

# **STUDY OF OHMIC HEATING BEHAVIOUR OF MANGO JUICE**

**Thesis**

**Submitted to the Punjab Agricultural University  
in partial fulfillment of the requirements  
for the degree of**

**MASTER OF SCIENCE  
in  
PHYSICS  
(Minor Subject: Mathematics)**

**By**

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## **CERTIFICATE – I**

This is to certify that the thesis entitled, “**Study of ohmic heating behaviour of mango juice**” submitted for the degree of Master of Science in the subject of **Physics** (Minor subject: **Mathematics**) of Punjab Agricultural University, Ludhiana, is a bonafied research work carried out by **Kanupriya Dawar** (L-2012-BS-295-M) under my supervision and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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## CERTIFICATE –II

This is to certify that the thesis entitled, “**Study of ohmic heating behaviour of mango juice**” submitted by **Kanupriya Dawar (L-2012-BS-295-M)** to the Punjab Agricultural University, Ludhiana, in partial fulfilment of the requirements for the degree of **Master of Science** in the subject of **Physics** (Minor subject: **Mathematics**) has been approved by the student’s Advisory Committee after an oral examination on the same, in collaboration with an External Examiner.

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#### **ABSTRACT**

New technologies for thermal processing of liquid foods are of great industrial and scientific interest. Ohmic heating is one of these new technologies. The present study aimed to design and built ohmic heating system. The ohmic system so developed showed adequate performance, and heating the product satisfactorily. Ohmic heating process is influenced by a number of factors such as electrical conductivity, viscosity, pH, solid content and electric field strength. The mango juice was heated on a laboratory scale static ohmic heater at different voltage gradients 7-27 V/cm. The voltage gradient was statistically significant on the ohmic heating rate for mango juice ( $P < 0.05$ ). Measurements were made from 14 to 70 °C and showed a linear fashion with electrical conductivity. The electrical conductivity of mango juice was in the range of 4-17 S/cm. The increase in the concentration of the juice from 50% to 90% enhanced the ohmic heating rate of mango juice. Other parameters- viscosity, pH and total soluble solids (TSS) were studied under ohmic heating. The viscosity of mango juice varied from 6.78 to 31.61 cP. Change so observed in the viscosity and pH of juice came out to be statistically significant for all the concentrations studied at different voltage gradients and ( $P < 0.01$ ). The pH of juice varied from 2.06 to 3.57. The TSS values recorded were in the range of 7.2 to 13.8 °Brix. The change in the TSS value of juice was statistically non-significant ( $p < 0.05$ ). The predictions of mathematical model using obtained electrical conductivity equation were found to be very accurate.

**Keywords:** Ohmic heating, temperature, electrical conductivity, TSS, pH, mango.

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## CONTENTS

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CHAPTER	TOPIC	PAGE NO.
I	INTRODUCTION	1-5
II	REVIEW OF LITERATURE	6-13
III	MATERIALS AND METHODS	14-27
IV	RESULTS AND DISCUSSION	28-67
V	SUMMARY	68-69
	REFERENCES	70-74
	VITA	

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## **CHAPTER I**

### **INTRODUCTION**

Food is indispensable to humans. Aside from the provision of energy and nutrients, it contributes to a range of important aspects of human life such as cultural identity and heritage. At the same time, food accounts for a significant global share of total environment impact and resource use.

Over the past years, food processing has evolved to meet the needs of the consumers by making food safe to eat and convenient to use. Changes in the lifestyle have necessitated that food be transported over long distances, stored for longer times and able to feed larger numbers of people. Today, our food comes from all over the world to meet consumer demands for variety, convenience, low cost and nutrition. Demand for high-quality foods that are fresh tasting and nutritious has created considerable interest in the development of new food processing technique. There are several commercial processes, such as canning, pasteurizing and freeze-drying that allow the food industry to offer a variety of foods in the supermarket. While commercial processing impacts the quality, shelf life and safety of the foods, it may also change a product's flavour, texture and colour. Advancement in technologies has encouraged to produce a higher quality food product- one that look, tastes and feels fresh.

New and alternative food processing methods and novel combinations of existing methods are continually being investigated by the industry in pursuit of producing better quality foods more economically. Both science and technology have gone through tremendous transformation in the last two centuries and today it is the most reliable method to assure food safety and stability. Heating is probably the oldest means of processing foods and has been used by the mankind for millennia. However, the technology used to heat foods in order to process them has had a spectacular evolution during the 20<sup>th</sup> century which has continued until now. Technologies such as ohmic heating, dielectric heating and inductive heating have been developed and can replace at least partially, the traditional heating methods which rely essentially on conductive, convective and radiative heat transfer. The internal resistance by conduction results in very heterogeneous treatment as the heat transfer is slow and thermal lags may appear in the food mixtures. This leads to loss of product quality and low energy efficiency. In order to maximize food quality High Temperature Short Time (HTST) processes have been used. The rapid and uniform heating made possible lends itself to high temperature short time (HTST) processes with potential benefits in terms of product taste, colour and texture.

Also infrared heating has been developed as a means of heat processing of foods. They all have a common feature: heat is generated directly inside the food and this has direct

implications in terms of both energetic and heating efficiency. These are called novel thermal processing technologies, which involves the change in temperature which is the main processing factor. Whereas, the novel non-thermal processing technologies such as pulsed electric fields, high pressure, pulsed light, ultrasound, gamma radiation, where temperature may also change but not mainly responsible for food processing. Thermal processing is one of the most important food preservation techniques and has evolved itself into one of the most scientific mature food processing techniques of recent times. Development in thermal processing have enhanced the utility of thermal processing principles and increased the awareness of possible alternative processing technologies.

Ohmic heating is an innovative heating technique employed for thermal processing. Ohmic heating derives its name from Ohm's law. Since the ohmic heating technique occurs in accordance with Joule's heating effect, hence ohmic heating is also known as "Joule Heating", "Electrical-Resistance Heating" and "Electro conductive Heating" (Sastry and Barach 2000, Benabderrahmane and Pain 2000). As compared to the conventional heating technologies and electro heating food processing methods, Joule's heating is far more cost convenient (Marra *et al* 2009, Icier and Ilicali 2005a, Zhong and Lima 2003). The basic principle of ohmic heating is the dissipation of electrical energy into heat (Sastry and Palaniappan 1992, Sastry and Li 1996). Ohmic heating is distinguished from other electrical heating methods by the presence of electrodes contacting the foods and the frequency applied which is far lesser than the microwave frequency range. It is a process where electric currents are passed through foods to heat them. For this purpose the food material is enclosed between the two electrodes which behave like an electrical resistor (Sastry 1991, Reznick 1996, Sastry and Salengke 1998, Icier and Ilicali 2005a, Srikalong *et al* 2011). A low frequency (50-60Hz) alternating electrical current (AC) is passed through it with the primary purpose of heating (Sastry and Barach 2000, Vicente *et al* 2006). Hence ohmic heating of the food material actually utilizes the inherent electrical resistance of the food sample (Wang *et al* 2007). The amount of heat generated is directly related to the current induced by the voltage gradient in the field (Shirsat *et al* 2004). Ohmic heating is an efficient technique as the electrical energy is dissipated into the heat energy which leads to rapid and relatively uniform heating (Zareifard *et al* 2003).

Ohmic heating is considered suitable for thermal processing of particulates in liquid foods (Piette *et al* 2004). It can be used to cook, pasteurize and sterilize anything from juice and dairy products to soups and stews. For a material to be ohmically heated, it must be capable of conducting electricity. For a material to be classified as a conductor, electrical charges must be able to move from one point to another within it to complete an electrical circuit (Brady and Humiston 1986). Most foods contain high levels of water and dissolved salts, these solutions can conduct electricity through electrolytic conduction. When a food

product conducts electricity by electrolytic conduction, the moving ions within it collide with other molecules and these collisions lead to momentum transfer to these molecules, which in turn increases their kinetic energy, thereby heating the product (Kemp and Fryer 2007). The moving charges experience a resistance due to its environment, thus causing heating. Due to the collision of ions friction occurs and heat is generated instantly and volumetrically inside the food material due to the ionic motion (Berthou and Aussudre 2000, Zareifard *et al* 2003, Lima 2007).

Ohmic heating has gained interest recently because the products are of a superior quality than those processed by conventional technologies (Castro *et al* 2003, Parrott 1992, Kim *et al* 1996, Allali *et al* 2010). Most food products can be heated successfully using ohmic heating. The main objective of ohmic heating is to increase the temperature of food materials to a point at which the food is considered adequately processed.

Conventional process for solid-liquid mixtures is dependent upon the heating of liquid phase which then transfers the heat to the solid phase. Whereas in ohmic heating particulates are heated simultaneously at the similar rate (Khalaf and Sastry 1996, Tucker 2004). The heating of the food material is more uniform and rapid resulting in higher yield and higher retention of nutritional value of food and particulate integrity (Castro *et al* 2004, Sagar and Kumar 2010, Halden *et al* 1990, Palaniappan and Sastry 1991a). Heat is generated inside the product rather than being conducted or radiated from outside. This makes ohmic heaters an excellent choice for products where traditional heat exchangers can lead to problems such as fouling, overheating leading to product quality reduction and where products are difficult to heat because of larger solid content. The ohmic heating is energy efficient technique as most of the electrical energy is converted into the heat energy (Sastry 2005, Ghnimi *et al* 2008).

Most food heating processes would not rank highly on a list of green processes; since the amount of energy needed to raise a food through a given temperature range is the same no matter what process is employed. However, the 'greenness' of ohmic heating is justified for two reasons. First, it is a very rapid process and therefore the time available for heat losses from the product being heated is small and environmental losses are minimized. Second, and more importantly, it is a direct application of electrical energy to the product and consequently the significant energy loss, implicit at each energy transformation or exchange step in the process, is significantly reduced, if not entirely eliminated. Hence, it can be regarded as a green process and within heating processes will rank as one of the greenest (Lyng and Mckenna 2011, Shirsat *et al* 2004). The major parameter in the effectiveness of ohmic heating of a liquid food product is its electrical conductivity. The modelling of the thermal and hydraulic behavior of ohmic heater can be done to predict the temperature distribution and possible overheating of the food being processed (Quarini 1995). Some of the

factors which influence the electrical properties of food sample are applied AC frequency, temperature, moisture content, density, chemical composition and non-homogeneity of products. Basic physics dictates that the electrical conductivity of a product determines its suitability for ohmic heating (Kumar *et al* 2011). Although it has been stated that it is theoretically possible to provide any food with enough ohmic power to induce a target temperature rise, this could require using large current densities or large electrical field strengths for foods where the electrical conductivity values become very large or very small (Piette *et al* 2004). Electrical properties of food materials are very important as they are used in the determination of water content, drying, heating, quality detection, sorting and grading of different food materials. The efficiency of ohmic heater is dependent on conductive nature of the food to be processed and hence knowledge of the electrical conductivity of food as a whole and its components are essential in designing a successful ohmic heater (Mckenna *et al* 2006).

Viscosity of liquid foods is also an important physical property which is associated with the quality of food products (Liu and Chang 2007). Regardless of the physical explanation of what causes viscosity, the fact remains that an external force is required to maintain a relative motion between different portions of a fluid and viscosity provides a satisfactory index for evaluating the magnitude of the required force. The Viscometer data are also essential for the design and evaluation of food processing equipments such as pumps, piping, heat exchangers, evaporators, sterilizers, filters and mixers. Viscosity of a liquid food depends on its temperature, concentration, pressure and intermolecular forces.

pH is another physiochemical property which is related with cation concentration of the solution and can provide the valuable information about heating characteristics of electrical conductivity of fluid food. Fruit juices in general are characterized by high acidity conditions.

Total Soluble Solids (TSS) determines the ohmic heating effect on fruit juices. Total soluble solids refer to a solid and how readily it will dissolve in a solvent. It is measured in degrees Brix ( $^{\circ}$  brix). Degrees Brix is the sugar content of an aqueous solution. One degree of Brix is equal to one gram of sucrose which is considered to be a sugar. It represents the strength of the solution by weight.

However, research on ohmic applications in fruits, vegetables, meat products has been recently undertaken by several authors (Wang and Sastry 2000, Marcotte *et al* 1999, Shirsat *et al* 2004, Sarang *et al* 2008, Darvishi *et al* 2011). Ohmic heating is currently being used for processing of whole fruits in Japan and The United Kingdom (Sastry and Barach 2000). A large number of potential future applications exist for ohmic heating, including its use in extraction, dehydration, blanching, etc.

Several varieties of juicy fruits are available in abundant quantities. Incidentally,

there is an increasing demand for fruit juices among people of all age groups due to vitamins, mineral and fibre contents. These products are essential for human and animal growth, aid metabolic activities and improve health standards. Although recent commercial productions of fruit juices by using ohmic systems have been developed, there is little information on the performance aspects of the ohmic heating systems for liquid foods. The data on the concentration and temperature-dependent electrical conductivity of concentrated non-pasteurized fruit juices, and the effects of the higher applied voltage gradients on the ohmic heating rates of different types of fruit juices are limited. No studies had been notified about ohmic heating behavior of mango juice. Most of the work has been done, in the past, regarding electrical conductivity and viscosity of liquid foods separately. Data on the relationship between electrical conductivity and viscosity at different temperature is inadequate. Also, information regarding TSS and pH under ohmic heating is scarce. It is, therefore, proposed to conduct an investigation with the following objectives:

- (a) To investigate electrical conductivities of mango juice at different concentrations, temperature and voltage gradient during ohmic heating.
- (b) To study the effect of fluid viscosity on the ohmic heating rate of mango juice.
- (c) To develop the mathematical model for predicting electrical conductivity of mango juice.
- (d) To notify the change in pH of mango juice due to ohmic heating at different voltage gradients
- (e) To apprise the change in TSS of mango juice under ohmic heating at different voltage gradients.

## CHAPTER II

### REVIEW OF LITERATURE

Over the last few decades, a number of attempts have been made to use ohmic heating in several food-processing applications (Palaniappan and Sastry 1990). In the latter part of the nineteenth century, a number of inventions were developed for the heating of flowable materials. The technology saw periodic revival with industrial applications, for example, in milk pasteurization in the 1930s, before being discontinued (Getchell 1935, Moses 1938), and this application was abandoned apparently due to high processing costs (De Alwis and Fryer 1990). In addition, other applications were abandoned because of the short supply of inert materials needed for the electrodes (Mizrahi *et al* 1975). The problems resulted mainly from improper contact between electrodes and the food product. Electrolysis and product contamination were observed following the use of unsuitable electrode materials. Before a reliable aseptic packaging technology existed, rapid and continuous sterilization techniques using ohmic heating were not practical. Recent developments in pumping technologies have ensured that particulate foods move without any mechanical damage.

In the 1980s, the technology was again revived, and it has achieved some industrial applications that include the pasteurization of liquid eggs and processing of fruit products (Salengke and Sastry 2007). New developments in various areas have improved the prospects for future use of this technology. Developments in power supply technology in the past 5 years have shown promise in significantly decreasing costs. The control of electrolytic effects has been greatly advanced by recent developments. Further, the emergence of new manufactures of low-cost ohmic heaters on the market suggests that the technology is under going improvement and refinement. Now this processing technology is preferred throughout the world on a wide variety of products. The applications of ohmic heating include sterilization, pasteurization, processing of fouling-sensitive materials, blanching, thawing, on-line detection of starch gelatinization (Li *et al* 2004), and as a pretreatment for drying and extraction.

Many ohmic heating systems were developed at the research level (Huang *et al* 1997, Marcotte 1999, Farid 2001, Shirsat *et al* 2004, Jun and Sastry 2005, Legrand *et al* 2007, Sarang *et al* 2008).

The use of static heaters has been reported in several studies for the measurement of electrical conductivity of foods during ohmic heating (Halden *et al* 1990). Palaniappan and Sastry (1991) studied the effects of insoluble solids and applied voltage on electrical conductivity of the pre-pasteurized carrot and tomato juices during ohmic heating. Qihua *et al* (1993) made performance evaluation of an ohmic heating unit for liquid foods. They reported that the temperature affected the electrical conductivity values of fresh orange juice, but the

relationships were not given. Lamsal (1994) measured electrical conductivity and developed mathematical model in terms of total soluble salts and the temperature of three different fruit juices orange, pineapple and tomato.

Amiali *et al* (2006) studied that the electrical conductivity increased linearly with increasing temperature for apple, orange and pineapple juices. The electrical conductivity was in the range 0.13 to 0.63 S/m. Icier *et al* (2008) found that the electrical conductivity increases with increase in temperature. The electrical conductivity of fresh grape juice was in the range 0.4 to 0.75 S/m. Marra *et al* (2009) developed a mathematical model of a solid food material undergoing heating in ohmic cell for stimulated heat transfer phenomenon.

The effect of fluid viscosity on the ohmic heating rates of fluid-particle mixtures was investigated by Khalaf and Sastry (1996). Fluid with identical electrical conductivity but different viscosity was heated in static and vibrating ohmic heater. In the static ohmic heater, the heating rate of fluid and particles were found to be comparable for the different fluids. . However in the vibrating ohmic heater; the heating rate of fluid and particles was found to increase with increasing fluid viscosity.

Zareifard *et al* (2003) investigated the ohmic heating behavior and electrical conductivity of two-phase food systems. The food system comprised of a liquid phase using 4% w/w starch solution with 0.5% w/w salt and a solid phase containing carrot puree and cubes of different sizes (6 and 13 mm) in different concentrations (30 and 50% w/w ). Food systems were ohmically heated using a static ohmic heater at a constant voltage gradient of 12.5 V/cm. Electrical conductivity values were calculated as a function of particle size, concentration, location and temperature. With particle size and concentration, the heating time increased. The electrical conductivity values ranged from 0.2 to 1.8 S/m as the temperature increased from 20 to 80 °C. EC decreased with increase in particle size and concentration. The thermal behavior was different when the two phases were in parallel, in series or in mixed condition. However, there was no significant difference between overall values of EC when liquid and solid phases were studied separately as compared with the mixed condition.

Castro *et al* (2004) studied the effects of field strength and multiple thermal treatments on electrical conductivity of strawberry products. Electrical conductivity increased with temperature and field strength. Thermal treatments caused a decrease in electrical conductivity values of strawberry pulps. Ascorbic acid degradation followed first order kinetics for both conventional and ohmic heating treatments and the kinetic constants were in the range of the values reported in the literature for other food systems. The presence of an electric field does not affect ascorbic acid degradation. Thermal treatments affect significantly electrical conductivity values for both strawberry pulps.

Icier and Ilicali (2004) studied the electrical conductivity of apple and sourcherry juice concentrates having 20-60% soluble solids were ohmically heated by applying five

different voltage gradients (20-60 V/cm). The result showed that the electrical conductivities of juices increased linearly by decreasing insoluble solid contents. It was observed that electrical conductivity of apple and sourcherry juices were significantly affected by temperature and concentration ( $p < 0.05$ ). The ohmic heating system performance coefficients (SPCs) were defined by using the energies given to the system and taken up by the juice samples. The SPCs were in the range of 0.47-0.92. The unsteady-state heat conduction equation for negligible internal resistance was solved with an ohmic heating generation term by the finite difference technique. The mathematical models, which take into account the system performance coefficients, can be used to predict accurately the ohmic heating times of fruit juices having different concentrations.

Icier and Ilicali (2005a) obtained temperature dependent electrical conductivities of fruit purees during ohmic heating. The determination of electrical conductivity changes and SPCs during ohmic heating is important in the design of ohmic heaters. In this study, the apricot and peach purees were heated on a laboratory scale static ohmic heater by applying voltage gradients in the range of 20-70 V/cm. The voltage gradient was statistically significant on the ohmic heating rates for both purees ( $P < 0.05$ ). A linear relation is there between temperature and electrical conductivity. The rate of change of temperature for the apricot puree was higher than the peach puree at all voltage gradients applied. Bubbling occurred above 60°C. The ohmic heating system performance coefficients were in the range of 0.49-1.00. The predictions of the mathematical model using obtained electrical conductivity equations found to be very accurate.

Icier and Ilicali (2005b) studied the effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. Ohmic heating can be especially used in pumpable food lines as an alternative heating unit. In this study, orange juice concentrates having 0.20-0.60 mass fraction soluble solids were heated ohmically by using five different voltage gradients (20-60 V/cm). They reported that the electrical conductivity of juices increased linearly by decreasing the insoluble solid content. The ohmic heating system performance coefficients were calculated using the energies given to the system and taken by the orange juice sample. The mathematical model results, considering system performance coefficients were in accordance with experimental ones. The predictions of the mathematical model were found to be very accurate.

Samarnayak *et al* (2005) proposed that minimization of electrochemical reactions during ohmic heating is desirable. The study examines a pulsed ohmic heating technique to determine its effect on electrochemical reactions. Effects of pulse parameters, such as frequency, pulse width and delay time were studied in comparison with conventional (60Hz, sine wave ) ohmic heating using various electrode materials. Analysis of electrode corrosion, hydrogen gas generation and pH change of the heating media were performed. The results

suggest that pulsed ohmic heating is capable of significantly ( $P < 0.05$ ) reducing the electrochemical reactions of stainless steel, titanium and platinised-titanium electrodes, compared with conventional 60Hz ohmic heating. For stainless steel electrodes, pulsed ohmic heating at higher frequencies and shorter pulse widths yields the lowest rates of electrochemical reactions. However, pulsed ohmic heating at lower frequencies and longer pulse widths is more effective in suppressing the electrochemical reactions of titanium and platinised-titanium electrodes. Delay time was found to be a critical factor in pulsed ohmic heating.

Liu and Chang (2007) studied the soymilk viscosity as influenced by heating methods and soybean varieties. For the study, soymilk was given two-step heating treatment. Firstly, it was heated at 55, 60, 65, 70, 75 or 80°C for 10 min and then heated at 97°C for another 10 min. the viscosity of the heated soymilk was measured after cooling to room temperature. Results showed that the two-step heating increased the soymilk viscosity up to six times. The maximum viscosity was reached when the first-step heating temperature was 70°C. Since the total heating time of the two-step heating method was 10 min longer than that of the one-step heating method and it had been reported that soymilk viscosity increased as heating time was increased. Three heat transfer methods, including ohmic heating, steam injection and water bath produced different viscosities of soymilk. Apart from heating, soymilk protein content and soybean variety also influenced the viscosity.

Magerramov *et al* (2007) measured the viscosities of two fruit juices (lemon and tangerine) with a capillary flow technique. Viscosity of juices was studied as function of temperature and concentration. The range of concentration was between 15 and 40 °Brix for tangerine juice and between 17 and 45 °Brix for the lemon juice. Observations were noted in the temperature range of 303 to 393 K. The Arrhenius type correlation equations for viscosity were used to represent the temperature dependence of viscosity. In order to represent concentration and temperature dependences the various models were applied to measured data for tangerine and lemon juices. The average absolute deviation between measured and calculated values from this correlation equation for the viscosity was 0.8% and 2.15 for tangerine and lemon juices, respectively.

Kong *et al* (2008) investigated the ohmic heating behavior of certain selected liquid food materials. Four kinds of liquid food materials (tap water, fruit-vegetable juice, yogurt and 0.5 % aqueous sodium chloride solution) were heated ohmically on the laboratory scale static ohmic heater. For the study, different voltage gradients (7.5, 11.25, 15, 18.75, 22.5 and 26.25 V/cm) were applied. Results indicated that the voltage gradient significantly influenced the ohmic heating rates for all four materials tested. The electrical conductivity also changed significantly with temperature. Under the same voltage gradient, ohmic heating rate of different materials got influenced by the electrical conductivity values. The ohmic heating

efficiency was highly dependent on electrical conductivity under the same voltage gradient. These different effects of voltage gradient on different products show the importance of the determining of electrical conductivities of foods to be processed by ohmic heating.

Sarang *et al* (2008) examined electrical conductivity of fruits and meats during ohmic heating. For this, consider six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meat (chicken, pork and beef). Observations were notified in the range of 25-140°C. It was observed that the EC of red and golden apple were not significantly different over the temperature range selected. Highly porous material like apples exhibited lower electrical conductivity. At higher temperature, apples and pineapple had low conductivity. Strawberry and peach had higher conductivity and significantly different compared to other fruits. The gap in the electrical conductivity between strawberry and peach, and other fruits increased with the temperature. Conductivity measurements of meat cuts showed that lean is much more conductive than fat. No strong relationship was observed between the electrical conductivity and the fat content of lean muscles. Fat distribution appears to be an important factor affecting the electrical conductivity of meat.

Allali *et al* (2009) investigated the effect of blanching by ohmic heating on the osmotic dehydration behaviour of apple cubes. The study showed that ohmic heating enhances mass transfer during the osmotic dehydration of apple cubes. The coupling of ohmic heating with osmotic dehydration makes it possible to obtain higher water and sugar transfer rates at a moderate temperature of 37°C. This can be explained by the ability of ohmic heating to permeabilize efficiently the cellular membranes and to cause significant modifications in the apple structure reflected by increase in the electrical conductivity of tissue and decrease of osmotic dehydration selectively.

Ikegwu and Ekwu (2009) determined thermal and physical properties of some tropical fruits and their juices. The various properties evaluated were density, moisture content, thermal conductivity, specific heat capacity, thermal diffusivity, and latent heat of fusion. The viscosity of the fruit juices was also determined. The results obtained showed that the thermal properties increased with increase in moisture contents for all the samples. The values of the specific heat capacity and the latent heat of fusion of the fruits and their juices ranged from 3.45-4.05 and 23785 kJ/ kg °C to 31825 kJ/Kg °C respectively. The total solids of the samples studied increased with decrease in moisture content of the fruits and their juices. The viscosity of the samples decreased with increase in moisture content. The observed increase in viscosity could be attributed to solubility and the quantity of total solids in the fruit juices.

Assawarachan (2010) estimated a model for electrical conductivity of red grape juice with different voltage gradients (10, 12 and 15 V/cm) and concentrations (10.5, 12.5 and

14.5°Brix) in the temperature range of 25-80°C. It was concluded that the electrical conductivity of sample increased with increase of concentration and temperature. Electrical conductivity was found to be in linear fashion with total soluble solids and temperature. The experimentally obtained electrical conductivity values were in the range of 0.4-1.15 S/m. It was also deduced that the rate of ohmic heating of red grape juice is influenced by voltage gradient. The mathematical models using multiple linear regression analysis indicated that electrical conductivity depended on temperature and concentration. The coefficients of the mathematical model of electrical conductivity prediction have given highest values of  $R^2$  and lowest  $\chi^2$  and root mean square error (RMSE). The established model was confirmed as highly accurate when estimating electrical conductivities of red grape juice. The reducing  $\chi^2$  and RMSE from the mathematical models were calculated and compared with the experimental data

Darvishi *et al* (2011) co investigated the temperature dependent electrical conductivities of lemon juice. For the process of ohmic heating, the lemon juice was heated on a laboratory scale in static ohmic cell at different voltage gradients in the range of 30-55 V/cm. Measurements were made from 20 to 74°C. Electrical conductivity was in linear relationship with increasing temperature. High coefficients of determination ( $R^2 > 0.97$ ) indicate the suitability of the linear model for conductivity variation with temperature. The voltage gradient was statistically significant on the ohmic heating rates for lemon juice ( $P < 0.05$ ). Ohmic heating times and performance coefficients are dependent on the voltage gradient used. System performance coefficients were in the range of 0.54-0.92. The level of agreement between the predicted and experimental heating times was relatively good. The electrical conductivity of lemon juice is strongly dependent on temperature. .

Darvishi *et al* (2012a) studied ohmic heating behavior and electrical conductivity of tomato paste. The ohmic heating rate of a food is highly influenced by its electrical conductivity. In this study, tomato juice was ohmically heated by using five different voltage gradients (6-14 V/cm). Measurements were made in the temperature range of 26-96°C. The voltage gradient was statistically significant on the heating time. The electrical conductivity of foods affects with temperature, applied voltage, concentration of the electrolytes, food particle size and type of pre-treatment. The ohmic heating system performance coefficients were in the range of 0.716-0.905. For lower voltage gradients, the conversion of electrical energy into heat was larger. The pH varied from 4.20 to 4.51 over the voltage gradient range studied. The pH value decreased with increase in voltage gradient. The behavior was probably due to the residence time of different reactions such as hydrolysis of the tomato samples. At high voltage gradient, the heating rate was high. Hence, the residence time for the sample to heat up from 26 to 96 °C was short, thus the change of the pH was limited.

Electrical conductivity and pH change of pomegranate juice was studied ohmically by

Darvishi *et al* (2012b) by applying alternating voltage gradient of the range (30-55 V/cm) in the temperature range of (20-85°C). As the voltage gradient increased, time, system performance coefficient and pH decreased. The range of electrical conductivity during ohmic heating was (0.209-1.013 S/m). Ohmic heating rate, electrical conductivity and pH are dependent on voltage gradients applied. The system performance coefficients for pomegranate juice samples were in the range of 0.764-0.939. The results showed that as the voltage gradient increased the role of energy losses increased, in other words SPC values decreased. Between the two models tested to fit the electrical conductivity of pomegranate juice, the linear model gave the best fit for all the data points. The voltage gradient was statistically significant on the ohmic heating rates, electrical conductivity, SPCs, electrical energy given to the system and pH for pomegranate juice. The range of the pomegranate juice pH after ohmic treatments was 3.22-3.35.

Olivera *et al* (2013) gave ohmic heating (OH) treatment to fresh foods and studied its effect on textural properties of foods. For the study, fresh solid foods were subjected to constant electrical field gradient of 1100 V/cm, 2200 V/cm and 3300 V/cm. The samples of fresh potatoes, carrots and apples of cylindrical shape having diameter = 30mm, height = 9.0mm. Fresh solid foods underwent ohmic heating treatment for 60, 120, 180 and 240 seconds. Texture measurements were performed in a universal testing machine Instron 4301 using a 100 N load cell at room temperature (~ 25°C). The firmness was defined as the force (measured in N) to deformation (in mm) ratio. Ten replicate experiments were conducted and data so obtained were statistically analyzed ( $\alpha = 0.05$ ). Stress-deformation behavior of food samples by OH differs appreciably from raw untreated samples for all cooking times. Firmness of solid samples decreased with OH time. The study so far performed confirmed that OH significantly affects texture of solid foods, producing structural damage, even though food has a low electrical conductivity.

Sarkis *et al* (2013) evaluated the key parameters during construction and operation of ohmic heating apparatus. This study aimed to design, build and validate an ohmic heating apparatus. An evaluation of its performance was done on liquid food processing. Three ohmic cells were developed and tested. On heating acerola and blueberry pulps in the ohmic heater, a non-linear behavior of electrical conductivity with temperature was observed, which differs from the linear relation obtained with the conductivity meter. This behavior is associated with bubble formation caused by water boiling due to temperature gradients inside the cells. A number of factors, such as solid content, electric field strength and ohmic cell size, influence this phenomenon. Higher solids content and electric field strengths showed to increase the temperature differences. The ohmic heating apparatus developed is adequate to conduct studies for better understanding of the technology called ohmic heating and its application on food processing. The ohmic cell designed and tested hold industrial relevance. The ohmic

heater constructed can be used to evaluate fundamental parameters such as electrical conductivity of the product, heating time and process homogeneity. It also provides a tool to monitor processing effects on the quality of products in order to find the best conditions for a continuous ohmic heating process on industrial scale.

Lakrari *et al* (2013) investigated the electrical properties of vegetable oils for the purpose of an application in electrical engineering. A comparative study of different vegetable oils: argan, rapeseed and sunflower was done. The behaviour of the electrical resistivity and viscosity was analyzed as a function of temperature. The growing importance of the issue for sustainable development requires the consideration of environment criteria in the development of all new materials and equipment. In the case of dielectric liquid, a better balance must be found between technical performance within the filled equipment and the impact on the environment –possible leaks. In transformers, a stable liquid, inert, with good electrical and thermal properties is necessary; outside, the liquid must be non-toxic to the environment and readily biodegradable. The intrinsic properties of natural vegetable oils in terms of fire resistance, environmental performance, electrical and thermal characteristics of dielectric compositions are particularly useful products in the field of electrical engineering.

Marra (2014) proposed the mathematical model of solid food pasteurization by ohmic heating. It involved the simultaneous solution of Laplace's equation, which describes the distribution of electrical potential within the food. The heat transfer equation using a source term involving the displacement of electric potential. The model was developed on the basis that thermo physical and electrical properties were taken as a function of temperature. It predicts that when temperature gradients are established in the proximity of outer ohmic cell surface, more cold areas are present at junctions of electrodes with lateral sample surface. Analysis was carried out in order to understand the influence of pasteurization process parameters on this temperature distribution. A successful model helps to improve understanding of these processing phenomenons, which in turn will help to reduce the magnitude of the temperature differential within the product and ultimately provide a more uniformly pasteurized product.

## **CHAPTER III**

### **MATERIAL AND METHODS**

The equipments and experimental procedures followed during the course of the study have been detailed in this chapter. Commercially available mango juice was purchased from a local departmental store. The experiments were performed at the PG Research Laboratory of Department of Mathematics, Statistics and Physics, Punjab Agricultural University, Ludhiana. The mango juice was heated ohmically and its properties such as density, electrical conductivity, viscosity, pH, total soluble solids (TSS) were determined. The corresponding change in these parameters as a result of ohmic heating of the mango juice was observed. Further information has been presented under the following sections:

1. Selection of juice
2. Preparation of the juice samples
3. Measurement of density
4. Ohmic heating systems
5. Measurement of electrical conductivity
6. Ostwald viscometer
7. Measurement of viscosity
8. pH meter
9. Measurement of pH
10. Hand held Refractometer
11. Measurement of total soluble solids (TSS)

#### **3.1 SELECTION OF JUICE**

Fresh juice was not considered for the study due to the rapid deterioration and variations in the raw product. It demanded good storage facilities. Further, processed juice was preferred over fresh juice mainly due to; firstly, long shelf life of processed juice as compared to fresh juice and secondly, to minimize error in measuring the various parameters- electrical conductivity, viscosity, total soluble solids (TSS) and pH. Commercially available mango juice was purchased from a local departmental store. Easy availability of the product in the market was the sole criteria in deciding the brand of the processed and packed juices used in the experiment. Although some organic and inorganic salts were already present in processed juices but the study aimed to gain an understanding about behavior of above said physical properties. Mango juice from the M/s Dabur India Limited, under the brand name- "Real juices" was selected. Ingredients of mango juice mentioned on the package were Water, Mango pulp (25%), Added sugar, Natural fruit sugar, Acidity regulator (INS 330), Stabilizer (INS 440) and Antioxidant (INS 300).

### 3.2 PREPARATION OF THE JUICE SAMPLES

The processed and packed mango juice purchased from the market was assumed to be of 100% concentration for the study. Further, this concentration was altered to obtain the new concentrations. For the study, the various concentrations of mango juice were attained by diluting it with the distilled water. The intention of choosing the different concentrations was to study the effect of changes in the various physical parameters-electrical conductivity, viscosity, TSS and pH with ohmic heating. The mango juice of an each concentration was treated ohmically at all the applied voltage gradient. The values of viscosity, TSS and pH were recorded as well as compared before and after ohmic heating of mango juice.

For the purpose of study, five different concentrations were prepared. Different modes can be opted for the preparation of various concentrations of juice. The modes known are mass by mass, mass by volume and volume by volume. In the present experiment, the mode of preparing different concentrations of juice was taken as percentage by volume (v/v). The concentrations selected for ohmic heating were 90%, 80%, 70% 60% and 50% by volume of the juice.

The method of making diverse concentrations of mango juice is quite simple. In order to have concentration of 90% by volume of juice sample, 90ml of juice was separated in a beaker. To it 10ml of distilled water was added to have a total volume of juice to be 100ml. In the same fashion other concentrations of 80%, 70%, 60% and 50% by volume of mango juice was provided by adding 20ml, 30ml, 40ml and 50ml of distilled water to 80ml, 70ml, 60ml and 50ml of juice respectively to obtain the final volume of 100ml. The experiment was replicated three times for each concentration by selecting a particular voltage gradient.

### 3.3 MEASUREMENT OF DENSITY

Density is merely one way to characterize a substance. Density ( $\rho$ ) is defined as mass (m) per unit volume (V). Thus, units of both mass (i.e. g) and volume (i.e. mL) are necessary in order to determine density. Density is measured in g/ml.

$$\text{Density} = \frac{\text{Mass of the solution}}{\text{Volume of the solution}}$$

$$\rho = \frac{M}{V} \quad (3.1)$$

The density of a liquid is often approximated by measuring its specific gravity. The specific gravity of a substance is the ratio of the density of that substance to the density of pure water. If equal volumes are considered, the specific gravity becomes simply the ratio of two masses. Numerically, the specific gravity is approximately equal to the density. Yet the specific gravity has no units, while density is expressed as grams per cubic meter, grams per decimetres and kilograms per cubic meter.

During the study of ohmic heating behavior of mango juice, the density of the mango juice was measured from equation (3.1). The density measurements were done at each prepared concentrations of mango juice. Density of the packed and processed juice which was assumed to be 100% was also calculated. For the purpose of density calculations, information regarding volume and weight of juice is required for each concentration. Volume measurements for liquids are made using a graduated container, for example, a graduated cylinder. To fulfil the requirement of mass for the measurement of density, a specific gravity bottle was used. Using the digital electronic weighing balance, the weight of the empty specific gravity bottle was determined. The volume contained in the bottle was 25ml. Further, the bottle was filled with mango juice of particular concentration. The filled bottle was weighed using digital electronic balance. The two weight measurements obtained were subtracted to give the weight of the juice contained in the specific gravity bottle. For the study, volume of the mango juice of various concentrations or specific gravity bottle is 25ml. Using these measurements, the density of mango juice were calculated at a particular concentration using equation (3.1). Similarly, the densities of the mango juice of other concentrations were obtained.

### **3.4 OHMIC HEATING SYSTEM**

For the purpose of the study of ohmic heating behavior of mango juice, the ohmic heating system was designed and fabricated in PG Research Laboratory of Department of Mathematics, Statistics and Physics, Punjab Agricultural University, Ludhiana, Punjab.

The static ohmic heating system consists of an energy supply system, a data acquisition system and an ohmic cell, which are described as follows. Continuous ohmic heating systems made for commercial applications can vary greatly. However, they include the flow system and cooling parts as well as the main parts of the ohmic heating systems.

#### **3.4.1 Energy Supply System**

Voltage, current and resistance are the primary characteristics of any electrical circuit. Voltage is the electrical driving force and can be supplied from a variety of sources such as the AC mains supply, battery or a generator. This driving force causes a flow of electric current measured in amperes and the physical makeup of the circuit (wires, etc.) contribute a resistance that opposes the flow and is measured in ohms. In Ohmic heating, this resistance is provided by the food material through which the current is passed. For most systems involving flow, there is a fundamental relationship that states that the pressure or driving force is equal to the product of the flow rate multiplied by the resistance. For electrical systems, this relationship is known as Ohm's law and is given by the equation

$$V = IR \quad (3.2)$$

Where  $V$  is the voltage (volts),  $I$  is the amperage (amperes) and  $R$  is the resistance (ohms)

The energy supply system includes an AC supply to give electrical energy to system, a manual voltage regulator ranging from 0 to 270 V to apply the desired voltage, the current and voltage measurement units.

### **3.4.2 Data Acquisition System**

The data acquisition system monitors and registers data related to electric current, voltage and temperature as a function of time. Data was recorded at constant time interval of 5 seconds. The equipment was calibrated using a multimeter and thermocouples. The data acquisition system performed satisfactorily and measured the temperature, voltage and current of an AC field simultaneously

### **3.4.3 Ohmic Heater**

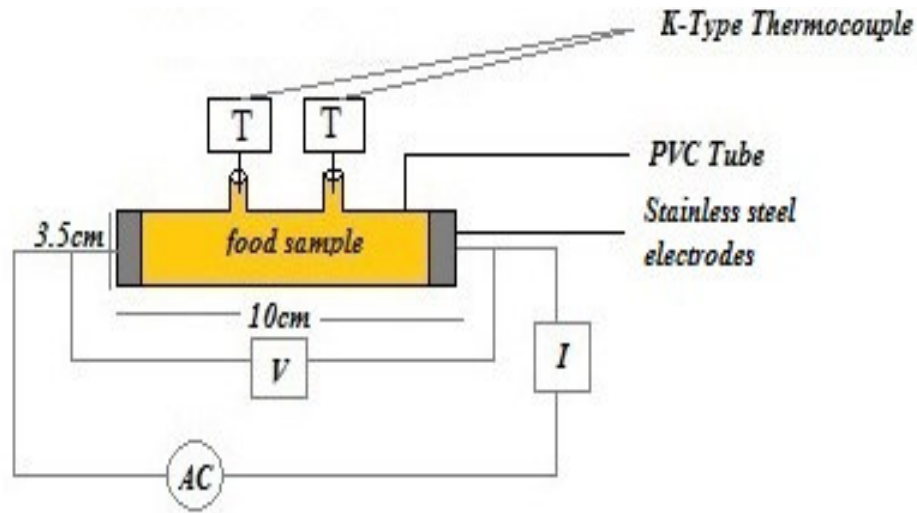
The determination of changes in the rheological properties of liquid foods during ohmic heating is important in the design of ohmic heater. A static ohmic heater is mostly employed at laboratory scale. An ohmic heater also known as a joule heater is an electrical heating device that uses a liquid's own electrical resistance to generate the heat. Heat is produced directly within the fluid itself by joule heating as electrical current passes through it and is not transmitted to it by means of temperature gradients or hot surfaces. This has a number of benefits in comparison to hot surface heaters for difficult fluid such as slurries, highly viscous materials, liquids containing large particles and materials susceptible to damage from hot surfaces.

For a material to be ohmically heated, it must be physically capable of conducting electricity. For a material to be classified as a conductor, electrical charges must be able to move from one point to another within it to complete an electrical circuit. We are well used to concept of metals being the best conductors of electricity (wires, etc.) and displaying metallic conduction due to the relatively free movement of electrons through metallic lattices. However, most foods contain high levels of water and dissolved salts and these solutions can conduct electricity through electrolytic conduction.

When a food product conducts electricity by electrolytic conduction, the moving ions within it collide with other molecules, which in turn increase their kinetic energy, thereby heating the product. The food sample selected for the study is mango juice.

Ohmic heater uses two electrodes to impart the current upon the fluid. They can be set up either as static systems in container vessel or with continuous flow through them. The mango juice which is to be heated is sandwiched between these electrodes. A simple open geometry is preferred which prevents damage to products, reduces the effects of fouling and makes cleaning easier. The rapid and uniform heating made possible with the technology leads itself to high temperature short time (HTST) processes with potential benefits in particular to food production in terms of product taste, colour and texture. The electrodes can be made from most conductive materials and are usually selected based on price and

corrosion resistance. For high product quality applications, metals such as stainless steel are preferred in the ohmic heating study of mango juice.



**Figure 3.1 Schematic diagram of ohmic heater**

The heat generated in the product will be passed to the electrode by conduction. In some products which are very heat sensitive this can cause burn on (e.g. liquid egg). In such cases the electrodes can have a cooling system built into them to ensure they remain well below the temperature of the product. The change in the temperature during the ohmic heating is very fast and could result in runaway heating in the juice if the control is not properly designed. K-type thermocouples have been used for the purpose of temperature measurement during the static ohmic heating of fluid foods.

A schematic diagram of ohmic heater is illustrated in figure 3.1. An ohmic cell was designed and built. Ohmic cell is a cylindrical chamber built in PVC with an internal diameter of 3.5 cm. The cell was provided with two openings for the insertion of thermocouples. Two thermocouple openings were provided to maintain the uniformity in temperature. The temperature variation at different points inside the cell was  $\pm 1^{\circ}\text{C}$ . Stainless steel electrodes were annexed at both the ends of the cell at a distance of 10 cm. The mango juice of approximately 95 ml was poured into the ohmic cell. All the ohmic heating experiments were started at room temperature ( $14^{\circ}\text{C}$ ). Power source was turned on and the mango juice of particular concentration was ohmically heated up to  $70^{\circ}\text{C}$  using different output voltages to obtain different voltage gradients of 27, 22, 17, 12 and 7V/cm. The mango juice of concentration 90, 80, 70, 60 and 50% were given ohmic heating treatment at the applied voltages. The ohmic heating experiments were performed in triplicate for each concentration and applied voltage gradient.



**Figure 3.2 Representation of apparatus for calculating various parameters**

### **3.5 ELECTRICAL CONDUCTIVITY MEASUREMENT**

Electrical conductivity of the samples was calculated from voltage and current data recorded by the system described in section 3.4, using the following equation:

$$\sigma = \frac{LI}{AV} \quad (3.3)$$

Where,  $\sigma$  is the electrical conductivity of the sample (S/m),  $L$  is the space between electrodes or the length of the ohmic cell(m),  $A$  is the cross-sectional area of the cell ( $m^2$ ),  $I$  is the electrical current passing through the sample (A) and  $V$  is the voltage applied (V).

Electric field was applied to the ohmic cell and the electrical conductivity was calculated from the geometry of the apparatus using equation (3.3).

The present study aimed at studying the variation of electrical conductivity with temperature. The mango juice of known concentration was given ohmic heating treatment by applying selective electric field strength. The electrical conductivity values were obtained from equation (3.3) corresponding to each temperature reading. Similarly, electrical conductivity values of mango juice with other concentrations were also acquired corresponding to each applied voltage gradient. Pictorial representation of the apparatus used for calculating various parameters has been shown in figure 3.2.

### **3.6 OSTWALD VISCOMETER**

The viscosity of liquid depends on its molecular size and shape, the intermolecular attractions and the liquid structure. With larger molecules the viscosity of the solution

depends on concentration of the solute, its molecular weight and the shape of solute molecule. A liquid viscosity increases with increasing pressure. Absolute methods of determining liquid viscosity measure either the resistance of liquids to the motion of objects being moved or rotated under a known force or the rate at which liquid flows under a known applied force. Relative methods compare the effect of the viscosity of the liquid to that of standard or reference liquid. The relative methods are usually quicker and easier, but must ultimately be referred to some precise absolute determination of the viscosity of the reference liquid.

The capillary method of poiseuille is direct and simple in concept. The time is measured for a volume of liquid under a constant pressure head to flow through a capillary. The viscosity is calculated using poiseuille's equation for laminar flow:

$$\eta = \frac{P\pi r^4 t}{8LV} \quad (3.4)$$

Where,  $P$  represents the pressure difference across the capillary,  $r$  is the radius of tube,  $t$  is the time of flow of fluid,  $L$  is the length of the capillary and  $V$  is the volume of liquid passed through the capillary.

The radius must be measured very carefully, since it appears to the fourth power in this equation. It is assumed that at a constant velocity all of the force exerted on the liquid is used to overcome friction.

The Ostwald method is a variation of the poiseuille method. It is also known as U-tube viscometer or capillary viscometer. The time for a fixed volume of liquid to fall through a capillary from mark A to B (figure 3.3) into a reservoir under a variable pressure head is a function of the density, dynamic viscosity of the liquid and dimensions (capillary) of the viscometer. The relationship between dynamic viscosity and density is called the kinematic viscosity and is defined as

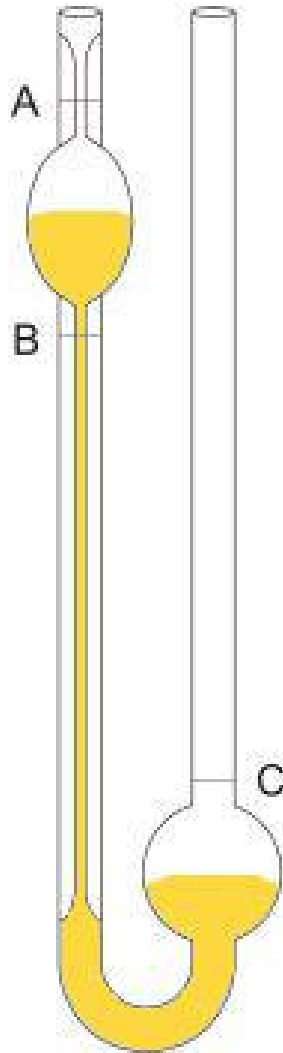
$$\text{Kinematic viscosity} = \frac{\text{Dynamic viscosity}}{\text{Density}}$$

The Ostwald viscometer, therefore, measures kinematic viscosity. An Ostwald viscometer is usually supplied with viscometer constant which can be used to calculate viscosity. However, if one is not available, the viscosity of the test fluid can be compared with one whose viscosity is known. The time and density are measured, and the viscosity of the given liquid is obtained relative to that of a reference liquid in the same viscometer from the following relationship. In the study, the reference liquid chosen to be is distilled water.

$$\frac{\eta_1}{\eta_2} = \frac{d_1 t_1}{d_2 t_2} \quad (3.5)$$

Where,  $\eta_2$  represents the coefficient of viscosity of reference liquid i.e. distilled water,  $\eta_1$  is the coefficient of viscosity of mango juice which is to be determined. Density of the juice ( $d_1$ )

and density of the liquid ( $d_2$ ) are obtained from section 3.3,  $t_1$  is the time taken by the juice to flow through the capillary and  $t_2$  is the time taken by the distilled water to flow through the capillary.



**Figure 3.3 Ostwald or U- tube viscometer**

Although the operations are simple, there is an inherent error in the method. As the liquid spends more time falling when the pressure head is lower, the average pressure head for each liquid is not the mean between the initial and final value, but an average over the time of experiment. If the two liquids have different drainage times, they have different average pressure heads. Thus equation (3.5) becomes an approximation rather than an exact relationship. It may be avoided by choosing a reference liquid whose drainage time approximates that of the liquid being investigated.

### **3.7 MEASUREMENT OF VISCOSITY**

The viscosity of two liquids can be compared by making use of an Ostwald Viscometer which consists of two bulbs, one attached with a capillary tube and U-tube below

the capillary tube while other bulb is attached to the other arm of u-tube at a level lower than the other bulb. The liquids of known densities are allowed to flow through the capillary maintaining the same differences of levels in the limbs and the time equation which governs the flow lead to the relation:

$$\frac{\eta_1}{\eta_2} = \frac{t_1 d_1}{t_2 d_2}$$

Or (3.6)

$$\eta_1 = \frac{t_1 d_1 \eta_2}{t_2 d_2}$$

Where  $\eta_1$ ,  $\eta_2$  are the viscosity coefficients of the liquid and water respectively.  $d_1$  and  $d_2$  are the densities of liquid and water, respectively. Knowing the value of viscosity of one liquid, one can calculate the viscosity of other liquid.

The procedure followed for the measurement of viscosity was simple. The viscometer was fixed vertically on the stand and 10 mL or 20mL of water was pipette into the lower bulb. The volume of sample was chosen to be 10ml to 20ml, so that the liquid can be conveniently sucked into the upper bulb leaving some in the lower bulb. It was sucked up using pump to the other bulb to a point about the mark above the bulb. On removing the pump, stop watch was started when the meniscus crosses the mark. The watch was stopped when the liquid reached the mark below the bulb. The time was recorded at the moment. The same procedure is repeated twice or thrice and their average is used in calculations. Thus value of viscosity was obtained using equation (3.6).

Similarly, the experiment is repeated with the mango juice. Using the specific gravity bottle, one can determine the specific gravity of the liquid and calculate the viscosity. The value of coefficient of viscosity of water at room temperature was taken from the standard table. On the same basis, values of viscosity were acquired for all the concentrations of mango juice, which were treated ohmically. Effect of ohmic heating was studied on the viscosity of mango juice, when it was heated at a series of voltage gradients. Other concentrations of mango juice were also investigated for viscosity.

### **3.8 pH METER**

A pH meter is an electronic instrument used to measure the pH (acidity or alkalinity) of a liquid (though special probes are sometimes used to measure the pH of semi-solid substances). A typical pH meter consists of a special measuring probe (a glass electrode) connected to an electronic meter that measures and displays the pH reading. A pH meter is a precise voltmeter that measures the potential difference, in thousandths of a volt (mV), between the reference electrode and the measuring pH electrode. It's scaled in such a way that it displays not the measured potential, but converts it to a display of pH. According to Nernst equation a standard pH electrode generates a voltage of about 59mV per pH and at pH 7

(neutral pH) the electrode produces 0 volts. Acids produce negative and bases positive voltages. A pH meter represents the hydrogen ion concentration in pH units. A pH meter consists of a glass electrode and a read out screen as shown in figure 3.4. The glass electrode is made of very thin glass that establishes and measures the electrical potential difference between the solution to be measured and an internal reference. The electrical potential is then converted into a pH reading for the sample.



**Figure 3.4 pH meter showing the pH probe and mercury thermometer**

This is due to the difference of  $H^+$  ion concentration between the test solution and the glass bulb electrode. The porous glass of the electrode prevents the  $H^+$  ions to diffuse from both sides, but allows the exchange of  $Na^+$  ions (contained in the silicates of the glass) with the external solution, for keeping the continuity of this electrical system. The  $H^+$  activity difference between the solution inside the electrode and the external one is measured as electric potential difference, then, converted in pH units (0-14) by the instrument.

Caring for a pH meter depends on the type of electrode in use. When an electrode is frequently used, it is better to keep the electrode moist, since moistening a dry electrode takes a long time. However, some pH meters do not mind their electrodes drying out provided they had been rinsed thoroughly in tap water or potassium chloride. A pH probe kept moist in an acidic solution can influence results when not rinsed before inserting it into the test sample. More precaution should be taken as a liquid of  $pH=4$  has 10,000 more hydrogen ions than a

liquid of pH=8. Thus a single drop of pH=4 in the fluid measuring 400 drops of pH=8 really upsets the measurements. The calibration solutions consists of chemical buffers that keeps pH levels constant, so contamination of the fluid to be tested with a buffer is going to affect the pH measurement.

### **3.9 MEASUREMENT OF pH**

For the measurement of pH of mango juice Systronics microprocessor based pH meter was used. A pH meter needs to be calibrated in order to correct for any deviation of the electrodes from their ideal behaviour.

Calibration should be performed with at least two standard buffer solutions that span the range of pH values to be measured. For calibration purpose, buffers at pH 4 and pH 7 are used. The pH meter has one control to set the meter reading equal to the value of the first standard buffer and a second control which is used to adjust the meter reading to the value of the second buffer. Standard buffer sachets, which can be obtained from a variety of suppliers, usually state how the buffer value changes with temperature.

The calibration process correlates the voltage produced by the probe with the pH scale. After each single measurement, the probe is rinsed with distilled water or deionized water to remove any traces of the solution being measured, blotted with cotton to absorb any remaining water which could dilute the juice and thus, alter the reading. When not in use, the probe must be kept wet at all times.

The pH probe and mercury thermometer were immersed in the sample using stand so that they do not touch the surface and walls of beaker. pH of mango juice of known concentration was measured before and after heating it ohmically. The various concentrations of mango juice which were heated ohmically at specific applied voltage gradient were checked for pH value.

### **3.10 HAND HELD REFRACTOMETER**

Refractometry is important from both the scientific and technological point of views owing to its numerous applications. The development of simple and compact refractometers is key for applications in industrial processing, quality control in food and beverage industries, etc. Hundreds of major corporations routinely use refractometers to control processes, concentrations, and solutions.

A refractometer is an instrument that measures the concentration of an aqueous solution by measuring its refractive index. All water-based solutions will make light bend. More concentrated the solution is, greater is the refraction. Hand held refractometers are one of the most popular analytical devices shown in figure 3.5. The hand held refractometer is a precise optical instrument that is small and light as well as easy to operate and recalibrate. They are simple, accurate and durable.



**Figure 3.5 Analog Hand held refractometer**

Refractometers work according to the principle that when a ray of light passes from one medium to another, the speed of the light changes according to the density of the transmitting medium.

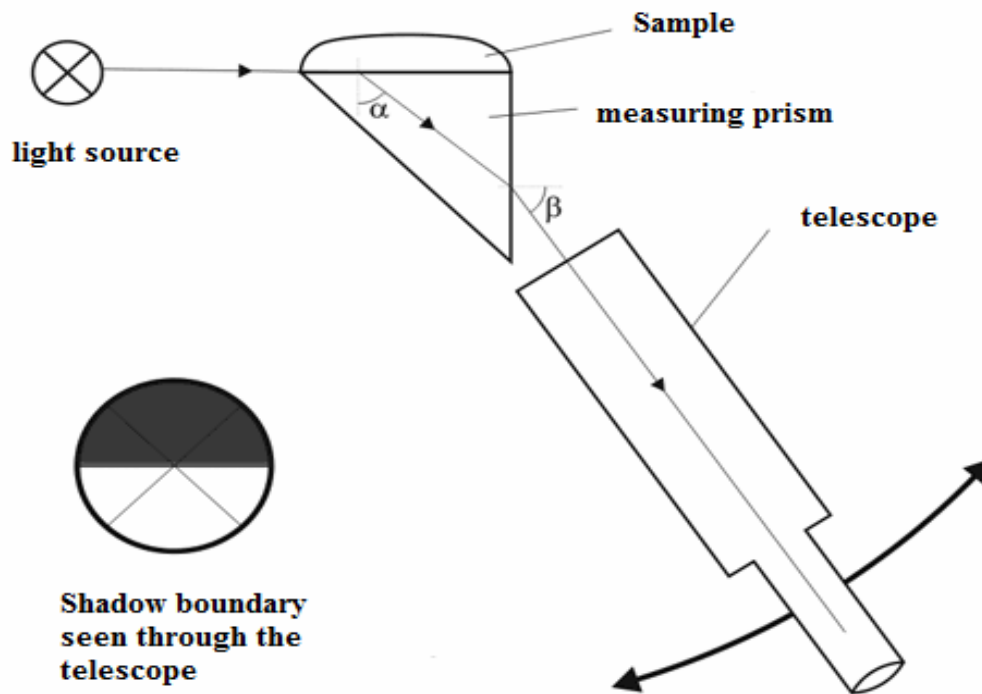
The refractive index (RI) of a substance is a measure of the speed of light in a substance relative to that in a vacuum (very close to the speed in air). The RI is a physical property that depends upon temperature and the wavelength of the light. For a particular substance the RI is a unique number when measured using a monochromatic light source at a fixed temperature.

Handheld refractometer measures the RI of a substance, usually a liquid. Scientists may wish to measure the RI when studying the physical properties of different liquids and solids. However, handheld refractometers are usually used to measure the concentration of a dissolved substance. The simplest and most popular use of a handheld refractometer is in measuring the concentration of sugar in water. As the concentration of sugar increases the RI increases. A bench or handheld refractometer can therefore be used to measure concentration of sugar provided the relationship between RI and concentration (and temperature!) is known.

The Brix scale is the most widely used scale and is based on the relationship between pure sucrose in water concentration (weight %) and RI. The Brix scale is used as a measure of 'nutritional value'. Thus soft drinks, juices, sauces, preserves etc. are assign a °Brix value

as part of the Quality Assurance for the product. Indeed, in the juice and soft drink industries, the Brix value is arguably the most important parameter in quality control.

A hand held refractometer is illustrated in figure 3.5. Instead of having an illuminating prism, hand held refractometers have an illuminator flap which produces a diffused light at a grazing angle and helps to keep the sample in place. Light passes through the sample, enters the measuring prism and possibly other lenses, and finally falls on the measuring scale where it can be read. Depending on the reason for using the refractometer, its scale can be graduated in Brix degrees.



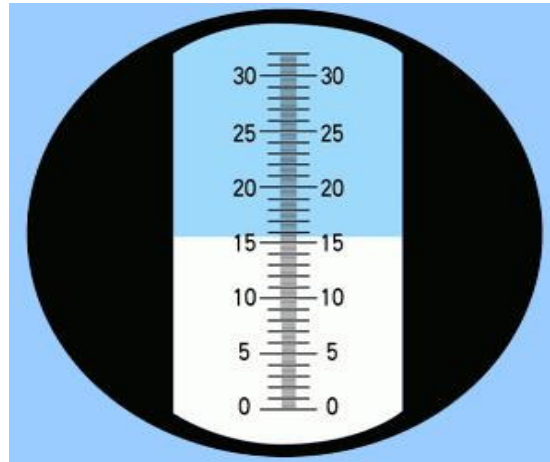
**Figure 3.6 An illustration of hand held refractometr**

To take care of temperature differences, simple hand held refractometers have to be either calibrated before taking measurements (using calibration screw and distilled water), or the result have to be converted using a temperature corrections table (which requires separate temperature measurement). However, many refractometers have built in temperature compensation - either scale or additional optical wedge are mounted on the bimetallic strip, which bends when the temperature changes, compensating for changes of refractive index. That makes them much easier to use.

### **3.11 MEASUREMENT OF TOTAL SOLUBLE SOLIDS**

Measurement of total soluble solids (TSS) using hand held refractometer is very simple. The measuring method is based upon the principle of total reflection of light beams that impinges at a certain angle on the liquid that is to be examined. These light beams are

refracted as a function of the concentration. While measuring there appears an easily readable light blue boundary on the instrument scale. The concentration is determined by the scale value.



**Figure 3.7 A solution containing sugar will display the percent sucrose in Brix units. The sample placed on this prism is displaying 16 °Brix.**

Firstly, the illuminator flap was opened which is connected to the device by a small hinge. The sample was put on the measurement prism surface. A pipette was used to put drops of mango juice on the prism surface. After closing the flap, look through the eyepiece and read result from the scale. A proper demarcation would be visible as shown in figure 3.7. For easier reading, place the refractometer in the direction of light source sun or lamp. After taking the reading, wipe the prism and flap with a clean and soft cloth. This gives the value of total soluble solids of mango juice which was heated ohmically. TSS value of juice was also measured before ohmic heating. Using hand held refractometer TSS value was measured for all the concentrations of juices which were given ohmic heating treatment by applying voltage gradient. Three replications were carried out for each sample placed on the prism surface.

## CHAPTER IV

### RESULTS AND DISCUSSIONS

The present work aimed at studying the ohmic heating behaviour of mango juice at different voltage gradients. This chapter deals with the results and discussions of the parameters like electrical conductivity, ohmic heating rate, viscosity, TSS and pH. The properties investigated for their dependence on voltage gradient, concentration and temperature. The physical properties used in the computation and experimental parameters are given in the Table 4.1.

**Table 4.1 The parameters and properties used in the experiment**

Property or parameter	Value	Unit
Distance between electrodes	0.10	m
Diameter of electrodes	0.035	m
Voltage gradients applied	7, 12, 17, 22, 27	V/cm
Concentrations of mango juice	50, 60, 70, 80, 90,	% (v/v)
Densities of mango juice of		
50%	1010.3	Kg/ m <sup>3</sup>
60%	1016.8	
70%	1070.0	
80%	1077.2	
90%	1082.4	

#### 4.1 OHMIC HEATING RATE

Acidity, composition, total solid content and viscosity of liquid food can affect the ohmic heating rate. If fluid food is in the form of a solid-liquid mixture, particle dimensions, orientation, density and electrical conductivity ratios of liquid to solid are critical in assessing overall ohmic heating lethality.

The observed values of temperature at different time intervals, voltage gradients and concentrations have been represented in the Tables 4.2 to 4.6. The plots of temperature versus time for five different concentrations (50, 60, 70, 80 and 90%) of mango juice at five different voltage gradients (7, 12, 17, 22 and 27 V/cm) are shown in the Figure 4.1 to 4.5. The variation of temperature with time shows smooth and regular variation. The slope of the curves increases with increase in concentration, which shows that heating is fast in case of higher concentration. In other words heating rate is more for higher concentrations. This is due to the reason that higher voltage gradient induces higher current in the mango juice and hence the heating of juice was enhanced.

The experimental ohmic heating times required to raise the temperature of mango juice during ohmic heating from 14°C to 70°C have been represented in tables 4.2 to 4.6. The

heating time decreased as a result of higher heating rates resulting from higher voltage gradient applied. The heating curve depicting the rate of ohmic heating under different voltage gradients are presented in figures 4.2 to 4.6. As the temperature increased, the slope of temperature curves decreased i.e. the heating rate decreased.

Ohmic heating times are dependent on the voltage gradient used. As the voltage gradient increases, the heat generation per unit time increases and hence the heating time necessary to reach the prescribed temperature decreases. The heating rate reported at 27V/cm was much higher followed by 22, 17, 12 and 7 V/cm. A time scale can be arranged by choosing the correct voltage gradient parameter (Icier and Ilicali 2005a). Ohmic heating rates depend on the type and composition of the food material, relating with its electrical conductivity and the voltage gradient applied.

The time required to heat the mango juice from room temperature to 70°C at applied voltage gradient of 27 V/cm was 190 seconds. The heating rate kept on decreasing and heating time increases as the experiment was proceeded to lower voltage gradients of 22, 17, 12 and 7 V/cm. The heating time recorded to reach temperature 70 °C for 7 V/cm was more than 3600 seconds. Since the electrical energy per treatment time converting to the heat energy was dependent both on the voltage gradient and the current passing through the sample, the temperature rise at the instant time was higher at higher voltage gradients. The voltage gradient had a significant effect on the heating rate of mango juice during ohmic treatment. The sharp decrease of the ohmic heating time with increasing voltage gradient was obvious in milk and reconstituted whey solutions having various concentrations (Icier and Ilicali 2004, 2008).

Palaniappan and Sastry (1991a) reported heating curves having increasing slopes for orange juices having re-suspended insoluble solids. Hong *et al* 1998 studied the changes in heating profiles of apple juice by ohmic heating and reported that heating rate was highly dependent on applied voltage gradient. In their study, it was found that heating rate was not affected by the frequencies ranging from 60 Hz to 60 KHz. The heating rate may be affected by varying either the electric field strength or product electrical conductivity.

Temperature uniformity was maintained. Electric field distributed more evenly and its intensity was comparatively stronger in the middle region between the two electrodes but in the electrodes plates and lateral regions, the electric field intensity was much weaker, where the heating phenomenon was not obvious. Temperature and voltage are not independently controllable in the experiment. At a given power level and temperature, the field strength may be increased only if the electrical conductivity of the medium is decreased to keep power constant. Electrical conductivity may be changed either by changing temperature or addition of NaCl concentration.

**Table 4.2** Variation of temperature with time during ohmic heating of mango juice at 27 V/cm.

Time (s)	Temperature (°C)				
	90% (v/v)	80% (v/v)	70% (v/v)	60% (v/v)	50% (v/v)
0	15	15	14	15	15
10	19	17	16	17	16
20	21	19	18	18	18
30	24	20	19	20	19
40	25	22	21	21	20
50	28	24	23	23	22
60	30	26	24	25	23
70	33	28	26	26	25
80	35	31	28	28	27
90	38	33	30	30	29
100	41	35	32	31	30
110	44	38	34	33	32
120	47	40	36	35	34
130	50	43	38	37	36
140	53	45	40	39	38
150	57	48	42	41	40
160	60	51	45	44	42
170	64	54	47	46	44
180	67	57	50	48	46
190	70	60	53	51	49

**Table 4.3** Variation of temperature with time during ohmic heating of mango juice at 22 V/cm.

Time (s)	Temperature (°C)				
	90% (v/v)	80% (v/v)	70% (v/v)	60% (v/v)	50% (v/v)
0	15	15	16	17	14
10	17	15	17	18	14
20	18	16	18	19	15
30	19	17	19	19	16
40	21	18	20	20	16
50	22	19	21	21	17
60	24	20	22	22	18
70	25	21	23	23	18
80	26	23	24	24	20
90	28	24	25	26	20
100	30	25	26	26	21
110	32	26	27	28	22
120	33	28	28	29	23
130	35	29	30	30	24
140	37	30	31	31	25
150	39	31	32	32	26
160	40	33	34	33	28
170	42	34	35	35	29
180	44	36	36	36	30
190	46	37	38	37	31
200	49	39	39	38	32
210	51	40	40	39	34
220	53	42	42	41	35
230	55	43	44	42	37
240	57	45	45	43	38
250	60	47	47	45	39
260	62	49	48	46	41

**Table 4.4 Variation of temperature with time during ohmic heating of mango juice at 17 V/cm.**

Time (s)	Temperature (°C)				
	90% (v/v)	80% (v/v)	70% (v/v)	60% (v/v)	50% (v/v)
0	15	15	15	15	15
10	16	15	16	16	15
20	17	16	17	17	16
30	17	17	17	17	16
40	18	17	18	18	17
50	19	18	19	18	18
60	20	19	20	19	18
70	20	19	20	19	18
80	21	20	21	20	19
90	22	21	22	21	20
100	23	21	22	21	20
110	23	22	23	22	21
120	24	23	24	22	21
130	25	23	25	23	22
140	26	24	25	24	22
150	27	25	26	24	23
160	28	26	27	25	24
170	28	26	27	26	24
180	30	27	29	27	25
190	30	28	29	27	25
200	31	29	30	28	26
210	32	30	31	29	27
220	33	30	32	29	27
230	34	31	32	30	28
240	35	32	33	31	29
250	36	33	34	32	29

260	37	33	35	32	30
270	38	34	36	33	31
280	39	35	37	34	31
290	40	36	37	35	32
300	41	37	38	36	33
310	43	38	39	37	34
320	44	40	40	37	34
330	45	40	41	38	35
340	46	42	42	39	36
350	47	42	43	40	36
360	48	43	44	41	37
370	50	44	45	42	38
380	51	45	46	42	39
390	52	46	47	43	39
400	53	48	49	44	40
410	54	49	50	45	41
420	56	50	51	46	41
430	57	51	52	47	42
440	59	52	53	48	43
450	60	53	54	49	44
460	61	54	55	50	44
470	62	55	56	51	45
480	64	57	58	52	46
490	66	58	59	52	47
500	67	59	60	53	48
510	69	60	61	54	49
520	70	62	63	55	49

**Table 4.5 Variation of temperature with time during ohmic heating of mango juice at 12 V/cm.**

Time (s)	Temperature (°C)				
	90% (v/v)	80% (v/v)	70% (v/v)	60% (v/v)	50% (v/v)
0	14	14	13	17	13
10	14	14	13	17	13
20	15	15	13	17	13
30	15	15	14	17	13
40	15	15	14	18	13
50	16	15	14	18	13
60	16	16	14	18	14
70	16	16	14	19	14
80	17	16	14	19	14
90	17	17	15	19	14
100	17	17	15	19	14
110	18	17	15	20	14
120	18	18	15	20	15
130	18	18	15	20	15
140	19	19	16	21	15
150	19	19	16	21	15
160	20	19	16	21	16
170	20	19	16	22	16
180	20	20	16	22	16
190	21	20	17	22	16
200	21	20	17	23	16
210	21	21	17	23	17
220	22	21	17	23	17
230	22	21	17	24	17
240	22	22	18	24	17
250	23	22	18	24	17
260	23	23	18	25	18
270	23	23	18	25	18
280	24	23	18	25	18
290	24	24	19	25	18

300	25	24	19	26	19
310	25	24	20	26	19
320	25	25	20	27	19
330	26	25	20	27	19
340	26	26	21	27	19
350	26	26	21	27	20
360	27	26	21	28	20
370	27	27	21	28	20
380	28	27	22	28	20
390	28	27	22	29	21
400	28	28	22	29	21
410	29	28	23	29	21
420	29	28	23	30	21
430	29	29	23	30	22
440	30	29	24	30	22
450	30	30	24	31	22
460	31	30	24	31	22
470	31	30	25	31	23
480	31	31	25	32	23
490	32	31	25	32	23
500	32	31	26	32	24
510	33	32	26	33	24
520	33	32	27	33	24
530	34	33	27	33	25
540	34	33	27	34	25
550	34	33	27	34	25
560	35	34	28	34	25
570	35	34	29	35	26
580	36	34	29	35	26
590	36	35	29	35	26
600	36	35	30	36	27
610	37	36	30	36	27
620	37	36	30	36	27
630	38	37	31	37	27

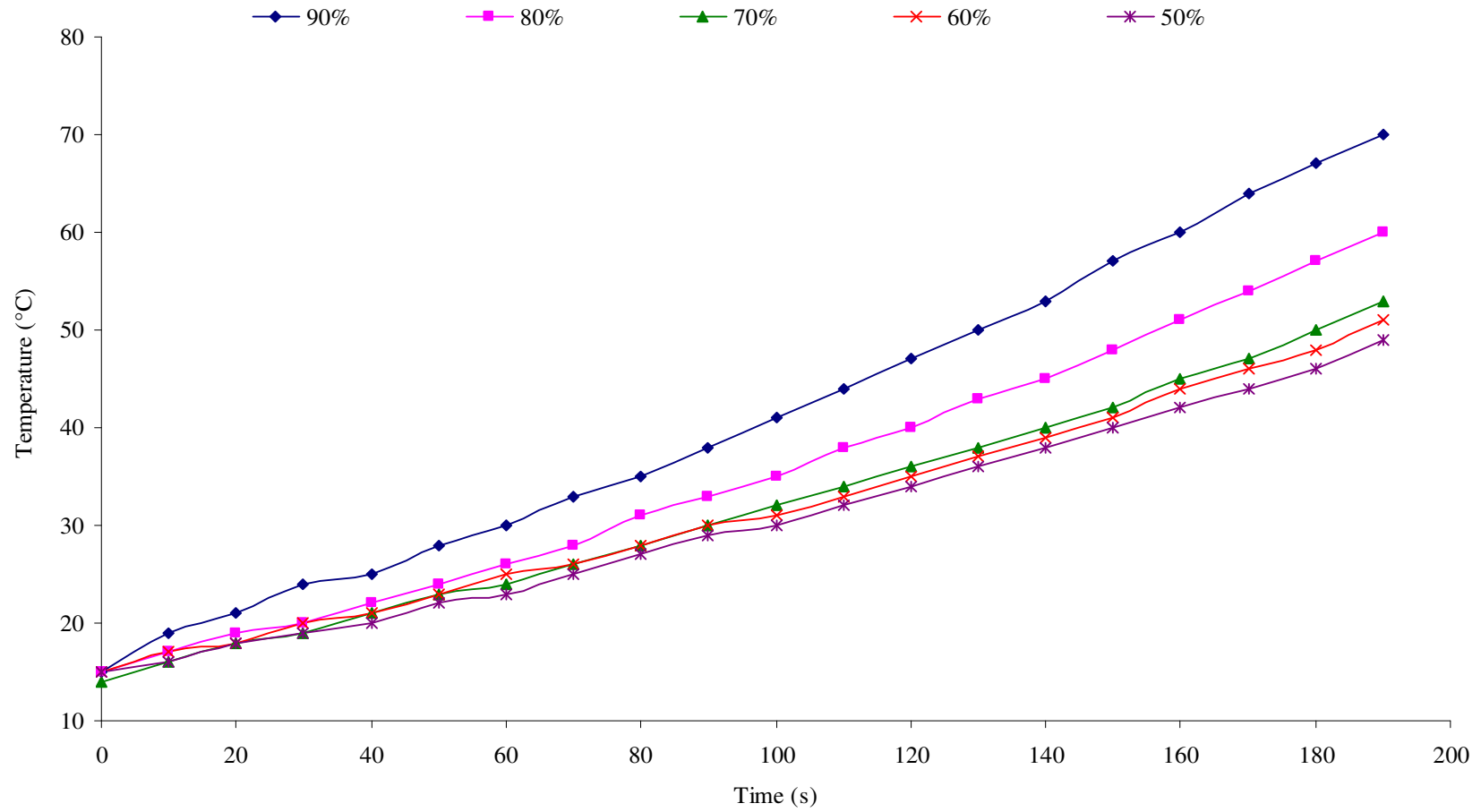
640	38	37	31	37	28
650	38	37	32	38	28
660	38	38	32	38	28
670	38	38	33	38	29
680	38	39	33	39	29
690	38	39	33	39	29
700	39	39	34	39	29
710	39	40	34	40	30
720	40	40	35	40	30
730	40	41	35	40	30
740	40	41	35	41	31
750	41	42	36	41	31
760	41	42	36	41	31
770	42	43	37	42	31
780	42	43	37	42	32
790	43	44	38	42	32
800	43	44	38	43	32
810	44	44	38	43	33
820	44	45	39	43	33
830	45	45	40	44	34
840	45	46	40	44	34
850	46	46	41	44	34
860	46	47	41	45	34
870	46	47	41	45	35
880	47	47	42	46	35
890	47	48	42	46	35
900	48	48	43	46	36
910	48	49	44	47	36
920	49	49	44	47	36
930	49	50	44	48	37
940	50	50	44	48	37
950	51	51	45	48	38
960	51	51	46	49	38
970	52	52	46	49	38

980	52	52	47	49	39
990	52	53	47	50	39
1000	53	53	48	50	39
1010	54	54	49	50	40
1020	54	54	49	51	40
1030	55	55	49	51	40
1040	55	55	50	52	41
1050	56	56	50	52	41
1060	56	56	51	52	41
1070	57	56	52	53	42
1080	57	57	52	53	42
1090	58	57	53	54	42
1100	58	58	53	54	43
1110	59	59	54	54	43
1120	59	59	54	55	44
1130	60	59	55	55	44
1140	61	60	56	55	44
1150	61	60	56	56	45
1160	62	61	57	56	45
1170	62	62	57	57	45
1180	63	62	58	57	46
1190	64	63	58	57	47
1200	64	63	59	58	47
1210	65	64	60	58	47
1220	65	64	61	58	47
1230	66	65	61	59	48
1240	67	65	61	59	48
1250	67	66	62	60	48
1260	68	66	63	60	49
1270	69	67	63	60	49
1280	69	67	64	61	50
1290	70	68	65	61	50

**Table 4.6** Variation of temperature with time during ohmic heating of mango juice at 7 V/cm.

Time (s)	Temperature ( °C)				
	90% (v/v)	80% (v/v)	70% (v/v)	60% (v/v)	50% (v/v)
0	17	17	17	17	16
50	22	21	21	18	16
100	23	22	21	18	17
150	24	23	22	19	17
200	26	24	22	20	18
250	26	24	23	20	18
300	27	25	23	21	19
350	27	25	24	21	19
400	29	26	25	22	20
450	29	27	25	22	20
500	31	28	26	23	21
550	31	28	26	23	21
600	32	29	27	24	21
650	33	29	27	24	22
700	33	30	28	25	22
750	34	31	28	25	23
800	34	31	29	26	23
850	35	32	29	26	24
900	35	32	30	27	24
950	36	33	30	27	25
1000	36	33	31	28	25
1050	37	34	31	28	25
1100	38	35	31	29	26
1150	38	35	32	29	26
1200	39	36	32	30	27
1250	39	36	33	30	27
1300	40	37	33	31	28
1350	41	38	34	31	28
1400	41	38	34	32	28
1450	42	39	35	32	29
1500	42	39	35	33	29
1550	43	40	36	33	30
1600	44	40	36	34	30
1650	44	41	37	34	30

1700	45	42	37	35	31
1750	45	42	38	35	31
1800	46	43	38	35	32
1850	46	43	38	36	32
1900	47	44	39	36	32
1950	48	44	39	37	33
2000	48	45	40	37	33
2050	49	45	40	38	34
2100	49	46	41	38	34
2150	50	46	41	39	34
2200	50	47	42	39	35
2250	51	47	42	40	35
2300	52	48	43	40	35
2350	52	48	43	40	36
2400	53	49	43	41	36
2450	53	49	44	41	37
2500	54	50	44	42	37
2550	54	50	45	42	37
2600	55	51	45	43	38
2650	56	51	46	43	38
2700	56	52	46	43	38
2750	57	53	47	44	39
2800	57	53	47	44	39
2850	58	53	47	45	40
2900	58	54	48	45	40
2950	58	54	48	46	40
3000	59	55	49	46	41
3050	59	55	49	47	41
3100	60	56	49	47	41
3150	60	56	50	47	41
3200	61	57	50	48	42
3250	61	57	51	48	42
3300	62	58	51	48	42
3350	62	59	51	49	43
3400	63	59	52	49	43



**Figure 4.1** Variation of temperature with time during ohmic heating of mango juice at 27 V/cm.

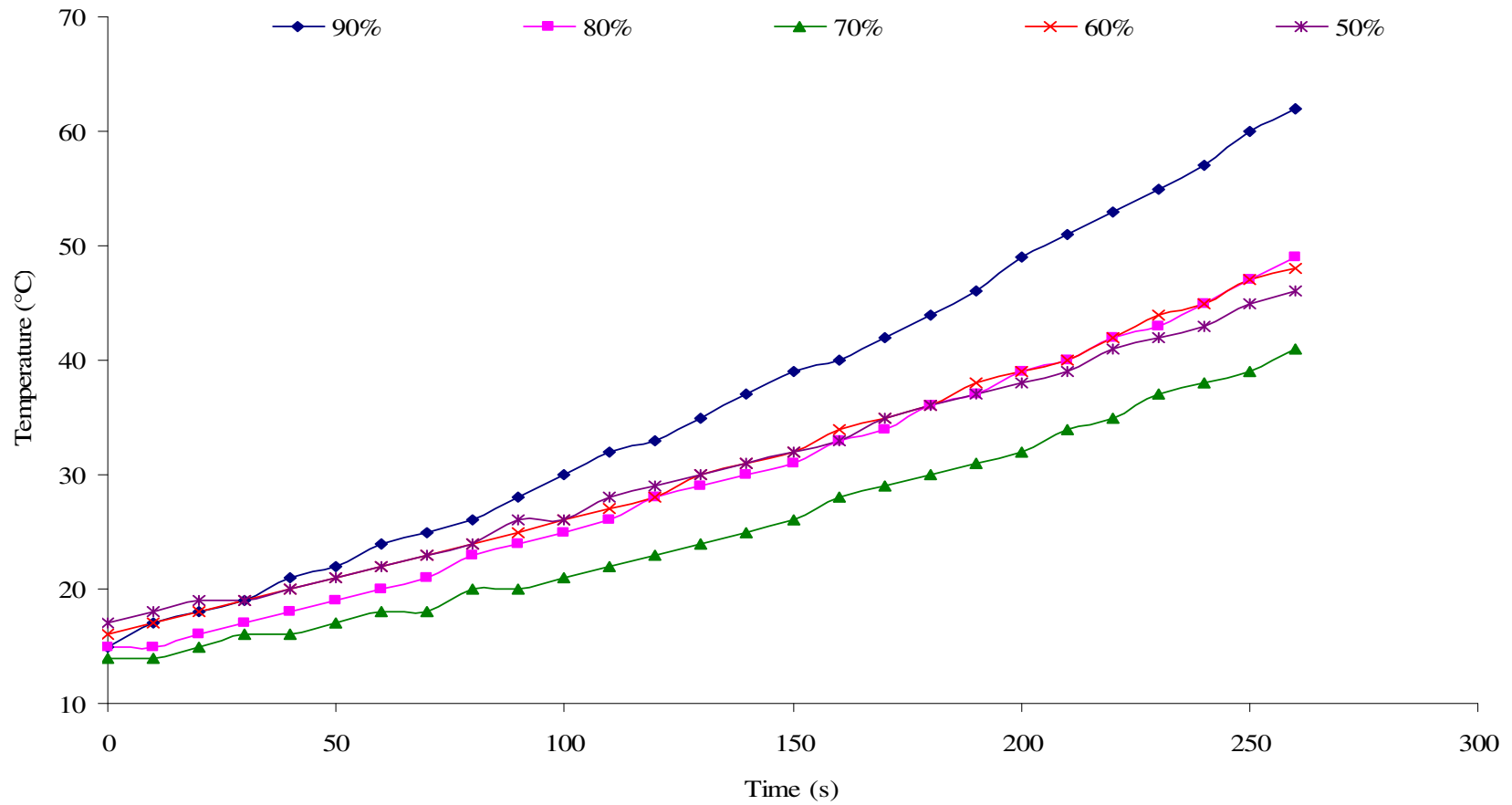


Figure 4.2 Variation of temperature with time during ohmic heating of mango juice at 22 V/cm.

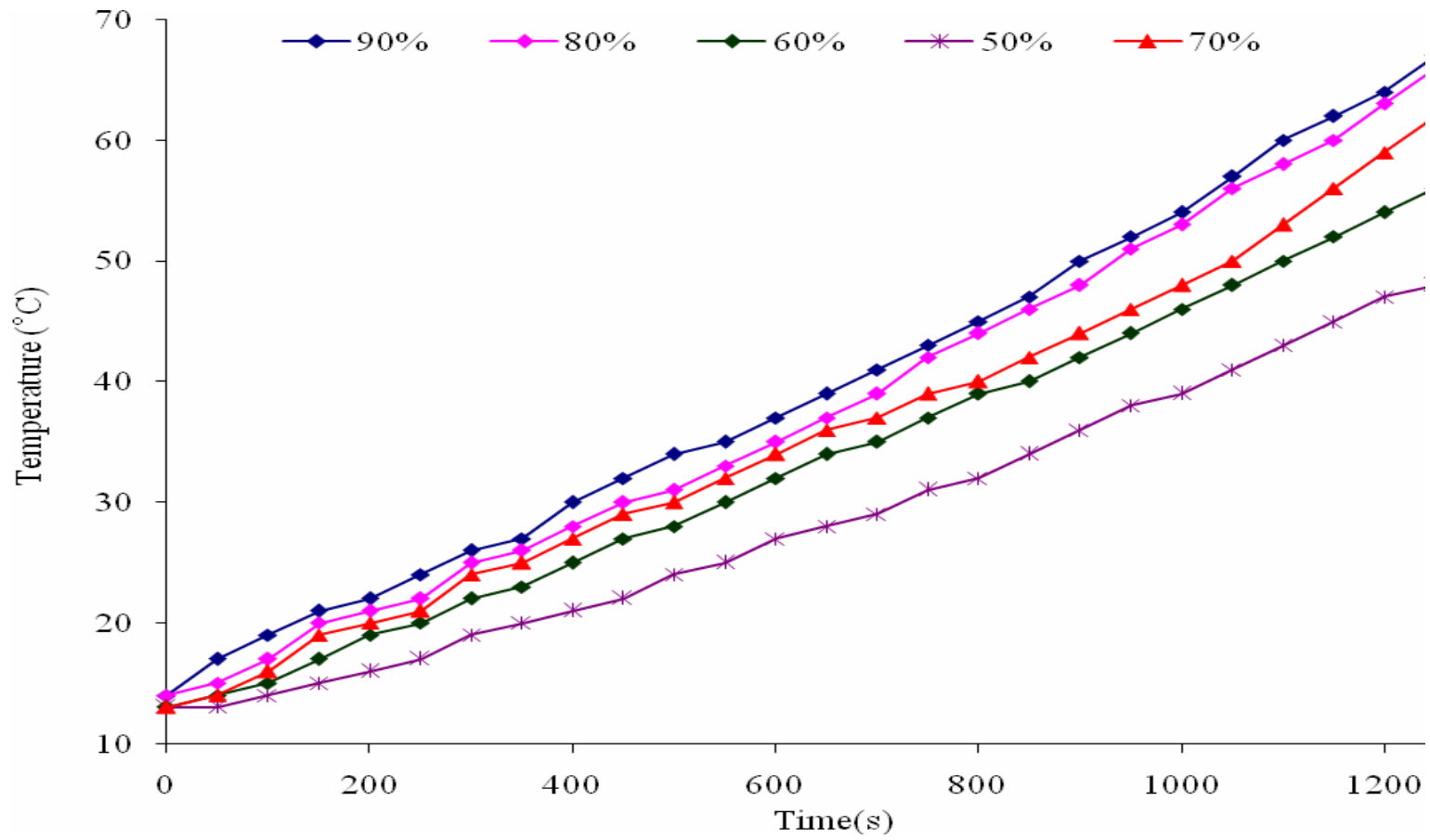
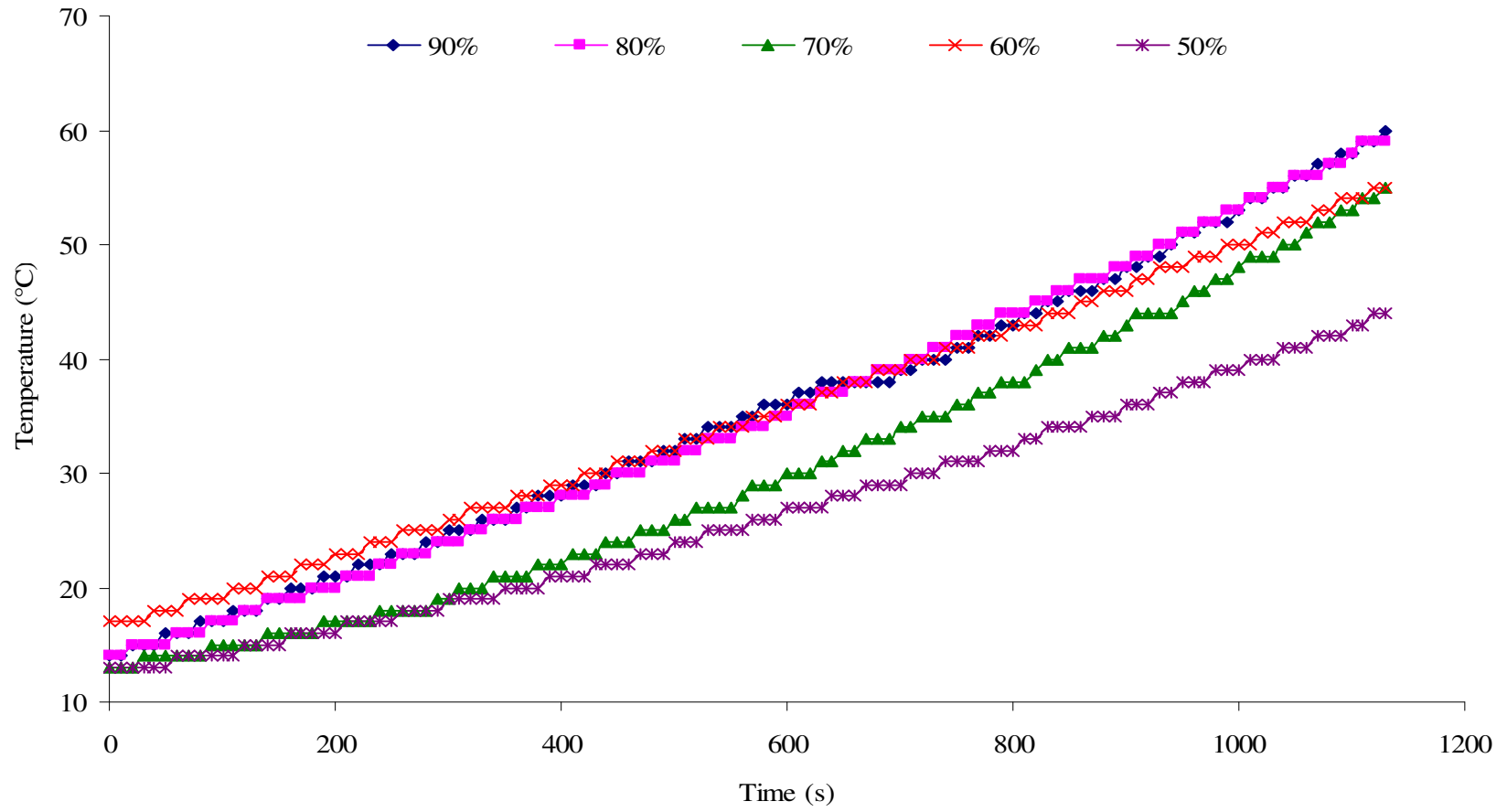


Figure 4.3 Variation of temperature with time during ohmic heating of mango juice at 17V/cm.



**Figure 4: Variation of temperature with time during ohmic heating of mango juice at 12 V/cm.**

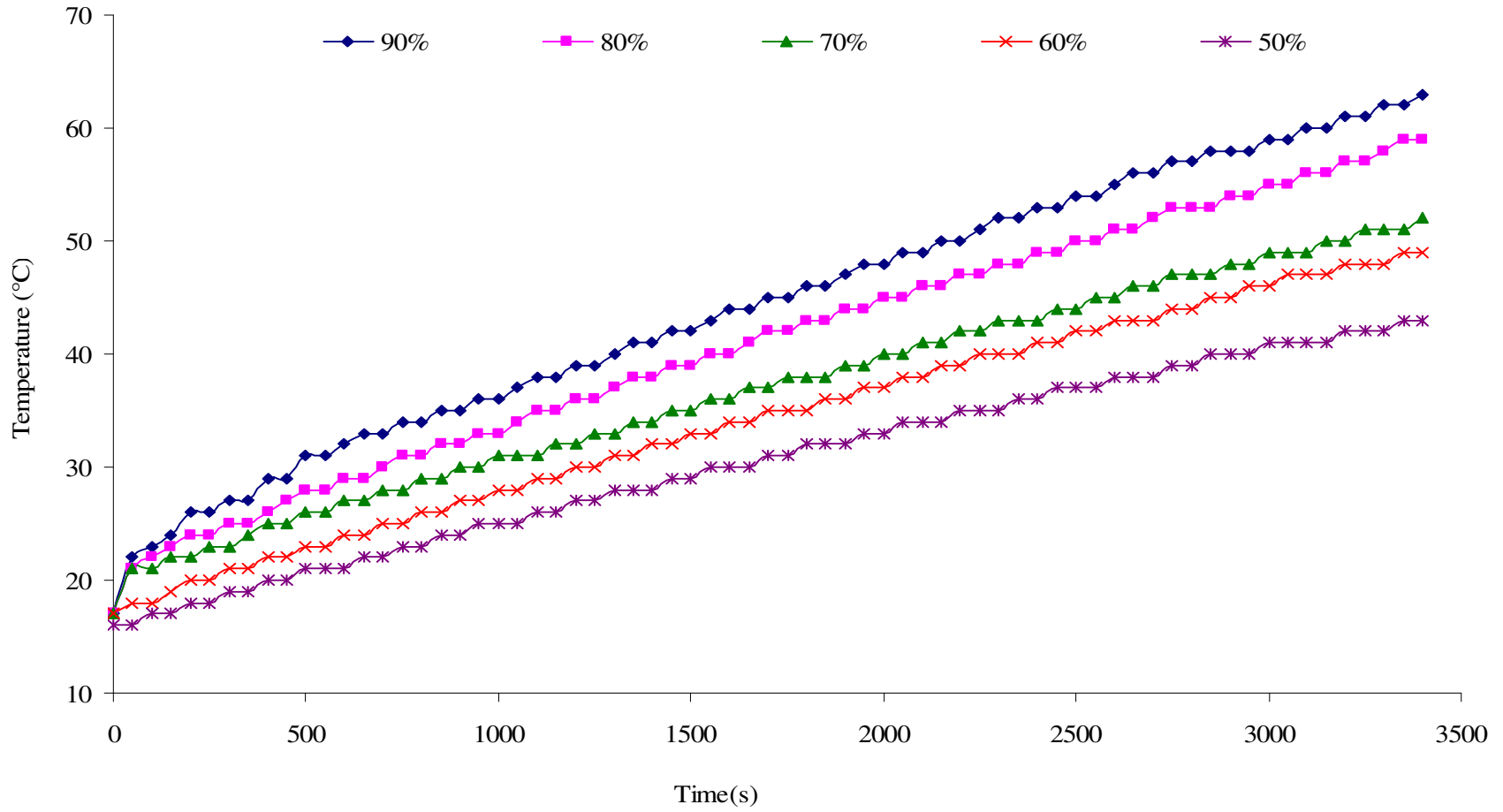


Figure 4.5 Variation of temperature with time during ohmic heating of mango juice at 7V/cm

De Alwis *et al* (1990) found that during ohmic heating electrode surface temperature were usually 2-3°C lower than the bulk. They attributed that the electrode can only heat by its resistance which is very low. It is only the conduction from the liquid that will cause the temperature rise. So if the system is not well mixed, temperature differences between the electrode and the food materials could be observed.

Formation of bubbles was observed during the heating process, especially when the temperature of heated samples reached around 50°C. The reason for this could be the release of gas in the liquid due to some electro-chemical reactions. Palaniappan and Sastry (1991b) reported that fruit juices are acidic resulting in the potential electrolytic hydrogen bubble formation. Zhao and Kolbe (1999) also discussed that the gas bubbles were the results of either water boiling due to localized high current densities or the formation of by-products of various oxidation or reduction reactions (e.g. H<sub>2</sub> or O<sub>2</sub> gas). The bubbles occurred much more quickly in high voltage gradient operations. Castro *et al* (2004) explained that in an unpressurized heater, if air is occluded in the sample, the air bubbles expanded with temperature, with the pressure remaining constant. Noticeable gas liberation at the stainless steel electrodes during ohmic heating of orange juice was reported by Lima and Sastry (1999). However, there was no visible gas liberation, electrode cavitations, metal dissolution or rusty tinge in the juice sample heated as the electrodes were food grade. Therefore releasing the bubbles needs serious consideration in designing the static ohmic heaters.

In addition to this, Icier and Ilicali (2004) reported that the decrease in the concentration of the apple and sour-cherry juices from 60% to 20% enhanced the ohmic heating rate of the juices. The experimental heating times of mango juice at higher concentration was least when maximum voltage gradient was applied. At same concentration, the reaction rate increases with the field strength or applied voltage gradient. The evidences also show that the value of electrical conductivity of a food heated electrically is different from that cooked by conventional heating by Fryer *et al* (1992). In fact, Wang and Sastry (1997) demonstrated that samples pre-heated by either conventional or ohmic heating had a higher heating rate due to increased electrical conductivity and that the values found for electrical conductivity were different in each case.

Ohmic heating is longer for lower solute concentrations of reconstituted whey solutions in solute concentration range of 8-24% w/v (Icier 2008). It is explained by the decreasing amount of free ions or charge carriers, which decrease the electrical conductivity, at lower concentrations. In that, the fast heating occurs in whey solutions having higher electrical conductivity.

Fruits and vegetable products are also successfully ohmically heated. Their high heating rates, which are dependent on the voltage gradient applied (Lima and Sastry 1999, Icier and Ilicali 2004, 2005a, b, Assiry *et al* 2003, Castro *et al* 2004, Leizeron and Shimoni

2005, Icier *et al* 2006, 2008, Alliali *et al* 2008, Yildiz *et al* 2009, 2010).

The specific electrical resistance can also be expressed as the inverse of the electrical conductivity. It is different from electrical resistance since the specific resistance decreases with a rise in temperature (Bhale 2004). The temperature dependency of the specific electrical resistance of the food and the dimensions of the ohmic application unit determines the power required to be applied (Reznick 1996).

The application of ohmic heating at high voltage gradients and at higher solute concentrations could be advantageous to obtain faster heating at the industrial processing of whey solutions. The precise measurement and the accurate control of the temperature during ohmic heating are crucial in the design procedures of ohmic heating systems.

#### **4.2 VARIATION OF ELECTRICAL CONDUCTIVITY**

Values of electrical conductivity at different temperatures for five different concentrations and different voltage gradients have been shown in Table 4.7 to 4.11. The curves depicting the variation of electrical conductivity with temperature are outlined in the Figures 4.6 to 4.10. The electrical conductivity of mango juice was found to increase with temperature. The rise in electrical conductivity was observed due to increase in the ionic mobility. Electrical conductivity varied with the temperature in a linear fashion. The electrical conductivity is greatly affected by applied voltage gradient. The maximum value of electrical conductivity recorded was approximately 17 S/cm. at 27 V/cm for 90% concentration of mango juice followed by 22, 17, 12 and 7 V/cm. In the study, the electrical conductivity values of mango juice concentrates have shown an increasing trend with temperature at all the applied voltage gradients. In addition to temperature, the electrical conductivity of foods is strongly affected by ionic content, moisture mobility and physical structure as well as the heating process. The electrical current is carried out by movement of ions in liquids (Shirsat *et al* 2004). The electrical conductivity varied from 4 to 17 S/cm.

The electrical conductivity increased with temperature as expected and consistent with literature data. (Kumar *et al* 2011, Icier *et al* 2008, Darvishi *et al* 2011, Kemp and Fryer 2007, Icier and Ilicali 2004, 2005a, Amiali *et al* 2006, Castro *et al* 2004). Qihua *et al* (1993) also found a linear relationship between temperature and electrical conductivity of orange juice. Castro *et al* (2004) reported that electrical conductivity of strawberry based products increased with temperature following linear or quadratic relations depending on product type tested. Icier and Ilicali (2004) explained the increase in electrical conductivity with temperature as reduced drag for the movement of ions. The results are similar to those reported by Kemp and Fryer (2007), Icier *et al* (2008), Icier and Ilicali (2004 and 2005a, b), Li *et al* (2004), and Tulsian *et al* (2008). Concerning the role of particle concentration in orange and tomato juices, Palaniappan and Sastry (1991b) revealed that overall electrical conductivity decreased as the percentage of solid constituents dispersed in the liquid phase

increased. With respect to particle size, the electrical conductivity increased as size decreased. Even Zareifard *et al* (2003) deduced that the particle size and concentration influenced the overall electrical conductivity of the two-phase food systems. Although the heating behavior was different, very slight changes in the values of the overall electrical conductivities of the two-phase food systems were observed.

It has been mentioned that electrical conductivity versus temperature is usually a linear relationship. However this is not always the case. Several examples exist where the curve became non-linear. This has been reported in the studies of Wang and Sastry (1997) and Castro *et al* (2004). This non-linearity has been attributed to the equilibration of solutes within the samples during heating, thus altering the value of the observed electrical conductivity.

For liquid foods, electrical conductivity has a linear relationship with temperature. But the value of electrical conductivity decreases if non-polar (or non-conductive) constituents are present. These constituents would be regarded as the “solid content” of the liquid (e.g., the pulp content of juice). This definitely is going to vary the electrical conductivity value of the juice sample. Castro *et al* 2003 showed that electrical conductivity decreased with increase in solids and sugar contents, suggesting that at higher solids content (>20% w/w) and sugar contents of >40 °Brix a different design of ohmic heater may be necessary. However, when dealing with salt concentrations, the effects of the salt rather than other components becomes dominant once its concentration exceeds about 1 % ( Marcotte *et al* 2000).

A similar influence of solids concentration on electrical conductivity has also been reported in the studies carried out by Zareifard *et al* (2003), but in these cases the solids were particles of significant sizes suspended in a fluid. This situation differs from the fore said because the value of electrical conductivity is not that of the fluid but a combined value for the mixture fluid and particles. In fact, not only solid content but also solid size will influence the fluid foods.

As the applied voltage gradient increased, the current passing through the system attained higher values at lower temperatures. This leads to bubbling in the samples and thus heating process was carried only up to 70°C.

It was observed that electrical conductivity decreased with temperature rise when bubbling started and heating was stopped. (Castro *et al* 2004) investigated that the air bubble so formed would further expand as temperature increases. This would mean that bubble volume would increase with temperature. Thus air, which can be roughly considered to be of zero electrical conductivity, will increase in area, tending to reduce the electrical conductivity of juice (Darvishi *et al* 2012a). This phenomenon appears due to localized high current densities of various oxidation or reduction reactions (H<sub>2</sub> or O<sub>2</sub> gas). The similar effect was

**Table 4.7 Variation of electrical conductivity of mango juice at 90% concentration during ohmic heating**

Sr. No.	Temperature (°C)	Electrical conductivity (S/cm)				
		27V/cm	22 V/cm	17 V/cm	12 V/cm	7 V/cm
1	22	6.512	7.356	6.947	6.750	5.582
2	24	7.164	7.356	7.237	6.750	5.582
3	26	7.815	7.815	7.526	7.105	5.582
4	28	7.815	8.275	7.815	7.460	6.699
5	30	8.463	8.735	8.394	7.815	6.699
6	32	9.118	9.195	8.684	8.171	6.699
7	34	9.118	9.195	8.684	8.526	7.815
8	36	9.769	9.655	9.263	8.881	7.815
9	38	10.421	10.114	9.552	9.237	8.932
10	40	10.421	10.574	9.842	9.592	8.932
11	42	11.072	10.574	10.131	9.592	8.932
12	44	11.723	11.034	10.421	9.947	10.049
13	46	11.723	11.494	11.000	10.302	10.049
14	48	12.375	11.953	11.289	10.658	10.049
15	50	12.375	12.413	11.289	11.013	11.165
16	52	13.026	12.873	11.868	11.368	11.165
17	54	13.677	13.333	12.158	11.723	12.282
18	56	13.677	13.333	12.447	12.079	12.282
19	58	14.329	13.792	12.737	12.079	13.398
20	60	14.980	14.252	13.026	12.434	13.398
21	62	14.980	14.712	13.316	12.789	14.515
22	64	15.631	15.172	13.895	13.145	14.515
23	66	16.283	15.631	14.184	13.500	14.515
24	68	16.283	16.091	14.474	13.855	15.631
25	70	16.934	16.091	14.763	13.855	15.631

**Table 4.8 Variation of electrical conductivity of mango juice at 80% concentration during ohmic heating**

Sr. No.	Temperature (°C)	Electrical conductivity (S/cm)				
		27V/cm	22 V/cm	17 V/cm	12 V/cm	7 V/cm
1	22	6.079	6.394	6.436	5.861	4.466
2	24	6.368	6.394	6.436	5.861	5.585
3	26	6.658	6.750	6.896	6.513	5.585
4	28	6.947	7.105	7.356	7.164	5.585
5	30	7.237	7.460	7.815	7.164	6.699
6	32	7.526	7.815	8.275	7.815	6.699
7	34	7.815	8.171	8.735	7.815	6.699
8	36	8.105	8.526	8.735	8.467	7.815
9	38	8.394	8.881	9.195	8.467	7.815
10	40	8.684	9.592	9.655	9.118	7.815
11	42	9.263	9.592	10.114	9.118	8.932
12	44	9.263	9.946	10.114	9.769	8.932
13	46	9.842	10.658	10.574	10.421	8.932
14	48	10.131	10.658	11.034	10.421	10.049
15	50	10.421	11.368	11.494	11.072	10.049
16	52	10.710	11.723	11.953	11.072	10.049
17	54	11.000	11.723	12.413	11.723	11.165
18	56	11.282	12.079	12.413	11.723	11.165
19	58	11.579	12.434	12.873	12.375	11.165
20	60	11.868	13.145	13.333	13.026	12.282
21	62	12.158	13.500	13.792	13.026	12.282
22	64	12.447	13.855	14.252	13.677	12.282
23	66	12.737	14.210	14.252	14.329	13.398
24	68	13.026	14.566	14.712	14.329	13.398
25	70	13.316	14.921	15.172	14.980	14.515

**Table 4.9 Variation of electrical conductivity of mango juice at 70% concentration during ohmic heating**

Sr. No.	Temperature (°C)	Electrical conductivity (S/cm)				
		27V/cm	22 V/cm	17 V/cm	12 V/cm	7 V/cm
1	22	6.658	5.329	5.976	5.210	3.349
2	24	6.947	5.684	6.436	5.210	3.349
3	26	7.237	6.039	6.436	5.861	3.349
4	28	7.526	6.394	6.896	5.861	4.466
5	30	8.105	6.750	7.356	6.513	4.466
6	32	8.394	7.105	7.815	6.513	4.466
7	34	8.684	7.460	7.815	7.164	5.582
8	36	8.973	7.815	8.275	7.164	5.582
9	38	9.552	8.171	8.735	7.815	5.582
10	40	9.842	8.526	9.195	7.815	6.699
11	42	10.421	8.881	9.195	8.467	6.699
12	44	10.421	8.881	9.655	8.467	6.699
13	46	11.000	9.237	10.114	9.118	6.699
14	48	11.579	9.592	10.574	9.118	7.815
15	50	11.868	9.947	10.574	9.769	7.815
16	52	12.158	10.302	11.034	9.769	7.815
17	54	12.447	10.658	11.034	10.421	8.923
18	56	12.737	10.658	11.494	10.421	8.923
19	58	13.316	11.013	11.953	11.072	8.923
20	60	13.605	11.368	12.413	11.072	9.357
21	62	13.605	11.723	12.413	11.723	9.357
22	64	14.184	12.079	12.873	11.723	10.213
23	66	14.474	12.079	13.333	12.375	10.213
24	68	14.763	12.434	13.792	12.375	10.213
25	70	15.342	12.789	13.792	13.026	11.004

**Table 4.10** Variation of electrical conductivity of mango juice at 60% concentration during ohmic heating

Sr. No.	Temperature (°C)	Electrical conductivity (S/cm)				
		27V/cm	22 V/cm	17 V/cm	12 V/cm	7 V/cm
1	22	6.368	6.039	3.218	3.907	3.349
2	24	6.368	6.394	3.678	3.907	3.349
3	26	6.947	6.750	3.678	4.559	3.349
4	28	7.237	7.105	4.137	4.559	3.349
5	30	7.526	7.460	4.137	5.210	4.466
6	32	7.815	7.815	4.597	5.210	4.466
7	34	8.105	7.815	4.597	5.861	4.466
8	36	8.684	8.171	5.057	5.861	4.466
9	38	8.973	8.526	5.057	6.513	5.582
10	40	9.263	8.881	5.517	6.513	5.582
11	42	9.552	9.237	5.517	6.513	5.582
12	44	9.842	9.592	5.976	7.164	5.582
13	46	10.131	9.947	5.976	7.164	5.582
14	48	10.421	10.302	6.436	7.815	5.582
15	50	11.000	10.302	6.436	7.815	5.582
16	52	11.000	11.013	6.896	8.467	6.635
17	54	11.579	11.368	6.896	8.467	6.635
18	56	11.579	11.368	7.356	8.467	6.635
19	58	12.158	11.723	7.356	9.118	6.635
20	60	12.447	12.079	7.815	9.118	7.794
21	62	12.737	12.434	7.815	9.769	7.794
22	64	13.026	12.789	8.275	9.769	7.794
23	66	13.316	13.145	8.275	10.421	7.794
24	68	13.895	13.500	7.735	10.421	8.812
25	70	14.184	13.855	8.735	11.072	8.812

**Table 4.11 Variation of electrical conductivity of mango juice at 50% concentration during ohmic heating**

Sr. No.	Temperature (°C)	Electrical conductivity (S/cm)				
		27V/cm	22 V/cm	17 V/cm	12 V/cm	7 V/cm
1	22	4.921	4.263	4.597	3.907	2.233
2	24	5.210	4.263	5.057	3.907	2.233
3	26	5.500	4.618	5.517	4.559	2.233
4	28	5.789	4.618	5.517	4.559	3.349
5	30	5.789	4.973	5.976	5.210	3.349
6	32	6.079	5.329	5.976	5.210	3.349
7	34	6.368	5.329	6.436	5.210	3.349
8	36	6.658	5.684	6.436	5.861	3.349
9	38	6.658	5.684	6.896	5.861	4.466
10	40	6.947	6.039	7.356	5.861	4.466
11	42	7.237	6.394	7.356	6.513	4.466
12	44	7.526	6.394	7.815	6.513	4.466
13	46	7.815	6.750	7.815	7.164	4.466
14	48	7.815	6.750	8.275	7.164	5.582
15	50	8.105	7.105	8.275	7.164	5.582
16	52	8.394	7.460	8.735	7.815	5.582
17	54	8.684	7.815	9.195	7.815	5.582
18	56	8.973	7.815	9.655	7.815	5.582
19	58	9.263	8.171	9.655	8.467	6.702
20	60	9.552	8.526	10.114	8.467	6.702
21	62	9.842	8.526	10.574	9.118	6.702
22	64	9.842	8.881	10.574	9.118	6.702
23	66	10.131	8.881	11.034	9.118	7.913
24	68	10.421	9.237	11.034	9.769	7.913
25	70	10.710	9.592	11.494	9.769	7.913

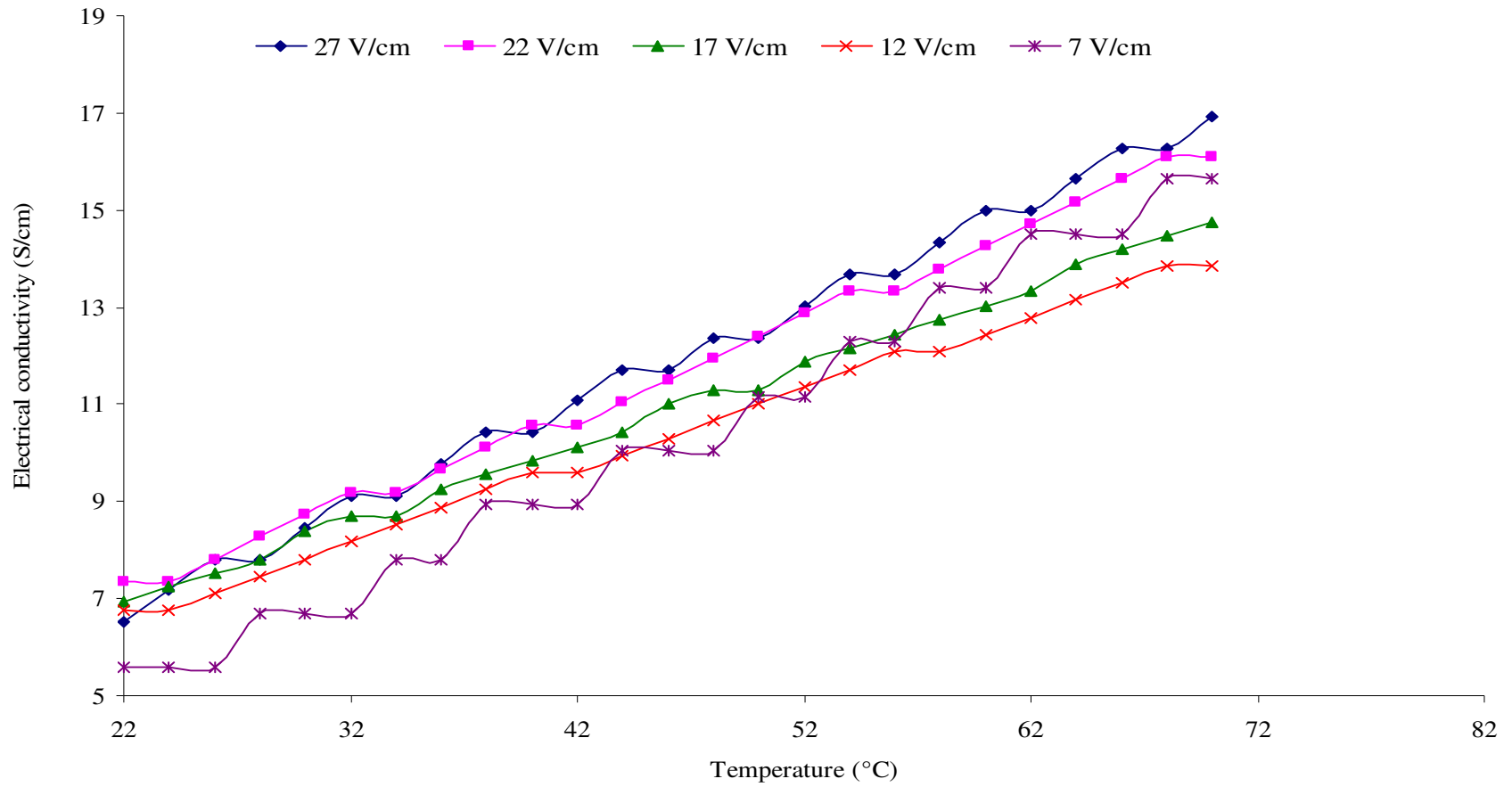


Figure 4.6 The change in electrical conductivity with temperature under five voltage gradients for 90% concentration of mango juice

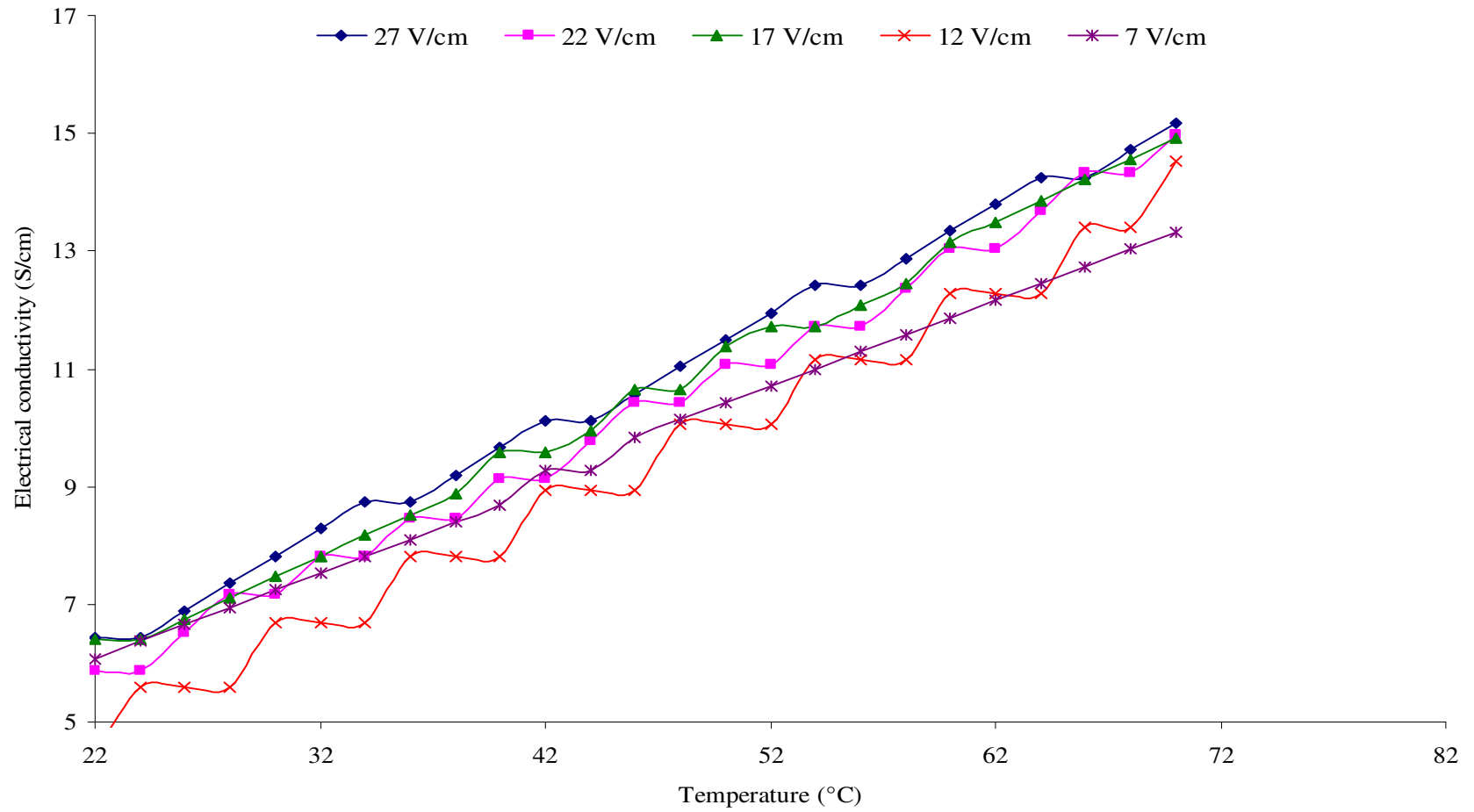
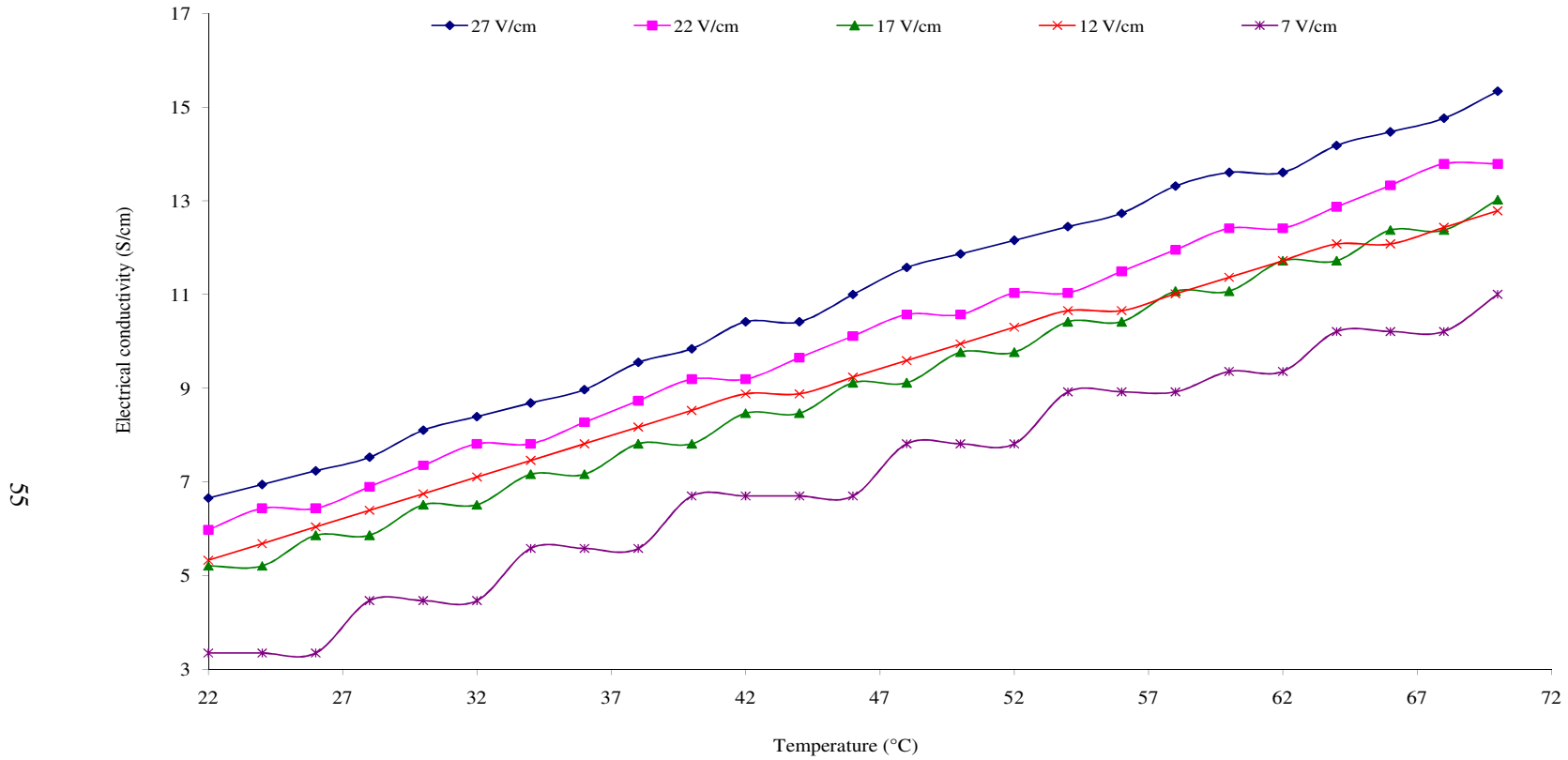


Figure 4.7 The change in electrical conductivity with temperature under five voltage gradients for 80% concentration of mango juice



**Figure 4.8** The change in electrical conductivity with temperature under five voltage gradients for 70% concentration of mango juice

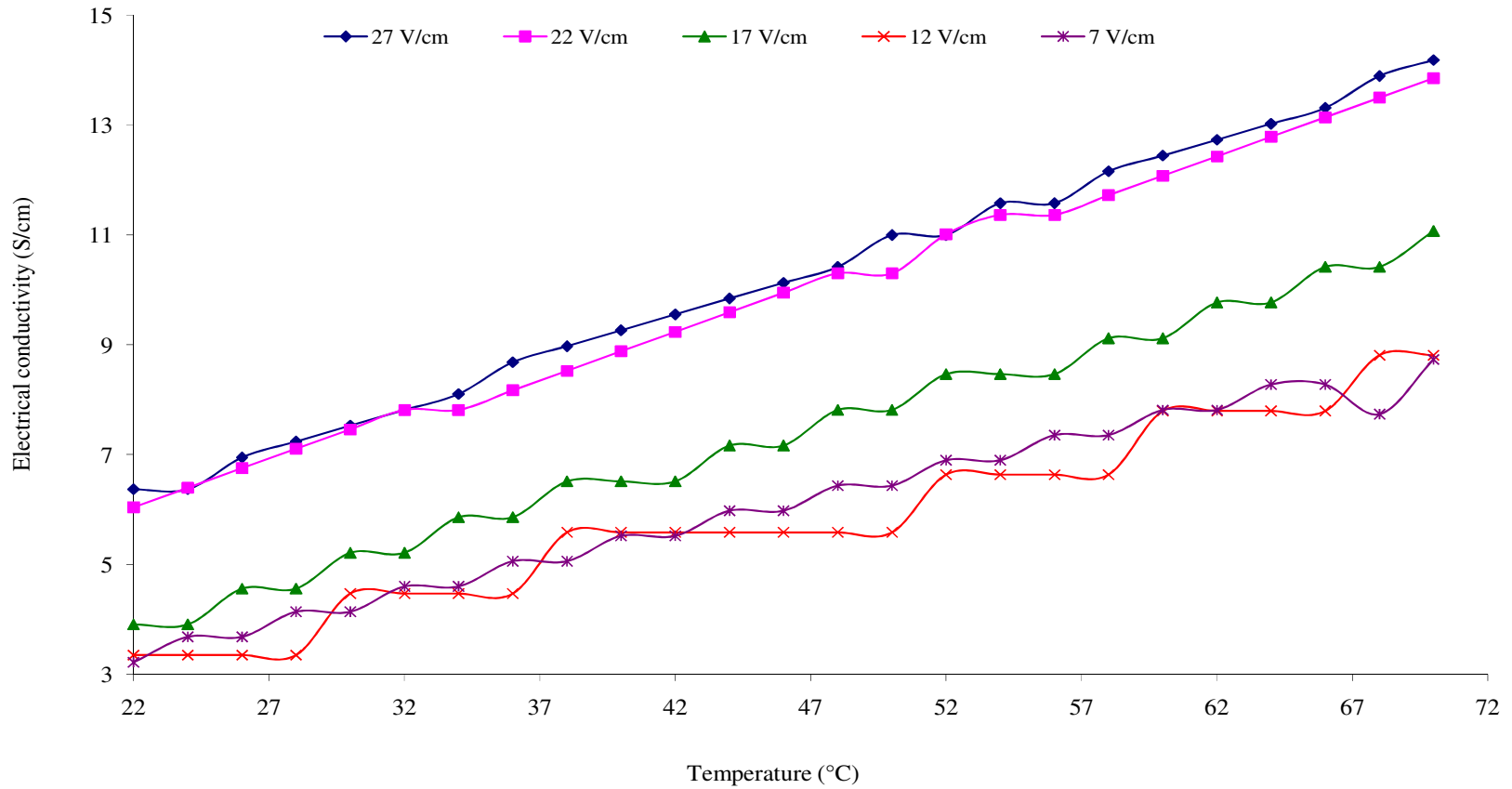


Figure 4.9 The change in electrical conductivity with temperature under five voltage gradients for 60% concentration of mango juice

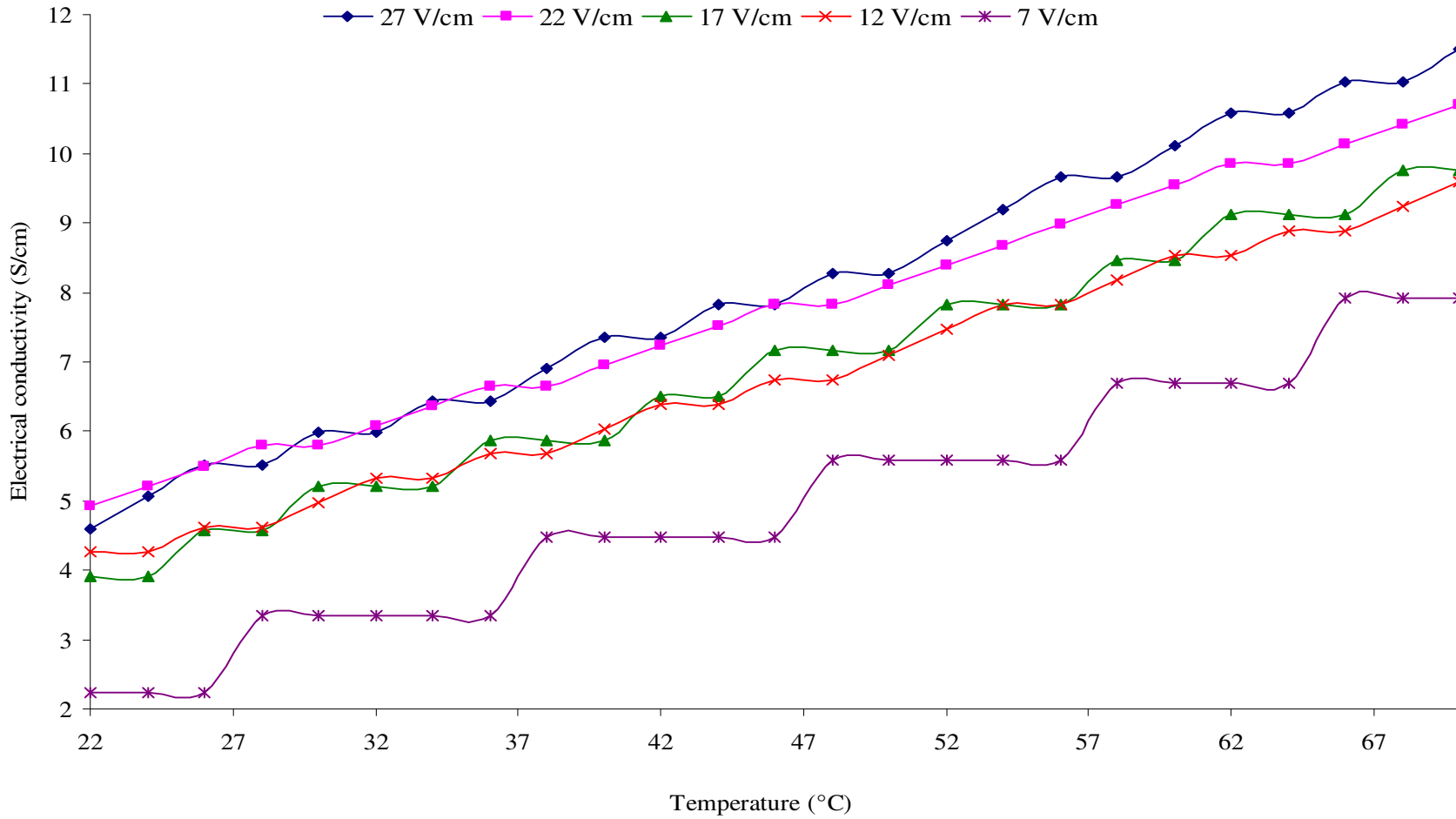


Figure 4.10 The change in electrical conductivity with temperature under five voltage gradients for 50% concentration of mango juice

reported by Lima and Sastry 1999.

Another major factor affecting electrical conductivity is the ionic content of the food: the higher the ionic content, the higher the value of electrical conductivity. The similar result had been reported by Zareifard *et al* 2003. This has been demonstrated by several authors namely Palaniappan and Sastry 1991, Castro *et al* 2003, Palaniappan *et al* (1991) and Wang and Sastry (1997).

Electrical conductivity was greatly affected by voltage gradient applied. Apart from this, concentration also contributed to the variation in electrical conductivity. The ohmic heating system gave higher conductivity values at 90% concentration of mango juice as compared to concentrations of 80, 70, 60 and 50% of mango juice. The value was larger irrespective of the applied voltage gradient. Cristina *et al* (1999) reported that the electrical conductivity was dependent on the concentration (°Brix) and the temperature (20-80°C) for lemon juice. The electrical conductivity increases with increasing concentration up to approximately 30°Brix, when it starts to decrease. The decrease in electrical conductivity may be due to the increase in viscosity of the juices with concentration which decreases the mobility of the ions.

For the same voltage gradient, the electrical conductivity values of fruit juice measured at the same temperature decreased as the concentration decreased (Icier and Ilicali, 2005a). The electrical conductivity measured in the study are comparable with the reported values of 0.4-1.0 S/m for lemon juice at 30-55 V/cm and 20-74 °C (Darvishi *et al* 2011), 0.38-0.78 S/m for grape juice at 20-40 V/cm and 20-80 °C (Icier *et al* 2008), 0.15- 1.15 for orange juice at 20-60 and 30-60 °C (Icier and Ilicali 2005a), 0.51-0.91 S/m for peach puree and 0.61-1.2 S/m for apricot puree at 20-70 V/cm and 20-60 °C (Icier and Ilicali, 2005b), 0.209-0.397 S/m for pomegranate at 30-55 V/cm and 20-80°C (Akbarpour *et al* 2009). Qihua *et al* (1994) used the static heating of fresh orange juice with voltage gradients of 3.6-40 V/cm.

#### **4.3 DEPENDENCE OF ELECTRICAL CONDUCTIVITY ON TEMPERATURE DURING OHMIC HEATING OF MANGO JUICE**

Temperature has remarkable effects on food properties in general and is considered the key factor in a thermal processing operation. Model validation is possibly the most important step in the model building sequence. Once a regression model has been constructed, it may be important to confirm the goodness of fit of the model and the statistical significance of the estimated parameters. Once a regression model has been fitted to a set of data, one can determine whether the independent variables are significant or non-significant. There is a need to check a significant relationship between the dependent and a set of explanatory variables. The mathematical models generally demonstrate the importance and uniformity of electrical conductivity in product temperature predictions.

The ohmic heating curves were stimulated using a model of electrical conductivity.

The linear model by Icier and Ilicali 2005a, b was used to fit the electrical conductivity data of mango juice.

$$\sigma (V,C,T) = A (V,C)+B (V,C)T \quad (4.1)$$

Where,  $\sigma(V,C,T)$  represents the electrical conductivity of mango juice obtained at a specific concentration in terms of percentage of mango juice by volume and applied voltage gradient in S/cm,  $A(V,C)$  and  $B(V,C)$  are constants,  $T$  is the temperature.

The constants  $A$  and  $B$  are the regression constants for a particular concentration ( $v/v$ ) and applied voltage gradient ( $V/cm$ ). Hence, they are function of concentration and voltage gradient. Physically,  $A(V,C)$  denotes the constant of electrical conductivity-temperature relationship whereas  $B(V,C)$  imparts the information about to what extent electrical conductivity values gets affected on raising the temperature. The regression constant  $A(V,C)$  and  $B(V,C)$  represents the slopes and the intercepts respectively for the curves shown in figure 4.6 to 4.10.

Electrical conductivity showed linear trend with temperature when mango juice was given ohmic heating treatment at various concentration and applied voltage gradient. The mathematical modelling was of electrical conductivity of mango juice with temperature was done using statistical software SPSS 16.0. The temperature dependent electrical conductivity relation was obtained by using linear regression analysis. The constants and coefficients of electrical conductivity-temperature relationships of mango juice heated ohmically at different voltage gradients are represented in the Table 4.12. The data represented in the table comprised of regression constants and coefficients. It depicts the linear relationship between electrical conductivity and temperature.

The coefficient of regression ( $R^2$ ) is of immense importance as it is the prime criterion for selecting the best model in order to define the ohmic heating curves. It is best known for the determination of goodness of fit. This was further elaborated as; higher the value of coefficient of determination ( $R^2$ ) more is the goodness of fit. Table 4.12 is illustrating the various relations of electrical conductivity with temperature as obtained by regression analysis.

It was observed that the values of  $R^2$  and adjusted  $R^2$  of mango juice for various permutations and combinations of concentration and voltage gradient were in the vicinity of 0.999. The values were in the range of 0.953 to 0.999. The various values of regression coefficients were in the neighbourhood of 0.999 indicating the higher extent of goodness of fit. These values were quite accurate.

Higher coefficients of determination ( $R^2 = 0.996$ ) indicates the suitability of the linear model for conductivity variation with temperature for all the concentrations of mango juice tested during ohmic heating. The results projects that the temperature significantly altered i.e. increased the electrical conductivity value of mango juice ( $P < 0.05$ ).

**Table 4.12** The constants and coefficients of electrical conductivity-temperature relationships of mango juice heated ohmically at different voltage gradients

Concentration (% by volume)	Voltage gradient (V/cm)	Electrical conductivity- Temperature model $\sigma = A + BT$	Regression coefficient	
			R <sup>2</sup>	Adjustment R <sup>2</sup>
50%	27	$\sigma = -0.522+0.119T$	0.966	0.964
	22	$\sigma = 1.585+0.113T$	0.995	0.995
	17	$\sigma = 1.208+0.123T$	0.990	0.989
	12	$\sigma = 2.289+0.119T$	0.997	0.997
	7	$\sigma = 1.579+0.141T$	0.994	0.994
60%	27	$\sigma = 0.954+0.111T$	0.985	0.985
	22	$\sigma = 0.674+0.112T$	0.953	0.953
	17	$\sigma = 2.68+0.145T$	0.992	0.992
	12	$\sigma = 2.531+0.160T$	0.998	0.998
	7	$\sigma = 5.658+0.163T$	0.998	0.998
70%	27	$\sigma = -0.291+0.161T$	0.984	0.983
	22	$\sigma = 2.184+0.153T$	0.996	0.996
	17	$\sigma = 1.471+0.163T$	0.995	0.995
	12	$\sigma = 2.370+0.165T$	0.996	0.996
	7	$\sigma = 2.600+0.182T$	0.998	0.997
80%	27	$\sigma = 0.565+0.191T$	0.986	0.986
	22	$\sigma = 1.546+0.188T$	0.994	0.994
	17	$\sigma = 2.204+0.185T$	0.997	0.997
	12	$\sigma = 1.992+0.184T$	0.997	0.997
	7	$\sigma = 2.668+0.153T$	0.999	0.999
90%	27	$\sigma = 0.044+0.223T$	0.988	0.987
	22	$\sigma = 3.192+0.155T$	0.998	0.997
	17	$\sigma = 3.329+0.163T$	0.998	0.998
	12	$\sigma = 2.888+0.190T$	0.997	0.997
	7	$\sigma = 2.124+0.211T$	0.996	0.996

The regression constants  $A(V,C)$  and  $B(V,C)$  for various relations of electrical conductivity and temperature represented in the data table 4.12 showcases dependence on concentration and applied voltage gradient. No specific pattern was followed for the regression constant  $A(V,C)$ . They were in the range of -0.291 to 2.888. The regression constant  $B(V,C)$  giving the rate of change of electrical conductivity with temperature had larger value at high voltage gradient corresponding to fixed concentration. They were in the range of 0.111 to 0.223. Several mathematical models have been developed to simulate the ohmic heating behaviour of fluid systems. Sastry and Palaniappan (1992), Benabderrahmane and Pain (2000) and Salengke and Sastry (2007) discussed the mathematical modelling of fluid foods. Quarini (1995) modelled the thermal and hydraulic behaviour of a model ohmic heater to predict the temperature distribution and possible overheating of the food being processed. The model showed that even though heating rates may be uniform, overheating can occur because of significant variations in the temperature distribution. The highest temperatures were found in regions of lowest fluid velocity.

Electrical conductivity is obviously a major factor in the effectiveness of ohmic heating. Palaniappan and Sastry (1991a) developed models to determine the effective electrical conductivity of liquid-particle mixtures and Wang and Sastry (1997) modelled the diffusion of salt into as a measure of increasing conductivity. The mathematical models are also useful in estimation of temperature distribution and assessing worst case scenarios in ohmic heater cells (Zhang *et al* 1992, Fryer *et al* 1992, Zhang and Fryer 1995, Sastry and Salengke 1998, Castro *et al* 2004, Marra *et al* 2009, Darvishi *et al* 2011).

#### **4.4 VARIATION OF VISCOSITY**

For liquid foods, it has been stated that concentration will affect the electrical conductivity as well as the viscosity of the liquid (Singh *et al* 2008, Icier and Ilicali 2005a). The coefficient of viscosity ( $\eta$ ) was calculated at each voltage gradient applied for various concentrations of mango juice. Prior information of density was required for the calculation of coefficient of viscosity. The densities for various concentrations selected for the study are represented in the table 4.1. The data recorded for viscosity before and after ohmic heating treatment has been represented in the Table 4.13.

The density of mango juice increased with increase in the concentration of mango juice. In the similar manner as the viscosity was measured before and after ohmic heating at room temperature, it increased with the elevation in concentration. As the viscosity was calculated for all the concentrations at various voltage gradients, change in the value of viscosity before and after ohmic heating was observed. The viscosity was in the range of 6.7849 to 31.6152 cP after ohmic heating of mango juice.

Statistical analysis using t-test was carried out for the coefficient of viscosity values before and after giving ohmic heating treatment to mango juice. The results obtained for

**Table 4.13 Viscosity values for different voltage gradients applied to five different concentrations of mango juice**

Concentration of mango juice (v/v)	Before ohmic heating	Viscosity values of mango juice ( $\eta$ ) (cP)				
		After ohmic heating				
		Voltage gradient (V/cm)				
		7	12	17	22	27
50 %	7.6011	7.0782	6.8997	7.4991	6.7849	7.1038
60%	10.4203	8.9632	11.5077	13.2083	11.0474	11.1880
70%	10.6606	20.1563	21.4702	22.9061	11.1753	10.7690
80%	13.6168	13.8959	14.2761	15.1776	14.8677	16.0792
90%	15.0479	28.6834	29.9057	31.6152	15.8084	16.3652

analysis of coefficient of viscosity has been represented in the Table 4.14. The change in the viscosities of mango juice before and after ohmic heating for various voltage gradients came out to be overall significant ( $p < 0.05$ ). The change so observed in the viscosity came out to be non-significant at 90% concentration of mango juice as the heating rate was higher. The heating took just 3 minutes; hence, the residence time was less. The change in viscosity value was more significant at lower concentrations i.e. 50%, 60%, 70 % as compared to lower concentrations 60% and 50%. This might be due to the reason that at lower concentrations the time required to heat the juice was more. Hence, the time required for further reaction to takes place in the juice was enhanced.

**Table 4.14 t- values for coefficient of viscosity for applied voltage gradients to five concentrations of mango juice**

Concentration (v/v)	Voltage gradient (V/cm)				
	7	12	17	22	27
50%	4.702*	15.246**	0.917 <sup>NS</sup>	10.523**	11.254**
60%	65.750 <sup>NS</sup>	4.782*	31.139**	3.410*	4.364*
70%	17.159**	21.865**	27.418**	1.562 <sup>NS</sup>	0.272 <sup>NS</sup>
80%	1.377 <sup>NS</sup>	3.910*	9.840*	6.046*	8.079*
90%	179.281 <sup>NS</sup>	87.309 <sup>NS</sup>	127.896 <sup>NS</sup>	1.892 <sup>NS</sup>	3.59*

\*\* t-values were significant at 1% level of significance

\* t-value significant at 5% level of significance

NS t-value is non-significant

Also, another factor contributing to the change in the value of coefficient of viscosity is voltage gradient. At a particular concentration, the coefficient of viscosity changes for all

the applied voltage gradients. The data corresponding to various voltage gradients has been represented in the table 4.13. A significant change was notified in the value of coefficient of viscosity at various applied voltage gradient. The change was more significant at 17 and 12 V/cm as compared to other voltage gradients. At lower voltage gradient i.e. 17, 12, 7 V/cm, the heating time was more, hence, the residence time was more as compared to higher voltage gradients-27 and 22 V/cm.

Viscosity of the fluid phase is an important consideration in ohmic heating. For the food system containing large particles fraction, the fluid viscosity must be sufficient to effectively entrain and convey it (Khalaf and Sastry 1996). Although some non-homogeneity in heating within the fluid phase surrounding the solids can occur if a motionless viscous carrier is being used (Fryer *et al* 1992), if fluid motion occurs, heating becomes significantly more uniform because of the mixture of hot and cold fluid in a continuous flow heater.

The effects of fluid viscosity on the ohmic heating rates of identical solid-liquid mixtures containing potato cubes were investigated by Khalaf and Sastry (1996). In their study, they compared the viscosity with static and vibrating as well as continuous flow conditions. Considering the commercial processing condition, the focus of their study was mixture of high solids concentrations. They reported that their focus were no significant effects of fluid viscosity on the heating rate of fluid and particles for static heating conditions, where the fluid was at stationary conditions with outermost limited conditions. However, in vibrating and continuous flow ohmic heater, where adequate fluid mixing occurs, the rate of heating increased with fluid viscosity. Furthermore, for a continuous flow heater, considering both the temperature and power dissipation data, they suggested that the use of high viscosity carriers could be useful in improving the overall heater rates.

Effects of different heat transfer methods, namely ohmic heating, water bath and steam injection on soymilk viscosity were studied by Liu and Chang (2007) using one and two-step heating procedures to different temperatures. Their results showed that the soymilk viscosity was increased by the two-step heating procedures for all three methods. Maximum increase was observed in water bath followed by ohmic heating and steam injection. They indicated that the differences in viscosity may arise from the different heating rates of the three applied procedures.

There are various studies which deal with the effects of fluid viscosity on ohmic heating rate; some of them report that higher-viscosity fluids tend to result in faster ohmic heating than lower viscosity fluids and others report vice versa. The conflict in these results is probably due to different reactions occurring during ohmic heating of different foods, depending on their composition or other process parameters applied. The data available on the effect of viscosity on electrical conductivity is very limited. An experiment was conducted on a series of solutions of different viscosities with similar initial electrical conductivity. Fryer *et*

al (1992) reported that the viscosity had little or no significant effect on the electrical conductivity. However, Singh *et al* (2008) found that the electrical conductivity of the juices apple, pineapple, orange and tomato strongly depend on the viscosity.

The change in the composition of the food during ohmic heating must be accurately determined and its effects on ohmic heating rate and temperature distribution should be taken into account in the process control procedure.

#### 4.5 VARIATION OF pH DURING OHMIC HEATING

Acidic nature of juice is the one of the factor which can affect the ohmic heating rate. The data depicting the changes in the pH values of mango juice at various concentrations and applied voltage gradients have been listed in the Table 4.15. In the light of experimental results in the given table, there was change in the pH of the mango juice based on the applied voltage gradient. The range of the pH of mango juice after ohmic heating treatment was 2.06 to 3.57.

The change in pH value at lower voltage gradient was probably due to the residence time of different reactions such as hydrolysis of the mango juice that might occur during ohmic heating. At higher voltage gradients, the heating rate was high, therefore, the residence time for the juice to heat up from 14°C to 70°C was short and thus the change of the pH was limited because the reaction time was short.

**Table 4.15 pH values for different voltage gradients applied to five different concentrations of mango juice**

Concentration of mango juice (v/v)	pH of mango juice					
	Before ohmic heating	After ohmic heating				
		Voltage gradient (V/cm)				
		7	12	17	22	27
50%	3.22	2.62	2.73	2.77	2.84	3.23
60%	2.46	2.90	2.06	3.19	2.06	2.90
70%	3.12	2.85	2.78	3.33	3.57	3.26
80%	3.01	2.18	2.54	2.44	3.03	3.06
90%	2.78	3.03	2.90	2.90	2.62	3.57

A statistical analysis of pH was carried out using t-test for applied voltage gradient. The analysis results are listed in the table 4.16 corresponding to each concentration and voltage gradient. The change in the pH value after ohmic heating process came out to be significant ( $p < 0.01$ ). The change in the pH value of mango juice at higher concentration was more significant as compared to the values at lower concentrations of mango juice. Also with each applied voltage gradients to a particular concentration, the values were more significant

at lower voltage gradients as compare to higher values. The result may vary to the product chosen for the study.

**Table 4.16 t-values for pH for applied voltage gradients to five concentrations of mango juice**

Concentration (v/v)	Voltage gradient (V/cm)				
	7	12	17	22	27
50%	25.115**	14.362**	43.301**	32.909**	0.866 <sup>NS</sup>
60%	22.00**	41.00*	42.147**	4.448*	38.105**
70%	11.371**	21.536**	8.578*	77.942**	6.102*
80%	19.936**	26.269**	49.363*	1.155 <sup>NS</sup>	4.330*
90%	24.00**	13.985**	20.785**	7.167*	51.718**

\*\* t-values were significant at 1% level of significance

\* t-values were significant at 5% level of significance

NS t-value is non-significant

Ohmic heating treatment results in the effective damage of cells by a combination of electrical and thermal effects, resulting in the important diffusion of soluble nutrients during ohmic heating. If electroporabilization occurs in vegetable or fruit pulps, pores formed in the cell membranes upon electric field exposure cause a drop in resistance as ions are allowed to pass through the membrane (Kulshrestha and Sastry 2006). Thus a slight change in pH of fluid foods during ohmic heating is possible. Hence, the variation in the pH value of mango juice was observed.

Ohmic heating generally does not cause much of difference in the acidic value of total soluble solids of fluid foods. The results were in accordance with the study (Icier and Ilicali 2004, 2005a, Kulshetra and Sastry 2006, Icier *et al* 2008, Bozkurt and Icier 2009, Yildiz *et al* 2009, 2010, Darvishi *et al* 2012b).

#### **4.6 VARIATION OF TSS DURING OHMIC HEATING**

There is another factor contributing to the ohmic heating rate of mango juice, Total Soluble Solids (TSS). The data obtained for the total solid content of mango juice for various concentrations at applied voltage gradients have been represented in the Table 4.17. TSS values were recorded before and after ohmic heating treatment. The Total soluble solids value increased with the increase in concentration of mango juice. With the each applied voltage gradient, a slight change in the TSS value of mango juice for every concentration was observed.

**Table 4.17 TSS values for different voltage gradients applied to five different concentrations of mango juice**

Concentration of mango juice (v/v)	TSS of mango juice (°Brix)					
	Before ohmic heating	After ohmic heating				
		Voltage gradient (V/cm)				
		7	12	17	22	27
50%	7.4	7.4	7.2	7.6	7.2	7.2
60%	9.2	9.0	8.8	8.8	8.6	9.0
70%	10.4	10.8	10.8	10.8	10.4	10.6
80%	12.6	12.2	12.2	12.4	12.4	12.4
90%	13.0	13.6	13.8	13.6	13.4	13.2

Ohmic heating treatment results in the effective damage of cells by a combination of electrical and thermal effects, resulting in the important diffusion of soluble nutrients during ohmic heating. If electroporabilization occurs in vegetable or fruit pulps, pores formed in the cell membranes upon electric field exposure cause a drop in resistance as ions are allowed to pass through the membrane (Kulshrestha and Sastry 2006). Thus a slight change in total soluble solids contents of fluid foods during ohmic heating is possible. Hence, the variation in the TSS value of mango juice was observed. The TSS was in the range of 7.2 to 13.8 after ohmic heating of mango juice for various concentrations and applied voltage gradients.

Statistical analysis for TSS was carried out using t-test before and after heating mango juice ohmically. The results obtained through statistical analysis have been represented in the table 4.18.

**Table 4.18 t-values for TSS for applied voltage gradients to five concentrations of mango juice**

Concentration (v/v)	Voltage gradient (V/cm)				
	7	12	17	22	27
50%	1.732 <sup>NS</sup>	3.464*	1.732 <sup>NS</sup>	1.732 <sup>NS</sup>	3.464*
60%	3.464*	6.928 <sup>NS</sup>	3.464*	5.196 <sup>NS</sup>	3.464*
70%	4.000 <sup>NS</sup>	2.464 <sup>NS</sup>	1.464 <sup>NS</sup>	0.000 <sup>NS</sup>	3.464*
80%	4.000 <sup>NS</sup>	4.464 <sup>NS</sup>	6.000 <sup>NS</sup>	5.000*	3.000*
90%	5.196 <sup>NS</sup>	6.928 <sup>NS</sup>	6.000 <sup>NS</sup>	0.000 <sup>NS</sup>	3.464*

\* t-values were significant at 5% level of significance

NS t-value is non-significant

As the concentration of mango juice increased, the change in the TSS value was noted. The change observed in the TSS value of mango juice before and after ohmic heating treatment came out to be non-significant ( $p < 0.01$ ).

To each concentration of mango juice, a voltage gradient was applied during ohmic heating. The change so observed on increasing the voltage gradient while performing ohmic heating process is not affecting the overall composition of mango juice. On the similar grounds, on increasing or decreasing the concentration of mango juice, change so observe came out to be statistically non-significant.

Ohmic heating generally does not cause much of difference in the value of total soluble solids of fluid foods. The results were in accordance with the study (Icier and Ilicali 2004, 2005a, Icier *et al* 2008, Bozkurt and Icier 2009, Yildiz *et al* 2009, 2010 Darvishi *et al* 2012a.).

## CHAPTER V

### SUMMARY

Ohmic heating is applied to the liquid foods such as fruit and vegetable products (juices, purees, pulps, etc.), soups, soymilk, egg, etc., for the purpose of heating, pasteurization and sterilization. Several other applications of ohmic treatment in the food industry include blanching, thawing, cooking, fermentation and peeling of fruits.

Research and technological efforts in the past two or three decades have made ohmic heating one of the leading thermal processing techniques for food processing. Creating data banks on the electrical conductivity of foods and developing process equipment are still a priority in ohmic heating research. Due to relatively high energy consumption of conventional thermal food processing techniques, the high cost of natural gas and petroleum and growing environmental global warming concerns, industries have been showing more interest in adapting other technology such as ohmic heating. Further, due to rapid and uniform heating, ohmic heating has great potential to be used in the processing of high-quality products and can be commercially adapted for the aseptic processing of particulate fluid foods.

The study aimed to design and build an ohmic heating apparatus at laboratory scale. For the purpose liquid food selected was mango juice. The equipment developed showed adequate performance, monitoring data and heating products satisfactorily. The mango juice of five concentrations (50, 60, 70, 80 and 90 %) was given ohmic heating treatment at applied voltage gradients (7, 12, 17, 22 and 27 V/cm). The mango juice was heated in the ohmic cell in the temperature range 14-70°C. All the data was recorded during the experiment at a time interval of 5 seconds. Electrical conductivity was calculated from voltage and current data recorded for the ohmic heating of mango juice. The other parameters-viscosity, pH and TSS were recorded using an Ostwald's viscometer, pH meter and hand held refractometer respectively.

Data so obtained for electrical conductivity was statistically analyzed using the software SPSS-16.0. A regression analysis was carried out on the electrical data which is a function of temperature, concentration and voltage gradient. Electrical conductivity, an important parameter was found to increase with the rise in temperature. Higher solids content and electric field strengths showed an increase with the temperature for all the combinations of the five concentrations and voltage gradients. Electrical conductivity is linearly dependent on temperature, which is evident from the regression equation:

$$\sigma (V,C,T) = A (V,C)+B (V,C)T$$

Where,  $\sigma (V, C, T)$  represents the electrical conductivity of mango juice obtained at a specific concentration in terms of percentage of mango juice by volume and applied voltage gradient in S/cm,  $A (V, C)$  and  $B (V, C)$  are regression constants,  $T$  is the temperature.

The larger value of coefficient of regression ( $R^2 = 0.996$ ) represents the linear model fitted to the electrical conductivity of mango juice during ohmic heating was highly accurate. As the concentration of mango juice was increased, the electrical conductivity value was raised. Also, as the voltage gradient increased from 7 to 27 V/cm, electrical conductivity got increased significantly. Ohmic heating rate tend to increase with increase in the voltage gradient. Higher the voltage gradient faster was the heating rate.

Viscosity of mango juice was also altered with concentration and voltage gradient. The change in viscosity was observed as heating affects the viscosity of juice. pH of juice was recorded before and after ohmic heating, the change in pH value was there with increase in concentration as well as voltage gradient. The deviation so produced in the pH value came out to be statistically significant. The change in TSS was notified with the variation in concentration of mango juice. TSS did not show much of significant variation with the elevation in the voltage gradient.

Ohmic heating is an excellent alternative food-processing technique that shows much promise in the food industry. With the more advancement in the field, this technology will become even more streamlined and efficient. Special design of ohmic heaters can be created for different foods, depending on their electrical conductivity range. In addition, a variety of novel products can be developed by controlling their electrical conductivity changes. The potential applications areas of ohmic heating could be expanded for a wider variety of foods in future. The ohmic heating appears to be having applications for a variety of processes. With the number of manufacturers increasing, the opportunity exists for industry to exploit this technology to their advantage.

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## PUBLICATIONS

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**Kaushal A**, Tarsikka P S and Dawar K (2012) Design and Development of ohmic heater and study of ohmic heating behaviour of sodium chloride solution, Crop improvement: (special issue) 1093-94.

**Dawar K**, Tarsikka P S and Javed M (2014) Ohmic heating behaviour and electrical conductivity of mango juice, Innovative Food Science and Emerging Technologies (Communicated).

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**Kaushal A**, Tarsikka P S and Dawar K (2012): Design and development of ohmic heater and study of ohmic heating behaviour of sodium chloride solution. Presented at International Conference on Sustainable Agriculture and Livelihood (ICSA-2012) held at Punjab Agricultural University, Ludhiana from 27-29 November 2012.

**Kaushal A**, Tarsikka P S and Dawar K (2013): Temperature dependent electrical conductivity of guava juice. Presented at 1<sup>st</sup> Indian Association of Physics Teachers (IAPT) Students Symposium on Physics held at Panjab University, Chandigarh from 25-27 February 2013.

**Kaushal A**, Tarsikka P S and Dawar K (2013): Variation in electrical conductivity and viscosity during ohmic heating of guava juice. Presented at DAV National Congress on Science and Technology (DAV NCST-2012) held at DAV Institute of Engineering and Technology, Jalandhar from 30-31 May 2013.

**Dawar K** and Tarsikka P S (2014): Ohmic heating of mango juice: electrical conductivity and viscosity. Presented at 2<sup>nd</sup> Indian Association of Physics Teachers (IAPT) Students Symposium on Physics held at Panjab University, Chandigarh from 17-19 January 2014.

**Dawar K** and Tarsikka P S (2014): Effect of ohmic heating on total soluble solids and viscosity of mango juice. Presented at Multi Disciplinary National Conference Science Colloquium: Emerging trends in basic and applied sciences held at DAV College, Jalandhar from 6-7 March 2014.

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