COLD PRESERVATION OF PERISHABLE FOOD PRODUCTS

A DISSERTATION

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WATER RESOURCES DEVELOPMENT

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in the dissertation entitled **"COLD PRESERVATION OF PERISHABLE FOOD PRODUCTS"** submitted, in partial fulfilment of the requirements for award of the degree of **MASTER OF TECHNOLOGY** in **WATER RESOURCES DEVELOPMENT** at **DEPARTMENT** of **WATER RESOURCES DEVELOPMENT AND MANAGEMENT**, of Indian Institute of technology Roorkee, is an authentic record of my own work carried out for a period from July 2005 to May 2006 under the supervision of **Prof. Gopal Chouhan**, Professor in the Department of Water Resources Development and Management, and **Dr. Ravi Kumar**, Associate Professor, in the Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee, India.

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ABSTRACT

Food products of perishable nature are needed to be preserved from spoiling using the precooling technique. Precooling is the process of cooling fruits and vegetables as soon as possible after the harvest and prior to transportation over long distance to a cold storage warehouse and marketing.

The present work is an attempt to investigate experimentally the heat transfer behaviour during precooling of fruits and vegetables in rectangular duct under forced convection. In the experimental study done of RAC lab at (MIED, IITR), on rectangular ducts the food commodities investigated are apple, papayas and grapes. Forced air cooling is achieved by suspending the food inside a 4 m long rectangular air duct of 0.3 x 0.3 m section of Galvanized Iron sheet which is insulated with 1 cm thick puff sheet. The humidity inside the duct is to be maintained constant. The temperatures of the cold air outside package and of the food product at different locations inside the package are to be measured at regular time intervals.

For better exposure of food commodity to the surrounding cold air, the fruits will be cooled in wire mesh package size 21 x 21 x 21 cm.

The air is circulated through the duct by means of a blower powered by 1.5 hp electric motor. The air is then made to pass through two coils. One coil is made evaporator coil of 5 ton capacity vapor compression plant and another coil has the forced flow of chilled water, which rejects heat to the refrigerant inside the chiller. The condenser cooling water cooled by means of induced draft cooling tower.

The test program were performed on three types of fruits that apples, grapes and papayas. Four air flow rate 1.6, 2.3, 3.3 and 4.1m/s were selected to examine the effects of cool air velocity on the cooling process. The temperature was monitor at three locations (surface, middle and centre) for apple and papaya, while monitor at two locations (surface and centre) for grape.

In the present study, a heat transfer coefficients have been obtained based on the transient temperature measurement techniques. Two cases adopted to determine the surface heat transfer coefficient namely, low Biot number and large Biot number. By product the slop of dimensionless temperature vs time curve with aid of one-dimensional transient heat equation, the Biot number of the cooling process can be predicted which, in turn, the heat transfer coefficient obtained. In addition, the Nusselt-Reynolds formulations were derived based on non-dimensional analysis.

It has been shown that the dimensionless of temperature of apples decreases exponentially with the time. High dropping in the temperature was occurred during the first 40 minutes of cooling which follows a lower rate of reduction in temperature. As the cooling air velocity increases, the cooling coefficient increases as well as the heat transfer coefficient which resulted in the acceleration rate of dropping temperature. Thus, the higher flow rates are recommended for fast cooling. Same trends were found when testing papayas and grapes. However, the grapes show higher dropping in the temperature than that occurred in papayas and apples. This is may be due to the small size of grapes compared to the big size of papayas.

The relationship between Nusselt-Reynold of foods was derived based on the following equation:

$$Nu = c\,\mathrm{Re}^m$$

From the correlation between Nu-Re, a regression analyses were carried out to determine the value of C and m in above equation. It was found that the Nu-Re for apples is:

$$N_u = 1.65\, R_e^{0.36}$$

For papayas is:

$$N_u = 48.594\, R_e^{0.17}$$

For grapes is:

$$N_u = 0.928\, R_e^{0.2}$$

As obvious from the formulas, the value of C (constant) for grapes is less than apple and papayas. Higher value of C has detected in papayas. This means that the Nusselt number is more in the papayas which in turn gives higher value of the heat transfer coefficient.

A program is written using MATLAB software, to verify the correlations. Results from the experiments and program are compared and found to be well in agreement.

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NOMENCLATRE

Symbols

υ	kinematic viscosity, m^2/s
α	Thermal diffusivity, m^2/s
B_i	Biot number
C	cooling coefficient, s^{-1}
D	diameter of duct, m
d	diameter, m
F_o	Fourier number
h	convective heat transfer coefficient, $W/m^2.K$
j	Intercept
k	thermal conductivity, W/m.K
Nu	Nusselt number
R	Radius, m
Re	Reynolds number
T	temperature, ^oC
t	time, sec
T_a	cold air temperature, ^oC
T_i	initial temperature for fruits, ^oC
v	air flow rate, m/s
W	water content by weight (in decimal units)
Y	dimensionless temperature

INTRODUCTION

1.1 NEED FOR FOOD PRESERVATION

Food Processing and Preservation, is the transformation of raw animal, vegetable, or marine materials into tasty, nutritious, and safe food products. The industry has its roots in ancient times, as humans have always needed to obtain food and store a portion for later use. Prehistoric humans may have dried fruits in the sun and stored meat in cold areas, such as caves. With the rapid growth of world population and increase in all around demand for food products, the importance of preservation of perishable food products has been felt throughout the world. The sudden and severe shortage of supply during calamities and emergencies revealed the wisdom of preservation during the time of surplus for future use in such crises. Our food requirements are basically met from two sources: one is of plant origin and the other of animal origin. The yield from these sources, especially from the plant origin is, however, seasonal, while the requirement is continuous. Due to inadequate preservation facility, glut in market occurs during the peak harvest period and the price of perishable falls to uneconomic levels and at the same time the products are available during short harvesting season only. Excess amount of food commodity, which is not consumed on harvest, is spoiled. Statistics have revealed the shocking fact that lack of preservation facilities has led to the spoilage of more than Rs. 50 millions worth of edibles annually in india (Subba Rao, 1996). Therefore it is now realized that "preservation of perishables is as important as production" which would meet the demands during off season and in places far from area of production, and provide better return for the farmers and ensure sustained supplies at reasonable price to the consumer during harvesting seasons as well as in off-seasons.

1.2 PROCESSING AND PRESERVATION METHODS

Food processing encompasses all the steps that food goes through from the time it is harvested to the time it arrives on supermarket shelves. At simplest, processing may involve only picking, sorting, and washing fruits and vegetables before they are sent to market. Some processing methods convert raw materials into a different form or change the nature of the product, as in the manufacture of sugar from sugar canes, oil from corn or olives, or cheese and paneer from milk. Processing may also involve an extremely complex set of techniques and ingredients to create ready-to-eat convenience foods.

Food preservation refers specifically to the processing techniques that are used to keep food from spoiling. Spoilage is any change that makes food unfit for consumption, and includes chemical and physical changes, such as bruising and browning; infestation by insects or other pests; or growth of microorganisms, such as bacteria, yeast, and molds.

Louis Pasteur, French scientist, made important contributions to many scientific fields during the mid-1800s. He is considered the founder of the field of microbiology, working with the germ theory of disease to establish and explain the causes for many diseases. In 1857 he showed that microorganisms are responsible for food spoilage.

Some food preservation techniques destroy enzymes, proteins that are present in all raw foods, which are responsible for the chemical and physical changes that naturally occur after harvesting. Food preservation techniques also helps to eliminate the moisture or temperature conditions that are favorable for the growth of microorganisms. As they multiply and grow, microorganisms are capable of causing food-borne illness. They also break down foods, producing unpleasant changes in taste, texture, and appearance-changes that we recognize as spoilage. Although people have known about spoilage and some preservation methods to prevent it for centuries, it was only in 1857 that French chemist Louis Pasteur demonstrated the role of microorganisms in the process.

1.2.1 Curing

Curing is one of the oldest forms of food preservation. It is used to preserve meat and fish, yielding common products such as mangoes, lemons, jackfruit, etc. Curing involves adding some combination of salt, sugar, spices, vinegar, or sodium nitrite to foods. Smoking, a flavoring technique and preservation method is another ancient technique that is commonly used with curing. Smoking involves cooking meat or fish very slowly over a low wood fire. Curing and smoking preserve food by binding or removing water so that it is not available for the growth of microorganisms. These methods impart a distinctive color and flavor to food and, in some cases, eliminate the need for refrigeration. Some studies, however, show that curing agents such as sodium nitrite may combine with other chemicals to form cancer-causing nitrosamines. In addition, cured products tend to be very salty, and the sodium in salty foods has been linked to high blood pressure. Smoked meats and fish may contain toxic and even carcinogenic compounds that they absorb from wood smoke.

1.2.2 Drying

Codfish drying on racks drying of fruits, fish, or meat is an excellent method of long-term food preservation. Drying reduces an item to roughly 50 percent of its original volume and 20 percent of its original weight through the gradual elimination of water. This dehydration process prevents spoilage by retarding the growth of microorganisms and reducing or halting enzymatic activity and chemical reactions. Dried food items can be kept almost indefinitely, as long as they are not rehydrated. Drying has been used to preserve food by cultures throughout the world since prehistoric times, when people learned that dried foods for example, fruits left out in the sun remains wholesome for long periods. In modern times, the dried foods industry greatly expanded after World War II (1939-1945) but remained restricted to certain foods, including milk, soup, eggs, fruits, yeast, some meats, and instant coffee, that are particularly suited to the process. Three basic methods of drying are used today: sun drying, a traditional method in which foods dry naturally in the sun; hot air drying, in which foods are exposed to a blast of hot air; and freeze-drying, in which frozen food is placed in a vacuum chamber to draw out the water. Removing the water preserves food because microorganisms need water to grow and food enzymes cannot work without a watery environment (Encarta, 2005). It also decreases the weight and volume of foods, thereby, reducing transportation and storage costs. However, dried foods may be less convenient for consumers because it often must be rehydrated before consumption. In addition, most dried foods only reabsorb about two-thirds of their original water content, leaving the rehydrated product with a tougher, chewier texture than the original. Some scientists and consumer groups have raised concerns about the sulfites commonly added to fruits before drying to prevent browning. These chemicals may cause severe allergic reactions in people with asthma or other people sensitive to the chemicals. In freeze-drying, frozen food is placed in a special vacuum cabinet. There, water escapes from the food by sublimation, a process in which ice changes from a solid directly to a vapor without first becoming a liquid. Freeze-dried foods retain their original flavor, texture, and nutrients upon rehydration but must be packaged in moisture-proof, hermetically sealed containers (Encarta, 2005). Freeze-drying is an expensive process used for such products as instant coffee, dried soup mixes, strawberries, mushrooms, and shrimp.

1.2.3 Canning

Canning is used to preserve a wide variety of foods, including soups, sauces, fruits, vegetables, juices, meats, fish, and some dairy products. Canning preserves food by heating it in airtight, vacuum-sealed containers. The cane is filled with food, and air is pumped out of the space remaining at the top of the cane to form vacuum. The container is sealed, heated in a cooker called a retort, and then cooled to prevent overcooking of the food inside. This process removes oxygen, destroys enzymes involved in food spoilage, and kills most microorganisms that may be present in the food. Canned foods are popular because they are already partially prepared and cooked, can be stored without refrigeration for long periods, and are generally low in cost. However, because of the high temperatures required for sterilization, canning affects the color, texture, flavor, and nutrient content of foods. Fat-soluble vitamins and minerals are barely affected by heat processing, but water-soluble vitamins, especially thiamine, riboflavin, and vitamin C, can leach into canning or cooking water that may later be thrown away during preparation. Up to half of the original content of water-soluble vitamins in a canned product can be lost in this way. Rapid, high temperature processes generally conserve nutrient content best, as every 4.4° C (18° F) rise in processing temperature yields approximately a ten-fold increase in microbial destruction, with little additional nutrient loss.

1.2.4 Additives

Food additives are chemicals that are added to food in small amounts. Direct additives are added deliberately during processing to make food look and taste better, maintain or improve nutritive value, maintain freshness, and help in processing or preparation. Some additives help to preserve food by preventing or slowing chemical changes and the growth of microorganisms in food. These substances enter food incidentally during handling or from processing equipment or packaging. Food additives have been used for thousands of years. The salts and other chemicals used in curing are additives, and before the advent of canning and mechanical refrigeration, chemical additives were the only means of preservation available. Additives were not limited to use as preservatives, however. People in ancient Rome added certain chemicals to wine and cooked vegetables to improve the color of these foods. Other examples of additives that have been used since ancient times include yeast and baking powder used as leavening in baked goods. In the 20th century, advances in the knowledge of chemistry have greatly expanded the number of additives that are used in foods. Such recent additions to the ranks of food additives include artificial sweeteners, fat replacements and colors, which is used in beverages, ice cream, cereals, and other foods. The development of new chemical additives has also played an enormous role in the growth of convenience foods. Additives that help ensure the quality of convenience foods include anti-caking agents, such as calcium silicate and magnesium stearate, to prevent lumps in dry mixes; humectants, such as glycerol, propylene glycol, and sorbitol, to help retain moisture in breads and cakes; emulsifiers, such as egg yolk, lecithin, and monoglycerides, which bind oil and water to improve the uniformity and smoothness of foods; and stabilizers and thickeners, such as guar gum, carrageenan, and gelatin (Encarta, 2005). As the use of food additives has grown, so has public concern about the type and amount of these additives and their potential to cause cancer or other illnesses in human beings. Some studies have suggested that saccharin, nitrites, and other additives may cause cancer, but these results remain controversial (Encarta, 2005). At the same time, some additives may actually provide a health benefit. For example, the vitamins used to fortify foods such as bread and milk are additives.

1.2.5 Freezing and Refrigeration

Low-temperature storage as a preservation method probably began when prehistoric humans stored meat and other foods in ice caves. However, mechanical refrigeration and large-scale freezing are relatively recent innovations. Mechanical refrigeration was pioneered by American inventor John Gorrie in 1842, but a mechanical refrigeration system suitable for widespread commercial use was not developed until the 1870s. American inventor Clarence Birdseye (1886-1956), developed procedures, equipment, and packaging for quick-freezing in the 1920s, and in 1953 frozen were introduced by C. A. Swanson and Sons (Encarta, 2005). Storage at low temperature slows many of the enzymatic reactions involved in spoilage and reduces the growth rate of microorganisms (though it does not kill them). To minimize microbial growth, refrigerators should be kept at 0° to 4° C (32° to 40° F) and freezers at or below 0° C

(32° F). Refrigeration is advantageous because it does not cause chemical or physical changes to food. Freezing allows foods to be stored for longer periods than refrigeration because it inhibits enzyme activity and microbial growth to a greater degree. The greatest disadvantage of freezing is that the water in food expands and forms ice crystals. The ice crystal formation disrupts the structure of plant and animal cells, giving frozen food a softer texture after thawing. Newer technologies in which freezing occurs more rapidly help minimize this problem: faster freezing means that smaller ice crystals form, resulting in less damage to cells (Encarta, 2005). Foods that should be refrigerated include meats, fish, eggs, milk, some fruits, and some vegetables. Many of these foods can also be frozen. Frozen produce is often high in quality and can rival the flavor of fresh. In many cases, produce frozen and stored under proper conditions contains more nutrients than produce picked unripened and allowed to mature during transportation. Briefly cooking vegetables in boiling water before freezing, a process known as blanching, inactivates enzymes altogether and reduces discoloration and nutrient loss (Encarta, 2005).

1.2.6 Controlled Atmosphere Storage

Apples and many other fruits and vegetables are often kept fresh in controlled atmosphere storage. Sealed in warehouses where the temperature, humidity, and composition of gases in the atmosphere are precisely controlled, fresh produce may be stored for several months. Fruits and vegetables are sometimes stored in sealed warehouses where temperature and humidity are closely controlled, and perhaps most importantly, the composition of gases in the atmosphere is altered to minimize spoilage. Usually, the concentration of oxygen is reduced, the concentration of carbon dioxide is increased, and ethylene, a gas naturally produced by plants that accelerates ripening, is removed from the atmosphere. This controlled environment helps slow the enzymatic reactions that eventually lead to decomposition and decay, and may increase the time that produce can be stored by several months (Encarta, 2005). Ripening rooms, in which ethylene gas is added to the atmosphere, also help produce higher quality fruits and vegetables. This technology enables produce to be picked before it is ripe, for easier handling, and then ripened quickly and uniformly under controlled conditions.

1.2.7 Aseptic Packaging

Aseptic packaging is now commonly used for packaging milk and juice. Like canning, aseptic packaging involves heat sterilization of food, but unlike canning, the package and food are sterilized separately. Food can be sterilized more rapidly and at lower temperatures in aseptic packaging than in canning, allowing the food to retain more nutrients and better flavor. Containers are sterilized with hydrogen peroxide rather than with heat, permitting the use of plastic bags and foil-lined cartons, which would be destroyed by heat sterilization. These containers cost less than the metal and glass containers used in canning and also weigh less, reducing transport costs. Aseptically packaged foods will keep without refrigeration for long periods of time, perhaps even years (Encarta, 2005). They are growing in popularity because of their low cost, good taste and nutrition, and convenience.

1.2.8 Irradiation

The U.S. Food and Drug Administration (FDA) has approved irradiation for use on mushrooms and several other types of foods. This method destroys microorganisms and enzymes involved in spoilage, helping food stay fresh. However, concerns about the possible formation of toxic products in food have limited the use of irradiation in the United States. Irradiation is a process in which food is passed through a chamber where it is exposed to gamma rays or X rays. These high-energy rays are strong enough to break chemical bonds, destroy cell walls and cell membranes, and break down deoxyribonucleic acid (DNA), the substance that carries genetic information in all cells. Irradiation kills most bacteria, molds, and insects that may contaminate food. Irradiation also delays the ripening of fruits and sprouting of vegetables, permitting produce to be stored for longer periods of time. Because irradiation involves minimal heating, it has very little effect on the taste, texture, and nutritive value of food. The FDA first approved irradiation for use on wheat and wheat flour in 1963, and later approved its use on white potatoes, spices, pork, some fresh produce (onions, tomatoes, mushrooms, and strawberries), and poultry. In 1997, in response to several food-borne illness outbreaks and increasing public concern over the safety of the food supply, irradiation was approved for use on poultry products. In 1999, irradiation was approved to curb pathogens in raw meats including ground beef, steaks, and pork chops. Irradiation is also used to preserve some meals eaten by astronauts during long-term space missions. Some consumer groups have raised concerns that irradiation might cause the formation of toxic compounds in food. Because of these and other concerns, only a limited amount of irradiated food has been sold in the United States.

1.2.9 Fermentation

Fermentation is a process in which microorganisms convert complex organic molecules into simpler molecules, it is often used in the production of cheese. Bacterias convert sugar found in milk into lactic acid, a compound that prevents the growth of other harmful microorganisms and helps preserve the food.

Fermentation is a chemical reaction carried out by many types of microorganisms to obtain energy. In fermentation, microorganisms break down complex organic compounds into simpler substances. Although chemical changes and microbial growth usually mean food spoilage, in some cases fermentation is desirable and microorganisms are actually added to foods. For example, in the production of beer, wine, and other alcoholic beverages, yeasts convert sugar into ethyl alcohol and carbon dioxide. In the making of yogurt and cheese, bacteria convert lactose, a sugar found in milk, to lactic acid. Alcohol, acids, and other compounds produced in fermentation act as preservatives, inhibiting further microbial growth. In addition to its use with alcoholic beverages, cheese, and yogurt, fermentation is used to produce yeast bread, soy sauce, cucumber pickles, sauerkraut, and other products.

1.2.10 Pasteurization

Pasteurization involves heating foods to a certain temperature for a specific time to kill harmful microorganisms. Milk, wine, beer, and fruit juices are all routinely pasteurized. Milk, for example, is usually heated to 63° C (145° F) for 30 minutes. Ultra-High Temperature (UHT) pasteurization, a relatively new technique, is used to sterilize foods for aseptic packaging. In UHT pasteurization, foods are heated to 138° C (280° F) for 2 to 4 seconds, allowing the food to retain more nutrients and better flavor.

1.2.11 Genetic Engineering

Genetic engineering is a means of improving the food supply even before harvest or slaughter by improving yields, increasing disease resistance, and enhancing the nutritional qualities of various foods. Broadly speaking, genetic engineering refers to any deliberate alteration of an organism's DNA. Genetic engineering has been practiced for thousands of years, ever since humans began selectively breeding plants and animals to create more nutritious, better tasting foods. In the past two decades, genetic engineering has become increasingly powerful as scientific advances have enabled the direct alteration of genetic material. Genes have been cut and pasted from one species to another, yielding, for example, disease-resistant squash and rice, frost-resistant potatoes and strawberries, and tomatoes that ripen-and therefore spoil-more slowly.

1.3 PRECOOLING

Precooling presents the deterioration of perishable food products. After harvesting, precooling may be done before or after packing.

Following are the methods employed in precooling:

(i) Room cooling and car cooling

(ii) Tunnel cooling

(iii) Forced air cooling

(iv) Hydrocooling

(v) Vacuum cooling

(vi) Hydrair cooling

(vii) Package icing

(viii) Evaporative cooling

Precooling and precooling methods are discussed in details in Chapter 2.

1.4 FOOD PACKAGING

Recycling Aluminum Cans Aluminum is a common packaging material, used for beverage cans. In an effort to conserve nonrenewable natural resources, many individuals recycle waste aluminum and other food packaging materials. The Alcoa Recycling Company in New Jersey processes aluminum cans into large bales at a collection point.

Regardless of the processing or preservation method used, proper packaging of food is essential to make sure the food remains wholesome during its journey from processor to consumer. Packaging contains food and makes it easier to handle, and protects it from environmental conditions, such as temperature extremes, during transport. It locks out microorganisms and chemicals that could contaminate the food, and helps prevent physical and chemical changes and maintain the nutritional qualities of food. For example, milk is often stored in opaque containers to prevent vitamins from being destroyed by light.

Both the type of food and the processing method used affect the choice of packaging. For example, since oxygen makes fats go rancid, oils are packaged in containers that are impermeable to oxygen. On the other hand, oxygen-permeable plastic wraps allow fruits and vegetables to "breathe" and ensure that meats will maintain a vibrant red color. Metal and glass containers have traditionally been used in canning because these materials can withstand the high temperatures and changes in pressure that are involved in this processing method.

The development of metal cans in the early 1800s represented the birth of the modern packaging industry. The first British patent for a tin-plated steel container was issued in 1810 to British inventor Peter Durand. Canned foods were produced for the

British armed forces in 1812 and offered commercially to the public two years later. Today, food cans are made of steel with various coatings to resist corrosion. Beverage cans are made of aluminum because it is lightweight and easy to manufacture.

In addition to metal, glass is often used for packaging heat-sterilized foods. Glass is impermeable to oxygen and water and does not change the flavor of food. Another advantage of glass is that it is transparent, enabling the consumer to see the product inside. However, glass is not impact-resistant and is relatively heavy.

Plastic, by contrast, is lightweight and unbreakable, and it has become an extremely common material for use in food packaging. Most plastics used in food packaging are heat resistant so that they can go through high-temperature sterilization processes. Plastic is made into a wide variety of shapes, including bottles, jars, trays, and tubs, as well as thin films that are used as bags and wraps.

By itself, paper is not frequently used in packaging, except for certain dry foods, such as flour and sugar. When paper is coated with plastic or other materials to make it stronger and impermeable to water, it can be more widely used. Paperboard is often used for cartons, and plastic-coated paperboard for packaging frozen foods. Cartons and containers for shipping are usually made of corrugated cardboard.

In recent years, environmental concerns have influenced food packaging. Scientists are working to develop packaging that is recyclable, biodegradable, or more compact so that it will use less landfill space, as well as to eliminate unnecessary packaging. Programs to recycle glass and aluminum beverage containers have been started all over the country. Plastic beverage bottles can be recycled as clothing or other products in addition to food containers. Aseptic packaging and several other new methods are compact and use a minimal amount of materials.

1.5 STORAGE OF FRUITS AND VEGETABLES

The design of equipment for cooling and cold storage of fresh fruits and vegetables must take into account that the respiration process continues and heat and carbon dioxide are produced. The intensity of the process is directly related to the rate of ripening and can be greatly reduced by lowering the temperature. The respiration of most fruits increases just prior to ripening; apples and pears are typical examples of fruits which exhibit this 'climatic'. But others, such as citrus fruits, have no climatic.

The respiration rate and possible storage time are also influenced by the composition of the atmosphere, and this can be used to advantage for some fruits in 'controlled atmosphere storage'. Relative humidity must be high in order to prevent undue dehydration, but not excessive so as to encourage rotting.

The keeping potential for different kinds of vegetable products varies widely. Many tropical fruits, as exemplified by bananas which represent the largest single item tonnage in refrigerated shipping, have a maximum keeping period of only about three or four weeks, depending on the variety and the state of development at the time of cutting. This is often barely sufficient for reaching the markets before the final ripening sets in, and extended storage is impossible. Most deciduous and citrus fruits offer greater storage possibilities and give more freedom of organized distribution.

The fruits and vegetables vary in their behavior in storage, more than any other products. For instance, variety, climate, soil characteristic, cultural treatment, psychopathological conditions, maturity at harvest and roughness of handling all have important effects. Additional treatment such as chemical dips or sprays, fumigation, ethylene conditioning, special warps, heat treatment etc. may change storage potential greatly. Therefore it is not generally possible to give a single recommendation for optimum storage conditions of a given fruit or vegetable.

1.6 FOOD DISTRIBUTION

Container Shipping on a Freight Train Modern methods of transportation enable fresh produce and other foods to be transported long distances, making a wide variety of foods available year-round in stores all over the world. Freight trains such as the one pictured here are often used to transport food. Large, sealed shipping containers are a common method of packing goods. During transport they ride piggyback on a type of freight car called a flatcar.

After food is processed and packaged, it enters an extensive distribution network that brings food products from the manufacturer to various retail outlets across the country and even around the world. Modern, high-speed methods of transportation-trucks, trains, and planes-and reliable methods of environmental control-especially refrigeration-enable even perishable food to be transported great distances. Distribution networks help satisfy consumer demand for variety, making available, even in remote areas, foods that are not locally grown or processed. In fact, although food distribution is all but invisible to the average consumer, it plays a vital role in ensuring the availability of even the most basic foodstuffs. The now-famous bread lines and bare supermarket shelves shown in images of the former Soviet Union were brought about not so much by inadequate food production as by the lack of an efficient distribution network to bring the food to the consumer.

Some large grocery store chains have the resources to buy food products directly from processors, transport the products, and store them in warehouses until they are needed at the store. However, for independent grocery stores and other small retailers, food wholesalers fulfill these roles. One type of wholesaler is a cooperative wholesaler, which is owned by the retailers that buy from them and usually sells only to these member-owners. In contrast, voluntary wholesalers are public companies that sell to any retailers without having membership requirements. Some food is sold directly to a retail store without going through a wholesaler first. This is common for foods such as bread and dairy products that must be delivered fresh every day or every few days. Smaller manufacturers often use food brokers as agents to arrange for their products to be shipped to retailers or warehouses.

Through these various distribution channels, food makes its way to food retailers, such as restaurants, fast food outlets, supermarkets, convenience stores, specialty shops, drug stores, and some department stores. Supermarkets are the predominant type of food retailer in the United States. They arose during the Great Depression (1930s) as a way of providing cheaper food products to consumers. The main cost-cutting measure was to have customers select products off the store shelves rather than having a clerk fill a client's order. In addition, these early supermarkets were located on the outskirts of town where land was cheaper. Since the first supermarket opened in Queens, New York, in 1930, the concept has spread throughout the world. There is example for food distribution shown in figure 1.1.

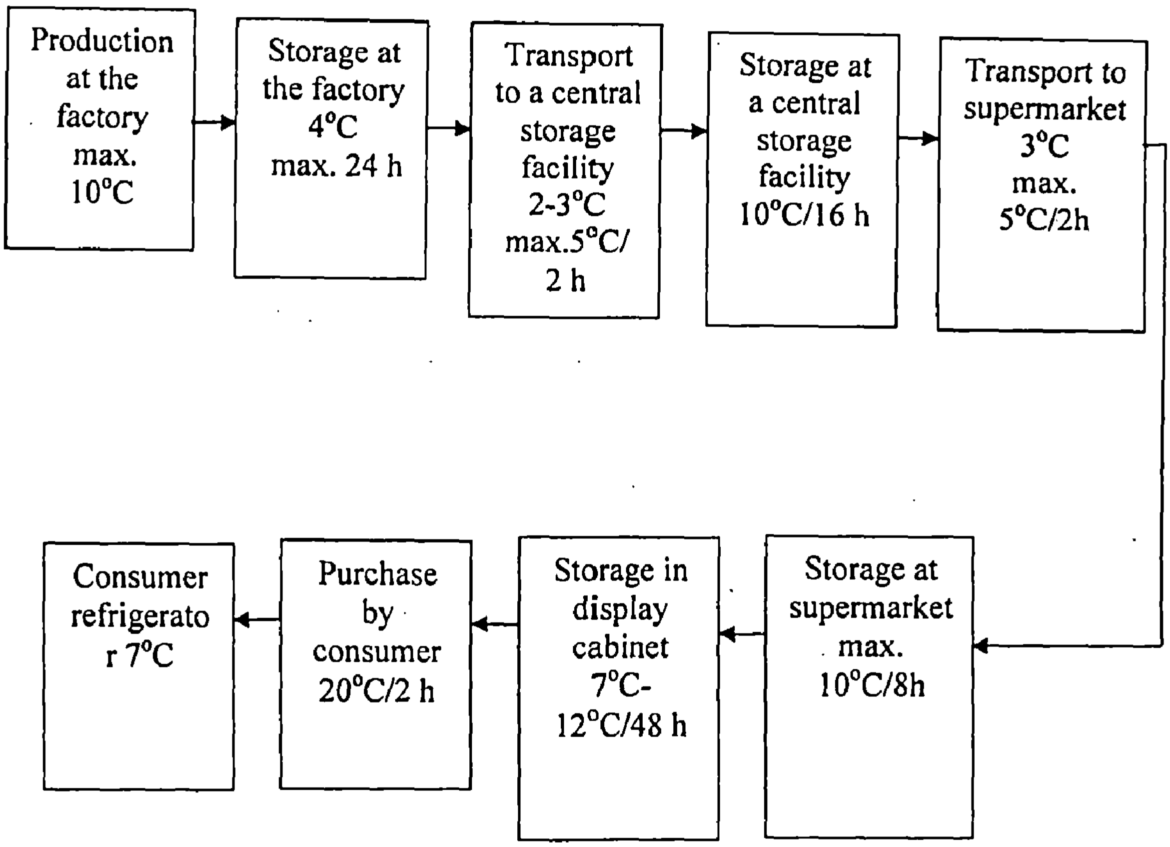

Fig.1.1 Simulated distribution chain of fresh processed fruit and vegetables

PRECOOLING AND STORAGE REQUIREMENTS

2.1 PRECOOLING

Precooling is the process of rapid cooling of a commodity after harvest, before or after packaging before it is stored or moved in transit prevents deterioration of the more perishable vegetables. Fruits and vegetables are precooled prior to transport, storage, or further processing in order to remove the initial 'field heat' from the fresh produce and also to reduce the refrigeration load on subsequent storage and transport.

Nearly all fruits and vegetables benefit from precooling. Highly perishable products such as potatoes, tomatoes, broccoli, cauliflower, and cabbage, must be precooled as soon as possible after harvest.

Commercially important fruits which are to be precooled immediately after harvest are: guavas, mangoes, papayas and pineapples. The same is true with pears, peaches, apples and oranges, though their rate of deterioration is relatively slower. However, precooling enhances the storage life of these products so that they can be stored for several months prior to marketing. Figure 2.1 shows typical example of deterioration of cantaloupes due to delay in cooling after harvest (Kasmire and Persons, 1971). It is very well established that the sooner the fresh produce is brought to its storage temperature after harvesting, the longer it can be preserved.

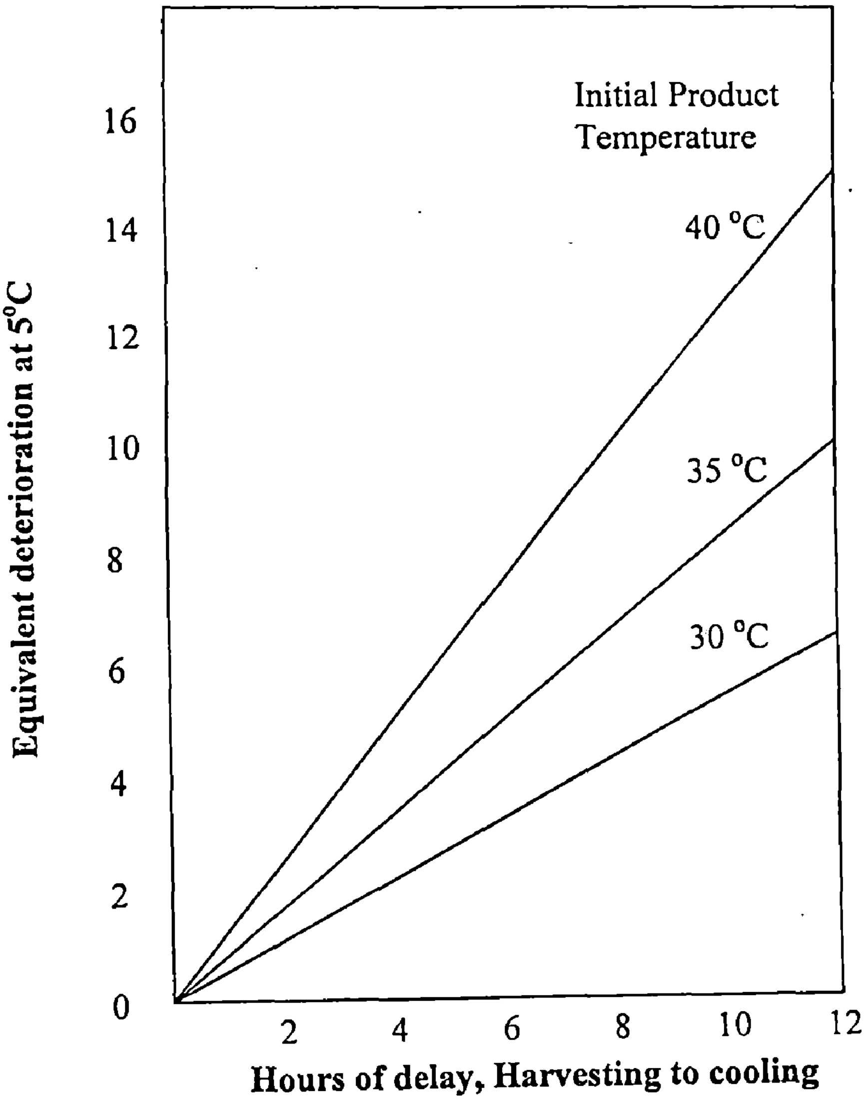

Fig.2.1 Cantaloupes – Deterioration caused delays from harvesting to cooling (Kasmire and Parsons, 1971)

2.2 PRECOOLING CHARACTERISTICS

In most cases, a portion of cooling curve for fruits and vegetables on semilog plot is linear. The following equation represents the cooling curve:

$$\frac{T - T_a}{T_o - T_a} = j * e^{-CR(\theta)}$$

where CR = cooling rate

T = products temperature at given time (^oC)

T_o = initial temperature (^0C)

T_a = temperature of surrounding medium (^0C)

θ = time (s)

j* = lag factor

This relationship is basically an exponential type of cooling called the Newtonian type if j* were equal to unity. The value of j* is an indicator of the error in assuming the Newtonian cooling.

In commercial cooling of fruits and vegetables, when temperature of cooling medium (chilled air or chilled water as the case may be) is constant the temperature gradient is established. Thus Thevenot (1955) had introduced a time constant, Z, or half-cooling time. By definition, the half cooling time is the time at which the temperature difference between the produce and its surrounding becomes one-half of the initial temperature difference. Normally, the produce temperature means the temperature at the centre of the fruit or vegetable or at the centre of a tight package such as apples, oranges or pears packed in boxes is considered. The half cooling time is a characteristic of the produce, the packaging and stowage and the cooling medium and for practical purposes, is independent of actual temperature in case of cooling by transient conduction within the product and convection only at the product surface. Therefore the half cooling time, Z, is a measure for expressing cooling rate and comparing them under a wide range of conditions.

Fig. 2.2 shows typical exponential cooling curve indicating the half cooling times. The time needed to reduce the temperature difference between the product centre and cooling medium to 50 percent is denoted as the 'first' half cooling time, and that to 25 percent is the 'second' half cooling time and so on. The first half cooling time, however, is more widely used in the literature for the purpose of comparison. The later half cooling times generally increase slightly. Starting with a product at a temperature of 20°C and cooled by air at 0°C, it would take about the same time for a later stage of cooling, i.e. from 4°C to 2°C as the first stage from 20°C to 10°C.

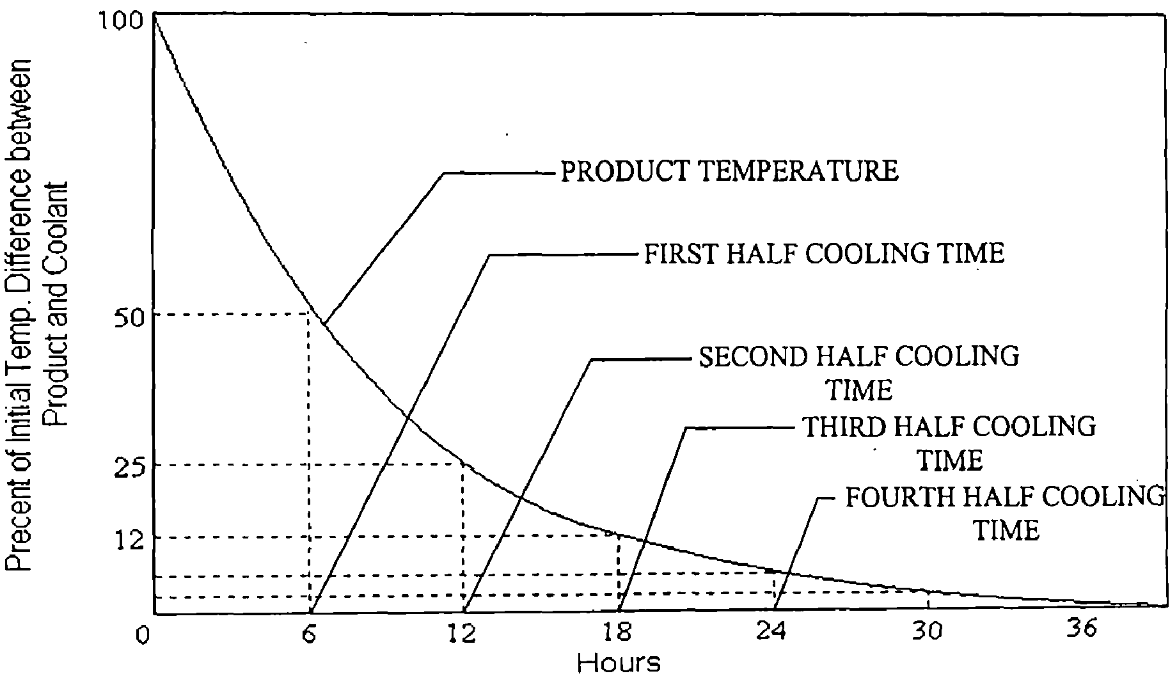

Fig.2.2 Example of six hours half cooling time (Hall, 1974)

2.3 PRECOOLING METHODS

ASHRAE guide and data book (2006) discussed various precooling techniques. Hall (1974) has discussed all the types of precooling techniques in detail. Mitchel and Kasmire (1974) have presented in detail the various aspects of precooling of fruits and vegetables such as when to cool, how much to cool, the different methods used and their relative merits and demerits, as shown in Appendix-A Table A.1.

2.3.1 Room cooling and car cooling

The simplest method of cooling fruits and vegetable is to expose the containers in a controlled environment cold room or in a refrigerated car. Most of heat being transmitted from fruit to fruit by conduction and the cooling time varies inversely with the ratio of exposed area to weight of product (R.Guillou,1958). The cold air is discharged into a cold room horizontally just below the ceiling. The air sweeps the height of the room and returns past the products arranged vertically in stacks over the floor. In this technique food packages and not individual products are exposed to cold air. This method though simple for plant design and operation, has some limitation for cooling due to low heat transfer rates. Cooling in a refrigerator car involves no additional handling. In case of car, the only cost to the shipper is that for fan operation and additional ice, making this usually the cheapest of all cooling methods.

2.3.2 Tunnel cooling

High velocity air is used to precool the food produce in tunnel cooling. In this technique, high velocity air is forced past relatively tight stow of packages in precooling tunnel. This system provides faster cooling rates with an air velocity of 5 m/s and uniformly distributed air gaps between the packages (Hall 1974). It has two major drawbacks: one is the requirement of greater fan power and the other is the loss of considerable amount of moisture from the products. Tunnel coolers are used in south Africa and have been tested in the northwest by Sainsbury (1961).

2.3.3 Forced air cooling

Forced air cooling is of two types:

(i) Pressure cooling

Pressure cooling is a special method of forcing the cooling air through the packages by establishing pressure gradients. It has been developed by Guillou (1956) in the Agriculture engineering department, University of California. Pressure cooling involves definite stacking patterns and the baffling of stacks, so that the cooling air is forced through the individual container with help of pressure differential. For high efficiency, a container with vent holes placed in the direction of air movement and minimum of packaging materials that would interface with the free movement of air in the container, are essential.

(ii) Velocity cooling

Velocity cooling involves forcing high velocity air in large volumes through the voids of bulk food products moving through a cooling tunnel on continuous conveyors. The heat transfer rates can be improved by subjecting the food product to a stream of cold air of high velocity. For the cooling of fresh produce, a difference in air pressure is created on opposite faces of stacks or vented containers. This ensures the flow of air around individual fruit or vegetable affecting fast cooling. Velocity cooling is quite effective but, is limited in application due to high cost of circulating large volumes of air at high velocities.

Fig. 2.3 shows the comparative cooling rates of grapes using different air precooling method (Hall, 1974). It can be observed from the figure that the forced-air precooling is faster than other air cooling methods.

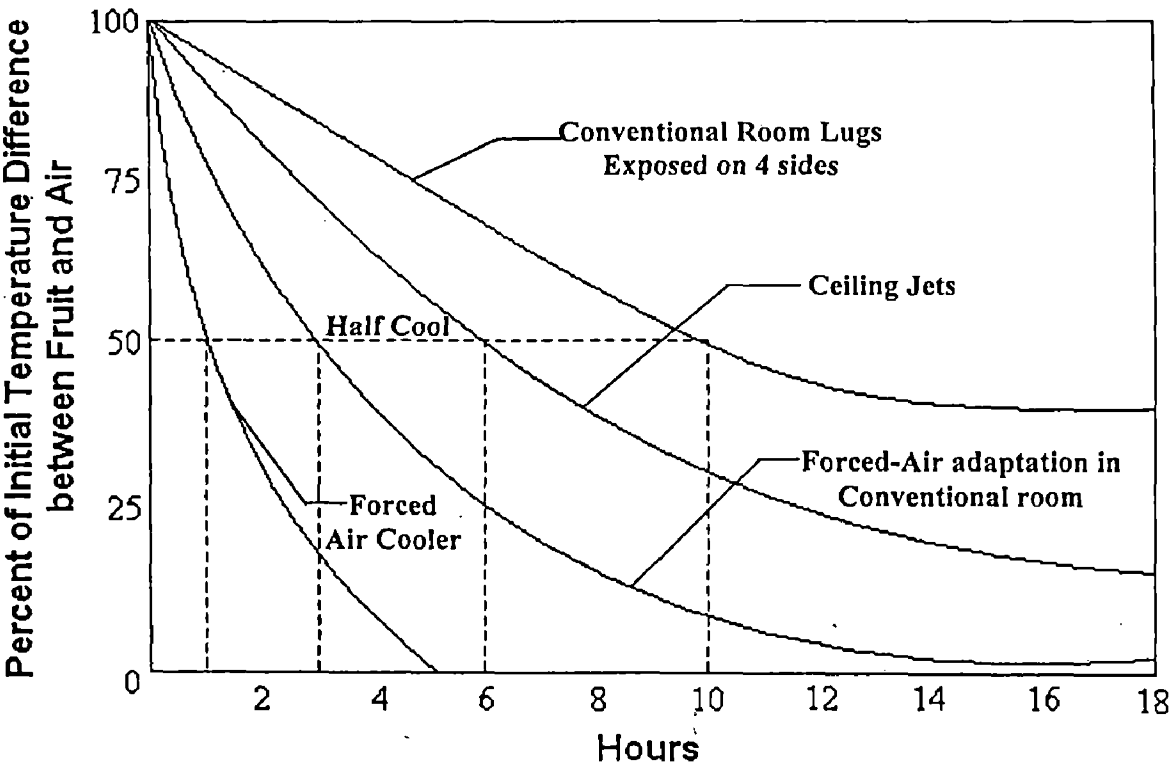

Fig.2.3 Comparative cooling of grapes by different methods, average fruit pulp temperatures in lidded lugs (Hall, 1974)

From the above discussion with regard to various air precooling techniques, it can be observed that the air precooling method is reasonable fast and requires relatively simpler equipment. However, the refrigeration requirements are quite enormous mainly due to heat input of the blower. Also, air precooling methods take away some of the water from the fresh produce, thereby affecting its appearance and also loss in the weight. For food or food products such as leafy vegetables, for which moisture loss is not desirable at all, air precooling method cannot be employed.

2.3.4 Hydrocooling

Hydrocooling, or cold water immersion cooling, was first used in U.S.A. about forty years ago, and in recent years it is being widely used in that country for pre-cooling vegetables such as lettuce, celery, peas, asparagus, sweet corn, and Brussels sprouts, and fruits such peaches, apricots, cherries and pears. Cooling rate for above fruits and vegetables are reported by Sadato Ishibashi (1967).

The hydrocooling is of two types:

(i) Spray type

Spray cooling is one of the several methods for chilling poultry carcasses. Veerkamp and Hofmans (1974) have studied spray cooling of poultry carcasses and they developed an empirical relation for calculating the cooling time.

(ii) Flood type

In this technique, chilled water flows past the produce submerging it in water. Stewart and Lipton (1960) have studied cooling process of cantaloupes using a pilot model flood type hydrocooler. They have observed that the water flow rate should at least be 6.8 $kg/s.m^2$ of cooler area and that flow rates in excess of 8.16 $kg/s.m^2$ do not improve cooling rate appreciably.

Fig 2.4 shows a comparison between air precooling method and hydrocooling method for peaches (Guillou, 1963). It is evident from the cooling curves that the faster rate of cooling is obtainable using hydrocooling. The Fig 2.4 also shows the relatively faster cooling achieved by forced air cooling compared to conventional room cooling.

Fig 2.5 depicts comparison of cantaloupe cooling rates by four different precooling methods (Kasmire and Parsons,1971).. The first three half cooling times are marked in this figure. The figure shows that faster cooling is obtained by hydrocooling. However, it is need to sanitation and daily cleaning to prevent storage disease. Also, the electrical must be proportional to the size of the refrigeration system requirements.

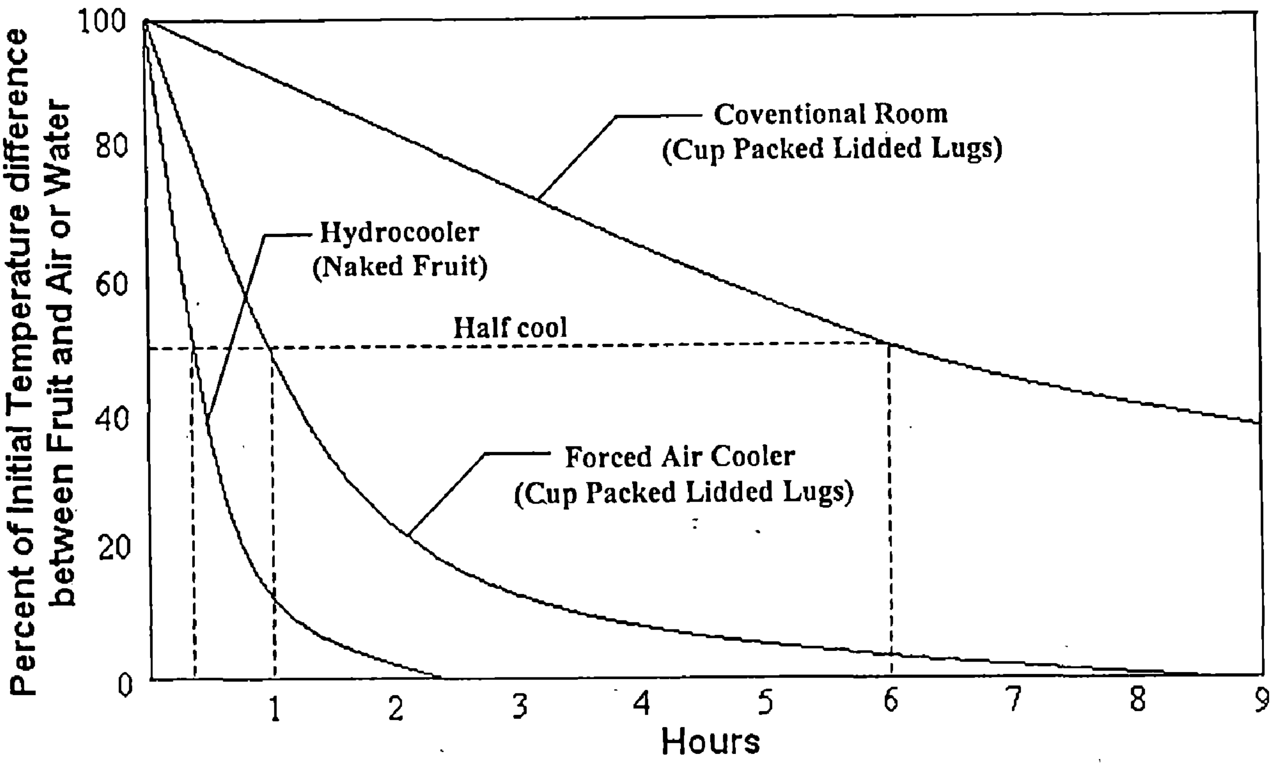

Fig.2.4 Comparison of cooling Peaches by different methods (Guillou, 1963)

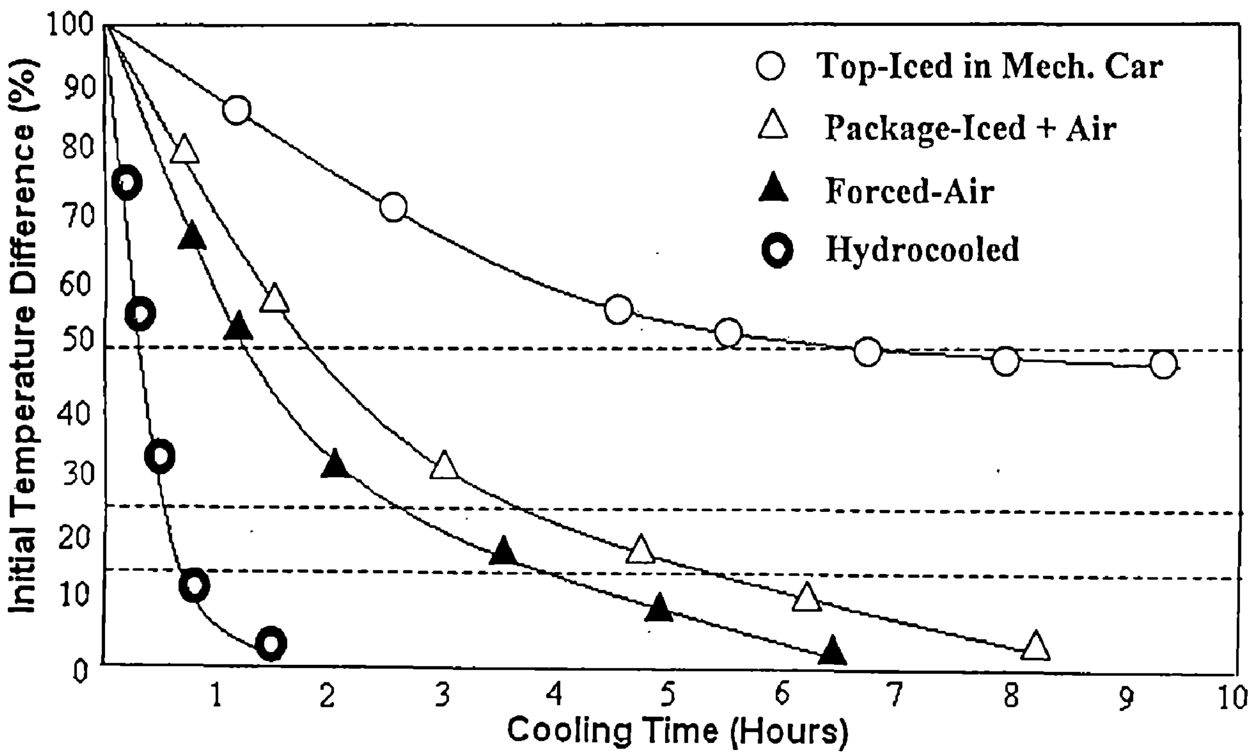

Fig.2.5 Comparison of cantaloupe cooling rates by different methods of cooling (Kasmire and Parsons, 1971)

2.3.5 Vacuum cooling

Vacuum cooling is the practice of precooling fresh produce, mostly vegetables having a high ratio of surface area to volume, by rapid evaporation of water from the product. Leafy vegetables like cabbage and lettuce are the most suitable for vacuum cooling. It produces quick uniform cooling, but is quite expensive due to the high initial cost of the equipment. Thevenot (1962) reports that the vacuum cooling is only economical with large working capacities of about 30 tons per hour and a relatively long shipping season.

Commodities to be vacuum cooled are placed in a pressure chamber which is evacuated rapidly. When the air pressure is reduced to a level at which water boils at the loading temperature of the produce, rapid evaporation and cooling begins. This is known as 'flash point'. At a pressure 4.6 mm Hg, water boils at 0°C and this is the principle a vacuum cooling technique uses. The heat required to evaporate one percent of a given quantity of water is sufficient to reduce the temperature of the rest of the water by 6°C. The water vapour is condensed by refrigeration and run into a sump. The chamber are evacuated either by high pressure steam ejectors with barometric condensers or rotary vacuum pumps.

Bennett (1964) has presented a brief discussion of the merits and demerits of the available precooling methods, viz., forced air precooling, hydrocooling and vacuum cooling. He points out that each method, when used as dictated by the nature of the job, the commodity, and convenience of the industry, is capable of effectively accomplishing the end result-that of rapid heat removal. Each method is also capable of efficient performance when applied to its particular optimum utilization.

2.3.6 Hydraircooling

Hydraircooling is a recent precooling technique. Hydraircooling is an effective method of precooling food products for which moisture loss is not desirable. It has the advantages of both air cooling and hydraircooling. Henry and Bennett (1973) presented result of hydraircooling unit loads (1 unit load=40 crates) of sweet corn with a water flow rate of 6.3 kg/s and using small spray nozzles. They reported that the cooling rate is better than a conventional hydrocooler circulating water at 25.2 kg/s. They have also reported that for a given water flow rate, increase in air circulation rate decreased the cooling time. Bennett and Wells (1976) have reported the results of hydraircooling of waxed peaches. When the cold air is passed over the food products that are continuously wetted by a thin film of water, there will be more effective cooling without much dehydration from the product compared to other conventional methods (Abdul Majeed, 1979).

2.3.7 Package icing

Package icing is used to cool some produce that is field packed into shipping containers. The ice may be finely crushed, flake ice, or a slurry of ice and water called liquid-ice. Liquid ice is injected in the container and has better contact with the produce than the other forms. More expensive water-tolerant containers are required, and the added weight of the ice decreases the weight of actual produce that can be shipped.

2.3.8 Evaporative cooling

Evaporative cooling is an inexpensive and effective method of lowering produce temperature (Figure 2.6). It is most effective in areas where humidity is low. Dry air is drawn through moist padding or a fine mist of water, then through vented containers of produce. As water changes from liquid to vapor, it absorbs heat from the air, thereby lowering the produce temperature. The incoming air should be less than 65 percent relative humidity for effective evaporative cooling. It will only reduce temperature, 9 to -12°C. This method would be suitable for warm-season crops requiring warmer storage temperatures (7.5 – 12.5°C), such as tomatoes, peppers, cucumbers or egg plant.

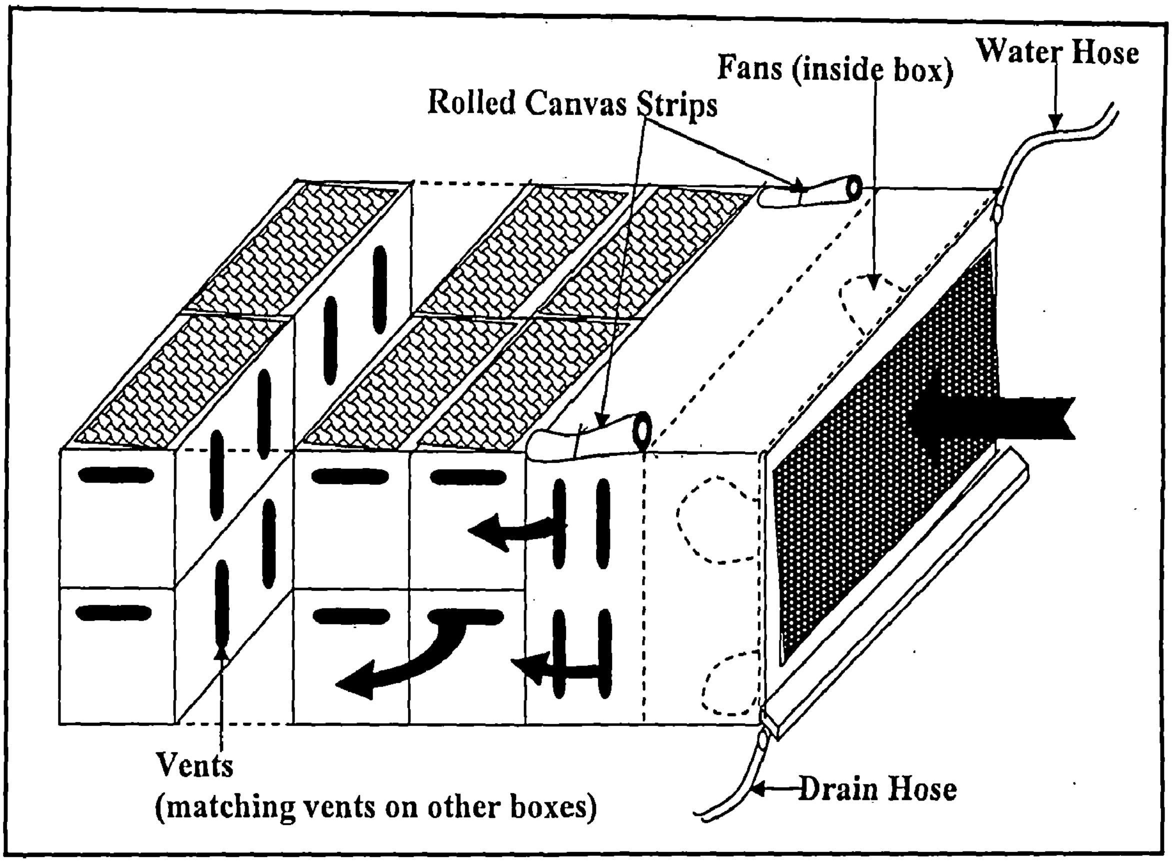

Fig.2.6 Evaporative cooling

LITERATURE REVIEW

Precooling is an important stage in the cold chain where the field temperature of a product is reduced to the storage or transport temperature immediately after harvest in order to prevent the spoilage and to maintain the quality of fruits and vegetables leading to their safe temporary storage (Dincer 1992a). During precooling, transient heat transfer between fluid medium and solid food product takes place. For most engineering heat transfer calculations performed in commercial food cooling applications, the estimates of the heat transfer rates, and in some cases heat and mass transfer rates are needed. Heat transfer rates produced by different cooling methods can be directly obtained from the time temperature variation curves of products.

Most commercial cooling systems for fruits and vegetables involve products in a bulk situation with a large number of products grouped together. Soule (1966) have conducted air cooling experiments on oranges, grape fruits and tangelos in bulk bin of 227 kg of load. The surface and centre averaged from six locations in the load and final mass average temperatures are calculated. They have evaluated the surface heat transfer coefficient at various velocities. The weight loss in their experiments is found to be 0.6% to 0.8% for a precooling period of 60 minutes.

Hicks (1955) normally fruits, vegetables and flowers are packed in various types of closed packages and precooled by ordinary room cooling or forced air cooling. During cooling of food commodity in closed packages, heat is carried away by slowly moving surrounding cold air, mainly from the surface of the package, while heat transfer within the package is almost entirely by conduction.

Baird (1975) have conducted experiments on orange, grape fruit, snap bean, bell paper and avocado in different arrangements of simulating bulk load containers, cartons, and crates. It was observed from the time-temperature characteristics of bulk cooling oranges that, the top layers cooled slower compared to the bottom layers, when air is forced from the bottom of the bulk load.

Gaffney (1985) used a numerical solution to calculate the steady-state product surface temperature and rate of moisture loss of apples, peaches and brussels sprouts as a function of air velocity, temperature and relative humidity. They considered the influence of respiratory heat generation, evaporative cooling, and convective and radiative heat transfer. They found that at low air velocities, products with high transpiration coefficient can cool sevrral degrees, below the temperature of the surrounding air and they also confirmed this experimentally.

Misener and Shove (1976) developed a digital computer model to simulate the temperatures and moisture loss during cooling of a deep bed of potatoes. They assumed negligible temperature gradient within the tubers and considered respiratory heat generation as a linear function of temperature. The model accounted for evaporation of moisture from the potatoes, possible condensation of moisture on the potatoes, and evaporation of the condensed moisture. They reported favourable comparison between the model predicted and experimentally measured product temperatures and total moisture loss during cooling at approach air velocities of 0.045 and 0.08 m/s.

Baired and Gaffney (1976) developed a finite difference model for the analysis of cooling of spherical shaped fruits and vegetables in bulk loads. Their model did not include moisture evaporation but did allow temperature gradients within individual fruits.

Since they applied their model to the cooling of a bed of citrus fruits, they developed a solution for a composite sphere to account for the varying thermal properties of the flesh and rind of citrus. They verified their model by showing excellent comparison with experimentally measured temperatures during cooling of 0.61m deep bed of oranges and grapefruits at approach air velocities ranging from 0.02 to 2 m/s.

Gaffney and Baird (1977) have obtained time temperature response as a function of air velocity and position during cooling of peppers in bulk with the air temperature at 17°C. It was observed from the time temperature characteristics that, the products in the bottom layers at the entry cooled faster compared to the products in the top layers. At low velocity , the difference between temperatures at different locations within the pepper at any location in the load was small but the gradient between the top and bottom load was found to be significant. At high velocities, the temperature differences were greater within the individual peppers but less within the load.

To determine the adaptability of forced air cooling to palletized handling of fresh fruits in corrugated containers, Parsons (1972) compared the types of stacking as affecting cooling efficiency. These investigators used the 7/8 cooling time as a measure of cooling rate. They defined the 7/8 cooling time as the time required to cool the slowest cooling fruit to 7/8 of the initial temperature difference. After the 7/8 cooling time, a temperature ratio of 1/8 instead of ½ in the case of the half cooling time, is reached. Active workers in this field claim that since 7/8 cooling time is in the vicinity of commercial practice, the cold storage operators can easily apply this method and conflicting methods of calculations can be avoided.

Hunter (1977) developed a simulation model for analysis of transient heat and mass transfer in ventilated potato storages. The model did not consider temperature gradient in the product and was applied for low airflow rates. Predictions included air and tuber temperatures, relative humidity, and weight loss as a function of position in the bed for input conditions of air velocity, temperature, and relative humidity, as well as skin permeability and respiration of potatoes.

Cumming and Wollin (1986) have discussed various systems for post harvest handling of table grapes. If grapes are cooled below dew points before packing, the condensation which forms on the fruits can cause problems which can be avoided by restoring to two stage cooling. The authors concluded that: (i) for best quality, the grapes should be cooled below dew point temperature before packing in the first stage and then cooled to storage temperature in the second stage in conveyor cooling; (ii) the next best option is to cool the product to the wet bulb temperature in the first stage and then to storage temperature in the second stage through conveyor cooling. This is comparatively less expensive.

Meffert (1973) have applied the formula presented by Luikov (1968) for one dimension heat conduction with constant heat generation in an infinite slab to the cooling process of heat generating product for estimating time-temperature history. He reported that the theoretical and experimental temperatures at the centre of a box of flowers are in good agreement during starting period of the process up to a dimensionless time of 0.15. The theory and experimental curves deviate at higher times (F_o >0.15) because heat generation is not constant as cooling proceeds.

EXPERIMENTAL SETUP AND PROCEDURE

4.1 GENERAL

This chapter gives the information regarding the description, specifications and the fabrication of different components of the experimental setup. The procedure adopted, to carryout experimental runs, is also being discussed in this chapter.

4.2 DESCRIPTION OF EXPERIMENTAL SETUP

The experimental setup is represented by sketch shown in Fig.4.1 and schematic diagram, shown by Fig.4.2. It consists of rectangular air duct (1) cross section made of galvanized iron sheet insulated with 10 mm thick puff sheet. The air is circulated inside the duct by means of centrifugal blower (2). The blower is driven by means of an electric motor (3) connected with a belt and pulley arrangement (4). The air velocity in the duct is regulated by controlling the speed of blower by using the pulleys of different sizes. Two dampers are also provided to further control the circulation rates and temperature of air in the test and the return ducts, by adjusting the damper opening. The air is cooled by passing the air over the two sets of cooling coils, one is evaporator coil of R-22 vapour compression cycle (5) and other is chilled water cooling coil (6). Cooling by first set of coil is known as **direct cooling technique** and is done by placing R-22 evaporator coil of the vapour compression cycle in the path of air, i.e., in the duct. Heat of the air is absorbed by the refrigerant R-22 flowing inside the evaporator cooling coil. Cooling by second set of coil is called **indirect cooling technique** is achieved by placing the coil carrying the chilled water inside the duct. Heat of air is first absorbed by the chilled water coil and then this heat is rejected inside the chiller by means of another R-22 evaporator cooling coil. The two coils are never run simultaneously but only one coil is used at a time, owing to the limitation of the cooling capacity of the existing R-22 vapour compression refrigeration cycle. The refrigerant R-22 changes its state from liquid phase to vapour phase. These vapours are then sucked by compressor (7), compressor activates the refrigerant by compressing it to a higher pressure and higher temperature level after it has produced its refrigerant effect in the evaporator coils. The compressed refrigerant transfers its heat to the condenser and is condensed to liquid form. Here the two condensers, one air-cooled (8) and other water-cooled condenser (9) are used. However, only one is used at a time. Refrigerant leaves the condenser as saturated liquid, and enters the receiver (10). A sight glass (11) is also placed after receiver to see the liquid phase of the refrigerant. This liquid refrigerant is then throttled to a low pressure, low temperature vapour by means of hand operated expansion valves (12) to produce a refrigerating effect during evaporation inside the first set of evaporator coil and inside the chiller (13). The condenser cooling water is cooled by induced draft cooling tower (14) and is circulated by means of centrifugal pump #1 (15). The chilled water on the other hand is circulated by another pump, namely, centrifugal pump #2 (16). The test section (17) is made inside the air duct with an arrangement having tray to hold food commodities known as food package (18). The temperature at various locations inside the test section and food package is measured by thermocouples (19). The air velocity is measured by digital anemometer (20). Air temperature and humidity is measured by digital multimeter (21).

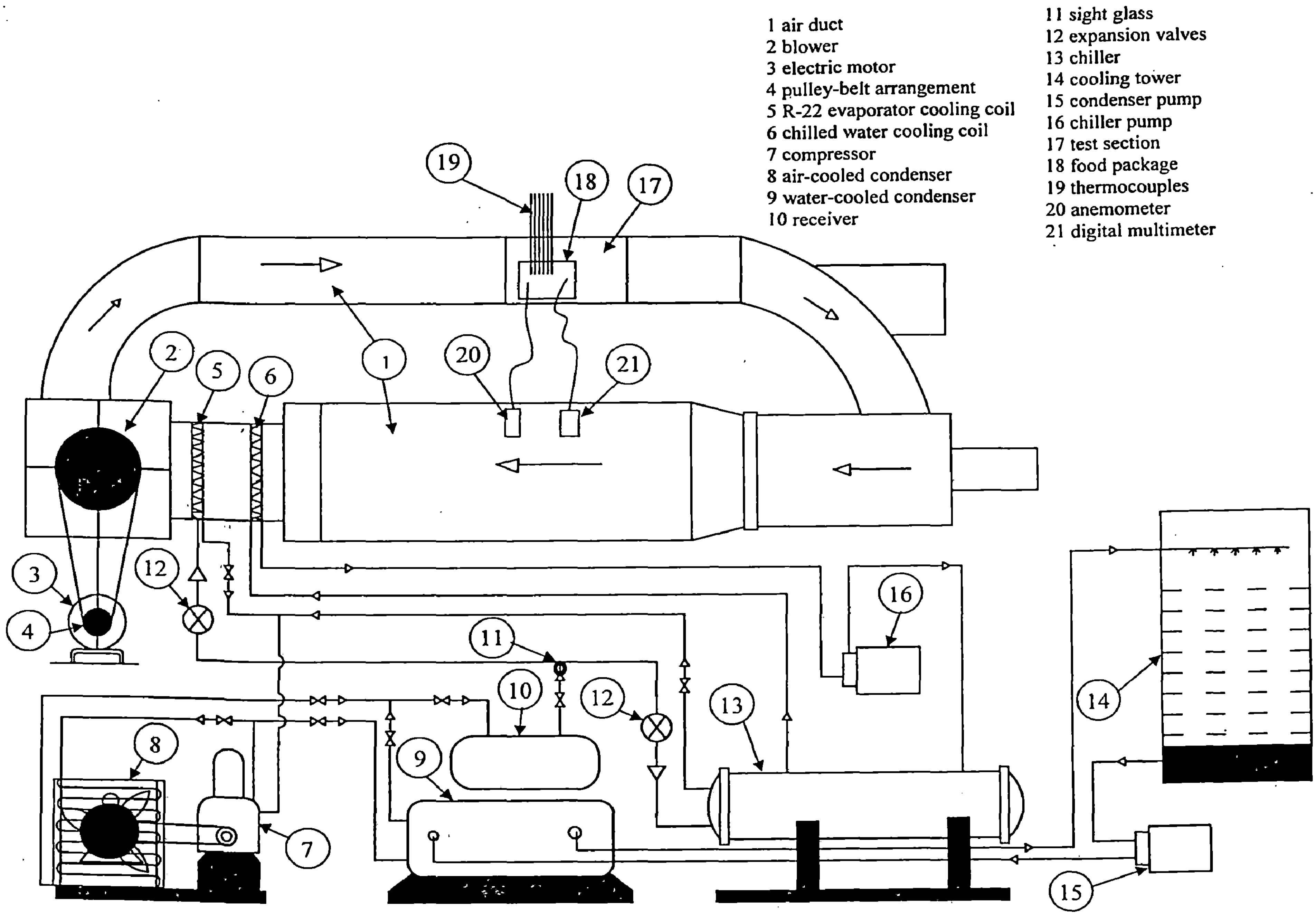

Fig. 4.1 Sketch of forced air precooling experimental setup

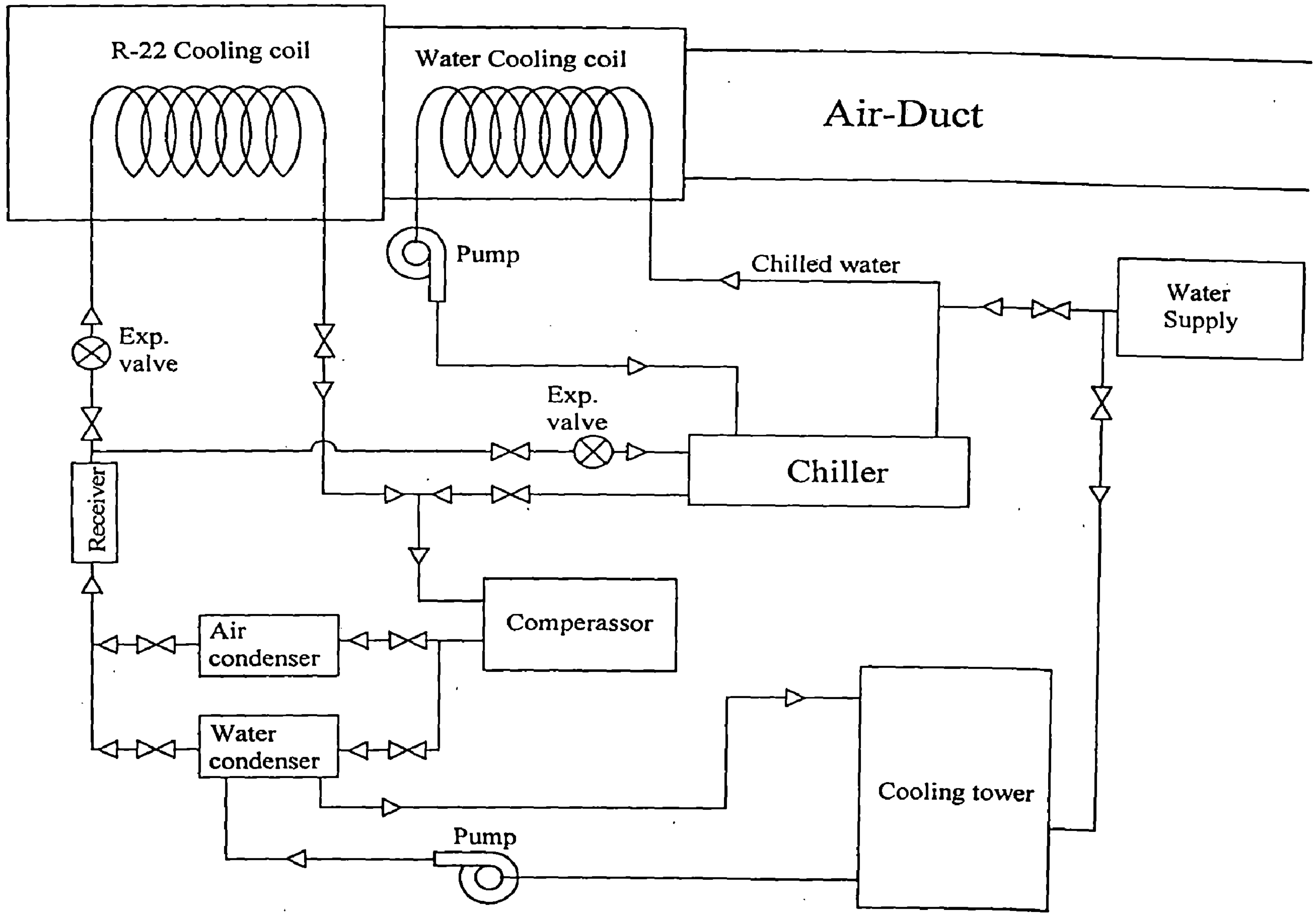

Fig. 4.2 Schematic diagram of experimental setup

4.3 SETUP SPECIFICATIONS

The specifications for different components of the experimental setup as shown in Appendix-E are as follow:

4.3.1 Air Duct

Air duct is made up of Galvanized Iron sheet having 4 m length and a cross section of 300 x 300 mm. The duct is insulated by 12 mm thick puff sheet.

4.3.2 Blower

Type	Centrifugal
Drive	V- belt
Motor voltage	3 ph 400/440 AC
Speed	1420 rpm

4.3.3 Cooling coils

Make	Bareo
No. of turns	6
Material of fin	Aluminum

4.3.4 Compressor

Make	Bitzer, Germany
Type	Open type, reciprocating, two cylinder
Cooling capacity	5 ton
Speed	550 rpm

4.3.5 Compressor Motor

Make	Crompton and Parkinson
Rated speed	1440 rpm
Rated power	7.5 hp
Motor voltage	3 ph /440 volts

4.3.6 Air-cooled condenser

Type	Forced
Tube	Copper tube of 3/8" diameter
Fin	Aluminum
Capacity	5 Ton

4.3.7 Water-cooled condenser

Type	Shell-and-tube type
Tube	Copper tube of 3/8" diameter
Capacity	5 Ton

Fig.4.3 shows water-cooled condenser with water in shell side and refrigerant in tube side.

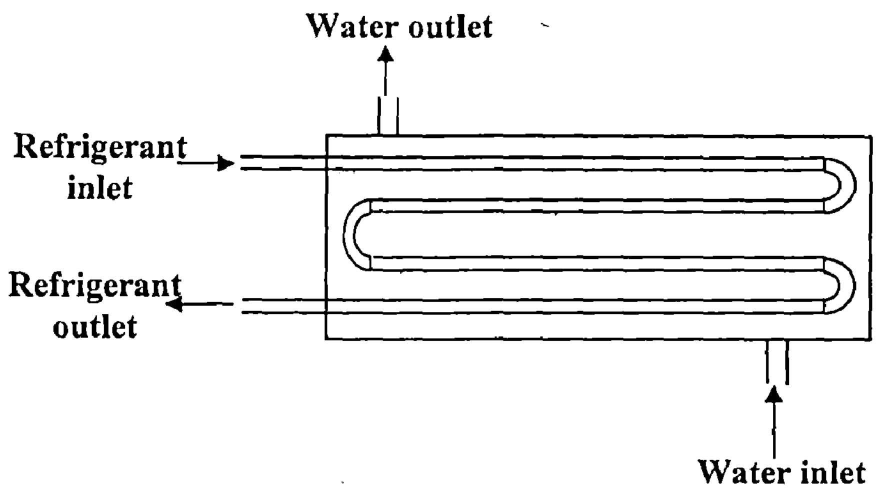

Fig 4.3 Water-cooled condenser

4.3.8 Expansion valves

The two manual expansion valves have been used in the present experimental facility. The first expansion valve is used with R-22 evaporator cooling coil (5) and the second with the chiller (13).

4.3.9 Chiller

Fig. 4.4 shows shell-and-tube type water chiller with refrigerant inside tubes and water in shell side. The refrigerant gets superheated in the portion of the set of tubes and is collected in the end chamber from where it is sucked by the compressor.

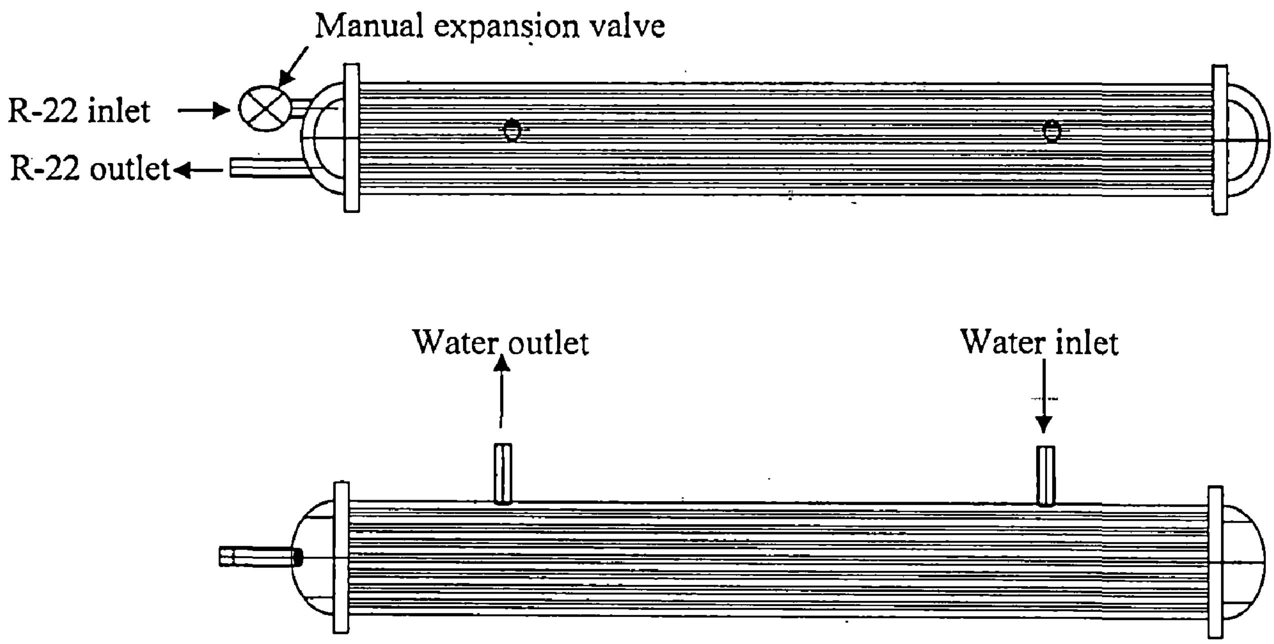

Fig.4.4Water Chiller

4.3.10 Cooling Tower

Fig.4.5 shows the schematic diagram of induced draft cooling tower. The cooling tower is used to cool the condenser cooling water. The hot water from the condenser is pumped into the cooling tower and sprayed through the nozzles over the set of asbestos sheets arranged in zig-zag fashion as shown in Fig.4.5. While flowing through the plates, water comes in contact with air sucked by a blower placed at the end of cooling tower. The hot water rejects heat to the flowing air and becomes cool. The cold water is then pumped back to the water cooled condenser.

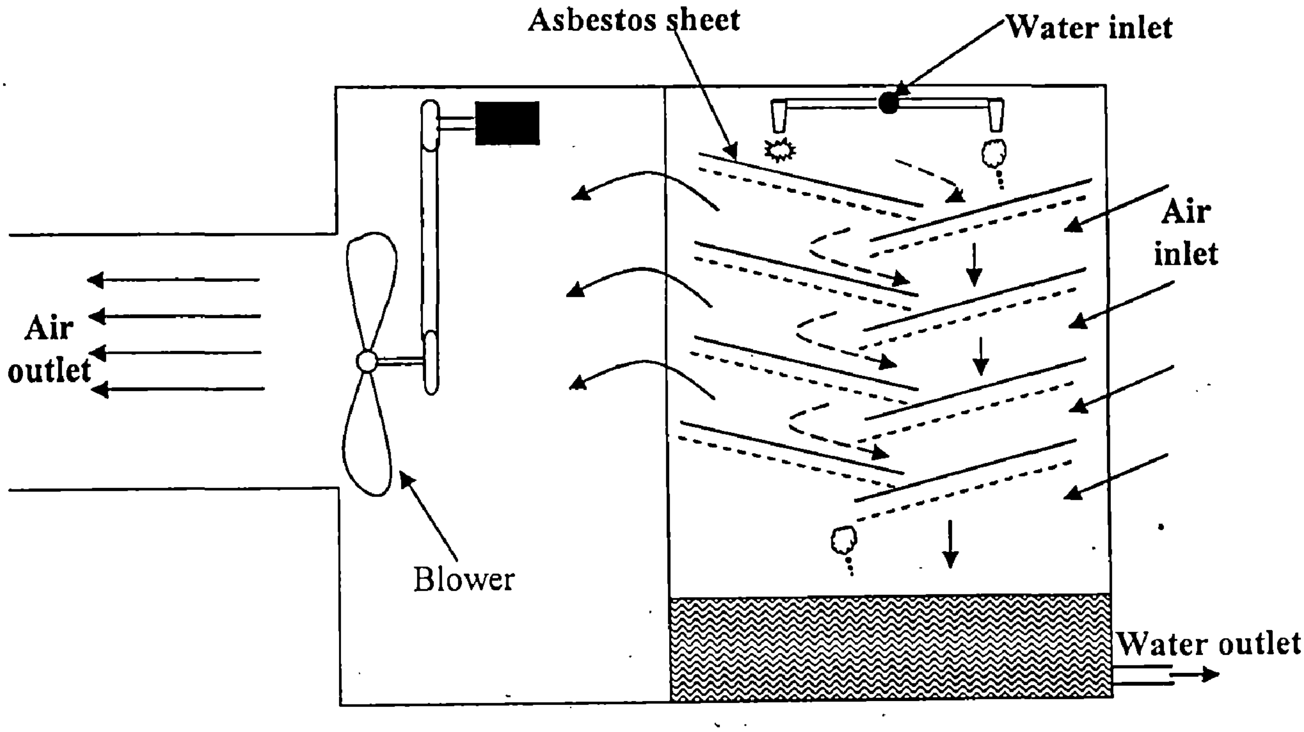

Fig 4.5 Cooling Tower

4.3.11 Chiller pump

Type	Centrifugal pump
Total head	10 m
Rated voltage	220 / 240 V
Rated power	0.65 hp
Speed	2650 rpm

4.3.12 Cooling Tower pump

Make	Batliboi and Co. Ltd.
Type	Centrifugal pump
Total head	12 m
Speed	2850 rpm
Rated voltage	220 / 240 V
Rated power	0.5 hp / 0.373 kW

4.3.13 Cooling Tower blower

Make	National Electrical Industries
Type	Single phase Induction Motor
Speed	1430 rpm
Rated Current	3.5 A
Rated voltage	230 V
Rated power	0.5 hp

4.4 EXPERIMENTAL SETUP FABRICATION

The process of fabrication involves cleaning, repair of existing equipment, manufacturing a part for the experimental setup, covering with rexine etc. The whole experimental setup was painted as per standard colour codes and finally the labeling of equipments was done. The part wise fabrication of experimental setup is described under:

4.4.1 Compressor

The open type compressor of 5 ton capacity was subjected to repair work. The operations performed during the repair of the compressor are described below:

1. Suction and discharge valves were replaced
2. Oil seal changed
3. All piston rings of the two pistons replaced
4. Facing was performed on the cover and camshaft
5. All gaskets were replaced
6. Oil changed

4.4.2 Cooling Tower

Cooling tower was not in use for more than 25 years. Some of the work performed on Cooling Tower is discussed below:

1. The tower was first cleaned by removing the longstanding rust and dust
2. The electrical connections of the blower motor and cooling tower pump were restored
3. Plumbing for the condenser cooling water circulation cycle was performed.
4. Nozzles for spraying hot water from condenser were welded to the water line at the top of the cooling tower.
5. Asbestos sheets were placed in zig- zag fashion to allow more contact of sprayed water with air. Moreover, holes in each sheet were drilled to achieve better performance from the cooling tower.

4.4.3 Air Duct

Air cooled duct and returned duct, earlier, were insulated with glass wool. The glass wool insulation was removed. To avoid infiltration, the slits and openings at the joints of the duct was first filled by putty and puff sheet insulation of 12mm thickness was then placed on the ducts by means of adhesive solution. In order to give a decorative look to the experimental setup, the whole duct was then covered with rexine.

4.4.4 Chiller

The chiller was lying idle for more than two decades. An exhaustive cleaning of chiller was conducted to bring it back in working condition. Petrol was used as cleaning agent to remove rust and oil from the tubes. Gaskets at both end chambers of the chiller are changed to remove leaks. The two layers of puff sheet insulation were then put over the chiller to minimize heat transfer. A centrifugal pump for circulating chilled water was installed and all necessary plumbing work associated with it was done.

4.4.5 Condensers

Earlier 5 ton capacity water-cooled condenser, Carrier make had leak in the tubes. So water cooled condenser 5 ton capacity was checked for leaks and installed. In the experimental setup provision of air-cooled condenser of the same capacity was made in case if any of the condensers stopped working one must be available at the operator's disposal and the work would not suffer. At the same time the performance of the two condensers could also be compared by operating one by one for the same set of input conditions.

4.4.6 Receiver

Receiver valves had leakages and were changed. It is then painted with black color.

4.4.7 Electric Board

All the electric connections were in a bad condition with wires insulation broken from several places. All old wiring were removed and replaced by new electric lines. Fig.4.6 shows the schematic diagram of the electric board for the experimental setup. The electric board for the experimental set up was redesigned with dedicated starters with circuit breakers for compressor and duct blower. One circuit breaker was dedicated to AC mains three phase supply. One small circuit breaker was also fixed for low power rating

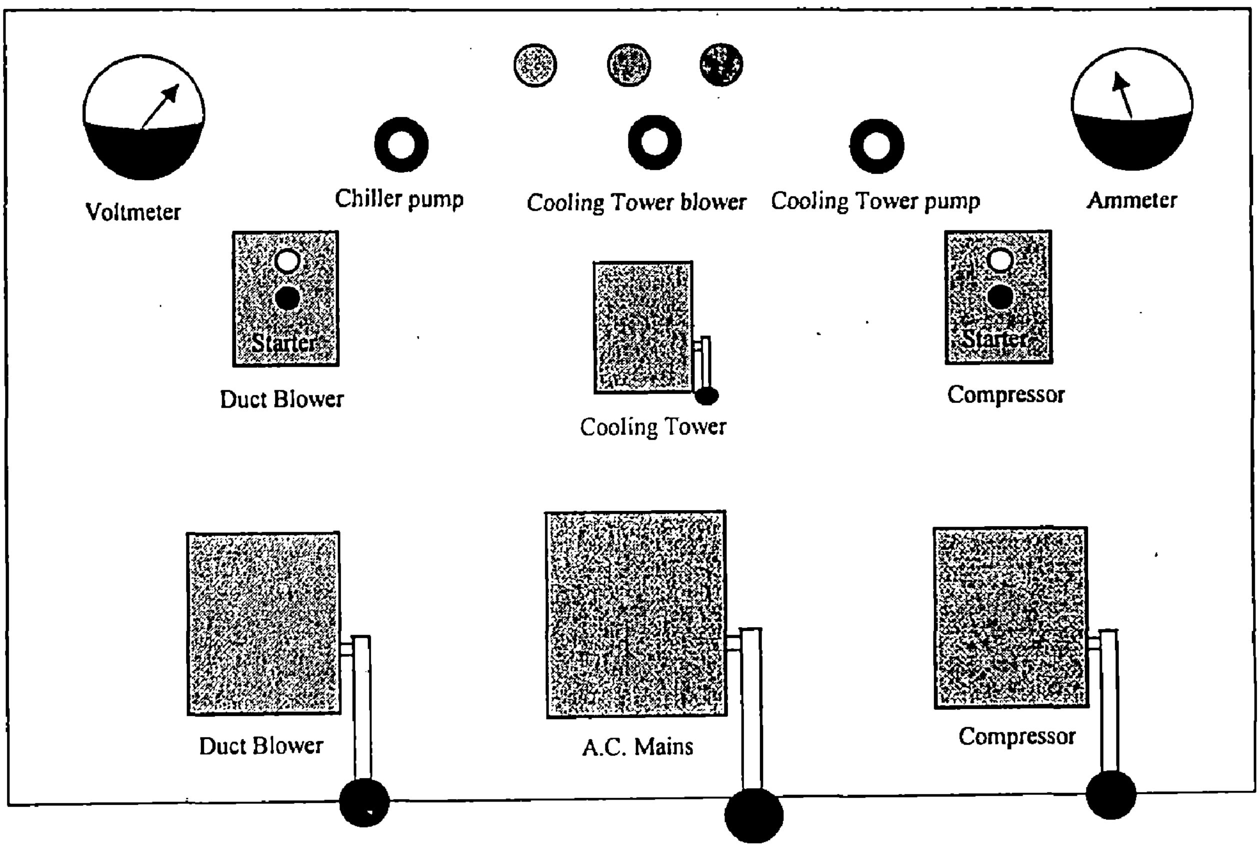

Fig.4.6 Electric Board

equipments viz., chiller pump, cooling tower pump and cooling tower blower with separate switches for each. The voltmeter and ammeter are placed at the top corners of the board to indicate the voltage and current respectively. Three low wattage electric bulbs are placed on the board to indicate the availability of all the phases.

4.5 EXPERIMENTAL PROCEDURE

The experimentation involves a number of phases as shown in Appendix-E like leak detection, charging, calibration of thermocouple, the readings or experimental runs for different set of conditions are taken, the experimental data is analyzed and results are plotted and conclusions on the basis of results obtained are drawn.

4.5.1 Leak detection by water and soap bubble method

During the fabrication every part of refrigeration system was checked separately by pressurized air upto 300 psi (20 bar) and plunging in the water and note if any bubble coming out means a leak was detected it was rectified by usual methods. Then again the system is pressurized to 300 psi and plunging in the water if no any bubbles coming out means no leak in this part. After the fabrication of the experimental setup, leak detection of the system was done in order to find out leakage, if any. The system was first pressurized by air compressor upto 300 psi and all the hand shut off valves were closed. Then soap solution was applied with a spun to all the brazed joints and fasteners like flair nuts, gauge adopters, unions and hand shut off valves to check the leaks (if there is any leak a bubble is formed).Once a leak was detected it was rectified by usual methods. Then again the system is pressurized to 300 psi and all the hand shut off valves were closed and the system was left as such for 24 hours. If a fall in pressure was indicated, the whole procedure was repeated. No change in the pressure in any particular section ensured that no leaks were present in the system.

4.5.2 Leak detection by Vacuum

The system was evacuated to a high vacuum, -30 psi; by removing air from the system by running the same compressor (suction of the compressor is connected to the system). System was allowed to stand in this position for 24 hours. Retention of same vacuum for 24 hours ensured that the system is perfectly leak proof.

4.5.3 Charging of refrigerant in the system

After ensured that the system is leak proof, again was made vaccum more than half hour for make ensure the moisture and a trace of air in the system was removed, because if moisture remain in the system can cause adverse effects and deterioration of the performance, then the system was charged with R-22 to its full capacity.

4.5.4 Calibration of thermocouples

Copper constantan thermocouples, which were used for measurement of temperature for different place of fruits, were calibrated with the help of dry block calibrators T-350P and T-650P, type Presys , this calibrators control temperature of an insert in order to calibrate thermocouples, thermoresistances, glass thermometers, thermoswitches etc. Besides providing high accuracy temperature values, they also allow the measurement of signals generated by thermo-elements like thermocouples, thermoresistances and thermoswitches, which are being calibrated. This is possible due to an embedded calibrator specific for these types of signal, including 4-20 mA. Thus, they incorporate the functions of dry block, standard thermometer and calibrator for RTD, TC and also mA.

- T-350P / T-650P calibrators model generate temperatures from room temperature to 350°C (662°F) and 650°C (1202°F), respectively.
- Present input for thermocouples, thermoresistances and thermoswitches. Besides generating temperature, they measure the signal from the sensor being calibrated.
- Make no use of external standard thermometer.
- Carry out completely automatic calibrations with or without the use of a computer.
- Accuracy to 0.1°C + 0.1% of reading, stability of 0.05°C and resolution of 0.01°C.
- Documenting capabilities: communication with computer and CS-504 Calibration Software.
- Portable, compact, provide interchangeable inserts and carrying case.

Table 4.1 shown calibration report:

Table 4.1 calibration report for Copper constantan thermocouples

CALIBRATION REPORT

Page: 1

COMPANY: Presys Instruments, Inc.

INSTRUMENT: Thermocouple	SERIAL No.: 0004
FUNCTION: testing of TC	TAG: 4000
CALIBRATION FREQUENCY: 12 months	AREA: Area 1

TECHNICAL INFORMATION

INSTRUMENT	OPERATION CONDITION	DOCUMENTS
MANUFACTURER: RAC_LAB MODEL: TC_T INPUT: Temp. Probe OUTPUT: TC-T ACCURACY: ± 2.00 % of Full Scale	CALIBRATION: 5.00 to 80.00 (°C) TOLERANCE: ± 2.10 % of Full Scale	PROCEDURE: Calibration

CALIBRATION AND ADJUST

As Found

Time	Calibration (°C)	Reference (°C)	Corr. Cal. (°C)	Corr. Ref. (°C)	Reading (°C)	Error (%)	
00:07:29	5.00	5.0	5.00	5.0	4.0	-1.25	ok
00:10:34	20.00	20.0	20.01	20.0	20.4	0.50	ok
00:13:49	35.00	35.0	35.00	35.0	36.3	1.62	ok
00:16:48	50.00	50.0	50.00	50.0	51.9	2.38	ERROR
00:19:39	65.00	65.0	65.00	65.0	67.4	3.00	ERROR
00:22:26	80.00	80.0	80.01	80.0	82.9	3.63	ERROR

Confidence Level [illegible] %

CALIBRATION CONDITIONS

LOCATION:	ATMOSPHERIC PRESS.:	LOCAL TEMP.:
MAX DIF.: 0.0 (°C) MAX UNCERT 0.0 (°C)	DIAG.:	NEXT CALIBRATION: 10/24/2006

4.5.5 Data acquisition

The data obtained from the experimental tests carried out in present study has been recorded in Appendix B for apples, papayas and grapes respectively.

4.6 INSTRUMENTATION AND CONTROL

4.6.1 Measurement of temperature

The temperature at the centre, middle and surface temperature of the fruits were measured with help of 28 SWG copper-constantan thermocouples. The lead wires of all the thermocouples were connected with a selector switch and the temperature indicator. The temperature and humidity of air circulating in the duct surrounding the fruits were measured with the help of digital multimeter and in the same time temperature for cold air measured by thermometer and compared with the temperature data from multimeter.

4.6.2 Measurement of Air-Stream Velocity

The air-stream velocity in the cooling duct was measured with an anemometer.

4.6.3 Measurement of Relative Humidity of Air

Relative humidity of air was measured by using hygrometer and multimeter.

4.6.4 Measurement of Refrigeration system Pressure

The suction and discharge pressure of compressor measured by borden gauge.

4.7 EXPERIMENTAL PROCEDURE

4.7.1 Experimental Procedure for Apples

The cooling plant along with the air blower was run for about 2 hours so that the temperature and relative humidity of the circulating air were changed, and the rate of change temperature and humidity of the air circulating depend on the velocity of blower, and the blower velocity was changed by using different size pulley arrangement, when the pulley that diameter 7.5 cm gives air velocity 1.6 m/s, the pulley diameter 10 cm gives air velocity 2.3 m/s, the pulley diameter 13 cm gives air velocity 3.3 m/s and the pulley diameter 15 cm gives air velocity 4.1 m/s. The approach air velocity inside the duct was measured with help of anemometer. The apples used for cooling were placed in the wire mesh test chamber in the duct. The temperature inside the fruits were measured with the help of thermocouples were used three thermocouples for apples the probes was fixed in different place on the distance (R = 0) were measured surface temperature of apples, when thermocouples probes was fixed on the distance(R = d / 2) were measured centre temperature of apples, and when the thermocouples probes was fixed on the distance (R = d / 4) were measured middle temperature of apples. In the same time was measured surrounding air temperature with help of multimeter and thermometer. The centre, middle and surface temperature of apples were measured at regular time interval of 10 minutes during cooling process. The temperature values at different air flow rates were recorded. Cooling curves were drawn for apples based upon the the temperature data obtained.

4.7.2 Experimental Procedure for Papayas

In these experiments same procedure for apples was followed except that the papayas have two diameters were measurement had took miner diameters.

4.7.3 Experimental Procedure for Grapes

In these experiments same procedure for apples was followed except that the grapes have small diameter therefore were measured centre and surface temperature of grapes, i.e. at the distance (R = 0) and (R = d / 2) respectively.

Chapter 5

METHOD OF FORMULATION

5.1 DETERMINATION OF HEAT TRANSFER COEFFICIENT

Techniques used to determine heat transfer coefficients generally fall into three categories:

1. Steady-state temperature measurement methods
2. Transient temperature measurement methods
3. Surface heat flux measurement methods

Of these three techniques, the most popular methods are the transient temperature measurement techniques. Transient methods for determining the surface heat transfer coefficient involve the measurement of product temperature with respect to time during cooling or freezing process.

Two cases were considered when performing transient tests to determine the surface heat transfer coefficient: low Biot number ($Bi \leq 0.1$) and large Biot number ($Bi > 0.1$). The Biot number, Bi, is the ratio of external heat transfer resistance to internal heat transfer resistance and is defined as follows:

$$Bi = \frac{hR}{k} \tag{5.1}$$

A low Biot number indicates that the internal resistance to heat transfer is negligible, and thus, the temperature within the object is uniform at any given instant. A large Biot number indicates that the internal resistance to heat transfer is not negligible, and thus, a temperature gradient may exist within the object.

In typical blast cooling or freezing operations for foods, the Biot number is large, ranging from 0.2 to 20. Thus, the internal resistance to heat transfer is generally not negligible during food cooling and freezing and a temperature gradient will exist within the food item.

One method for obtaining the surface heat transfer coefficient of a food product with an internal temperature gradient involves the use of cooling curves. For simple, one dimensional food geometries such as infinite slabs, infinite circular cylinders or spheres, there exist empirical and analytical solutions to the one dimensional transient heat equation. The slope of the cooling curve may be used in conjunction with these solutions to obtain the Biot number for the cooling process. The heart transfer coefficient may then be determined from the Biot number.

The fractional unaccomplished temperature difference, Y, is defined as follows:

$$Y = \frac{T - T_a}{T_i - T_a} \tag{5.2}$$

From Fig. 5.1, it can be seen that the linear portion of the cooling curve can be described as follows:

$$Y = je^{-Ct} \tag{5.3}$$

where C is the cooling coefficient, which is minus the slope of linear portion of the cooling curve.

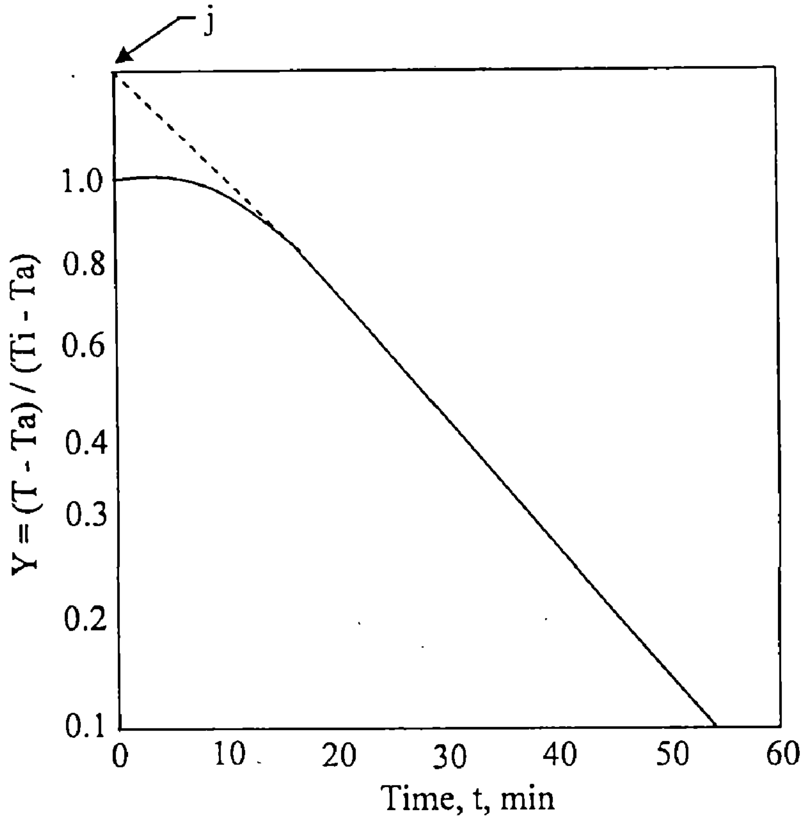

Fig.5.1 Typical cooling curve

For simple geometrical shapes, such as infinite slabs, infinite circular cylinders and spheres, analytical expression for cooling or freezing time may be derived. To derive these expressions the following assumptions are made:

1. The thermophysical properties of the food items and the cooling medium are constant

2. The internal heat generation and moisture loss from the food item are neglected

3. The food item is homogeneous and isotropic

4. The initial temperature distribution within the food item is uniform

5. Heat conduction occurs only in one dimension

6. Convective heat transfer occurs between the surface of the food item and the cooling medium.

With these assumptions, the one dimensional transient heat conduction equation may be written as follows for infinite slabs, infinite circular cylinders and spheres:

$$\frac{1}{x^m}\frac{\partial}{\partial x}\left(x^m\frac{\partial T}{\partial x}\right)=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{for } t\geq 0,\ 0\leq x\leq x_o \qquad (5.4)$$

Where:

m = 0 for slab, 1 for cylinder, 2 for sphere

x = distance of the point under consideration from the central plane of slab, central axis of the cylinder or center of the sphere

5.2 INITIAL AND BOUNDARY CONDITIONS

5.2.1 Initial condition

In most of the precooling analyses reported in the literature, an initial constant temperature is assumed through the characteristic length (half thickness of the slab or radius of cylinder or sphere)

$$T=T_i \qquad (5.5)$$

5.2.2 Centre boundary condition

The symmetry condition along the central plane of the slab, along the central axis of the cylinder or along the centre of the sphere provides the first boundary condition given by:

$$\frac{\partial T}{\partial x} = 0 \qquad \text{for } t \geq t_o \; x = 0 \tag{5.6}$$

This condition holds good in any case of symmetrical cooling of regular shaped food products.

5.2.3 Surface boundary condition

The second boundary condition is deduced from the mode of heat transfer at the product surface. If only convective heat transfer is considered at the product surface, the boundary condition can be written as

$$-k\frac{dT}{dr} = h(T - T_a) \tag{5.7}$$

This completes the mathematical formulation for the transient heat transfer analysis during precooling.

The technique developed in this work to determine heat transfer coefficients from experimental cooling curves is base upon the infinite series solution of equation (5.4) given by Incropera and Dewitt, for the dimensionless center temperature of a sphere:

$$Y = \frac{T - T_a}{T_i - T_a} = \sum_{n=1}^{\infty} \frac{2Bi \sin\lambda_n}{\lambda_n - \sin\lambda_n \cos\lambda_n} e^{-\lambda_n^2 F_o} \tag{5.8}$$

After the initial 'lag' period has passed, in which case $F_o \geq 0.2$, the second and higher terms of equation (5.8) are neglected. Thus equation (5.8) can be simplified as follows:

$$Y = \frac{2Bi \sin \lambda_1}{\lambda_1 - \sin \lambda_1 \cos \lambda_1} e^{-\lambda_1^2 F_o} \qquad (5.9)$$

λ_1 is a parameter specified by a characteristic equation from (Allan. D.Kraus, 2001):

$$\lambda_1 \tan \lambda_1 = B_i \qquad (5.10)^*$$

The parameter λ_1 may also be determined from the cooling coefficient, C, defined in equation (5.3). By comparing equations (5.3) and (5.9), it can be seen that:

$$-Ct = -\lambda_1^2 F_o \qquad (5.11)$$

The value of λ_1 can be obtained by arranging equation (5.11):

$$\lambda_1 = \sqrt{\frac{Ct}{F_o}} \qquad (5.12)$$

Then, the Biot number, Bi, can be obtained from equation (5.10) and the surface heat transfer coefficient, h, may be obtained through algebraic manipulation of the definition of the Biot number, equation (5.1)

The thermal conductivity and thermal diffusivity for foods are estimated by using the following Sweat and Riedel correlations:

$$k = 0.148 + 0.493W \qquad (5.13)$$

$$\alpha = 0.088 * 10^{-6} + (\alpha_w - 0.088 * 10^{-6})W \qquad (5.14)$$

where W is the water content by weight (in decimal units)

5.3 NUSSELT-RENOLDS CORRELATIONS

Non dimensional analysis were performed to develop Nusselt-Reynolds correlations for fruits. The Nusselt number is a dimensionless heat transfer coefficient defined as:

$$Nu = \frac{hd}{k_a} \tag{5.15}$$

Physical reasoning indicates a dependence of the heat transfer process on the flow field, and hence on the Reynolds number:

$$\mathrm{Re} = \frac{Vd}{\nu} \tag{5.16}$$

The relative rates of diffusion of heat and momentum are related by the Prandtl number, Pr, and hence, Prandtl number is expected to be a significant parameter in the determination of heat transfer coefficients.

An exponential function is commonly used to relate the Nusselt number to the Reynolds number:

$$Nu = c\,\mathrm{Re}^m \tag{5.17}$$

where c and m are constants determined from experimental data.

Chapter 6

RESULTS AND DISCUSSIONS

The results of the studies on the precooling of perishable food viz. apples, papayas and grapes are discussed below:

6.1 COOLING CURVES AT DIFFERENT AIR FLOW VELOCITIES

Fig. 6.1 to Fig. 6.4 are drawn taking time as abscissa and the dimensionless temperature of apple has been cooling measured at three radial positions i.e. geometric centre, half radius and surface of apple as ordinate. The air velocity blown over apples is ranging from 1.6 m/s to 4.1 m/s. It has been observed that the temperature of apples decreases exponentially with cooling time. The initial rate of fall in the centre, middle and surface temperature of apples high. With the increase in air velocity, the rate decrease in temperature of apples is increased.

6.1.1 Cooling of apples

Fig. 6.1 represents the variation of dimensionless temperature at centre, middle and surface of apples under air velocity of 1.6 m/s. It has been observed from this graph that the centre, middle and surface temperature of apples decreases exponentially with time. This can be analyzed quantitatively in the following way:

From Fig. 6.1 during first 40 minutes of time the drop in dimensionless centre temperature is 0.41. For the next 40 minutes i.e. during 40 to 80 minutes, the drop observed is 0.24 which is 58% of initial drop as said above and during 80 to120 minutes drop observed is only 0.14, which is 34% of initial drop, see Appendix-B.

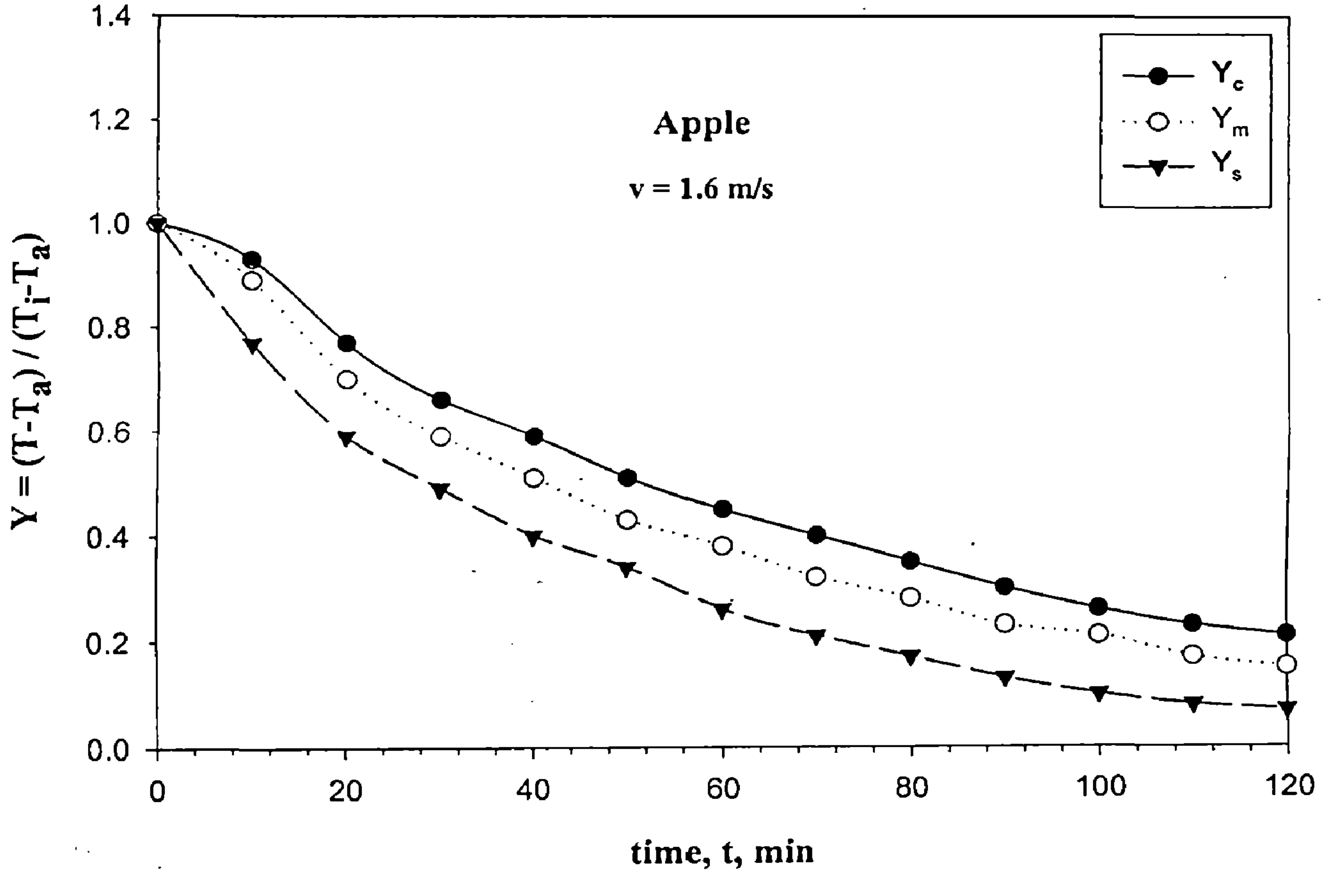

Fig. 6.1 Dimensionless Temperature – time graph for apples at v = 1.6 m/s
(k = 0.531W/m.k, $\alpha = 1.34*10^{-7}$ m^2/s, d = 0.062 m $T_i = 22°C$, $T_a = -4.5°C$)

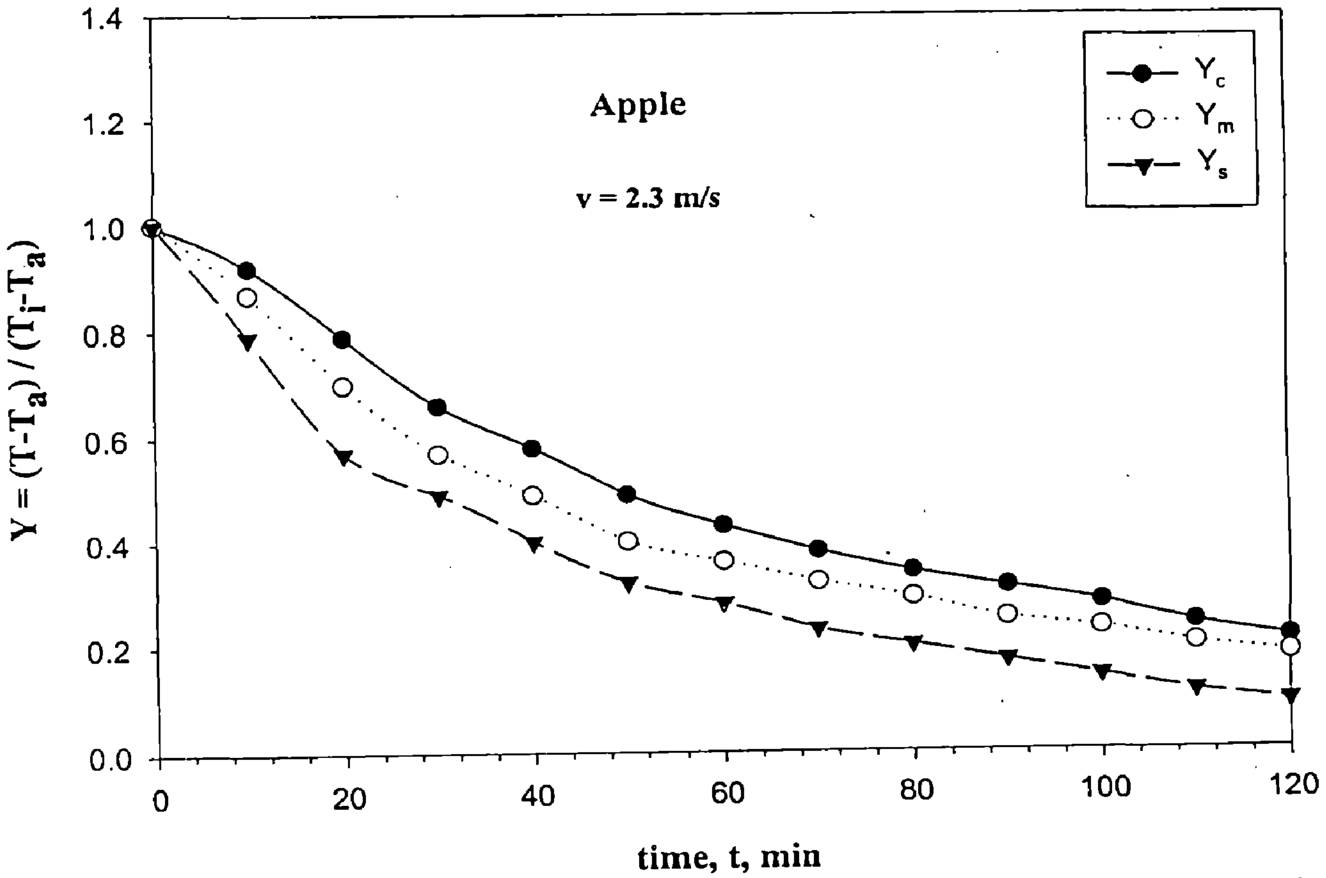

Fig. 6.2 Dimensionless Temperature – time graph for apples at v = 2.3 m/s
(k = 0.531W/m.k, $\alpha = 1.34*10^{-7}$ m^2/s, d = 0.062 m $T_i = 21°C$, $T_a = -2.5°C$)

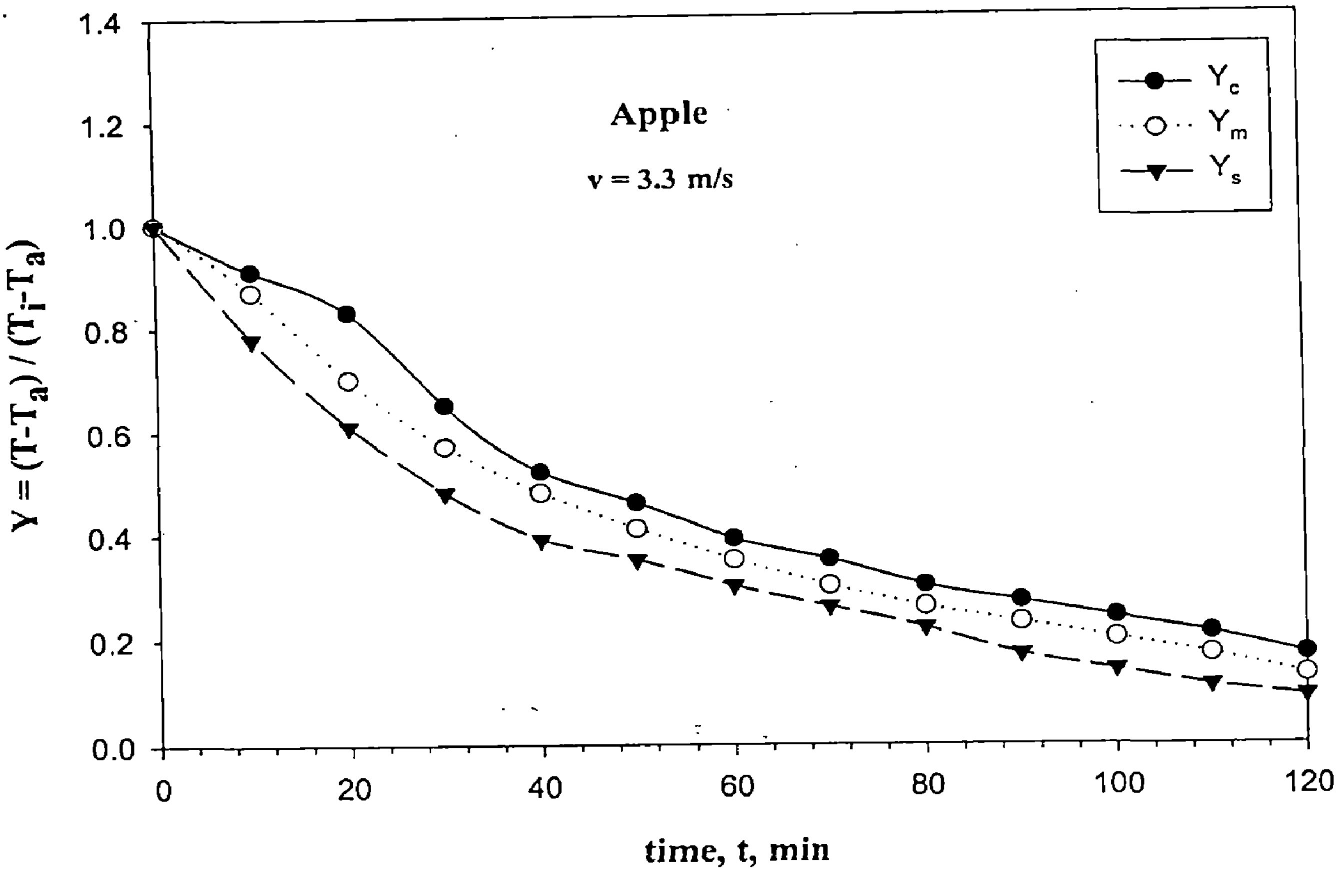

Fig. 6.3 Dimensionless Temperature – time graph for apples at v = 3.3m/s (k = 0.531W/m.k, $\alpha = 1.34*10^{-7}$ m^2/s, d = 0.065 m $T_i = 22°C$, $T_a = -1°C$)

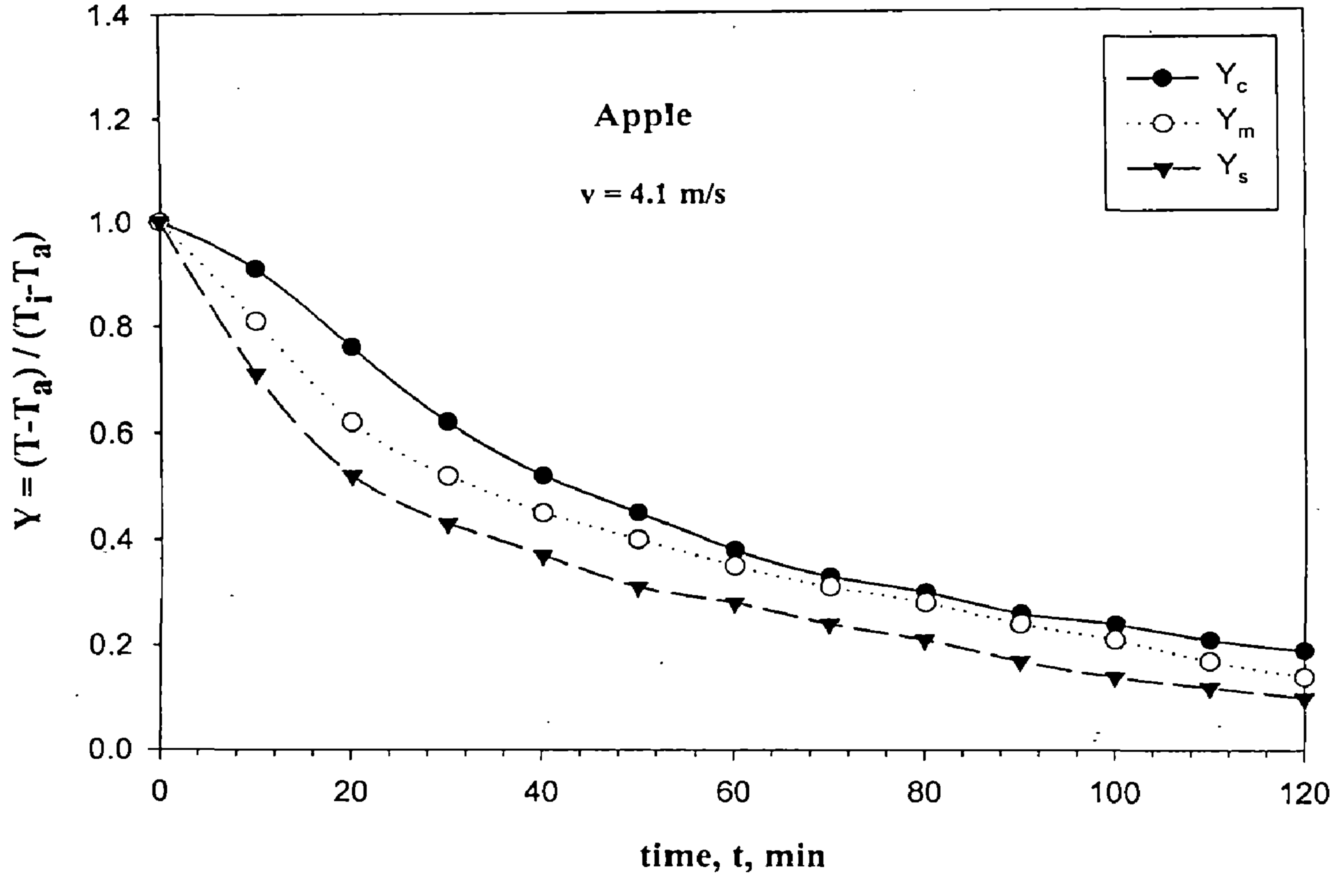

Fig. 6.4 Dimensionless Temperature – time graph for apples at v = 4.1m/s (k = 0.531W/m.k, $\alpha = 1.34*10^{-7}$ m^2/s, d = 0.065 m $T_i = 21°C$, $T_a = 0°C$)

After 120 minutes there is no significant drop in the dimensionless temperature. So, it can be concluded that initial rate of drop in temperature is significantly high because of large temperature difference between food item and cooling medium.

Fig. 6.2 represents variation of centre, middle and surface dimensionless temperature of apples at an air velocity of 2.3 m/s. Slope of this graph is slightly lower than that of Fig. 6.1, which clearly shows that increase in air flow rate accelerates the rate of drop of temperature. In this graph for the first 40 minutes drop observed is 0.58, which is 10% lower than that of drop observed for the flow rate of 1.6 m/s. So, higher flow rates are desirable for fast cooling of food items. This can justified from the Fig. 6.3 and 6.4 drawn for increasing order of air flow rates for apples.

Similarly graphs for papayas represented in Fig. 6.6 to 6.9 and grapes represented in Fig. 6.11 to 6.14 can be analyzed. The results of these analyses for apples, papayas and grapes are represented in Table 6.1, 6.2 and 6.3 respectively.

Table 6.1 Temperature drop for apples at different air velocities

Air flow velocity (V, m/s)	Y = (T-Ta)/(Ti-Ta) Y(0 – 40min)	Y = (T-Ta)/(Ti-Ta) Y(40 – 80min)	Y = (T-Ta)/(Ti-Ta) Y(80 – 120min)
1.6	0.41	0.24	0.14
2.3	0.42	0.24	0.13
3.3	0.48	0.22	0.13
4.1	0.48	0.22	0.11

Table 6.2 Temperature drop for papayas at different air velocities

Air flow velocity (V, m/s)	Y = (T-Ta)/(Ti-Ta) Y(0 – 40min)	Y = (T-Ta)/(Ti-Ta) Y(40 – 80min)	Y = (T-Ta)/(Ti-Ta) Y(80 – 120min)
1.6	0.34	0.16	0.10
2.3	0.35	0.23	0.11
3.3	0.35	0.23	0.12
4.1	0.39	0.23	0.13

Table 6.3 Temperature drop for grapes at different air velocities

Air flow velocity (V, m/s)	Y = (T-Ta)/(Ti-Ta) Y(0 – 40min)	Y = (T-Ta)/(Ti-Ta) Y(40 – 80min)	Y = (T-Ta)/(Ti-Ta) Y(80 – 120min)
1.6	0.39	0.18	0.14
2.3	0.42	0.21	0.14
3.3	0.43	0.23	0.15
4.1	0.43	0.24	0.21

Fig. 6.5 is drawn taking time as abscissa and the dimensionless centre temperature of apples as ordinate at different velocities of cold air ranging from 1.6 m/s to 4.1 m/s. To draw this graph dimensionless temperature is chosen as ordinate because during experiments the initial temperature of apples at different air flow rate is not same. So, to compare the cooling rates at different air flow rates dimensionless temperature scale is required. For the first 40 minutes of cooling for apple, the dimensionless temperature at the air flow rate of 1.6 m/s is 0.59 and at the flow rate of 4.1 m/s, dimensionless temperature is 0.52. It is observed that the dimensionless centre temperature of apples

decreases exponentially with time. With the rise in air velocity the rate of fall of the dimensionless centre temperature was increased, this is because the cooling coefficient is increased with the increase in air velocity. Cooling coefficient is defined as "the change in product temperature per unit change of cooling time for each degree temperature difference between the product and its surroundings".

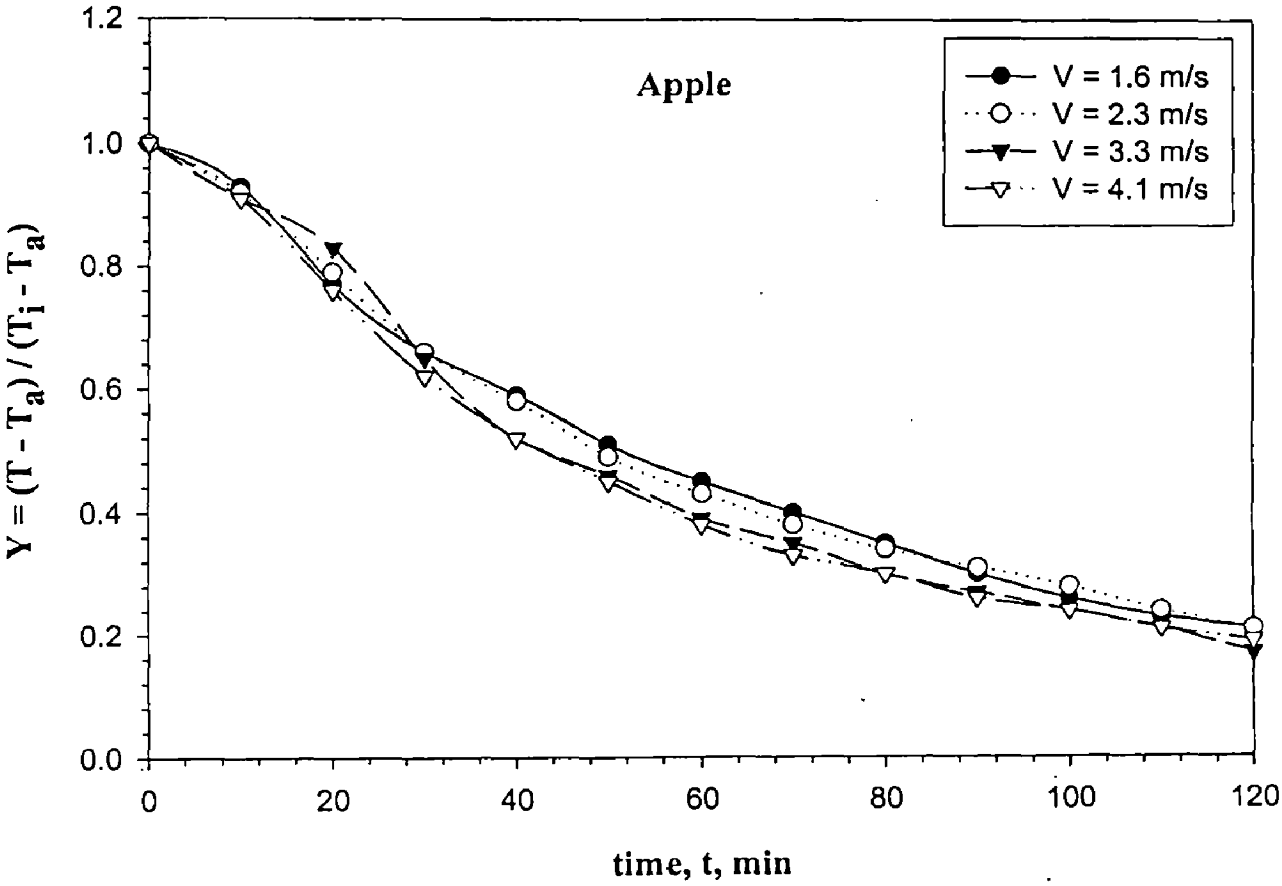

Fig. 6.5 variation in dimensionless centre temperature of apples with time at different air velocity ranging from 1.6 m/s to 4.1 m/s

From the Fig. 6.5 dimensionless temperature, Y and cooling time, t, can be represented as,

$$Y = j\, e^{-Ct}$$

The slope of linear portion of logarithmic dimensionless centre temperature – time graph gives the cooling coefficient (C) value at particular air flow rate. From the Fig. 6.5 cooling coefficient of apples at all the flow velocities were found and with dimensionless temperature for apples, Y, and cooling time, t, are found intercept, j, reported in Table 6.4.

Table 6.4 Cooling coefficients of apples at different air flow rate

Flow velocity, v, m/s	Cooling coefficient, C, $sec^{-1} x10^{-4}$	Intercept, j
1.6	0.013	0.99
2.3	0.014	1.02
3.3	0.016	0.98
4.1	0.016	0.98

6.1.2 Cooling of papayas

Fig. 6.6 to Fig. 6.9 have been drawn taking time as abscissa and the centre, middle and surface dimensionless temperature of papayas as ordinate at different velocities of cold air ranging from 1.6 m/s to 4.1 m/s. It has been observed that the dimensionless temperature of papayas decreases exponentially with time. The initial rate of fall in the centre, middle and surface dimensionless temperature are high. With the increase in air velocity, the rate of fall in centre, middle and surface dimensionless temperature of papayas was increased.

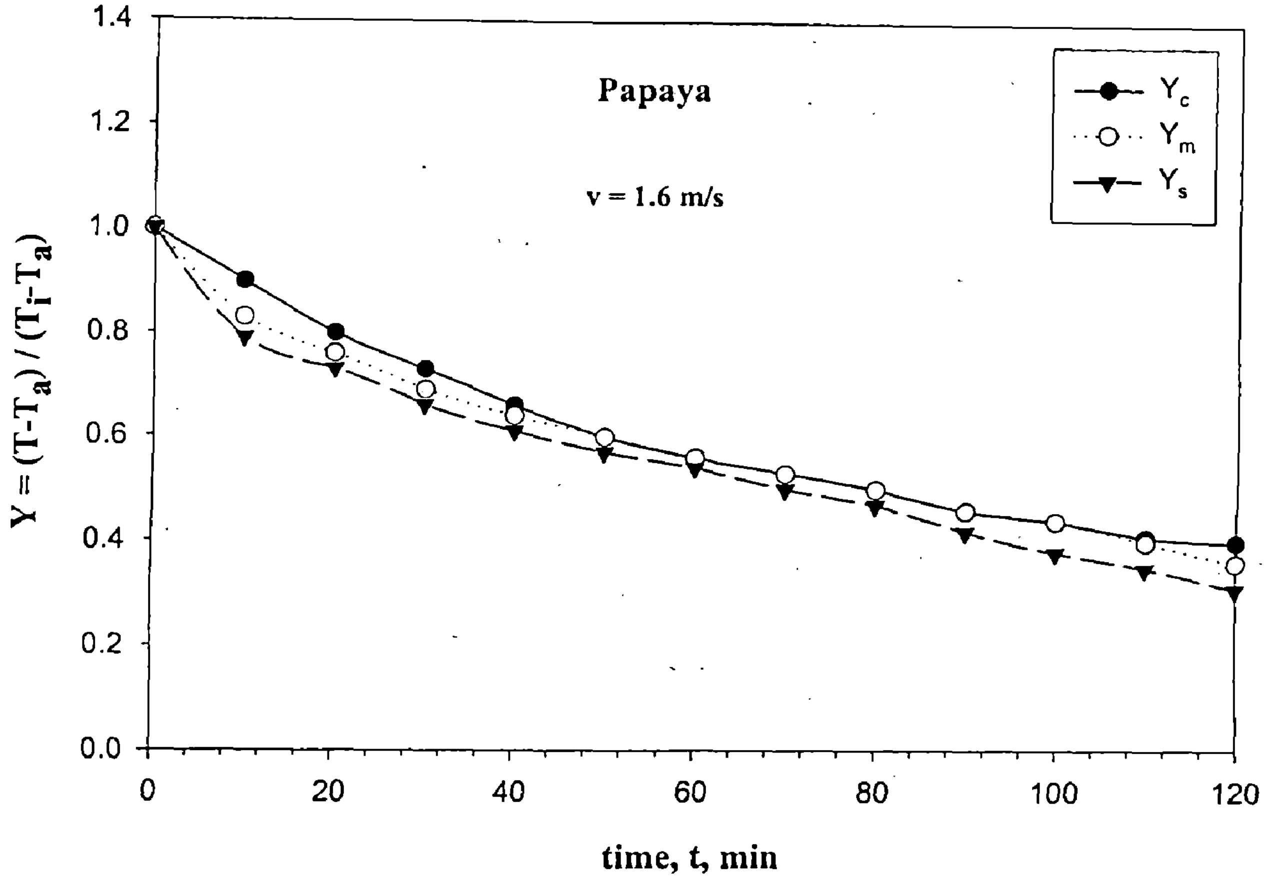

Fig. 6.6 Dimensionless Temperature – time graph for papayas at v = 1.6 m/s (k = 0.602 W/m.k, α = $1.423*10^{-7}$ m^2/s, d = 0.137m, T_i = 22 °C, Ta = -7.1 °C)

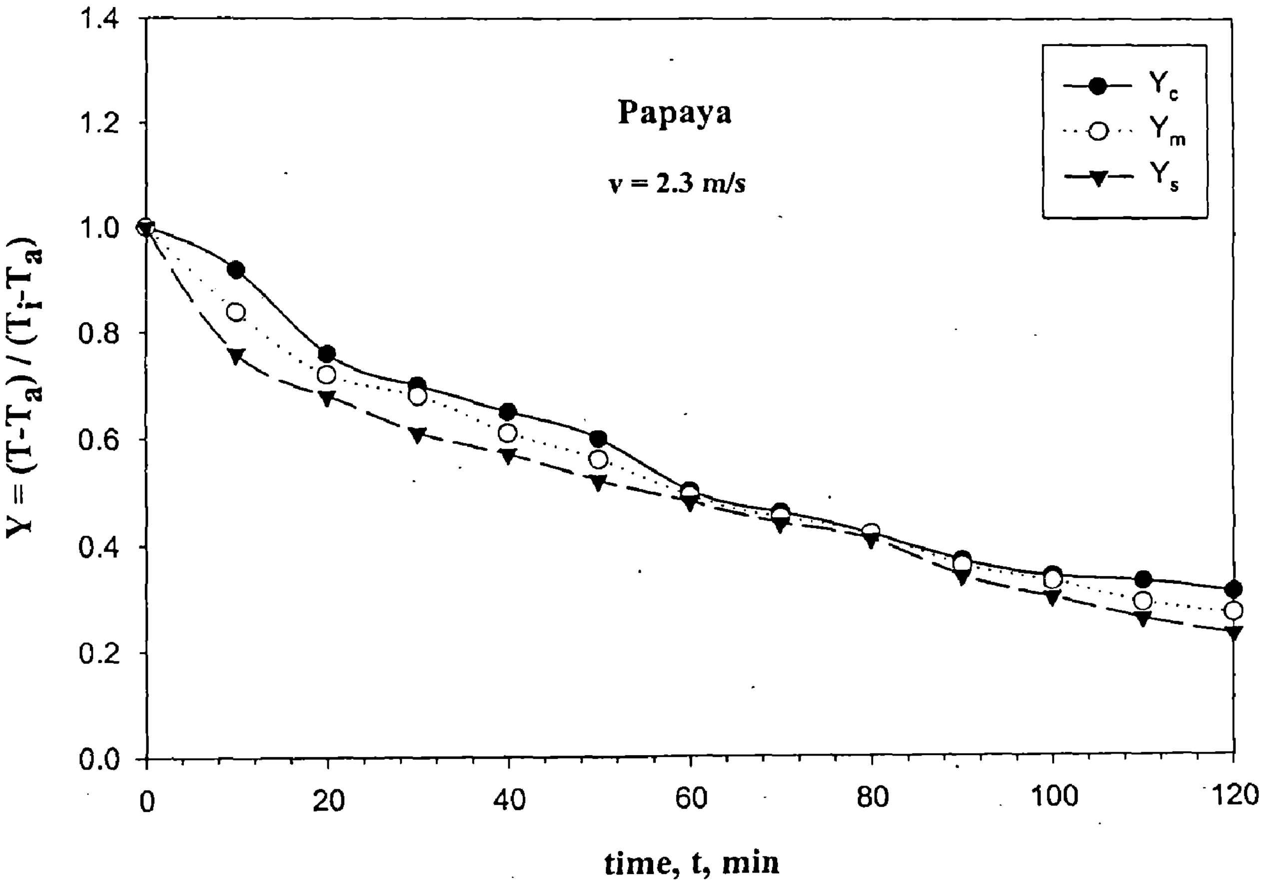

Fig. 6.7 Dimensionless Temperature – time graph for papayas at v = 2.3 m/s (k = 0.602 W/m.k, α = $1.423*10^{-7}$ m^2/s, d = 0.137m, T_i = 22 °C, Ta = -2.6 °C)

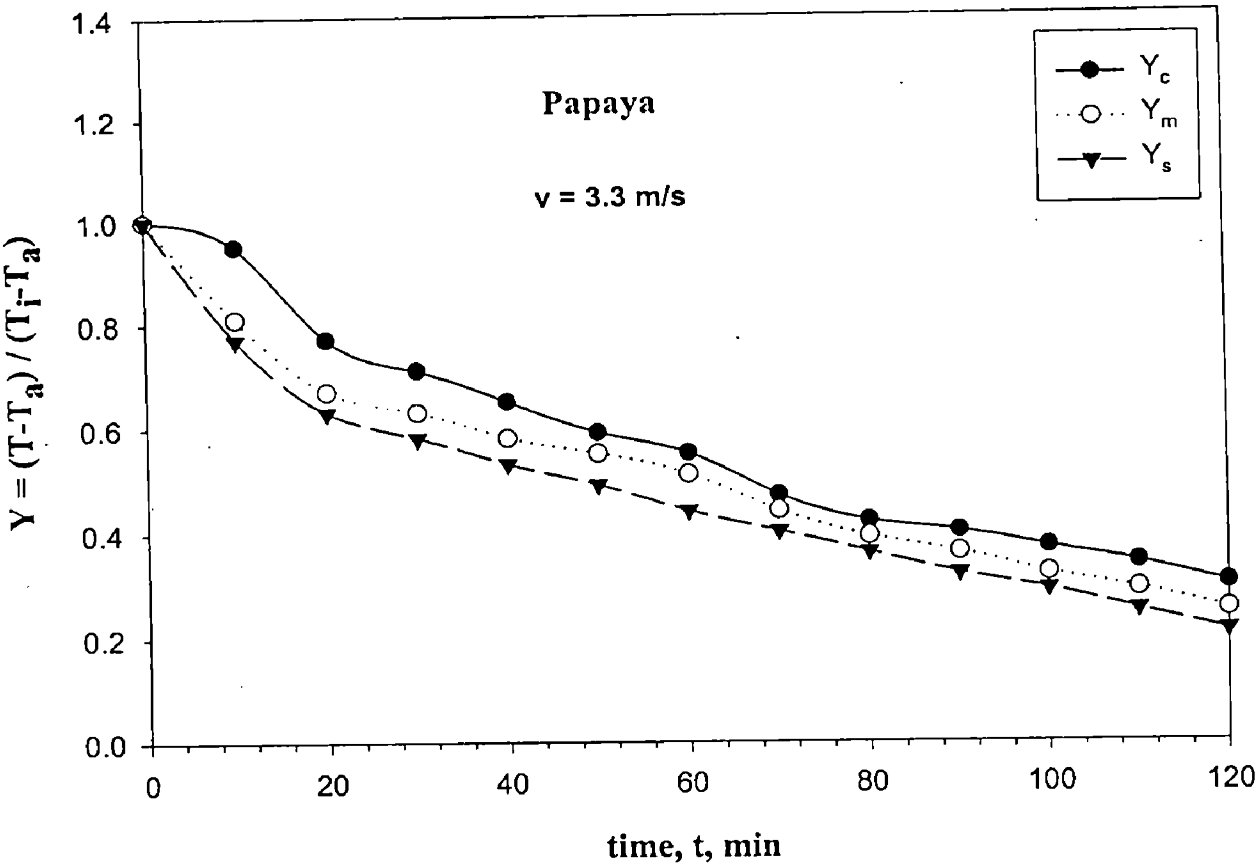

Fig. 6.8 Dimensionless Temperature – time graph for papayas at v = 3.3 m/s (k = 0.602 W/m.k, α = 1.423*10^{-7} m^2/s, d = 0.137 m, T_i = 21 °C, Ta = -0.4 °C)

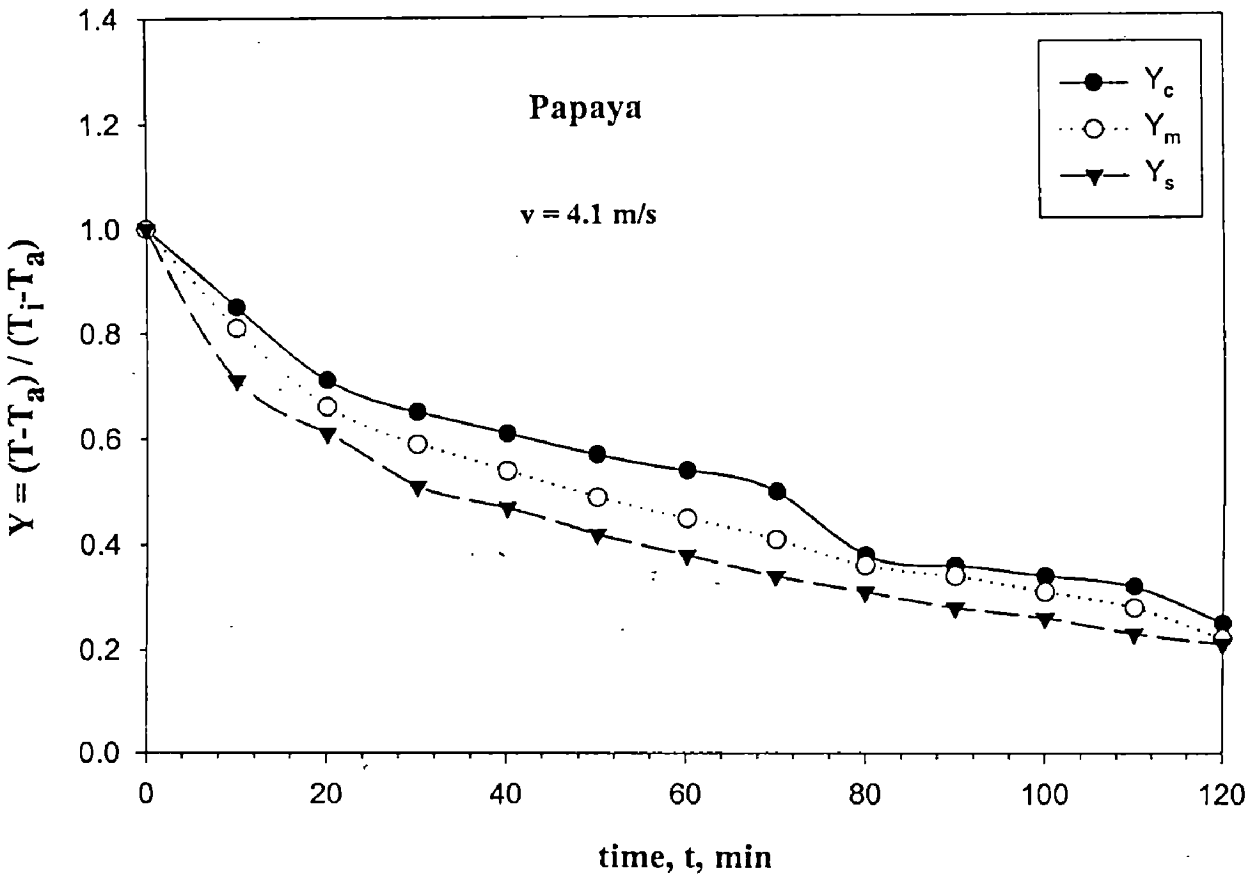

Fig. 6.9 Dimensionless Temperature – time graph for papayas at v = 4.1 m/s (k = 0.602W/m.k, α = 1.423*10^{-7} m^2/s, d = 0.137 m, T_i = 23 °C, Ta = 2.5 °C)

Fig. 6.10 is drawn taking time as abscissa and the dimensionless centre temperature of papayas as ordinate at different velocities of cold air ranging from 1.6 m/s to 4.1 m/s. It has been observed that the dimensionless centre temperature of papayas decreases exponentially with time. With the rise in air velocity the rate of fall of the dimensionless centre temperature was increased, this was because the cooling coefficient was increased with the increase in air velocity.

From the Fig. 6.10 cooling coefficient of papayas at all the flow velocities are found and from cooling coefficient, C, with dimensionless temperature for papayas, Y, and cooling time, t, are found intercept, j, by using equation 5.3, and reported in Table 6.5.

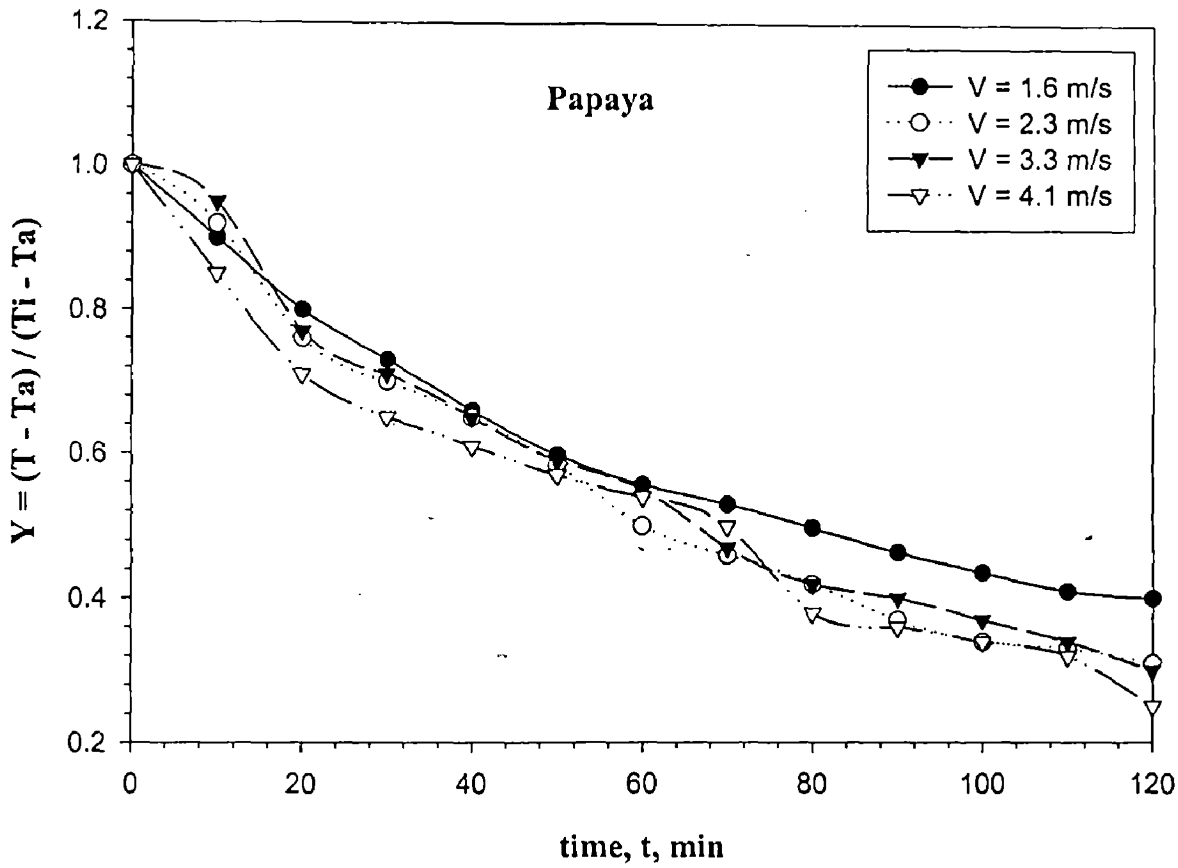

Fig. 6.10 variation in dimensionless centre temperature of papayas with time at different air velocity ranging from 1.6 m/s to 4.1 m/s

Table 6.5 Cooling coefficients of papayas at different air flow rate

Flow velocity, v, m/s	Cooling coefficient, C, $sec^{-1} x 10^{-4}$	Intercept, j
1.6	0.01	0.98
2.3	0.011	1.01
3.3	0.011	1.01
4.1	0.012	0.99

6.1.3 Cooling of grapes

Fig. 6.11 to Fig. 6.14 have been drawn taking time as abscissa and the centre and surface dimensionless temperature of grapes as ordinate at different velocities of cold air ranging from 1.6 m/s to 4.1 m/s. It has been observed that the centre and surface dimensionless temperature of grapes decreases exponentially with the time. The initial rate of fall in the centre and surface dimensionless temperature is high. With the increase in air velocity, the rate of fall in temperature was increased.

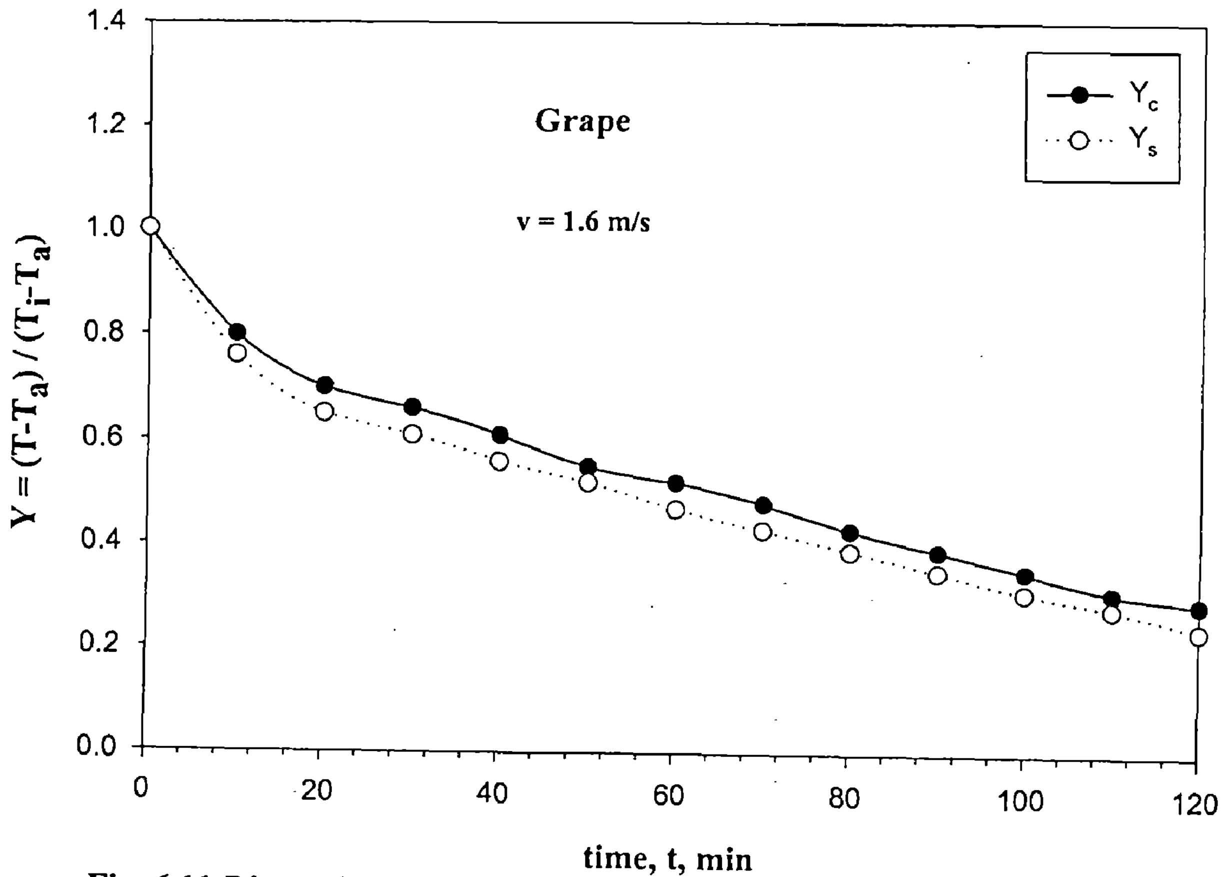

Fig. 6.11 Dimensionless Temperature – time graph for grapes at v = 1.6 m/s ($k = 0.548$ W/m.k, $\alpha = 1.38*10^{-7}$ m^2/s, $d = 0.021$m, $T_i = 22$ °C, $Ta = -7.1$ °C)

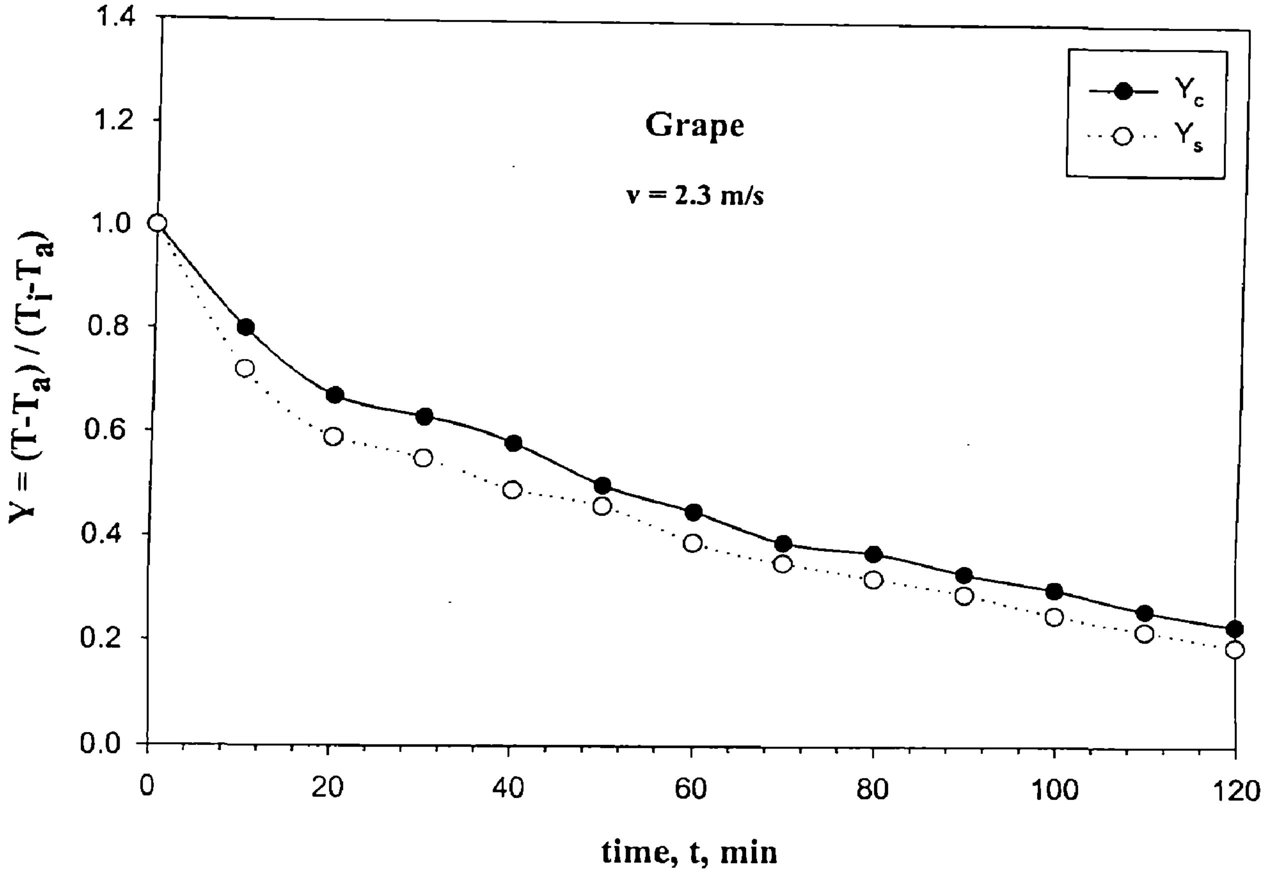

Fig. 6.12 Dimensionless Temperature – time graph for grapes at v = 2.3 m/s ($k = 0.548$ W/m.k, $\alpha = 1.38*10^{-7}$ m^2/s, $d = 0.02m$, $T_i = 22$ °C, $Ta = -2.6$ °C)

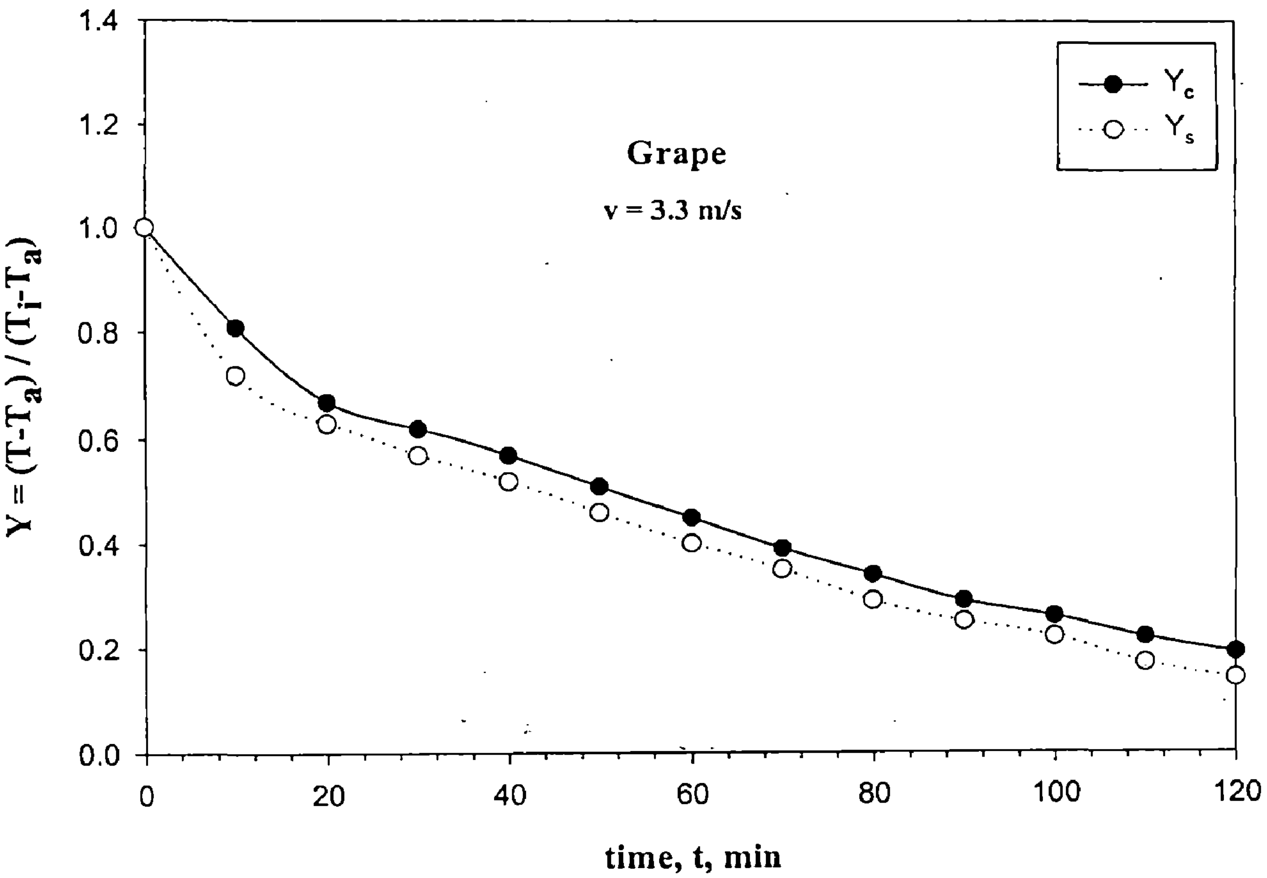

Fig. 6.13 Dimensionless Temperature – time graph for grapes at v = 3.3 m/s ($k = 0.548$ W/m.k, $\alpha = 1.38*10^{-7}$ m^2/s, $d = 0.021m$, $T_i = 21$ °C, $Ta = -0.4$ °C)

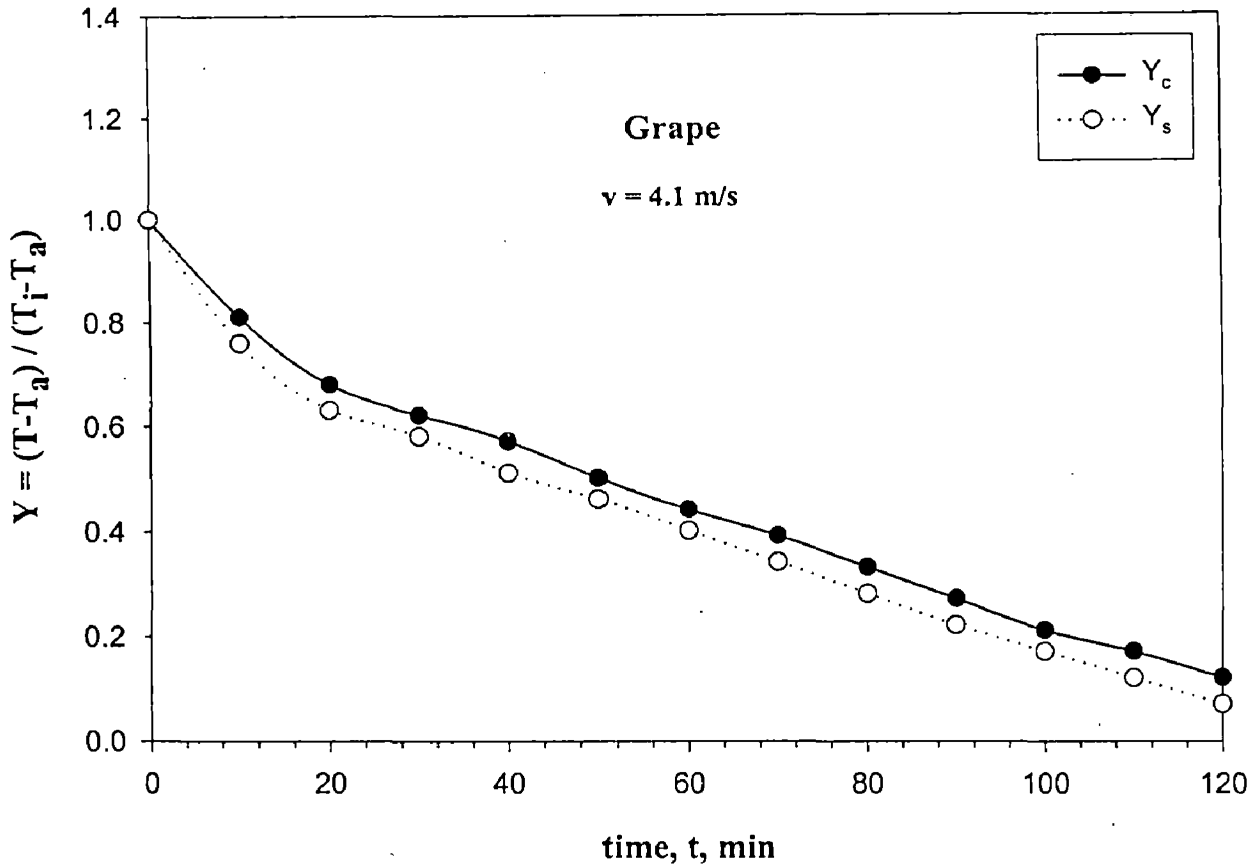

Fig. 6.14 Dimensionless Temperature – time graph for grapes at v= 4.1 m/s (k = 0.548 W/m.k, α = 1.38*10^{-7} m^2/s, d = 0.021m, T_i = 23 °C, Ta = 2.5 °C)

Fig. 6.15 is drawn taking time as abscissa and the dimensionless centre temperature of grapes as ordinate at different velocities of cold air ranging from 1.6 m/s to 4.1 m/s. It has been observed that the dimensionless centre temperature of grapes decreases exponentially with time. With the rise in air velocity the rate of fall of the dimensionless centre temperature was increased, this was because the cooling coefficient was increased with the increase in air velocity.

From the Fig. 6.15 cooling coefficients of grapes at all the flow velocities are found and from cooling coefficient, C, with dimensionless temperature for grapes, Y, and cooling time, t, are found intercept, j, by using equation 5.3, and reported in Table 6.6.

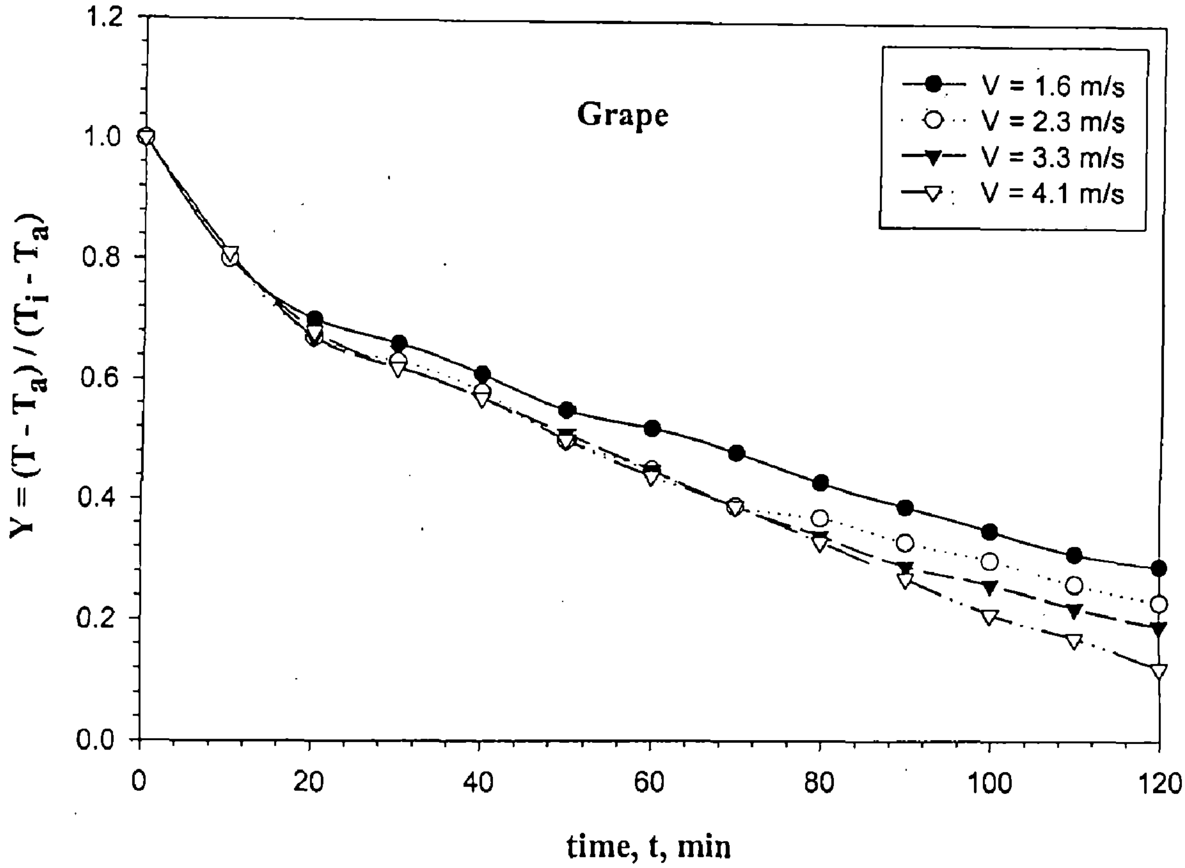

Fig. 6.15 variation in dimensionless centre temperature of grapes with time at different air velocity ranging from 1.6 m/s to 4.1 m/s

Table 6.6 Cooling coefficients of grapes at different air flow rate

Flow velocity, v, m/s	Cooling coefficient, C, $sec^{-1} x10^{-4}$	Intercept, j
1.6	0.012	0.986
2.3	0.0136	0.999
3.3	0.0141	1.0
4.1	0.0141	1.0

6.1.4 Heat transfer coefficient

The obtained cooling coefficient value (C) was substituted in the equation 5.12 and using equation 5.10 and 5.1, the value of heat transfer coefficient (h) at a particular air flow rate for apples, papayas and grapes are found. Similarly heat transfer coefficients for all other air flow rates are calculated and tabulated in the Tables 6.7, 6.8 and 6.9 for apples, papayas and grapes respectively.

Table 6.7 convective heat transfer coefficient and Biot number for apples cooled in different air flow rates

S.No.	Air flow velocity (v, m/s)	Apples		
		d (mm)	Bi	h ($W/m^2.K$)
1	1.6	62	1.64	28.1
2	2.3	62	1.76	30.1
3	3.3	65	2.21	36.1
4	4.1	65	2.21	36.1

Table 6.8 convective heat transfer coefficient and Biot number for papayas cooled in different air flow rates

S.No.	Air flow velocity (v, m/s)	Papayas		
		d (mm)	Bi	h ($W/m^2.K$)
1	1.6	137	5.98	52.5
2	2.3	137	6.54	57.5
3	3.3	137	6.54	57.5
4	4.1	137	7.2	63.3

Table 6.9 convective heat transfer coefficient and Biot number for grapes cooled in different air flow rates

S.No.	Air flow velocity (v, m/s)	Grapes		
		d (mm)	Bi	h ($W/m^2.K$)
1	1.6	21	0.168	8.8
2	2.3	20	0.172	9.4
3	3.3	21	0.197	10.3
4	4.1	21	0.197	10.3

From Table 6.7, Table 6.8 and Table 6.9 it is observed that Biot number values for papayas higher than apples and grapes at the same air flow rate, and Biot number values for grapes are less compared to that of apples at same air flow rate, this is because the convective heat transfer coefficient values and dimensions of grapes are less than that of apples and papayas, and the convective heat transfer coefficient values and dimension of apples are less than that of papayas.

Fig. 6.16, Fig. 6.17 and Fig. 6.18 shows the variation of convective heat transfer coefficient with the variation of air flow rate from 1.6 to 4.1 m/s for apples, papayas and grapes respectively. The cooling coefficients are found to vary with an increase in the flow rate, and are found to be highly sensitive to the size of the products and their surfaces exposed to the cooling medium. The convective heat-transfer coefficients for the individual products are found to be strongly dependent on the cooling coefficients. Increase in air flow velocity from 1.6 to 4.1 m/s during cooling increased both heat transfer coefficient and Biot number. This increased heat transfer indicates the faster extraction of heat from the products, which provides the cooling effect.

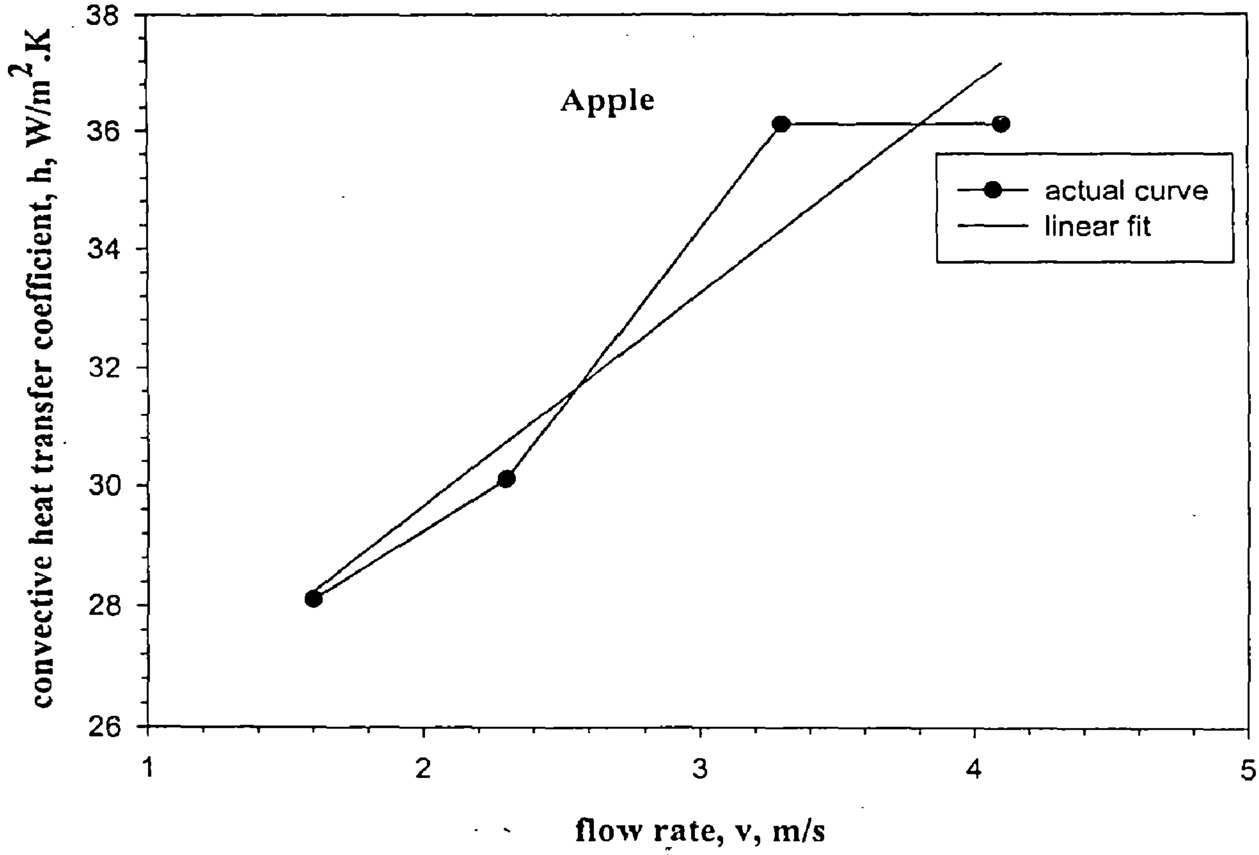

Fig.6.16 variation of convective heat transfer coefficient with cooling air velocity for Apples

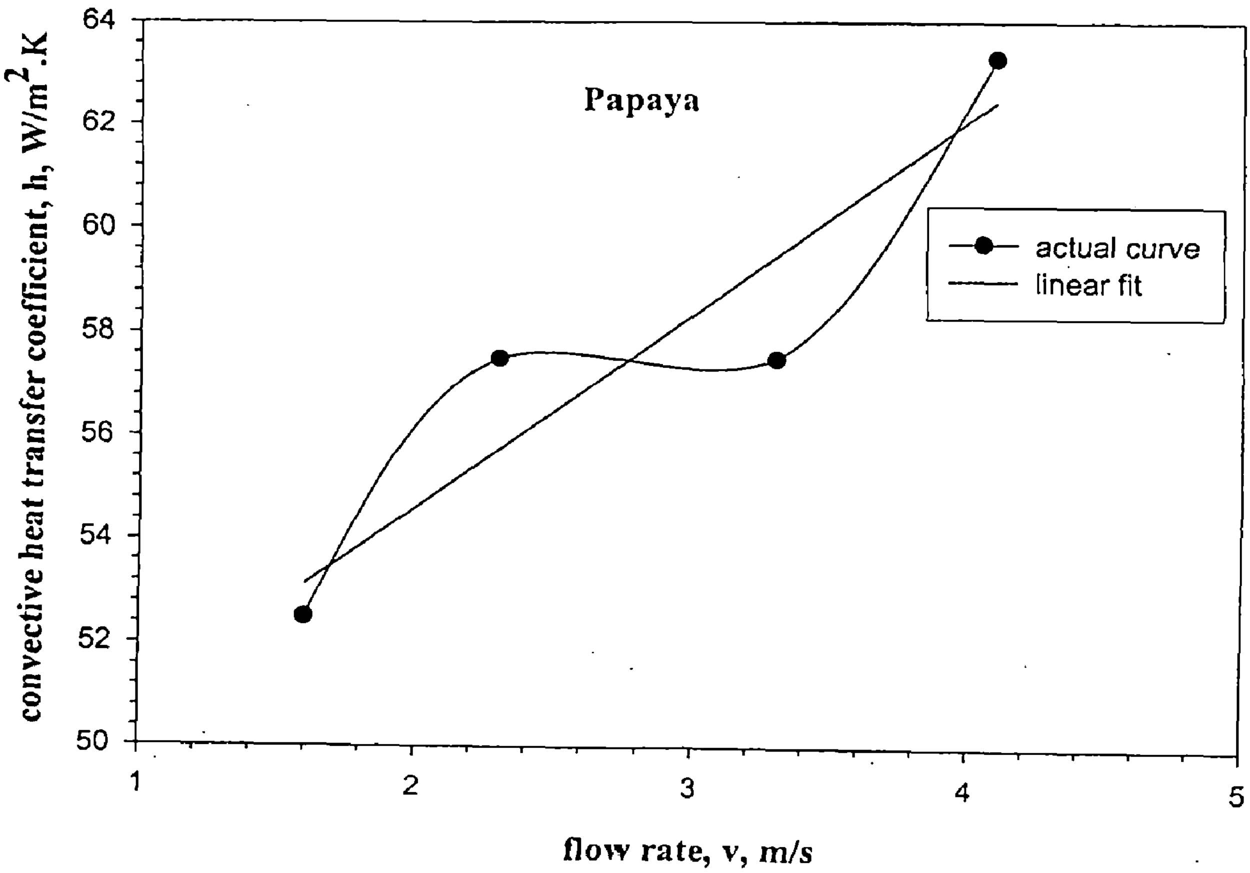

Fig.6.17 variation of convective heat transfer coefficient with cooling air velocity for Papayas

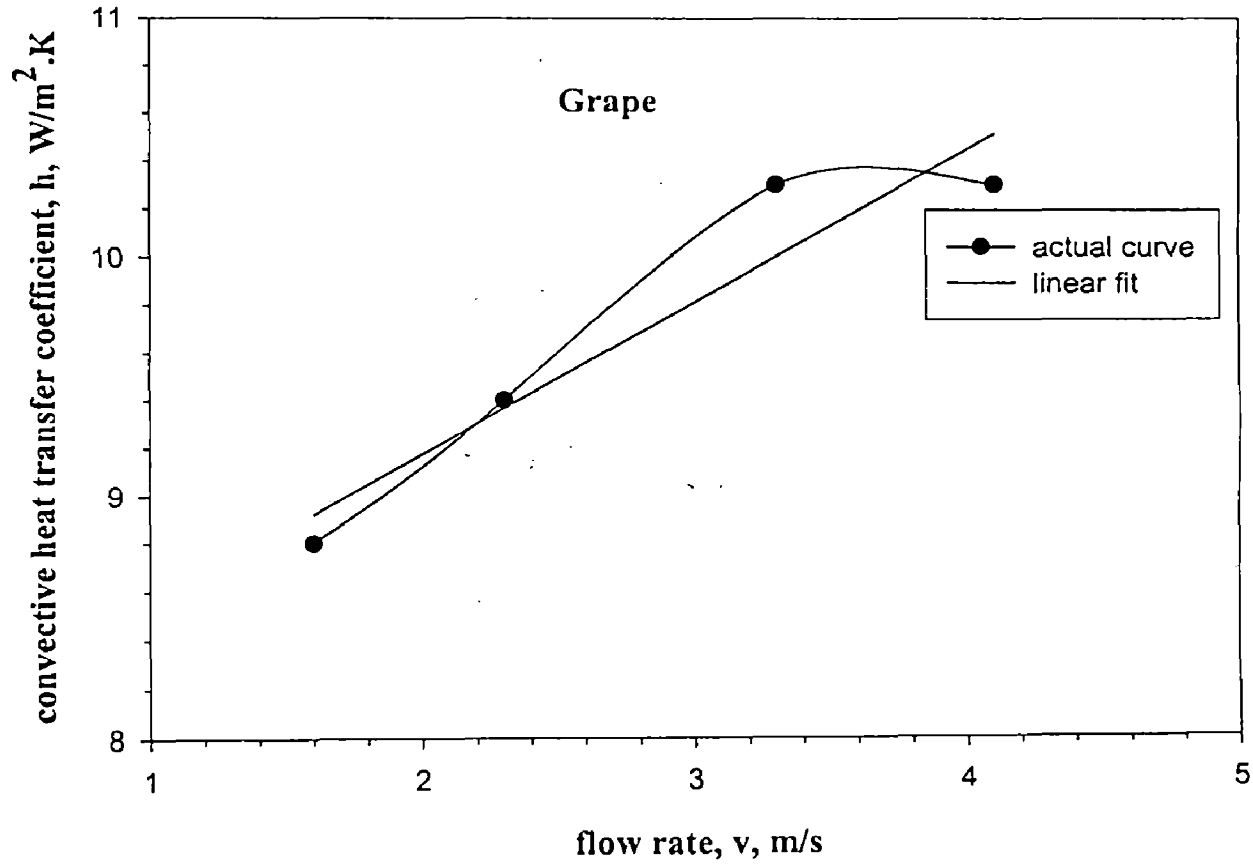

Fig.6.18 variation of convective heat transfer coefficient with cooling air velocity for Grapes

6.2 NUSSELT-REYNOLDS CORRELATIONS

Nusselt - Reynold correlation for foods are obtained in the form given by equation (5.17). For this, the Reynolds and Nusselt numbers are determined for each cooling curve using equations (5.15) and (5.16) in conjunction with the reported air temperature, fruits size, air flow rate. Results are tabulated in Tables (6.10) , (6.11) and (6.12) for apples, papayas and grapes respectively.

Table 6.10 Nusselt and Renolds numbers for apples at different air flow rates

S.No	v (m/s)	d (mm)	h (W/m^2-K)	Re	Nu
1	1.6	62	28.1	36364	72.6
2	2.3	62	30.1	52273	77.8
3	3.3	65	36.1	75000	97.8
4	4.1	65	36.1	93182	97.8

Table 6.11 Nusselt and Renolds numbers for papayas at different air flow rates

S.No	v (m/s)	d (mm)	h (W/m^2-K)	Re	Nu
1	1.6	137	52.5	36364	300
2	2.3	137	57.5	50735	328
3	3.3	137	57.5	72794	328
4	4.1	137	63.3	90441	361

Table 6.12 Nusselt and Renolds numbers for grapes at different air flow rates

S.No	v (m/s)	d (mm)	h (W/m^2-K)	Re	Nu
1	1.6	21	8.8	36364	7.7
2	2.3	20	9.4	52273	7.8
3	3.3	21	10.3	75000	9.0
4	4.1	21	10.3	90441	9.0

Regression analysis was performed on the collective log (Nu) v/s log (Re) for a particular food. This regression analysis yielded the constant, C, and the exponent, m, of equation 5.17.

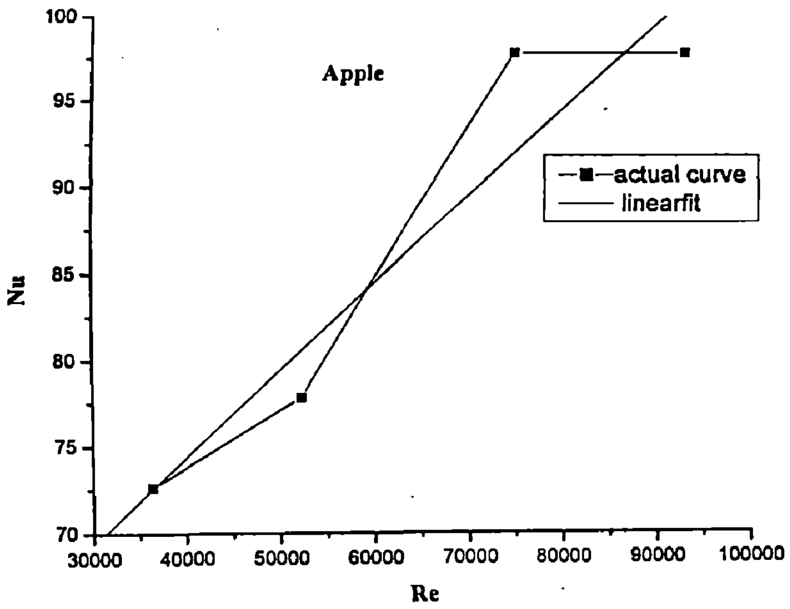

Fig. 6.19 Nusselt-Reynolds correlation for apples

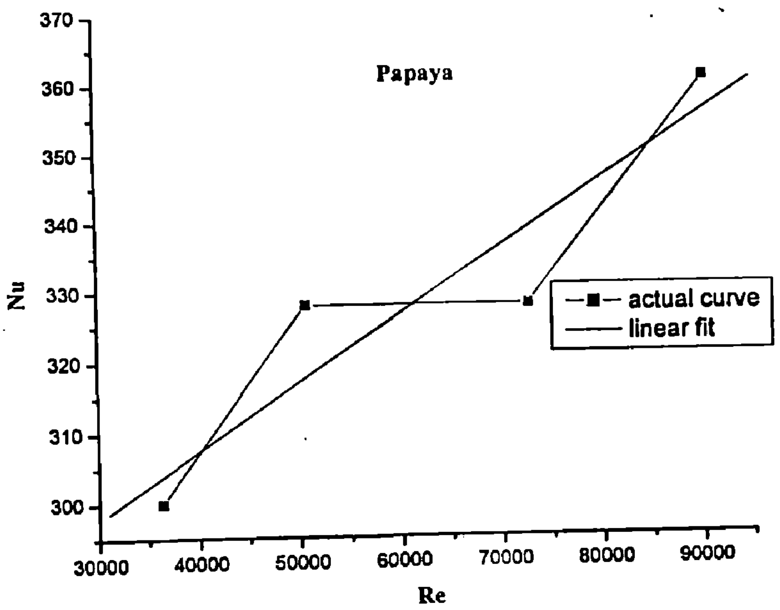

Fig. 6.20 Nusselt-Reynolds correlation for papayas

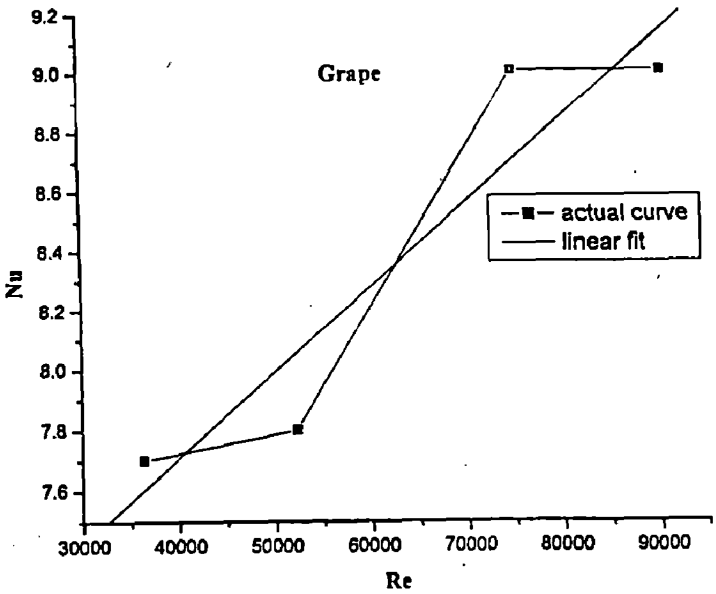

Fig. 6.21 Nusselt-Reynolds correlation for grapes

Figs. 6.19, 6.20 and 6.21 represent the regression analysis for apples, papayas and grapes respectively. From these graphical analyses correlations for apples, papayas and grapes were developed and represented in Table 6.13.

Table 6.13 Nusselt-Reynolds correlations for apples, papayas and grapes

Food product	Reynolds number range	Number of data points	Coefficient of determination, r^2	Nu-Re Correlation
Apples	36364<Re<93182	4	0.919	$Nu = 1.656Re^{0.36}$
Papayas	36364<Re<90441	4	0.854	$Nu = 48.594Re^{0.17}$
Grapes	36364<Re<90441	4	0.867	$Nu = 0.928Re^{0.2}$

6.3 ANALYSIS OF RESULTS

To verify the correlations, experiments were conducted at an air flow velocity of 3.3 m/s with three the food items, and temperature – time curves were drawn. Heat transfer coefficients, h, were found by substituting the air flow velocity in the correlations, which were found by experiments as shown in the Table 6.13. Partial differential equation 5.4, which represents the heat transfer through conduction in spherical products was solved using a MATLAB program. This solution yields temperature – time curve for a particular food item. The graphs obtained from experimental data and MATLAB program for apples, papayas and grapes were represented in Fig 6.22, Fig 6.23 and Fig 6.24 respectively.

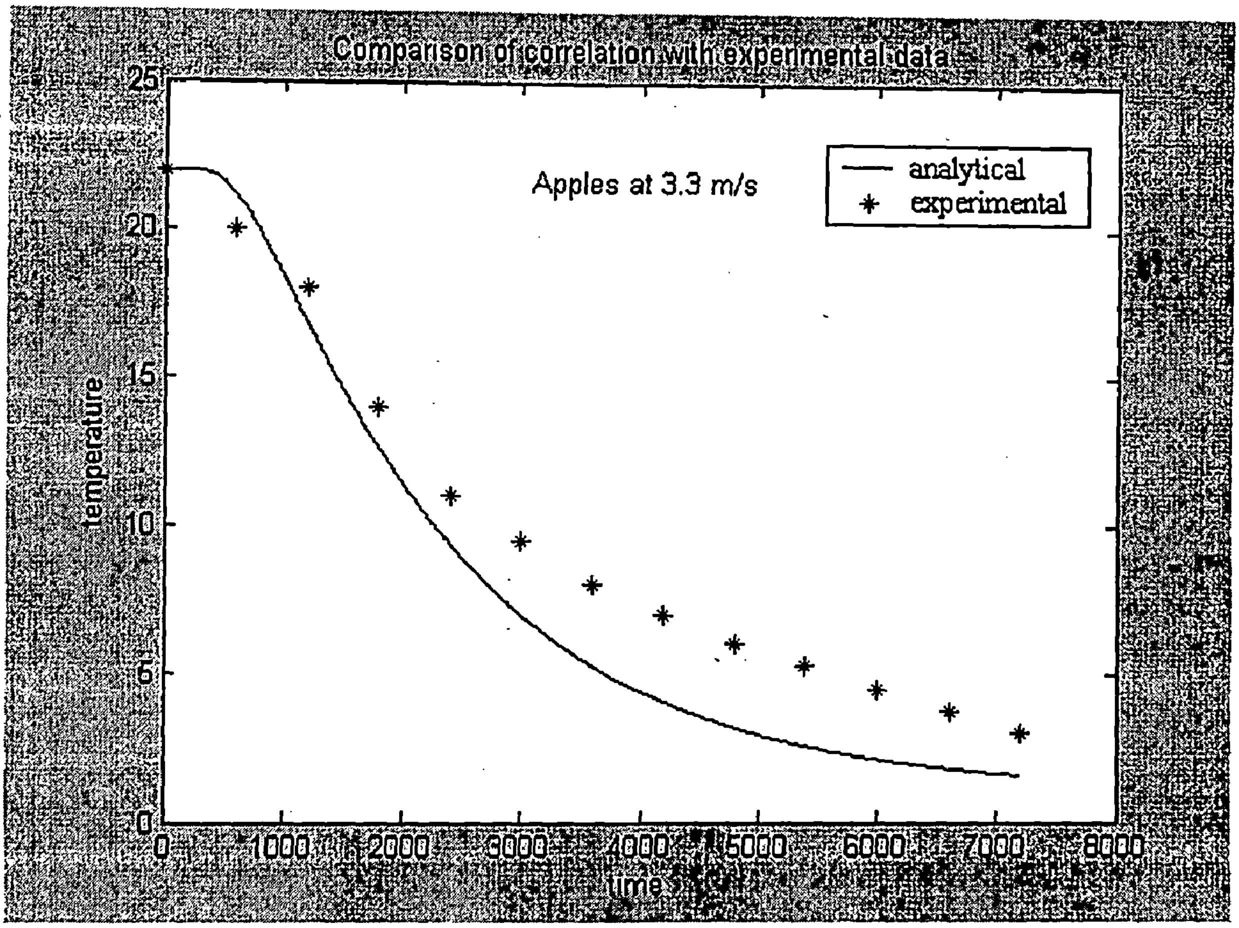

Fig 6.22 Correlation verification graph for Apples

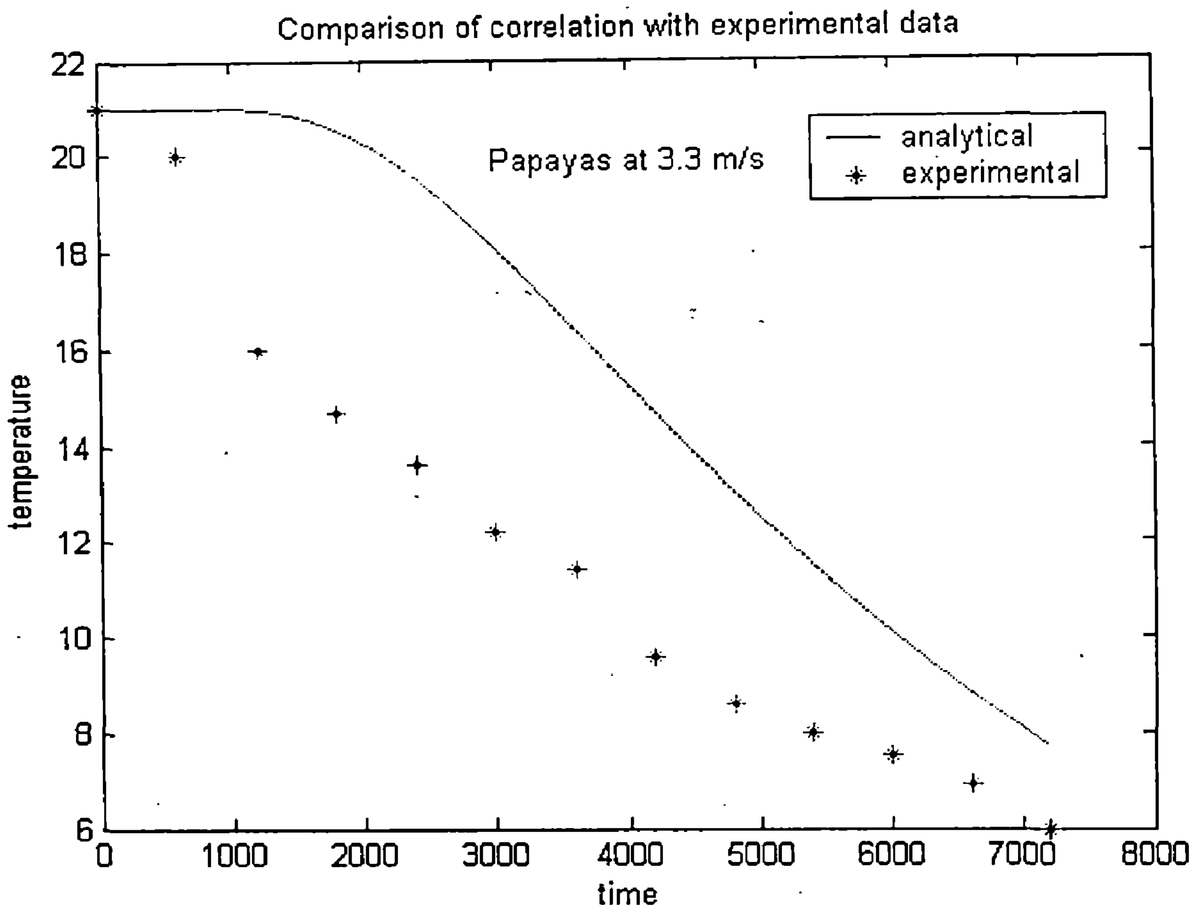

Fig 6.23 Correlation verification graph for Papayas

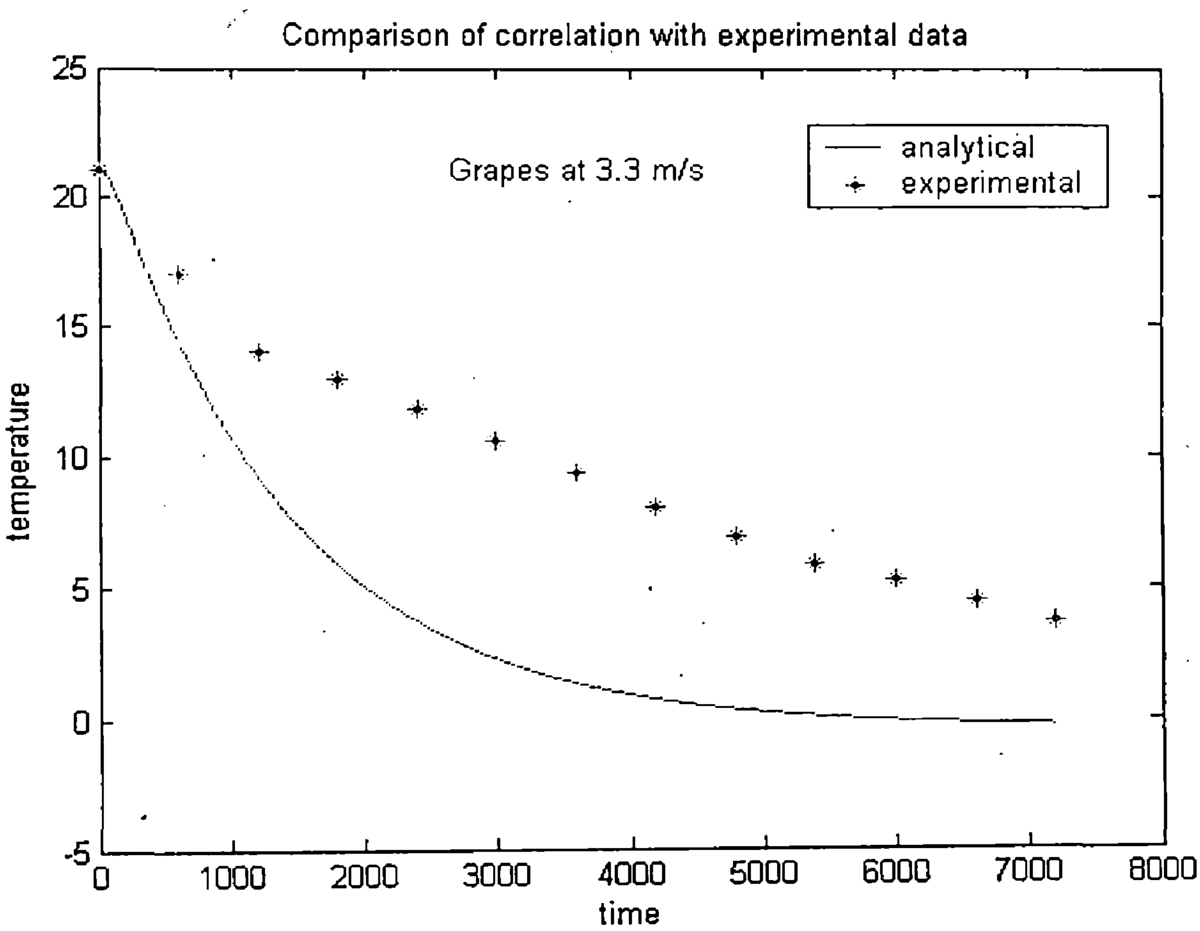

Fig 6.24 Correlation verification graph for Grapes

Fig 6.22, Fig 6.23 and Fig 6.24 shows that analytical data from correlations and data obtained from experiments are well in agreement, and these correlations can be used for practical purposes such as design of cold storages and precooling of food items. MATLAB program for above three Figs shown in Appendix-D.

CONCLUSIONS

This study was initiated to resolve deficiencies in transient cooling and find heat transfer coefficient for precooling of perishable food products. The conclusions drawn on the basis of above study are as follows:

1. A simplified model is developed for transient cooling of food produce inside rectangular boxes. It assumes pseudo-effective properties for the whole box.
2. Heat transfer coefficients have been found for apples, papayas and grapes during forced air precooling process at various air flow rates. It has been observed that heat transfer coefficients increases with increase in air flow rate.
3. Nu-Re correlations were found for apples, papayas and grapes in the Reynolds number range of 36000 to 94000.
4. The proposed model is very simple, efficient and of acceptable accuracy and can be easily used by a practical engineer and designer working in low temperature preservation food industry.
5. MATLAB program was written to verify the correlations derived from the experimental data.

The data and correlations resulting from this thesis could be used by designers of precooling systems for food products. This information will make possible a more accurate determination of cooling times and corresponding refrigeration loads. Similar correlations could also be developed in future with other perishable fruits like apricots, pears, bananas, mangoes etc.

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DETAIL OF PRECOOLING OF FRUITS AND VEGETABLES

Table A.1 COOLING & STORAGE REQUIREMENT FOR FRESH FRUITS, VEGETABLES & FLOWERS

Common Name	Optional Storage, Temp. °C	Optional Relative Humidity , %	Approx Storage Life	Highest Freeaing Temp, °C	Ethylene Productio n rate	Ethylene Sensitivity	Respiration rate
FRESH FRUITS							
Apples	0 to 3	90 to 95	3 to 6 months	-1.5	Very high	High	Low
Apricots	-0.5 to 0	90 to 95	1 to 3 weeks	-1.1	Moderate	Moderate	Low
Bananas	13 to 15	90 to 95	1 to 4 weeks	-0.8	Moderate	High	Low
Berries							
Blackberries	-0.5 to 0	90 to 95	3 to 5 days	-0.8	Low	Low	Moderate
Blueberries	-0.5 to 0	90 to 95	2 weeks	-1.3	Low	Low	Low
Cranberries	2 to 5	90 to 95	8 to 16 weeks	-0.9	Low	Low	Low
Dewberries	-0.5 to 0	90 to 95	2 to 3 days	-1.3	Low	Low	
Elderberries	-0.5 to 0	90 to 95	5 to 14 days	-0.9	Low	Low	
Gooseberries	-0.5 to 0	90 to 95	3 to 4 weeks	-1.1	Low	Low	
Loganberries	-0.5 to 0	90 to 95	2 to 3 days	-1.3	Low	Low	
Raspberries	-0.5 to 0	90 to 95	3 to 6 days	-0.9	Low	Low	Moderate
Strawberries	0	90 to 95	7 to 10 days	-0.8	Low	Low	Low
Melons							
Casaba	7 to 10	85 to 90	3 to 4 weeks	-1.0	Low	Low	
Crenshaw	7 to 10	85 to 90	2 to 3 weeks	-1.1	Moderate	High	
Honeydew	5 to 10	85 to 90	3 to 4 weeks	-1.1	Moderate	High	Low
Persian	7 to 10	85 to 90	2 to 3 weeks	-0.8	Moderate	High	
Cherries							

Sour	0	90 to 95	3 to 7 days	-1.7			Low
Sweet	-1 to 0	90 to 95	2 to 3 weeks	-2.1			Low
Coconut	0 to 2	85 to 90	1 to 2 months	-0.9			
Currants	-0.5 to 0	90 to 95	1 to 4 weeks	-1.0	Low	Low	
Dates, cured	-18 to 0	75	6 to 12 months	-15.7	Very Low	Low	Low
Figs, Fresh	-0.5 to 0	85 to 90	7 to 10 days	-2.4	Moderate	Low	Low
Grapefruit	14 to 15	85 to 90	6 to 8 weeks	-1.1	Very Low	Moderate	Low
Grapes							
American Gra.	-1 to -0.5	90 to 95	1 to 6 months	-1.4	Very Low	Low	Low
Table Grape	-0.5 to 0	90 to 95	2 to 8 weeks	-2.7	Very Low	Low	Low
Guavas	5 to 10	90	2 to 3 weeks		Low	Moderate	Moderate
Kiwifruits	0	90 to 95	3 to 5 months	-0.9	Low	High	Low
Lemons	10 to 13	85 to 90	1 to 6 months	-1.4			Low
Limes	9 to 10	85 to 90	6 to 8 weeks	-1.6			Low
Lychees	1 to 2	90 to 95	3 to 5 weeks		Moderate	Moderate	Low
Mangoes	13	85 to 90	2 to 3 weeks	-1.4	Moderate	Moderate	Moderate
Nectarines	-0.5 to 0	90 to 95	2 to 4 weeks	-0.9	Moderate	Moderate	Low
Olives, Fresh	5 to 10	85 to 90	4 to 6 weeks	-1.4	Low	Moderate	Low
Oranges							
CA, Az, dry ar.	3 to 9	85 to 90	3 to 8 weeks	-0.8	Very Low	Moderate	Low
FL,Humid area	0 to 2	85 to 90	8 to 12 weeks	-0.8	Very Low	Moderate	Low
Papayas	7 to 13	85 to 90	1 to 3 weeks	-0.9			Low
Peaches	-0.5 to 0	90 to 95	2 to 4 weeks	-0.9	High	Moderate	Low
Pears	-1.5to-0.5	90 to 95	2 to 7 months	-1.7	High	High	Low
Pineapples	7 to 13	85 to 90	2 to 4 weeks	-1.1	Low	Low	Low
Plums&Prunes	0	90 to 95	2 to 5 weeks	-0.8	Moderate	Moderate	Low
Pomegranates	-0.5 to 0	90 to 95	2 to 3 months	-3.0			Low
Passion fruit	10	85 to 90	3 to 4 weeks		Very High	Moderate	Very High
Sapotes	13 to 15	85 to 90	2 to 3 weeks	-2.3			
Tangerines	4 to 7	90 to 95	2 to 4 weeks	-1.1	Very Low	Moderate	Low
Watermelons	10 to 15	90	2 to 3 weeks	-0.4	Very Low	High	Low

Common Name	Optional Storage, Temp. °C	Optional Relative Humidity, %	Approx Storage Life	Method of Holding	Highest Freezing Temp, °C
FLOWERS AND VEGETABLES					
Cut Flowers					
Calla Lilly	4.4	90 to 95	1 week	Dry pack	
Camellia	7	90 to 95	3 to 6 days	Dry pack	-0.8
Carnation	-0.6 to 0	90 to 95	3 to 4 weeks	Dry pack	-0.7
Chrysanthemum	-0.6 to 0	90 to 95	3 to 4 weeks	Dry pack	-0.8
Daffodil (Narcissus)	0 to 0.6	90 to 95	1 to 3 weeks	Dry pack	-0.1
Dahila	4.4	90 to 95	3 to 5 days	Dry pack	
Gardenia	0 to 1	90 to 95	2 weeks	Dry pack	-0.6
Gladiolus	2 to 5.5	90 to 95	1 week	Dry pack	-0.3
Ins, tight buds	-0.6 to 0	90 to 95	2 weeks	Dry pack	-0.8
Lily, Easter	0 to 1.7	90 to 95	2 to 3 weeks	Dry pack	-0.5
Lily of the valley	-0.6 to 0	90 to 95	2 to 3 weeks	Dry pack	
Orchid	7 to 13	90 to 95	2 weeks	Waters	-0.3
Peony, tight buds	0 to 1.7	90 to 95	4 to 6 weeks	Dry pack	-1.1
Rose, tight buds	0	90 to 95	2 weeks	Dry pack	-0.4
Snapdragon	4.4 to 5.5	90 to 95	1 to 2 weeks	Dry pack	-0.9
Sweet Peas	-0.6 to 0	90 to 95	2 weeks	Dry pack	-0.9
Tulips	-0.6 to 0	90 to 95	2 to 3 weeks	Dry pack	
Greens					
Asparagus(Plumosus)	1.7 to 4	90 to 95	2 to 3 weeks	Polylined Ca.	-3.3
Fern,dagger and wood	-1 to 0	90 to 95	2 to 3 months	Dry pack	-1.7
Fern, leatherleaf	1 to 4	90 to 95	1 to 2 months	Dry pack	
Holly	0	90 to 95	4 to 5 weeks	Dry pack	-2.8
Huckleberry	0	90 to 95	1 to 4 weeks	Dry pack	-2.9

Laurel	0	90 to 95	2 to 4 weeks	Dry pack	-2.4
Magnolia	1.7 to 4.4	90 to 95	2 to 4 weeks	Dry pack	-2.8
Rhododendron	0	90 to 95	2 to 4 weeks	Dry pack	-2.4
Salal	0	90 to 95	2 to 3 weeks	Dry pack	-2.9
Bulbs					
Amaryllis	3 to 7	70 to 75	5 months	Dry	-0.7
Caladium	21	70 to 75	2 to 4 months		-1.3
Crocus	9 to 17	70 to 75	2 to 3 months		-1.3
Dahlia	4 to 9	70 to 75	5 months	Dry	-1.8
Gladiolus	7 to 10	70 to 75	5 to 8 months	Dry	-2.1
Hyacinth	17 to 20		2 to 5 months		-1.5
Iris, Dutch, Spanish	20 to 25	70 to 75	4 months	Dry	-1.5
Gloriosa	10 to 17	70 to 75	3 to 4 months	Poly.	
Candidum	-0.6 to 0	70 to 75	1 to 6 months	Poly. &Peat	
Croft	-0.6 to 0	70 to 75	1 to 6 months	Poly. &Peat	
Longiflorum	-0.6 to 0	70 to 75	1 to 10 months	Poly. &Peat	-1.7
Speciosum	-0.6 to 0	70 to 75	1 to 6 months	Poly. & Peat	
Peony	0.6 to 1.7	70 to 75	5 months	Dry	
Tuberose	4.4 to 7	70 to 75	4 to 12 months	Dry	
Tulip	17	70 to 75	2 to 6 months	Dry	-2.4
Nursery Stocks					
Trees & Shrubs	0 to 2	95	4 to 5 months		
Rose Bushes	0.5 to 2	85 to 95	4 to 5 months	B.r. with p.	
Strawberry Plants	-1 to 0	80 to 85	8 to 10 months	B.r. with p.	-1.2
Rooted cuttings	-0.5 to 2	85 to 95		Polywrap	
Herbaceous Perennials	-2.8 to -2.2	80 to 85	4 to 8 months		
	-0.6 to 1.7	80 to 85	3 to 7 months		
Christmas Trees	-5.5 to 0	80 to 85	6 to 7 weeks		

DATA OBTAINED FROM EXPERIMENTS

Table B.1 Variation of temperature of apples with time at different air flow rates

Time, t,min.	Measured temperature of apples, T, °C							
	V = 1.6 m/s				V = 2.3 m/s			
	T_c	T_m	T_s	T_a	T_c	T_m	T_s	T_a
0	22.0	22.0	22.0	24.0	21.0	21.0	21.0	22.0
10	20.0	19.0	16.0	12.0	19.0	18.0	16.0	11.0
20	16.0	14.0	11.0	6.0	16.0	14.0	11.0	7.0
30	13.0	11.0	8.5	4.0	13.0	11.0	9.0	5.0
40	11.0	9.0	6.0	2.0	10.0	9.0	7.0	3.0
50	9.0	7.0	4.5	1.0	9.0	7.0	5.0	2.0
60	7.5	5.5	2.5	0.0	7.5	6.0	4.0	1.0
70	6.0	4.0	1.0	-1.0	6.5	5.0	3.0	0.0
80	4.8	2.8	0.0	-2.0	5.5	4.3	2.3	-0.8
90	3.5	1.5	-1.0	-2.8	4.8	3.5	1.5	-1.5
100	2.5	1.0	-1.8	-3.5	4.0	2.8	0.8	-2.0
110	1.5	0.0	-2.3	-4.0	3.2	2.3	0.0	-2.2
120	1.0	-0.5	-2.4	-4.5	2.5	1.8	-0.5	-2.5

Time, t,min.	Measured temperature of apples, T, °C							
	V = 3.3 m/s				V = 4.1 m/s			
	T_c	T_m	T_s	T_a	T_c	T_m	T_s	T_a
0	22.0	22.0	22.0	23.0	21.0	21.0	21.0	22.0
10	20.0	19.0	17.0	15.0	19.0	17.0	15.0	13.0
20	18.0	15.0	13.0	11.0	16.0	13.0	11.0	10.0
30	14.0	12.0	10.0	9.0	13.0	11.0	9.0	8.0
40	11.0	10.0	8.0	7.0	11.0	9.5	7.8	6.5
50	9.5	8.5	7.0	5.5	9.5	8.3	6.5	5.3
60	8.0	7.0	6.0	4.0	8.0	7.3	5.8	4.3
70	7.0	6.0	5.0	3.0	7.0	6.5	5.0	3.5
80	6.0	5.0	4.0	2.0	6.3	5.8	4.3	2.5
90	5.3	4.3	3.0	1.3	5.5	5.0	3.5	1.8
100	4.5	3.5	2.3	0.5	5.0	4.3	3.0	1.0
110	3.8	2.8	1.5	-0.3	4.5	3.6	2.5	0.5
120	3.0	2.0	1.0	-1.0	4.0	3.0	2.0	0.0

Table B.2 Variation of temperature of papayas with time at different air flow rates

Time, t,min.	Measured temperature of papayas, T, °C							
	V = 1.6 m/s				V = 2.3 m/s			
	T_c	T_m	T_s	T_a	T_c	T_m	T_s	T_a
0	22.0	22.0	22.0	24.0	22.0	22.0	22.0	23.2
10	19.0	17.0	16.0	11.0	20.0	18.0	16.0	12.5
20	16.0	15.0	14.0	1.9	16.0	15.0	14.0	7.3
30	14.0	13.0	12.0	-1.0	14.5	14.0	12.5	6.0
40	12.0	11.5	10.5	-2.7	13.5	12.4	11.3	4.9
50	10.3	10.3	9.5	-3.7	11.8	11.2	10.2	3.0
60	9.1	9.1	8.5	-4.5	9.6	9.4	9.2	2.0
70	8.3	8.2	7.5	-5.3	8.6	8.4	8.3	1.3
80	7.4	7.3	6.5	-6.0	7.8	7.6	7.5	0.5
90	6.4	6.4	5.0	-6.5	6.6	6.2	5.8	-0.5
100	5.6	5.6	4.0	-6.8	5.8	5.6	4.8	-1.5
110	4.8	4.5	3.0	-7.0	5.4	4.6	3.8	-2.0
120	4.5	3.5	2.0	-7.1	5.0	4.0	3.0	-2.6

Time, t,min.	Measured temperature of papayas, T, °C							
	V = 3.3 m/s				V = 4.1 m/s			
	T_c	T_m	T_s	T_a	T_c	T_m	T_s	T_a
0	21.0	21.0	21.0	22.0	23.0	23.0	23.0	25.3
10	20.0	17.0	16.0	12.0	20.0	19.0	17.0	17.0
20	16.0	14.0	13.0	8.0	17.0	16.0	15.0	13.0
30	14.7	13.0	12.0	6.5	15.8	14.5	13.0	11.0
40	13.6	12.1	11.0	5.2	15.0	13.5	12.1	9.0
50	12.2	11.4	10.0	4.0	14.2	12.6	11.2	7.5
60	11.4	10.4	9.1	3.0	13.5	11.7	10.3	6.0
70	9.6	9.0	8.2	2.2	12.8	10.9	9.5	4.7
80	8.6	8.0	7.3	1.5	10.4	9.8	8.8	3.5
90	8.0	7.2	6.5	1.0	10.0	9.4	8.2	3.1
100	7.5	6.4	5.7	0.5	9.5	8.8	7.8	2.8
110	6.9	5.7	5.0	0.1	9.0	8.3	7.3	2.6
120	6.0	5.0	4.0	-0.4	7.7	7.0	6.8	2.5

Table B.3 Variation of temperature of grapes with time at different air flow rates

Time, t,min.	Measured temperature of grapes, T, °C					
	V = 1.6 m/s			V = 2.3 m/s		
	T_c	T_s	T_a	T_c	T_s	T_a
0	22.0	22.0	24.0	22.0	22.0	23.2
10	16.0	15.0	11.0	17.0	15.0	12.5
20	13.2	11.9	1.9	14.0	11.9	7.3
30	12.0	10.6	-1.0	12.8	10.8	6.0
40	10.7	9.3	-2.7	11.6	9.5	4.9
50	9.0	7.9	-3.7	9.8	8.7	3.0
60	8.0	6.7	-4.5	8.5	6.9	2.0
70	6.8	5.4	-5.3	7.1	6.0	1.3
80	5.4	4.2	-6.0	6.5	5.2	0.5
90	4.3	3.0	-6.5	5.6	4.4	-0.5
100	3.0	2.0	-6.8	4.7	3.6	-1.5
110	2.0	1.0	-7.0	3.8	2.8	-2.0
120	1.2	0.0	-7.1	3.0	2.0	-2.6

Time, t,min.	Measured temperature of grapes, T, °C					
	V = 3.3 m/s			V = 4.1 m/s		
	T_c	T_s	T_a	T_c	T_s	T_a
0	21.0	21.0	22.0	23.0	23.0	25.3
10	17.0	15.0	12.0	19.0	18.0	17.0
20	14.0	13.0	8.0	16.4	15.5	13.0
30	12.9	11.8	6.5	15.2	14.3	11.0
40	11.8	10.7	5.2	14.1	13.0	9.0
50	10.6	9.5	4.0	12.8	11.9	7.5
60	9.3	8.2	3.0	11.6	10.7	6.0
70	8.0	7.0	2.2	10.5	9.4	4.7
80	6.9	5.9	1.5	9.2	8.2	3.5
90	5.8	5.0	1.0	8.0	7.0	3.1
100	5.2	4.2	0.5	6.8	5.9	2.8
110	4.4	3.3	0.1	5.9	4.9	2.6
120	3.6	2.5	-0.4	5.0	4.0	2.5

Table B.4 Variation of dimensionless temperature of apples with time at different air flow rates

Time, t,min.	Measured dimensionless temperature of apples					
	V = 1.6 m/s			V = 2.3 m/s		
	Y_c	Y_m	Y_s	Y_c	Y_m	Y_s
0	1.00	1.00	1.00	1.00	1.00	1.00
10	0.93	0.89	0.77	0.92	0.87	0.79
20	0.77	0.70	0.59	0.79	0.70	0.57
30	0.66	0.59	0.49	0.66	0.57	0.49
40	0.59	0.51	0.40	0.58	0.49	0.40
50	0.51	0.43	0.34	0.49	0.40	0.32
60	0.45	0.38	0.26	0.43	0.36	0.28
70	0.40	0.32	0.21	0.38	0.32	0.23
80	0.35	0.28	0.17	0.34	0.29	0.20
90	0.30	0.23	0.13	0.31	0.25	0.17
100	0.26	0.21	0.10	0.28	0.23	0.14
110	0.23	0.17	0.08	0.24	0.20	0.11
120	0.21	0.15	0.079	0.21	0.18	0.09

Time, t,min.	Measured dimensionless temperature of apples					
	V = 3.3 m/s			V = 4.1 m/s		
	Y_c	Y_m	Y_s	Y_c	Y_m	Y_s
0	1.00	1.00	1.00	1.00	1.00	1.00
10	0.91	0.87	0.78	0.91	0.81	0.71
20	0.83	0.70	0.61	0.76	0.62	0.52
30	0.65	0.57	0.48	0.62	0.52	0.43
40	0.52	0.48	0.39	0.52	0.45	0.37
50	0.46	0.41	0.35	0.45	0.40	0.31
60	0.39	0.35	0.30	0.38	0.35	0.28
70	0.35	0.30	0.26	0.33	0.31	0.24
80	0.30	0.26	0.22	0.30	0.28	0.21
90	0.27	0.23	0.17	0.26	0.24	0.17
100	0.24	0.20	0.14	0.24	0.21	0.14
110	0.21	0.17	0.11	0.21	0.17	0.12
120	0.17	0.13	0.09	0.19	0.14	0.10

Table B.5 Variation of dimensionless temperature of papayas with time at different air flow rates

Time, t,min.	Measured dimensionless temperature of papayas					
	V = 1.6 m/s			V = 2.3 m/s		
	Y_c	Y_m	Y_s	Y_c	Y_m	Y_s
0	1.00	1.00	1.00	1.00	1.00	1.00
10	0.90	0.83	0.79	0.92	0.84	0.76
20	0.80	0.76	0.73	0.76	0.72	0.68
30	0.73	0.69	0.66	0.70	0.68	0.61
40	0.66	0.64	0.61	0.65	0.61	0.57
50	0.60	0.60	0.57	0.60	0.56	0.52
60	0.56	0.56	0.54	0.50	0.49	0.48
70	0.53	0.53	0.50	0.46	0.45	0.44
80	0.50	0.50	0.47	0.42	0.42	0.41
90	0.46	0.46	0.42	0.37	0.36	0.34
100	0.44	0.44	0.38	0.34	0.33	0.30
110	0.41	0.40	0.35	0.33	0.29	0.26
120	0.40	0.36	0.31	0.31	0.27	0.23

Time, t,min.	Measured dimensionless temperature of papayas					
	V = 3.3 m/s			V = 4.1 m/s		
	Y_c	Y_m	Y_s	Y_c	Y_m	Y_s
0	1.00	1.00	1.00	1.00	1.00	1.00
10	0.95	0.81	0.77	0.85	0.81	0.71
20	0.77	0.67	0.63	0.71	0.66	0.61
30	0.71	0.63	0.58	0.65	0.59	0.51
40	0.65	0.58	0.53	0.61	0.54	0.47
50	0.59	0.55	0.49	0.57	0.49	0.42
60	0.55	0.51	0.44	0.54	0.45	0.38
70	0.47	0.44	0.40	0.50	0.41	0.34
80	0.42	0.39	0.36	0.38	0.36	0.31
90	0.40	0.36	0.32	0.36	0.34	0.28
100	0.37	0.32	0.29	0.34	0.31	0.26
110	0.34	0.29	0.25	0.32	0.28	0.23
120	0.30	0.25	0.21	0.25	0.22	0.21

Table B.6 Variation of dimensionless temperature of grapes with time at different air flow rates

Time, t,min.	Measured dimensionless temperature of grapes			
	V = 1.6 m/s		V = 2.3 m/s	
	Y_c	Y_s	Y_c	Y_s
0	1.00	1.00	1.00	1.00
10	0.80	0.76	0.80	0.72
20	0.70	0.65	0.67	0.59
30	0.66	0.61	0.63	0.55
40	0.61	0.56	0.58	0.49
50	0.55	0.52	0.50	0.46
60	0.52	0.47	0.45	0.39
70	0.48	0.43	0.39	0.35
80	0.43	0.39	0.37	0.32
90	0.39	0.35	0.33	0.29
100	0.35	0.31	0.30	0.25
110	0.31	0.28	0.26	0.22
120	0.29	0.24	0.23	0.19

Time, t,min.	Measured dimensionless temperature of grapes			
	V = 3.3 m/s		V = 4.1 m/s	
	Y_c	Y_s	Y_c	Y_s
0	1.00	1.00	1.00	1.00
10	0.81	0.72	0.81	0.76
20	0.67	0.63	0.68	0.63
30	0.62	0.57	0.62	0.58
40	0.57	0.52	0.57	0.51
50	0.51	0.46	0.50	0.46
60	0.45	0.40	0.44	0.40
70	0.39	0.35	0.39	0.34
80	0.34	0.29	0.33	0.28
90	0.29	0.25	0.27	0.22
100	0.26	0.22	0.21	0.17
110	0.22	0.17	0.17	0.12
120	0.19	0.14	0.12	0.07

UNCERTAINTY ANALYSIS

C.1 Procedure for Uncertainty Analysis

There are always chances of errors in all experimental measurements regardless of the care taken. It is, therefore, necessary to analyze the system to determine the maximum possible error and hence the validity of experimental measurements. The error in measurement is usually defined as the difference between its true value and the measured value.

A precise method of estimating uncertainty in experimental results has been suggested by Kline and Mcclintock. The method is based on a careful specification of the uncertainties in the various primary experimental measurements.

If a parameter is calculated using certain measured quantities as:

$$y = y[x_1, x_2, x_3 ....] \qquad \text{C.1}$$

Then uncertainty in measurement of 'y' is given by:

$$\frac{\delta y}{y} = \left[\left(\frac{\delta y}{\delta x_1}\cdot\delta x_1\right)^2 + \left(\frac{\delta y}{\delta x_2}\cdot\delta x_2\right)^2 + \left(\frac{\delta y}{\delta x_3}\cdot\delta x_3\right)^2 + ...\right]^{\frac{1}{2}} \qquad \text{C.2}$$

Where $\delta x_1, \delta x_2, \delta x_3......$ are uncertainties in measurement of $x_1, x_2, x_3......$

In the present investigation the important parameters are

1. heat transfer coefficient, h

$$h = \frac{B_i \times k}{R} \qquad \text{C.3}$$

2. Reynolds number, Re

$$Re = \frac{vD}{\upsilon} \qquad \text{C.4}$$

C.2 Calculation for Uncertainty

The uncertainty for individual measurements can be given as follows, if the temperature is measured by T-type thermocouples, air flow rate is measured by anemometer, dimensions of food items are measured by vernier calipers.

Sr.No.	Measurement	Uncertainty Interval	Remark
1	Diameter of product	$\pm 0.02mm$	L.C.of vernier
2	Air flow rate	$0.1m/s$	
3	Temperature	$\pm 0.1\,^{\circ}C$	
4	Time	0.17	

To calculate the uncertainty the data for apples at an air flow rate of 1.6 m/s is taken,

Air flow rate, v = 1.6 m/s

Thermal conductivity, k = 0.531 W/m.K

Thermal diffusivity $\alpha = 1.34 \times 10^{-7}$ $W/m^2.K$

Diameter of product, d = 65 mm

Initial temperature of product, $T_i = 22\ ^{\circ}C$

At time, t = 40 minutes, the center temperature of product = 11 °C

Dimensionless center temperature, Y = 0.59

1. Uncertainty in dimensionless centre temperature, Y :

$$Y = \frac{T - T_a}{T_i - T_a} \qquad \text{C.5}$$

$$\frac{\delta Y}{Y} = \left(\frac{1}{T_i - T}\right)\left[\left(\frac{\delta T}{T}\right)^2\right]^{\frac{1}{2}} \qquad \text{C.6}$$

$$= \left(\frac{1}{22-(-4.5)}\right)\left[\left(\frac{0.1}{11}\right)^2\right]^{\frac{1}{2}}$$

$= 3.45 \times 10^{-4}$

2. Uncertainty in cooling coefficient, C :

$$C = \frac{\ln Y}{t} \qquad \text{C.7}$$

$$\frac{\delta C}{C} = \left[\frac{1}{Y}\left(\frac{\delta Y}{Y}\right)^2 + \left(\frac{\delta t}{t}\right)^2\right]^{\frac{1}{2}} \qquad \text{C.8}$$

$= 6.18 \times 10^{-4}$

3. Uncertainty in λ :

$$\lambda = \sqrt{\frac{Ct}{F_o}} = \sqrt{\frac{CR^2}{\alpha}} \qquad \text{C.9}$$

No uncertainty in α as this is taken from from standard tables.

$$\frac{\delta \lambda}{\lambda} = \left[\frac{1}{2}\left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta R}{R}\right)^2\right]^{\frac{1}{2}} \qquad \text{C.10}$$

$= 7.55 \times 10^{-4}$

4. Uncertainty in Biot number :

$$B_i = 1 - \lambda \cot \lambda \qquad \text{C.11}$$

$$\frac{\delta B_i}{B_i} = \left[\left(\frac{\delta\lambda}{\lambda}\right)^2 + \left[\left(-\cos ec^2\lambda\right)\frac{\delta\lambda}{\lambda}\right]^2\right]^{\frac{1}{2}} \quad \text{C.12}$$

$= 1.08 \times 10^{-3}$

5. Uncertainty in Heat transfer coefficient, h :

$$h = \frac{B_i k}{R} \quad \text{C.13}$$

As no uncertainty in k,

$$\frac{\delta h}{h} = \left[\left(\frac{\delta B_i}{B_i}\right)^2 + \left(\frac{\delta R}{R}\right)^2\right]^{\frac{1}{2}} \quad \text{C.14}$$

$= 1.24 \times 10^{-3}$

6. Uncertainty in Reynolds number :

$$\mathrm{Re} = \frac{vD}{\upsilon} \quad \text{C.15}$$

$$\frac{\delta \mathrm{Re}}{\mathrm{Re}} = \left[\left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta D}{D}\right)^2\right]^{\frac{1}{2}} \quad \text{C.16}$$

$= 6.3 \times 10^{-2}$

MATLAB PROGRAM TO SOLVE TRANSIENT HEAT TRANSFER CONDUCTION EQUATION FOR INDIVIDUAL SPHERICAL FOOD PRODUCE

D.1 *APPLES at V = 3.3 m/s:*

```
function pdex1
m = 2;
x = linspace(0,.0325,100);
t = linspace(0,7200,600);

sol = pdepe(m,@pdex1pde,@pdex1ic,@pdex1bc,x,t);
u = sol(:,:,1);
%experimental data
time = [0 10 20 30 40 50 60 70 80 90 100 110 120]*60;
temp = [22 20 18 14 11 9.5 8 7 6 5.3 4.5 3.8 3];
% A surface plot is often good way to study a solution
% figure;
% surf(x,t,u);
% title('Numerical solution computed with 20 mesh points');
% xlabel('Distance x');
% ylabel('Time t');
%
% figure;
% plot(t,u);
% title('Numerical solution computed with 20 mesh points');
% xlabel('Distance x');
% ylabel('Time t');

figure;
plot(t,u(:,1),time,temp,'*');
title('Comparison of correlation with experimental data');
xlabel('time');
ylabel('temperature');

% figure;
% plot(x,u(300,:));
% title('Comparison of correlation with experimental data');
% xlabel('radius');
% ylabel('temperature');
%-----------------------------------------------------
```

```
function [c,f,s] = pdex1pde(x,t,u,DuDx);
alp = 1.34e-7;    %thermal diffusivity
c = 1/alp;
f = DuDx;
s = 0;
%-----------------------------------------------------
function u0 = pdex1ic(x);
u0 = 22;      %initial centre temperature of food produce
%-----------------------------------------------------
function [pl,ql,pr,qr] = pdex1bc(xl,ul,xr,ur,t);
h = 36.1;       % heat transfer coefficient
k = 0.531;     %thermal conductivity
ts = 1;        %cooling air temperature
pl = 0;
ql = 1;
pr = -h*(ts - ur);
qr = k;
```

D.2 ***PAPAYAS at V= 3.3 m/s:***

```
function pdex2
m = 2;
x = linspace(0,.0685,100);
t = linspace(0,7200,600);

sol = pdepe(m,@pdex1pde,@pdex1ic,@pdex1bc,x,t);
u = sol(:,:,1);
%experimental data
time = [0 10 20 30 40 50 60 70 80 90 100 110 120]*60;
temp = [21 20 16 14.7 13.6 12.2 11.4 9.6 8.6 8 7.5 6.9 6];
% A surface plot is often good way to study a solution
% figure;
% surf(x,t,u);
% title('Numerical solution computed with 20 mesh points');
% xlabel('Distance x');
% ylabel('Time t');
%
% figure;
% plot(t,u);
% title('Numerical solution computed with 20 mesh points');
% xlabel('Distance x');
% ylabel('Time t');

figure;
```

```
plot(t,u(:,1),time,temp,'*');
title('Comparison of correlation with experimental data');
xlabel('time');
ylabel('temperature');

% figure;
% plot(x,u(300,:));
% title('Comparison of correlation with experimental data');
% xlabel('radius');
% ylabel('temperature');
%------------------------------------------------------
function [c,f,s] = pdex1pde(x,t,u,DuDx);
alp = 1.423e-7;    %thermal diffusivity
c = 1/alp;
f = DuDx;
s = 0;
%------------------------------------------------------
function u0 = pdex1ic(x);
u0 = 21;      %initial centre temperature of food produce
%------------------------------------------------------
function [pl,ql,pr,qr] = pdex1bc(xl,ul,xr,ur,t);
h = 57.5;       % heat transfer coefficient
k = 0.602;     %thermal conductivity
ts = -0.4;       %cooling air temperature
pl = 0;
ql = 1;
pr = -h*(ts - ur);
qr = k;
```

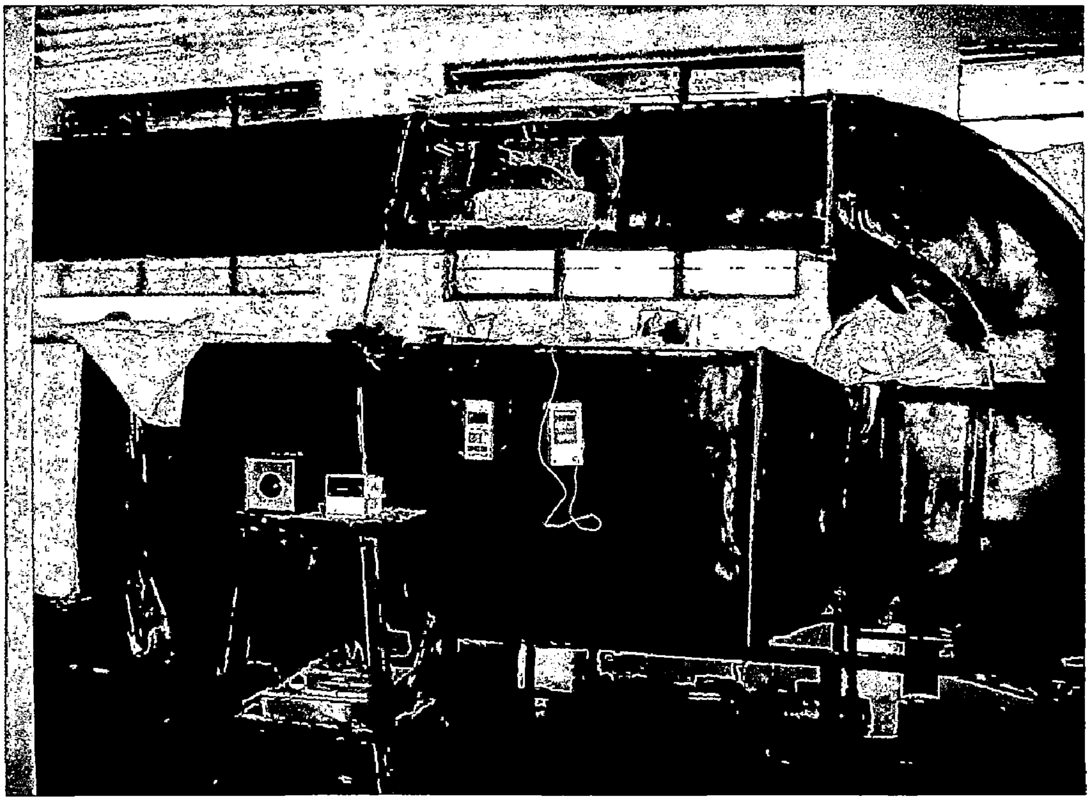
D.3 *GRAPES at V = 3.3 m/s:*

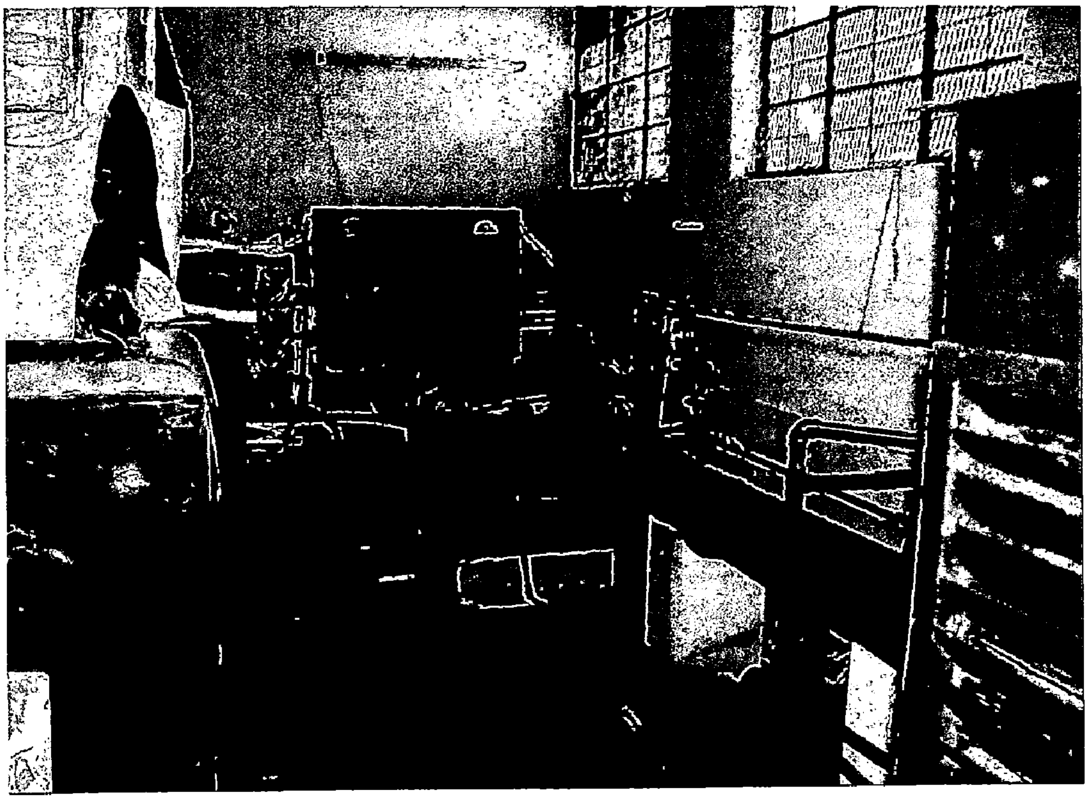
```
function pdex3
m = 2;
x = linspace(0,.0105,100);
t = linspace(0,7200,600);

sol = pdepe(m,@pdex1pde,@pdex1ic,@pdex1bc,x,t);
u = sol(:,:,1);
%experimental data
time = [0 10 20 30 40 50 60 70 80 90 100 110 120]*60;
temp = [21 17 14 12.9 11.8 10.6 9.3 8 6.9 5.8 5.2 4.4 3.6];
% A surface plot is often good way to study a solution
% figure;
% surf(x,t,u);
% title('Numerical solution computed with 20 mesh points');
```

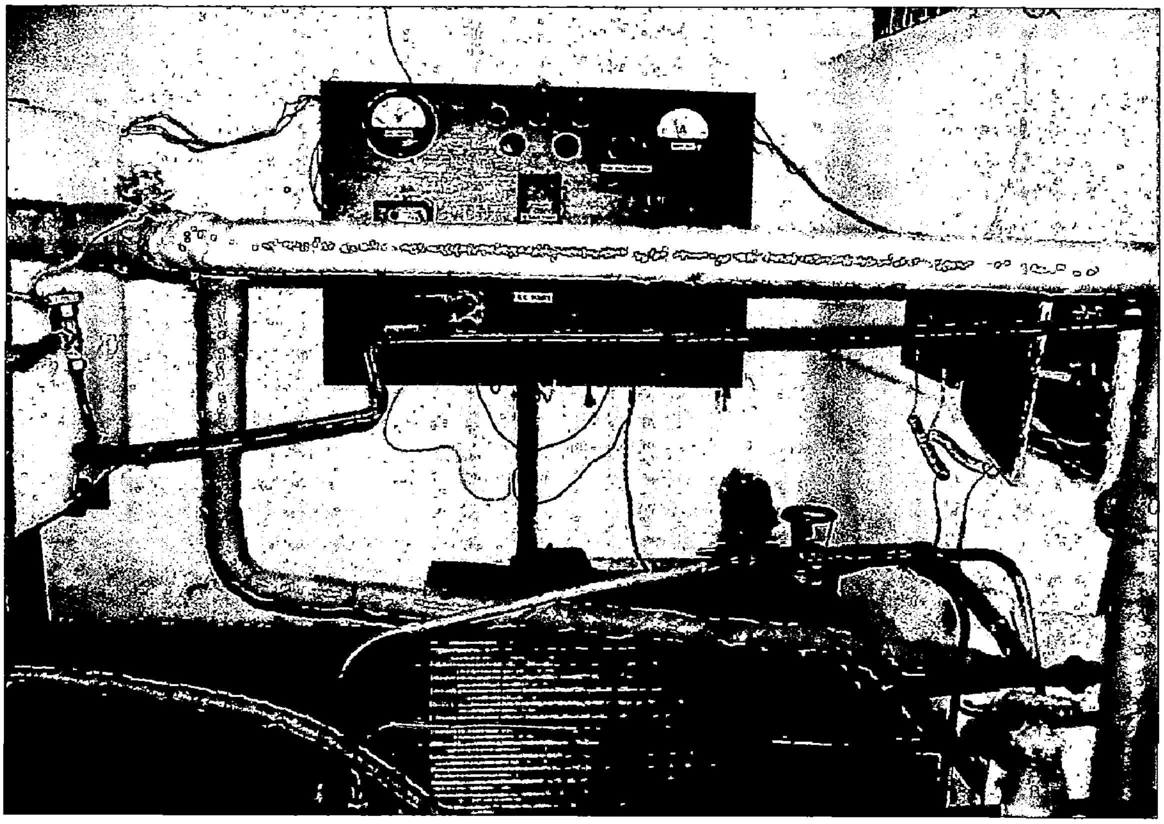
```
% xlabel('Distance x');
% ylabel('Time t');
%
% figure;
% plot(t,u);
% title('Numerical solution computed with 20 mesh points');
% xlabel('Distance x');
% ylabel('Time t');

figure;
plot(t,u(:,1),time,temp,'*');
title('Comparison of correlation with experimental data');
xlabel('time');
ylabel('temperature');

% figure;
% plot(x,u(300,:));
% title('Comparison of correlation with experimental data');
% xlabel('radius');
% ylabel('temperature');
%-----------------------------------------------------------
function [c,f,s] = pdex1pde(x,t,u,DuDx);
alp = 1.38e-7;    %thermal diffusivity
c = 1/alp;
f = DuDx;
s = 0;
%-----------------------------------------------------------
function u0 = pdex1ic(x);
u0 = 21;      %initial centre temperature of food produce
%-----------------------------------------------------------
function [pl,ql,pr,qr] = pdex1bc(xl,ul,xr,ur,t);
h = 10.3;       % heat transfer coefficient
k = 0.548;      %thermal conductivity
ts = -0.4;      %cooling air temperature
pl = 0;
ql = 1;
pr = -h*(ts - ur);
qr = k;
```

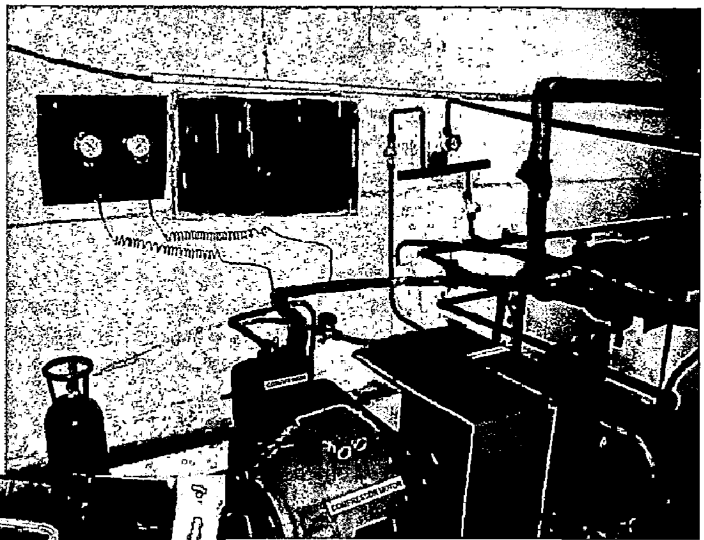
EXPERIMENTAL SETUP PHOTOS

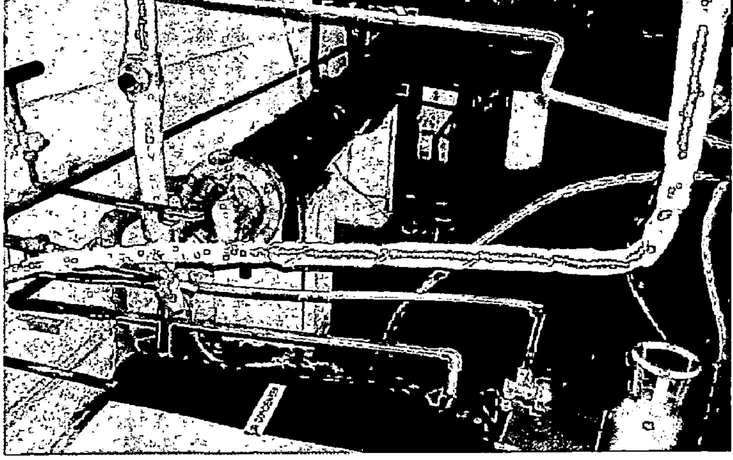
E.1 Photos for experimental setup components

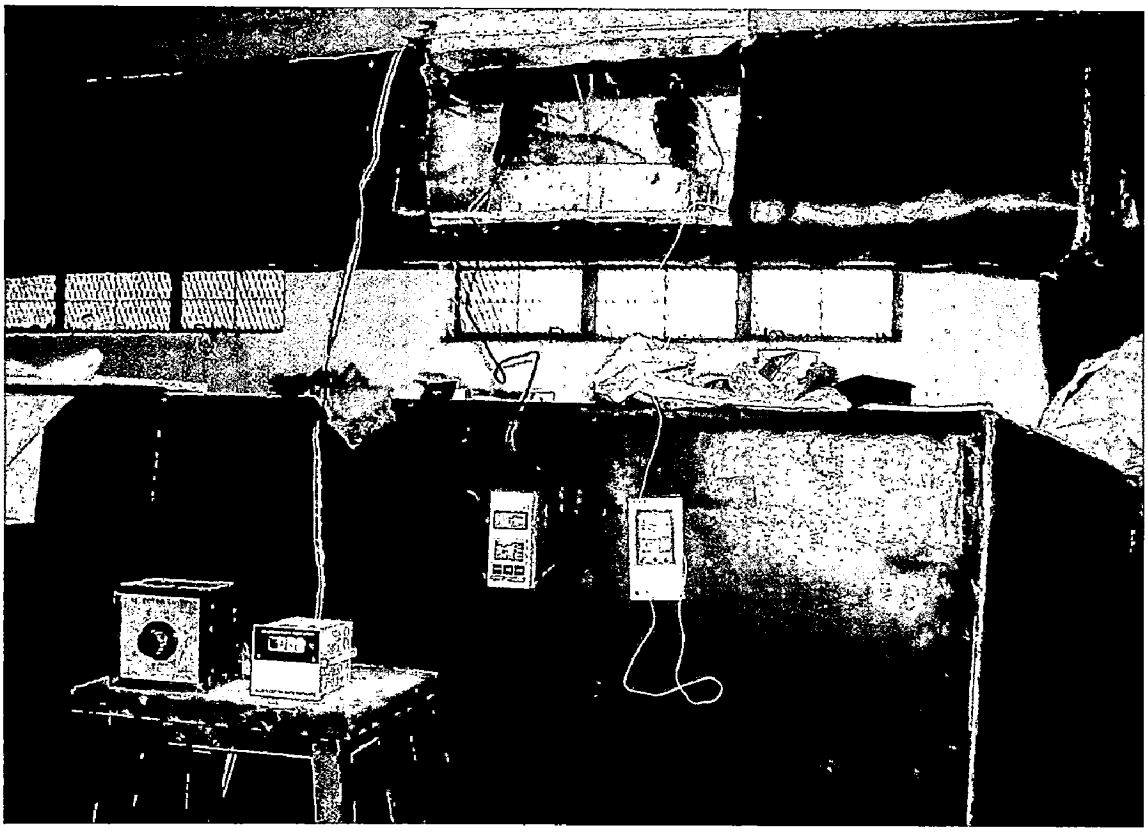


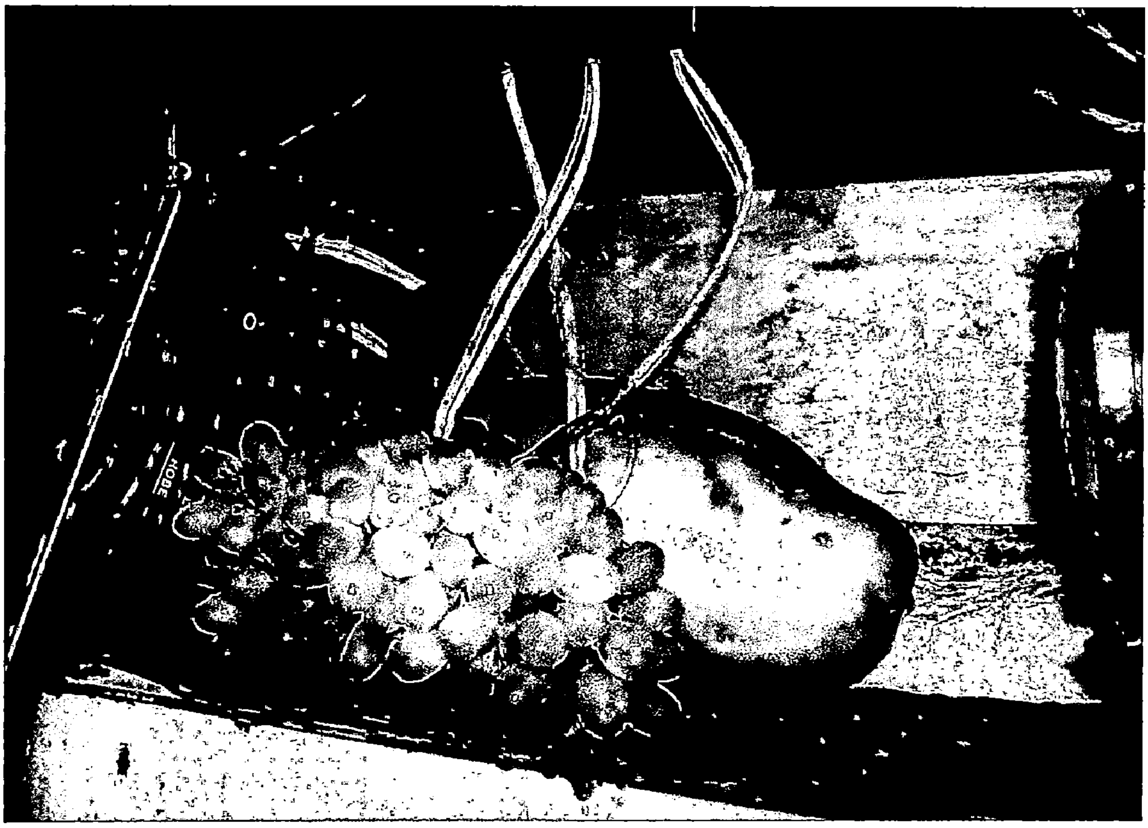












E.2 Photos for experimental procedure