

**MEASUREMENT AND MODELLING OF  
THERMAL PROPERTIES OF *CHHANA***

**THESIS SUBMITTED TO THE  
NATIONAL DAIRY RESEARCH INSTITUTE, KARNAL  
(DEEMED UNIVERSITY)  
IN PARTIAL FULFILMENT OF THE REQUIREMENT  
FOR THE DEGREE OF**

**MASTER OF TECHNOLOGY  
IN  
DAIRYING  
(DAIRY ENGINEERING)**

**BY  
*ASIM KR. NAYAK*  
B.Tech. (D.T)**

**DIVISION OF DAIRY ENGINEERING  
NATIONAL DAIRY RESEARCH INSTITUTE  
( I. C. A. R. )**

**KARNAL - 132 001 (HARYANA), INDIA  
1999**

**Regn. No. 3049702**

1743



74054

26-7-21

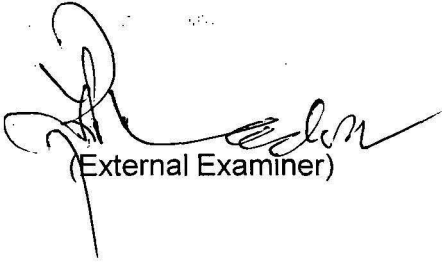
# MEASUREMENT AND MODELLING OF THERMAL PROPERTIES OF CHHANA

By

**ASIM KUMAR NAYAK**

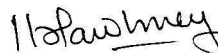
Thesis submitted to the  
National Dairy Research Institute  
(Deemed University), Karnal  
in partial fulfilment of the requirement  
for the degree of

**Master of Technology  
in  
Dairying  
(Dairy Engineering)**



(External Examiner)

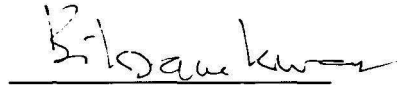
Approved By



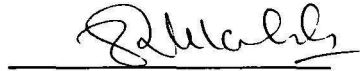
(Er. I.K. Sawhney)  
(Major Advisor and Chairman)  
(Guide)

## **Members of Advisory Committee**

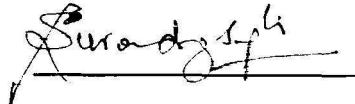
1. **Er. Bikram Kumar**  
Sr. Scientist,  
DE Division



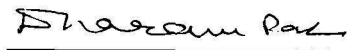
2. **Dr. R.K. Kohli**  
Sr. Scientist,  
DE Division



3. **Sh. Surendra Singh**  
Sr. Scientist,  
DES&M Division



4. **Dr. Dharam Pal**  
Sr. Scientist,  
DT Division



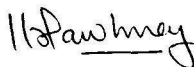
*Er. I.K. Sawhney*  
*Sr. Scientist*

DAIRY ENGG. DIVISION  
**NATIONAL DAIRY RESEARCH INSTITUTE**  
(DEEMED UNIVERSITY)(I.C.A.R.)  
KARNAL - 132 001 (HARYANA) INDIA

DATED: 31<sup>ST</sup> DEC. 1999

## **C E R T I F I C A T E**

This is to certify that the thesis entitled "**MEASUREMENT AND MODELLING OF THERMAL PROPERTIES OF CHHANA**" submitted by **MR. ASIM KUMAR NAYAK** towards the partial fulfilment of the the award of the degree of **MASTER OF TECHNOLOGY IN DAIRYING (DAIRY ENGINEERING)** of the **NATIONAL DAIRY RESEARCH INSTITUTE (DEEMED UNIVERSITY)**, Karnal, Haryana, India is a bonafide research work carried out by him under my supervision and guidance and no part of the thesis has been submitted for any other degree or diploma.



**(I.K. SAWHNEY)**  
**MAJOR ADVISOR & CHAIRMAN**  
**(GUIDE)**

*Dedicated*

*to my*

*Parents*

## Acknowledgements

**I** express my profound sense of gratitude and regards to *Er. I.K. Sawhney, Senior Scientist, Dairy Engineering Division, National Dairy Research Institute, Karnal* for his sagacious guidance, keen and untiring interest, creative and constructive criticism and deep affection during the course of this endeavour.

*I wish to express my reverence to Dr. B.N. Mathur, Director, National Dairy Research Institute, Karnal and Dr. S.P. Agarawala, Head, Dairy Engineering Division for providing necessary facilities during my study.*

*Sincere gratitude is extended to the Advisory Committee members Er. Bikram Kumar, Dr. R.K. Kohli, Sh. Surendra Singh, Dr. Dharam Pal whose wisdom, valuable thoughts and assistance made me to carry out the work.*

*My sincere thanks go to all the Scientists and Staff members of Dairy Engineering Division for their high degree of co-operation.*

*I am also thankful to my classmates, Kishore, Tavva, Dharma, Khojare, for their wonderful company throughout my stay at NDRI.*

*I am really grateful to all my friends especially, Suman, Shyamal, Bijoy, Mohan, Koushik, Malay, Nilesh, Bishu, Anita, Monalisha, Meena, Jayshekher, Ritu, Jyotshna, Singhal, for their evergreen company since the early days of my professional carrier.*

*I feel wordless to express my gratitude to all my seniors especially Sadhan da, Ravi sir, Badshah sir, Koushik da, Sudipto da, Dhali da, Sujit da, Shekher, Jayakumar.*

*I owe a deep sense of love and affection to Guru, Srinibas, Ujjwal, Shieby, Sudhir, Hari, Ramesh, Santanu, Ganguli, Goutam, Pawa, Amar, Jayendra, Rajib, Anil, Nagareddy, Bidhan, Siddhartha.*

*I am also thankful to all my friends at NDRI to whom my language and my culture never became a barrier to interact during the short span of my NDRI life.*

*At last, no word would be adequate to express my gratitude to my parents, my sister, brother and all my family members whose love and care always help me to reach the destination.*

  
(Asim Kumar Nayak)

# Contents

| TITLE   | PAGE NO.     |
|---|--------------|
| <b>1. INTRODUCTION</b>                                    | <b>1-3</b>   |
| <b>2. REVIEW OF LITERATURE</b>                            | <b>4-31</b>  |
| 2.1. TECHNOLOGY OF <i>CHHANA</i> PRODUCTION               | 5            |
| 2.1.1. Composition of <i>chhana</i>                       | 5            |
| 2.2. THERMAL PROPERTIES OF FOODS                          | 7            |
| 2.2.1. Thermal conductivity                               | 7            |
| 2.2.2. Specific heat                                      | 19           |
| 2.2.3. Thermal diffusivity                                | 25           |
| <b>3. MATERIALS AND METHODS</b>                           | <b>32-43</b> |
| 3.1. PREPARATION OF <i>CHHANA</i>                         | 32           |
| 3.1.1. Preparation of Coagulant                           | 32           |
| 3.1.2. Changing the Compositions of <i>Chhana</i>         | 33           |
| 3.2. MEASUREMENT OF THERMAL CONDUCTIVITY OF <i>CHHANA</i> | 33           |
| 3.2.1. Experimental Set-up                                | 33           |
| 3.2.2. Measurement of Resistance of Heater Wire           | 35           |
| 3.2.3. Measurement of Temperature                         | 35           |
| 3.2.4. Calibration of Thermocouples                       | 35           |
| 3.2.5. Location of Thermocouples                          | 36           |
| 3.2.6. Experimental Procedure                             | 36           |
| 3.2.7. Calculation of Thermal Conductivity                | 37           |
| 3.3. MEASUREMENT OF SPECIFIC HEAT OF <i>CHHANA</i>        | 37           |
| 3.3.1. Experimental Procedure                             | 37           |
| 3.3.2. Calculation of Specific Heat                       | 38           |
| 3.4. MEASUREMENT OF THERMAL DIFFUSIVITY                   | 39           |
| 3.4.1. Experimental Set-up                                | 39           |
| 3.4.2. Diffusivity Tube                                   | 39           |
| 3.4.3. Experimental Procedure                             | 39           |
| 3.4.4. Calculation of thermal diffusivity                 | 40           |

---

|  |                   |
|--|-------------------|
| 3.5. ANALYTICAL METHODS  | 41                |
| 3.5.1. Determination of Moisture Content of <i>Chhana</i>          | 41                |
| 3.5.2. Determination of Protein Content in <i>Chhana</i>           | 42                |
| 3.5.3. Determination of Fat Content of <i>Chhana</i>               | 43                |
| <b>4. RESULTS AND DISCUSSION</b>                                   | <b>44-49</b>      |
| 4.1. THERMAL PROPERTIES OF <i>CHHANA</i>                           | 44                |
| 4.2. EFFECT OF TEMPERATURE ON THERMAL PROPERTIES OF <i>CHHANA</i>  | 45                |
| 4.3. EFFECT OF COMPOSITIONS ON THERMAL PROPERTIES OF <i>CHHANA</i> | 45                |
| 4.3.1. Effect of Moisture Content                                  | 45                |
| 4.3.2. Effect of Fat Content                                       | 46                |
| 4.3.3. Effect of Protein Content                                   | 47                |
| 4.4. MODELLING OF THERMAL PROPERTIES OF <i>CHHANA</i>              | 48                |
| 4.4.1. Prediction Model for Thermal Conductivity (K)               | 48                |
| 4.4.2. Prediction Model for Specific Heat ( $C_p$ )                | 48                |
| 4.4.3. Prediction model for thermal diffusivity ( $\alpha$ )       | 49                |
| <b>5. SUMMARY AND CONCLUSIONS</b>                                  | <b>50-52</b>      |
| <b>BIBLIOGRAPHY</b>  | <b><i>i-x</i></b> |
| <b>APPENDIX</b>  | <b><i>i</i></b>   |

---

## *List of Figures*

| <b>Fig.</b> | <b>Title</b>   | <b>After<br/>Page No.</b> |
|-------------|--|---------------------------|
| 2.1.        | Methods used for making <i>chhana</i> from cow milk  | 6                         |
| 3.1.        | Schematic diagram of thermal properties measurement set-up                                       | 33                        |
| 3.2.        | Schematic diagram of thermal conductivity measurement set-up                                     | 33                        |
| 3.3.        | Log time vs. temperature for thermal conductivity calculation                                    | 37                        |
| 3.4.        | Log time vs temperature (Linear portion)   | 37                        |
| 3.5.        | Schematic diagram of thermal diffusivity measurement set-up                                      | 39                        |
| 3.6.        | Time vs temperature curve for thermal diffusivity measurement                                    | 40                        |
| 4.1.        | Variation of thermal properties with temperature (Constant Moisture, Fat, Protein)               | 45                        |
| 4.2.        | Variation of thermal properties with different moisture levels (Constant Moisture, Fat, Protein) | 45                        |
| 4.3.        | Variation of thermal properties with fat content (Constant Moisture, Fat, Protein)               | 46                        |
| 4.4.        | Variation of thermal properties with protein content (Constant Moisture, Fat, Protein)           | 47                        |

## *List of Tables*

| <b>Table</b> | <b>Title</b>  | <b>After<br/>Page No.</b> |
|--------------|---|---------------------------|
| 2.1.         | Average composition of <i>chhana</i>  | 5                         |
| 2.2.         | Coefficients of equation 2.17 to predict dairy product's thermal conductivity | 17                        |
| 4.1.         | Thermal conductivity of <i>chhana</i> at various conditions                   | 44                        |
| 4.2.         | Specific heat of <i>chhana</i> at various conditions                          | 44                        |
| 4.3.         | Thermal diffusivity of <i>chhana</i> at various conditions                    | 44                        |

## *List of Plates*

| <b>Plate</b> | <b>Title</b>  | <b>After<br/>Page No.</b> |
|--------------|---|---------------------------|
| 3.1.         | Experimental set-up for thermal properties measurement                | 33                        |
| 3.2.         | Sample holder for thermal conductivity measurement                    | 33                        |
| 3.3.         | Sample holder with <i>chhana</i> for thermal conductivity measurement | 33                        |
| 3.4.         | Diffusivity tube with <i>chhana</i>                                   | 39                        |

## *List of Abbreviations*

---

|          |   |   |
|----------|---|---|
| $a_w$    | = | Water activity                            |
| $C_P$    | = | Specific heat (cal/g°C)                   |
| F        | = | Fat (%)                                   |
| I        | = | Current (amps)                            |
| K        | = | Thermal conductivity (w/m°C)              |
| M        | = | Moisture (%)                              |
| N        | = | Dispersed phases                          |
| P        | = | Protein (%)                               |
| R        | = | Resistance (ohms)                         |
| T        | = | Temperature (°C)                          |
| V        | = | Voltage (Volts)                           |
| X        | = | Fraction of composition                   |
| $\alpha$ | = | Thermal diffusivity (m <sup>2</sup> /sec) |
| $\theta$ | = | Time (sec)                                |
| $\rho$   | = | Density (kg/m <sup>3</sup> )              |

### **Subscripts**

|   |   |                      |
|---|---|----------------------|
| 1 | = | Initial              |
| 2 | = | Final                |
| a | = | Ash                  |
| C | = | Carbohydrate         |
| c | = | Continuous component |
| d | = | Dispersed component  |
| f | = | Fat                  |
| m | = | Moisture             |
| p | = | Protein              |
| s | = | Total solid          |
| l | = | Liquid component     |

---

# **CHAPTER-1**

## **INTRODUCTION**

# 1. INTRODUCTION

---

1.1. Thermal properties of any material are those which control the thermal energy transport and/or storage within it, as well as the transformations undergone by the material under the action of heat. Foods are no exception to this general rule. Thermal processing is widely used in dairy and food industry. The design of equipments for such processes require the knowledge of thermal properties such as thermal conductivity, specific heat and thermal diffusivity of the product to be processed. It is essential that the design engineer is able to quantify the rate of heat transfer during manufacture of specific products. It is also important that critical energy balance is considered in design of heat exchangers for processing of these products. Therefore, the determination of thermal properties has become a primary concern and has received the most attention in heat transfer application.

1.2. *Chhana*, also called *paneer* in certain parts of the country, an important base and filler for several varieties of Indian sweets (*rasgolla*, *sandesh*, *cham-cham*, *rasmalai*, *pantooa*, *rajbhog*, *chhana-murki* etc.) occupies a prominent place in the dairy economy of India. It can be defined as the milk-solids obtained by the acid coagulation of boiled hot whole milk and subsequently drainage of whey. It is estimated that about 4 percent of total milk is converted into *chhana* per

annum (Aneja, 1998). Until recently indigenous dairy products were manufactured in the unorganized sector by *halwais* using traditional technology. In recent years some changes have taken place in the production of these products when the organized dairies started the processing and marketing of these products. Attempts are going on to develop equipment for continuous manufacture of these products. One of the main problems faced by the design engineers for efficient design of these equipments is the lack of availability of thermal properties data on indigenous dairy products.

**1.3.** Thermal properties have been reported to be affected by product temperature and composition in regard to water, fat and protein content. The measurement of thermal properties under every conceivable condition would be an enormous task. Therefore, the use of models to predict thermal properties as a function of composition and temperature is the best way to assure the availability of data. Before such models can be generated considerable data on thermal properties must be collected.

**1.4.** *Chhana* has water, fat and protein as its major constituents. The relative proportion of these constituents in *chhana* vary with the type of milk used for making *chhana* and the extent of straining of coagulated mass. This would alter the thermal properties of *chhana* and to assign a single value to these properties would be erroneous. *Chhana* is produced by coagulating the milk at 70°C and the final temperature of freshly made *chhana* is around 55°C. The product needs to be cooled to a temperature of 5 to 10°C for storage. The knowledge of variation of thermal properties of the product with temperature is thus essential to estimate the thermal load requirements in its refrigeration.

**1.5.** In a view of the above facts it was proposed in the present study to generate the engineering data on thermal properties of *chhana* and evaluate the effect of temperature and composition on these properties.

The specific objectives of the study are:

1. To characterise the thermal properties of *chhana* at different product compositions.
2. To develop prediction equations for thermal properties of *chhana*.

# **CHAPTER-2**

## ***REVIEW OF LITERATURE***

## 2. REVIEW OF LITERATURE

---

*Chhana* is a coagulated whole milk product of the Indian subcontinent. It is the milk-solids obtained by the acid coagulation of boiled hot whole milk and subsequent drainage of whey. The acids commonly used are lactic or citric, in both natural and chemical forms. By virtue of its economic importance, *chhana*, amongst all indigenous dairy products, attracted the attention of most research workers. Many studies have been conducted on the method of production, quality of the products and the keeping quality of *chhana*. However, no information is available with regard to the thermal properties of *chhana viz.*, thermal conductivity, thermal diffusivity and specific heat. The related literature has been reviewed under the following sub-headings:

- 2.1. Technology of *chhana* production
  - 2.1.1. Composition of *chhana*
- 2.2. Thermal properties of foods
  - 2.2.1. Thermal conductivity
  - 2.2.2. Specific heat
  - 2.2.3. Thermal diffusivity

## 2.1. TECHNOLOGY OF *CHHANA* PRODUCTION

According to the PFA Rules (1976), *chhana* is the product obtained from cow or buffalo milk or combination thereof by precipitation with sour milk, lactic acid or citric acid. It should not contain more than 70 percent moisture, and the milk fat content should not be less than 50 percent of the dry matter.

Skim milk *chhana* is the product obtained from cow or buffalo skim milk by precipitation with sour milk, lactic acid or citric acid. It should not contain more than 70 percent moisture. The milk fat content of the product should not exceed 13 percent of the dry matter.

*Chhana* making is essentially a process involving destabilization of casein particle by addition of dilute acid to milk aided by relatively higher temperature. Acid affects the stability of casein directly by disturbing the charges carried by the particles and indirectly by releasing the calcium ion from colloidal calcium-caseinate phosphate complex. The destabilization results in formation of large structural aggregates (called coagulum) from the normal colloidal dispersion of casein micelles in which milk fat, serum proteins and other constituents get entrained together.

### 2.1.1. Composition of *Chhana*

The chemical composition of *chhana* depends mainly on the initial composition of milk; the conditions of coagulation, the technique of straining and losses of milk solids in the whey.

An average chemical composition of fresh, laboratory made whole milk *chhana* is shown in Table 2.1 as reported by

Ray and De (1953). Cow milk of 4.5 percent fat and 13 percent total solid and buffalo milk of 8.4 percent fat and 17.9 percent total solids was used for making *chhana*.

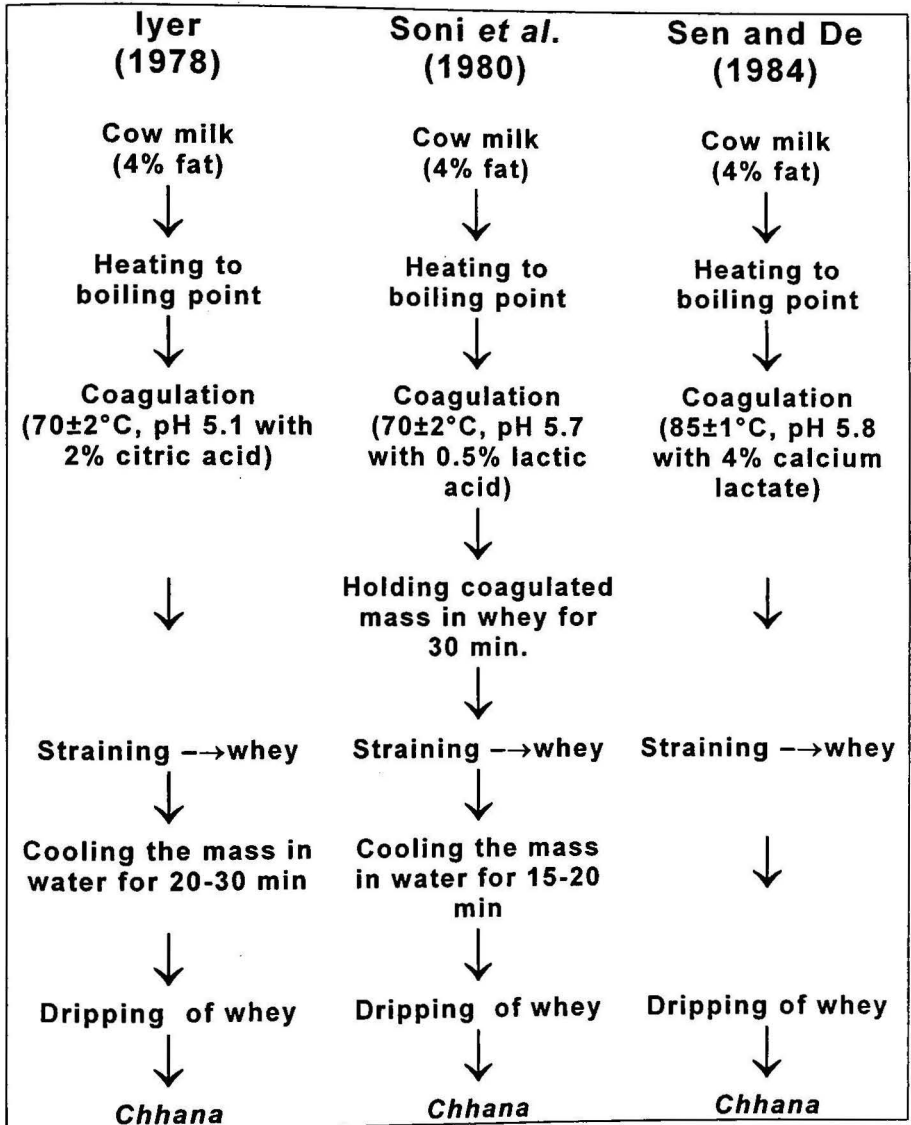
**Table 2.1. Average composition of *chhana***

| Type of milk | Composition of <i>chhana</i> |      |         |         |     |
|--------------|------------------------------|------|---------|---------|-----|
|              | Moisture                     | Fat  | Protein | Lactose | Ash |
| Cow milk     | 53.4                         | 24.8 | 17.4    | 2.1     | 2.1 |
| Buffalo milk | 51.6                         | 29.6 | 14.4    | 2.3     | 2.0 |

Source: Ray and De (1953)

The technique of *chhana* production is known for a long time. The method of production is developed and set through experience. Many research workers have attempted to standardize the process of *chhana* making with a view to improve the product quality and its yield. However, the basic method of production of *chhana* till date remained same, i.e., coagulation of hot milk using acid or acid salts as the coagulant solution. Fig-2.1 describes the different methods standardized by various research workers for processing of cow milk into *chhana*. Iyer (1978) reported that cow milk *chhana* obtained by coagulation at pH 5.1 was soft and cohesive with minimum losses of milk solids in whey. However, Soni *et al.* (1980) suggested *chhana* prepared by coagulation of milk with 0.5% lactic acid, suitable for *rosogolla* preparation. Sen and De (1984) studied on the use of calcium lactate as a coagulant for *chhana* indicated that the yield was higher (23.6 and 24.8%) when compared to citric acid (16.8%, 18.0%) at coagulation temperature of 85°C and 80°C.

**Fig. 2.1. Methods used for making *chhana* from cow milk**



## 2.2. THERMAL PROPERTIES OF FOODS

Thermal properties of any material are those which control the thermal energy transport and/or storage within it, as well as the transformations undergone by the material under the action of heat. Foods are no exception to this general rule. Thermal properties of foodstuffs primarily comprise: specific heat and enthalpy, thermal conductivity and diffusivity, heat penetration coefficient. Early heat transfer analysis for heating or cooling food products required constant uniform values of thermal properties. These analysis were typically oversimplified and inaccurate. Present day analytical techniques such as the finite-element method are much more sophisticated and can account for non uniform thermal properties, which change with time, temperature and location as a food product is heated or cooled. The large and ever-increasing number of food products available today creates a great demand for knowledge of the thermal properties of a wide variety of foods. These informations are needed for a variety of research and engineering application to design and optimize the operation of handling and processing units.

### 2.2.1. Thermal Conductivity

The *thermal conductivity* of a material is a measure of its ability to conduct heat. In foods, thermal conductivity depends mostly on composition, but also on any factor that affects the heat flow paths through the material, such as percent void spaces, shape, size and arrangement of void spaces. The amount of heat,  $Q$ , that flows through a slab of material of

thickness  $x$  and thermal conductivity  $K$  is calculated by the equation:

$$Q = \frac{AK(T_1 - T_2)}{x} \dots\dots\dots (2.1)$$

Where,  $A$  is the surface area of the material normal to the direction of heat flow and  $T_1$  and  $T_2$  are the surface temperatures of the material. For as long as foods are heated or cooled there will be a need for thermal conductivity data in order to predict heating or cooling rates. In dairy industry not only the heating or cooling rates determination but also the thermal conductivity data can help to design of continuous processing equipments.

### **2.2.2.1. Measurement of thermal conductivity**

Methods of measurement of thermal conductivity can be divided into two broad categories, namely those using the steady-state condition of heat transfer and those using the transient state. A brief discussion of the basic methods is given below:

#### **Steady-state longitudinal heat flow methods:**

##### **Guarded hot plate**

This method is regarded as the most accurate and most widely used apparatus for the measurement of thermal conductivities of poor conductors of heat. This method is suitable for dry homogenous specimens in slab forms. The thermal conductivity is computed by measuring the amount of heat input required to maintain the steady-state temperature profile across the test specimen. The following is the computing equation:

$$K = qd/2A\Delta t \quad \dots\dots\dots (2.2.)$$

Where,

d = Specimen thickness

q = Measured rate of heat input

A = Area of specimen

$\Delta t$  = temperature difference between specimen surfaces normal to heat flow

### **Steady-state radial heat flow methods**

The radial heat flow techniques are used for conductivity measurements of loose, unconsolidated, powder or granular materials. The methods used can be classified as follows:

#### **Cylinder with central heating source**

The sample is confined in a cylinder that is assumed to be infinite in length and thus end effects can be neglected. The central heat source provides heat to be transferred through the material with a thermal conductivity to be calculated as follows:

$$K = \frac{p \ln(r_2/r_1)}{2\pi L(t_1 - t_2)} \quad \dots\dots\dots (2.3)$$

Where, p is the power used by the central heater, L is the length of the cylinder, and  $t_1$  and  $t_2$  are the temperatures of the specimen at radii  $r_1$  and  $r_2$ , respectively.

#### **Sphere with central heating source**

In this case the specimen completely enclose the heating source, eliminating the end losses. Assuming that the surface

of the central heater at a radial distance  $r_1$  and the outer specimen surface at  $r_2$ , reach at the same temperature after the steady state has been established, heat flow will be essentially radial and the following equation can be used for determining thermal conductivity.

$$K = \frac{p(1/r_1 - 1/r_2)}{4\pi(t_1 - t_2)} \dots\dots\dots (2.4)$$

**Unsteady-state methods**

Transient-state methods of thermal conductivity measurements make use of either a line source of heat or one or more plane sources of heat.

**Fitch method**

The Fitch method is one of the most common transient methods used to measure the thermal conductivity of poor conductors. After taking a record of time and temperature, the following equation is used to calculate thermal conductivity:

$$K = 2.303 \frac{MCL \log(I_1/I_2)}{A \theta} \dots\dots\dots (2.5)$$

Where, M and C are mass and specific heat of the receiver or heat sink,  $I_1$  and  $I_2$  are temperature differences at beginning and the end of experiment, A and L are the area and thickness of the test specimen, respectively.

**Line heat source method**

This is one of the most common transient methods used particularly with granular materials. This method was first suggested by Schleirmacher (1988).

The line heat source technique utilizes a constant heat source to an infinite solid along a line with infinitesimal diameter. Heater wire is heated to heat the sample at a constant rate. After a brief transient period, the plot of the natural logarithm of time versus temperature is linear, having a slope equal to  $Q/4\pi K$ . Thermal conductivity can be written :

$$K = \frac{Q}{4\pi(T_2 - T_1)} \ln \frac{\theta_2}{\theta_1} \quad \dots\dots\dots (2.6)$$

Where, K is the thermal conductivity of the sample (w/m°C), Q is the power generated by the heater (w/m),  $T_1$  and  $T_2$  are the temperature (°C) at times  $\theta_1$  and  $\theta_2$  (sec.) respectively. By using the theory of line heat source, thermal conductivity probe was developed. The equation for calculating thermal conductivity is the same as equation 2.6.

Line heat source method to measure thermal conductivity was suggested by Schleirmacher (1988). Hutchinson (1945) adopted this method and reported that it was accurate even for liquids. The line heat source method as suggested by Schleirmacher was developed by Van der Held and Van Druman (1949) for measuring thermal conductivity of foods. Hooper and Lepper (1950) used a line heat source probe to determine the thermal conductivity. The apparatus consisted of a metal tube inside of which heater wire and a thermo couple were inserted. They recommended a probe length to diameter ratio as high as 100 to eliminate the errors. Hooper and Lepper also introduced time correlation factor while measuring thermal conductivity of liquids, which was further elaborated by Nix *et al.* (1967).

Thermal conductivity of liquid dairy products has been measured by several investigators, but very few studies were

found for non-liquid products. Konrad and Rambke (1970) worked with whole milk, skim milk and cream at different concentrations. Lepikin and Berisov (1970) measured thermal conductivity of milk and cream products over a range of fat content from 3.2 to 96%. Reidel (1949) and Spell (1960) reported conductivity data for butterfat. Butter and margarine were included in a study by Hooper and Chang (1953).

✓ \*Farrall *et al.* (1970) measured thermal conductivity of different types of powdered milk. The conductivity of the nonfat powder was found to be slightly greater than the whole milk powder. \* The effect of concentration on thermal conductivity of whole milk was studied by Agrawal *et al.* (1972). They observed that the thermal conductivity of raw milk was slightly higher than that of distilled water at all temperature levels. But same was less at higher concentrations of milk. Thermal conductivity increased considerably with temperature. Fernandez-Martin *et al.* (1977) determined thermal conductivity of creams of about 20, 30 and 40% fat at several temperature between 5 and 75°C. An equation was derived for the thermal conductivity of cream as a function of temperature and volume fraction of the fat phase.

‡ Sweat *et al.* (1979) utilized line heat source thermal conductivity probe to measure the thermal conductivity of 28 dairy products and margarine at 0, 20 and 40°C. They correlated thermal conductivity of products to their mass density, fat and moisture content. Murdia (1982) used line heat source method to measure the thermal conductivity of butter, *ghee*, *paneer* and *khoa* using different set-ups for liquid and solid products. Thermal conductivity of reconstituted milk during processing was determined by Reddy *et al.* (1994) and was found to increase with increase in moisture content and temperature.

Choi and Okos (1983a) determined the thermal conductivity and thermal diffusivity of tomato juice. Thermal conductivity of tomato juice was found to increase with increase in temperature. An equation was also developed to correlate the thermal conductivity with temperature and concentration. Califano and Calvelo (1991) calculated the thermal conductivity of potato cut into cylindrical sample, between 50 and 100°C. Thermal conductivity ranged from 0.545 to 0.957 w/m°C for potatoes mass density 1070 kg/m<sup>3</sup> and moisture 80%.

Unklesbay *et al.* (1992) analyzed thermal conductivity of extruded beef/corn flour blends at the temperature range of 91°C and 109°C. The extruded products had densities of 1.054 to 1.091 kg/m<sup>3</sup>. Specific heat was 2.944 to 3.055 KJ/Kgk and thermal conductivity 0.26 to 0.39 w/mk.

Daubert *et al.* (1997) studied electric field effects on the thermal conductivity of milk chocolate by using 'mirror image method'. An applied electric field of up to 450 v/mm at 60Hz was found to have no significant effect on the heat transfer properties of milk chocolate. The thermal conductivity was found to have an average value of 0.163 w/mk over a temperature range varying from 25 to 60°C.

Tsai *et al.* (1998) calculated thermal conductivity of restructured beef products at different isothermal temperatures. Thermal conductivity ranged from 0.45 – 0.47 w/m°C, close to the value 0.45 w/m°C reported by Baghe-Khandan and Okos (1981) for ground beef.

Thermal conductivity of bread samples, moisture content 5% to 44%, (w/w, wet basis) and porosity 0.18 to 0.90, was

measured in a selected stainless steel vessel using the probe method from 25 to 85°C by Goedeken *et al.* (1998). Significant difference was observed in measured thermal conductivity before and after air pressure was applied to the sample indicating the influence of vapour phase moisture migration on thermal conductivity.

\* Jayakumar (1998) developed a probe for determination of thermal conductivity of some selected indigenous dairy products like *khoa*, *paneer*. Thermal conductivity of *khoa* and *paneer* was evaluated at different temperature and moisture levels. The thermal conductivity of both products increased with both temperature and moisture level. He reported that thermal conductivity of *paneer* (moisture 41-58%) varied from 0.212 to 0.353 w/m°C, between 6-40°C and for *khoa* (moisture 32-68%) varied from 0.259 to 0.473 w/m°C between 10-90°C.

\* Willix *et al.* (1998) measured thermal conductivity-temperature relationships of 27 foods in the temperature range from -40 to 40°C by using a guarded hot plate apparatus. Foods examined included meat, fish, fats, fruits and dairy products. Values were corrected for product thickness, thermal imbalance, effective area and plate thermocouple calibration.

### **2.2.1.2. Prediction equations for thermal conductivity**

The thermal conductivity of a food is influenced by the compositions of the food. Other factors which can affect it are the pressure which is particularly important in freeze-drying operations and temperature. There have been several attempts to model thermal conductivity of various food materials. These usually were applied to a limited number of food products.

Riedel (1949, cited by Dickerson 1968) developed the following equation for fruit juices and sugar solutions:

$$K = (307 + 0.645 f - 0.00104 f^2) (0.46 + 0.0054 w) \times 10^3 \text{ Btu/hr-ft}^\circ\text{F} \quad \dots\dots\dots (2.7)$$

Where, *f* is fat content and *w* is water content.

Spells (1960) used a linear equation in the following form to correlate water content with thermal conductivity of liquid biological materials having water content greater than 50 percent

$$K = 0.056 + 0.0057 M w/m^\circ\text{C} \quad \dots\dots\dots (2.8)$$

Poppendick *et al.* (1966) assumed the thermal conductivity of a biological material to be a weighted function of the individual thermal conductivities of the water, protein and fat fractions. This method requires a knowledge of the composition of the product as well as the thermal conductivities of the protein and fat components. The expression for their model was

$$K = \rho \sum_{n=0}^n \frac{K_n W_n}{\rho_n} \quad \dots\dots\dots (2.9)$$

Kopelman (1966) has presented three models to investigate thermal conductivity of foods for two component homogenous dispersion systems. The following models were proposed:

$$\frac{K}{K_c} = \frac{1 - M^2(1 - K_d/K_c)}{1 - M^2(1 - K_d/K_c)(1 - M)} \quad \dots\dots\dots (2.10)$$

For case where  $K_c \gg K_d$ , equation reduces to :

$$\frac{K}{K_c} = \frac{1-M^2}{1-M^2(1-M)} \quad \dots\dots\dots (2.11)$$

For two component anisotropic system, two expressions are proposed one for the K values as measured parallel to the fibre and second for K values as measured perpendicular to the fibre:

$$K_{\text{parallel}} = K_i [1 - N^2 (1 - K_s/K_i)] \quad \dots\dots\dots (2.12)$$

$$K_{\text{perpendicular}} = K_i \left( \frac{1 - Q''}{1 - Q''(1 - N)} \right) \quad \dots\dots\dots (2.13)$$

$$\text{Where } Q'' = \frac{N}{1 - K_s/K_i}$$

Earle (1966) has proposed the following expression for foods above freezing point:

$$K = \frac{0.55}{100} \times \% \text{water} + \frac{0.26}{100} (100 - \% \text{water}) \quad \dots\dots\dots (2.14)$$

Harper (1972) reported the following equation for estimating thermal conductivity of foods with water content W:

$$K = (0.5 + 0.005 W) K_{\text{water}} \quad \dots\dots\dots (2.15)$$

This equation includes temperature indirectly since the thermal conductivity of water varies with temperature.

Kolarov and Gromov (1973) reported that the thermal conductivities of fruit and vegetable juices may be estimated by an equation based on solids content, temperature and density. They proposed the following equation:

$$K = \frac{A}{B} \times \rho \times T \quad \dots\dots\dots (2.16)$$

Where A = A function of concentration

B = Temperature coefficient

The analytical expression developed was as follows:

$$K = \frac{(5.75 - 0.048 S) \times 10^{-4}}{(1.11 - 0.0036T)} \times (993 + 5S - 0.57)$$

Where, 'S' is total solid.

This equation has been suggested for determining K of all kinds of fruits and vegetable juices and syrups.

Fernandez-Martin and Montes (1972) developed a quadratic model to predict thermal conductivity of different types of milk for temperature from 5 to 75°C and solids content, 'S' up to 40%.

$$K = a_0 + a_1 S + (a_2 + a_3 S) T + (A_4 + a_5) T^2 \dots\dots\dots (2.17)$$

The coefficients a<sub>1</sub>, are listed in the Table 2.2.

**Table 2.2. Coefficients of equation 2.17 to predict dairy product's thermal conductivity**

| Type of milk | $a_0$ | $a_1 \times 10^2$ | $a_2 \times 10^2$ | $A_3 \times 10^4$ | $A_4 \times 10^4$ | $a_5 \times 10^6$ | Standard error |
|--------------|-------|-------------------|-------------------|-------------------|-------------------|-------------------|----------------|
| Skim         | 13.00 | -4.01             | 5.21              | -1.2              | -1.78             | 0.3               | 0.06           |
| 50% fat      | 12.61 | -4.92             | 7.24              | -15.6             | -3.23             | 11.2              | 0.1            |
| Whole        | 13.21 | -7.63             | 7.70              | -13.5             | -5.07             | 12.1              | 0.14           |

Thermal conductivities of dairy products and margarine were correlated by Sweat and Parmelee (1978), by means of a linear equation in water mass fraction  $W_w$

$$K = 0.141 + 0.412W_w \quad \dots\dots\dots (2.18)$$

Murdia (1982) developed following empirical equations to predict the thermal conductivity of some of the Indian dairy products such as *khoa*, *paneer*, *ghee* and also butter.

Thermal conductivity of butter at different temperature :

$$K = 3.5452 - 1.3421 \log T \quad \dots\dots\dots (2.19)$$

Thermal conductivity at various moisture levels of butter during manufacture of *ghee*:

$$K = 0.196276358 + 0.022682593 \log M \quad \dots\dots\dots (2.20)$$

Thermal conductivity of *paneer* made from buffaloes milk at various temperature:

$$K = 0.450435 - 0.006714T \quad \dots\dots\dots (2.21)$$

Thermal conductivity of *Khoa* at different moisture

$$K = 0.00356439 M + 0.223544 \quad \dots\dots\dots (2.22)$$

Jayakumar (1998) proposed the following equations for estimating the thermal conductivity of *khoa* and *paneer* as function of moisture and temperature :

For *khoa*:

$$K = 0.115 + 0.435 M + 0.0009T \quad \dots \quad (2.23)$$

For *Paneer* :

$$K = 0.603M + 0.00135T - 0.044 \quad \dots \quad (2.24)$$

Choi and Okos (1983) developed an equation for thermal conductivity of liquid foods as function of moisture, protein, carbohydrate, lipid and ash content. The equation developed was:

$$K = 0.61X_m + 0.20X_p + 0.205X_c + 0.175X_f + 0.135X_a \quad \dots \quad (2.25)$$

This equation was developed for liquid foods but it is also relatively accurate for solid foods.

Sweat (1995) developed an equation by using 430 data point for liquids and solids. The proposed equation was

$$K = 0.58X_m + 0.155X_p + 0.25X_c + 0.16X_f + 0.133X_a \quad \dots \quad (2.26)$$

### 2.2.2. Specific Heat

Specific heat is the amount of heat required to increase the temperature of 1 kg of material by 1°C at a given temperature. The ratio of the heat supplied  $Q$  to the corresponding temperature rise  $\Delta t$  is defined as the heat capacity of a body. Specific heat is the mass heat capacity,

defined as the heat capacity of a body per unit mass of the body.

$$C = \frac{Q}{(WV)\Delta t} \dots\dots\dots (2.27)$$

Where C is specific heat, W is specific weight and V is volume. Depending on the way in which heat is stored in the material, this thermal property can be given either as specific heat at constant volume denoted by  $C_v$ , or specific heat at constant pressure denoted by  $C_p$ . However, it is common to use the constant pressure specific heat,  $C_p$ . Foodstuffs are not an exception, as all processes involving them are carried out at that condition. The units of  $C_p$  is KJ/Kg°C or Kcal/Kg°C

### 2.2.2.1. Measurement of specific heat

Two common procedures for measurement of constant pressure specific heat are the method of mixture by calorimetry and the guarded plate method.

#### Method of mixtures

In this method the specimen at a known mass and temperature is dropped into a calorimeter of known specific heat is then computed from a heat balance equation between the heat gained or lost by the water and calorimeter and that lost or gained by the specimen.

#### Method of guarded-plate

In this method the specimen is surrounded by electrically heated thermal guard. This thermal guard is maintained at the same temperature as the specimen, which is also being heated electrically, and thus there is ideally no heat loss. In this case the electric heat supplied to the specimen in a given

time  $\theta$  is set equal to the heat gain by the specimen as given by the following expression:

$$Q = CW\Delta t = 3.41 VI\theta$$

$$C = \frac{3.41 V\theta}{W\Delta t} \quad \dots\dots\dots (2.28)$$

Where,  $V$  and  $I$  are respectively average voltage and current reading during time  $\theta$  hours and 3.41 is the conversion factor from watts to BTU/hr.

Hwang and Hayakawa (1979) present a good, simple technique for measuring specific heat with a vacuum calorimeter. The differential scanning calorimeter (DSC), if one is available, is recommended for measuring specific heat. It has been described briefly by Mohsenin (1980) and in more detail by Lund (1983).

Clark *et al.* (1946) for measurement of specific heats of vegetable oils used a calorimeter with a constant temperature bath. The specific heat was calculated from measurements of the weight of the oil, the actual temperature rise of the oil, and the heat energy supplied to the oil corrected for the heat capacity of the calorimeter.

Frechette *et al.* (1968) measured specific heat of McIntosh apple by using the method of mixtures. The Calorimetry tests resulted in a mean specific heat of 0.90 cal/g°C for the McIntosh apples.

Agrawal and Ojha (1973) reported that specific heat of concentrated whole milk varied between 0.6985 cal/g°C and

0.995 cal/g°C for temperatures ranging from 60°C to 90°C and for total solid ranging from 14 to 28 percent.

Reddy and Datta (1994) measured thermophysical properties of reconstituted milk during processing. Specific heat of milk samples were determined at concentration between 40 and 70% and at temperature of 35-65°C. and observed that increasing temperature and moisture content resulted in increased specific heat. Maximum specific heat was 3.350 KJ/Kg°C, minimum was 2.0 KJ/Kg°C at 70% concentration and 45°C.

Choi and Okos (1983) determined specific heat of tomato juice concentrates for concentration range of 4.8 percent to 80 percent solids and a temperature range of 20°C to 150°C. On the basis of available data they also formed an empirical equation for the specific heat.

Constenla *et al.* (1989) reported specific heat of apple juice of soluble solid in the range 6 to 75° Brix with temperature between 30 and 90°C. An empirical equation as a function of concentration of apple juice was also developed.

Unklesbay *et al.* (1992) determined specific heat of extruded beef/corn flour blends using a 1L Dewar flask with a plastic foam lid through which a thermo-couple (Type 'K') was placed to measured the equilibrium temperature after mixing the sample with water.

Gromov (1993) investigated the effects of temperature, diameter of casein molecules, DM content in curds and pH on the density, thermal conductivity and specific heat of casein during the drying process.

Mandhyan *et al.* (1994) studied about the effect of particle size, moisture content, pressure and temperature on specific heat of soybean. They studied that specific heat was mainly affected by moisture content and temperature.

Shen *et al.*, (1995) investigated specific heat of potato starch using DSC (Differential Scanning Calorimetry). They also found that series model best explained the heat transfer mechanism in gel.

Chaiwanichsiri *et al.* (1996) measured the specific heat of pineapples at high (60 to 100°C) and low (-10 to -30°C) temperature and at moisture content of 60-80% using a modified form of the method of mixture. At high temperature, the specific heat of the samples varied with temperature and moisture content while at sub-zero temperatures only dependence on moisture content was significant.

Muthukumarappan *et al.* (1997) measured the heat capacity of cheddar cheese and proposed a modeling equation for specific heat as a function of fat, protein and moisture.

#### **2.2.2.2. Prediction equations for specific heat**

Most specific heat prediction model for food systems are function of only water content (de dios Alvarado 1991, Gupta 1990). However the specific heats of protein, fats and carbohydrates differ from one another and therefore have variable effects on the specific heat of a composite food material (Sweat, 1995). Some models include different components food and express specific heat as a linear combination of the  $C_p$ 's of water, fat, protein, carbohydrate and/or ash (Oguntunde and Akintoye, 1991; Rahman, 1993).

An inverse relationship was obtained by Hammer and Johnson (1913) between specific heat and temperature of the specimen.

Siebel (1892) formula for the specific heat below and above freezing point is the earliest example expressed specific heat as a function of water content.

$$C_p = 0.2 + 0.008 (\text{moisture content, \%}) \dots\dots\dots (2.29)$$

Dickerson Jr. (1969) presented the following expression which has been used considerably in higher moisture food products, such as, fruit juices and meat products.

$$C_p = 0.4 + 0.006 (\text{water content, \%}) \dots\dots\dots (2.30)$$

The expression is consistent in the range of 26 to 100 percent moisture content.

Charm (1971) proposed the following model for prediction of specific heat of foods

$$C_p = 0.5 X_f + 0.3 X_s + 1.0 X_m \dots\dots\dots (2.31)$$

Where,  $X_f$ ,  $X_s$ , and  $X_m$  are the mass fractions of fat, solids and water content of the food sample.

The above concept can be expended further to incorporate specific heat of even more basic components of the product such as protein, carbohydrate etc., to give the following expression:

$$C_p = 0.34 X_c + 0.37 X_p + 0.4 X_f + 0.2 X_a + 1.0 X_m \dots\dots\dots (2.32)$$

Heldman and Singh (1981) proposed the following model on the similar pattern for the specific heat calculation of foods:

$$C_P = 1.424X_C + 1.549X_P + 1.675X_r + 0.837X_a + 4.187X_m \dots (2.33)$$

Choi and Okos (1983a) formulated the following empirical equation to determine the specific heat of tomato juice

$$C_P = C_{P_s} X_s + C_{P_m} X_m \dots \dots \dots (2.34)$$

Choi and Okos (1983b) prescribed another empirical equation based on the same compositions used by Heldman and Singh (1981) for a wide range of food products but this model is well below an "engineering accuracy" of 2-5%.

$$C_P = 4.180 X_m + 1.711X_p + 1.928X_r + 1.547X_C + 0.908X_a \dots (2.35)$$

Constenla *et al.* (1989) reported an empirical equation for the specific heat of apple juice as a function of concentration and temperature. The equation was as follows:

$$C_P = 0.80839 - 4.3416 \times 10^{-3} X + 5.6063 \times 10^{-4} T \dots \dots \dots (2.36)$$

Where X = concentration of juice.

**2.2.3. Thermal diffusivity**

*Thermal diffusivity* can be defined as the thermal conductivity divided by the product of specific heat and mass density. Thermal diffusivity is used in the determination of

heat transfer rates in solid food objects of any shape. In physical terms, thermal diffusivity gives a measure of how quickly the temperature will change when it is heated or cooled. Materials with a high thermal diffusivity will heat or cool quickly, conversely, substances with a low thermal diffusivity will heat or cool slowly. Thus, thermal diffusivity is an important property when considering unsteady-state heat transfer situations.

**2.2.3.1. Measurement of thermal diffusivity**

There are two general approaches to the problem of measuring thermal diffusivity. It may be calculated from the relation :

$$\alpha = K / \rho C_p \quad \dots\dots\dots (2.37)$$

Where,  $\alpha$  = thermal diffusivity;  $K$  = thermal conductivity;  
 $\rho C_p$  = volumetric heat capacity

or it may be measured directly.

In the first approach, thermal conductivity, density and specific heat may be evaluated by either transient or steady-state methods. Since thermal conductivity, density and specific heat values are not generally available for foods, and each property represents a separate determination at several temperatures, a direct measurement of thermal diffusivity is preferred.

Dickerson (1965) described an apparatus based on transient heat transfer conditions requiring only a time temperature data. The apparatus consists of an agitated water bath in which a cylinder with high thermal conductivity

containing the sample was immersed. One thermocouple is placed at the surface of cylinder and one thermocouple is placed at the centre of the cylinder. The cylinder is placed in the agitated water bath and the time-temperature is recorded. Under the condition of constant temperature rise, the Fourier's equation can simplify in the following form

$$\alpha = \frac{AR^2}{4(T_0 - T_c)} \dots\dots\dots (2.38)$$

Where,  $\alpha$  is the thermal diffusivity of the sample ( $m^2/sec$ ),  $R$  is the radius of cylinder ( $m$ ),  $T_0$  and  $T_c$  are temperature ( $^\circ C$ ) of outside and centre of cylinder.

Jakob (1949) stated that the main handicap of the transient methods is to define and satisfy the boundary conditions and measure the varying temperature with sufficient accuracy. The advantages of the transient methods, however, are impressive. Generally, no heat flow measurements are required. In addition, the heat flow that causes the changing temperatures is usually large enough to completely overshadow heat exchange with the environment.

Nix *et al.* (1967) determined thermal diffusivity with the line heat source using an additional thermocouple in the sample at a known distance from the line heat source.

Hayakawa (1972) discussed a computer aided method to determine apparent thermal diffusivity of food for heat condition expressed in cylindrical coordinates. Hayakawa and Bakal (1973) used a sample of an infinite slab geometry to predict thermal diffusivity. Computational Program prepared by them may be used whenever the assumptions, which are imposed to derive the theoretical formulas of heat conduction are satisfied. Great advantages of the developed procedure

are that sample food can be exposed to any time variable heating or cooling temperature and there is no need for monitoring surface temperatures.

Uno and Hayakawa (1980) developed a procedure to estimate thermal diffusivity. This method was applied to temperature data collected from heat transfer experiments. Gaffney *et al.* (1980) measured thermal diffusivity via a transient heating computer technique.

Choi and Okos (1983a) measured thermal diffusivity via a line heat source thermal conductivity probe with an auxiliary thermocouple. This technique is good for liquid foods, where the distance between the line heat source probe and the auxiliary thermocouple (on a second probe) is fixed. Because its results are quite sensitive to the distance between the probes, this technique is limited to applications where the distance between the probes does not vary or can be precisely measured.

Andrieu *et al.* (1986) presented the pulse method applied to foodstuffs. The sample, shaped as a slab or disk, with parallel faces is submitted to an energy pulse on one of its faces, for a very short time, by means of a flash lamp, capable of delivering about 800 J in 0.01S. The temperature rise of the opposite face is recorded. Thermograms of reduced temperature Vs times give parameters which lead to the calculation of  $\alpha$  by simple relationship.

Sanz *et al.* (1987) listed various literature values of thermal diffusivity of meat products at different temperature and compositions. Unklesbay *et al.* (1992) determined thermal diffusivity value of the extruded products varied over a relatively narrow range. They also reported that water

content, temperature, composition and porosity were the major factors affecting thermal diffusivity.

Thomareis and Hardy (1992) studied about thermal diffusivity of processed cheeses by using the method of the infinite cylinder. A prediction model was developed to describe the thermal diffusivity of processed cheeses if their composition and temperature are known. Muthukumarappan *et al.* (1997) calculated thermal diffusivity value of cheddar cheese and suggested an empirical equation for thermal diffusivity based on moisture, fat and protein.

Pasqualone and Mastandrea (1995) measured thermal diffusivity of various animal foods like beef, pork, fish, octopus, whole milk, skim milk and butter over the temperature range  $-1$  to  $-40^{\circ}\text{C}$ . Tsai *et al.* (1998) reported that thermal diffusivity of beef products ranged from  $1.25 \times 10^{-7}$  to  $1.322 \times 10^{-7} \text{ m}^2/\text{sec}$ .

#### **2.2.3.2. Prediction equations for thermal diffusivity**

Thermal diffusivity is a measure of how quickly a substance will change its temperature during heating or cooling process. Factors that are likely to affect the temperature rise are the temperature of the heating medium, the thermal conductivity of the food and the specific heat value. This thermal diffusivity value can be expressed in terms of different models and some of them are discussed below:

Olson and Schultz (1942) have shown that a simulation of the mathematical model for a cylinder of finite length and diameter is possible if the length to diameter ratio ( $L/D$ ) is greater than 4.

Riedel (1969) describes the prediction model of thermal diffusivity as a function of water content. This expression encompasses a wider range of food products.

$$\alpha = 0.088 \times 10^{-6} + (a_w - 0.088 \times 10^{-6})M \quad \dots\dots\dots (2.39)$$

Where  $a_w$  is the water activity and  $M$  is the moisture content of food.

Dickerson and Read (1975) used the above model and found good agreement with experimental values of thermal diffusivity for a variety of meats.

Martens (1980) investigated the influence of water, fat, protein, carbohydrate and temperature on thermal diffusivity and reported that temperature and water content are the major factors affecting thermal diffusivity. Solid, fat, carbohydrate, protein had a small influence on thermal diffusivity. He also developed a prediction model on the basis of water content and temperature for variety of food products.

$$\alpha = 0.057363M + 0.000288 (T+273) \times 10^{-6} \quad \dots\dots\dots (2.40)$$

Choi and Okos (1983) expressed thermal diffusivity of tomato juice, assuming a linear relation of soluble solids suspension on thermal diffusivity:

$$\alpha = \alpha_s X_s + \alpha_m X_m \quad \dots\dots\dots (2.41)$$

Where,  $X_s$ ,  $X_m$  are mass fraction of solid and water.  $\alpha_s$ ,  $\alpha_m$  are thermal diffusivity of solid and water

They also expressed thermal diffusivity of pure tomato solids as a function of temperature in the following form:

$$\alpha = A + BT + CT^2 \quad \dots\dots\dots (2.42)$$

Where, A,B,C are constants.

On thorough review of literature, it is observed that no attempts have been made so far to investigate the thermal properties of *chhana*. The present study was therefore carried out to collect the engineering data on the thermal properties of *chhana* and to develop prediction equations for these thermal properties.

# **CHAPTER-3**

## ***MATERIALS AND METHODS***

## 3. MATERIALS AND METHODS

---

### 3.1. PREPARATION OF *CHHANA*

For preparation of *chhana* 20 litre of cow milk was heated in a stainless steel jacketed-kettle. The stirring-cum-scraping of milk was constantly done with a ladle or khunti. As soon as the milk reached first boil, the steam supply to jacketed kettle was stopped and milk was allowed to cool to 70°C. Coagulant solution was added at this temperature in a thin stream and while addition of coagulant a slow stirring with ladle was done so as to avoid foam formation. When milk was coagulated completely which could be identified by seeing the clear whey and solid mass, the addition of coagulant was stopped. The coagulated mass was then allowed to precipitate. Solid mass was then removed by straining through a muslin cloth immediately. The delay in straining causes the *chhana* to retain more moisture. The cloth containing the coagulated solids was then removed, tied up into a bundle without pressure and hung up to drain out the whey completely and to allow the cooling of the *chhana-pat*.

#### 3.1.1. Preparation of Coagulant

Citric acid (LR Type 99.5%, Assay) was used as a coagulant. Normally 2.5g citric acid is required to coagulate 1 kg of milk. On the basis of requirement as per the quantity

of milk, citric acid was taken and made into 1 percent coagulating acid solution. The solution was heated to 70°C before adding it to the milk.

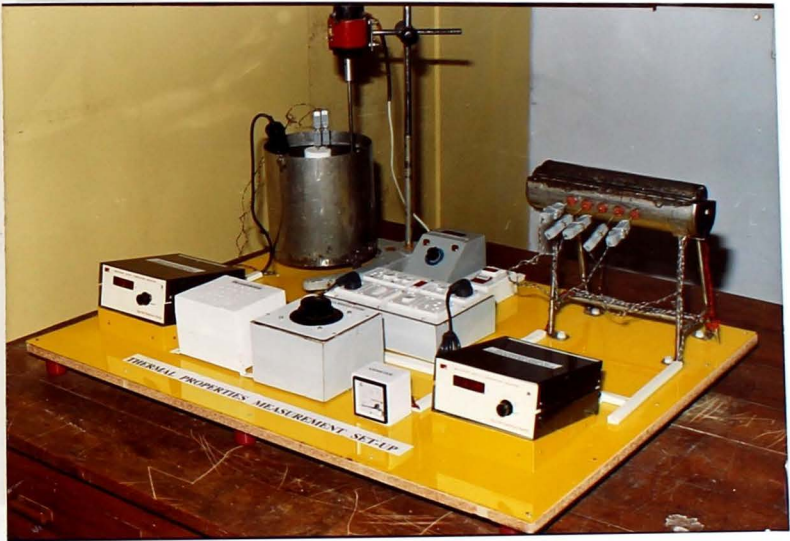
### **3.1.2. Changing the Compositions of *Chhana***

The main constituents of *chhana*, viz., moisture content, protein and fat percentage was changed to study the effect of compositions on thermal properties. Moisture content in *chhana* was varied by effecting the delay in coagulant mass and by altering the hung up time. Delay in time of straining after the coagulation of milk increased the moisture percentage in *chhana*. Also the increase hung up time of *chhana* in the muslin cloth decreased the moisture of *chhana*. Above two methods were followed to change the moisture contents in the *chhana* sample. The protein and fat content of *chhana* was varied by adding skim milk powder to the whole milk at 40°C at various levels before processing the milk into *chhana*. During measurement of thermal properties of *chhana* temperature, moisture, fat and protein content varied in the range of 33-56°C, 57-59%, 16-25%, 17-25% respectively.

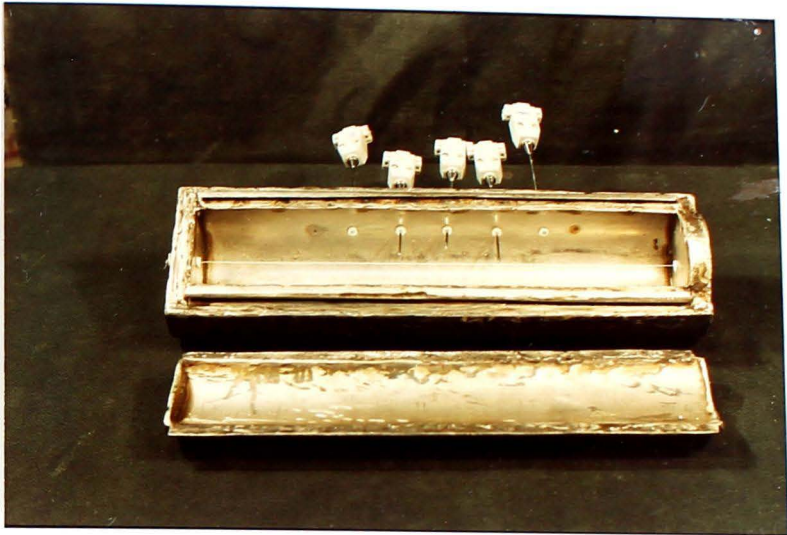
## **3.2. MEASUREMENT OF THERMAL CONDUCTIVITY OF CHHANA**

### **3.2.1. Experimental Set-up**

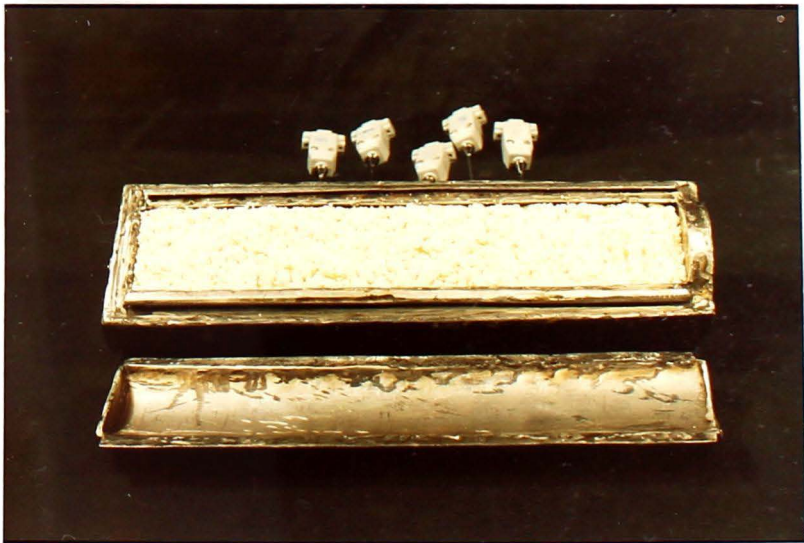
Thermal conductivity of *chhana* was measured on the basis of 'line heat source' method, one of the most common transient methods. The schematic diagram of the experimental set-up is in Fig. 3.1 and Fig. 3.2. The set-up consists of sample holder, a transformer, voltage regulator, ammeter, digital temperature indicator and thermocouples.



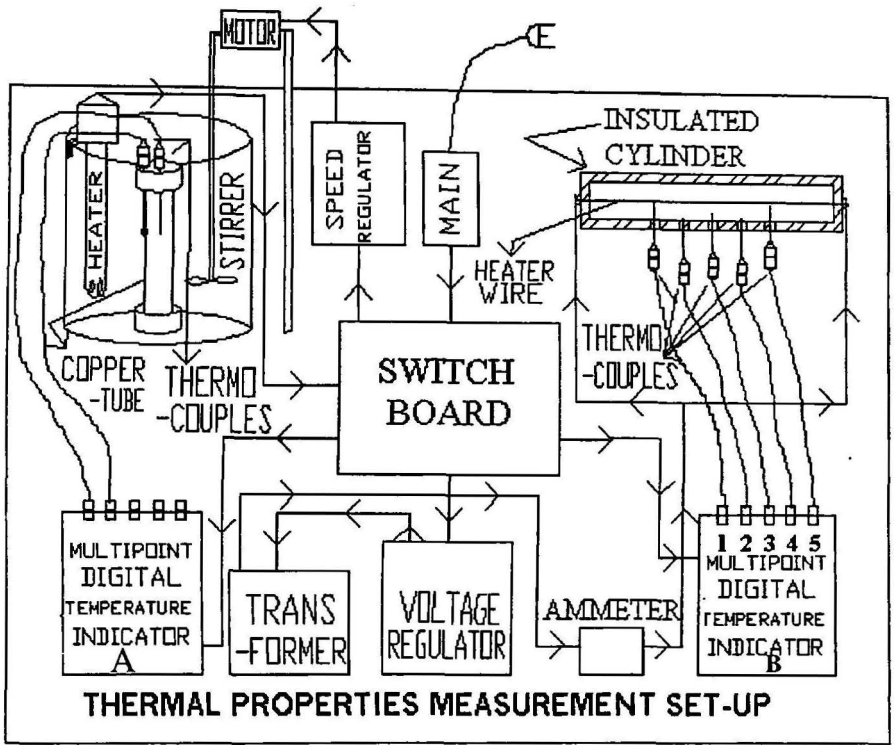
**Plate-3.1. Experimental set-up for thermal properties measurement**



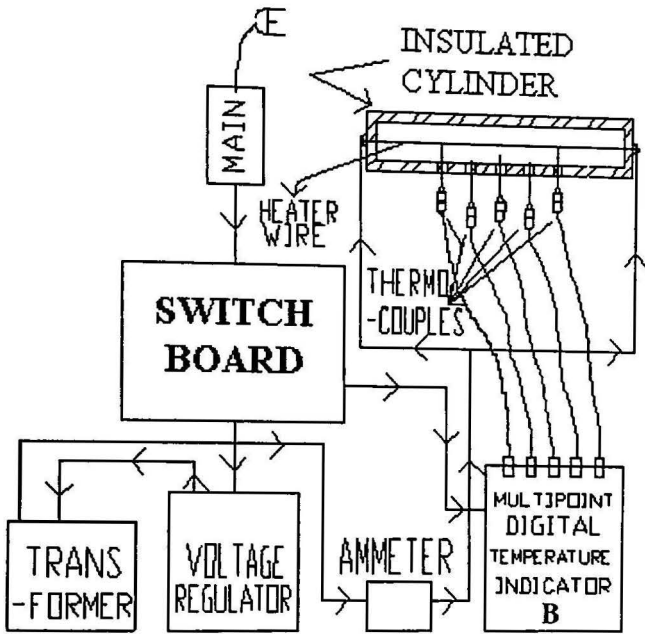
**Plate-3.2. Sample holder for thermal conductivity measurement**



**Plate-3.3. Sample holder with *chhana* for thermal conductivity measurement**



**FIG-3.1: SCHEMATIC DIAGRAM OF THERMAL PROPERTIES MEASUREMENT SET-UP**



**FIG-3.2: SCHEMATIC DIAGRAM OF THERMAL CONDUCTIVITY MEASUREMENT SET-UP**

The cylindrical sample holder (Length 35cm, Dia 3.5cm) was made of stainless steel. It was jacketed with S.S. plate, inside which there was glass-wool of thickness 1cm to prevent the heat loss from the sample holder to the outside. Sample holder has two parts. Upper part could be dislodged and after placing the sample in lower part again upper part could be fixed with the lower part. 1.2 kg *chhana* was required to fill the sample holder. Five holes were made at the surface of sample holder body for inserting thermocouples. One cubic Teflon block ( $1 \times 1 \times 1 \text{cm}^3$ ) was provided in each hole. Each Teflon block had a hole equal to the diameter of the thermocouples through which the thermocouples were inserted. 1, 2, 3, 4, 5 marking on the multipoint digital temperature indicator (B) represent the positions of thermocouples as B/1, B/2, B/3, B/4, B/5, respectively. Two Teflon blocks ( $1 \times 1 \times 1 \text{cm}^3$ ) were also placed at the centre of both end plates of the cylindrical sample holder. Insulated Nichrome heater wire (37gauge) used as a heating element placed at the centre of the sample holder and passed through these Teflon blocks. Both ends of heater wire were naked and tied with the screw, attached with Teflon blocks. The heater wire was tightened by rotating the screw in such a way that it remained straight even after placing the sample in the sample holder.

An electrical circuit was made in such a manner that current was passed through the main switch, distributor switch board, voltage regulator, transformer and ammeter respectively. The output current, which was regulated by voltage regulator and measured by ammeter, was connected with the both ends of heater wire. Five thermocouples. B/1, B/2, B/3, B/4, B/5 were inserted through their corresponding holes. End points of all thermocouples were connected with the multipoint digital temperature indicator. Temperature of the

different thermocouples was measured by rotating the selector switch of multipoint digital temperature indicator.

### **3.2.2. Measurement of Resistance of Heater Wire**

Accurate measurement of resistance of heater wire is critical as the same is to be used for calculation of thermal conductivity. The Nichrome wire was straightened and brought to the working temperature range. The terminals were then connected to the Standard Motwane multimeter which directly showed the value of the resistance in ohms for the given length of the wire. The determined value was counter checked with the values given in the literature.

### **3.2.3. Measurement of Temperature**

Thermocouples were used to measure the temperature at various locations in the sample container at any instant of time. Copper-constantan ('T' type) thermocouple with a temperature range of  $-200^{\circ}\text{C}$  to  $371^{\circ}\text{C}$  were used. The leads of all thermocouples were connected to the multipoint digital temperature indicator. Temperature of different location could be read by rotating the selector switch of the multipoint temperature indicator.

### **3.2.4. Calibration of Thermocouples**

Calibration of thermocouples were done before starting every experiment. For this purpose all the thermocouples were dipped in a beaker containing tap water. If there was any difference of temperature, indicated by digital temperature indicator, with the calibrated mercury thermometer which was also dipped in the same water then that particular thermocouple(s) was calibrated. If there was no difference of temperature then no calibration was required. For calibrating

the thermocouple, it was dipped in ice and adjusted to 0°C by rotating the adjusting screw (zero), dipped in the boiling water and adjusted to 100°C by rotating the adjusting screw (span). After that thermocouple indicated actual temperature.

### **3.2.5. Location of Thermocouples**

To measure the temperature distribution throughout the sample, thermocouples were inserted into their respective inserting holes in the sample holder. Thermocouples B/1 and B/5 were placed near to the heater wire at a distance of 2mm. Thermocouples B/2 and B/4 were placed near to the surface of the sample holder at a distance of 2mm from inside surface. Thermocouple B/3 was placed between the heater wire and surface of the sample holder at a distance of 15mm from heater wire.

### **3.2.6. Experimental Procedure**

The *chhana* was filled in the sample holder in such a way that there was no air gap in the sample and such that heater wire remained straight even after placing the sample. The upper part of the sample holder was fitted. The thermocouples, were inserted at their predetermined location in the sample. Regulated the voltage supply to adjust the current at 0.5amp. The temperature of different thermocouples were recorded after every 10 sec. interval. The experiment was terminated as soon as the temperature of B/2 and B/4 thermocouples placed near to the sample holder surface changed. Current was then increased to 0.6amp and recorded the temperature after every 10 sec. interval. Experiments were repeated by changing the composition of *chhana*.

### 3.2.7. Calculation of Thermal Conductivity

The line heat source technique utilizes a constant heat source to an infinite solid along a line with infinitesimal diameter, such as a thin resistant Nichrome wire. Having the heat source imbedded in the mass of material whose conductivity is to be measured, the line-source is energized and the temperature rise at a given distance from source is measured after a short heating time. The rate of rise in temperature of the specimen is then a function of thermal conductivity of the material. The equation used for calculating thermal conductivity is reduced to the following form:

$$K = \frac{I^2 R \times 2.3}{4\pi \times (\text{slope of log. time vs. temperature})} \quad \text{-----} \quad (3.1)$$

Where,

I = Current (amp)

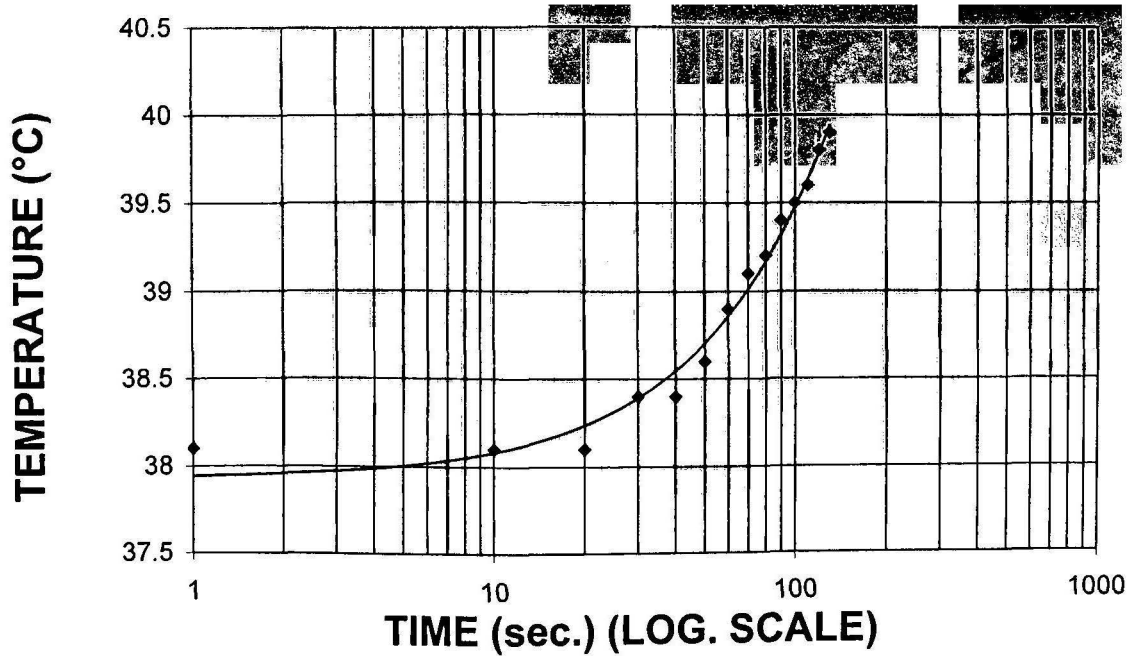
R = Resistance (ohm)

Log time vs temperature curve is plotted. Compared to transient heat transfer point; slope of linear portion is determined which is shown in Fig-3.3 & Fig-3.4.

## 3.3. MEASUREMENT OF SPECIFIC HEAT OF *CHHANA*

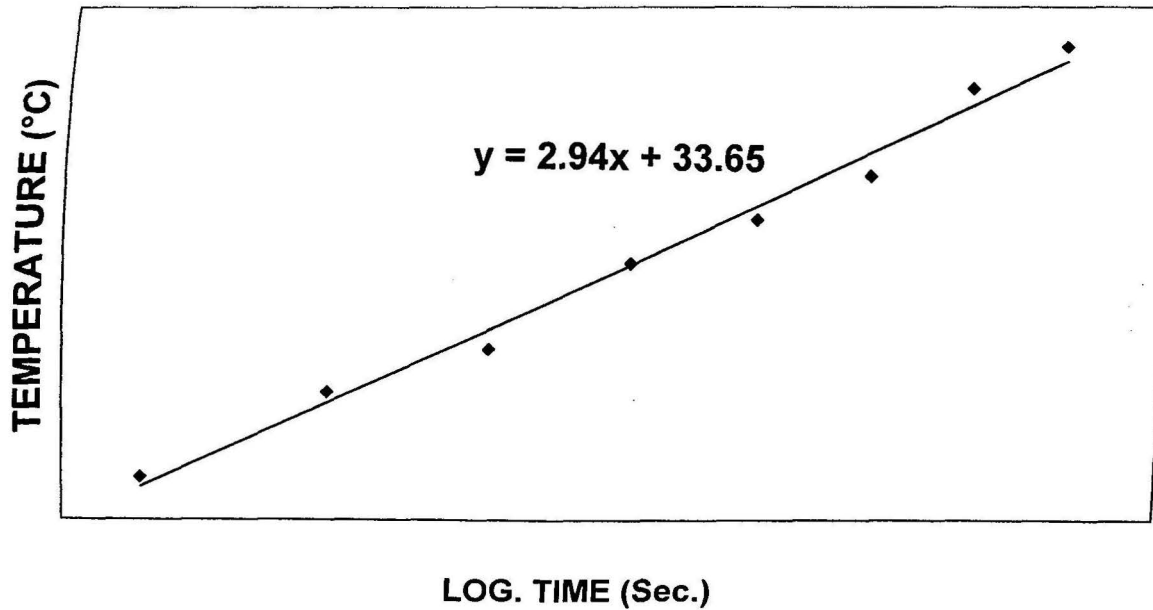
### 3.3.1. Experimental Procedure

Specific heat of *chhana* was measured on the basis of 'method of mixtures' in a vacuum jacketed calorimeter. Water was taken as a reference liquid whose specific heat is 1 cal/g°C. Weight and temperature of water was recorded before transferring into the calorimeter. Process was repeated for



Moisture:55.2%, Fat: 23.2% , Protein:17.8%,Temperature:40°C

**FIG-3.3.: LOG. TIME vs TEMPERATURE FOR THERMAL CONDUCTIVITY CALCULATION**



**Moisture:55.2%, Fat: 23.2%, Protein:17.8%, Temperature: 40°c**

**FIG-3.4: LOG. TIME Vs. TEMPERATURE (LINEAR PORTION)**

chhana. Temperature of mixture was recorded on attaining equilibrium.

### 3.3.2. Calculation of Specific Heat

Specific heat was calculated by using the following relationship:

$$C_P = \frac{W_w C_{P_w} (T_2 - T_e)}{W_g (T_e - T_1)} - \frac{W_{eq}}{W_g} \dots\dots\dots (3.2.)$$

Where,

- $T_2$  = Temperature of hot water
- $T_1$  = Temperature of sample
- $T_e$  = Equilibrium temperature of mixtures
- $W_g$  = Weight of sample

$$W_{eq} = \frac{W_w C_{P_w} (T_i - T_e)}{T_i - T_2} \dots\dots\dots (3.3.)$$

Where,

- $W_w$  = Weight of water
- $C_{P_w}$  = Specific heat of water
- $T_i$  = Initial temperature of water
- $T_2$  = Initial temperature of calorimeter
- $T_e$  = Equilibrium temperature

### **3.4. MEASUREMENT OF THERMAL DIFFUSIVITY**

#### **3.4.1. Experimental Set-up**

Experimental apparatus described by Dickerson (1965) was used to measure thermal diffusivity of *chhana*. The set-up is based on transient heat transfer conditions requiring only time-temperature data.

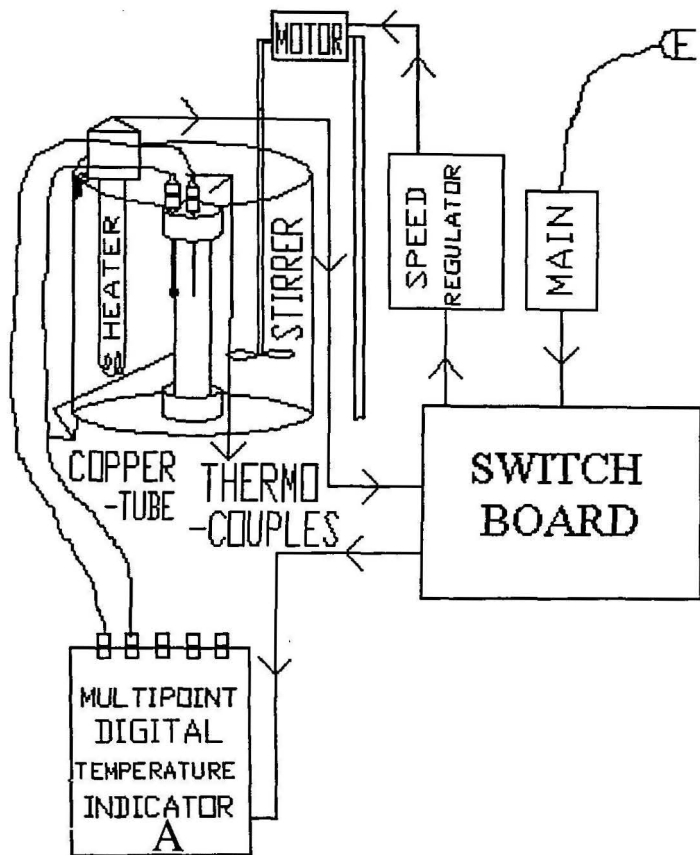
Experimental set-up of thermal diffusivity is shown in the Fig-3.1 and Fig-3.5. The apparatus consists of thermal diffusivity tube, two thermocouples alongwith multipoint digital temperature indicator, immersion rod water heater, stirrer, water bath. Diffusivity tube along with top and bottom Teflon cap was placed at the centre of the cylindrical (Dia. 10" and Length 10") water bath. Water was agitated with the help of stirrer whose speed can be regulated by speed regulator. Heater was provided to heat the water. One of the thermocouples was placed at the centre of the diffusivity tube and the other at the surface of the tube. Both thermocouples were connected with the digital temperature indicator.

#### **3.4.2. Diffusivity Tube**

Diffusivity tube is generally made of high thermal conductivity material. Copper tube (Dia. 3.8cm, Length 20.5cm) was used as diffusivity tube. The both ends of the tube were attached with caps, made of Teflon.

#### **3.4.3. Experimental Procedure**

Diffusivity tube was inserted in the bottom cap. Sample was filled in the tube with a uniform rate. Thermocouples were inserted to full immersion to ensure proper radial positioning. The tube was placed in the agitated water bath and temperature of both outside and inside of tube was measured



**FIG-3.5: SCHEMATIC DIAGRAM OF THERMAL DIFFUSIVITY MEASUREMENT SET-UP**

with one minute interval until a constant rate of temperature rise was obtained for both inner and outer thermocouples. The constant temperature difference between outer and inner thermocouple was used for calculation of thermal diffusivity. The time-temperature graph indicates the constant temperature difference is shown in Fig-3.6.

### 3.4.4. Calculation of thermal diffusivity

Under the condition of constant temperature rise, the Fourier's equation for radial temperature gradient exists (Eq.3.4) was used to calculate thermal diffusivity:

$$\frac{A}{\alpha} = \frac{\delta^2 t}{\delta r^2} + \frac{1}{r} \times \frac{\delta t}{\delta r} \quad \text{-----} \quad (3.4)$$

Where A equals the constant rate of temperature rise at the outside surface of cylinder. Since temperature gradient is no longer time dependent in Eq.(3.4)  $\delta^2$  can be changed to  $d^2$  with the following solution:

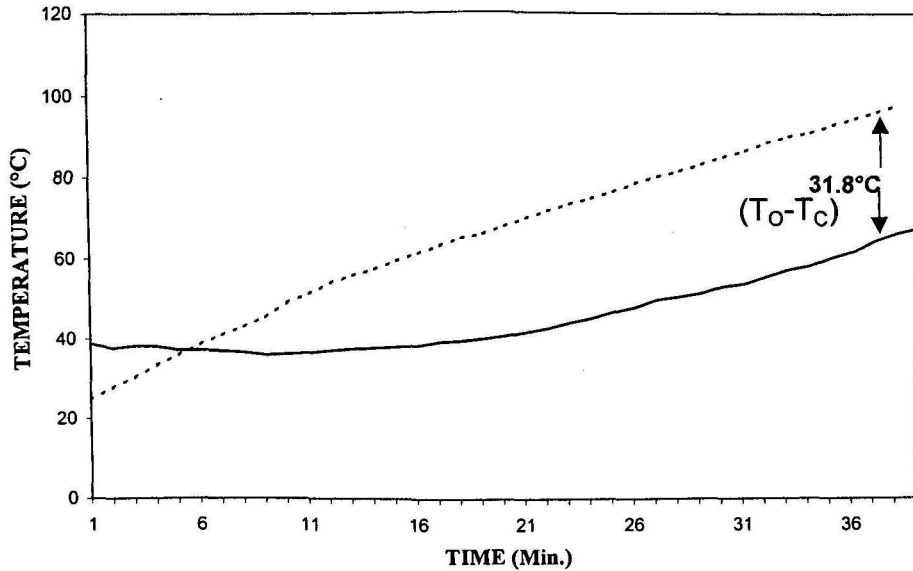
$$t = \frac{Ar^2}{4\alpha} + C_1 \ln(r) + C_2$$

Outside surface and centre temperature  $T_o$  and  $T_c$  for the boundary conditions of

$$\begin{aligned} t + A6 &= T_o, & \delta > 0, & \quad r = R \\ \frac{dt}{dr} &= 0, & \delta > 0, & \quad r = r \end{aligned}$$

The solution reduces to:

$$(T_o - T_c) = \frac{A}{4\alpha} (R^2 - r^2)$$



-----Temperature of outside surface ( $T_O$ ) — Temperature of centre of tube ( $T_C$ )

Moisture: 54.27%, Fat: 23.44%, Protein: 17.88%, Temperature: 42°C

**FIG-3.6: TIME VS. TEMPERATURE CURVE FOR THERMAL DIFFUSIVITY MEASUREMENT**

Taking  $r = 0$

$$\text{Thermal diffusivity } (\alpha) = \frac{AR^2}{4(T_o - T_c)} \text{ ----- (3.5)}$$

Constant temperature difference ( $T_o - T_c$ ), which was derived from the graph plotted time Vs. temperature, (Fig. 3.6) was used for calculation of thermal diffusivity.

### 3.5. ANALYTICAL METHODS

#### 3.5.1. Determination of Moisture Content of *Chhana*

Moisture content was determined by the modified, Gravimetric method used for cheese (IS:4079)

Weighed 2gm of grated *chhana* into a dish previously dried and weighed. Heated the dish containing *chhana* in the oven at  $102 \pm 1^\circ\text{C}$  for four hours. Cooled in the desiccator and weighed. Repeated the process of drying, cooling and weighing at 30 minutes interval until the difference between the two consecutive weighing were less than 0.01 mg.. Recorded the lowest weight.

$$\text{Percent moisture} = \frac{(W_1 - W_2) \times 100}{(W_1 - W)} \text{ ..... (3.6)}$$

Where,

$W_1$  = Weight in gm of the dish with *chhana* before drying.

$W_2$  = Weight in gm of the dish with *Chhana* after drying

$W$  = Weight in gm of the empty dish

### 3.5.2. Determination of Protein Content in *Chhana*

The total protein content of *chhana* was determined by Micro Kjeldahl method (Mennefee and Overman, 1940) using Kjeltex Automatic Digester and Distillation equipment.

200mg sample was weighed on a aluminium foil and transferred to a clean, dry digestion tube. Digestion tablet (1.5g K<sub>2</sub>SO<sub>4</sub> and 0.0075 gm Se) was added to the tube followed by 5ml H<sub>2</sub>SO<sub>4</sub> from the dispenser of the apparatus. The tube contents being mixed carefully by swirling the tube. The digestion tube placed in a stand was fitted into the digester and digestion carried out till the foaming stopped (usually taking 100-120min). The stand along with the tube(s) was removed and placed in a cooling stand. Distillation was then carried out in the kjeltex 1026 distillation unit selecting the programme for appropriate levels of alkali, i.e., 50 percent NaOH (2 strokes : 50ml), delay time (0.7min), steam time (4.7min) and prefixed dilution volume, and using 25ml boric acid solution. The distillate in the receiver flask was titrated with N/50 HCl to neutral gray. Similarly, a blank determination was carried out and percent nitrogen calculated as under:

$$\text{Total Nitrogen \%} = \frac{(S-B) \times N \times 14.007 \times 100}{W} \dots\dots (3.7)$$

Where,

S = ml of HCl required for sample

B = ml of HCl required for blank

N = Normality of HCl used, and

W = Weight of sample in mg.

Percent total protein = Percent Total Nitrogen x 6.38

### **3.5.3. Determination of Fat Content of *Chhana***

Fat content was determined by Gerber method used for cheese described in SP : 18 (Part XI) 1981. 3 gm of grated *chhana* was taken in the cheese butyrometer (3gm). 5ml of water (60°C) was added to make a dilute mixture. Then it was cooled with the tap water. Followed by 10ml of Gerber acid (Conc. Sulphuric acid) was added to the mixture. When it was completely mixed, 1ml of Amyl Alcohol was added. To make up the proper volume in the butyrometer, required amount of water was added. Then mixed the solution very carefully. Then it was centrifuged (1200rpm) for 5 min. Whatever fat percent was showed, that was the fat percent of the sample.

# **CHAPTER-4**

## ***RESULTS AND DISCUSSION***

## 4. RESULTS AND DISCUSSION

---

Results of the experimentation and their discussions have reported under the following sub heading:

- 4.1. Thermal properties of *chhana*
- 4.2. Effect of temperature on thermal properties of *chhana*
- 4.3. Effect of compositions on thermal properties of *chhana*
- 4.4. Modelling of thermal properties of *chhana*

### 4.1. THERMAL PROPERTIES OF *CHHANA*

The values of thermal conductivity of *chhana* determined for different product compositions and temperature of measurement have been presented in Table-4.1. Thermal conductivity of *chhana* varied from 0.331 to 0.442 w/m°C under the experimental range of measurements.

The values of specific heat of *chhana* calculated for different product compositions and temperature of measurement have been presented in Table-4.2. Specific heat of *chhana* varied from 0.662 to 0.725 cal/g°C under the experimental range of measurements.

The values of thermal diffusivity of *chhana* determined for different product compositions and temperature of measurement have been presented in Table-4.3. Thermal

**TABLE-4.1: THERMAL CONDUCTIVITY OF CHHANA AT VARIOUS CONDITIONS**

| Temperature (°C) | Moisture (%) | Fat (%) | Protein (%) | Thermal Conductivity (w/m°C) |           | Error   | % Error |
|------------------|--------------|---------|-------------|------------------------------|-----------|---------|---------|
|                  |              |         |             | Experimental                 | Predicted |         |         |
| 41.2             | 52.746       | 22.605  | 20.648      | 0.331                        | 0.332     | -0.0009 | -0.261  |
| 46.0             | 53.068       | 25.088  | 18.145      | 0.345                        | 0.352     | -0.0071 | -2.075  |
| 40.0             | 54.276       | 24.000  | 17.884      | 0.341                        | 0.341     | -0.0003 | -0.095  |
| 44.4             | 50.608       | 24.075  | 20.982      | 0.335                        | 0.324     | 0.0114  | 3.388   |
| 40.2             | 53.026       | 23.030  | 21.098      | 0.354                        | 0.347     | 0.0065  | 1.846   |
| 40.0             | 57.422       | 18.010  | 20.027      | 0.383                        | 0.392     | -0.0083 | -2.170  |
| 45.0             | 57.757       | 18.264  | 20.050      | 0.400                        | 0.416     | -0.0159 | -3.980  |
| 41.5             | 53.179       | 16.929  | 25.897      | 0.380                        | 0.375     | 0.0051  | 1.354   |
| 43.4             | 59.639       | 18.790  | 18.183      | 0.432                        | 0.422     | 0.0107  | 2.465   |
| 46.7             | 58.351       | 18.935  | 19.214      | 0.442                        | 0.426     | 0.0163  | 3.679   |

**TABLE-4.2: SPECIFIC HEAT OF CHHANA AT VARIOUS CONDITIONS**

| Temperature<br>(°C) | Moisture<br>(%) | Fat<br>(%) | Protein<br>(%) | Specific Heat<br>(cal/g.°C) |           | Error   | % Error |
|---------------------|-----------------|------------|----------------|-----------------------------|-----------|---------|---------|
|                     |                 |            |                | Experimental                | Predicted |         |         |
| 56.0                | 51.757          | 18.864     | 24.550         | 0.662                       | 0.6656    | -0.0030 | -0.457  |
| 55.5                | 50.608          | 24.075     | 20.982         | 0.663                       | 0.6629    | -0.0001 | -0.012  |
| 50.0                | 54.276          | 23.440     | 17.884         | 0.690                       | 0.6807    | 0.0094  | 1.362   |
| 54.5                | 52.446          | 22.605     | 20.448         | 0.695                       | 0.6790    | 0.0156  | 2.248   |
| 53.0                | 54.044          | 24.123     | 18.000         | 0.695                       | 0.6987    | -0.0040 | -0.570  |
| 51.5                | 59.639          | 18.790     | 18.183         | 0.697                       | 0.7145    | -0.0172 | -2.463  |
| 50.0                | 55.757          | 18.864     | 20.550         | 0.704                       | 0.7079    | -0.0035 | -0.492  |
| 49.5                | 52.768          | 25.088     | 18.145         | 0.707                       | 0.6892    | 0.0176  | 2.495   |
| 52.0                | 56.049          | 19.000     | 21.356         | 0.716                       | 0.7120    | 0.0043  | 0.606   |
| 46.0                | 57.049          | 18.873     | 20.348         | 0.725                       | 0.7245    | 0.0005  | 0.065   |

**TABLE-4.3: THERMAL DIFFUSIVITY OF CHHANA AT VARIOUS CONDITIONS**

| Temperature (°C) | Moisture (%) | Fat (%) | Protein (%) | Thermal Diffusivity (m <sup>2</sup> /sec.)X10 <sup>-7</sup> |           | Error     | % Error |
|------------------|--------------|---------|-------------|---|-----------|-----------|---------|
|                  |              |         |             | Experimental  | Predicted |           |         |
| 33.0             | 53.179       | 16.929  | 25.897      | 0.925   | 0.907     | 1.78E-02  | 1.930   |
| 36.0             | 57.422       | 15.751  | 21.727      | 0.949   | 0.930     | 1.82E-02  | 1.914   |
| 38.2             | 59.639       | 18.790  | 18.183      | 0.961   | 0.978     | -1.73E-02 | -1.803  |
| 38.0             | 51.757       | 18.864  | 24.550      | 0.987   | 1.001     | -1.44E-02 | -1.459  |
| 40.2             | 57.526       | 18.830  | 18.898      | 0.989   | 1.005     | -1.61E-02 | -1.629  |
| 42.0             | 54.276       | 23.440  | 17.884      | 0.999   | 0.999     | 7.50E-04  | 0.075   |
| 44.3             | 52.351       | 25.935  | 18.214      | 1.073   | 1.079     | -5.77E-03 | -0.538  |
| 44.4             | 50.608       | 24.075  | 20.982      | 1.085   | 1.115     | -3.09E-02 | -2.848  |
| 46.0             | 52.768       | 25.088  | 18.145      | 1.170   | 1.130     | 3.98E-02  | 3.404   |
| 45.7             | 52.446       | 22.605  | 20.448      | 1.176   | 1.168     | 7.90E-03  | 0.672   |

diffusivity of *chhana* varied from  $0.925 \times 10^{-7}$  to  $1.17 \times 10^{-7}$   $m^2/sec$  under the experimental range of measurements.

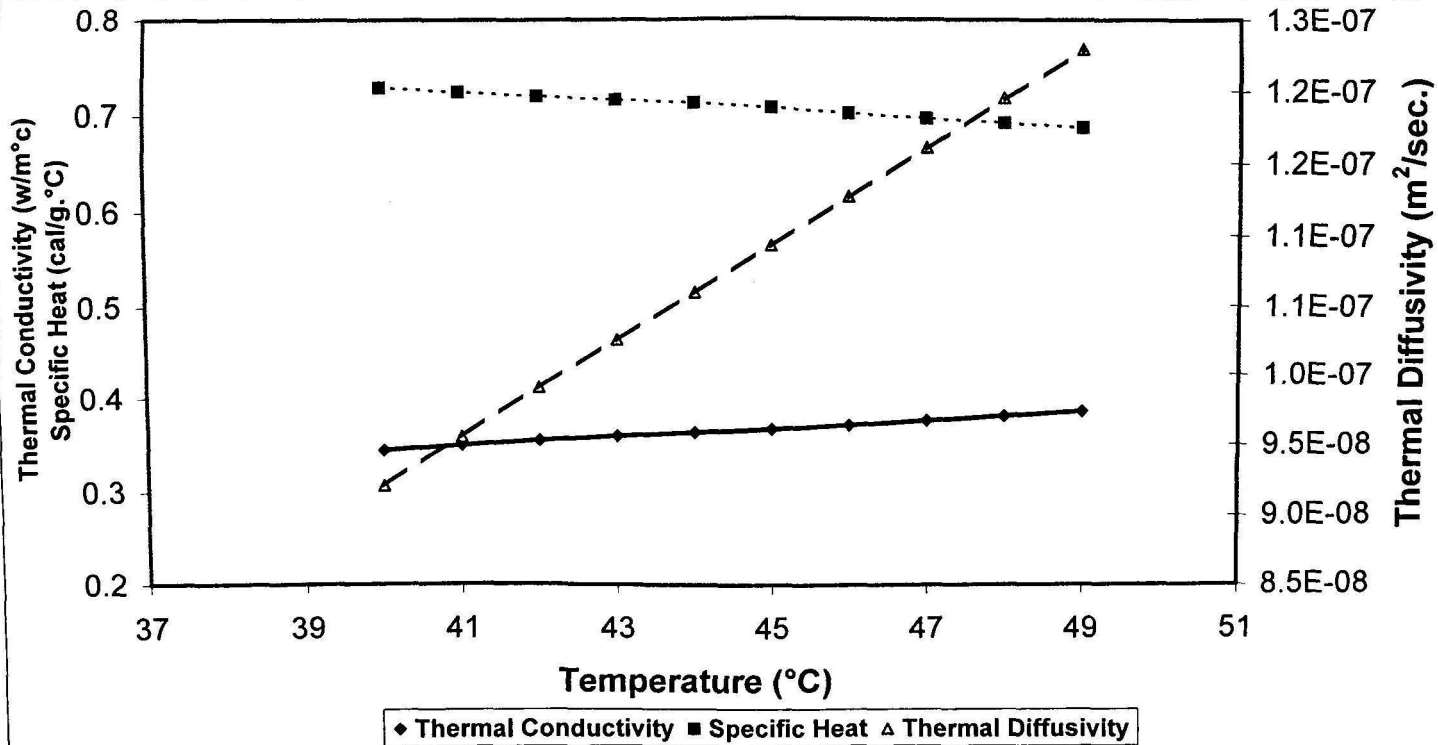
## 4.2. EFFECT OF TEMPERATURE ON THERMAL PROPERTIES OF *CHHANA*

Fig-4.1 illustrates the effect of temperature on thermal conductivity ( $k$ ), specific heat ( $C_p$ ) as well as thermal diffusivity ( $\alpha$ ) of *chhana*. It can be observed that the thermal conductivity of *chhana* increased linearly with temperature. It increased from  $0.344 \text{ w/m}^\circ\text{C}$  at  $40^\circ\text{C}$  to  $0.384 \text{ w/m}^\circ\text{C}$  at  $49^\circ\text{C}$ . Increase in thermal conductivity with increase in temperature has also been reported for *paneer* by Jayakumra (1998). Thermal diffusivity of *chhana* showed a positive correlation with temperature. It increased from  $0.921 \times 10^{-7} \text{ m}^2/sec$  at  $40^\circ\text{C}$  to  $1.23 \times 10^{-7} \text{ m}^2/sec$  at  $49^\circ\text{C}$ . Increase in thermal diffusivity with increase in temperature has also been reported for Mexican tortillas dough by Griffith (1985). A reverse trend has been observed for specific heat of *chhana* which decreased from  $0.729 \text{ cal/g}^\circ\text{C}$  at  $40^\circ\text{C}$  to  $0.687 \text{ cal/g}^\circ\text{C}$  at  $49^\circ\text{C}$ . As the rate of increase in thermal diffusivity of *chhana* was higher than that of thermal conductivity, the specific heat of *chhana* decrease with increase of temperature. This can be established from the relation  $\alpha = k/\rho C_p$ .

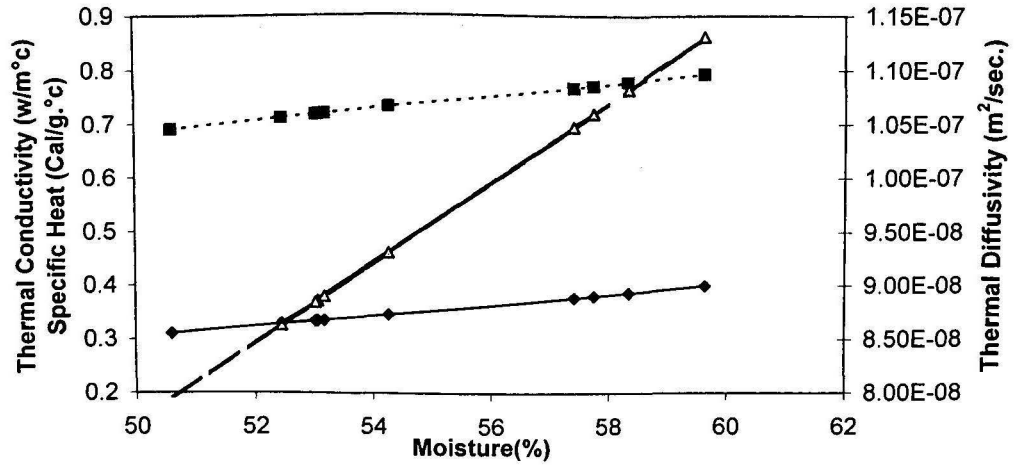
## 4.3. EFFECT OF COMPOSITIONS ON THERMAL PROPERTIES OF *CHHANA*

### 4.3.1. Effect of Moisture Content

Effect of moisture content on thermal properties of *chhana* is illustrated in Fig-4.2. A positive correlation has been observed between thermal conductivity and water content. Thermal conductivity of *chhana* increased from  $0.328 \text{ w/m}^\circ\text{C}$  at 52% moisture to  $0.387 \text{ w/m}^\circ\text{C}$  at 58% moisture.



**FIG.4.1: VARIATION OF THERMAL PROPERTIES WITH TEMPERATURE (Constant Moisture, Fat, Protein)**



◆ Thermal Conductivity      ■ Specific Heat      —△— Thermal Diffusivity

**FIG.4.2: VARIATION OF THERMAL PROPERTIES WITH DIFFERENT MOISTURE LEVELS (Constant Temperature,Fat,Protein)**

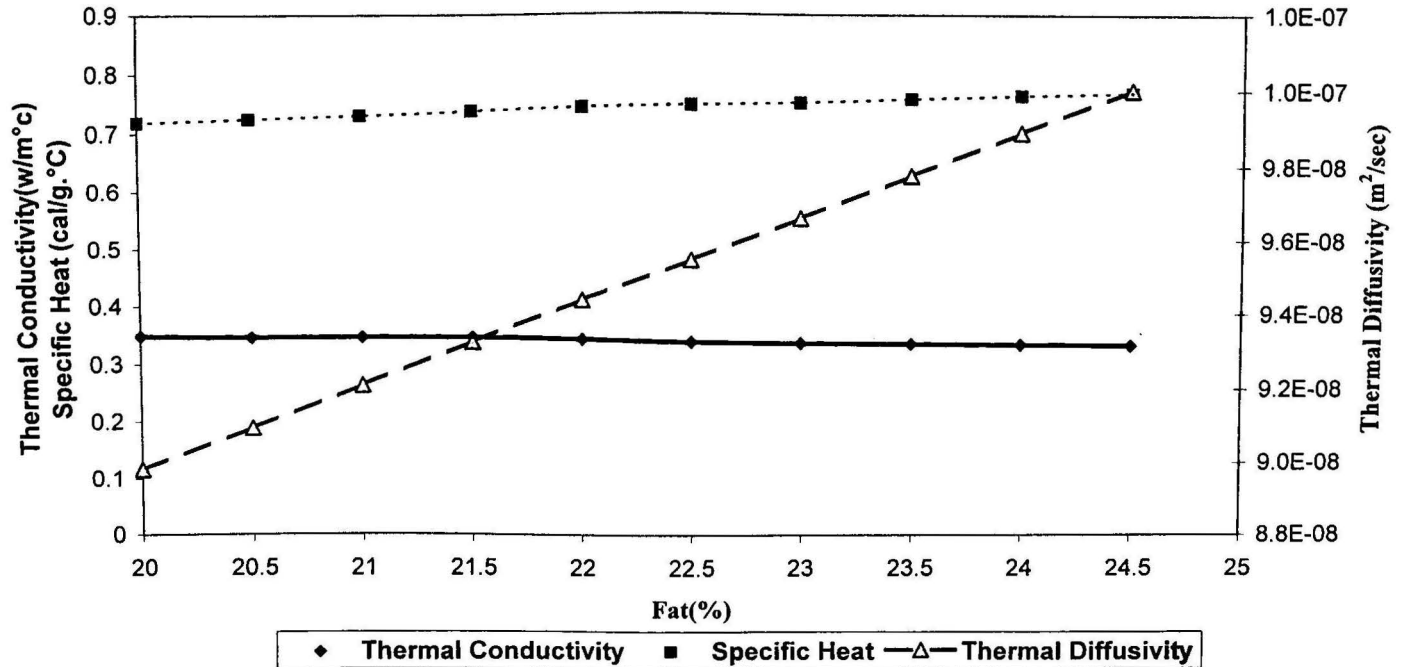
Sweat *et al.* (1978) had also reported similar results for various dairy products. The effect of increase in moisture content has been attributed to the moisture migration effect. In most cases this effect is one of evaporation in the warm region, transmission of the vapour by diffusion and their subsequent condensation in the cooler region. Under such conditions heat, largely in the form of latent heat, is transmitted by this mechanism which is in addition to heat transfer by conduction. This phenomenon of moisture migration thus continuously alters the thermal conductivity.

Specific heat of *chhana* increased with increase in moisture content. It increased from 0.711 cal/g°C at 52% moisture to 0.779 cal/g°C at 58% moisture. As the specific heat of water is 1 cal/g°C, which is more than that of *chhana*, an increase in moisture content resulted in the increase of specific heat of *chhana*.

Thermal diffusivity of *chhana* also increased with increase of moisture content. Thermal diffusivity increased from  $0.803 \times 10^{-7}$  m<sup>2</sup>/sec at 52% moisture to  $1.08 \times 10^{-7}$  m<sup>2</sup>/sec at 58% moisture. An increase in specific heat of a food product indicates the decrease in its thermal diffusivity, yet the later increased with increase in moisture content of *chhana*. The reason for this could be attributed to the decrease in mass density of *chhana* with the increase in its moisture content.

#### **4.3.2. Effect of Fat Content**

Fig-4.3 illustrates the effect of fat content on thermal properties of *chhana*. There was an inverse correlation between thermal conductivity of *chhana* and its fat content. It decreased from 0.347 w/m°C at 20% fat to 0.331 w/m°C at 24.5% fat content. Backstrom and Emblik (1965) reported thermal conductivity of fat as 0.18 w/m°C which is



**FIG.4.3 : VARIATION OF THERMAL PROPERTIES WITH FAT CONTENT  
(Constant Moisture, Protein, Temperature)**

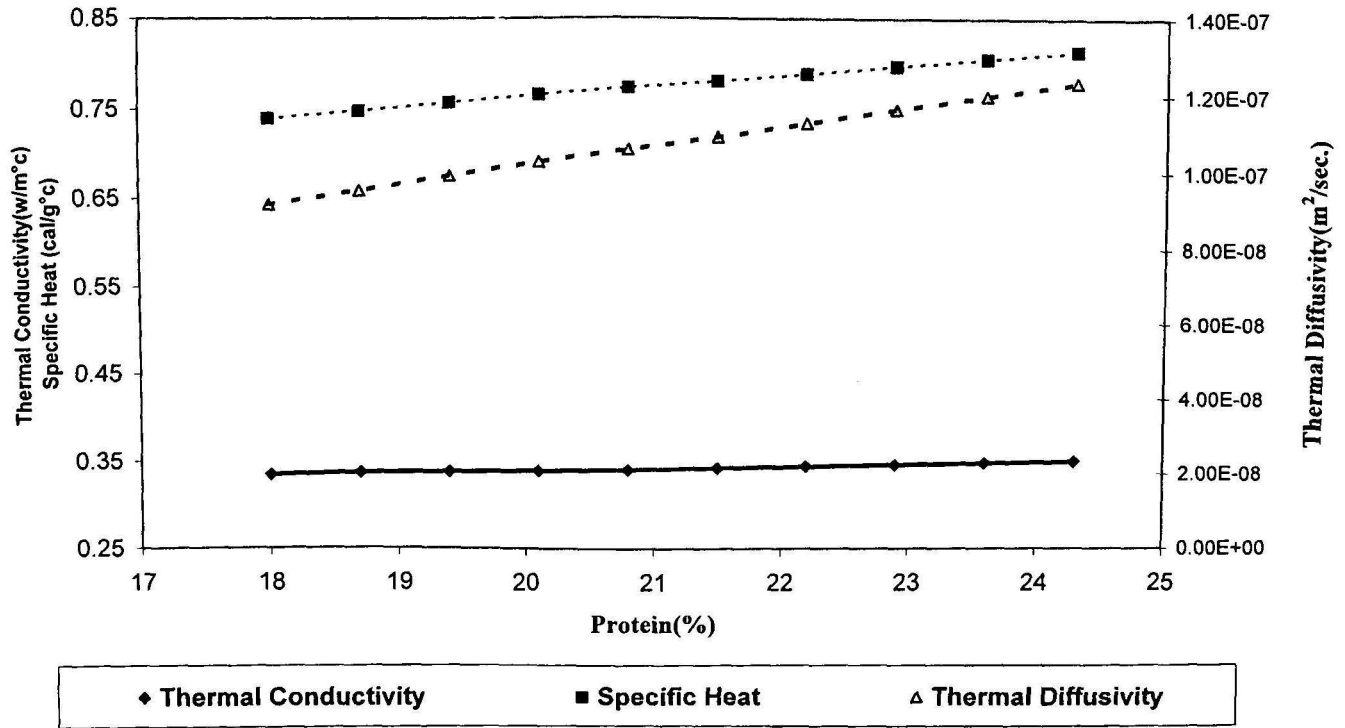
comparatively lower than the experimental value of thermal conductivity determined for *chhana*. Hence an increase in fat content of *chhana* decreased the thermal conductivity of the product.

There was a positive correlation between thermal diffusivity of *chhana* and its fat content. It increased from  $0.898 \times 10^{-7} \text{ m}^2/\text{sec}$  at 20% fat content to  $1.00 \times 10^{-7} \text{ m}^2/\text{sec}$  at 24.5% fat content.

However, a positive correlation was found between specific heat of *chhana* and its fat content. It increased from  $0.718 \text{ cal/g}^\circ\text{C}$  at 20% fat content to  $0.767 \text{ cal/g}^\circ\text{C}$  at 24.5% fat content. As the mass density of fat ( $0.93 \text{ g/cm}^3$ ) is much lower than that of other constituents, specific heat of *chhana* increased with increase of fat content even though its thermal conductivity decreased and the thermal diffusivity increase with increase in fat content.

#### **4.3.3. Effect of Protein Content**

Variation in thermal properties with protein content of *chhana* illustrated in Fig-4.4. Thermal conductivity of *chhana* increased from  $0.334 \text{ w/m}^\circ\text{C}$  at 18% protein content to  $0.350 \text{ w/m}^\circ\text{C}$  at 24% protein content. Protein content also showed a positive correlation with thermal diffusivity as well as specific heat of *chhana*. Specific heat of *chhana* varied from  $0.739 \text{ cal/g}^\circ\text{C}$  at 18% protein content to  $0.813 \text{ cal/g}^\circ\text{C}$  at 24 % protein content. Thermal diffusivity increased from  $0.915 \times 10^{-7} \text{ m}^2/\text{sec}$  at 18% fat content to  $1.23 \times 10^{-7} \text{ m}^2/\text{sec}$  at 24% protein content.



**FIG. 4.4 : VARIATION OF THERMAL PROPERTIES WITH PROTEIN CONTENT (Constant Temperature, Fat, Moisture)**

#### 4.4. MODELLING OF THERMAL PROPERTIES OF *CHHANA*

Experimental values of thermal properties of *chhana* at different compositions and temperature of measurement were statistically analysed by using 'Systat' and 'Excel' softwares. Prediction models developed for different thermal properties are discussed as under:

##### 4.4.1. Prediction Model for Thermal Conductivity (K)

The 'K' values obtained under different sets of conditions were statistically analysed and an equation was developed to correlate thermal conductivity of *chhana* with its temperature, moisture, fat and protein content. The developed equation is given as under:

$$K = 0.00994772M - 0.0036978F + 0.0025041P + 0.00452695T - 0.3441016 \quad \dots\dots\dots (4.1)$$

Where,

K = Thermal conductivity of *chhana* (w/m°C)

T = Temperature of *chhana* (°C)

M, F, P = % moisture, fat, protein content of *chhana*, respectively.

Equation 4.1 has a coefficient of determination ( $R^2$ ) 0.89. The error between the experimental and predicted values have been found to be  $\pm 3.6$  percent.

##### 4.4.2. Prediction Model for Specific Heat ( $C_P$ )

The ' $C_P$ ' value obtained under different sets of conditions were statistically analysed and an equation was developed to

correlate specific heat of *chhana* with its temperature, moisture, fat and protein content. The developed equation is given as under:

$$C_p = 0.011496M + 0.010784F + 0.011852P - 0.00469T - 0.155 \dots (4.2)$$

Where,

$C_p$  = Specific heat of *chhana* (cal/g°C)

$T$  = Temperature of *chhana* (°C)

$M, F, P$  = % moisture, fat, protein content of *chhana* respectively

Equation 4.2 has a coefficient of determination ( $R^2$ ) 0.87. The error between the experimental and predicted values have been found to be  $\pm 2.5$  percent.

#### 4.4.3. Prediction model for thermal diffusivity ( $\alpha$ )

The ' $\alpha$ ' value obtained under different sets of conditions were statistically analysed and an equation was developed to correlate thermal diffusivity of *chhana* with its temperature, moisture, fat and protein content. The developed equation is given as under:

$$\alpha = (0.03729M + 0.02267F + 0.0506P + 0.03429T - 3.902) \times 10^{-7} \dots (4.3)$$

Where,

$\alpha$  = Thermal diffusivity of *chhana* (m<sup>2</sup>/sec.)

$T$  = Temperature of *chhana* (°C)

$M, F, P$  = % moisture, fat, protein content of *chhana* respectively

Equation 4.3 carry on a coefficient of determination ( $R^2$ ) 0.92. The error between the experimental and predicted values have been found to be -2.8 to 3.4 percent.

# **CHAPTER-5**

## ***SUMMARY AND CONCLUSIONS***

## 5. SUMMARY AND CONCLUSIONS

---

- 5.1. The process of *chhana* preparation has remained traditional and unchanged over several decades. Design of equipment for processing, storage and packaging of *chhana* require the knowledge of thermal properties of the product under various sets of storage and processing conditions and product compositions. The present study aimed at generation of engineering data on thermal properties of *chhana* and development of prediction models.
- 5.2. A thermal conductivity measurement set-up was developed on the basis of 'line heat source' method to determine thermal conductivity of *chhana* under different sets of conditions. Specific heat of *chhana* was measured as per the 'method of mixtures' in a vacuum jacketed calorimeter. A set-up for thermal diffusivity measurement on the basis of 'transient heating technique' was also developed.
- 5.3. The composition of *chhana* was varied in terms of its moisture, fat and protein content to study the effect of compositions on the thermal properties.
- 5.4. Thermal conductivity of *chhana* varied from 0.331 to 0.442 w/m°C in the range of temperature 40-47°C, moisture 52-59%, fat 17-25% and protein 17-25%.

5.5. Specific heat of *chhana* varied from 0.662 to 0.725 cal/g°C in the range of temperature 50-56°C, moisture 51-59%, fat 19-25%, protein 18-24%.

5.6. Thermal diffusivity of *chhana* varied from  $0.925 \times 10^{-7}$  to  $1.17 \times 10^{-7} \text{m}^2/\text{sec}$  in the range of temperature 33-46°C, moisture 52-59%, fat 16-25%, protein 18-25%.

5.7. Prediction models for different thermal properties of *chhana* are as follows:

(i) Thermal conductivity

$$K = 0.00994772M - 0.0036978F + 0.0025041P + 0.00452695T - 0.3441016$$

Coefficient of determination ( $R^2$ ) = 0.89

Standard Error = 0.0026

(ii) Specific heat

$$C_p = 0.011496M + 0.010784F + 0.011852P - 0.00469T - 0.155$$

Coefficient of determination ( $R^2$ ) = 0.87

Standard Error = 0.0038

(iii) Thermal diffusivity

$$\alpha = (0.03729M + 0.02267F + 0.0506P + 0.03429T - 3.902) \times 10^{-7}$$

Coefficient of determination ( $R^2$ ) = 0.92

Standard Error = 3.356E-09



- 5.8. There was a positive correlation between temperature and thermal conductivity as well as thermal diffusivity. However, there was an inverse correlation between temperature and specific heat of *chhana*.
- 5.9. Thermal conductivity, specific heat and thermal diffusivity increased with the increase of moisture content. There was an inverse correlation between thermal conductivity of *chhana* and its fat content. A positive correlation was found between fat content and specific heat as well as thermal diffusivity. Protein was not an important parameter for thermal conductivity variation. But there was a positive correlation between protein content and thermal diffusivity as well as specific heat of *chhana*.
- 5.10. As the standard error in the developed prediction models is very low, i.e., less than 0.0038, these model would help in prediction of thermal properties of *chhana* accurately under different product compositions and temperatures.

# ***BIBLIOGRAPHY***

# BIBLIOGRAPHY

- Agrawal, S.P. and Ojha, T.P. 1972. The effect of the concentration on thermal conductivity of whole milk. *J. Agril. Engg.*, 37(2): 24-30.
- Agrawal, S.P. and Ojha, T.P. 1973. Specific heat of concentrated whole milk at higher temperature. *Indian J. Dairy Sci.*, 26(2) : 83-87.
- Andrieu, J., Gonnet, E. and Laurent, M. 1986. Pulse method applied to foodstuffs : Thermal diffusivity determination in food engineering and procedural applications. Vol. 1, Transport Phenomena, Le Maguer and Jelen, Eds. Elsevier App. Sci., London, U.K. 103-122.
- Aneja, V.P. 1998. Continuous chhana making equipment. The fourth short course on advance in traditional dairy products organized under the aegis of "Centre of Advance Studies in Dairy Technology" from 16<sup>th</sup> Dec., 1997 to 6<sup>th</sup> Jan., 1998 at NDRI, Karnal, India.
- Backstrom, E.H.M. and Embliek, E. 1965. *Kaltetechnik*, 3<sup>rd</sup> ed. Verlag G. Braun, Karlsruhe. Cited : Sweat, V.E. (1994). *Engineering Properties of Foods*. Ed. Rao, M.A. and Rizvi, S.S. H., Marcel Dekker, Inc., New York, pp 130.
- Califano, A.N. and Calvelo, A. 1991. Thermal conductivity of potato between 50 and 100°C. *J. Food Sci.*, 56(2) : 586-587.
- Chaiwanichsiri, S., Laohasongkram, K., Thunpithayakul, C. and Mekmanee, S. 1996. Thermophysical properties of

fresh and frozen pineapples. *ASEAN-Food J.*,  
11(1) : 1-5.

Charm, S.E. 1971. *The Fundamentals of Food Engineering*,  
2<sup>nd</sup> Edition, AVI Publishing Co., Westport, conn.

\*Choi, Y. and Okas, M.R. 1983a. The thermal properties of  
tomato juice concentrates. *Trans. ASAE*, 26(1) :  
305-311.

Choi, Y. and Okos, M.R. 1983b. Thermal properties of liquid  
foods. Review. Presented at the 1983 winter  
meeting of the American Society of Agricultural  
Engineer. Chicago, Paper No. 83-6516.

Choi, Y. and Okos, M.R. 1983C. Thermal properties of liquid  
foods – review. Presented at the 1983 winter  
meeting of the American Society of Agricultural  
Engineers, Chicago, Ill., Paper No. 83-6516.

Clark, P.E., Waldenland, C.R. and Cross, R.P. 1946. Specific  
heats of vegetable oils from 0 to 250°C. *Industrial  
and Engineering Chemistry*, 38(3) : 350-353.

\*Constenla, D.T., Lozano, J.É. and Crapiste, G.H. 1989.  
Thermophysical properties of clarified apple juice  
as a function of concentration and temperature. *J.  
Food Sci.*, 54(3) : 663-668.

Copper, A.H. 1930. Latent heats of common foods.  
*Refrigeration Engineering*, 20:107.

Daubert, C.R., Steffe, J.F. and Lloyd, J.R. 1997. Electric field  
effects on the thermal conductivity of milk  
chocolate determined using the 'mirror image  
method'. *J. Food Process Engg.*, 20(1) : 77-89.

- \* de dios Alvarado, J. 1991. Specific heat of dehydrated pulps of fruits. *J. Food Process Engg.*, 14 : 189-195.
- \* Dickerson, R.W. Jr. 1965. An apparatus for the measurement of thermal diffusivity of foods. *Food Technol.*, 19(5) : 198-204.
- Dickerson, R.W. Jr. 1968. Thermal properties of foods, in: The freezing preservation of foods, 4<sup>th</sup> edition. Vol.2. Editors, D.K. Tressler, W.B. Van Aredel and M.J. Capley, AVI Publishing Co., Westport, Connecticut.
- Dickerson, R.W. Jr. 1969. Thermal properties of food. Freezing preservation of foods, 4<sup>th</sup> ed., Vol.,2, D.K. Tressler, W.B. Van Arsdel and M.J. Copley (Eds). AVI, Westport, Conn.
- Dickerson, R.W. Jr. and Read, R.B. Jr. 1975. Thermal diffusivity of meats. *ASHRAE Trans.*, 81 (1) : 356-359.
- Farrall, A.W., Chen, A.C., Wang, P.Y., Dhanak, A.M., Hedrick, T.I. and Heldman, D.R. 1970. Thermal conductivity of dry milk in a packed bed. *Transaction of the ASAE.*, 391-394.
- \* Fernandez-Martin, F. and Montes, F. 1977. Thermal conductivity of creams. *J. Dairy Res.*, 44(1) : 103-109.
- Frechette, R.J. and Zabradnik, J.W. 1968. Thermal properties of the McIntosh apple. *Transactions of the ASAE*, 21-45.
- Gaffney, J.J., Baird, C.D. and Eshleman, W.D. 1980. Analysis of the transient method for determining thermal

diffusivity of fruits and vegetables. *ASHRAE Trans.*, 86(2) : 261-280.

\* Goedeken, D.L., Shah, K.K. and Tong, C.H. 1998. True thermal conductivity determination of moist porous food materials at elevated temperatures. *J. Food Sci.*, 63(6) : 1062-1066.

\* Griffith, C.L. 1985. Specific heat, thermal conductivity, density and thermal diffusivity of Mexican tortillas dough. *J. Food Sci.*, 50(5): 1333-1337, 1341.

Gromov, M.A. 1993. Thermo-physical properties of casein. *Molochnaya-Promyshlennost*, 4 : 20-22.

Gupta, T.R. 1990. Specific heat of Indian unleavened flat bread (chapati) at various stages of cooking. *J. Process Engg.*, 13 : 217-227.

Hammer, B.W. and Johnson, A.R. 1913. Specific heat of milk and milk derivatives. *IOWA Agr. Exp. Sta. Bulletin No. 14*. Ames, IOWA, USA.

Harper, J.C. 1972. Elements of food engineering. Thesis, University of California, Davis, California.

\* Hayakawa, I.K. 1972. A new method for computerized determination of the apparent thermal diffusivity of food. In *Proc. of 1st Pacific Chem. Engineering Congress, Part II*, p.129. Soc. Chem. Eng., Japan.

\* Hayakawa, I.K. and Bakal, A. 1973. New computational procedure for determining the apparent thermal diffusivity of a solid body approximated with an infinite slab. *J. of Food Sci.*, 38(4) : 623-629.

Heldman, D.R. and Singh, R.P. 1981. Thermal properties of frozen foods. Presented at the 1983 winter meeting of the American Society of Agricultural Engineers, Chicago, Ill., Paper No. 83 -6518.

Hooper, F.G. and Lepper, F.R. 1950. Transient heat flow apparatus for the determination of the thermal conductivities. *ASHVE Transaction*, 56 : 309-324.

Hooper, F.C. and Chang, S.C. 1953. Development of the thermal conductivity probe. *ASHVE*, 24(10): 125-129.

Hutchinson, E. 1945. Measurement of thermal conductivity of liquids. *Trans. Farradays Soc.*, 41 : 87-89.

Hwang, M.P. and Hayakawa, K. 1979. A specific heat calorimeter for foods. *J. Food Sci.*, 44(2) : 435-438.

IS : 4079. 1976. Indian Standard methods of testing dairy products. Indian Standard Institution, New Delhi

Iyer, M. 1978. Physico-chemical studies on *chhana* from cow's and buffalo's milk. M.Sc. Thesis, Kurukshetra University, Kurukshetra, India.

Jakob, M. 1949. Heat transfer, Vol.1. John Wiley and Sons, New York, p. 313.

Jayakumar D.R. 1998. Development of probes for determination of thermal conductivity of some selected indigenous dairy products. M.Tech. Thesis. NDRI (Deemed University), Karnal, India.

Kolarov, K.M. and Gromov, M.A. 1973. A universal equation for computing the thermal conductivity of fruit and

vegetable juices and syrups. *Khranitelna Pramishlenest (Sofia)*, 22(10) : 33-34.

Konrad, H. and Rambke, K. 1970. Physikalische Eigenschaften flüssiger Milchprodukte. 4. Mitt. Wärmeleitfähigkeit Von Milch, Rahm und Milchkonzentraten. *Die Nahrung*, 15(3) : 269-277.

✶ Kopleman, I.J. 1966. Transient heat flow transfer and thermal properties in food systems. Ph.D. Thesis, Michigan State University, East Lansing, Michigan.

Lepilkin, A.M. and Berisov, V.I. 1970. Untersuchung des Einfurses der temperatur auf den thermophysikalischen Eigenschaften von milch. *Molo-Sanja Promils*, 28(9) : 35-37.

Lund, D.B. 1983. Application of differential scanning calorimetry in food. In physical properties of food, M. Peleg and E.B. Bagley (Eds), Chapter 4, AVI, Westport, Conn.

✶ Mandhyan, B.L. and Prasad, S. 1994. Effect of particle size, moisture content, pressure and temperature on the physical and thermal properties of soybean. *J. Food Sci. and Tech.*, Mysore, 31(5) : 395-399.

Martens, T. 1980. Mathematical model of heat processing in flat containers. Ph.D. Thesis, Katholieke Univ. Leuven, Belgium.

Meneffee, S.G. and Overman, O.R. 1940. A semi-micro kjeldahl method for determination of total nitrogen in milk. *J. of Dairy Sci.*, 23 : 143-147.

- Mohsenin, N.N. 1980. Thermal properties of foods and agricultural materials. Gordon and Breach, New York.
- Murdia, L.K. 1982. Measurement of thermal conductivity of dairy products by line heat source method. M.Sc. Thesis, NDRI (Deemed University), Kurukshetra, India.
- Muthukumarappan, K., Tirtarachardja, L. and Gunasekaran, S. 1997. Modelling thermal properties of cheddar cheese. ASAE Annual International Meeting, Minneapolis, Minnesota, USA, 10-14 Aug. 1997. Paper-American-Society of Agricultural Engineers. 1997. No. 97-6024, 9 pp.
- Nix, G.H., Lowery, G.W., Vachon, R.I. and Tanger, G.E. 1967. Direct determination of thermal diffusivity and conductivity with a refined line heat source technique. Progress in aeronautics and astronautics: Thermophysics of spacecraft and Planetary Bodies., 20: 865-878. Academic Press, New York.
- Oguntunde, A.O. and Akintoye, A.O. 1991. Measurement and Comparison of density, specific heat and viscosity of cow's milk and soymilk. *J. Food Engg.*, 13(3) : 221-230.
- Olson and Schultz. 1942. Temperature in solids during heating and cooling. *Ind. Eng. Chem.*, 34(7) : 874-876.

- #
- Pasqualone, S. and Mastandreh, N. 1995. Thermal properties of frozen foods.II. Animal Foods. *Indurie-Alimentari.*, 34(5) : 1001-1007.
- Poppendick, H.P., Randall, R., Breeden, J.A., Chambers, J.E. and Murphy, J.R. 1966. Thermal conductivity measurement and prediction for biological fluids and tissues *Cryobiology*, 3(4) :635-639.
- Rahman, S. 1993. Specific heat of selected fresh seafood. *J. Food Sci.*, 58 : 522-524, 566.
- Ray, S.C. and De, S. 1953. Indigenous milk products of India-III-Chhana. *Indian Dairyman*, 5(1):15-18.
- Reddy, C.S. and Datta, A.K. 1994. Thermophysical properties of reconstituted milk during processing. *J. Food Engg.*, 21(1) : 31-40.
- Reidel, L. 1949. Warmeleit-fahigkeitsmessungen an Zuckerlösungen, Fruchtsäften und Milch. *Chem. Ing. Technol.*, 21(17/18): 340-341.
- Riedel, L. 1969. Diagramm zur Bestimmung der Temperatur leitfähigkeit wasserreicher Lebensmittel, *Kaltetechnik*, 21(11) ; DKV-Arbeitsblatt, 8-28; *Kaltetechnik*, 21: 315.
- Sanz, P.D., Alonso, M.D. and Mascheroni, R.H. 1987. Thermophysical properties of meat products: general bibliography and experimental values. *American Soc. of Agr. Eng.*, 30(1) : 283-289, 296.
- Schleirmacher, A.L.E.F. 1988. Vher die warmeleitung der gase. *Weidemann Ann. Phys.*, 34 : 625.

- Sen, D.C. and De, S. 1984. Studies on calcium lactate as chhana coagulant. *J. Food and Technol.*, 21(4) : 243-244.
- Shen, B.Z., Oshita, S.T., Heribe, K. and Hashimoto, A. 1995. Studies on thermal properties of food (Part-I), Potato starch.
- Siebel, E. 1892. Specific heats of various products. *Ice and Refrigeration*, 2: 256-257.
- Soni, K., Bandyopadhyay, A.K. and Ganguli, N.C. 1980. Manufacture of rasogolla from buffalo milk. *Indian J. Dairy Sci.*, 33(3) : 357-365.
- SP : 18 (Part XI). 1981. Determination of fat in milk and milk products by the Gerber method. Handbook of food analysis – Part XI, Dairy Products. Bureau of Indian Standards, New Delhi, pp 66.
- Spells, K.E. 1960. Thermal conductivity of some biological fluids. *Phys. Medic. U. Biol.*, 5(7) : 139.
- Sweat, V.E. 1995. Thermal properties of foods. Ch. 4 in Engineering properties of foods. M.A. Rao and S.S.H. Rizvi (Ed.), 2<sup>nd</sup> ed. p. 99-167. Marcel Dekker Inc., New York.
- Sweat, V.E. and Parmelee, C.E. 1978. Measurement of thermal conductivity of dairy products and margarines. *J. of Food Process Engg.*, 2(2) : 187-197.
- Thomareis, A.S., Hardy, J. 1992. Thermal diffusivity of processed cheeses: Experimental study and

development of a prediction model. *Sciences-des-Aliments*, 12(1) : 5-18.

Tsai, J.S., Unklesbay, N., Unklesbay, K. and Clarke, A. 1998. Thermal properties of restructured beef products at different isothermal temperature. *J. of Food Sci.*, 63(3) : 481-484.

Unklesbay, N., Unklesbay, K., Hsieh, F. and Sandik, K. 1992. Thermophysical properties of extruded beef/corn flour blends. *J. of Food Sci.*, 57(6) : 1282-1284.

\*  
Uno, J. and Hayakawa, K. 1980. A method for estimating thermal diffusivity of heat conduction food in a cylindrical can. *J. food Sci.*, 45(3) : 692-695.

Vander Held, E.F.M. and Van Druman, F.G. 1949. A method measuring the thermal conductivity of liquids. *Physica.*, 15 : 865-881.

\*  
Willix, J., Lovatt, S.T. and Amos, N.D. 1998. Additional thermal conductivity values of foods measured by a guarded hot plate. *J. Food Engg.*, 37(2) : 159-174.

# ***APPENDIX***

# Appendix

---

## Specifications

### 1. Kjeldahl Apparatus

*Kjeltec System*

1026 Distilling Unit

*Digestion System 12*

1009 Digester

*Make* : ITI Fecator

### 2. Multipoint Digital Temperature Indicator

*Type* : 5 Point

*Make*: New Tech. Enterprise, Roorke

### 3. Ammeter

*Range* : 0-2amp

*Make* : Newstar

### 4. Voltage Regulator

*Range* : 0-260V

*Make* : Newstar

### 5. Speed Regulator

*Range* : Low, Medium, High

*Make*: Akash-deep, Delhi

### 6. Stirrer

*RPM* : 6000

*HP/Watts* : 1/12

*Amps* : 0.75

*Make* : Remi Udyog, Bombay-2

### 7. Immersion Rod (Water Heater)

*Supply Voltage* : 230 V AC

*Range* : 1 W

*Make* : Melode

### 8. Oven

*Temperature range* : 0-200°C

*Time setter range*: 0-6hr.

### 9. Thermocouples

*Type* : 'T'

*Temperature range* : -200 to 371°C

74054

26/7, 8K

VERIFIED

11/20/22

Signature