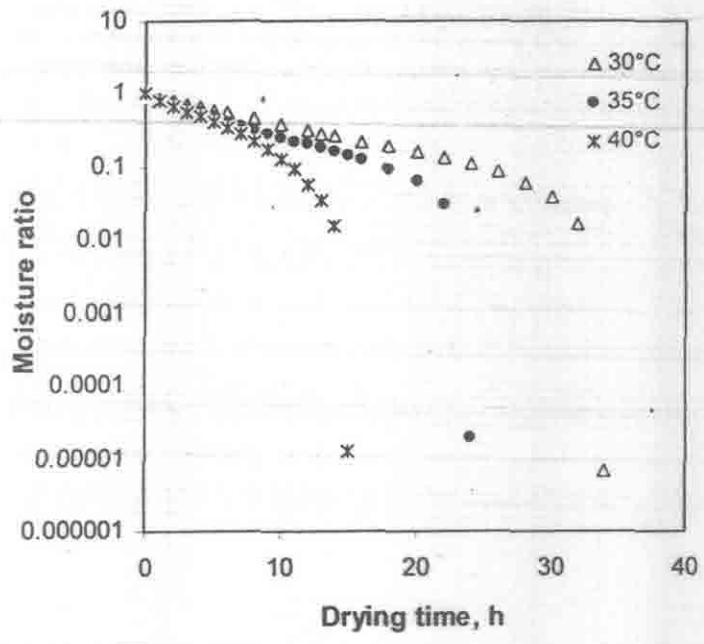


Fig. 5.18 Fitting Lewis equation to experimental drying data of chilli dried in heat pump dryer

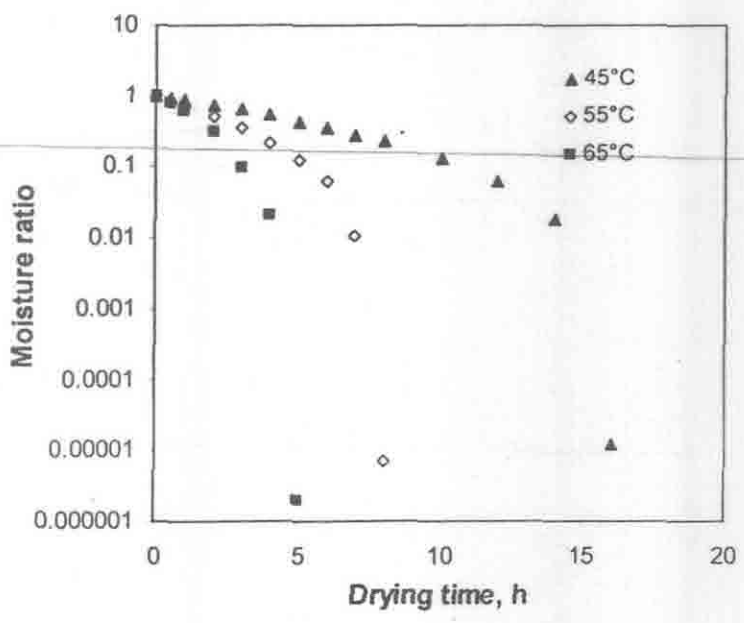


Fig. 5.19 Fitting Lewis equation to experimental drying data of chilli dried in hot air dryer

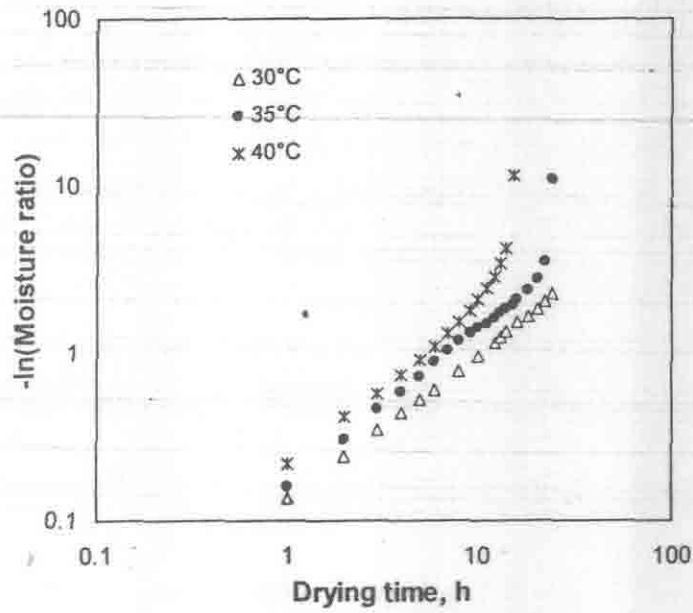


Fig. 5.20 Fitting Page equation to experimental drying data of chilli dried in heat pump dryer

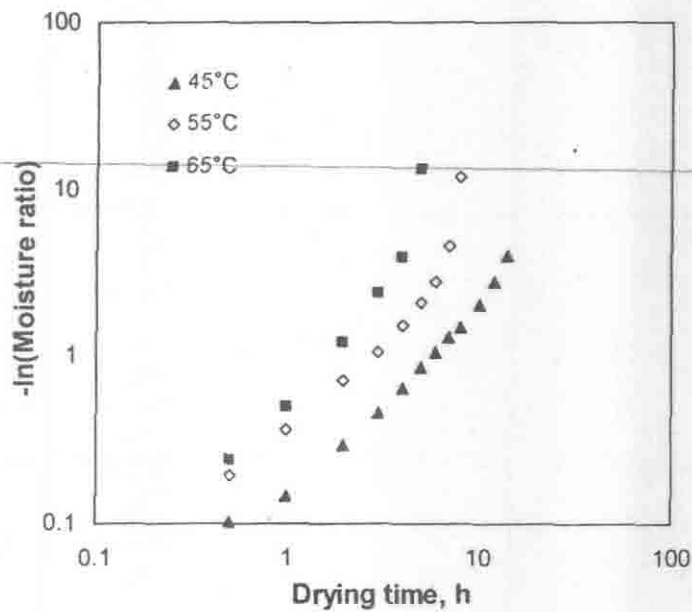


Fig. 5.21 Fitting Page equation to experimental drying data of chilli dried in hot air dryer

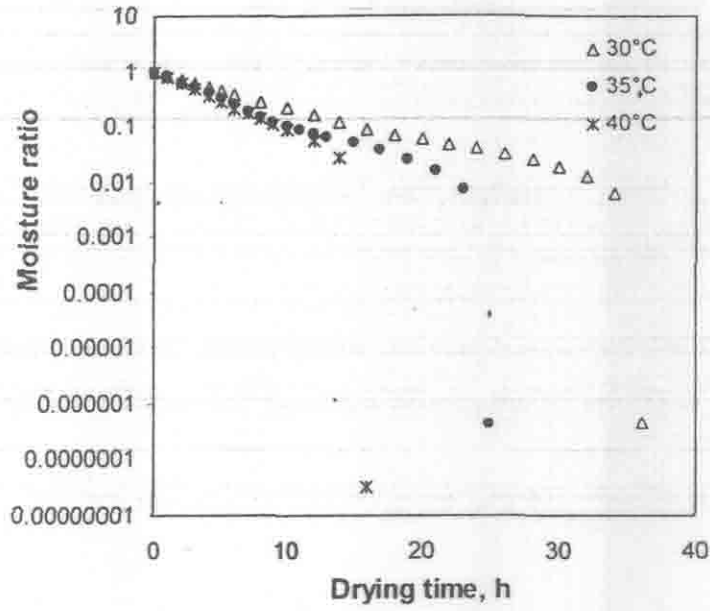


Fig. 5.22 Fitting Lewis equation to experimental drying data of sweet pepper dried in heat pump dryer

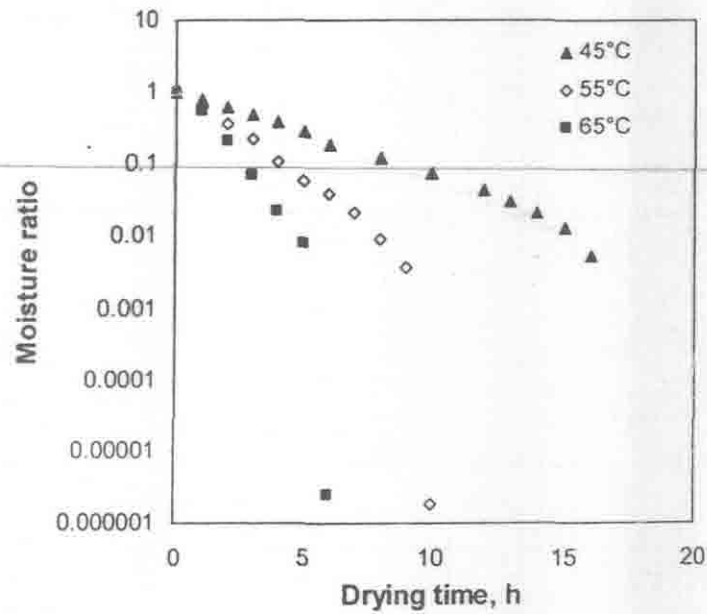


Fig. 5.23 Fitting Lewis equation to experimental drying data of sweet pepper dried in hot air dryer

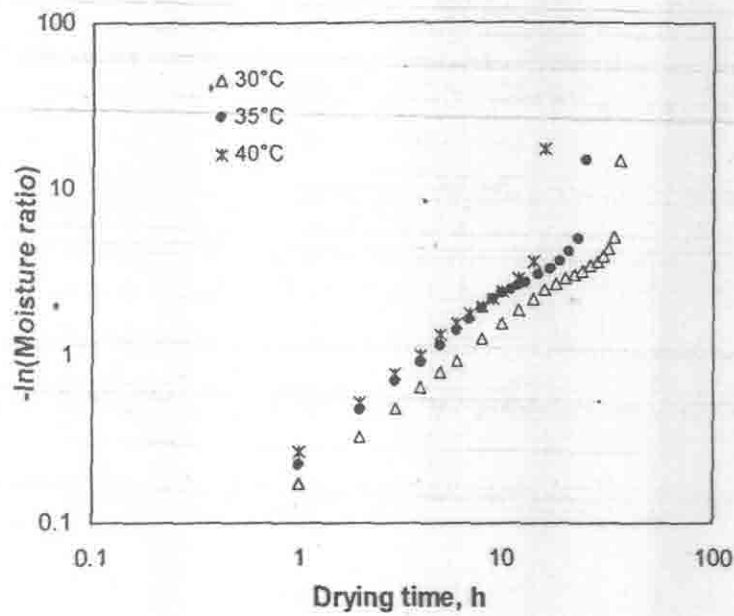


Fig. 5.24 Fitting Page equation to experimental drying data of sweet pepper in heat pump dryer

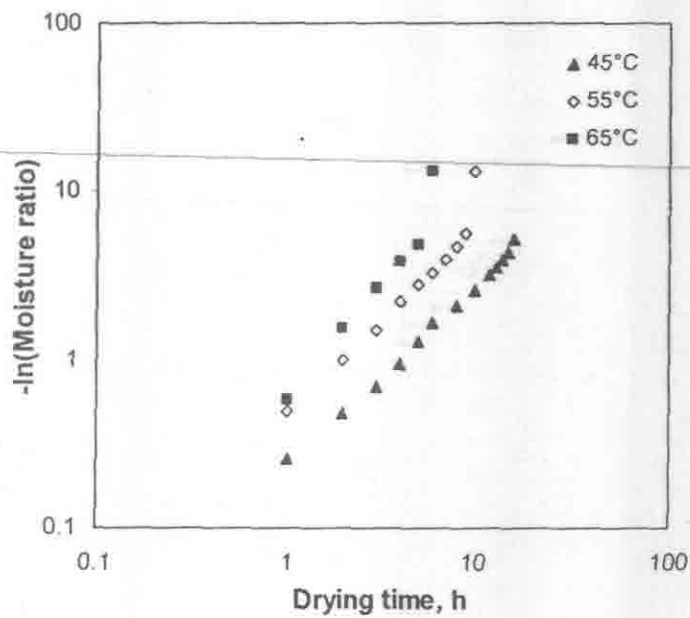


Fig. 5.25 Fitting Page equation to experimental drying data of sweet pepper in hot air dryer

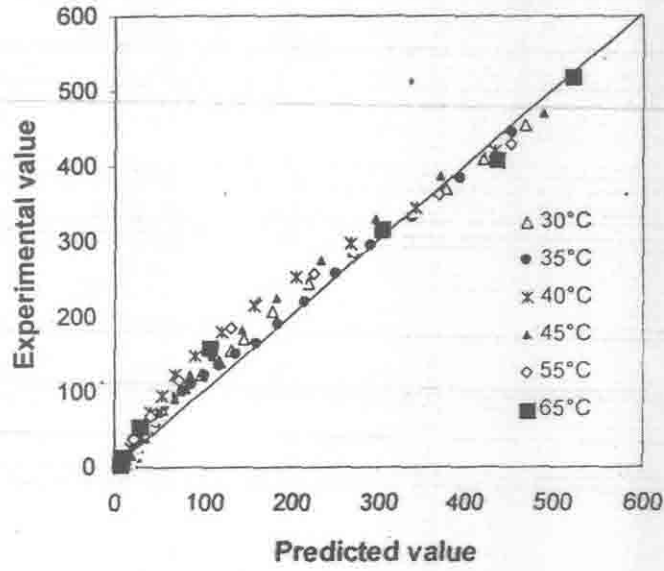


Fig. 5.26 Comparison of experimental and calculated moisture content values of green chilli by using Page model

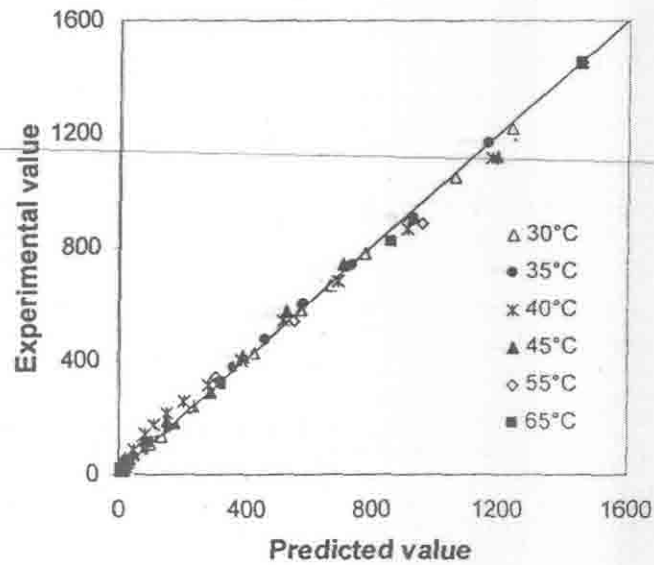


Fig. 5.27 Comparison of experimental and calculated moisture content values of green sweet pepper by using Page model

### Characteristic drying curve

The dimensionless drying rate versus moisture ratio are plotted at different drying air conditions to represent the characteristic drying curves which are shown in Figs. 5.28 and 5.29. These figures show that all drying curves obtained with the moisture ratio and dimensionless drying rate for different tested conditions, are fairly close together, indicating that the effect of variation in different conditions is small over the range tested. A polynomial model was found to best fit the dimensionless experimental data. Similar results are obtained by Lahsasni *et al.* (2004) for prickly pear cladode.

For chilli

$$f_{dr} = 2.6292 MR^4 - 4.2634 MR^3 + 1.9955 MR^2 + 0.5965 MR + 0.0359 \quad (5.1)$$
$$(R^2 = 0.969)$$

For sweet pepper

$$f_{dr} = 2.2984 MR^4 - 3.923 MR^3 + 1.8382 MR^2 + 0.7782 MR + 0.9069 \quad (5.2)$$
$$(R^2 = 0.985)$$

where,

$f_{dr}$  = Dimensionless drying rate

MR = Moisture ratio

#### 5.2.4 Comparison between hot air and heat pump dryer

Drying in heat pump dryer at 40°C took less time compared to hot air drying at 45°C for both green chilli and sweet pepper. This may be due to the low relative humidity of the drying air in heat pump dryer though the drying air temperature is less.

Initially, the drying rate was observed to be more in HPD at 40°C but at the later part of drying, it was more in HAD at 45°C (Figs. 5.30 and 5.31). This indicates that the effect of low relative humidity of air in HPD is prominent during the initial period of drying when the product is moist. The effect of temperature is observed to be prominent at the later part of drying which acts as a driving force for moisture diffusion.

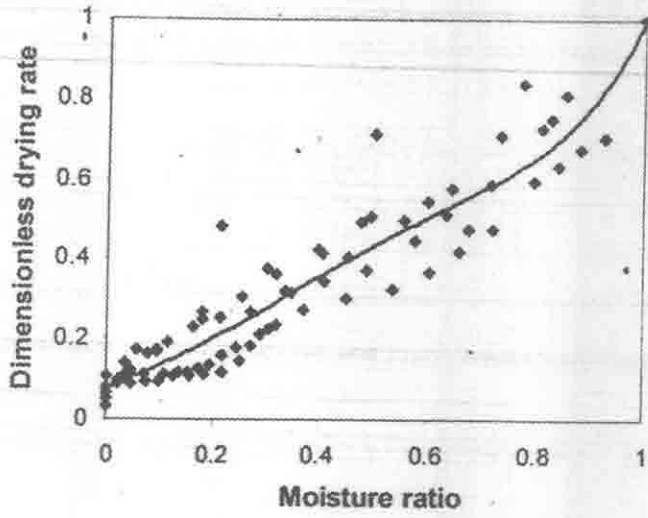


Fig. 5.28 Characteristic drying curve for chili

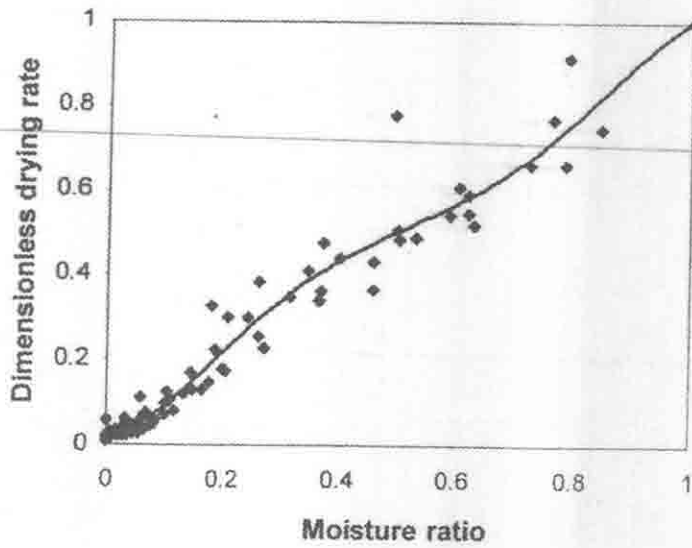


Fig. 5.29 Characteristic drying curve for sweet pepper

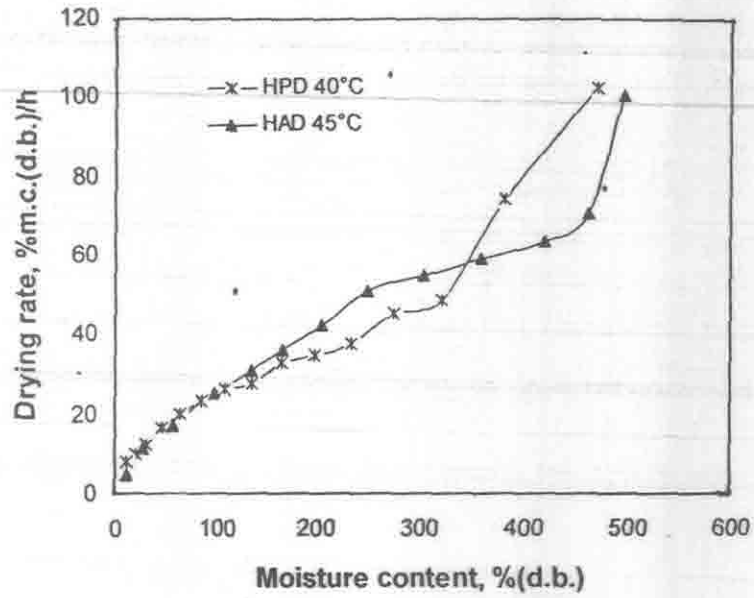


Fig. 5.30 Comparison of drying rates of chilli dried in hot air and heat pump dryer

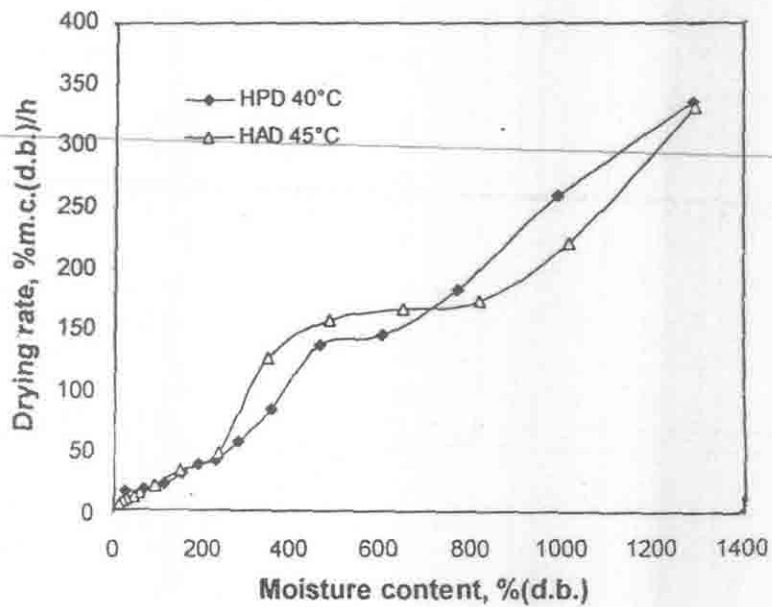


Fig. 5.31 Comparison of drying rates of sweet pepper dried in hot air and heat pump dryer

### 5.3 Quality Parameters of Dehydrated Product

#### 5.3.1 Dehydration ratio and rehydration ratio

The dehydration ratios of control chilli samples were observed to be varied from 5.9 to 6.1 at all the drying air temperatures and that of sweet pepper ranged from 15.0 to 15.4 with the higher values for higher drying air temperatures (Table 5.8). The dehydration ratio is less in control sample due to higher value of residual moisture content after drying which adds to the weight of the sample. The same effect is also reported by Gupta *et al.* (2006) for tomato slices. The dehydration ratios of treated samples were observed to be highest for both chilli and sweet pepper owing to higher initial moisture content and removal of outer waxy skin due to lye treatment which promotes moisture removal during drying (Figs. 5.32 and 5.33).

**Table 5.8 Mean values of dehydration ratio for chilli and sweet pepper dried in different conditions**

Product	Sample	HPD				HAD	
		30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	5.9	6.0	6.1	6.0	6.0	6.1
	Treated	7.0	7.1	7.2	7.1	7.2	7.3
	Blanched	6.0	6.1	6.2	6.1	6.3	6.4
Sweet pepper	Control	15.0	15.1	15.2	15.1	15.3	15.4
	Treated	17.0	17.1	17.2	17.0	17.2	17.3
	Blanched	15.8	15.8	15.9	15.8	15.9	16.0

The rehydration ratios ranged from 3.9 to 4.5 for chilli, whereas 6.5 to 7.2 for sweet pepper control samples (Table 5.9). The rehydration ratios were observed to be more in heat pump dried product at lower drying air temperature as compared to hot air dried product. This might be due to the structural change to the product at higher drying air temperature that inhibit proper reconstitution. The rehydration ratios of control, treated and blanched dehydrated sweet pepper samples obtained from drying at 30°C were observed to be 7.2, 7.5 and 6.3, respectively. The rehydration ratios of chilli and sweet pepper were observed to be highest for treated sample and lowest for blanched sample at all the drying air temperatures (Figs. 5.34 and 5.35). The elasticity of cell walls and swelling power, which are important for good rehydration were reduced during blanching, hence the lower rehydration ratios of blanched samples. The results were similar to the findings of Rama and John (2000) for dried mushrooms. The higher rehydration ratio of treated sample may be attributed to the retention of pore structure due to presence of salt and removal of outer waxy skin due to lye treatment which promotes moisture uptake during rehydration. The variation of rehydration and dehydration ratios with temperature and treatment were observed to be significant at 5% level (Tables 5.13 and 5.14).

**Table 5.9 Mean values of rehydration ratio for chilli and sweet pepper dried in different conditions**

Product	Sample	HPD				HAD	
		30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	4.5	4.4	4.2	4.1	4.0	3.9
	Treated	4.8	4.6	4.5	4.4	4.2	4.2
	Blanched	3.8	3.7	3.7	3.5	3.5	3.4
Sweet pepper	Control	7.2	7.0	6.9	6.8	6.6	6.5
	Treated	7.5	7.3	7.3	7.1	7.0	6.8
	Blanched	6.3	6.2	6.2	6.0	5.9	5.8

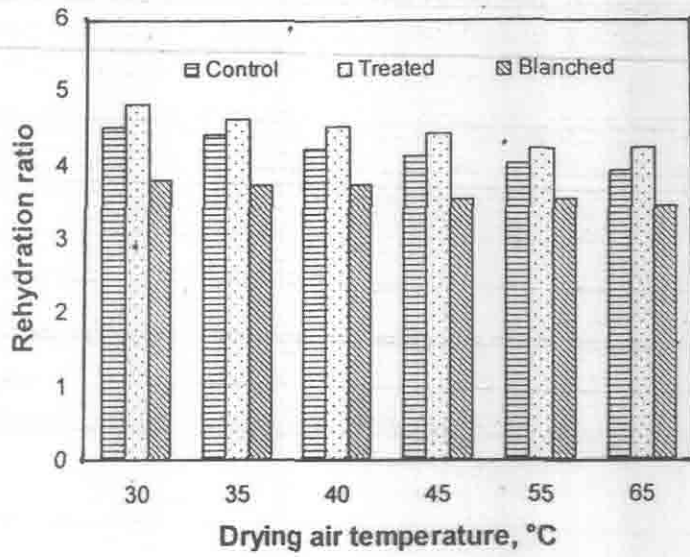


Fig. 5.34 Effect of pre-treatment and drying air temperature on rehydration ratio of chili

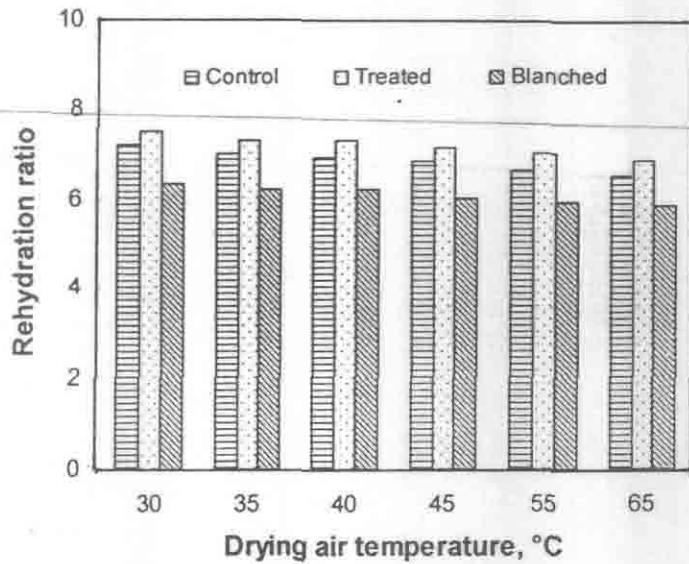


Fig. 5.35 Effect of pre-treatment and drying air temperature on rehydration ratio of sweet pepper

### 5.3.2 Total chlorophyll content

Total chlorophyll content of sweet pepper reduced from an initial value of 103 to 66 mg/100g d.b. in hot air dryer at 65°C and to 96 mg/100g d.b. in heat pump dryer at 30°C (Table 5.10). It was observed that chlorophyll content of final dried product decreased with increase in drying air temperature which might be due to the temperature sensitivity of the pigment. The investigation by Nindo *et al.* (2003) also showed that particles of asparagus tips that were tray dried at 60°C found to be the least green. The chlorophyll content of treated samples were observed to be at par with control but the blanched samples showed a significant loss of chlorophyll (Figs. 5.36 and 5.37) which might be due to change of the pigment to an olive green colour during steam blanching at higher temperature. Steam blanching alone followed by hot air drying produced a pale green product since the heat labile chlorophyll degraded to pheophytin a and b due to loss of magnesium ion ( $Mg^{++}$ ). Similar observation was reported by Rocha *et al.* (1993) while studying the dehydration of basil leaves.

The same behaviour was also observed in case of green chilli which showed a decrease in total chlorophyll content from an initial value of 79 to 73 mg/100g d.b. at 30°C in HPD and to 45 mg/100g d.b. at 65°C in hot air dryer. The chlorophyll contents of chilli dried at 65°C were observed to be 45, 44 and 33 mg/100g d.b. for control, treated and blanched samples, respectively.

**Table 5.10 Mean values of total chlorophyll content (mg/100g d.b.) for chilli and sweet pepper dried in different conditions**

Product	Sample	HPD			HAD		
		30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	73	71	67	64	57	45
	Treated	72	71	65	63	55	44
	Blanched	63	60	55	53	47	33
Sweet pepper	Control	96	93	89	86	78	66
	Treated	95	92	89	87	77	64
	Blanched	81	79	76	72	66	55

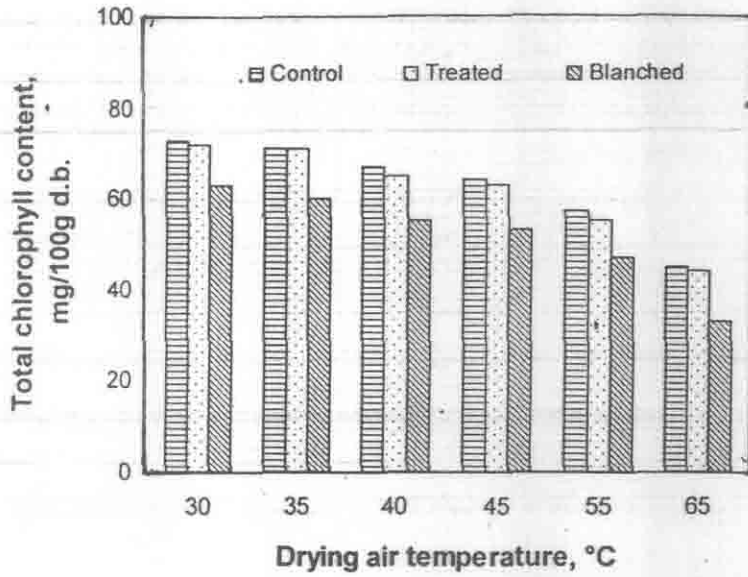


Fig. 5.36 Effect of pre-treatment and drying air temperature on total chlorophyll content of dried chilli

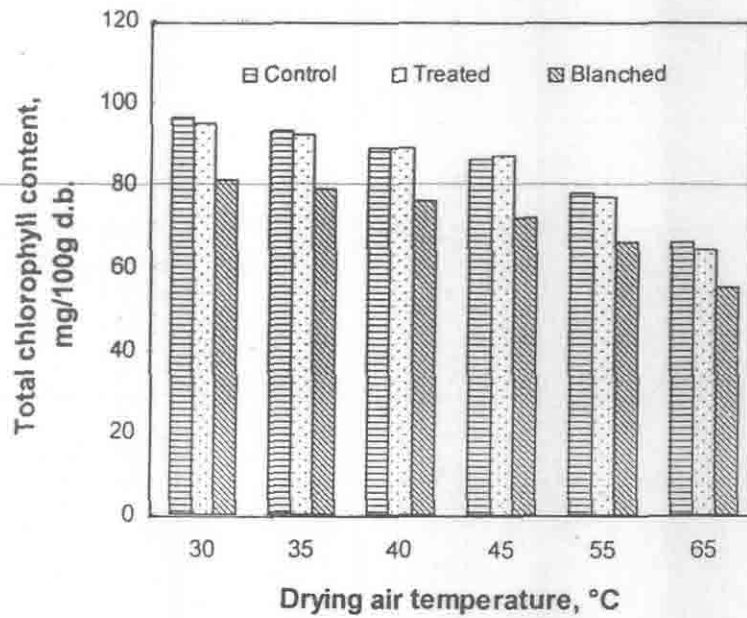


Fig. 5.37 Effect of pre-treatment and drying air temperature on total chlorophyll content of dried sweet pepper

Drying of both chilli and sweet pepper in hot air dryer at higher temperatures reduced considerably the green colour of dried product. Among the various pre-treatments, blanching in solution containing 0.5% lye and 0.25% magnesium carbonate at 95°C for 2 minutes resulted in minimum loss of chlorophyll. Clydesdale and Francis (1968) also found that blanching of spinach in a solution of  $MgCO_3$  increased the formation of chlorophyllides and decreased the conversion of both chlorophyll and chlorophyllides into pheophytins and pheophorbides, respectively. Chin and Dudek (1988) suggested to maintain an alkaline pH and high concentration of magnesium in the environment during blanching to stabilize chlorophyll in processed vegetables.

### 5.3.3 Ascorbic acid content

The ascorbic acid content of control sweet pepper samples decreased from an initial value of 1060 to 337 mg/100g d.b. when dried at 35°C in heat pump dryer and to 174 mg/100g d.b. in hot air dryer at 65°C (Table 5.11). From Fig 5.38, it was observed that the ascorbic acid content of dried green sweet pepper decreased with increase in drying air temperature for all the samples because of its temperature sensitiveness. The retention of ascorbic acid was highest in heat pump dried samples and least in samples dried in HAD at higher temperatures. Nindo *et al.* (2003) stated that heated air inherently exposes products to oxidation, thus reducing the total ascorbic acid content of dried asparagus.

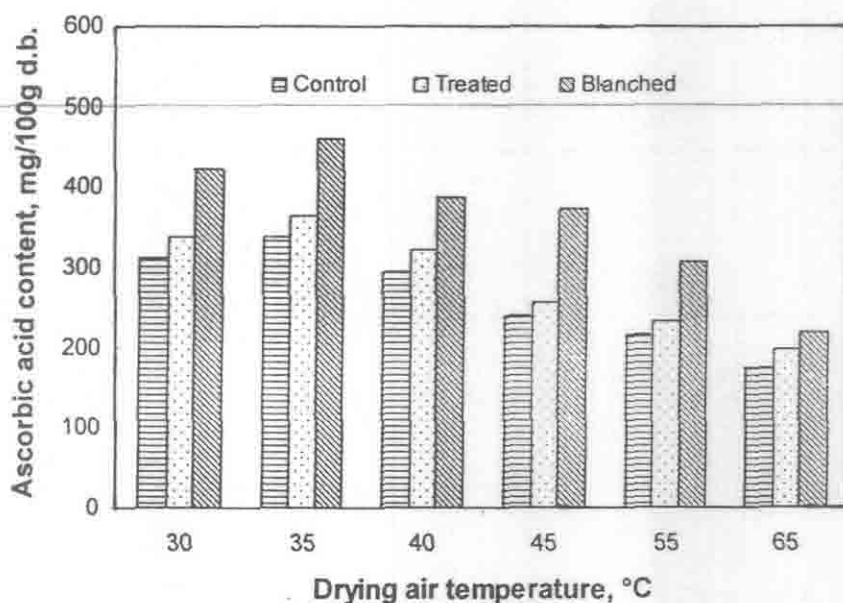
Ascorbic acid content of sweet pepper samples dried at 30°C in HPD was found less than that obtained at 35°C. This may be due to the long drying time (32-36 hours) that facilitates the oxidation of ascorbic acid content as reported by Nindo *et al.* (2003) for freeze dried asparagus. Jayaraman and Gupta (1995) also stated that slow drying methods like sun drying caused increase in loss of ascorbic acid. The combination of short drying time and less temperature drying is important for retention of ascorbic acid in dried sweet pepper.

The ascorbic acid content of control, treated and blanched sweet pepper samples obtained from drying at 35°C in HPD were observed to be 337, 364 and 459 mg/100g d.b., respectively. The retention of ascorbic acid was more in blanched samples as compared to treated and control samples for all the drying air temperatures. This may be due to the inactivation of ascorbic acid oxidase during

steam blanching' which is responsible for degradation of the vitamin. Vitamin C is highly water soluble and as there is no contact with water more amount of vitamin C is retained in blanched sample. Blanched products are more stable for ascorbic acid losses probably due to low oxygen atmosphere during steam blanching and increased tocopherol which acts as anti-oxidant. Similar results were also reported by Ramesh *et al.* (2001). The ascorbic acid content of treated samples were observed to be less than that of blanched samples which might be due to leaching of the water soluble vitamins during treatment.

**Table 5.11 Mean values of ascorbic acid content (mg/100g d.b.) for sweet pepper dried in different conditions**

Product	Sample	HPD				HAD	
		30°C	35°C	40°C	45°C	55°C	65°C
Sweet pepper	Control	312	337	294	238	216	174
	Treated	338	364	320	256	232	198
	Blanched	423	459	387	372	306	217



**Fig. 5.38 Effect of pre-treatment and drying air temperature on ascorbic acid content of dried sweet pepper**

### 5.3.4 Capsaicin content

The capsaicin content of chilli dried under different conditions as estimated in terms of optical density are presented in Table 5.12. The results indicated that the capsaicin content of heat pump dried samples were higher than that of hot air dried samples.

The optical density was observed to be more when dried at 30°C in heat pump dryer indicating higher retention of capsaicin content at lower temperature. But there is no appreciable difference in capsaicin content of chilli dried at higher temperature range of 40 to 65°C for all the samples. Pordesimo *et al.* (2004) also reported that drying air temperature did not affect the concentration of total capsaicinoids in dried Jalapeno peppers. The lower value of optical density for treated and blanched samples as compared to control indicated loss of capsaicin during treatment and blanching. Capsaicin content was observed to be less in treated samples probably due to the leaching loss of alkaloids during treatment.

**Table 5.12 Optical density of capsaicin extract of chilli dried in different conditions**

Product	Sample	HPD				HAD	
		30°C	35°C	40°C	45°C	55°C	65°C
Chilli	Control	0.633	0.616	0.583	0.569	0.567	0.564
	Treated	0.508	0.486	0.452	0.442	0.439	0.437
	Blanched	0.584	0.566	0.525	0.514	0.509	0.508

### Data analysis

Two way analysis of variance was performed to estimate the variables that contributed significantly ( $P=5\%$ ) to the total drying time, dehydration ratio, rehydration ratio, total chlorophyll content, capsaicin content and ascorbic acid content. The variables considered were drying air temperature and pre-treatment. Tables 5.13 and 5.14 show the two way ANOVA results for quality attributes of dried chilli and sweet pepper, respectively. It is clear from the Tables that the two factors, drying air temperature and pre-treatment are independent in their effects for all the quality attributes except that for ascorbic acid of sweet pepper. The calculated F values for all the properties are higher than tabular F values indicating significance of

the variables at 5% level. So, drying air temperature as well as pretreatment both play significant role in influencing the quality parameters of dehydrated chilli and sweet pepper.

**Table 5.13 Two way ANOVA for quality attributes of green chilli**

	df	SS	MSS	F <sub>cal</sub>	F <sub>table</sub> (5%)	CD <sub>5%</sub>	Sem
<b>Total drying time</b>							
Treatment	2	21.555	10.777	9.238 <sup>s</sup>	3.55	0.926	0.311
Temperature	5	3013.889	602.777	516.666 <sup>s</sup>	2.77	1.310	0.441
Interaction	10	10.444	1.044	0.895 <sup>ns</sup>	2.79	2.269	0.763
Error	18	21	1.166				
<b>Dehydration ratio</b>							
Treatment	2	8.986	4.493	367.636 <sup>s</sup>	3.55	0.094	0.032
Temperature	5	0.330	0.066	5.400 <sup>s</sup>	2.77	0.134	0.045
Interaction	10	0.053	0.005	0.436 <sup>ns</sup>	2.79	0.232	0.078
Error	18	0.220	0.012				
<b>Rehydration ratio</b>							
Treatment	2	4.557	2.278	101.271 <sup>s</sup>	3.55	0.128	0.043
Temperature	5	1.234	0.247	10.975 <sup>s</sup>	2.77	0.182	0.061
Interaction	10	0.079	0.008	0.353 <sup>ns</sup>	2.79	0.315	0.106
Error	18	0.405	0.022				
<b>Chlorophyll content</b>							
Treatment	2	888	444	115.826 <sup>s</sup>	3.55	1.679	0.565
Temperature	5	3362.667	672.533	175.443 <sup>s</sup>	2.77	2.374	0.799
Interaction	10	13.333	1.333	0.347 <sup>ns</sup>	2.79	4.113	1.384
Error	18	69	3.833				
<b>Optical density (for capsaicin content)</b>							
Treatment	2	0.102	0.051	3511.030 <sup>s</sup>	3.55	0.003	0.0011
Temperature	5	0.023	0.005	322.443 <sup>s</sup>	2.77	0.005	0.0016
Interaction	10	0.0002	1.83E-05	1.252 <sup>ns</sup>	2.79	0.008	0.0027
Error	18	0.0003	1.46E-05				

<sup>s</sup> significant

<sup>ns</sup> not significant

**Table 5.14 Two way ANOVA for quality attributes of green sweet pepper.**

	df	SS	MSS	F <sub>cal</sub>	F <sub>table</sub> (5%)	CD <sub>5%</sub>	Sem
<b>Total drying time</b>							
Treatment	2	21.555	10.777	9.238 <sup>s</sup>	3.55	0.795	0.267
Temperature	5	3013.889	602.777	516.666 <sup>s</sup>	2.77	1.125	0.378
Interaction	10	10.444	1.044	0.895 <sup>ns</sup>	2.79	1.949	0.656
Error	18	21	1.166				
<b>Dehydration ratio</b>							
Treatment	2	23.495	11.747	660.812 <sup>s</sup>	3.55	0.114	0.038
Temperature	5	0.392	0.078	4.412 <sup>s</sup>	2.77	0.161	0.054
Interaction	10	0.037	0.003	0.212 <sup>ns</sup>	2.79	0.280	0.094
Error	18	0.32	0.017				
<b>Rehydration ratio</b>							
Treatment	2	7.635	3.817	171.8 <sup>s</sup>	3.55	0.127	0.043
Temperature	5	1.635	0.327	14.72 <sup>s</sup>	2.77	0.180	0.060
Interaction	10	0.044	0.004	0.2 <sup>ns</sup>	2.79	0.313	0.105
Error	18	0.4	0.022				
<b>Chlorophyll content</b>							
Treatment	2	1293.056	646.527	192.355 <sup>s</sup>	3.55	1.572	0.529
Temperature	5	3424.806	684.961	203.790 <sup>s</sup>	2.77	2.223	0.748
Interaction	10	26.611	2.661	0.791 <sup>ns</sup>	2.79	3.851	1.296
Error	18	60.5	3.361				
<b>Ascorbic acid content</b>							
Treatment	2	64261.556	32130.777	833.363 <sup>s</sup>	3.55	5.325	1.792
Temperature	5	151076.560	30215.311	783.682 <sup>s</sup>	2.77	7.530	2.535
Interaction	10	7090.444	709.044	18.390 <sup>s</sup>	2.41	13.043	4.390
Error	18	694	38.555				

<sup>s</sup> significant

<sup>ns</sup> not significant

### 5.3.6 Sensory attributes

The mean sensory scores for different quality attributes of dried chilli and sweet pepper are presented in Tables 5.15 and 5.16. From the organoleptic evaluation of dried chilli samples for their appearance, it was observed that heat pump dried samples at lower temperature were better than hot air dried product. Increase in drying air temperature from 30 to 65°C significantly decreased the colour score. The scores for texture, flavour and overall acceptability also decreased significantly with increase in drying air temperature from 30 to 65°C for all the samples. The dehydrated green chilli and sweet pepper obtained from different drying conditions and pretreatments are shown in Figs. 5.39 through 5.40 and Figs 5.42 through 5.43, respectively.

The texture scores of control samples were more, whereas colour, flavour and overall acceptability scores were higher for treated samples of chilli as well as sweet pepper. Control samples showed uneven pale green patches whereas treated samples possessed an attractive shiny appearance with slight wrinkling on the pods. Treated samples obtained higher sensory scores followed by control and blanched samples. Steam blanching decreased the colour, texture, flavour and overall acceptability scores for both chilli and sweet pepper.

Among the drying methods, HPD produced dried chilli and sweet pepper with higher greenness/chlorophyll content compared to HAD. Chillies dried at higher temperatures were comparatively less green.

Rehydrated chilli and sweet pepper appeared slightly lighter in greenness as compared to fresh samples, but the product still looked excellent for use (Fig. 5.41 and 5.44).

**Table 5.15 Mean sensory scores for different quality attributes of dehydrated chilli**

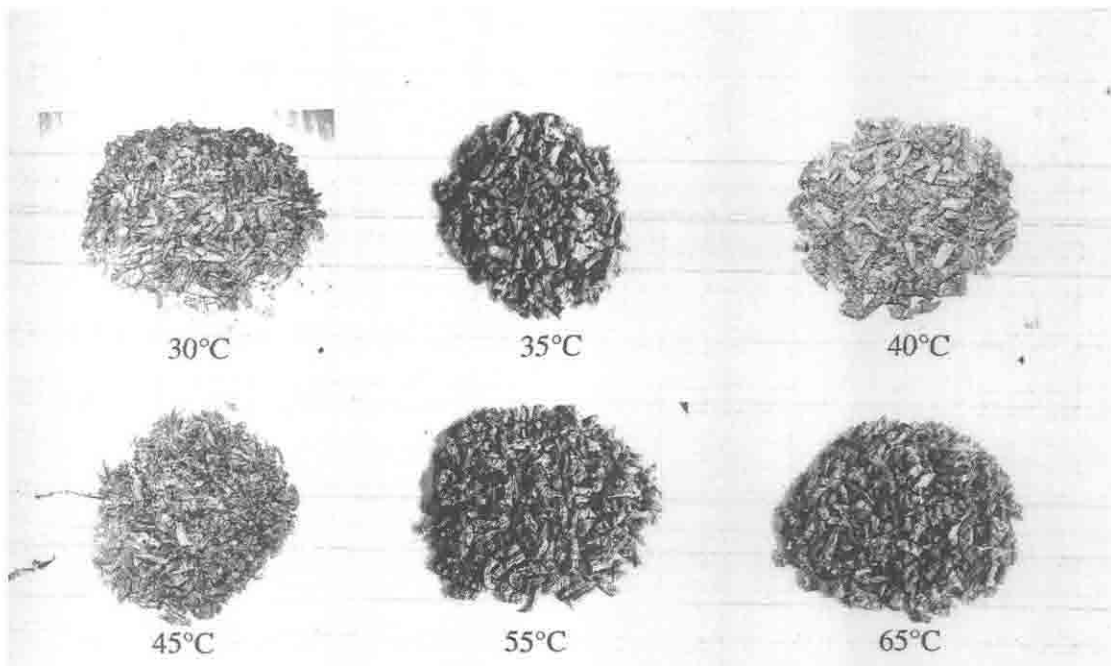
Sample	Dryer	Drying Temperature (°C)	Sensory score			
			Colour	Texture	Flavour	Overall acceptability
Control	HPD	30	8.1	8.0	7.9	7.3
		35	7.9	7.8	7.8	7.2
		40	7.5	7.3	7.4	6.8
	HAD	45	7.0	6.8	6.8	6.5
		55	6.4	6.4	5.8	6.1
		65	5.1	5.8	4.6	5.5
Treated	HPD	30	8.6	7.7	8.3	7.6
		35	8.4	7.6	8.2	7.5
		40	8.1	7.2	7.8	7.2
	HAD	45	7.6	6.6	7.1	6.8
		55	7.2	6.3	6.0	6.3
		65	6.3	5.6	4.9	5.6
Blanched	HPD	30	5.5	4.5	4.5	4.8
		35	5.3	4.4	4.5	4.7
		40	5.0	4.3	4.4	4.6
	HAD	45	4.6	4.0	4.2	4.2
		55	4.2	3.5	3.8	3.9
		65	3.7	3.2	3.6	3.5

Each value of sensory score is average of ten observations in 9 point scale

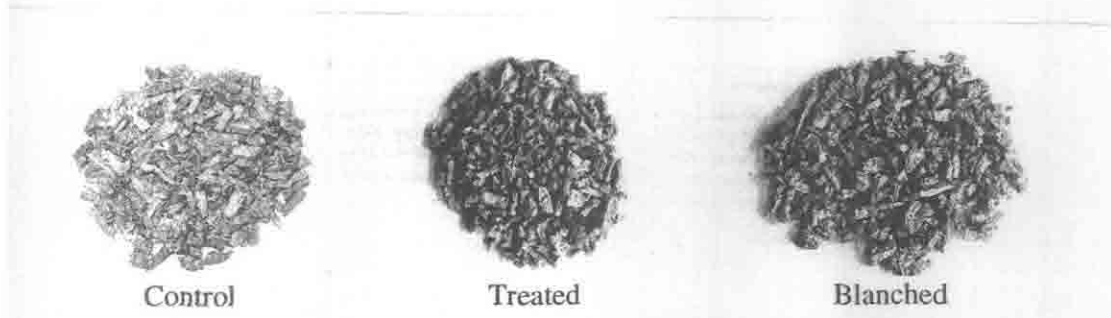
**Table 5.16 Mean sensory scores for different quality attributes of dehydrated sweet pepper**

Sample	Dryer	Drying Temperature (°C)	Sensory score			Overall acceptability
			Colour	Texture	Flavour	
Control	HAD	30	8.0	7.5	7.9	7.5
		35	7.8	7.4	7.7	7.4
		40	7.4	7.1	7.1	7.1
	HPD	45	7.1	6.8	6.0	6.5
		55	6.3	6.7	5.1	5.8
		65	5.6	6.4	4.2	5.2
Treated	HAD	30	8.3	7.2	8.1	7.7
		35	8.1	7.2	7.9	7.6
		40	7.7	6.9	7.2	7.3
	HPD	45	7.2	6.3	6.2	6.6
		55	6.8	6.2	5.4	6.0
		65	6.1	5.7	4.5	5.2
Blanched	HAD	30	5.6	5.2	5.0	5.7
		35	5.5	5.2	4.8	5.5
		40	5.3	4.8	4.3	5.0
	HPD	45	4.7	4.5	3.9	4.5
		55	4.1	4.1	3.4	4.1
		65	3.6	3.8	3.0	3.6

Each value of sensory score is average of ten observations in 9 point scale



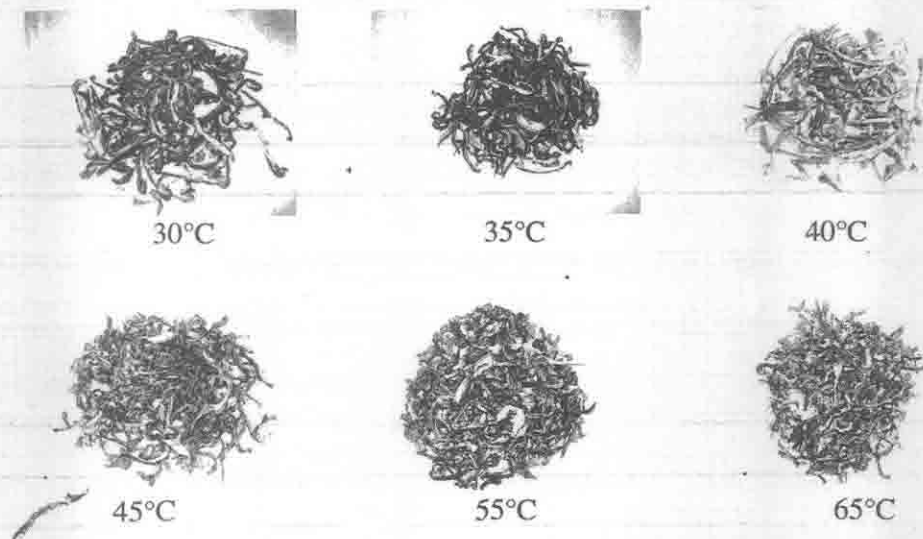
**Fig. 5.39 Dehydrated green chilli obtained from different temperatures of drying**



**Fig. 5.40 Dehydrated green chilli obtained from different pretreated samples dried at 35°C**



**Fig. 5.41 Fresh, dried and rehydrated green chilli samples**



**Fig. 5.42 Dehydrated green sweet pepper obtained from different temperatures of drying**



**Fig. 5.43 Dehydrated sweet pepper obtained from different pretreated samples dried at 35°C**



**Fig. 5.44 Fresh, dried and rehydrated green sweet pepper samples**

## 5.4 Storage Characteristics of Dehydrated Product

### 5.4.1 Sorption study

The experimental results for desorption and adsorption EMC of chilli and sweet pepper for different water activities at 35°C temperature are shown in Figs. 5.45 and 5.46. The values for the EMC of chilli increased with the increase in ERH in both the adsorption and desorption processes at constant temperature of 35°C. Similar findings were also reported in case of chilli by Wesley *et al.* (2000). The sorption isotherms of chilli and sweet pepper showed the typical sigmoid shaped curve (Figs. 5.45 and 5.46).

The equilibrium moisture content increased steadily above 49.2% relative humidity for chilli and 47.2% for sweet pepper as indicated by the inflexion point. So, 8.08% m.c.(d.b.) was observed to be critical for chilli and 12.92% m.c.(d.b.) for sweet pepper. Thus, the product when stored at this RH and 35°C will be stable with respect to moisture loss or uptake. Above these relative humidity, the sample were moist and discoloured. The EMC of chilli at 35°C for adsorption and desorption were observed to be 5.13 and 5.32% (d.b.) at 10.8% ERH, whereas 14.95 and 15.44% (d.b.) at 74.3% ERH, respectively.

Generally, it is recognised that the product, which equilibrates to 70% RH and above is prone to rapid physico-chemical changes in the product. Hence, the moisture content corresponding to 70%RH will be the critical moisture content for dried chilli and sweet pepper product. At 70% RH, with an EMC of 13.67% (d.b.) for chilli and 19.01% (d.b.) for sweet pepper, the product turned soft textured and developed mould growth.

The adsorption and desorption isotherms exhibited the phenomenon of hysteresis, in which the desorption EMC was higher than adsorption EMC at all the equilibrium relative humidities. Kaleemullah and Kailappan (2004) obtained similar types of results in case of red chilli. The hysteresis (desorption moisture content minus adsorption moisture content) existed over the entire ERH range. The hysteresis values started declining after 63% ERH.

Chilli samples were slightly brownish with few patches of chlorophyll at relative humidities higher than 63%, whereas sweet pepper samples turned black at

higher ERH. The samples had visible mould growth, musty smell at higher ERH and hence, the samples were discarded.

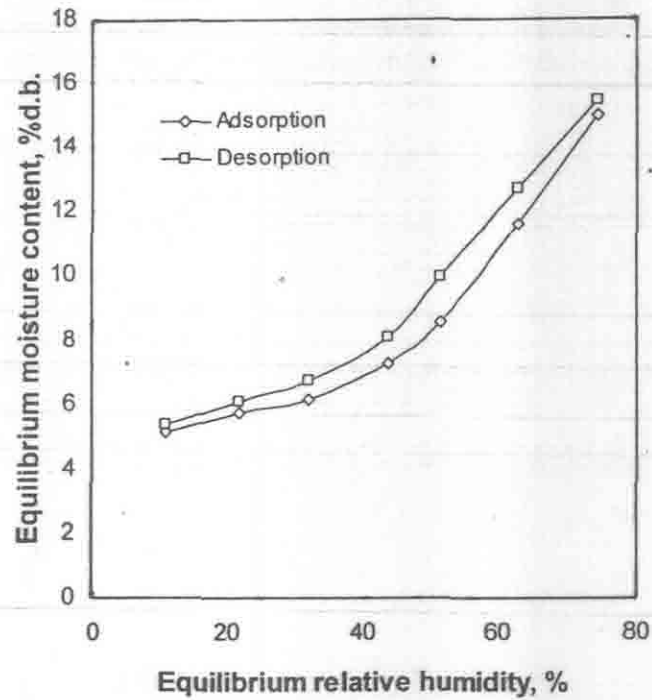


Fig. 5.45 Adsorption and desorption isotherms of chilli at 35°C

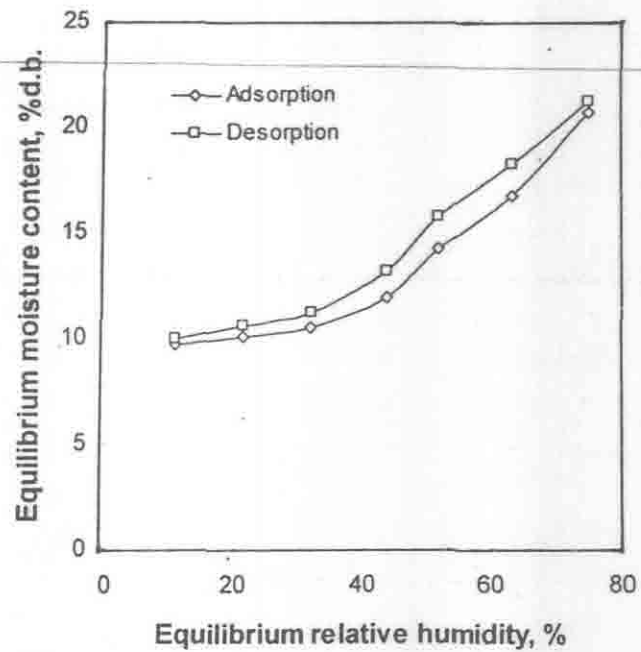


Fig. 5.46 Adsorption and desorption isotherms of sweet pepper at 35°C

#### 5.4.2 Effect of storage period on quality attributes

The quality attributes of dehydrated chilli and sweet pepper during storage for 6 months are presented in Tables 5.17 and 5.18. Moisture content of samples increased during storage due to ingress of atmospheric moisture. The increase in moisture content was less in samples stored in Metallised Polyester Polyethylene (MPP) as compared to Poly Propylene (PP). The moisture content of control chilli dried samples stored in PP and MPP pouches increased to 11.12 and 8.01% (d.b.), respectively after 6 months of storage. Lower moisture content of samples stored in MPP may be due to better moisture barrier property of MPP over PP. The total chlorophyll content of both dried chilli and sweet pepper decreased with storage period. However, the retention of colour in samples stored in MPP was better than PP pouches. No appreciable difference was obtained in case of capsaicin content of chilli stored in both the packaging materials. The rehydration ratio of both chilli and sweet pepper stored in MPP pouches were better than that stored in PP pouches. Ascorbic acid content of sweet pepper showed a decreasing trend during storage and its retention was observed to be more in samples stored in MPP pouches.

The treated samples retained higher chlorophyll than control even after 180 days of storage under ambient conditions. The chlorophyll content of treated chilli and sweet pepper dried samples stored in MPP pouches were found to be 61 and 79 mg/100g d.b. after 6 months of storage which were closer to freshly dried samples. The green colour of control sample was faded in some patches during storage, whereas light green colour was retained in treated samples. The capsaicin content decreased during storage in both the packaging materials. The ascorbic acid content of treated sweet pepper dried samples stored in PP and MPP pouches were observed to be 285 and 313 mg/100g d.b. and for dried control sample 246 and 279 mg/100g d.b., respectively after 6 months of storage. The retention of chlorophyll and ascorbic acid content were observed to be more in treated samples as compared to control samples in both the packaging materials with less increase in moisture content.

Quality attributes of treated samples retained well during storage in MPP pouch as compared to control samples. Therefore, MPP is recommended for safe storage of dried chilli and capsicum products.

**Table 5.17 Quality attributes of dehydrated chilli during storage for 6 months**

Quality attributes	Control				Treated			
	Storage period, month				Storage period, month			
	0	2	4	6	0	2	4	6
<b>Poly propylene</b>								
Moisture content	6.10	7.92	9.64	11.12	6.02	7.75	9.33	10.87
Rehydration ratio	4.40	4.29	4.14	3.99	4.60	4.46	4.30	4.12
Chlorophyll content	71.0	58	48	41.0	71.0	63.0	58.0	50.0
Capsaicin content	0.616	0.607	0.581	0.543	0.486	0.464	0.435	0.416
<b>Metallised Polyester Polyethylene</b>								
Moisture content	6.10	6.69	7.35	8.01	6.02	6.58	7.24	7.98
Rehydration ratio	4.40	4.33	4.26	4.17	4.60	4.51	4.41	4.35
Chlorophyll content	71.0	65.0	57.0	49.0	71.0	68.0	65.0	61.0
Capsaicin content	0.616	0.609	0.585	0.546	0.486	0.466	0.436	0.419

**Table 5.18 Quality attributes of dehydrated sweet pepper during storage for 6 months**

Quality attributes	Control sample				Treated sample			
	Storage period, month				Storage period, month			
	0	2	4	6	0	2	4	6
<b>Poly propylene</b>								
Moisture content	10.71	11.58	12.75	14.54	10.13	11.05	12.49	13.93
Rehydration ratio	7.00	6.80	6.61	6.39	7.30	7.02	6.76	6.57
Chlorophyll content	93.0	77	63	55.0	92.0	86	77	68.0
Ascorbic acid content	337	299	278	246	364	322	307	285
<b>Metallised Polyester Polyethylene</b>								
Moisture content	10.71	11.12	11.96	12.61	10.13	10.86	11.73	12.35
Rehydration ratio	7.00	6.88	6.75	6.62	7.30	7.12	6.96	6.82
Chlorophyll content	93.0	86.0	76.0	67.0	92.0	89.0	85.0	79.0
Ascorbic acid content	337	318	296	279	364	344	329	313

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**CHAPTER VI**  
**SUMMARY AND CONCLUSIONS**

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## SUMMARY AND CONCLUSIONS

Chilli (*Capsicum annuum* L.) is a spice-cum-vegetable of commercial importance. It is the most widely used spice all over the world as a condiment, culinary supplement or as a vegetable and virtually an indispensable item in the kitchen. The wide popularity of chilli is due to its wide range of shapes and sizes and sensory attributes such as colour, pungency, taste and distinctive aroma that generally make insipid bulk nutritive flesh and cereal foods more appetizing. Both red and green chilli can be used as fresh but dried chilli are also used extensively. Sweet pepper also called as bell pepper or Paprika is the mild or non-pungent variety of chilli or capsicum. The green paprika is used as curried vegetable, salad and is one of the richest sources of ascorbic acid. India is the largest producer and exporter of chilli in the world.

Green chilli has a delicious capsicum flavour in addition to the hotness, which adds zest to various food preparations. The fresh fruit is also used in salads, pickles and canned products. When eaten fresh with salads, it being rich in vitamins A and C, serves as a good vitamin supplement in addition to its being an appetizer. Thus green chilli is more nutritious than ripe, dried chilli as most of the vitamins are lost during drying. Besides, green chilli also contains an anti-cancer compound.

The prices of chilli are fluctuating during the year. They decline during post harvest season and increase in the off season. Preservation of these seasonal gluts permits seasonal products to become available round the year as well as prevents post harvest losses. As far as preservation of vegetables is concerned, drying is the most widely used method for reducing the water activity of the perishable commodities to the safe storage level to prevent microbial infection. Among the various dehydration techniques, hot air circulation around the commodity is commonly used. This technique is energy intensive and characterised by low drying efficiency specially during last phases of drying cycle. Selection of proper drying conditions is necessary for minimizing thermal stress, over-drying and maintenance of relevant compounds (chlorophyll, vitamin C, capsaicin) which determine the quality of the product.

Thermal drying often conducted at high temperatures. The distinct aromatic odour, colour and pungency are seldom carried over to the processed products. The

chemicals responsible for the delicate odours and attractive colours of spice-vegetables are highly heat sensitive and are lost during dehydration. Further conventionally air dried products do not rehydrate satisfactorily because of structural changes in the product due to excessive thermal damage. So, emphasis has been laid on improving the rehydration characteristics and quality attributes of hot air dehydrated commodities by changing process variables, using pre-drying treatments and low temperature processes.

Thus drying at low temperature to enhance the quality of food products has been a growing interest in recent years. High value products, which are extremely heat sensitive, are often freeze dried. However, this is an extremely expensive drying process. A drying system that is both energy efficient and preserves product quality is desired. Heat pumps have been known to be energy efficient when used in conjunction with drying operations. The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust as well as their ability to control independently the drying air temperature and humidity. Many researchers have acknowledged the importance of heat pump dryers in producing a range of precise drying conditions to dry a wide range of products and improve their quality.

The literature available on dehydration of green chilli and sweet pepper is meager. Some researchers have studied the effects of pre-treatments and drying conditions on drying characteristics and product quality. But the information pertaining to the effect of dehumidified air drying at near ambient temperature of fruits and vegetables in general and green chilli/sweet pepper in particular and its effect on product quality is scarce.

Therefore, the present work was undertaken with the following objectives.

1. To develop a dehumidified air dryer using heat pump system
2. To study the performance of the developed heat pump dryer
3. To study the drying characteristics of green chilli and sweet pepper
4. To develop mathematical expressions for green chilli and sweet pepper dried in heat pump and hot air dryer
5. To compare the quality attributes of dehumidified air dried product with that obtained from hot air dryer

## 6. To study the storability of dried green chilli and sweet pepper

Mathematical modeling of a heat pump assisted batch dryer has been developed based on the heat and mass balance of refrigerant and drying air which is useful for design of the dryer. A laboratory model heat pump dryer with special features of variable drying air temperature and mode of operation was fabricated. The developed dryer consists of dehumidifier unit (evaporator, compressor, condenser, and expansion device) and drying chamber. The dryer was operated with R22 refrigerant to study the drying air condition and performance of the dryer.

Thin-layer drying experiments under controlled conditions were conducted for green chilli and sweet pepper in two different types of tray dryers; (1) hot air dryer and (2) heat pump dryer. Different combinations of air temperatures ranging from 30-65°C and relative humidities ranging from 19-55% were used in both the dryers. Fresh green chilli and sweet pepper used for the experiment were procured from the local market, sorted and washed properly. Green chillies were destalked manually and the cups, seeds and stems of sweet pepper were separated. These were then sliced into 0.5cm thick slices using stainless steel knives. The samples were divided into three lots, one lot was steam blanched for 2 minutes, second lot was given required pretreatment (blanching in solution containing 0.5% lye and 0.25% magnesium carbonate at 95°C for 2 minutes) and the third one was used as control. The drying rates were computed from the experimental data and drying characteristics curves were plotted. The single exponential Lewis equation and Page's power equation were fitted to the experimental data. The characteristics drying curve for chilli and sweet pepper are fitted by plotting dimensionless drying rate and moisture ratio.

Quality parameters such as rehydration ratio, total chlorophyll content, ascorbic acid content (for sweet pepper) and capsaicin content (for chilli) of dehydrated green chilli and sweet pepper obtained from different drying conditions are analysed in order to optimize the drying process. Colour, texture, flavour and overall acceptability of the dehydrated sample were compared through sensory evaluation.

Fresh and dried green chilli and sweet pepper slices were exposed to seven levels of relative humidities (10.8% to 74.3%) at 35°C using static method to study the sorption behaviour. Dehydrated green chilli and sweet pepper were stored in Poly

Propylene (PP) and Metallised Polyester Polyethylene (MPP) pouches under ambient condition ( $27\pm 5^{\circ}\text{C}$ ,  $65\pm 8\%$  RH) for 6 months. The quality parameters of the samples were analysed after every 2 months interval.

Results obtained from the present study has been summarised as follows.

1. A batch type heat pump assisted dehumidified air dryer was developed successfully and a medium range of temperatures ( $30\text{--}41^{\circ}\text{C}$ ) for safe drying of heat sensitive crops were achieved. Dehumidification system of the developed heat pump dryer maintained the relative humidity of air entering the drying chamber below 40%.
2. The drying air temperature and relative humidity in the closed air circuit heat pump mode attained a value of  $41^{\circ}\text{C}$  and 19% under no load condition after 90 minutes of the dryer operation when the corresponding ambient values were  $32^{\circ}\text{C}$  and 72%, respectively.
3. The inlet drying air temperature decreased during early hours followed by rapid rise between the 2<sup>nd</sup> and 10<sup>th</sup> hours, after which the temperature was almost stable. The relative humidity of inlet and exhaust drying air increased initially and decreased subsequently with drying time as product became drier.
4. The heat pump dryer was found to have a specific moisture extraction rate between 0.55 and 1.10 kg/kWh. Specific Moisture Extraction Rate (SMER) for heat pump dryer for drying sweet pepper at  $40^{\circ}\text{C}$  was found more (1.1 kg/kWh) than hot air dryer (0.93 kg/kWh) while operating at  $45^{\circ}\text{C}$ .
5. Energy consumption for heat pump dryer for 24 hours of operation was found less (4.48-5.05 kWh) than the hot air dryer (5.65-9.6 kWh) while operating under different drying conditions.
6. The moisture content of green chilli and sweet pepper slices reduced exponentially with drying time. As the temperature increased, the drying curve exhibited a steeper slope, thus exhibiting an increase in drying rate.
7. The heat pump dryer when operated with drying air temperature at  $30^{\circ}\text{C}$  took 34 hours to reduce the moisture content of green chilli from 521.1 to 6%(d.b.) while hot air dryer at  $65^{\circ}\text{C}$  took only 5 hours.

8. It took 36, 25 and 16 hours at 30, 35 and 40°C in heat pump dryer and 17, 10 and 6 hours at 45, 55 and 65°C in hot air dryer, respectively to dry sweet pepper from 1452.8 to 10% m.c.(d.b.).
9. Similarly the drying time for chilli were observed to be 34, 24 and 15 hours in heat pump dryer at 30, 35 and 40°C and 16, 8 and 5 hours in hot air dryer at 45, 55 and 65°C, respectively to reduce the moisture content from 521.1 to 6%d.b.
10. Substantial reduction in total drying time with rise in temperature at lower levels was observed for both the samples.
11. Drying of green chilli and sweet pepper took place mainly under falling-rate period. Migration of moisture during this period occurred through the mechanism of diffusion. The drying rate increased considerably with increase in drying air temperature for both the samples.
12. Total drying time required for complete drying of treated and blanched samples was found less as compared to control.
13. The Page equation was found to be better than Lewis equation to describe the thin-layer drying of green chilli and sweet pepper with higher co-efficient of determination and lower root mean square error.
14. Drying in heat pump dryer at 40°C took less time compared to hot air drying at 45°C for both green chilli and sweet pepper. The drying rate was observed to be more initially in HPD at 40°C but at the later part of drying, it was more in HAD at 45°C.
15. The dehydration ratios of control chilli samples were observed to be varied from 5.9 to 6.1 at all the drying air temperatures and that of sweet pepper ranged from 15.0 to 15.4 with the higher values for higher drying air temperatures.
16. The rehydration ratios ranged from 3.9 to 4.5 for chilli, whereas 6.5 to 7.2 for sweet pepper control samples. The rehydration ratios were observed to be more in heat pump dried product at lower drying air temperature as compared to hot air dried product.

17. Total chlorophyll content of sweet pepper reduced from an initial value of 103 to 66 mg/100g d.b. in hot air dryer at 65°C and to 96 mg/100g d.b. in heat pump dryer at 30°C. Chlorophyll content of final dried product decreased with increase in drying air temperature.
18. Green chilli showed a decrease in total chlorophyll content from an initial value of 79 to 73 mg/100g d.b. in HPD at 30°C and to 45 mg/100g d.b. at 65°C in hot air dryer.
19. The chlorophyll content of treated samples were observed to be at par with control but the blanched samples showed a significant loss of chlorophyll.
20. The retention of ascorbic acid was highest in heat pump dried sweet pepper samples and least in samples dried in HAD at higher temperatures.
21. The retention of ascorbic acid was more in blanched samples as compared to treated and control samples for all the drying air temperatures.
22. Ascorbic acid content of sweet pepper samples dried at 30°C in HPD was found less than that obtained at 35°C which may be due to the long drying time.
23. Capsaicin content of heat pump dried samples were observed to be higher than that of hot air dried samples. But there is no appreciable difference in capsaicin content of chilli dried at higher temperature range of 40 to 65°C for all the samples.
24. Both drying air temperature as well as pretreatment play significant role in influencing the quality parameters of dehydrated chilli and sweet pepper.
25. The mean sensory scores for colour, texture, flavour and overall acceptability decreased significantly with increase in drying air temperature from 30 to 65°C for all the samples.
26. Heat pump dryer produced dried chilli and sweet pepper with higher greenness/chlorophyll content compared to hot air dryer.
27. Treated samples obtained higher sensory scores followed by control and blanched samples.

28. Keeping in view the energy consumption and quality attributes of dehydrated products, it is proposed to dry green chilli and sweet pepper at 35°C in heat pump dryer.
29. EMC of chilli increased with the increase in the ERH in both the adsorption and desorption processes at constant temperature of 35°C. The sorption isotherms of chilli and sweet pepper showed the typical sigmoid shaped curve.
30. Chlorophyll content of both dried chilli and sweet pepper decreased with increase in storage period. Quality attributes of treated samples retained well during storage in MPP pouch as compared to control samples. Therefore, MPP is recommended for safe storage of dried chilli and capsicum products.

From the above study, it can be concluded that heat pump dryer can be used successfully for drying treated green chilli and sweet pepper to safe storage moisture content with maximum retention of quality attributes and less energy consumption. Dried green chilli and sweet pepper can be stored safely in MPP pouches for 6 months.

The research findings of this investigation are expected to help in developing commercial model of heat pump dryer. The dehumidified air dryer using heat pump system can be used successfully for drying fruits, vegetables, spices, condiments, medicinal, aromatic and other high value commodities at near ambient temperature for producing better quality dehydrated product.

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## **REFERENCES**

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## REFERENCES

- Aceves-Saborio, S. 1993. Analysis of energy consumption in heat pump and conventional dryers. *Heat Recovery Systems and CHP*, 13:419-428
- Acharyaviriya, S., Soponronnarit, S., Terdyothin, A. 2000a. Mathematical model development and simulation of heat pump fruit dryer. *Drying Technology- An International Journal*, 18(1 & 2):479-491
- Adapa, P. K., Sokhansanj, S., Schoenau, G. J. 2002. Performance study of a recirculating cabinet dryer using a household dehumidifier. *Drying Technology*, 20(8):1673-1689
- Ade-Omowaye, B. I. O., Rastogi, N. K., Angersbach, A., Knorr, D. 2002. Osmotic dehydration of bell peppers: influence of high intensity electric field pulses and elevated temperature treatment. *Journal of Food Engineering*, 54(1): 35-43
- Ahmed, J., Shivhare, U. S., Raghavan, G. S. V. 2000. Rheological characteristics and kinetics of colour degradation of green chilli puree. *Journal of Food Engineering*, 44:239-244
- Ahmed, J. and Shivhare, U. S. 2001. Effect of pre-treatment on drying characteristics and colour of dehydrated green chillies. *Journal of Food Science and Technology*, 38(5):504-506
- Almeida, M. S., Gouveia, M. C., Zdebsky, S. R., Parise, J. A. R. 1990. Performance analysis of a heat pump assisted drying system. *International Journal of Energy Research*. 14:397-406
- Alves-Filho, O., Strommen, I. 1996. The application of heat pump in drying of biomaterials. *Drying Technology*, 14(9):2061-2090
- Alves-Filho, O. 2002. Combined innovative heat pump drying technologies and new cold extrusion techniques for production of instant foods. *Drying Technology*, 20(8):1541-1557
- Alzamora, S. M., Chirife, J. 1980. Some factors controlling the kinetics of moisture movement during avocado dehydration. *Journal of Food Science*, 45: 1649-1652
- Anese, M., Manzocco, L., Nicoli, M. C., Lerici, C. R. 1999(a and b). Antioxidant properties of tomato juice as affected by heating. *Journal of the Science of Food and Agriculture*, 79:750-754
- Anthon, G. E., Barrett, D. M. 2002. Kinetic parameters for the thermal inactivation of quality related enzymes in carrots and potatoes. *Journal of Agricultural Food Chemistry*, 50:4119-4125
- AOAC. 1995. *Official Methods of Analysis*(16th Ed.). Association of Official Analytical Chemists: Washington DC

- Arora, C. P. 1981. Refrigeration and Air Conditioning, Tata Mc-Graw Hill Publishing Co. Ltd: New Delhi
- Arslan, N., Togrul, H. 2005. Moisture sorption isotherms for crushed chillies. *Biosystems Engineering*, 90(1): 47-61
- ASHRAE 1981. Fundamentals Handbook. ASHRAE: Atlanta, G.A.
- ASTA. 1985. Official Analytical Methods(3rd Ed.). The American Spice Trade Association: New York
- Baker, G. J. 1997. Industrial Drying of Foods, Chapman and Hall: U.K.
- Bannister, P., Carrington, C. G., Liu, Q. 1995. Influence of enhancing features on dehumidifier performance: laboratory measurements. *International Journal of Energy Research*, 19:397-406
- Bender, A. E. 1966. Nutritional effects of food processing. *Journal of Food Technology*, 1:261
- Benterud, A. 1977. Vitamin lossess during thermal processing. In Høyen and Kvale(Ed.), *Physical, Chemical and Biological Changes in Food Caused by Thermal Processing*. Applied Science Publishers Ltd: London
- BIS. 1972. Specifications for Dehydrated Peas. IS:4624, Bureau of Indian Standards: New Delhi
- Brennan, J. G., Butters, J. R., Cowell, N. D., Lilly, A. E. V. 1990. Dehydration. In *Food Engineering Operations* (3<sup>rd</sup> Ed.). pp: 371-415. Elsevier Applied Science: London
- Brundrett, G. W. 1987. *Handbook of Dehumidification Technology*. pp:230. Butterworths: London
- Cardona, T. D., Driscoll, R. H., Paterson, J. L., Szrednicki, G. S., Kim, W. S. 2002. Optimising conditions for heat pump dehydration of lactic acid bacteria. *Drying Technology*, 20(8):1611-1632
- Carrington, C. G., Wells, C. M., Sun, Z. F., Chen, G. 2002. Use of dynamic modeling for the design of batch-mode dehumidifier dryers. *Drying Technology*. 20(8):1645-1657
- Chen, G., Bannister, P., Carrington, C. G., Velde, P. T., Burger, F. C. 2002. Design and application of a dehumidifier dryer for drying pine cones and polen catkins. *Drying Technology*, 20(8):1633-1643
- Chin, H. B., Dudek, J. A. 1988. Composition and nutritive value of raw and processed vegetables. In B. S. Luh and J. G. Woodroof (Ed.), *Commercial Vegetable Processing*. Pp: 647-682, AVI Book. Van Nostrand Reinhold: New York

- Chua, K. J., Majumdar, A. S., Chou, S. K., Hawlader, M. N. A., Ho, J. C. 2000a. Heat pump drying of banana, guava and potato pieces: effect of cyclic variations of air temperature on convective drying kinetics and colour change. *Drying Technology*, 18(4 & 5):907-936
- Chua, K. J., Majumdar, A.S., Chou, S.K., Ho, J.C., Hawlader, M.N.A. 2000b. Principles, applications and potential of heat pump drying systems. In A.S. Majumdar (Ed.). *Drying Technology in Agriculture and Food Science*. Pp: 213-251, Oxford and IBH Publishing Co. Pvt. Ltd: New Delhi
- Chua, K. J., Mujumdar, A. S., Hawlader, N. A., Chou, S. K., Ho, J. C. 2001. Convective drying of agricultural products: effect of continuous and stepwise change in drying air temperature. *Drying Technology*, 19(8):1949-1960
- Chua, K. J., hawlader, M. N. A., Chou, S. K., Ho, J. C. 2002a. On the study of time-varying temperature drying- effect on drying kinetics and product quality. *Drying Technology*, 20(8):1559-1577
- Chua, K. J., Chou, S. K., Ho, J. C., Hawlader, M. N. A. 2002b. Heat pump drying: recent developments and future trends. *Drying Technology*, 20(8):1579-1610
- Cleland, A. C. 1988. Computer subroutines for rapid evaluation of refrigerant thermodynamic properties. *International Journal of Refrigeration*, 9(Nov.):346-351
- Clements, S., Jia, X., Jolly, P. 1993. Experimental verification of a heat pump assisted continuous dryer simulation model. *International Journal of Energy Research*, 17:19-28
- Clydesdale, F.M., Francis, F.J. 1968. Chlorophyll changes in thermally processed spinach as influenced by enzyme conversion and pH adjustment. *Food Technology*, 22:135-138
- David, I. 1982. Up-to-date methods for red pepper processing. *Kouserv-es Paprikaipar*, 1:34
- Erenturk, S., Gulaboglu, M. S., Gultekin, S. 2004. The thin-layer drying characteristics of Rosehip. *Biosystems Engineering*, 89(2):159-166
- Gal, S. 1987. The need for, and practical applicatons of sorption data. In R. Jowitt, F. Escher, B. Hallstrom, H. Mefert, W. Spiess and G. Vos (Ed.), *Physical Properties of Foods - 2*. pp:13-25, Elsevier Applied Science: London
- Giridhar, N., Satyanarayana, A., Joshi, G. J. 1996. Studies on preparation and storage of ginger-garlic paste. *Indian Food Packer*, 50(3): 13-21
- Gonzalez-Aguilar, G. A., Ayala-Zavala, J. F., Ruiz-Cruz, S., Acedo-Felix, E., Diaz-Cinco, M. E. 2004. Effect of temperature and modified atmospheric packaging

- on overall quality of fresh-cut bell peppers. *Lebensm-Wiss.u. Technol.* 37:817-826
- Govindarajan, V. S. 1985. Capsicum- production, technology, chemistry and quality. Part I: history, botany, cultivation and primary processing. *CRC Crit. Rev. Food Sci. Nutr.*, 22(2):109-176
- Govindarajan, V. S., Rajalakshmi, D., Chand, N. 1987. Capsicum production, technology, chemistry and quality. Part IV: evaluation of quality. *CRC Crit. Rev. Food Sci. Nutr.*, 25:185-282
- Gupta, S., Ghuman, B. S., Sandhu, K. S. 2006. Preparation of tomato powder on small scale. *Journal of Food Science and Technology*, 43(1):31-33
- Henderson, S. M., Pabis, S. 1962. Grain drying theory: IV, the effect of air flow rate on drying index. *Journal of Agricultural Engineering Research*, 16:169-172
- Hentges, D. L., Weaver, C. M., Nielsen, S. S. 1991. Changes of selected physical and chemical components in development of the hard-to-cook bean defect. *Journal of Food Science*, 56: 436-442
- Hernandez, J. A., Pavon, G., Garcia, M. A. 2000. Analytical solution of mass transfer equation considering shrinkage for modelling food drying kinetics. *Journal of Food Engineering*, 45: 1-10
- Hesse, B. 1995. Energy efficient electric drying systems for industry. *Drying Technology*, :1543-1562
- Hodgett, D. L. 1976. Efficient drying using heat pump. *Chemical Engineer*, July-August:510-612
- Hoffman, P. G., Lego, M. C., Galetto, W. G. 1983. Separation and quantification of red pepper major heat principles by reverse-phase high-performance liquid chromatography
- Holdsworth, S.D. 1986. Advances in the dehydration of fruits and vegetables. In D. McCarthy (Ed.). *Concentration and Drying of Foods*. Pp: 293-303. Elsevier Applied Science Publishers:London
- Hossain, M. A., Bala, B. K. 2002. Thin-layer drying characteristics for green chilli. *Drying technology*, 20(2):489-505
- Ihl, M., Monslaves, M., Bifani, V. 1998. Chlorophyllase inactivation as a measure of blanching efficacy and colour retention of Artichokes (*Cynara scolymus*-L.). *Lebensm-Wiss Technol.*,31:50-56
- Indira, P., Rajan, S.1997. *Paprika: A Dollar Earning Crop*. Publication Unit. Directorate of Extension, Keral Agricultural University: Trissur

- Jayaraman, K.S., Gupta, D.K.D. 1995. Drying of fruits and vegetables. In A: S. Majumdar (Ed.). Handbook of Industrial Drying, Marcel Dekker Ins: New York
- Jia, X., Jolly, P., Clements, S. 1990. Heat pump assisted continuous drying Part 2: simulation results. *International Journal of Energy Research*, 14:771-782
- Jolly, P., Jia, X., Clements, S. 1990. Heat pump assisted continuous drying Part 1: simulation model. *International Journal of Energy Research*, 14:757-770
- Kaleemullah, S., Kailappan, R. 2004. Moisture sorption isotherms of red chillies. *Biosystems Engineering*, 88(1): 95-104
- Kaur, C., Kapoor, H. C. 2001. Antioxidant activity and quality of minimally processed Indian cabbage. *Journal of Food Processing Preservation*, 25:367-380
- Kim, D. Y., Rhee, C. O., Chin, S. C. 1982. Changes in colour of red pepper during dehydration and milling. *J. of Korean Agricultural and Chemical Society*, 25:1-6
- Kim, M. H., Toledo, R. T. 1987. Effect of osmotic dehydration and high temperature fluidized bed drying on properties of dehydrated rabbiteye blueberries. *J. Food Science*, 52(4):980-989
- Klein, B. P. 1992. Fruits and Vegetables. In J. Bowers.(Ed.). Food Theory and Application. Pp: 687-766, MacMillan Publishing Co.: New York
- Krokida, M. K., Marouli, Z. B., Saravakas, G. D. 2001. The effect of the method of drying on the colour of dehydrated products. *International Journal of Food Science and Technology*, 36:53-59
- Lahsasni, S., Kouhila, M., Mahrouz, M., Kechaou, N. 2002. Experimental study and modelling of adsorption and desorption isotherms of prickly pear peel (*Opuntia ficus indica*). *Journal of Food Engineering*, 55(3): 201-207
- Lahsasni, S., Kouhila, M., Mahrouz, M., AIT. Mohamed, L., Agorram, B. 2004. Characteristic drying curve and mathematical modeling of thin-layer solar drying of prickly pear cladode (*Opuntia Ficus Indica*). *Journal of Food Process Engineering*, 27:103-117
- Lantz, E. M. 1946. Effect of canning and drying on the carotene and ascorbic acid content of chillies. *New Mexico Agric. Res. Stn. Bull.*, 327 (April): 21
- Lease, J. G., Lease, E. J. 1962. Effect of drying conditions on initial colour retention and pungency in red peppers. *Food Technology(USA)*, 16:104-106
- Lewis, W. K. 1921. The rate of drying of solid materials. *Ind. Engg. Chem.*, 13:427

- Lima, A. G. B., Queiroz, M. R., Nebra, S. A. 2002. Simultaneous moisture transport and shrinkage during drying of solids with ellipsoidal configuration. *Chemical Engineering Journal*, 86: 85-93
- Luhadiya, A. P., Kulkarni, P. R. 1978. Dehydration of green chilli. *Journal of Food Science and Technology*, 15:139-142
- Luning, P. 1995. Characterisation of the flavour of fresh bell peppers (*Capsicum annuum*) and its changes after hot-air drying: an instrumental and sensory evaluation, WAU dissertation no. 1978
- Madamba, P. S., Driscoll, R. H., Buckle, K. A. 1996. The thin layer drying characteristic of garlic slices. *Journal of Food Engineering*, 29: 75-97
- Malchev, E., Chenov, N. S., Ioncheva, N. I., Tanchev, S. S., Kalpakchieva, K. K. 1982. Quantitative changes in carotenoids during the storage of dried red pepper powder. *Nahrung*, 26:415-418
- Martin, T. W. 1961. Improved computer oriented methods for calculation of steam properties. *Journal of Heat Transfer*, 83:515-516
- Maskan, A., Kaya, S., Maskan, M. 2002. Hot air and sun drying of grape leather. *Journal of Food Engineering*, 54: 81-88
- Mazza, G. 1983. Dehydration of carrots: effects of pre-drying treatments on moisture transport and product quality. *Journal of Food Technology*, 18: 113-123
- McMinn, W. A. M., Magee, T. R. A. 1999. Studies on the effect of surfactant, blanching and osmotic pretreatments on the convective drying of potatoes. *Journal of Food Process Engineering*, 22: 419-433
- Menkov, N. D. 2000. Moisture sorption isotherms of vetch seeds at four temperatures. *Journal of Agricultural Engineering Research*, 76: 373-380
- Miaruddin, M., Amiruzzaman, M., Choudhury, J. C. S., Bhuiyan, M. I. M. 1995. Effect of containers on insect damage, viability and shelf life of dried chilli during storage. *Bangladesh Journal of Agricultural Research*, 20(1):39-45
- Mishra, R. N. 1972. Sorption and Desorption Isotherms for Groundnut and Chillies. M. Tech. Thesis (unpublished), Indian Institute of Technology: Kharagpur
- Murthy, N. S. R. 1995. Chillis-quality improvement at farm level. In *Quality Improvement of Chillis*, Spices Board: Kochi
- Myhara, R. M., Taylor, M. S., Slominski, B. A., Al-Bulushi, I. 1998. Moisture sorption isotherms and chemical composition of Omani dates. *Journal of Food Engineering*, 37(4): 471-479
- Odland, D. and Eheart, M. S. 1975. Ascorbic acid, mineral and quality retention in frozen broccoli blanched in water, steam and ammonia steam. *Journal of Food Science*, 40:1004

- Nindo, C. I., Sun, T., Wang, S. W., Tang, J., Powers, J. R. 2003. Evaluation of drying technologies for retention of physical quality and anti-oxidants in asparagus (*Asparagus officinalis* L.). *Lebensm-Wiss.u. Technol.*, 36:507-516
- Page, G. E. 1949. Factors Influencing the Maximum Rate of Air Drying Shelled Corn in Thin-Layers. M.S. Thesis, Purdue University: West Lafayette Indiana
- Pendyala, V. R., Devotta, S., Patwardhan, V. S. 1990b. Heat-pump-assisted dryer Part 2: experimental study. *International Journal of Energy Research*, 14:493-507
- Peter, K. V., Nybe, E. V., Thanuja, T. V. 2004. Spices: future prospects. *Survey of Indian Agriculture, The Hindu*
- Pezzuti, A., Crapiste, G. H. 1997. Sorptional equilibrium and drying characteristics of garlic. *J. of Food Engineering*, 31:113-123
- Pierre, Bo. 1955. The co-efficient of heat transfer for boiling Freon-12 in horizontal tubes. *S. F. Review*, 2(1)
- Pordesimo, L. O., Li, H., Lee, J. H., Reddick, B. B. 2004. Effects of drying procedure, cultivar and harvest number on capsaicin levels in dried Jalapeno peppers. *Applied Engineering in Agriculture*, 20(1):35-38
- Prasertsan, S., Saen-saby, P., Prateepchaikul, G., Ngamsritrakul, P. 1995. Factors influencing heat pump dryer performance. *Proceedings of the 6<sup>th</sup> ASEAN Conference on Energy Technology*. Bangkok, pp. 371-379
- Prasertsan, S., Saen-saby, P., Nyamsritrakul, P., Prateepchaikul, G. 1996. Heat pump dryer Part 1: simulation of the models. *International Journal of Energy Research*, 20:1067-1079
- Prasertsan, S., Saen-saby, P., Nyamsritrakul, P., Prateepchaikul, G. 1997. Heat pump dryer Part 2: results of the simulation. *International Journal of Energy Research*, 21:1-20
- Prasertsan, S., Saen-saby, P. 1998a. Heat pump drying of agricultural materials. *Drying Technology*, 16(1 & 2):235-250
- Prasertsan, S., Saen-saby, P. 1998b. Heat pump dryers: research and development needs and opportunities. *Drying Technology*, 16(1 & 2):251-270
- Pruthi, J. S. 1993. *Major Spices of India: Crop Management and Post harvest Technology*(Ed.), Indian Council of Agricultural Research: New Delhi
- Pura Naik, J., Nagalakshmi, S., Balasubrahmanyam, N., Dhanraj, S., Shankaracharya, N. B. 2001. Packaging and storage studies on commercial varieties of Indian chillis (*Capsicum annuum* L.). *J. of Food Science and Technol*, 38(3):227-230

- Rama Rao, V. V., Ojha, T. P. 1972. Drying of corn, jowar, groundnut and chillies. Proc. ICAR Seminar on Post Harvest Technology of Cereals and Pulses, 21-23 December 1972, New Delhi
- Rama, V., John, J. P. 2000. Effects of methods of drying and pretreatments on quality of dehydrated mushroom. *Indian Food Packer*. 54: 59-64
- Ramesh, M. N., Wolf, W., Tevini, D., Jung, G. 2001. Influence of processing parameters on the drying of spice paprika. *J. of Food Engineering*, 49:63-72
- Ranganna, S: 1986. Handbook of Analysis and Quality Control for Fruit and Vegetable Product. (2nd Ed.), Tata McGraw-Hill Publishing Company Limited: New Delhi
- Regalado, M. J. C., Bekki, E., Madamba, P. S. 2000. Dehumidification drying of high-moisture rough rice in a radial-flow circular bin. *Drying technology*, 18(10):2307-2326
- Rich, D. G. 1973. The effect of fin spacing on the heat transfer and friction performance of multi-row, smooth plate fin-and-tube heat exchangers. *ASHRAE Trans.*, 137-145
- Rizvi, S. S. H. 1986. Thermodynamics of foods in dehydration. In M. A. Rao and S. S. H. Rizvi (Ed.). *Engineering Properties of Food*. pp: 133-214, Marcel Dekker: New York
- Rocha, T., Lebert, A., Marty-Audouin, C. 1993. Effect of pre-treatments and drying conditions on drying rate and colour retention of basil. *Lebensm-Wiss Technol.*, 26:456-463
- Rossi, S. J., Neues, L. C., Kicokbusch, T. G. 1992. Thermodynamic and energetic evaluation of a heat pump applied to the drying of vegetables. In A. S. Majumdar (Ed.). *Drying '92*. pp: 1475-1478, Elsevier Science
- Saensabai, P., Prasertsan, S. 2003. Effects of component arrangement and ambient and drying conditions on the performance of heat pump dryers. *Drying Technology*, 21(1):103-127
- Saravacos, G. D. 1995. Mass transfer properties of food. In M. A. Rao and S. S. H. Rizvi (Ed.). *Engineering Properties of Foods*. pp: 169-221. Marcel Dekker: New York
- Scoville, V. L. 1912. Note on capsicum. *J. Am. Pharm. Assoc.*, 1:453
- Shatadal P., Jayas, D. S. 1992. Sorption isotherms of foods. In Majumdar, A. S. (Eds.), *Drying of Solids*. Pp: 433-448, Oxford and IBH Publishing Co. Pvt. Ltd.: New delhi
- Singh, R. P., Heldman, D. R. 2001. Introduction to Food Engineering (3rd Ed.). Academic press: California

- Somogyi, J. P., Luh, B. S. 1988. Vegetable Dehydration. In J. G. Woodroof and B. S. Luh (Ed.). Commercial Vegetable Processing. pp:387-473, AVI Publishing Co.: Westport CT
- Sosle, V., Raghavan, G. S. V., Kittler, R. 2003. Low-temperature drying using a versatile heat pump dehumidifier. *Drying Technology*, 21(3):539-554
- Steltz, W. G., Silvestri, G. J. 1958. The formulation of steam properties for digital computer application, *Trns. ASME*, 80:967-973
- Strahm, B. S., Flores, R. A. 1994. Dehydration of low-grade asparagus. *Drying Technology*, 12:903-921
- Strommen, I., Kramer, K. 1994. New applications of heat pumps in drying process. *Drying Technology*, 12(4):889-901
- Teeboonma, U., Tiansuwan, J. and Soponronnarit, S. 2003. Optimisation of heat pump fruit dryers. *Journal of Food Engineering*, 59:369-377
- Thimmaiah, S. R. 1999. Standard Methods of Biochemical Analysis (Ed.), Kalyani Publishers: New Delhi
- Tong, C. H., Lund, D. B. 1990. Effective moisture diffusivity in porous materials as a function of temperature and moisture content. *Biotechnology Progress*, 6(1):67-75
- Turaga, M., Lin, S., Fazio, P. P. 1988. Correlation for heat transfer and pressure drop factors for direct expansion air cooling and dehumidifying coils. *ASHRAE Trans.*, 94(2):616-629
- ~~Van Meel, D. A. 1958. Adiabatic convection batch drying with recirculation of air. *Chem. Engg. Science*, 9:36-44~~
- Vazquez, G., Chenlo, F., Moreira, R., Cruz, E. 1997. Grape drying in a pilot plant with a heat pump. *Drying Technology*, 15(3 & 4):899-920
- Von Elbe, J. H. 1986. Chemical changes in plant and animal pigments during food processing. In R. F. Owen, W. H. Chang, and C. Y. Lii (Ed.). *Role of Chemistry in Quality of Processed Foods*. pp: 41-64, USA: Westport.
- Wang, D., Chang, C. S. 2001. Energy efficiency of a new heat pump system for drying grain. *Transactions of the ASAE*, 44(6):1745-1750
- Wesley, B. J., Chakraverty, A., Sukumaran, C.R. 2000. Equilibrium moisture content of chillies. *The Andhra Agricultural Journal*, 47(3-4):254-257
- Yang, C. S. T., Atallah, W. A. 1985. Effect of four drying methods on the quality of intermediate moisture lowbush blueberries. *J. Food Science*, 50:1233-1237

Yanishlieva-maslarova, N. V. 2001. Inhibiting oxidation. In J. Pokorny, N. Yanishlieva and M. Gordon(Ed.). Antioxians in Foods. Pp: 22-70, Boca Raton FL: CRC Press LLC



## APPENDIX A

**Table A.1 Properties of R22 Refrigerant (Performance based on –  
15°C evaporator temperature and 30°C condenser temperature)**

Freon 22 (R22)	
Chemical name	Chlorodifluoromethane
Chemical formula	CHClF <sub>2</sub>
Molecular weight	86.5
Boiling point (°C) at 101.3kPa	-40.8
Evaporator pressure at -15°C (kPa)	296.4
Condensing pressure at 30°C (kPa)	1203.0
Freezing point (°C) at 101.3 kPa	-160.0
Critical temperature, °C	96.1
Critical pressure, kPa	4936.1
Compressor discharge temperature (°C)	55.0
Compression ratio (30°C/-15°C)	5.06
Latent heat of vaporization at -15°C (kJ/kg)	217.7
Horsepower/ton refrigerant, ideal	1.011
Refrigerant circulated/ton refrigeration (kg/s), ideal	2.1 x 10 <sup>-2</sup>
Compressor displacement/ton refrigeration (m <sup>3</sup> /s)	1.7 x 10 <sup>-4</sup>
Stability (toxic decomposition products)	Yes
Flammability	None
Odour	Ethereal
Evaporator temperature range (°C)	-87 to 10

**Table A.2 Coefficients for empirical equations to calculate thermodynamic properties of R22**

Coefficient	Value	Coefficient	Value
a <sub>1</sub>	21.25384	a <sub>20</sub>	2390.321
a <sub>2</sub>	-2025.4518	a <sub>21</sub>	1.01859
a <sub>3</sub>	248.94	a <sub>22</sub> (x 10 <sup>-4</sup> )	5.09433
a <sub>4</sub>	200000	a <sub>23</sub> (x 10 <sup>-6</sup> )	-14.8464
a <sub>5</sub>	1170.36	a <sub>24</sub> (x 10 <sup>-7</sup> )	-2.49547
a <sub>6</sub>	1.68674	a <sub>25</sub> (x 10 <sup>-3</sup> )	5.23275
a <sub>7</sub> (x 10 <sup>-3</sup> )	5.2703	a <sub>26</sub> (x 10 <sup>-6</sup> )	-5.59394
a <sub>8</sub>	250027	a <sub>27</sub> (x 10 <sup>-5</sup> )	3.45555
a <sub>9</sub>	367.265	a <sub>28</sub> (x 10 <sup>-7</sup> )	-2.31649
a <sub>10</sub>	-1.84133	a <sub>29</sub> (x 10 <sup>-7</sup> )	5.80303
a <sub>11</sub> (x 10 <sup>-3</sup> )	-11.4556	a <sub>30</sub> (x 10 <sup>-9</sup> )	-3.20189
a <sub>12</sub>	155482	a <sub>31</sub>	1.137423
a <sub>13</sub> (x 10 <sup>-3</sup> )	2.85446	a <sub>32</sub> (x 10 <sup>-3</sup> )	-1.50914
a <sub>14</sub> (x 10 <sup>-7</sup> )	4.0129	a <sub>33</sub> (x 10 <sup>-6</sup> )	-5.59643
a <sub>15</sub> (x 10 <sup>-6</sup> )	13.3612	a <sub>34</sub> (x 10 <sup>-6</sup> )	-8.74677
a <sub>16</sub> (x 10 <sup>-8</sup> )	-8.11617	a <sub>35</sub> (x 10 <sup>-7</sup> )	-1.49547
a <sub>17</sub> (x 10 <sup>-8</sup> )	14.1194	a <sub>36</sub> (x 10 <sup>-8</sup> )	5.97029
a <sub>18</sub> (x 10 <sup>-10</sup> )	-9.53294	a <sub>37</sub> (x 10 <sup>-9</sup> )	1.41458
a <sub>19</sub>	-11.82344	a <sub>38</sub> (x 10 <sup>-4</sup> )	-4.52580

**Table A.3 Coefficients for empirical equations to calculate steam properties**

<b>Coefficient</b>	<b>Value *</b>
b <sub>1</sub>	7.46908269
b <sub>2</sub>	-7.50675994 x 10 <sup>-3</sup>
b <sub>3</sub>	-4.6203229 x 10 <sup>-9</sup>
b <sub>4</sub>	-1.215470111 x 10 <sup>-3</sup>
b <sub>5</sub>	35.15789
b <sub>6</sub>	24.592588
b <sub>7</sub>	2.1182069
b <sub>8</sub>	-0.3414474
b <sub>9</sub>	0.15741642
b <sub>10</sub>	-0.031329585
b <sub>11</sub>	0.003865828
b <sub>12</sub>	-0.000249018
b <sub>13</sub>	6.8401559 x 10 <sup>-6</sup>

# APPENDIX B

**Table B.1 Design calculations of heat pump dryer in MS EXCEL spread sheet**

A	B	C	D	E	F	G	H
1	Drying air temp			7.469083	-7.51E-03		
2	Drying air RH		40 °C	-4.62E-09	-1.22E-03		
3	Amount to be dried per batch		15 %				
4	Initial MC		4 kg		35.15789		
5	Final MC		92 %		24.59259		
6	Drying time		10 %		2.118207		
7	Moisture to be removed		12 h		-0.34145		
8	Moisture removed per hour		3.644444444 kg		0.157416		
9	mole fraction		0.303703704 kg/h		-0.03133		
10	Vap pr at dbt		-601.398 kPa		0.003866		
11	Partial pr		7.37E+00 kPa		-0.00025		
12	Humidity		1.11E+00 kg water/kg dry air				
13	Enthalpy of drying air		6.87E-03 kJ/kg dry air				6.84E-06
14	Assume dew point temp		5.79E+01 °C				
15	Assume wbt vap pr wbt		8.46E+00 °C				
16	sp heat		8.46E+00 °C				
17	Sp volume		8.46E+00 °C				
18	Heat requirement for drying		2.03E+01 °C				
19	Air req		2.37E+00 kPa				
20	Vol air req		2.02E+01 °C				
21			1.02E+00 K				
22			1.02E+00 K				
23			0.918330875 cum/k g dry air				
24			10129.12593 kJ				
			2.33E-02 kg/s				
			2.14E-02 cum/s				

	A	B	C	D	E	F	G	H	I
25	Humidity at dryer outlet	$C13+C9/(C23*3600)=$	1.05E-02	kg water/kg dry air					
26	Temp at dryer outlet	$(C14-C25*2501.4)/(1.005+1.88*C25)=$	3.09E+01	°C					
27	By pass factor	0.2	0.2						
28	Sat humidity at evp surface	$(C13-C27*C25)/(1-C27)=$	0.005960941	kg water/kg dry air					
29	Vap pr at evp surface	$(C28*101.325)/(0.622+C28)=$	0.96183115	kPa					
30	assume Evp surface temp	7.65	7.65	°C					
31	Evap surface temp	$(6687.848/(50.10987-LN(C29)-4.655564*LN(C30+273.15)))-273.15=$	6.648412275	°C					
32	Refrigerant temp at Evp	$C31-5=$	1.648412275	°C					
33	Air temp at evp outlet	$C31+C27*(C26-C31)=$	1.15E+01	°C					
34	Condenser surface temp	$(C2-C27*C33)/(1-C27)=$	47.12518754	°C					
35	Refrigerant temp at condenser	$C34+5=$	52.12518754	°C					
36	T cond - T evp	$C35-C32=$	50.47677527	°C					
37	P-suction	$EXP(E37+F37/(C32+G37))/1000=$	524.9492317	kPa	21.25384	-2025.45	248.94	20000	1170.36
38	P-discharge	$EXP(E37+F37/(C35+G37))/1000=$	2035.437319	kPa	1.68674	5.27E-03	250027	367.26	-1.84133
39	H3 = H4=	$(H37+I37*C35+E38*C35^2+F38*C35^3)/1000=$	266.3345777	kJ/kg	-1.15E-02	155482	11.8234	2390.3	1.01659
40	H-1	$(G38+H38*C32+I38*C32^2+E39*C32^3+F39)/1000=$	406.1093494	kJ/kg	5.09E-04	-1.48E-05	-2.50E-07	1.1374	-1.51E-03
41	v-saturated	$EXP(G39+H39/(C32+273.15))*((I39+E40*C32+F40*C32^2+G40*C32^3)=$	4.48E-02	g cum/kg	-5.60E-06	-8.75E-06	-1.50E-07	5.97E-08	1.41E-09
42	c_constant	$H40+I40*C32+E41*C32^2+F41*C32^3+C36+G41*C32^2+C36+H41*C32^2+C36^2+I41*C32^2+C36+E42*C36=$	1.11E+00	kJ/kg	-4.53E-04				
43	delta-H	$((C42/(C42-1))*C37*1000*C41*((C38/C37)*((C42-1)/(C42)-1))/1000=$	34.13164756	kJ/kg					
44	H-2	$C40+C43=$	440.240997	kJ/kg					
45	Enthalpy of dryer outlet air	$(1.005*C26)+C25*(2501.4+1.88*C26)=$	5.79E+01	kJ/kg dry air					
46	Enthalpy of air at evpr outlet	$(1.005*C33)+C13*(2501.4+1.88*C33)=$	2.89E+01	kJ/kg dry air					
47	Cooling load	$(C45-C46)*C23=$	6.76E-01	kJ/s					

A	B	C	D	E	F	G	H
48	Refrigerant flow rate	$C47 \cdot 3600 / (C40 - C39) =$	17.42267777				
49	Power req	$C48 \cdot (C44 - C40) / 3600 =$	0.165184638				
50	Piston displacement	$C48 \cdot C41 / 0.9 =$	8.67E-01				
51	Heating load	$(C14 - C46) \cdot C23 =$	6.76E-01				
52	Ref flow rate to int condenser	$C51 \cdot 3600 / (C44 - C39) =$	14.00322552				
53	Ref flow rate to ext condenser	$C48 - C52 =$	3.419452254				
54	Moisture extraction rate	$C23 \cdot (C25 - C13) \cdot 3600 =$	3.04E-01				
55	SMER	$C54 / C49 =$	1.84E+00				
56	COP	$C51 / C49 =$	4.10E+00				
57	Evaporator model	$C23 \cdot (1 - C27) \cdot (C25 - C28) \cdot 3600 =$	3.04E-01				
58	Moisture removed	$(1.005 \cdot C31) + C28 \cdot (2501.4 + 1.88 \cdot C31) =$	21.66685922				
59	Sat enthalpy at evp surface	$(C23 \cdot (1 - C27) \cdot (C45 - C59) \cdot 3600) - (C58 \cdot C31 \cdot 4.18) =$	2.42E+03				
60	Heat transfer- air side	$C48 \cdot (C40 - C39) =$	2435.250808				
61	Heat transfer- refr side						
62	conenser model						
63	Heat transfer rate	$C23 \cdot (1.005 + 1.88 \cdot C13) \cdot (C2 - C33) \cdot 3600 =$	2.44E+03				
64	Enthalpy at cond surface	$(1.005 \cdot C34) + C13 \cdot (2501.4 + 1.88 \cdot C34) =$	6.51E+01				
65	Heat transfer- air side	$C23 \cdot (1 - C27) \cdot (C65 - C46) \cdot 3600 =$	2.44E+03				
66	Heat transfer - ref side	$C52 \cdot (C44 - C39) =$	2435.250808				
67	Dryer efficiency	$(C2 - C26) \cdot 100 / (C2 - C19) =$	4.60E+01				
68							
69							

E1:F13 Coefficients to determine the properties of air  
E37:I41 and E42 Coefficients to determine the properties of refrigerant

## APPENDIX C

**Table.C.1 Specifications of the instruments and equipments used in the investigation**

Sl. No	Instrument	Manufacturer	Range	Uncertainty
1	Digital temperature indicator and thermocouples	Electronics India, Model-431E, Cr/Al	0-1200°C	±1°C
2	Hygrometer	Barigo, Germany	0-100%	±1%
3	Digital anemometer	Vikram Scientific Instrument, Calcutta Model-AM-4201	0.4-30 m/s	±0.1 m/s
4	Refrigerant rotameter	Eureka Industrial Equipments Pvt. Ltd., Pune, Model-SVS-PG-2	6.6-66 lph	±1 lph
5	Energymeter	Alstrom	0-9999 kWh	±0.1 kWh
6	Refrigerant pressure gauge	Wika	0-150 psi (suction) 50-300 psi (delivery)	±5 psi
7	Electronic weighing balance	Anamed Model-Mx7301A	0-100g	±0.001g
8	Spectrophotometer	Systronics Sr. No. 4612	0-1	0.001
9	Laboratory Centrifuge	Remi, Mumbai Model-R8C	0-9999 RPM	±10RPM
10	Incubator	BD Instrumentation (India), Ambala Cant	0-100°C	±1°C
11	Vacuum oven	International Sale Corporation, New Delhi	0-760mm Hg 0-100°C	±10mm Hg ±1°C
12	Hot air dryer	Indian Instruments and Chemicals, Calcutta	30-90°C	±1°C

## APPENDIX D

**Table D.1 Temperature (°C) profile at different locations of the heat pump dryer with drying time**

Drying Time (h)	Ambient air	Dryer inlet air	Dryer outlet air	Evaporator outlet air	Evaporator surface	Condenser surface
0	32.0	41.0	41.0	20.5	-17	49
2	33.6	35.0	34.0	18.5	-16	47
4	35.0	36.5	35.0	16.5	-18	45
6	34.5	38.5	37.5	16.0	-19	46
8	34.0	39.5	38.0	15.0	-17	45
10	33.0	40.0	39.0	15.5	-19	46
12	32.0	40.5	39.5	16.0	-18	45
14	30.0	41.0	40.0	16.5	-20	47
16	29.0	41.0	40.0	16.0	-19	47
18	27.0	41.0	40.0	15.5	-18	46
20	28.5	41.0	40.5	16.5	-20	47
22	30.5	41.0	40.5	15.0	-17	48
24	31.0	41.0	40.5	15.0	-19	48

**Table D.2 Relative humidity (%) profile of air at different locations of the heat pump dryer with drying time**

Drying Time (h)	Ambient air	Dryer inlet air	Dryer outlet air
0	72	19	19
2	62	48	61
4	55	44	58
6	56	42	55
8	58	40	51
10	60	38	49
12	62	36	46
14	66	33	42
16	69	31	39
18	80	29	37
20	78	26	32
22	77	24	28
24	75	21	25

## APPENDIX E

**Table E.1 Variation in moisture content (% d.b.) with drying time in heat pump dryer for control chilli sample**

Time(h)	30°C		35°C			40°C		
	M.C. (%d.b.)	MR	Time(h)	M.C. (%d.b.)	MR	Time(h)	M.C. (%d.b.)	MR
0.00	521.12	1.00	0.00	521.12	1.00	0.00	521.12	1.00
1.00	454.90	0.87	1.00	445.98	0.85	1.00	419.54	0.80
2.00	410.46	0.78	2.00	385.13	0.74	2.00	345.90	0.66
3.00	371.07	0.71	3.00	332.23	0.63	3.00	297.91	0.57
4.00	339.78	0.65	4.00	294.03	0.56	4.00	253.04	0.48
5.00	312.37	0.59	5.00	256.85	0.49	5.00	215.56	0.41
6.00	288.15	0.55	6.00	219.97	0.42	6.00	180.98	0.34
8.00	245.74	0.46	7.00	189.13	0.36	7.00	148.50	0.28
10.00	206.26	0.39	8.00	165.64	0.31	8.00	121.32	0.22
12.00	170.52	0.32	9.00	148.90	0.28	9.00	95.51	0.17
13.00	155.07	0.29	10.00	135.15	0.25	10.00	72.41	0.13
14.00	141.03	0.26	11.00	121.88	0.22	11.00	52.73	0.09
16.00	121.90	0.22	12.00	109.87	0.20	12.00	36.16	0.06
18.00	106.23	0.19	13.00	99.83	0.18	13.00	23.97	0.04
20.00	91.42	0.16	14.00	90.20	0.16	14.00	13.92	0.02
22.00	77.28	0.14	15.00	81.30	0.15	15.00	5.92	0.00
24.00	63.28	0.11	16.00	72.51	0.13			
26.00	51.04	0.09	18.00	55.41	0.10			
28.00	38.88	0.06	20.00	38.68	0.06			
30.00	27.18	0.04	22.00	22.18	0.03			
32.00	15.61	0.02	24.00	6.10	0.00			
34.00	6.87	0.00						

**Table E.2 Variation in drying rate (%m.c.(d.b.)/h) with moisture content in heat pump dryer for control chilli sample**

30°C		35°C		40°C	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
488.01	66.22	483.55	75.14	470.33	101.58
432.68	44.43	415.56	60.85	382.72	73.64
390.77	39.39	358.68	52.90	321.91	47.99
355.43	31.29	313.13	38.20	275.48	44.88
326.08	27.42	275.44	37.18	234.30	37.48
300.26	24.22	238.41	36.88	198.27	34.57
266.94	21.20	204.55	30.84	164.74	32.48
226.00	19.74	177.38	23.49	134.91	27.18
188.39	17.87	157.27	16.74	108.42	25.80
162.79	15.44	142.03	13.75	83.96	23.10
148.05	14.05	128.52	13.27	62.57	19.68
131.46	9.57	115.88	12.01	44.44	16.57
114.06	7.83	104.85	10.04	30.06	12.19
98.82	7.41	95.01	9.62	18.95	10.05
84.35	7.07	85.75	8.91	9.92	8.01
70.28	7.00	76.90	8.79		
57.16	6.12	63.96	8.55		
44.96	6.08	47.05	8.37		
33.03	5.85	30.43	8.25		
21.39	5.78	14.14	8.04		
11.24	4.37				

**Table E.3 Variation in moisture content (% d.b.) with drying time in hot air dryer for control chilli sample**

Time(h)	45°C		55°C		65°C	
	M.C.(%d.b.)	MR	M.C.(%d.b.)	MR	M.C.(%d.b.)	MR
0	521.12	1.00	521.12	1.00	521.12	1.00
0.5	471.20	0.90	430.05	0.82	410.44	0.79
1	451.25	0.86	362.11	0.69	317.84	0.61
2	388.36	0.74	257.49	0.49	160.37	0.30
3	329.87	0.63	184.27	0.35	53.93	0.09
4	275.61	0.52	116.18	0.21	16.07	0.02
5	225.22	0.43	67.90	0.12	5.18	0.00
6	183.19	0.34	37.16	0.06		
7	147.25	0.27	11.25	0.01		
8	122.21	0.23	5.60	0.00		
10	72.35	0.13				
12	37.94	0.06				
14	15.71	0.02				
16	5.87	0.00				

**Table E.4 Variation in drying rate (%m.c.(d.b.)/h) with moisture content in hot air dryer for control chilli sample**

45°C		55°C		65°C	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
496.16	99.83	475.58	182.13	465.78	221.36
461.22	69.87	396.08	135.88	364.14	185.20
419.80	62.88	309.80	104.62	239.10	157.47
359.12	58.49	220.88	73.21	107.15	106.43
302.74	54.26	150.22	68.09	35.00	37.86
250.42	50.39	92.04	48.28	10.63	10.89
204.21	42.03	52.53	30.73		
165.22	35.94	24.21	25.91		
134.73	30.49	8.43	5.65		
97.28	24.93				
55.15	17.20				
26.83	11.12				
10.79	4.92				

**Table E.5 Effect of pre-treatment on drying rate (%m.c.(d.b.)/h) of chilli dried at 40°C in heat pump dryer**

Control		Treated		Blanched	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
470.33	101.58	558.28	190.60	483.44	130.13
382.72	73.64	393.58	138.79	360.27	116.21
321.91	47.99	274.20	99.96	256.04	92.26
275.48	44.88	196.55	55.36	190.21	39.41
234.30	37.48	148.79	40.15	151.56	37.88
198.27	34.57	103.07	25.65	118.59	28.06
164.74	32.48	68.25	18.35	93.42	22.28
134.91	27.18	51.57	15.00	73.44	17.69
108.42	25.80	38.54	11.05	56.52	16.15
83.96	23.10	28.10	9.83	41.80	13.30
62.57	19.68	18.42	9.53	29.96	10.37
44.44	16.57	9.59	8.11	20.56	8.42
30.06	12.19			13.21	6.27
18.95	10.05			7.68	4.80
9.92	8.01				

**Table E.6 Effect of pretreatment on drying rate (%m.c.(d.b.)/h) of chilli dried at 65°C in hot air dryer**

Control		Treated		Blanched	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
444.67	207.67	564.50	356.33	465.78	221.36
264.81	152.06	414.55	243.45	364.14	185.20
127.61	122.35	263.90	179.58	239.10	157.47
40.63	51.61	121.20	105.83	107.15	106.43
9.87	9.90	46.37	43.84	35.00	37.86
		14.72	19.47	10.63	10.89

**Table E.7 Variation in moisture content (% d.b.) with drying time in heat pump dryer for control sweet pepper sample**

Time(h)	30°C		Time(h)	35°C		Time(h)	40°C	
	M.C. (%d.b.)	MR		M.C. (%d.b.)	MR		M.C. (%d.b.)	MR
0.00	1452.80	1.00	0.00	1452.80	1.00	0.00	1452.80	1.00
1.00	1223.13	0.84	1.00	1166.99	0.80	1.00	1118.12	0.77
2.00	1051.63	0.72	2.00	904.78	0.62	2.00	860.78	0.59
3.00	899.31	0.62	3.00	735.85	0.50	3.00	679.39	0.46
4.00	774.22	0.53	4.00	596.86	0.41	4.00	534.65	0.36
5.00	661.92	0.45	5.00	471.35	0.32	5.00	397.92	0.27
6.00	578.65	0.39	6.00	372.27	0.25	6.00	312.92	0.21
8.00	423.73	0.29	7.00	286.75	0.19	7.00	254.92	0.17
10.00	319.47	0.21	8.00	223.51	0.15	8.00	211.73	0.14
12.00	237.47	0.16	9.00	174.98	0.11	9.00	171.18	0.11
14.00	178.04	0.12	10.00	151.55	0.10	10.00	138.91	0.09
16.00	131.64	0.08	11.00	131.82	0.08	12.00	89.32	0.05
18.00	108.99	0.07	12.00	114.91	0.07	14.00	48.14	0.03
20.00	92.33	0.06	13.00	102.58	0.06	16.00	10.59	0.00
22.00	80.02	0.05	15.00	81.09	0.05			
24.00	68.74	0.04	17.00	62.59	0.04			
26.00	57.92	0.03	19.00	47.53	0.03			
28.00	47.74	0.03	21.00	33.61	0.02			
30.00	38.03	0.02	23.00	20.75	0.01			
32.00	28.56	0.01	25.00	10.71	0.00			
34.00	19.49	0.01						
36.00	10.96	0.00						

**Table E.8 Variation in drying rate (%m.c.(d.b.)/h) with moisture content in heat pump dryer for control sweet pepper sample**

30°C		35°C		40°C	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
1337.96	229.66	1309.89	285.81	1285.46	334.68
1137.38	171.50	1035.88	262.20	989.45	257.34
975.47	152.32	820.32	168.93	770.08	181.39
836.77	125.09	666.36	138.99	607.02	144.74
718.07	112.31	534.11	125.51	466.28	136.74
620.28	83.26	421.81	99.09	355.42	84.99
501.19	77.46	329.51	85.52	283.92	58.01
371.60	52.13	255.13	63.24	233.32	43.19
278.47	41.00	199.24	48.53	191.45	40.55
207.76	29.71	163.26	23.43	155.04	32.27
154.84	23.20	141.68	19.73	114.11	24.79
120.31	11.33	123.36	16.91	68.73	20.59
100.66	8.33	108.74	12.33	29.36	18.78
86.18	6.16	91.83	10.75		
74.38	5.64	71.84	9.25		
63.33	5.41	55.06	7.53		
52.83	5.09	40.57	6.96		
42.89	4.85	27.18	6.43		
33.30	4.74	15.73	5.02		
24.03	4.54				
15.23	4.26				

**Table E.9 Variation in moisture content (% d.b.) with drying time in hot air dryer for control sweet pepper sample**

Time(h)	45°C		Time(h)	55°C		Time(h)	65°C	
	M.C. (%d.b.)	MR		M.C. (%d.b.)	MR		M.C. (%d.b.)	MR
0.00	1452.80	1.00	0.00	1452.80	1.00	0.00	1452.80	1.00
1.00	1123.89	0.77	1.00	886.17	0.61	1.00	815.50	0.56
2.00	905.48	0.62	2.00	540.79	0.37	2.00	320.37	0.22
3.00	733.98	0.50	3.00	336.61	0.23	3.00	112.89	0.07
4.00	567.95	0.39	4.00	168.13	0.11	4.00	43.22	0.02
5.00	411.54	0.28	5.00	96.81	0.06	5.00	21.60	0.01
6.00	286.10	0.19	6.00	64.65	0.04	6.00	9.79	0.00
8.00	188.67	0.12	7.00	40.00	0.02			
10.00	118.84	0.08	8.00	23.24	0.01			
12.00	72.00	0.04	9.00	15.50	0.00			
13.00	54.47	0.03	10.00	10.09	0.00			
14.00	40.89	0.02						
15.00	28.89	0.01						
16.00	18.26	0.01						
17.00	10.50	0.00						

**Table E.10 Variation in drying rate (%m.c.(d.b.)/h) with moisture content in hot air dryer for control sweet pepper sample**

45°C		55°C		65°C	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
1288.34	328.91	1169.48	566.62	1134.15	637.29
1014.68	218.41	713.48	345.38	567.94	495.14
819.73	171.50	438.70	204.18	216.63	207.48
650.96	166.03	252.37	168.48	78.05	69.67
489.74	156.41	132.47	71.32	32.41	21.62
348.82	125.44	80.73	32.16	15.69	11.80
237.39	48.71	52.33	24.65		
153.76	34.92	31.62	16.76		
95.42	23.42	19.37	7.74		
63.23	17.53	12.80	5.41		
47.68	13.58				
34.89	12.00				
23.57	10.63				
14.38	7.76				

**Table E.11 Effect of pre-treatment on drying rate (%m.c.(d.b.)/h) of sweet pepper dried at 40°C in heat pump dryer**

Control		Treated		Blanched	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
1285.46	334.68	1381.89	545.00	1273.06	469.31
989.45	257.34	877.80	463.17	847.20	382.41
770.08	181.39	481.52	329.41	517.82	276.35
607.02	144.74	259.25	115.11	331.77	95.74
466.28	136.74	156.12	91.16	243.44	80.93
355.42	84.99	93.39	34.31	178.21	49.52
283.92	58.01	65.74	20.98	133.91	39.08
233.32	43.19	48.39	13.73	99.14	30.46
191.45	40.55	36.99	9.06	72.62	22.58
155.04	32.27	28.12	8.68	52.66	17.36
114.11	24.79	19.32	4.47	38.01	11.93
68.73	20.59	11.94	2.91	26.41	5.64
29.36	18.78			15.49	5.27

**Table E.12 Effect of pre-treatment on drying rate (%m.c.(d.b.)/h) of sweet pepper dried at 65°C in hot air dryer**

Control		Treated		Blanched	
MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate	MC(%d.b.)	Drying rate
1134.15	637.29	1191.47	925.84	1173.69	668.05
567.94	495.14	504.23	448.64	588.18	502.98
216.63	207.48	184.56	190.70	226.29	220.79
78.05	69.67	63.74	50.93	89.95	51.88
32.41	21.62	24.20	28.15	47.10	33.82
15.69	11.80			20.00	20.37

## APPENDIX F

### Proforma for sensory evaluation

Proforma for the evaluation of \_\_\_\_\_

Name of the evaluator: \_\_\_\_\_

Date: \_\_\_\_\_

Sample code	Colour	Texture	Flavour	Overall acceptability	Remarks (if any)
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Signature \_\_\_\_\_

### Hedonic Scale

Expression	Points to be given
Liked extremely	9
Liked very much	8
Liked moderately	7
Liked slightly	6
Neither liked nor disliked	5
Disliked slightly	4
Disliked moderately	3
Disliked very much	2
Disliked extremely	1

## APPENDIX G

**Table G.1 Water activities of saturated salt solutions at various temperatures**

Salt	Water activity at temperature ( °C ) of:			
	35	45	55	65
Lithium chloride	0.108	0.103	0.098	0.094
Potassium acetate	0.216	0.197	0.182	0.168
Magnesium chloride	0.318	0.308	0.300	0.291
Potassium carbonate	0.436	0.429	0.424	0.418
Magnesium nitrate	0.515	0.496	0.480	0.465
Sodium nitrite	0.628	0.599	0.576	0.554
Sodium chloride	0.743	0.727	0.710	0.696
Potassium chloride	0.821	0.786	0.764	0.739
Potassium sulphate	0.961	0.961	0.955	0.952

**Table G.2 Equilibrium moisture content of chilli and sweet pepper**

Salt solution	ERH (%)	Chilli		Sweet pepper	
		EMC (% d.b.)		EMC (% d.b.)	
		Adsorption	Desorption	Adsorption	Desorption
Lithium chloride	10.8	5.13	5.32	9.63	9.95
Potassium acetate	21.6	5.66	6.01	10.04	10.52
Magnesium chloride	31.8	6.07	6.66	10.48	11.19
Potassium carbonate	43.6	7.22	8.02	11.89	13.13
Magnesium nitrate	51.5	8.53	9.88	14.22	15.73
Sodium nitrite	62.8	11.54	12.69	16.74	18.23
Sodium chloride	74.3	14.95	15.44	20.61	21.18

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