INFLUENCE OF OHMIC HEATING ON ELECTRICAL PROPERTIES OF TOMATO PUREE

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, "**Influence of ohmic heating on electrical properties of tomato puree"** submitted for the degree of **Master of Science**, in the subject of **Physics** (Minor subject : **Mathematics**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Kiranjot Kaur (L-2017-BS-307-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, "**Influence of ohmic heating on electrical properties of tomato puree**" submitted by **Kiranjot Kaur (**Admn. No. **L-2017-BS-307-M)** to the Punjab Agricultural University, Ludhiana, in partial fulfilment of the requirements for the degree of **M.Sc**. in the subject of **Physics** (Minor subject: **Mathematics**) has been approved by the Student's Advisory Committee after an oral examination on the same.

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ABSTRACT

Ohmic heating is a green processing technique that is different from other processing methods. In this process electric current is allowed to pass through the food sample and heating occurs due to inherent resistance of sample. It is highly efficient technology and provides rapid and uniform heating. In this study, ohmic heating treatment was applied to different concentrations (100, 90, 80, 70 and 60%) of tomato puree. The puree was ohmically heated from 30 to 70^0 C at four different voltage gradients of 8, 6, 4 and 2V/cm for different concentrations. Measurements have been made on electrical conductivity, ohmic heating rate, density, pH, TSS and specific heat. The voltage gradient and concentration has significant effect on electrical conductivity of tomato puree. Electrical conductivity and ohmic heating increases linearly with rise in temperature, concentration and voltage gradient. pH and TSS are also noted before and after the ohmic heating treatment. Statistical analysis has been conducted and observed that this treatment has no significant effect on pH and TSS values. System performance coefficient was also calculated for ohmic heater at different voltage gradients and observed that as the concentration of tomato puree decreases the efficiency of ohmic heating apparatus shift towards higher voltage gradient in prescribed voltage range.

Keywords: ohmic heating, tomato puree, electrical conductivity, specific heat, pH, TSS, system performance coefficient.

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Signature of Major Advisor   **Signature of Student**

ਥੀਸਿਸ ਦਾ ਸਿਰਲੇਖ	: ਟਮਾਟਰ ਪਿਊਰੀ ਦੀ ਬਿਜਲਈ ਵਿਸ਼ੇਸ਼ਤਾਵਾਂ ਉੱਤੇ ਓਮਿਕ ਹੀਟਿੰਗ ਦਾ ਪ੍ਰਭਾਵ
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ਸਾਰ-ਅੰਸ਼

ਓਮਿਕ ਹੀਟਿੰਗ ਇੱਕ ਪ੍ਰੋਸੈਸਿੰਗ ਤਕਨੀਕ ਹੈ, ਜੋ ਕਿ ਬਾਕੀ ਤਕਨੀਕਾਂ ਨਾਲੋਂ ਅਲੱਗ ਹੈ।ਇਸ ਤਕਨੀਕ ਵਿੱਚ ਆਮ ਤੌਰ ਤੇ ਤਰਲ ਭੋਜਨ ਪਦਾਰਥਾਂ ਨੂੰ ਪ੍ਰੋਸੈਸਿੰਗ ਲਈ ਗਰਮ ਕੀਤਾ ਜਾਂਦਾ ਹੈ। ਇਸ ਵਿੱਚ ਤਰਲ ਭੋਜਨ ਵਿੱਚੋ ਦੀ ਬਿਜਲੀ ਨੂੰ ਲੰਘਾਇਆ ਜਾਂਦਾ ਹੈ ਅਤੇ ਭੋਜਨ ਆਪਣੇ ਅੰਦਰੂਨੀ ਰਜਿਸਟੈਂਸ ਕਾਰਣ ਗਰਮ ਹੋ ਜਾਂਦਾ ਹੈ।ਇਹ ਬਹੁਤ ਉੱਚ ਪੱਧਰੀ ਤਕਨੋਲਜੀ ਹੈ, ਜਿਸ ਵਿੱਚ ਭੋਜਨ ਤੇਜ਼, ਇਕਸਾਰ ਗਰਮ ਹੁੰਦਾ ਹੈ ਅਤੇ ਊਰਜਾ ਕੁਸ਼ਲਵੀ ਹੈ। ਇਸ ਅਧਿਐਨ ਵਿੱਚ ਵੱਖ-ਵੱਖ ਗਾੜ੍ਹੇਪ੍ਰਣ ਵਾਲੀ ਟਮਾਟਰ ਪਿਊਰੀ (100, 90, 80, 70 ਅਤੇ 60%) ਉੱਤੇ ਓਮਿਕ ਹੀਟਿੰਗ ਦਾ ਪ੍ਰਭਾਵ ਦੇਖਿਆ ਗਿਆ ਹੈ। ਪਿਊਰੀ ਨੂੰ 30 ਤੋਂ 70 ਡਿਗਰੀ ਸੈਲਸੀਅਲ ਤੱਕ ਚਾਰ ਵੱਖ-ਵੱਖ ਵੋਲਟੇਜ਼ ਗਰੇਡਿਏਂਟ 8, 6, 4 ਅਤੇ 2 ਵੋਲਟ/ਸੈਂਟੀਮੀਟਰ ਨਾਲ ਗਰਮ ਕੀਤਾ ਗਿਆ ਸੀ।ਇਸ ਅਧਿਐਨ ਵਿੱਚ ਟਮਾਟਰ ਪਿਊਰੀ ਦੀ ਬਿਜਲਈ ਚਾਲਕਤਾ, ਹੀਟਿੰਗ ਰੇਟ, ਘਣਤਾ, ਪੀ ਐਚ, ਟੀ ਐਸ ਐਸ ਅਤੇ ਸਪੈਸਫਿਕ ਹੀਟ ਨੂੰ ਮਾਪਿਆ ਗਿਆ ਸੀ।ਬਿਜਲਈ ਚਾਲਕਤਾ ਅਤੇ ਹੀਟਿੰਗ ਰੇਟ ਤਾਪਮਾਨ, ਵੋਲਟੇਜ਼ ਗਰੇਡਿਏਂਟ ਅਤੇ ਗਾੜ੍ਹੇਪ੍ਰਣ ਨਾਲ ਵੱਧਦੇ ਹਨ ਅਤੇ ਰੇਖਿਕ ਵਿਹਾਰ ਨੂੰ ਦਰਸਾਉਂਦੇ ਹਨ। ਪੀ ਐਚ ਅਤੇ ਟੀ ਐਸ ਐਸ ਦਾ ਮਾਪ ਓਮਿਕ ਹੀਟਿੰਗ ਤੋਂ ਪਹਿਲਾਂ ਅਤੇ ਬਾਅਦ ਵਿੱਚ ਇਹ ਦਰਸਾਉਂਦਾ ਹੈ ਕਿ ਓਮਿਕ ਹੀਟਿੰਗ ਦਾ ਇੰਨ੍ਹਾਂ ਉੱਤੇ ਕੋਈ ਮਹੱਤਵਪੂਰਨ ਪ੍ਰਭਾਵ ਨਹੀਂ ਹੈ।ਓਮਿਕ ਹੀਟਿੰਗ ਸਿਸਟਮ ਦੀ ਕਾਰਗੁਜ਼ਾਰੀ ਇਹ ਦਰਸਾਉਂਦੀ ਹੈ ਕਿ ਟਮਾਟਰ ਪਿਊਰੀ ਦੇ ਗਾੜ੍ਹੇਪ੍ਰਣ ਘਟਾਉਣ ਨਾਲ ਸਿਸਟਮ ਦੀ ਵਧੀਆ ਕਾਰਗੁਜਾਰੀ ਵੱਧ ਵੋਲਟੇਜ਼ ਗਰੇਡੀਐਂਟ ਉੱਤੇ ਹੁੰਦੀ ਹੈ।

ਖਾਸ-ਸ਼ਬਦ: ਓਮਿਕ ਹੀਟਿੰਗ, ਟਮਾਟਰ ਪਿਊਰੀ, ਬਿਜਲਈ ਚਾਲਕਤਾ, ਸਪੈਸਫਿਕ ਹੀਟ, ਪੀ ਐਚ, ਟੀ ਐਸ ਐਸ,ਸਿਸਟਮ ਦੀ ਕਾਰਗੁਜ਼ਾਰੀ

ਮੁੱਖ ਸਲਾਹਕਾਰ ਦੇ ਹਸਤਾਖਰ **ਵਿਦਿਆਰਥੀ ਦੇ ਹਸਤਾਖਰ**

CONTENT

CHAPTER 1

INTRODUCTION

Indian agriculture is a way of life and it endures about 60 percent of population for their living and contributes 17 percent of GDP in India. Engineering inputs play a vital role in modernization of agriculture, agro processing and rural living. It is required for development and optimum utilization of natural resources, economic competitiveness and sustainability. Food is the foremost requirement of people for their survival. It provides nutrients like carbohydrates, proteins, fats, vitamins and minerals. Agriculture is practiced in two forms. One is the production agriculture and their goal is to get higher productivity while the other is post production agriculture where the major objectives are prevention of loss and value addition.

In ancient times, the agricultural products which were available for consumer were unprocessed. Nowadays food is processed to destroy the enzymes that deteriorate the food and make it microbiologically safe to eat. The food packaging can isolate the food from outer environment, prevents food spoilage and easy to store and transport. With the passage of time, industrial processing methods took over the traditional methods and food was started processing on large scale as it converts the fresh food into the attractive, salable and enhanced shelf life food products. Food processing is used to impart value to the raw materials including meat, poultry and marine products which can be eat by human beings or animals. Raw food materials are converted into edible products by processing and value addition.

Food preservation techniques are based on the prevention of microbial growth and microbial inactivation as microbial spoilage is common cause of food spoilage. Two types of processing technologies, thermal and non-thermal are based on the physical technique for food preservation has the potential to achieve the consumer’s demand and provide high quality processed food with additive free shelf life. Non-thermal processing technique represents a novel set of tools for food processing. In this method, properties of food or its environment are manipulated without the use of heat. Irradiation, pulsed light, high pressure processing, pulsed electric fields and modified atmosphere are some examples of this processing technology. In thermal processing, the food was heated to inactivate the pathogenic microorganisms and obtain the safe product. Examples are blanching, pasteurization, canning, baking, roasting, salting, frying and many more.

Heating of food is highly efficient way of preserving the food stuff as it destroy the harmful microorganisms and pathogens whose presence could alter the food and make it unfit for consumption. The two types of heating are direct heating and indirect heating. In direct heating, heat is generated inside the material whereas in indirect heating, heat transfer takes place by processes like radiation, conduction and convection. Heating by conduction requires a direct contact between source and the object. In convection, heat transfer takes place through the flow of a liquid or a gas which itself is heated by a heat source. The main requirement is good air circulation and enclosure of heated air to raise the temperature of the substance. Whereas the radiation process involves the heating of food substances with the radiations emitted from the hotter objects such as sun, open fire or an infrared lamp. Dielectric or microwave heating, inductive heating and ohmic heating are some examples of direct heating while infrared heating is example of indirect heating. Convectional heating leads to degradation of outer portion of food particulates and change of flavor. So direct heating is preferred over the indirect one.

In dielectric heating, food material is heated by passing high frequency electromagnetic radiation through it. The food particulates contain moisture in it. When radio frequency electric field or microwave is applied to the food materials, dipoles in water molecules and other ionic components orient themselves in the direction of applied electric field. As the molecules start agitating, it increases the average kinetic energy of molecules. Temperature is directly related to average kinetic energy this will cause sharp elevation in temperature of material. Radio frequency heating and microwave heating differ from each other in terms of operating frequency. Radio frequency operates at low frequencies (27 MHz) while microwave heating operates at high frequency (915 and 2450 MHz).

In infrared heating, thermal energy is transferred in the form of electromagnetic waves. The food materials are heated due to absorption or emission of radiation. The wavelength of radiation emitted by source lies in far infrared region. This radiation is absorbed by the object and further it reflects the radiation of different wavelengths. The absorbed radiation of suitable wavelength is the basic cause of infrared heating within the food molecule. The emission of radiation occurs in the range of wavelength 780 nm to 1 mm.

Induction heating is the process in which electrically conducting food material is heated by means of electromagnetic induction. In this method heat is generated inside the food itself, instead of supplying by external heating sources. As a result, the food can be heated rapidly. Moreover it is non-contact heating and hence contamination is not an issue. When high-frequency alternating current is applied to an induction coil, a time-varying magnetic field is generated. Without being touching the coil food sample to be heated is placed inside the magnetic field. Then alternating electromagnetic field induces eddy currents in the food sample that leads to resistive losses consequently the material gets heated up.

Ohmic heating take its name from Ohm's law. It is also known as Joule heating or electro heating or resistive heating (Sastry and Barach 2000). In 1841, James Prescott Joule discovered that the passage of electric current releases heat that was proportion to product of wire resistance and square of electric current. Ohmic heating is a process in which heating occurs due to inherent resistance of food when electric current is allowed to pass through the food material (Razak *et al* 2017). Heat is generated instantly and volumetrically within the food sample. The motion of charged particles inside the food material results in raising the temperature and kinetic energy of material. The moving charge particles within the food sample are ions or other molecules like proteins, which moves toward the opposite polarity electrodes (Razak *et al* 2017). The basic principle of ohmic heating is the dissipation of supplied electric energy directly into heat which results in the generation of internal energy (Eliot *et al* 1991). Moreover it simultaneously heats both the phases by internal heat generation.

Ohmic heating is not a new concept. In late 1920s, it was referred as "Electro-Pure" process and widely used for pasteurization of milk. The technology was abandoned due to lack of inert materials for making the electrodes (Castro *et al* 2003). This technique was again revived in 1980s and achieved industrial applications like processing of fruit products and pasteurization of liquid food (Tusiyan *et al* 2008). Recently, the world's food processing industry increasing the attention on the ohmic heating of pump-able food as it gave the products of superior quality (Castro *et al* 2003).

There are several advantages of ohmic heating over other heating methods. Heating is very rapid and homogeneous. Since there is no hot heat transfer surfaces therefore less chance of fouling and burning of food sample (Cappato *et al* 2017). It results in minimum mechanical damage and better retention of vitamins and nutrients. Operating of this process does not produce any noise due to the absence of rotating parts in system. Another main advantage of this technology is its high energy conversion efficiency. It converts around 90% of the supplied electrical energy into heat. It also maintains the uniformity of heating. The solid particles in the sample get heated at the same rate as the fluid does. This technique is very flexible as the temperature of the system can be raised quickly by increasing voltage and instant shutdown is also provided (Kumar 2018). It also requires low capital investment as compared to other conventional heating methods. This technology is also useful for pre-heating of products before canning process.

Ohmic heating brought a revolution in food processing industry due to its applications including pasteurization, extraction, fermentation, blanching, sterialization, thawing, enzyme stabilization, microbial inactivation, starch gelatinizing and heating the food stuff. It can applied to a wide range of food products including milk, seafood, meat, vegetables, paste, fruits and fruit products like juice, puree etc. This technique is currently used in United Kingdom (UK), United States Of America (USA), Canada, Sweden, Japan, Switzerland and Itlay (Kumar 2018). There are only 18 commercial ohmic heating plants around the world and are mostly used for pasteurization and sterilization of fruits, vegetables, juices, pulps, milk, egg, ice- cream mix, whey soups, soyamilk etc. In India ohmic heating is still limited to laboratory scale only due to lack of economic studies.

Tomato is widely grown commercial vegetable in the world. Tomatoes are rich in beta-carotene and source of vitamin A, $B_{6,}$ C, niacin, potassium, thiamin, manganese and phosphorous (Chang *et al* 2006). Besides, they are low in saturated fat and high in sugar and dietary- fiber. Since tomatoes are seasonal product and quickly decayed due to their high moisture content so they are processed into different products through various methods. The common tomato products are tomato juice, tomato paste, tomato ketchup, tomato sauce, tomato puree, and tomato chips. Moreover, its waste can also be used to produce methane gas.

The term "*puree*" is of French origin, which means *purified* or *refined*. A thick liquid obtained by cooking and straining tomatoes is known as tomato puree. Tomato paste, tomato sauce and tomato puree can be distinguished on the basis of consistency; tomato puree has thicker consistency than paste and sauce. Another parameter is TSS value; puree has TSS value 10-12^{o}brix where as in paste it is more than 25^{o} brix. Purees are generally used in baby food production. The thermal processes applied to the baby food products are important to assure their microbiological safety.

Ohmic heating depends upon electrical conductivity, heating rate, pH change particle size, concentration and density of food sample. However the electrical conductivity can be considered the most important influencing parameter (Sarang *et al* 2008). It is the measure of the material's ability to permit the transport of electric charge. Foods containing ionic salts and water excess are most suitable to use in applications of ohmic heating. The efficiency of ohmic heating depends upon conductive nature of food (Darvishi *et al* 2012). Various parameters such as temperature, frequency, applied voltage gradient and concentration of electrolytes greatly affect electrical conductivity of liquid foods (Icier and Ilicali 2005, Ye *et al* 2004). Alcohol, fats and lipids decrease electrical conductivity of food while ionic components, acids and moisture enhance it. Therefore the knowledge regarding electrical conductivity for a given food product is an important parameter for conducting a safe thermal process.

The ohmic heating rate of food product can be controlled by electrical conductivity which is further the function of structure of food material that often changes during heating. Products having high heating rate generally needs less time to reach the desired temperature. Specific heat, particle size, shape, concentration, orientation in applied field, concentration, applied voltage are some factors that can modify the heating rate.

Since pH is a direct measure of acid content so it plays a major role in food processing. Variations of pH can impact flavor, consistency, and shelf-life. It has a great influence on temperature and the processing time of food products. Higher pH values correspond to high processing time periods which can adversely affect the quality of food products. It is defined as the degree of acidity or basicity of a substance which is usually measured on a scale of 0 to 14. Solutions having pH values greater than 7 are basic while those with values less than 7 are acidic. The measurement of pH in food processing is done for the production of products with consistent well defined properties and to meet regulatory requirements. pH is basically the negative of the logarithm to the base 10 of the concentration and is measured in terms of moles per litre of hydrogen ions. pH is the most common among all the other analytical measurements in industrial processing.

Total soluble solids (TSS) are solids dissolved within a substance. It is measured by using a hand refractometer. Degree Brix (^{o}brix) is the unit of TSS. One ^{o}brix is equal to one gram of sucrose in 100g of solution. Dissolved solids affect both refractive index and density of the liquid. The soluble solids are basically sugars like sucrose, fructose and glucose. Acid and minerals in sample also contributes to soluble solids.

Another parameter is density of the solution. It is the sum of mass concentrations of the components of that solution. It is an important quality parameter which can be used to confirm the purity of the substance. Density is also used to ensure homogeneity. If a manufactured part is not at all homogeneous, key performance parameters such as strength and crack resistance are highly affected. So, density helps to measure the purity and homogeneity of the products. Density basically tells how firmly the particles of the material are bound together.

The system performance coefficient of an ohmic heating apparatus is defined as the ratio of energy gained by the food sample to the energy supplied to that sample. The energy given to the sample and the amount of heat required to heat up the sample to certain temperature is calculated by using voltage, current and temperature values noted during heating experiment. This parameter provides the knowledge that at which voltage gradient our ohmic heater performs better.

Ohmic heating studies have been done on tomato paste only and there is insufficient information regarding the electrical properties of tomato puree during ohmic heating. Therefore this study had been conducted with the following aim:

- To determine the electrical conductivity and heating rate at various concentrations of tomato puree.
- To study the effect of ohmic heating on different parameters such as TSS, pH and density of tomato puree.
- To investigate the system performance coefficients (SPS) for different voltage gradients applied during ohmic heating.

CHAPTER-II

REVIEW OF LITERATURE

This chapter gives the information regarding the research that had done using ohmic heating technique and helpful in making a picture in mind regarding this technology. The critical examination of the literature seems to be useful in finding the product that can be heated and check the influence of various parameters on ohmic heating.

A successful application of electricity in food processing was developed in 19^{th} century to pasteurize milk called “Electropure Process” (Getchel 1935). But this application was dejected due to its high processing costs. So an alternative technique was developed which is helpful in maintaining the nutritional value of the food and enhances its shelf- stable life and this promising technique is ohmic heating.

Halden *et al* (1990) studied the changes in the electrical conductivity of various foods during ohmic heating. At that time a few information was available on the dependence of ohmic heating rates on electrical conductivity of food. They observed that melting of fats, starch transition, cell structure changes can affect the electrical conductivity of food. The diffusion of cell fluids in food had also enhanced by the electric field. In order to raise the electrical conductivity of food sample and made them useful to ohmic processing, pre-heating had been done.

Lima and Sastry (1999) examined the effect of ohmic heating frequency on hot-air drying rate and juice yield. It has found that frequency of alternating current can change the transfer of heat and mass properties. The hot air drying rate of yam and the juice yields of apple has been compared using 4 Hz sawtooth wave and 60Hz sine wave and check whether the lowering frequency can give rise to futher improvements to these processes. The 4Hz sawtooth wave faster the drying rate. The electric field strength also alter the drying rate. The efficiency of mass transfer processes significantly depend on frequency and waveform of alternating current.

Castro *et al* (2003) determined the electrical conductivity values of strawberries and other strawberry based products at various electrical field strengths, particle size, ^{o}Brix values and solids contents(0-20% w/w). Two different industrial strawberry pulps (P_1 and P_2) for six different concentrations (from 14.5^{o}Brix to 41.0^{o} Brix and from 26.5^{o}Brix to 59.5^{o}Brix*)*, respectively were prepared by adding sucrose. The strawberry pulp samples had heated up to 100^{o}C using eight different power supply voltages (32 V/cm to 100 V/cm) with a gap of 2cm between electrodes and four different power supply voltages were applied. Initially the electric field was adjusted to the predictable electrical conductivity of the product in test. The experimental set up included a heater consisted of a cylindrical glass tube having length 30 cm and 2.3 cm inner diameter. Three thermocouple openings were provided; one at the centre of tube to insert the thermocouple and other two at equidistant from the center. On both ends of tube two titanium electrodes with teflon pressure caps were placed. A set of experiments was conducted to check whether the electrical conductivity changes during ohmic heating by varing input voltage. It was concluded that the electrical conductivity values rises with temperature but decreases with higher sugar contents; and this decrease was more significant for bigger sized particles.

Icier and Ilicali (2005) determined the temperature dependent electrical conductivities of fruit purees during ohmic heating. In this study, the peach and apricot purees, supplied by a commercial fruit juice producer, were heated on a laboratory scale static ohmic heater at different voltage gradients in the range of 20-70 V/cm. The electrical conductivity of fruit purees is dependent on temperature, ionic concentration and pulp content. Their electrical conductivity increased linearly with rise in temperature. Bubbling observed above 60^{0}C especially at higher voltage gradients. The system performance coefficients were found in the range of 0.49-1.00. The mathematical models taking the system performance coefficients into account can be used to predict accurately the ohmic heating times of fruit purees.

Magerramov *et al* (2007) measured the viscosity of two fruit juices (lemon and tangerine) with a capillary flow technique. Behavior of viscosity as a function of concentration and temperature was studied in this segment. The range of concentration selected for the study of tangerine and lemon juice was between 15-40 °Brix and 17-45 °Brix respectively. The temperature range of 303 to 393 K was opted to note the observations of viscosity for both types of juices. For the representation of the temperature dependence of viscosity, the Arrhenius type correlation equations for viscosity were used. Different models were applied to measured data in order to represent temperature and concentration dependences for tangerine and lemon juices. The average absolute deviation between calculated and measured values obtained from this correlation equation for the viscosity was 0.8% and 2.15% for tangerine and lemon juices, respectively.

Kong *et al* (2008) attempted to design and fabricate the ohmic heating cell. The performance of laboratory scale static ohmic heater was calculated by heating four different kinds of food materials (tap water, fruit–vegetable juice, yoghurt and 0.5% aqueous sodium chloride solution) at different voltage gradients (7.5, 11.25, 15, 18.75, 22.5 and 26.25 V/cm). The main aim of the study was to detect the effect of different electrical field strengths and temperatures on the heating rate and electrical conductivity of above mentioned food materials. In order to calculate the electrical conductivity, voltage, current and temperature were recorded at 30s intervals. The results proved that the voltage gradient has significant effect on the ohmic heating rates for all four materials. The electrical conductivity also significantly varies with temperature. The experimental ohmic heating units showed a good performance. The liquid samples were heated from room temperature to 80° C. The influence of voltage gradient and temperatures on ohmic heating behavior of selected liquid materials had studied. The heating rate was strongly dependent on either the electric-field strength or electrical conductivity. Ohmic heating rate of different materials was influenced by the electrical conductivity values under different voltage gradients. The importance of the determining electrical conductivities of foods to be processed by ohmic heating is reflected through these different effects of voltage gradient on different products. The present study concluded that in order to tackle a great deal of heat loss and non-uniform electrical field, the ohmic heating system requires a modification to improve its performance.

Sarang *et al* (2008) investigate the electrical conductivity of meats and fruits during ohmic heating. Each sample was heated upto 140°C by using alternate current and voltage between 15 to 20V. It was observed that electrical conductivity of various meats and fruits were increased linearly with temperature at particular voltage gradient. Highly porous materials such as apple showed lower conductivity. They had also showed that there was no significant relationship between fat content of the lean muscle cuts and their electrical conductivity.

Ikegwu and Ekwu (2009) studied the physical and thermal properties of some tropical fruits and their juices. Various properties such as viscosity, density, thermal conductivity, moisture content, thermal diffusivity, specific heat capacity and latent heat of fusion were evaluated during this experiment. The results showed that increase in moisture content of the samples lead to an increase in thermal properties of the samples. The viscosity values were decreased with increase in the moisture content of the samples. This decrease was explained on the basis of solubility and the quantity of total solids in the fruit juices. The values of the specific heat capacity and the latent heat of fusion of the fruits and their juices were recorded in the range 3.45-4.05 kJ/ kg °C and 23785 to 31825 kJ/Kg °C respectively. The decrease in moisture content of the fruits leads to an increase in total solids content of the juices.

Assawarachan (2010) investigated the electrical conductivity of red grape juice and prepared a mathematical model for electrical conductivity of red grape juice. In this study, different concentrations of 10.5, 11.5, 12.5, 13.5 and 14.5 ºBrix of red grape juice were prepared and ohmic heating treatment was applied on them. Three different voltage gradients of 10, 12 and 15V/cm were chosen for ohmically heating the sample from 25-80 ºC. Controller system and ohmic heating system were the two major parts of the whole experimental set up. The controller system consisted of a PLC whose program was written in Visilogic version. The data was analyzed using SPSS and multiple regression analysis was carried out to find the best fit mathematical model for the various concentrations of the juice was calculated. The electrical conductivity of the juice was in the range of 0.92-1.13 S/m. A linear trend of the electrical conductivity of the juice was obtained as the electricity increases linearly with an increase in temperature. The heating rate of the concentrate juice ranged between 0.1316-0.0573ºC/s. Hence, both the conductivity and heating rates increased linearly as the voltage gradient increased from 10-15 V/cm. The expected mathematical model was considered as a best fit as the data of the predicted mathematical model and observed experiment were in a good agreement.

Tumpanuvatr and Jittanit (2011) determined the behavior of 10 kind of different juices and purees in a static ohmic cell upto a temperature of 80^0C by varying the voltage gradients from 10 to 32 V/cm. In this study, the data regarding sample temperature, electric current and voltage gradients were recorded. It was concluded that various factors such as temperature and concentration affected the electrical conductivity of fruit juices and puree. The empirical models proved electrical conductivities as function of these factors with good fitting result. Other parameters such as TSS, pH, density and specific heat of juices and purees were also evaluated.

Darvishi *et al* (2011) studied the temperature dependent electrical conductivities of lemon juice at different voltage gradients in the range of 30-55 V/cm. First the lemons were washed properly with water to remove dirt from the skin and then dried to drain the excess water on the skin surface. They were crushed and squeezed and then the juice was filtered. The whole experimental apparatus consisted of a power supply, an isolating transformer, microcomputer, a variable transformer and three digital multimeters. Pyrex was used to fabricate the ohmic heater cell. The two electrodes having diameter 0.04m were 0.05m apart. The total sample volume of ohmic heating tube was 53.8 ml. A K-type thermocouple was fitted in to the geometric center of the cell to note the temperature of the juice samples. The samples were ohmically heated from 20ºC to final temperature of 70°C at 30, 35, 45 and 55V/cm at 60Hz. All the measurements were made from 20 to 74ºC and showed that the electrical conductivity raised linearly with increase in temperature. They observed that the electrical conductivity of lemon juice was strongly dependent on temperature. Voltage gradient significantly affected the ohmic heating rates for lemon juice that was tested statistically ($p< 0.05$). Temperature change for 55V/cm was higher than the other voltage gradients applied. Voltage gradient greatly affected ohmic heating times and performance coefficients. Time and performance coefficient decreased with an increase in the voltage gradient values. System performance coefficients were in the range of 0.54–0.92. This modeling procedure can be useful in designing and controlling ohmic heating processes that can be used for thermal sterilization and safety of ohmically heated food products.

Darvishi *et al* (2012) examined the ohmic heating behavior and electrical conductivity of tomato paste. In this paper, pH changes, system performance coefficients and effects of voltage gradients on ohmic heating rates were studied. Tomato samples were procured from local market in Iran, stored at 5^0C for approximately 2 hours and then homogeneous samples were washed, crushed and mixed to obtain a red less-viscous liquid.

The tomato paste was heated in a tube having diameter 5cm and length 15cm. The ohmic heater was operated at five different voltages varying from 30-60 V at 50 Hz frequency. It was observed that electrical conductivity increases linearly with the rise in temperature due to increase in ionic mobility and then decreases as the temperature increases after bubbling started. The heating of the sample was stopped as bubbling started.

Darvishi *et al* (2013) studied the effect of voltage gradient on electrical conductivity, pH, heating rate and system performance coefficient of pomegranate juice during ohmic heating. The pomegranate juice was heated by applying four voltage gradients 30, 35, 45 and 55 V/cm at 60 Hz from 20 to 85 °C. It was observed that the time required for heating the pomegranate juice at 45, 35 and 30 V/cm was 1.5, 2.44 and 3 times longer than at 55 V/cm respectively. The observed ohmic heating rates were 4.171, 2.755, 1.688 and 1.392 °C/s at voltage gradients of 55, 45,35 and 30 V/cm, respectively. To the test significance/ non-significance of voltage gradient on ohmic heating, one way analysis of variance was applied which showed that voltage gradient had a significant effect ($p<0.05$) on the electrical conductivity of pomegranate juice. The electrical conductivity increased with an increase in temperature but it started decreasing with further increase in temperature after bubbling. The range of electrical conductivity during ohmic heating was 0.219-1.013 S/m. They confirmed that the linear model was the most suited model for describing the electrical conductivity curve of the ohmic heating process of pomegranate juice with R^2 value of 0.9986–0.9930, χ^2 value of 0.0005–0.0025 and RMSE of 0.0179–0.0406. Voltage gradient was statistically significant on the system performance coefficients (SPC) and pH for pomegranate juice. As the voltage gradient increased, pH and time decreased. The results showed that as the voltage gradient increased, in other words SPC values decreased. Bubbling occurred at high voltage gradients above 81°C. System coefficients were observed in the range of 0.764-0.939.

Nistor *et al* (2013) determined the ohmic heating process characterization during the processing of apple puree. For heating, the ohmic heating batch installation was used which contains a generator for AC, a voltmeter, intensity meter, conductivity meter and a ohmic cell consisting two electrodes (0.5×26cm). The Ida red apples were supplied by local producer of Romania. Apple puree was prepared by washing, peeling, cutting and mincing the apples with a blender. The sample was ohmically heated up to boiling temperature which is 60^0C at different voltage gradients from 15-20 V/cm. It was observed that electrical conductivity was influenced by the product nature, temperature and by the value of voltage gradient. For larger value of voltage gradient, the time of ohmic heating processing was shorter.The minimum processing time was 300s for 20 V/cm. The rheological character of the apple puree was invariant under ohmic heating.

Mohsen *et al* (2013) studied the processing of mango pulp using ohmic heating treatment. They compared the ohmic heating method with other conventional methods used for the processing of mango pulp. The results showed that processing of mango pulp caused a decrease in the contents of TSS, total carbohydrates, total acidity, total sugars (reducing & non-reducing sugar) whereas the phenolic content, ascorbic acid and carotenoids were increased irrespective of the method used for the processing of the mango pulp. Mango pulp processed by ohmic heating contained more phenolic compounds, carbohydrates and vitamin C and less HMF (5-hydroxymethyel furfural) as compared to that produced by conventional one. Ohmic heating slightly reduced the total pectin and its fractions while these reductions were even more for the conventional method. Results also showed that both the processing methods reduced the total plate count and mold & yeast. However, ohmic heating method after processing and during storage caused lesser reduction in total plate count and mold & yeast as compared to that in conventional method. Coliform and thermophilic bacteria were completely inhibited with the both methods after processing and during storage. Results showed that the conventional method lead to a reduction in polyphenoloxidase (PPO) & polygalacturonase (PG) enzymes activity in mango pulp. However these activities were completely inhibited due to the effective ohmic heating treatment. Mango pulp processed by ohmic heating resulted into an improvement in the organoleptic properties as compared to conventional process.

Singh *et al* (2013) examined the quality characteristics of ohmically heated aonla pulp. Different voltage gradients (11-17 V/cm) were applied to aonla pulp. Various characteristics such as vitamin C, tannin content, colour, titrable acidity and microbial counts were studied. Results showed that all the quality parameters were affected with the treatment and addition of potassium meta-bisulphite significantly. Ohmically heated aonla pulp at 90ºC for was observed to be sufficient for safe storage with little quality losses. The quality losses in terms of vitamin C, tannin, titrable acidity and color lightness were correlated to each other. In this study, it was found that the aonla pulp ohmically heated at 17 V/cm voltage gradient was best in terms of all the quality parameters.

Olivera *et al* (2013) studied the effect of ohmic heating treatment on foods such as fresh potatoes, carrots and apples. These food samples were heated for a time period of 60, 120, 180 and 240 seconds at constant electric field gradients of 1100V/cm, 2200V/cm and 3300V/cm. The results showed that the stress–deformation behavior of food samples which were processed by OH differs appreciably from raw untreated samples for all cooking times. More ohmic heating times resulted into a decrease in firmness of solid samples. This study observed the significant effects of ohmic heating on texture of solid foods and produces structural damage even though these food samples have a low electrical conductivity. Carrot, potato and apple showed low electrical conductivity in the prescribed voltage gradient range. The treatment of above food samples needed electric field strength higher than 1100 V/cm. The electric field strength of 2200 V/cm and higher favored appreciable firmness disintegration of food samples. It was found that apple was most sensible to the softening effects due to OH treatment. The knowledge of texture evolution can be applied during the selection of process conditions to obtain a product with predefined textural characteristics.

Lien *et al* (2014) examined ohmic heating of soya milk for tofu making. Freshly prepared raw soya milk was chosen for the experiment. The soya milk was adjusted to concentration of 10˚Brix. Ohmic heating treatment was applied to the soya milk at the voltages140, 150 and 160V. It was concluded that larger voltage gradient resulted in faster temperature rise. The heating rate of soya milk was observed to be 3.82˚C/min. Curves plotted between current and time concluded that currents were larger at the beginning and were dominated by the first-order dynamics. There was a linear relationship between the temperature and electrical conductivity for different voltage gradients. It was noted the electrical conductivity of soya milk had a positive temperature effect when the temperature was in between 22 and 60˚C, but after this temperature this effect saturated.

Athmaselvi and Chakraborty (2014) studied the effect of ohmic heating on physiochemical properties such as pH, TSS, % acidity, ascorbic content and color of the guava juice at various voltage gradients ranged between 13.13 - 23.33 V/cm. The study investigated the ohmic heating effects of guava pulp with various mass fractions of 0.1, 0.2, 0.3, 0.4 and 1 in the temperature range of 95°-100°C at voltage gradients 16.67, 20, 23.33 and 26.67 Vcm^{-1} using titanium and stainless steel electrodes respectively. They also observed the time dependence of the pulp to reach boiling point at the heating conditions. The time taken to heat the guava pulp from room temperature to 100 ºC decreased with the increase in concentration and the voltage gradient applied. The change in the electrical conductivity of guava pulp at various concentrations and dielectric properties at various frequencies was also studied. The linear trend of electrical conductivity of the pulp was noted .The electrical conductivity of guava pulp at 23.33 Vcm^{-1} at various mass fractions viz. 0.1, 0.2, 0.3, 0.4 and 1 were 0.131, 0.147, 0.186, 0.163, 0.147 S m^{-1} and 0.1406, 0.153, 0.227, 0.147 S m^{-1} for stainless steel and titanium electrode respectively. The electrical conductivity values were in the range of 0.015–0.4 S m^{-1}. In addition to guava pup, the dielectric properties of the guava pulp powder were also studied at three ranges of frequencies: low frequency (0.001MHz-0.1MHz), medium frequency (0.2MHz-0.9MHz) and high frequency (1MHz-5MHz). Maximum values of dielectric constants were obtained at low frequencies (0.001MHz). There was an increase in the value of dielectric constant up to 80 ºC and after that dielectric constant decreased with further increase in temperature. At medium frequencies (0.2 MHz-0.9MHz), the dielectric constant decreased slightly with increase in frequency. At the high frequency range (1MHz-5MHz), the dielectric constant increased gradually with increased frequency. They concluded that the dielectric properties of the pelletized guava powder decreased as the frequency was increased, especially at high temperatures (above 100ºC) and gradually increased at frequency above 3 MHz.

Kumar and Hussain (2014) compared the inactivation effects of ohmic heating and conventional heating on yeasts and moulds, Califorms, total plate count, *E.coli* and *salmonella* in buffalo milk by using similar temperature conditions. Milk samples were heated conventionally and ohmically to required temperatures and paneer was manufactured from those milk samples. It was concluded that microbial destruction was lower in case of conventionally heated milk sample than ohmically treated. *Salmonella* was completely destroyed by ohmic heating. Soft paneer obtained from ohmic heating was found to be of superior quality than that from conventional method. This study proved that ohmic heating is an effective tool for the pasteurization of buffalo milk.

Shivmurti *et al* (2014) compared the chemical properties of milk when heated conventionally and ohmically. This work contains the analysis of chemical properties such as acidity, fat, protein, SNF (solid not fat) and total solids of buffalo milk before and after ohmic heating and conventional heating methods. Fresh raw buffalo milk was obtained from the identified farm at Anand, India. Milk is conventionally heated in water bath at 72^{0}C for 15 seconds. In ohmic heating, milk is ohmic heating chamber having length 20 cm and inner diameter 6 cmwith 110V supply, 0.6A current and electric field intensity 8.38 V/cm to obtain 72^{0}C. Acidity of conventionally heated milk is more than ohmically heated. Fat is decreasing in ohmic heated milk whereas conventionally it remains constant. Protein is decreasing in both cases. The time reduction in ohmic heating was about 18% as compared to conventional heating.

Pham *et al* (2014) studied the effect of indirect ohmic heating on total soluble salts, pH, color, polyphenol oxidase activity and texture of ready- to- eat pineapple packed in a polypropylene pouch. Different voltage gradient (20, 30, 40 V/cm) were applied to pre-packed sample placed in the ohmic heating jar filled with 0.5% sodium chloride solution temperatures (60, 70 and 80°C) for 60s. The results concluded that ohmic heating at 30 V/cm voltage gradients at 70°C is the best for indirect ohmic heating for RTE pineapple sample packed in PP pouches. This treatment was preferred on the basis of the optimized quality of pH, TSS, color changes, inactivation of PPO and textural firmness of the sample stored at 4°C as compared to other conditions and untreated sample.

Kautkar *et al* (2015) investigated the temperature dependent electrical conductivities of ginger paste during ohmic heating. The ginger puree was prepared by grinding the ginger rhizomes for 3 minutes with fruit to water ratio of 1:1. The ginger paste was obtained after adding salts and organic acid to the puree. In this study, the electrical conductivity was measured in terms of bulk and point electrical conductivity. The ginger paste of different salt concentration (0-2% w/w) was heated in a laboratory scale ohmic heater by applying five voltage gradients 5, 7, 9, 11 and 13 V/cm. The temperature dependent electrical conductivity was noted at different time interval of 0, 5 and 10 minute for different temperatures 30, 40, 50 and 60^{0}C. Bubbling was observed above 70^{0}C especially at high voltage gradients. The electrical conductivity of ginger paste linearly increased with temperature. Point electrical conductivity was varied from 4.41 to 6.63 mS/cm whereas bulk electrical conductivity showed variation from3.75 to 5.87 mS/cm.

Boladiji *et al* (2015) studied the ohmic heating effects on tomato samples at different voltage gradients 6-14 V/cm. They determined the effect of ohmic heating technique on electrical conductivity, heating rate, water evaporation rate, color, pH and energy consumption on tomato samples. The tomato samples were ohmically heated till the moisture content of tomato samples reduced to 2.2. They observed that the results of the nonlinear mathematical model comprising the effects of voltage gradient level and the temperature on the electrical conductivity changes. This observation showed a good agreement ($R \geq 0.955$) with the experimental data. The electrical conductivity rises with concentration of tomato samples. It was observed in the range of 3.19–8.95 S/m during ohmic heating. They noted that processing time decreased from 28.32 to 4.3 min over the voltage gradient range from 6 to 14 V/cm. The change in pH was limited due to increased heating rate and water evaporation rate at high voltage gradient. Processing time, pH, color, specific energy consumption values were optimum at 14 V/cm voltage gradient levels. The heating time, pH and specific energy consumption values falls with an rise in the voltage gradient values. The best values of all the above mentioned parameters were obtained at 14 V/cm.

Wongsa and Sastry (2015) studied the effect of ohmic heating on tomato peeling. The industrial methods of tomato peeling such as lye and steam peeling, has many disadvantages; environment problems, high pH waste with the former and excessive water use with the latter. In this study, ohmic heating was attempted to overcome these problems and to deliver higher quality products in aseptic processing. The tomatoes were heated in presence of NaCl solution in ohmic heating tube. The effect of medium concentration and field strength was studied using single tomato with initial temperature 25^{o}C, NaCl concentrations of 0.01g/100ml (field strength 8060, 9680, 11300 and 12900 V/m), 0.02g/100ml (field strength 4340, 6450, 8060 and 9680 V/m) and 0.03g/100ml (field strength 6450, 8060, 9680 and 11300V/m). It was observed that the best conditions for ohmic heating were at 25^{o}C and 0.01g/100ml NaCl with 9680 V/m, 60^{o}C and 0.01g/100ml NaCl with 9680 v/m and 50^{o}C and 0.01g/100ml NaCl with 11300 V/m. These conditions show potential because they take a relatively short time. Field strength, initial temperature, fruit and NaCl concentration influenced peel cracking. Since lye peeling yields the best peeling quality so it was concluded that the combination of ohmic and lye peeling will be a good choice to get advantages from both methods.

Saini and Kumar (2015) developed the design and construction of an ohmic heating system. They obtained the electrical conductivity of sweet lime juice. Lemon fruits were firstly washed, then peeled and cut down into small pieces. Then 1.5% NaCl was added into it to balance the sensory parameters of juice. The ohmic heating apparatus was designed with the help of pyrex material and was drawn into a long cylindrical glass chamber of length 0.2 m. Two teflon coated electrodes were placed in the glass chamber with a gap of 0.15 m. Sweet lime juice was heated in that ohmic heating system and ammeter, voltmeter and thermometer was used to record the values of current, voltage and temperature respectively after each 2 min interval. The electrical conductivity of the sweet lime juice increased linearly with temperature, but this rise in conductivity was even more with the addition of 1.5% NaCl solution. The reason behind this increase in conductivity was probably the increased ionic mobility. Bubbling of the juice was observed near 79ºC which was due to the electrochemical reactions in the juice. The maximum value of conductivity was 3.760S/cm, which was reported at maximum voltage of 60V. The linear model was considered as the most suitable fit for the actual electrical conductivity changeable data with R^2 values ranging from 0.9728-0.9958.

Poojitha and Athmaselvi (2016) compared the storage studies on banana pulp by ohmic and conventional heating. Bananas were obtained from local market in Guduvanchery, India. They were washed, peeled and then pulped. For this study four samples were taken, first was without sugar and other contains 10%, 30% and 50% sugar. These samples were heated at three voltage gradients of 13.33, 20 and 26.66 V/cm. It was observed that electrical conductivity and heating rates started increasing with rise in voltage gradient. The pulp was kept for 2 minutes at the bubbling temperature to increase its shelf life. The pH value of pulp varies from 4.5-4.63 after ohmic heating and remains almost constant under conventional heating. The color of pulp changed during ohmic heating due to browning. Ascorbic acid content decreased with rise in voltage gradient. It was concluded that ohmic heated banana pulp was better in maintaining shelf life.

Sakharam *et al* (2016) developed a laboratory scale ohmic heater for the extraction of rapeseed oil. This designed laboratory model can be successfully used for ohmic and enzyme assisted aqueous extraction of rapeseed oil. The various factors like material for the construction of chamber and electrode, cementing material, wiring, transformer and thermostat play an important role in the fabrication of ohmic heating apparatus for enzyme assisted oil extraction of rapeseed. Ohmic heating chamber was constructed with the help of PVC pipes of 7 cm diameter, having length 16.8 cm and thickness 2mm. Volume and density of the rapeseed slurry predicted the size of ohmic heating heater cell. By knowing the density and volume of rapeseed slurry, the capacity of ohmic heating chamber along with other dimensions like length, breadth and thickness of chamber were also determined. Rapeseed slurry was prepared by mixing 100 g of husked and grinded rapeseeds with sufficient amount of water and capacity of ohmic heating chamber was determined. Stainless steel with 5.5 cm diameter was selected as electrode material.Characteristics like electrical conductivity, heating rate, power factor, energy efficiency and heating power were determined during the ohmic heating process using digital temperature controller, ammeter, thermocouple, volt meter. In this setup the liquid particulate food were heated from 20˚C to 100˚C in 60s at voltage gradient of 16 V/cm. The heating remained uniform for all practical purposes. Capacity of the ohmic heating equipment detected for rapeseed slurry was found to be 3.84 kg/hr. Boiling and expansion of rapeseed slurry during ohmic heating must be avoided especially above 60 ˚C.

Athmaselvi *et al* (2017) investigated the effect of ohmic heating on the electrical conductivity and various physiochemical properties such as pH and color of the watermelon juice at various voltage gradients (10-23.33V/cm).Watermelon is a fruit comprising of 91% water content due to which it acts as the major hub of many micro-organisms. Preservation of watermelon by application of conventional means is very difficult due to high water content. The watermelon juice was heated on a static ohmic heater by applying various voltage gradients 10, 13.33, 16.66, 20 and 23.33V/ cm at 50Hz frequency, until the temperature reached 95°C. The ohmic heating rate was determined at various voltage gradients. It was observed that the ohmic heating rate was higher for high voltage gradients. The time required to heat the water melon juice samples were 180 s, 150 s, 130 s, 100 s and 90s for 10, 13.33, 16.66, 20 and 23.33 V/cm voltage gradients respectively from 30°C to 95°C.With an increase in voltage gradient, the time required to heat the substance to a particular temperature decreased. The trend of electrical conductivity was also observed. Linear model gave the best fit to the electrical conductivity of watermelon juice. The electrical conductivity increases with rise in temperature but it started decreasing with an increase in temperature after bubbling starts. The effect of ohmic heating on the pH and color of the watermelon juice during storage was studied. Variations in pH and color also increased with an rise in voltage gradient, ohmic heating time and storage period. Changes in pH and total color difference with voltage gradient and treatment time were statistically significant ($p< 0.05$). The bubbling of juice was observed above 60°C at all voltage gradients. Ohmically heated watermelon juice showed better retention of physiochemical properties than conventional heating. This study concludes that ohmic heating is the best suited method for the preservation of watermelon juice.

Sawant *et al* (2018) determined the performance and evaluation of ohmic heating assisted lye and salt concentration on peeling quality of tomato. The various methods of peeling have many disadvantages which include use of caustic, problem of waste disposal, high pH, high pressure and energy and excessive use of water. In this study, ohmic peeling was applied to overcome these problems. The peeling performance of final product was determined in terms of time of skin cracking, percentage and ease of peeling. As lye- salt concentration of the medium increases, the heat generation in the medium would also rises due to enhanced electrical conductivity. In terms of time of cracking, the best performance of ohmic treatment was obtained at 0.3% NaOH concentration for 1214.28 V/m. This condition was good for processing because it needs relatively short time (less than 60 s, approximately). Moreover, preheated media to 60 ºC with reusable media could further reduce the peeling time. Ohmic tomato peeling treatments with NaOH (0.1, 0.2 0.3 and 0.4%) were better than those by ohmic heating with either KOH or NaCl.

Leite *et al* (2018) studied the effect of concentration and consistency on ohmic heating. The aim of this study was to verify the impact of consistency and concentration on OH, by determining the electrical conductivity of various carboxymethyl cellulose (CMC) solutions. CMC solutions of different concentration (0.5–3%) were processed by high-pressure homogenization (HPH) at 100 and 200 MPa (unprocessed as control), to get the solutions with different consistencies but same concentration. At 25°C electrical conductivity rises as the solution concentration was increased (ranging from 0.118 Sm^{-1} at 0.5% to 0.493 Sm^{-1} at 3%), and HPH treatment also rises the electrical conductivity (ranging, at 3%, from 0.493 Sm^{-1} at 0 MPa to 0.575 Sm^{-1} at 200 MPa). No significant difference was observed between 100 and 200 MPa samples. Various correlations were possible among concentration, electrical conductivity and consistency. These correlations can be used to obtain consistency from electrical conductivity and also be applied in process and equipment design. The results support the potential of ohmic heating in fluids with high consistency.

CHAPTER- III

MATERIALS AND METHODS

This chapter deals with the methodological analysis of the whole experiment and provides sufficient information about the sample preparation and instruments which have been used during the experiment. This chapter acts an excellent source if someone wants to conduct the experiment in future.

Commercially available tomato puree has selected for ohmic heating treatment. Different parameters like electrical conductivity, heating rate, density, pH, SPC and TSS have been measured. The effect of ohmic heating on these parameters were observed. All the experiments were performed in the Post Graduate research Laboratory of Department of Mathematics, Statistics and Physics, Punjab Agricultural University, Ludhiana.

3.1 SELECTION OF PUREE

Canned tomato puree was purchased from local market. It was preferred over the fresh puree because of its long shelf life and to minimize the error in measuring parameters such as electrical conductivity, heating rate, TSS, pH and density. Fresh puree was also rejected due to lack of proper storage conditions and limited resources. There were some fluctuations in the measurable parameters that were due to the variation in the raw materials used to prepare tomato puree.

3.2 SAMPLE PREPARATION

The purchased puree has been assumed to be 100% concentrated. For measuring the effect of ohmic heating on various parameters five different concentrations were prepared by diluting the puree with distilled water. Since dilute water did not contain any ions so the electrical conductivity is only due to the puree. There are three methods of preparing concentration – mass by mass, volume by volume and mass by volume. The volume by volume method is used for preparing five concentrations (100%, 90%, 80%, 70% and 60%). 60% concentration was prepared by adding 60 ml of puree and 40 ml of distilled water. Other concentrations 90, 80, and 70% has also prepared in similar manner by adding 10, 20 and 30 ml distilled water respectively. The basic purpose of selecting different concentrations is to study the effect of various concentrations of tomato puree on different parameters under the ohmic heating treatment. Tomato puree has been ohmically heated at four different voltage gradients of 8, 6, 4 and 2 V/cm which are statistically significant. In order to check the reproducibility of results, the whole experiment has been repeated thrice at each concentration and for each voltage gradient.

3.3 DETERMINATION OF DENSITY

Density is defined as mass (m) per unit volume (V). It describes how tightly any substance is packed. Mass is generally expressed in the units of g while volume is measured in ml. The units of both mass and volume are important in determining the density of the material. Specific gravity bottle is used for measuring the density of tomato puree. Density is denoted by a Greek letter 'ρ' and is given as:

$$\rho = M / V \qquad - (3.1)$$

where M= Mass of the sample (in g) and V= Volume of the sample (in cm^3)

Density of tomato puree sample =ρ = mass of sample (g) / volume of sample (ml) = M/V

= (M/25) (g/ml)

$$= (M/25)\ (g/cm^3) \qquad - (3.2)$$

For greater accuracy, three readings were taken for each concentration of the puree. All the density measurements were carried at room temperature ().

3.4 DESCRIPTION OF pH METER

Hanna's waterproof pH meter with model no. HI98128 having range -2.00 to 16.00 is used to measure pH of puree samples with different concentrations. LCD screen of pH meter displayed pH value along with temperature readings with 0.01 pH resolution and an accuracy ±0.05 pH. There are many advance features of this meter such as two point calibration, buffer recognition and automatic temperature compensation. A clock tag appearing on display screen has automatically disappears when the reading becomes stable. It has battery life of 1200 hours of continuous use and it got auto-off after 8 minutes of non-use. A typical Hanna pH meter of model no. HI98128 which was used in the study is illustrated in Figure 3.1

3.5 MEASUREMENTOF pH

Hanna's pH meter is used to find the pH value of tomato puree. The meter is calibrated before use with buffers of pH 4 and 7. Then it is dipped into the puree sample of specific concentration (say 80%). The reading has been noted down after it became stable. pH value at other concentrations are also measure in the same manner. pH is measured before and after ohmic heating of the sample, at four different voltage gradients and five different concentrations. Three set of readings are taken for each voltage gradient and concentration in order to check the reproducibility and minimize the statistical error.

Figure 3.1 Hanna's pH meter

3.6 HAND-HELD REFRACTOMETER

A hand-held refractometer is a device used to measure the concentration of solution through the measurement of its refractive index. It worked on the principle that when a ray of light passes from one medium to another, the ray changes its direction as its speed suddenly changes. This is known as refraction. The hand-held refractometer is a small, precise, light-weighted optical instrument and was easy to operate and recalibrate. Simplicity, accuracy and durability are some of the major characteristics of the refractometers. It can be used to measure the refractive index of different solutions. All water-based solutions will make light bend. More concentrated the solution is, greater is the refraction. Analog and digital are the two types of hand held refractometers. Analog hand refractometer (ERMA type) has been used to determine the TSS of the prepared puree sample. A typical analog hand-held refractometer used in the study is shown in Figure 3.2

Refractometer can measure the amount of solids dissolved in liquid by measuring the refracted angle displayed on a scale through the passage of light into the liquid medium. The Brix scale is the most commonly used scale to measure the total soluble solids. The number of grams of pure cane sugar dissolved in 100 grams of pure water (grams sugar/100 grams $H_2$0) is defined as degree Brix. 'Sucrose content ' of the liquid substances is reflected from the °Brix values. Juices, soft drinks, sauces etc. are assigned a °Brix value as part of the Quality Assurance for the product. Hand-held refractometers are better than other refractrometers as they do not require an energy source.

Figure 3.2 Analog hand-held Refractometer.

Hand held refractometer has an illuminator flap that produced a diffused light at a grazing angle and keep the sample in place as shown in figure 3.3. Light after passing through the sample, entered the measuring prism, and then falls on the measuring scale where it could be read. Refractometer basically worked on the critical angle principle according to which prisms and lenses project a shadow line onto a small glass rectile inside the instrument, that can be viewed by the user using a magnifying eyepiece.

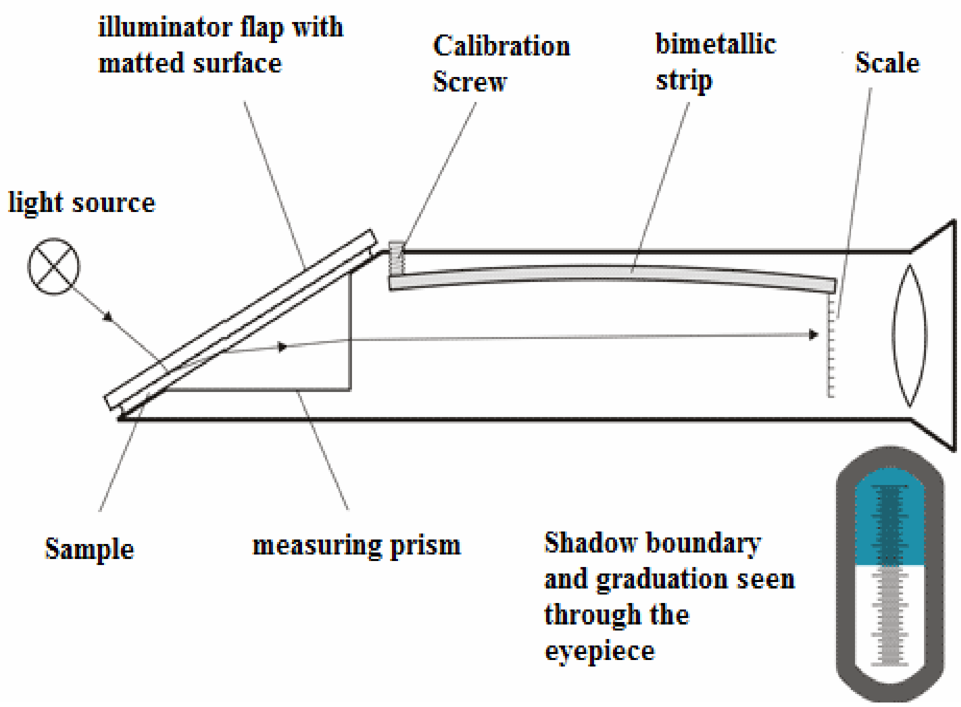

Figure 3.3 Schematic diagram of the Hand Refractometer

3.7 TSS MEASUREMENT

The initial step is to calibrate the refractometer. Distilled water is used for calibration, a drop of it is poured on the measuring prism and then its reading has been noted and it should be 0. After cleaning the prism surface, a drop of tomato puree is placed on it and the reading is again noted. Data is recorded for four different voltage gradients and for five different concentrations before and after ohmic heating treatment. At particular voltage gradient and for given concentration the readings were recorded thrice to get concordant values. The reading on prism shows 16 °Brix as shown in figure 3.4, which means the solution contains 16% sucrose content.

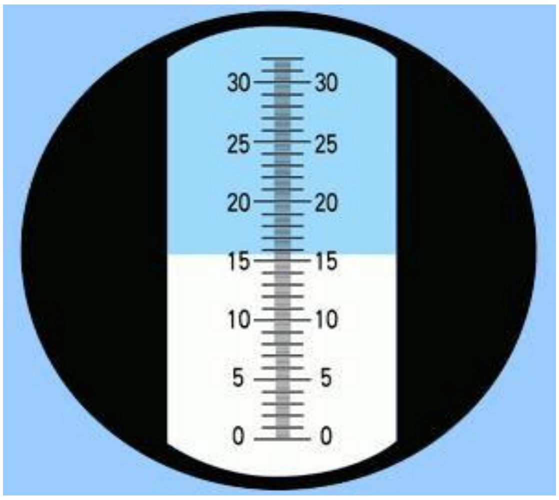

Figure 3.4 Reading scale of Hand held refractometer.

3.8 DESCRIPTION OF OHMIC HEATING SYSTEM

In order to study the ohmic heating behavior of tomato puree, modeling and fabrication of ohmic heating apparatus is done in the Post Graduate Research Laboratory, Department of Mathematics, Statistics and Physics, Punjab Agricultural University, Ludhiana, Punjab. The ohmic heating experiment is conducted at laboratory scale only. The ohmic heating system consists of a power supply, a variable autotransformer and ohmic cell. The ohmic cell is a PVC (Polyvinyl tetrachloride) cylinder having 3.47cm diameter, length 10.5cm and two stainless steel (food grade) electrodes of thickness 0.2cm are placed on its extreme ends. The capacity of this cell is 100ml. Two holes each having diameter 0.5cm is created on surface of cell for the purpose of inserting K type thermocouples to measure the temperature change and check the uniformity of heating. Another purpose of hole creation is to observe the bubbling because heating should be stopped when bubbling occurs. An ammeter (0-2 A) and voltmeter (0-300V) is connected in series and parallel respectively between the variac (power source) and ohmic heating cell. The systematic diagram of ohmic heating apparatus is shown in figure 3.5:

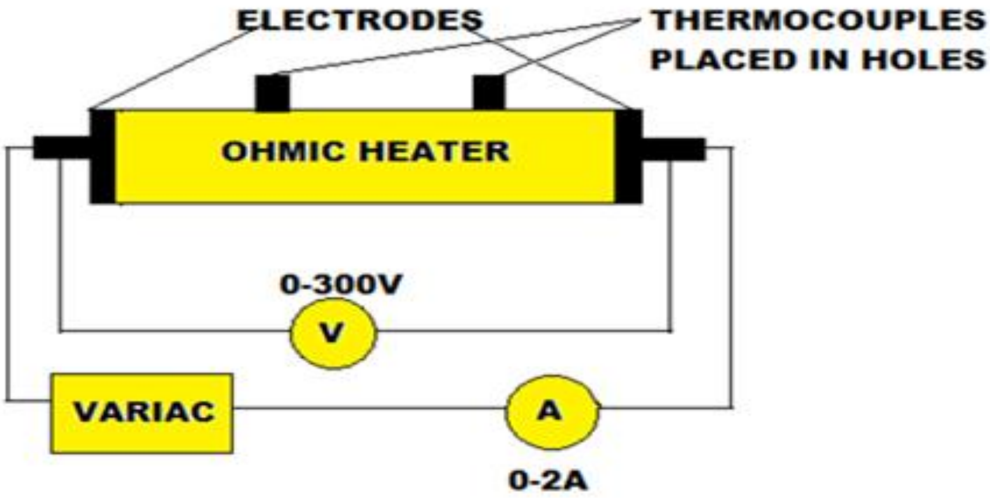

Figure 3.5 Schematic diagram of ohmic heater

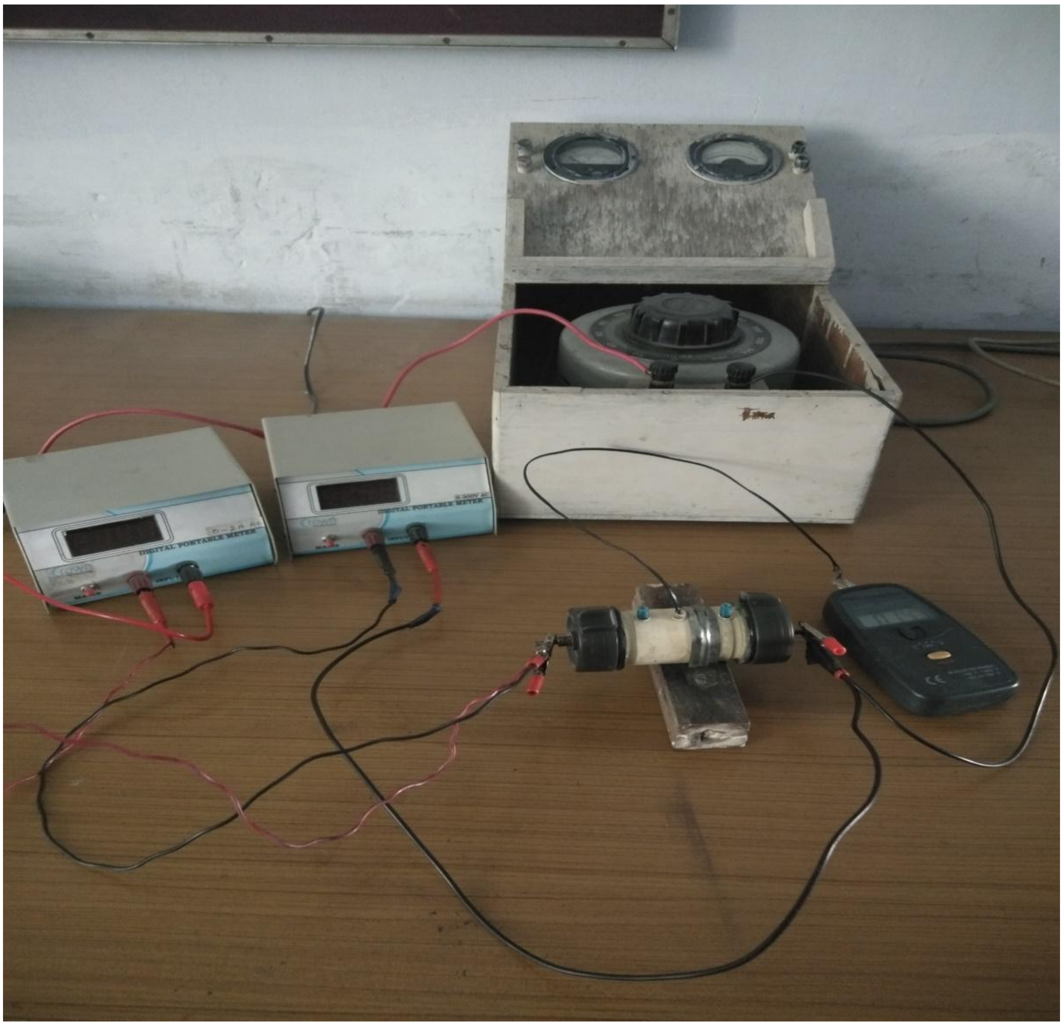

Figure 3.6 Experimental set up of ohmic heater

3.9 MEASUREMENT OF ELECTRICAL CONDUCTIVITY

The electrical conductivity of samples has been measured from the voltage and current data. A sample of known concentration has been poured into the cell and different voltages were applied. The current passing through the sample and applied voltage was noted. The change in current and temperature has recorded at regular interval of time. With the passage of time, the temperature increased and the experiment was performed till the temperature reaches 70°C.

Electrical conductivity of sample (σ) can be measured from voltage and current data using the following equation:

$$\sigma = IL/VA \qquad -(3.3)$$

Where, L is the length 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). S/m is the units of electrical conductivity.

The same procedure has been applied to remaining concentrations and at various voltage gradients. Each experiment had repeated thrice to get concordant readings.

3.10 SYSTEM PERFORMANCE COEFFICIENT (SPC) AND ITS MEASUREMENT

System performance coefficient of the ohmic heater can be calculated using the following relation:

SPC = Energy gained by the sample/ Energy supplied to the sample

$$= m\, C_p(T_f - T_i) / \Sigma VIt \qquad -(3.4)$$

Where C_p is specific heat capacity, m is the mass of tomato puree in the ohmic heating cell, T_i is the initial temperature of tomato puree before ohmic heating and T_f is the final temperature after ohmic heating and I is the current passed through the puree, V is voltage applied and t is time taken by the sample to heat from an initial temperature (T_i) to final temperature (T_f).

It is clear from the expression (3.4) that the calculation of both the energies i.e. energy supplied and energy gained by the sample is a crucial step to determine SPC of the ohmic heater cell. All the parameters mentioned in the numerator of expression (3.4) were known except specific heat of tomato puree (C_p). Moreover due to lack of literature values of specific heat of tomato puree, much emphasis was laid on the experimental calculation of C_p values of puree. Next step was to determine the denominator of expression (3.4). The whole experimental procedure is explained in the following section:

The procedure to calculate (C_p) is based on Newton's law of cooling. It states that the loss of heat is directly proportional to the difference in temperature between the system and the surroundings. A copper calorimeter of capacity 100 ml is used. The experiment involved the heating of a particular volume of water say, 100 ml approximately 40 °C higher than room temperature. Then the stop watch has started immediately without any delay in time as the hot water has poured in the copper calorimeter. Then falling temperatures is noted at fixed intervals of time. The stop watch has been stopped when the temperature of the water is few degrees higher than the room temperature. The mass of water is also noted with help of an electronic balance. Then the tomato puree of same volume has taken and heated to the temperature upto which water has heated. In the same way data was recorded for tomato puree at same regular intervals of time. Then a graph has been plotted between the time and temperature values by taking temperature on ordinate- axis and time on abscissa-axis. The data of water and tomato puree was plotted on the same graph. Two lines are drawn in such a way that they intersect the water and tomato puree curves. Times for both the water and tomato puree was obtained in this manner. Then specific heat has been calculated by using the following relation:

$$\text{Specific heat of puree } (S_2) = (((WS + M_1S_1)\, t_2/\, t_1)\text{-}WS)/M_2$$

Where W is weight of calorimeter, S is specific heat of material taken in calorimeter, M_1 is mass of water, S_1 is specific heat of water, M_2 is the weight of tomato puree and t_1 and t_2 are times of water and puree respectively. Specific heat capacity has calculated for all the five concentrations and the whole experiment was repeated thrice in order to obtain a mean concordant reading. To calculate the energy supplied to the ohmic heater i.e. ΣVIt a graph is plotted between current and time. From the equation of line obtained from the graph used to calculate the desired energy. Dividing both the energies i.e. energy gained to the energy supplied, SPC is obtained.

CHAPTER-IV

RESULTS AND DISCUSSION

In this chapter the experimental results of various parameters such as electrical conductivity, ohmic heating rate, pH, TSS and SPC and the influence of different concentrations and voltage gradients has been discussed. Statistical analysis has also carried out for pH and TSS values. The various parameters and properties have been represented by Table 4.1.

Table 4.1 The parameters and properties used in the experiment

Property or parameter	Value	Unit
Concentrations of tomato puree	60, 70, 80, 90, 100 %	% (v/v)
Voltage gradients applied	2, 4, 6, 8	V/cm
Diameter of electrodes	0.0347	m
Distance between electrodes	0.105	m
Densities of tomato puree of 100% 90% 80% 70% 60%	 1.057 1.052 1.049 1.043 1.040	g/ cm^3

4.1 OHMIC HEATING RATE

Heating rate is defined as the change in temperature with time. Ohmic heating rate is mainly the measurement of the total time taken by food sample to heat up to required temperature. The quality of heated product such as flavor, appearance, colour, aroma etc. is determined by this parameter. Viscosity, acidity, density, applied voltage, composition, particle dimensions, concentration are some factors that affect the heating rate of food product.

In ohmic heater, voltage is applied across its two electrodes and the current starts passing through the sample which in turn generates heat due to the resistance offered by food sample, such a heating rate is called ohmic heating rate. When the time taken by food sample to heat upto certain temperature is less i.e. shorter processing time, then the heating rate is high and the quality of food product is preserved. Thus high heating rates are generally preferred.

The ohmic heating rate has been experimentally determined for five different concentrations (60, 70, 80, 90 and 100%) at regular interval of time for four different voltage gradients (8, 6, 4 and 2 V/cm). The observed variation of temperature with time has been presented in table 4.2-4.5 and their graphs are plotted. The data has been taken for five different concentrations of tomato puree and the each sample is heated from 30^{o}C to 70^{o}C. Heating has been stopped as soon as sample attained 70^{o}C because bubbling is observed over 70^{o}C. The graphs are plotted for five different concentrations by keeping the voltage gradient constant. It can be clearly observed from the plots that there is linear increase in temperature with time. The time taken by 100% concentrated puree sample at 8V/cm is 80s, at 6V/cm is 130s, at 4V/cm is 320s and at 2V/cm is 1350s. The decrease in voltage gradient increases the processing time consequently heating rate falls. For 60% concentration, the experimental observed values for ohmic heating rate are 0.2815, 0.1628, 0.0683, 0.0176 ^{o}C/sec at voltage gradients 8, 6, 4 and 2V/cm respectively. From these values, it is clear that heating rate increases with increase in voltage gradient. Thus heating rate is linearly dependent on voltage gradient. Same observations are given by Assiry *et al* 2003, Icier and Ilicali 2005a, Darvishi *et al* 2011, 2013 and Kautkar *et al* 2015.

It is found that at high voltage gradient heating is more efficient and rapid as compared to low voltage gradients. This can be due to the fact that at high voltage gradients the current flowing through sample is high which leads to high heat generation rate. Nistor *et al* 2013 and Kautkar *et al* 2015 also noticed that for low voltage gradient, time taken by sample to attain desired temperature is longer than that for high voltage gradients. Thus voltage gradient has significant effect on the ohmic heating rate of tomato puree.

It has been observed from the graphs that concentration of sample also contributes in heating rate. For higher concentration, the heating rate is high. At 8V/cm voltage gradient, the observed heating rates for 60, 70, 80, 90, 100% concentrations are 0.2815, 0.3196, 0.3385, 0.3964 and 0.4850^{o}C/sec respectively. The heating rate is high for pure sample due to the presence of greater number of free ions or charge carriers as they cause more number of collisions among them. Hence the heat transfer is more. Assiry *et al* 2010 also observed similar trend. Thus it can be concluded that along with voltage gradient concentration also has significant ($p<0.05$) effect on ohmic heating rate of tomato puree.

At industrial scale of processing, in order to attain faster heating, higher voltage gradient as well as higher solute concentration is preferred. In addition to this, the precise measurement and the accurate control of temperature during ohmic heating play an important part in the design of ohmic heating equipments.

Table 4.2 Change in temperature with time during ohmic heating of tomato puree at 8 V/cm

Time (s)	Temperature (°C)				
	100%	90%	80%	70%	60%
0	30	30	30	30	30
10	37	35	33	33	32
20	41	38	36	35	34
30	46	43	39	38	37
40	50	46	43	42	40
50	55	50	46	44	42
60	60	53	50	48	45
70	65	58	53	52	48
80	70	63	57	55	51
90	-	66	60	59	55
100	-	70	63	62	58
110	-	-	67	65	61
120	-	-	70	67	63
130	-	-	-	70	66
140	-	-	-	-	68
150	-	-	-	-	70

Table 4.3 Change in temperature with time during ohmic heating of tomato puree at 6 V/cm

Time (s)	Temperature (°C)				
	100%	90%	80%	70%	60%
0	30	30	30	30	30
10	35	34	33	32	32
20	38	36	37	34	34
30	40	38	40	36	35
40	43	41	42	38	36
50	45	43	44	40	38
60	50	46	46	42	39
70	52	48	49	45	41
80	54	50	51	47	43
90	56	53	54	49	44
100	60	55	56	51	46
110	63	59	59	53	47
120	65	62	61	55	48
130	70	65	63	57	50
140	-	68	65	59	52
150	-	70	67	61	54
160	-	-	69	63	56
170	-	-	70	65	57
180	-	-	-	67	59
190	-	-	-	69	60
200	-	-	-	70	62
210	-	-	-	-	64
220	-	-	-	-	66
230	-	-	-	-	68
240	-	-	-	-	70

Table 4.4 Change in temperature with time during ohmic heating of tomato puree at 4V/cm

Time (s)	Temperature (^oC)				
	100%	**90%**	**80%**	**70%**	**60%**
0	30	30	30	30	30
20	32	32	33	33	34
40	36	35	35	35	35
60	40	38	38	37	36
80	44	40	40	38	37
100	46	42	41	40	38
120	48	44	43	42	40
140	50	47	45	43	41
160	53	49	47	45	42
180	55	51	50	47	43
200	57	54	52	48	45
220	60	56	54	50	46
240	62	57	56	52	47
260	64	60	58	54	48
280	66	63	60	56	50
300	68	66	63	57	51
320	70	68	65	59	53
340	-	69	67	61	54
360	-	70	68	63	55
380	-	-	69	65	57
400	-	-	70	67	58
420	-	-	-	68	60
440	-	-	-	69	61
460	-	-	-	70	62
480	-	-	-	-	64
500	-	-	-	-	66
520	-	-	-	-	68
540	-	-	-	-	69
560	-	-	-	-	70

Table 4.5 Change in temperature with time during ohmic heating of tomato puree at 2V/cm

Time (s)	Temperature (^oC)				
	100%	**90%**	**80%**	**70%**	**60%**
0	30	31	30	29	30
50	34	33	32	30	33
100	36	34	33	31	34
150	37	35	34	32	35
200	38	36	35	34	36
250	40	38	36	35	37
300	41	39	37	36	38
350	42	40	38	37	38
400	43	41	39	38	40
450	45	42	40	39	41
500	46	43	41	41	42
550	48	44	42	42	42
600	49	46	43	43	43

Time (s)	**Temperature (°C)**				
	100%	**90%**	**80%**	**70%**	**60%**
650	50	47	44	44	44
700	52	48	46	45	45
750	53	49	47	46	46
800	54	50	49	47	47
850	56	52	50	48	48
900	57	53	51	49	49
950	58	54	52	50	50
1000	60	55	53	52	51
1050	61	56	54	52	51
1100	62	57	55	53	52
1150	64	58	56	54	53
1200	65	60	57	55	54
1250	67	61	59	56	54
1300	68	62	60	58	55
1350	70	63	61	59	56
1400	-	64	62	59	57
1450	-	65	63	60	58
1500	-	66	64	61	58
1550	-	67	65	62	59
1600	-	68	66	63	60
1650	-	69	67	64	61
1700	-	70	68	66	62
1750	-	-	69	67	63
1800	-	-	70	68	64
1850	-	-	-	69	65
1900	-	-	-	70	66
1950	-	-	-	-	67
2000	-	-	-	-	68
2100	-	-	-	-	69
2150	-	-	-	-	70

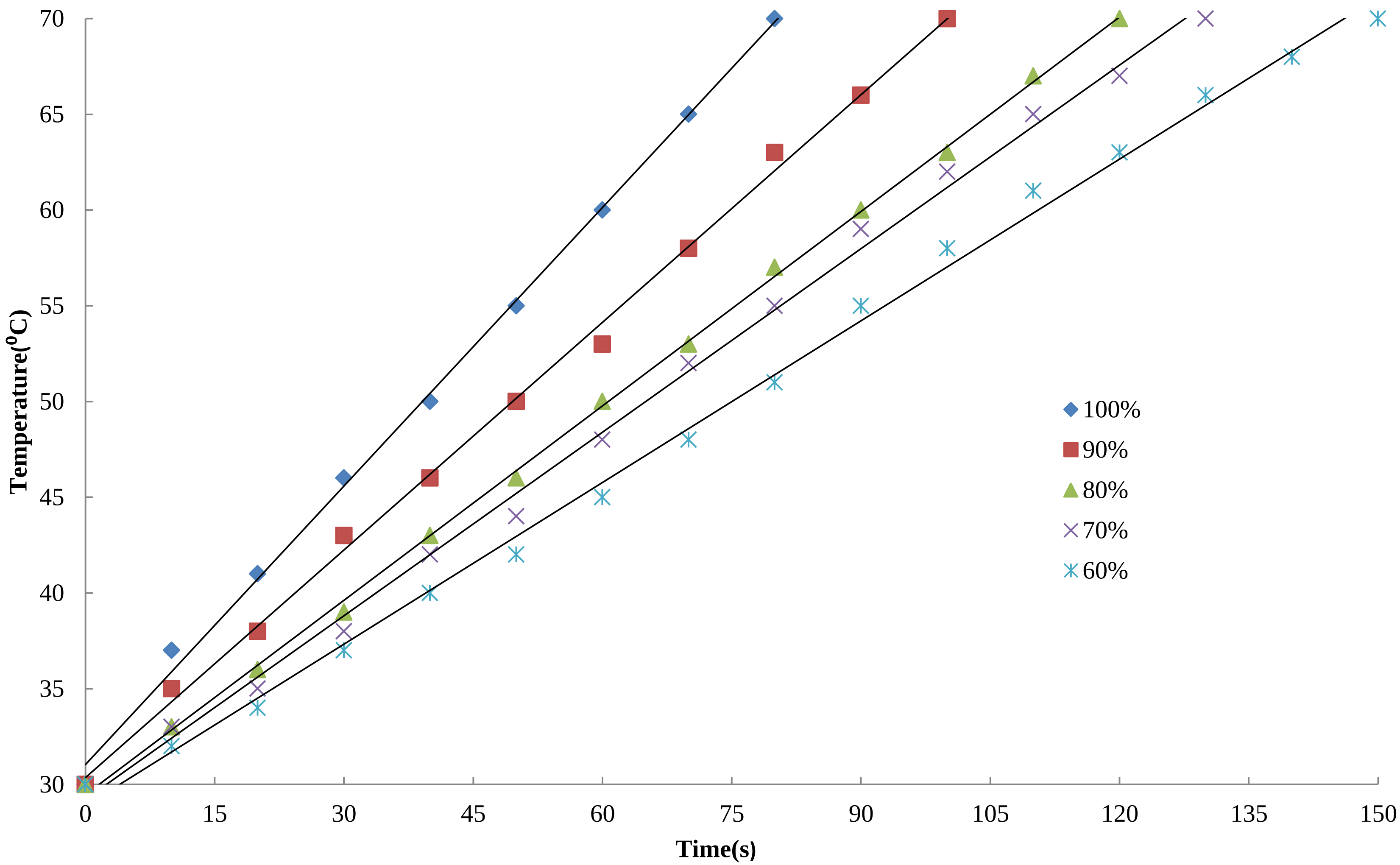

Figure 4.1 Variation of temperature with time during ohmic heating of tomato puree of different concentrations at 8 V/cm

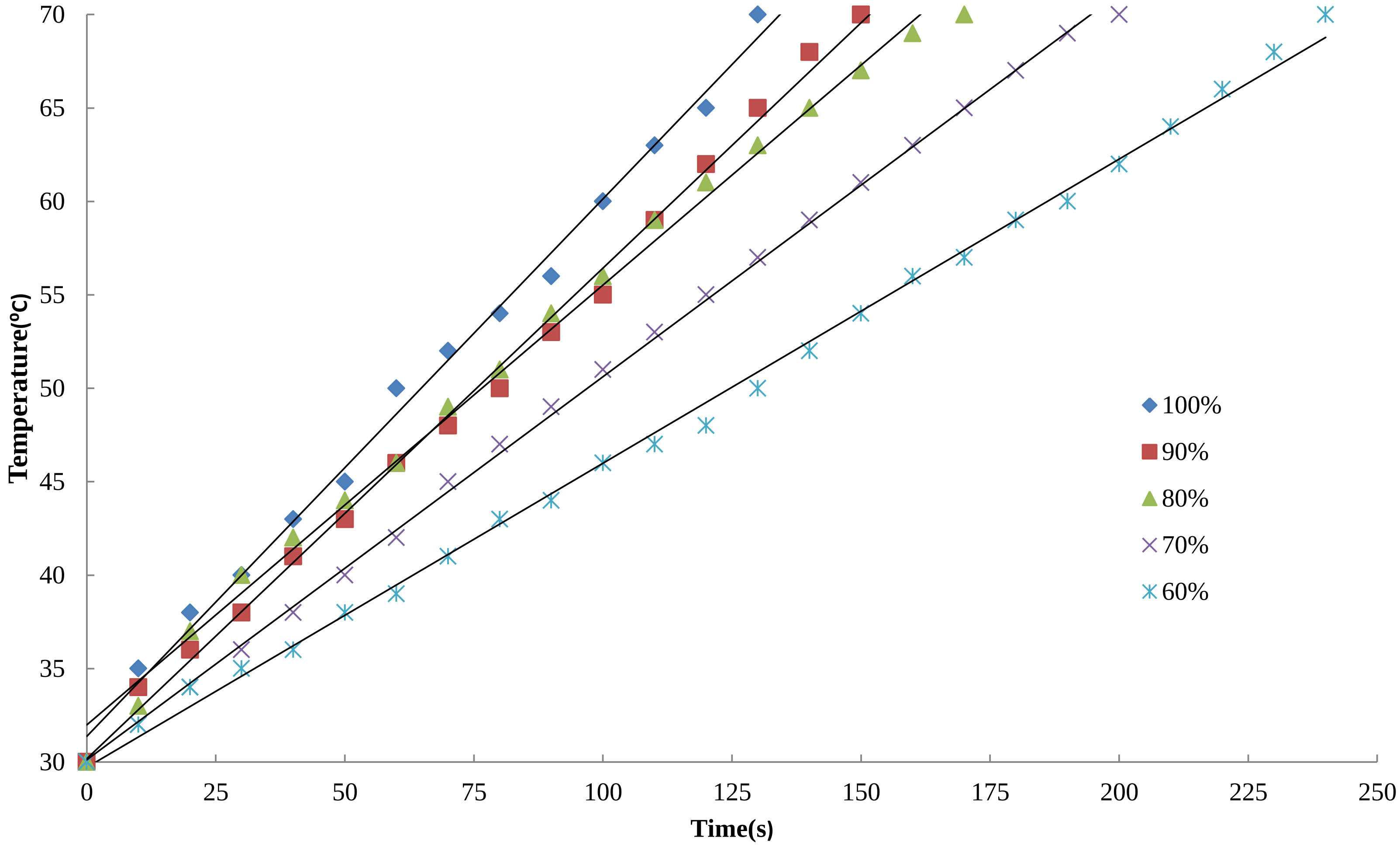

Figure 4.2 Variation of temperature with time during ohmic heating of tomato puree of different concentration at 6 V/cm

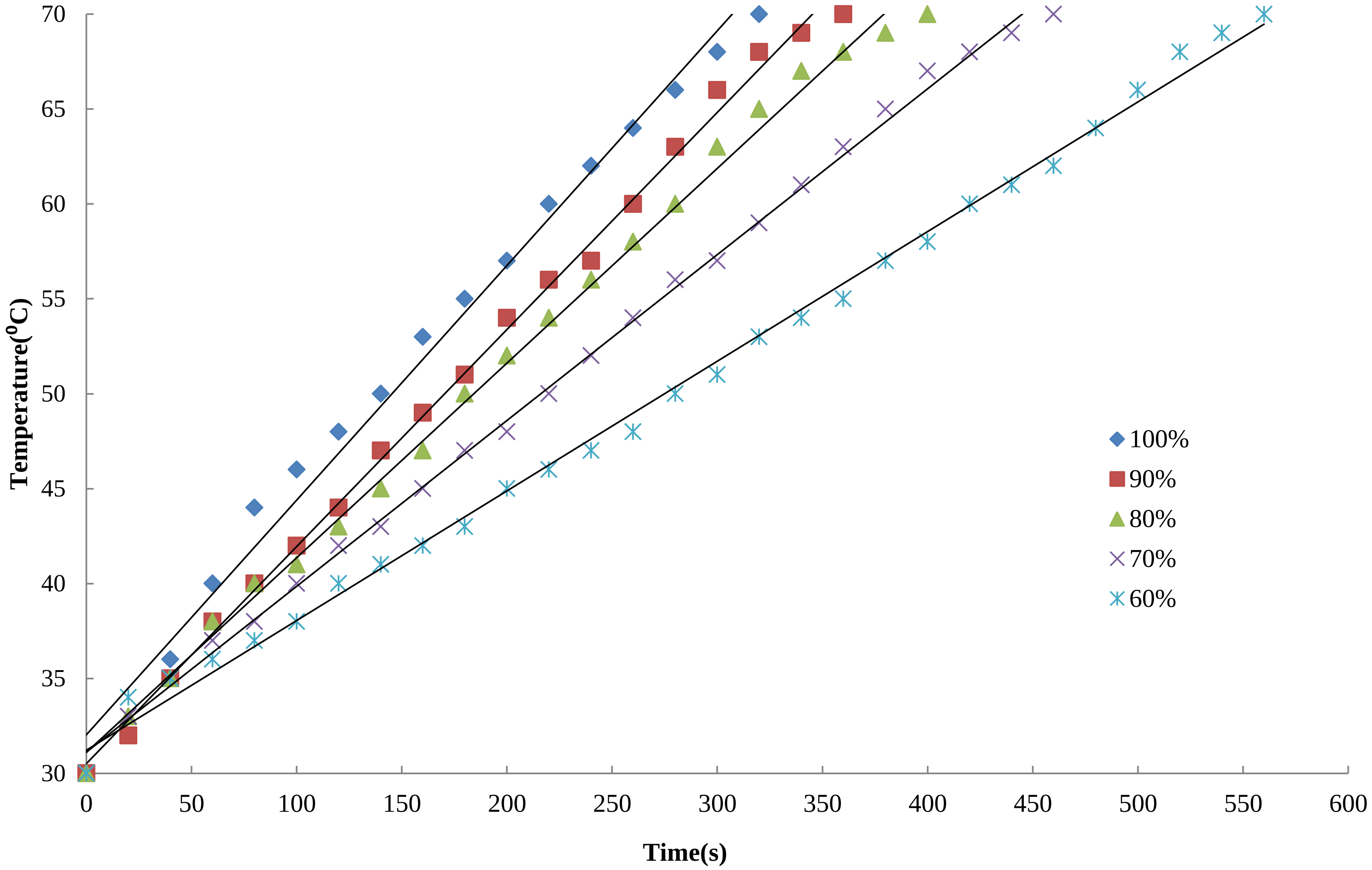

Figure 4.3 Variation of temperature with time during ohmic heating of tomato puree of different concentration at 4 V/cm

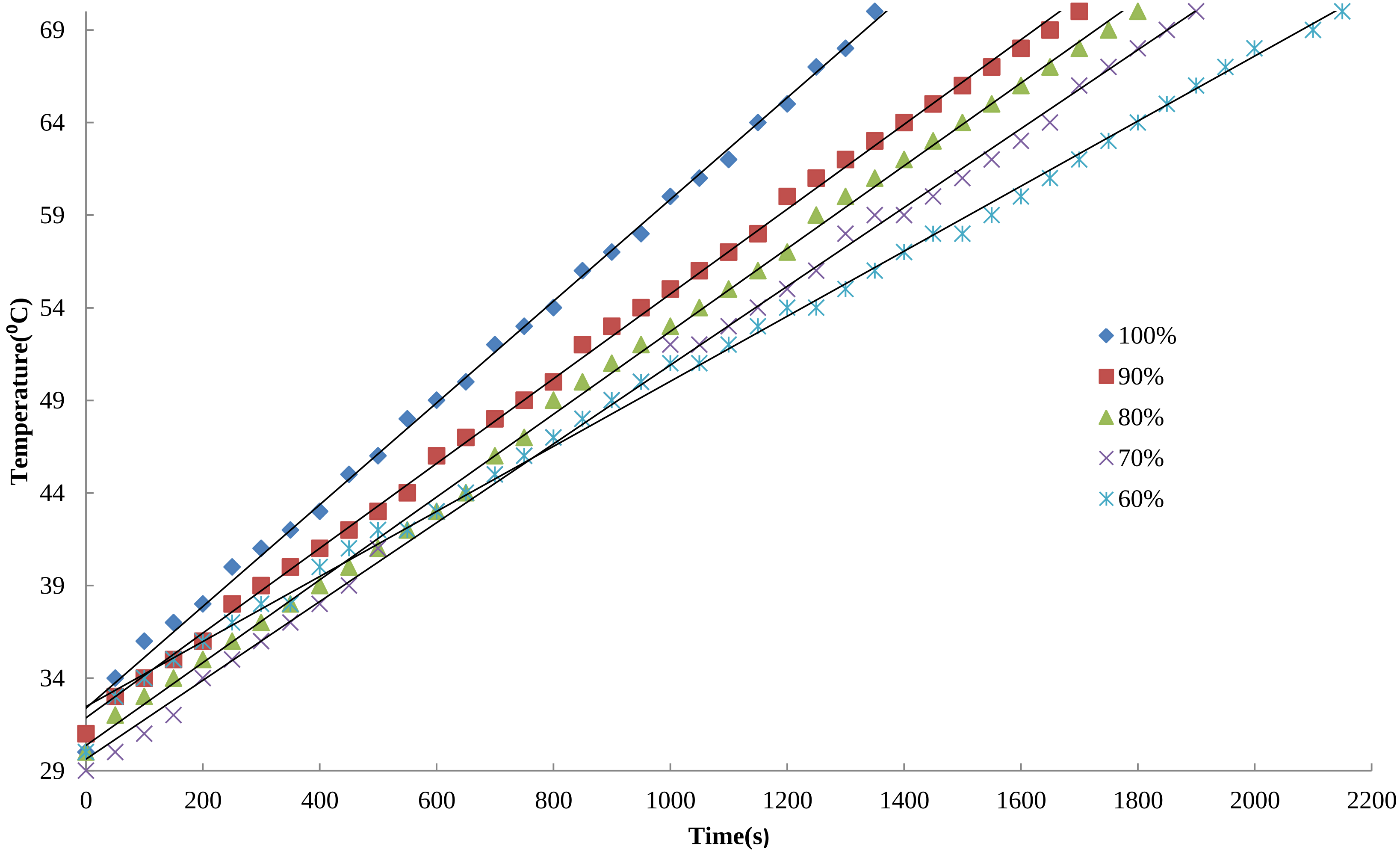

Figure 4.4 Variation of temperature with time during ohmic heating of tomato puree of different concentrations at 2 V/cm

4.2 VARIATION OF ELECTRICAL CONDUCTIVITY

Electrical conductivity of any food is a function of its components. The ionic contents (salts), acids and moisture enhance the electrical conductivity while fats, alcohols and lipids depressed it. It is highly influenced by applied voltage, concentration, temperature and frequency. The experimental values of electrical conductivity with temperature for different concentrations of tomato puree and voltage gradients have been represented in tables 4.6 to 4.9. Each sample has been heated from 30ᵒC to 70ᵒC and data is taken at four different voltage gradients for five different concentrations. The graphs describing the variation of electrical conductivity with temperature of five different concentrations of tomato puree at a given voltage gradients are shown in the figure 4.5 to 4.8. It can be clearly seen from the plots that the variation of electrical conductivity with temperature follows a linear trend.

It has been found that voltage gradient has significant effect on the variation of electrical conductivity with temperature. For pure tomato puree sample, the conductivity values increases from 1.612 to 1.782 S/m as the voltage gradient increases from 2 to 8V/cm at 30ᵒC. The maximum values of electrical conductivity are observed for 8V/cm followed by 6, 4 and 2V/cm. For a particular voltage gradient and at given concentration of tomato puree, the electrical conductivity increases linearly with temperature. This trend is consistent with the results obtained by Kumar *et al* 2011, Icier *et al* 2008, Kemp and Fryer 2007, Darvishi *et al* 2011 and Amiali *et al* 2006. The increase in the conductivity with temperature may due to the reduced drag for the motion of ions.

The explanation for increasing electrical conductivity with rise in voltage gradient is caused by the electro-osmotic effects (Halden *et al* 1990). Castro et al 2003 examined the effects of voltage on the electrical conductivity of various strawberry products. They found that electrical conductivity increases with temperature for all products. Sarang *et al* 2008 investigated the electrical conductivity of various fruits and found that it increases linearly with temperature rise during ohmic heating at 60Hz for voltage gradients in the range 15-20V/cm. Highly porous materials like apple, pineapple and pear show low electrical conductivity than peach and strawberry. This is due to their harder tissues and low ionic mobility. Olivera *et al* 2013 also reported the increase in conductivity of fresh food samples as the voltage gradient increased from 1100 to 3300 V/cm.

Electrical conductivity of food sample is also affected due to its concentration. At 30ᵒC the conductivity of 100, 90, 80, 70and 60% concentrated sample at 8V/cm is 1.782, 1.627, 1.486, 1.342 and 1.139 S/m respectively. This implies that the higher concentrated sample has higher electrical conductivity. This trend is also observed by Assiry *et al* 2010. High concentration means more number of ions that will accelerate the electric current through the sample. Thus concentration of food sample is also responsible for the change in electrical conductivity.

The increase in electrolytic contents of food product can raise its electrical conductivity. This can be done by salt infusion. It can either be achieved by rapid blanching or slow soaking process in salt solution (Wang and Sastry 1993). In vegetables, the shape of parenchyma cell and the orientation of vascular bundles can affect its electric conductance. The pre-treatment in salt water enhances the electrical conductivity as well as improving the final textural quality of processed food product.

Leite *et al* 2018 observed linear correlation between consistency and electrical conductivity. This can be helpful in designing the ohmic heating equipments. Cristina *et al* 1999 examined the electrical conductivity was highly dependent on concentration of lemon juice and found that it increased with elevation in concentration. But this increase is up to a particular concentration after which electrical conductivity values decreased which may be due to an increase in viscosity of juice samples resulting in the decrease of mobility of ions. Kaushal 2013 showed that the guava juice samples having more TDS values, possess higher electrical conductivity. As TDS value decreases, conductivity also decreases. Thus electrical conductivity variation depends on the concentration of ions. Icier and Ilicali 2005 examined the conductivity of orange juicec decreases with dilution of purees with distilled water.

During the ohmic heating of tomato puree, bubbling is observed when the temperature reached around 70^{o}C. The electrical conductivity starts falling as the bubbling starts so heating has been stopped at this temperature otherwise it can destroy the nutrients of puree. Darvishi *et al* 2012a studied the ohmic heating of pomegranate juice. They observed the bubbling around 80^{o}C and the conductivity of juice has been found in the range of 0.25 to 1.13S/m. As most of the juices are acidic, there is release of gas in liquid due to some electrochemical reaction (Palaniappan and Sastry 1991). This results in the potential electrolytic hydrogen bubble formation in juice. Zhao *et al* 1990 explained that formation of bubble may be due to localized high current densities. Sometimes the by-products formed during redox reactions also give rise to bubbling. Darvishi et al 2012b concluded that the decrease in conductivity of tomato paste was due to the air which possesses negligible electrical conductivity.

The proficiency of ohmic heating is depending on the conductive nature of food that has to be processed and hence the information of the electrical conductivity of food product is important in designing an efficient ohmic heating process.

Table 4.6 Variation of electrical conductivity of tomato puree at 8V/cm during ohmic heating

Sr. No.	Temp.(°C)	Electrical conductivity (in S/m)				
		100%	90%	80%	70%	60%
1	30	1.782	1.627	1.486	1.342	1.139
2	35	1.852	1.693	1.632	1.453	1.216
3	40	1.989	1.799	1.744	1.547	0.363
4	45	2.152	1.885	1.840	1.635	0.375
5	50	2.213	2.007	1.941	1.743	0.387
6	55	2.340	2.119	2.065	1.847	0.399
7	60	2.462	2.287	2.174	1.974	0.411
8	65	2.514	2.359	2.301	2.096	0.423
9	70	2.668	2.513	2.416	2.196	0.435

Table 4.7 Variation of electrical conductivity of tomato puree at 6V/cm during ohmic heating

Sr. No.	Temp.(°C)	Electrical conductivity (in S/m)				
		100%	90%	80%	70%	60%
1	30	1.751	1.523	1.439	1.342	1.069
2	35	1.802	1.617	1.537	1.415	1.121
3	40	1.936	1.742	1.646	1.492	1.201
4	45	2.052	1.843	1.748	1.601	1.283
5	50	2.167	1.916	1.848	1.691	1.361
6	55	2.270	1.997	1.954	1.772	1.457
7	60	2.386	2.168	2.042	1.875	1.530
8	65	2.482	2.224	2.129	1.978	1.613
9	70	2.631	2.372	2.237	2.135	1.703

Table 4.8 Variation of electrical conductivity of tomato puree at 4V/cm during ohmic heating

Sr. No.	Temp.(°C)	Electrical conductivity (in S/m)				
		100%	90%	80%	70%	60%
1	30	1.721	1.452	1.347	1.305	1.016
2	35	1.797	1.567	1.451	1.389	1.104
3	40	1.905	1.657	1.541	1.453	1.178
4	45	1.996	1.742	1.628	1.546	1.255
5	50	2.121	1.836	1.735	1.649	1.324
6	55	2.248	1.964	1.830	1.736	1.399
7	60	2.366	2.097	1.922	1.821	1.468
8	65	2.469	2.129	2.033	1.965	1.552
9	70	2.594	2.246	2.124	2.135	1.621

Table 4.9 Variation of electrical conductivity of tomato puree at 2V/cm during ohmic heating

Sr. No.	Temp.(°C)	Electrical conductivity (in S/m)				
		100%	90%	80%	70%	60%
1	30	1.612	1.412	1.352	1.257	1.009
2	35	1.714	1.498	1.384	1.302	1.055
3	40	1.865	1.596	1.465	1.374	1.175
4	45	1.936	1.687	1.534	1.446	1.208
5	50	2.095	1.754	1.658	1.543	1.281
6	55	2.197	1.854	1.725	1.643	1.343
7	60	2.318	1.954	1.836	1.746	1.414
8	65	2.423	2.035	1.914	1.839	1.478
9	70	2.523	2.213	2.012	1.954	1.545

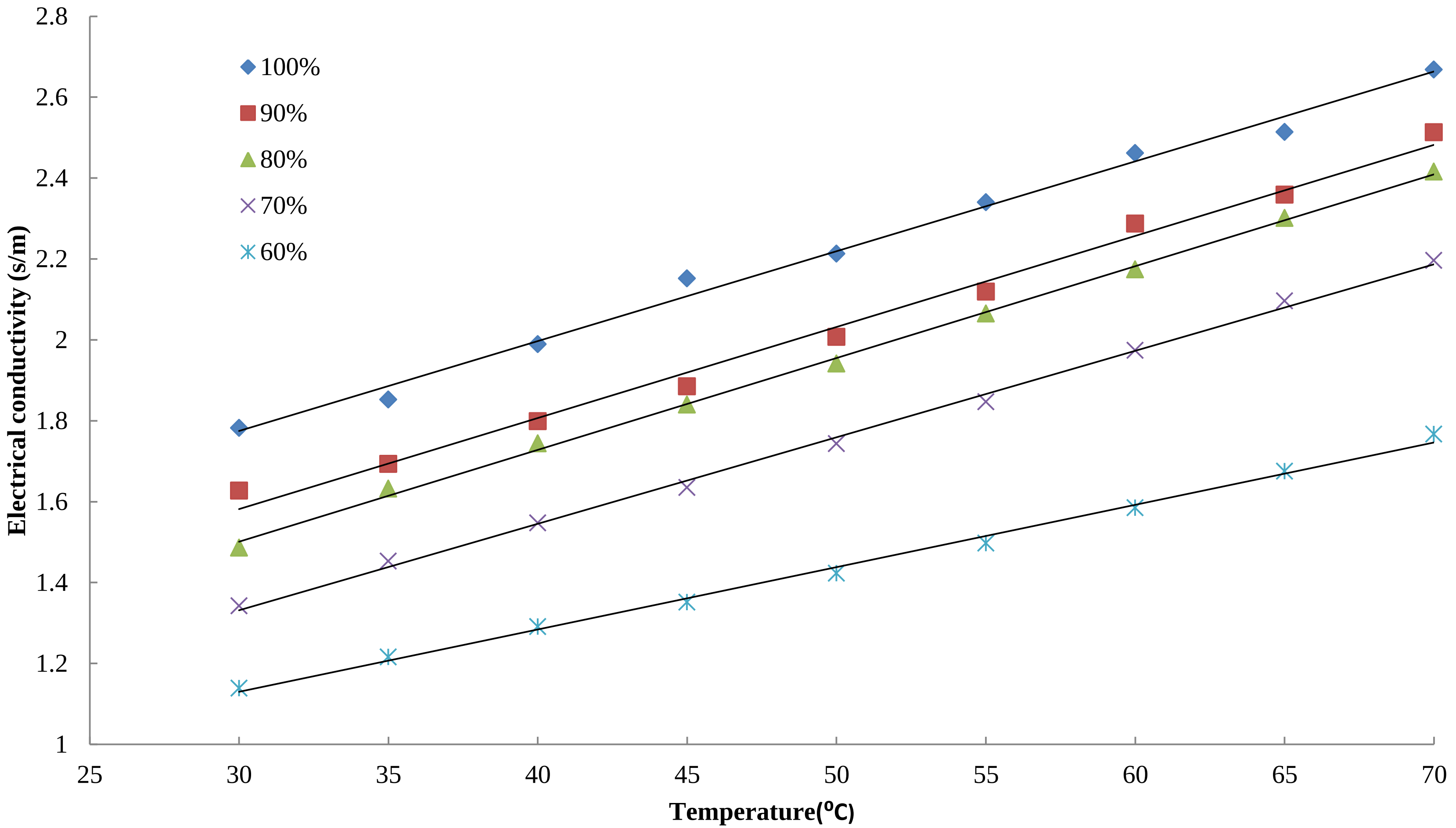

Figure 4.5 Change in the electrical conductivity with temperature for five concentrations of tomato puree at 8 V/cm voltage gradient.

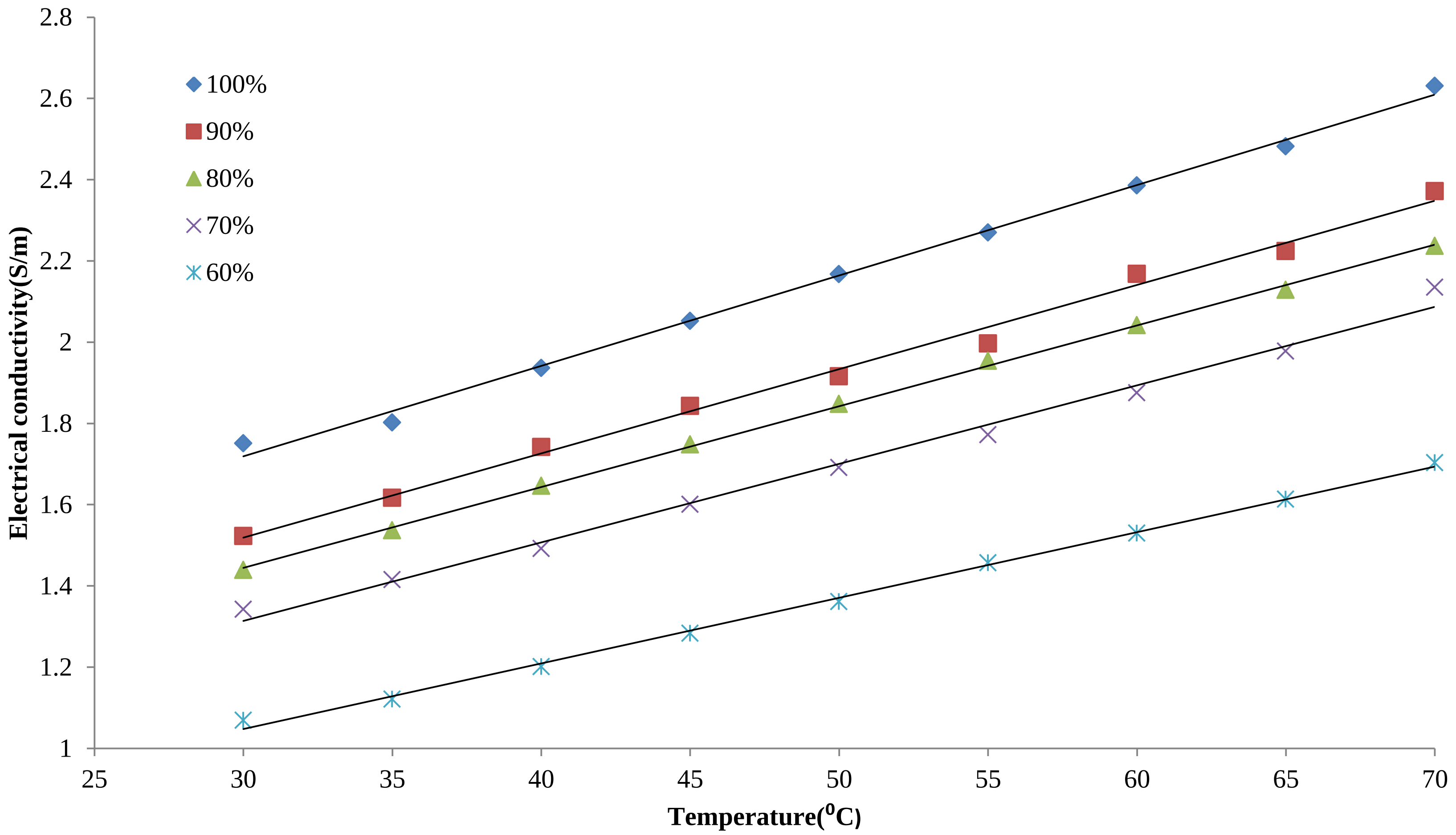

Figure 4.6 Change in the electrical conductivity with temperature for five concentrations of tomato puree at 6 V/cm voltage gradient.

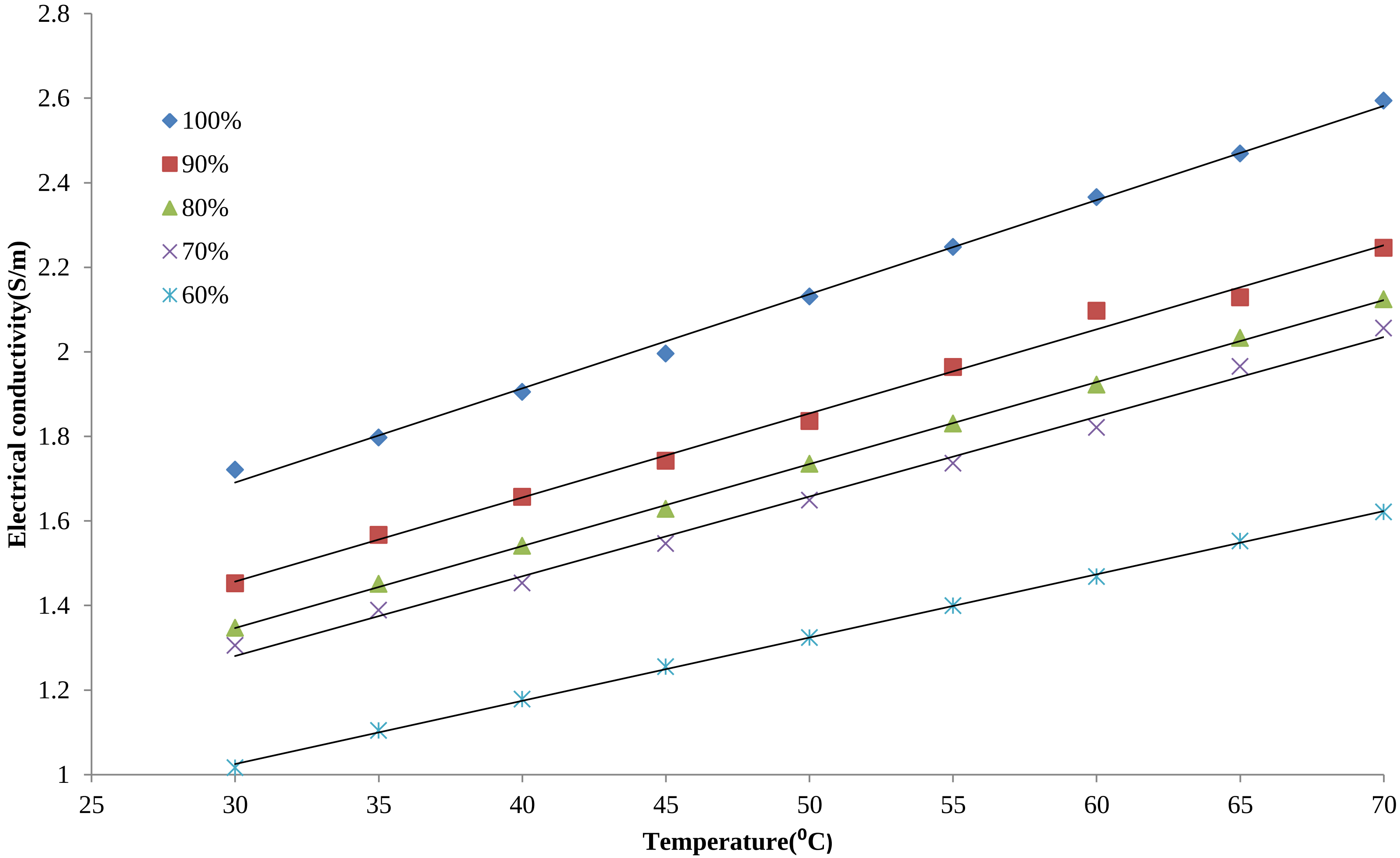

Figure 4.7 Change in the electrical conductivity with temperature for five concentrations of tomato puree at 4V/cm voltage gradient.

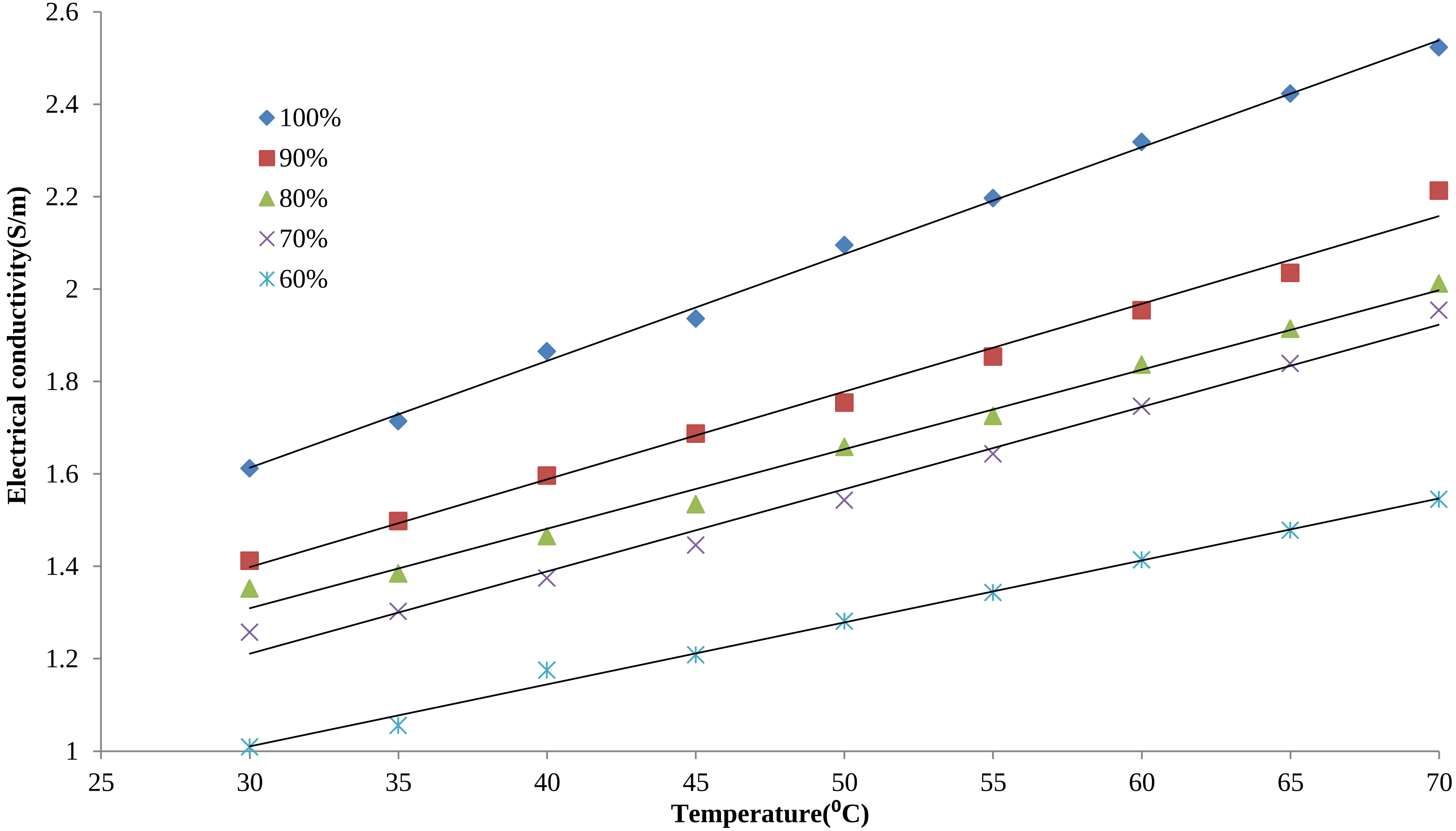

Figure 4.8 Change in the electrical conductivity with temperature for five concentrations of tomato puree at 2V/cm voltage gradient.

4.3 MODELING OF ELECTRICAL CONDUCTIVITY

Modeling is an approach that constructs a summary model displaying the current knowledge. The models are then fitted to data to check the goodness of fit. It is an important step for estimation the statistical significance of parameters. Regression analysis is a statistical process used for the estimation of relationship among different variables. It is used for modeling the relationship between a single variable called as response, output or dependent variable and one or more predictors, input, independent or explanatory variables. Regression analysis is beneficial not only in testing the significance or non- significance of the independent parameters on the dependent parameter, but it also measures the changes produced in a dependent variable by the independent variables independently. Coefficient of determination (R^2), reduced chi-squared value (χ^2) and root mean square error (RMSE) are used to check the goodness of fit (Darvishi *et al* 2012a).

For tomato puree samples, the experimental variation of tomato puree with temperature follows linear trend. Therefore a linear model can be used to fit the electrical conductivity data of puree.

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

where σ (V,C,T) represents the electrical conductivity of tomato puree obtained at a given voltage gradient for a particular concentration. A (V, C) and B (V, C) are regression constants and are function of applied voltage gradient (V/cm) and concentration. A (V, C) is the intercept of plots shown in figure 4.5-4.8 and denotes the constant of electrical conductivity-temperature relationship whereas B (V, C) is the slope of curve and measures the extent to which electrical conductivity values change on raising the temperature.

A mathematical modeling of electrical conductivity of tomato puree with temperature has been done using Microsoft Excel software. The temperature dependent electrical conductivity relation was obtained using linear regression analysis. Table 4.10 shows the regression coefficients of ohmically heated different concentrations of tomato puree and at different voltage gradients along with mathematically fitted equation. The value ranges from 0.988 to 0.999. The goodness of fit is confirmed by these large values and also specify the significant variation with temperature at all concentrations and voltage gradients. Modeling equations can provide an access to find the electrical conductivity value at any required temperature. The linear model was also suggested by Icier and Illicali 2005, Assiry *et al* 2010 and Darvishi *et al* 2011.

Table 4.10 The constants and coefficients of electrical conductivity- temperature relationship of tomato puree ohmically heated at different voltage gradients.

Concentration (% by volume)	Voltage gradients (V/cm)	Electrical conductivity-Temperature Model	Regression Coefficient (R^2)
60	8	σ = 0.015T+0.668	0.996
	6	σ = 0.016T+0.564	0.998
	4	σ = 0.015T+0.576	0.999
	2	σ = 0.013T+0.608	0.995
70	8	σ = 0.021T+0.730	0.988
	6	σ = 0.019T+0.734	0.992
	4	σ = 0.019T+0.715	0.994
	2	σ = 0.018T+0.677	0.989
80	8	σ = 0.023T+0.822	0.998
	6	σ = 0.020T+0.848	0.999
	4	σ = 0.019T+0.765	0.999
	2	σ = 0.017T+0.793	0.991
90	8	σ = 0.022T+0.907	0.991
	6	σ = 0.021T+0.896	0.994
	4	σ = 0.020T+0.860	0.994
	2	σ = 0.021T+0.670	0.998
100	8	σ = 0.022T+1.108	0.993
	6	σ = 0.022T+1.051	0.996
	4	σ = 0.022T+1.023	0.997
	2	σ = 0.023T+0.920	0.997

4.4 EFFECT OF OHMIC HEATING ON pH

Tomato and its product all are acidic in nature. pH measurements are taken to determine the acidity of tomato puree. Table 4.11 shows the experimentally observed pH values for different concentrations at different voltage gradients. The values are noted before and after the experiment. The pure tomato puree is more acidic. The maximum and minimum values for tomato puree before heating treatment is 4.26, 4.20 and after heating treatment is 4.40, 4.22 respectively.

Table 4.11 pH values for different voltage gradients applied to different concentrations of tomato puree

pH values of tomato puree					
Concentration Of tomato puree (v/v)	Before Ohmic Heating	After Ohmic Heating			
		Voltage Gradient (V/cm)			
		8	6	4	2
100%	4.20	4.29	4.27	4.23	4.25
90%	4.21	4.27	4.24	4.24	4.22
80%	4.22	4.25	4.26	4.24	4.25
70%	4.23	4.26	4.26	4.25	4.25
60%	4.26	4.40	4.40	4.37	4.30

Statistical analysis using paired t-test has been carried out for the pH values of tomato puree before and after the ohmic heating and the t-values are represented in table 4.12. The change in the pH of tomato puree before and after treatment is non-significant except for pure tomato puree at 8, 6, 2V/cm and for 90% concentration at 4 V/cm.

Table 4.12 t-values for pH for applied voltage gradients to five concentrations of tomato puree

Concentration (v/v)	Voltage Gradient (V/cm)			
	8	6	4	2
100%	12.095**	10.583**	3.024 ^{NS}	14.000**
90%	2.000 ^{NS}	0.500 ^{NS}	5.000*	1.732 ^{NS}
80%	1.000 ^{NS}	0.000 ^{NS}	1.732 ^{NS}	0.000 ^{NS}
70%	0.277 ^{NS}	2.000 ^{NS}	0.000 ^{NS}	0.500 ^{NS}
60%	1.000 ^{NS}	0.000 ^{NS}	0.500 ^{NS}	4.000 ^{NS}

*t-values are significant at 5% level of significance

** t-values are significant at 10% level of significance.

^{NS} t-value is non-significant.

It can be noted that the variation in the pH values of puree tomato puree at different voltage gradients (except 4 V/cm) is significant and for the other concentrations it is overall non-significant. For 100% concentration at 2 V/cm, the heating rate is very low so there is maximum change in the pH value. This result is in agreement with the results given by Darvishi *et al* 2012. It is observed that the acidity of tomato puree decrease with increase in voltage gradient at particular concentration. This can be due to the occurrence of various chemical reactions or corrosion of the electrodes during heating.

4.5 EFFECT OF OHMIC HEATING ON TSS

Total soluble solid (TSS) is important parameter for determining the quality of product. It basically measures the sugar content that is present in the food product. TSS content in tomato is mainly due to sugar (fructose). The experimentally obtained TSS values of tomato puree at different voltage gradients and for different concentrations are shown in table 4.13. After the heating treatment, maximum value for TSS is 7.0°brix for pure tomato puree while minimum value is 3.4°brix corresponding to 60%. Moreover TSS value increases with rise in concentration due to increasing number of solid paricle in the sample.

Table 4.13 TSS values for different voltage gradients applied to tomato puree of different concentrations

TSS values (°brix) of tomato puree					
Concentration Of tomato puree (v/v)	**Before Ohmic Heating**	**After Ohmic Heating**			
		Voltage Gradient (V/cm)			
		8	**6**	**4**	**2**
100%	8.0	7.0	7.0	7.0	7.0
90%	6.0	6.2	6.4	6.0	6.0
80%	6.0	5.5	5.4	5.8	5.7
70%	5.0	4.7	4.5	4.4	4.6
60%	3.8	3.6	3.3	3.5	3.4

For statistical analysis, paired t test is applied for different voltage gradient and the results were listed in the following table. The variation in TSS value of tomato puree before and after treatment shows significant result only at 8V/cm for 80% concentration and for rest of the concentrations and voltage gradients changes are non-significant. As there is no significant change in TSS value so the quality parameters are preserved during treatment.

Table 4.14 t-values for TSS for applied voltage gradients to five concentrations of tomato puree

Concentration (v/v)	**Voltage Gradient (V/cm)**			
	8	**6**	**4**	**2**
100%	NS	NS	NS	NS
90%	1.732^{NS}	1.220^{NS}	1.000	1.000^{NS}
80%	7.000*	NS	1.732^{NS}	2.000^{NS}
70%	4.000^{NS}	2.646^{NS}	4.000^{NS}	2.000^{NS}
60%	3.462^{NS}	7.000^{NS}	2.500^{NS}	NS

*t-values are significant at 5% level of significance.

NS t-value is non-significant.

NS shows that t value cannot be computed as the standard error of difference is zero. It can be easily observed from the table 4.14 that there is no significant change in the TSS value of tomato puree before and after the ohmic heating treatment. These results are in consistent with that obtained by Icier *et al* 2008. They observed slight change in TSS value of grape juice after ohmic heating treatment. Icier and Ilicali 2005a reported that there was no significant change in TSS value of orange juice after ohmic heating.

4.6 SYSTEM PERFORMANCE COEFFICIENT (SPC)

The ratio of energy gained by the system to the energy supplied to the system gives the value of system performance coefficient. It depends upon the concentration of sample as well as the applied voltage gradient. These values can evaluated from temperature, current and voltage readings that are noted during the experiment. The experimentally calculated SPC values for five concentrations at four different voltage gradients are shown in the table 4.15.

Table 4.15 SPC values for four voltage gradients and five concentrations of tomato puree

Concentration (v/v)	Voltage Gradient (V/cm)			
	8	**6**	**4**	**2**
100%	0.90	0.89	0.96	0.82
90%	0.86	0.92	0.84	0.80
80%	0.92	0.98	0.90	0.84
70%	0.93	0.86	0.82	0.79
60%	0.90	0.83	0.70	0.76

For 80% concentration, SPC values are 0.92, 0.98, 0.90 and 0.84 at 8, 6, 4 and 2 V/cm respectively. For pure tomato puree 10% heat is lost when heated at 8V/cm whereas it is 18% at 2V/cm. The maximum heat loss for sample occurs at 4V/cm for 60% concentration while the minimum heat loss came out to be 4% at 4 V/cm for pure sample. This can be explained on the basis of heating rate. It is more for higher voltage gradients and low for small voltage gradients and more heat loses occurs at small voltage gradients as it requires more time to heat the sample up to desired temperature. These energy loses can also be due to the electrochemical reactions that takes place on stainless steel electrodes.

Darvishi *et al* 2013 observed that the SPC values lies in 0.76-0.93 for pomegranate juice. During ohmic heating of tomato paste Darvishi *et al* 2012 suggested that ohmic heated works best at 6V/cm. Park *et al* 2017 observed during the ohmic heating of apple juice that overall SPC values was higher for higher voltage gradient and are lies in the range 0.52-0.79. For pure sample the ohmic heater works best at 4V/cm, for 90% and 80% at 6V/cm, for 70% and 60% at 8V/cm. As the concentration of tomato puree decreases the efficiency of ohmic heating apparatus shift towards higher voltage gradient in the prescribed range.

CHAPTER-V

SUMMARY

First chapter deals with the Indian agriculture, role of modernization of agriculture and need of food processing. For food preservation various processing technologies have been discussed. Apart from convention heating methods, dielectric heating, infrared heating, inductive heating have been explained. Then the novel processing technique i.e. Ohmic heating, along with its principle, advantages have been fully described. After that information about ‘tomato’ and ‘puree’ and also the difference between ‘puree’ and ‘paste’ has presented. Then the various physicochemical parameters that can influence the ohmic heating have been discussed. At last the aim of the study has been present.

Second chapter provides the information regarding the various research works that had been done using ohmic heating technique. Various studies were reviewed to determine the influence of ohmic heating on the electrical properties, ohmic heating rate and other physicochemical parameters like density, pH, TSS, colour etc. of different food products. There were also some comparison studies between ohmic heating and conventional heating method applied on same product. Some works deal with the design and fabrication of ohmic heating cell. By examining all the works, it has become clear that variation of electrical conductivity as well as ohmic heating rate always vary in linear fashion whatever the product maybe and also ohmic heating is more effective than conventional heating techniques.

Third chapter describes the method of sample preparation, voltage gradients and concentrations that had been used during the experiment. It also gives the procedure for the measurement of different parameters like TSS, pH, density and SPC along with the description of their equipment. It also provides the description of ohmic heating system.

All the results obtained during the experiment have been discussed in the fourth chapter. Experimental data has been presented in tables and required graphs have been plotted. The slope of temperature versus time graph gives the ohmic heating rate and it had found that heating rate varies linear with concentration and voltage gradient. The variation of electrical conductivity with time have also been studied and observed that pure samples have more electrical conductivity and it increases with rise in voltage gradient. Mathematical modeling of electrical conductivity has been done using Microsoft Excel software that shows electrical conductivity and temperature are interrelated and represented by the following linear regression equation

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

where σ (V,C,T) represents the electrical conductivity of tomato puree ,A (V, C) and B (V, C) are regression constants. This equation ensures the linear relationship between electrical conductivity and temperature.

pH and TSS values had been noted before and after heating. Statistical analysis has been carried out by using paired t-test for these values and observed that there has overall non-significant effect of pH and TSS on ohmic heating. This ensures the retention of quality paramters of tomato puree. System performance coefficient (SPC) for different voltage gradients and concentrations has been calculated and observed that the efficiency of ohmic heater shifts toward higher voltage gradients, in the prescribed range, as the con concentration of sample decreases.

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%age of Marks	:	80.25
Master’s degree	:	M.Sc. (Physics)
University and year of award	:	Punjab Agricultural University, Ludhiana (2019)
OCPA	:	7.36/10.00
Title of Master’s thesis	:	Influence of ohmic heating on electrical properties of tomato puree