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Mathematical Modeling of Cooling Rates of Mango Fruits during Unsteady State Cooling in an Artificial Ripening Chamber

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Abstract:
Mango fruits need to be ripened artificially using ethylene in thermally insulated refrigerated chambers. The present experiments were conducted to determine the kinetics of cooling rates (with respect to time) of mangoes during unsteady state cooling before ripening the fruits. Ethylene based ripening systems becoming popular due to safe and healthy ripening unlike ripening using calcium carbide. Three different lots 4, 6 and 10 Metric Tons of mangoes placed in perforated plastic crates were cooled first to the desired optimum temperature for ripening. Temperature profiles of mangoes were monitored and recorded with a data logger. Time taken for the mangoes to reach the optimum set temperature of 16.8^{0}C is 16, 20 and 26 hours for 4, 6 and 10 MT respectively. During the unsteady state cooling (from approximately 30^{0}C to 16^{0}C), rate of cooling is modeled using three mathematical equations, viz. linear, exponential and polynomial. Experimental data of pre-cooling is fitted to the predicted values. Best fitting models are proposed based on highest R2 values for all three different quantities of mangoes pre-cooled. The results will be helpful for deciding the timing for ethylene injection and design of refrigeration equipment for part loads of the ripening chambers.

Keywords: *Mango processing, artificial ripening, cooling rates, mathematical modeling, pre cooling, ethylene gas.*

I. Introduction

Mangoes and bananas need to be artificially ripened before selling in the market. The basic need of ripening arises from the plucking of just matured fruits for enabling them to transport to long distances, otherwise the fruits get ripened in the transit and become unfit for consumption or less acceptable to the customer due to over ripening.

Calcium carbide, which is a carcinogenic substance, is widely used by traders, retailers and farmers for ripening of fruits like banana, mango and citrus fruits in India. This substance is banned by the Government of India for using it as ripening substance. However, traders appearing to be using this material due to its easy availability and non-awareness of its harmful effects in long term on human health (Ramesh Babu et al. 2019) [1]. Alternative technologies are available for ripening fruits artificially using ethylene either from an ethylene generator or gas cylinder or canisters. This technique is much simpler and safer. The important requirements of ripening in a ripening chamber are proper temperature of fruits and ethylene level in the air of the chamber. Typical temperature ranges are 15^{0}C to 20^{0}C based on variety, origin, growing conditions and maturity level while plucking.

A properly designed ripening chamber consists of an insulated chamber and sealing of the room to ensure maintaining ethylene levels for first 24 hours of ripening cycle. A refrigeration system consists of compressor, condenser, expansion device and cooling unit (Evaporator). This system pre-cools the produce to the desired temperature. Accessories required for a ripening chamber are the perforated plastic crates or ventilated

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corrugated fiber board (CFB) cartons, ethylene injection system, sensors for temperature & ethylene level measurement and controls. The objectives of the present experiments are to:

1. Investigate the temperature profiles of mango pulp temperature during pre-cooling stage during artificial ripening of mangoes
2. Model the rate of cooling during un-steady state pre-cooling stage
3. Study the effect of different quantities on the cooling rate
4. Fit the temperature profiles to the mathematical models (kinetics of temperature change with respect to time)

II. Literature Overview

Narasimha Rao et al. (1992, 1993a, 1993b) have studied the pre-cooling aspects of spherical fruits and modeled the pre-cooling process. They have used hydraircooling for pre-cooling process. They have used an experimental set up with both air and water spray to pre cool the produce [2-4]. Ramesh Babu et al. (2018) extensively investigated the handling of fruits and reported the incidence of surface damage during handling and loss of texture during storage. However they reported the firmness changes of apples during controlled atmosphere storage. Preserving the fruits in perforated plastic bins has been reported. The time taken for apples to pre-cool is 120 hours (fruit to reach temperature of 10C from an initial temperature of 25-30^{0}C) [5].

Cardenas Perez et al. (2018) evaluated basic parameters concerned with softening of Tommy Atkins mangos during ripening process. Notify as ripening index (RPI) value and Young's modulus of the primary cell of mango gradually decreases. It leads to physiochemical as well as chemical and mechanical changes. There are three fractions that are isolated with mango cell wall. They are water soluble (WSP), chelator soluble (CSP) and diluted alkali soluble (DASP). Two analysis X- ray and confocal laser scanning microscopy gives the complete information about changes occurred in the mango cell wall during maturation. Finally, a graph between 'E' and 'RPI' gives a linear fit curve [6].

Eyarkai Nambi et al (2017) observed the texture and rheological changes of Indian mangos like Banganapalli, Neelam and Alphonso during ripening. There by utilizing logistic models, easily predicts the changes occurring during ripening process. Finally, noticed that pulp exhibits high shear stress and low viscosity. By using Herschel Bulkley model observed that flow behavior index and yield stress gradually decreased. On the other hand, consistency coefficient increases during ripening process. Mango pulp exhibits elastic behavior rather than viscous behavior [7].

Ullah et al. (2016) Provides the information regarding non-invasive assessment of mango during ripening process by using fluorescence spectroscopy. Spectra records from the peel of Dasheri mango using light emitting diode at 460nm as excitation state. Results suggested that carotenoids depicts similar with chlorophyll pigment levels for a fruit maturity. But experiments repeated with a Langra mango, the peel remains green after fully ripening stage. Therefore, carotenoids fluorescence 540 nm may be useful for assessment of mangos during ripening process [8].

Eyarki Nambi et al. (2016) predict a color grade sheets for Indian mangos by classifying the ripening period into different stages. By considering the two Indian mango varieties Banaganpalli and Alphonso measures the physico-chemical properties, external-internal color values and texture characteristics are recorded throughout the ripening period. By introducing Hierarchical method, ripening period of mango is classified into five stages, viz. unripe, early ripe, partially ripe, ripe and over ripe. Based on this stages color grade sheets are developed. The developed grade sheets are useful for non-destructive grading tool at pack houses and packing industries [9].

Vu et al. (2019) reports that changes occurring in the physico-chemicals, chlorophyll and antioxidants of banana peel during ripening with and without usage of ethylene. As the fruit color changes from green to yellow chlorophyll degraded to 90% as well as carotenoids and flavonoids are increased to 50% and 27% respectively. Finally, the banana peel contains higher phenolic content and antioxidants without usage of ethylene than with usage of ethylene [10].

Zulkifli et al. (2019) investigated the potential of laser light back scattering imaging for predicting different ripening stages for a Berangan type banana. In order to investigate the different stages, a charge coupled device is coupled with a laser emitting diode at a wavelength of 658 nm is used. Grey level intensity and backstage area of the scattering images are used as a parameters for the estimating the quality properties of banana. Finally, a statistical analysis provides successful classification along with their sample ripening stages with a percentage corrected to 94.6% [11].

Campuzano et al. (2018) reported information about physicochemical changes and nutritional characteristics of banana flavor during ripening. At early stages of ripening such as second and third stages, the protein content is gradually increased and decrease in carbohydrate and amylase content. Finally, between these two stages significant decrease in total and resistant starch produced together with an increase in phenolic content and antioxidant activity [12].

Gowda et al. (2001) carried out experiments to determine the qualitative and quantitative changes and physico-chemical changes occurred at the time of ripening process for mangos. By conducting the experiments over a six varieties of mangos, concluded that there is a slight reduction in the fruit weight, volume, fruit length, thickness, firmness, pulp content, starch, vitamin C. On the other hand, there is an increase in peel, TSS, pH, sugar content, carotenoids are relatively high. Finally, the peel color changes from light green to light yellow as well as pulp color is changes from white to pale yellow or yellow to deep yellow and for particular variety mangos pulp color changes from deep yellow to orange color [13].

Maduwanthi et al. (2019) reported that there are many modern methods are available in the market in order to ripen the bananas. Such as ethylene gas, ethephon, ethylene glycol, acetylene, alkyl alcohols etc; whereas burning the leaves and kerosene are used in traditional methods of banana ripening. Here is the interesting point notice that naturally ripe bananas exhibits better sensory characteristics compare to artificially treated fruits [14].

Mayuoni et al. (2011) evaluated the effect of ethylene de-greening on the internal changes of Citrus fruit. Their results show that ethylene de-greens up to 3 days at specific temperature and it does not involve any internal changes in the fruit. Finally, it is concluded that ethylene cannot totally influence the parameter de-greening [15].

Ramesh Babu et al. (2019) reported the process of ripening of mango and banana without using harmful chemicals such as calcium carbide. They reported the consumer awareness on the bad practices and good practices on ripening of fruits. Their report recommended for wider dissemination of ethylene based ripening systems for safe and healthy fruits availability [16].

Ram Deshmukh et al. (2020) reported the importance of sealed chambers for maintaining gas composition in fruit storage chambers. The insulation panels of the fruit pre-cooling, controlled atmosphere storage need to be gas tight, so that oxygen, carbon dioxide gas levels can be maintained without any leakage [17].

III. Materials and Methods

Ripening process of mango needs proper temperature, RH and Ethylene level management. Proper air flow, temperature during un-steady state and steady state are ensured using electronically controlled refrigeration system, temperature sensors to monitor and control apart from data logging. To determine the cooling rates, arrangement is made with a temperature sensor carefully inserted in the pulp of mango and record the data continuously from chamber sealing time to the steady state temperature achievement. Technical details of instruments used are given below.

Data logger: Monitoring the precooling process using a temperature data logger: A temperature data logger is used - Model RC-4, Make: Eli-tech, United Kingdom. The data logger has a temperature range from -40°C to +80°C. The logger recording interval can be set from 10 seconds to 24 hours range. The logger has a capacity to store 16000 data points. It uses a probe to measure the temperature of the pulp. The probe is inserted into the fruit up to the centre (perpendicular to the diameter). The instrument is shown in Figure 1.

Figure1: Temperature data logger

Monitoring the room air temperature: A digital thermometer is placed at the return air of the cooling unit inside the ripening chamber which records the return air temperature, which is the temperature of the air that picked the heat from the fruits and going to enter the cooling unit for lowering the temperature and to be blown again on to the fruit crates. This instrument has been supplied by the supplier of the equipment, refrigeration unit of the ripening chamber.

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Fruits: Mangoes of green colour of uniform size are placed in 20 kg standard perforated plastic crate of Nilkamal make. Stacking of crates is done up to 7 high leaving 2 feet space between top layers of top crate and cooling unit height to allow free flow of air from the cooling unit fans. Stacking pattern is made such that there is no obstruction for the return air from the fruit crates to the cooling coil.

Flow chart for ripening process:

Mangoes are placed in plastic crates of 20 kg each
↓
Crates are stacked in the ripening chamber floor
↓
Cooling unit is switched-on
↓
Desired temperature is set
↓
Sensor of data logger is inserted in the fruit in the middle crate to record fruit pulp temp.
↓
Chamber door is closed hermetically
↓
Once set temp is achieved, Ethylene is released @ 100 ppm into the chamber
↓
After 24 hours of ethylene injection, door is opened to release CO_2
↓
After every 24 hours further, the door is opened for release of excess CO_2
↓
After achieving desired color, the fruit crates are removed from the chamber

IV. Results and Discussion

Cooling rates are calculated from the experiments conducted with different tonnage of mango (4MT, 6MT and 10MT). Data logging report is plotted in MS excel for further processing and determining the rate of cooling. As expected the time required to reach the set ripening temperature (which is the steady state temperature also) found to be higher for higher quantities of mangoes.

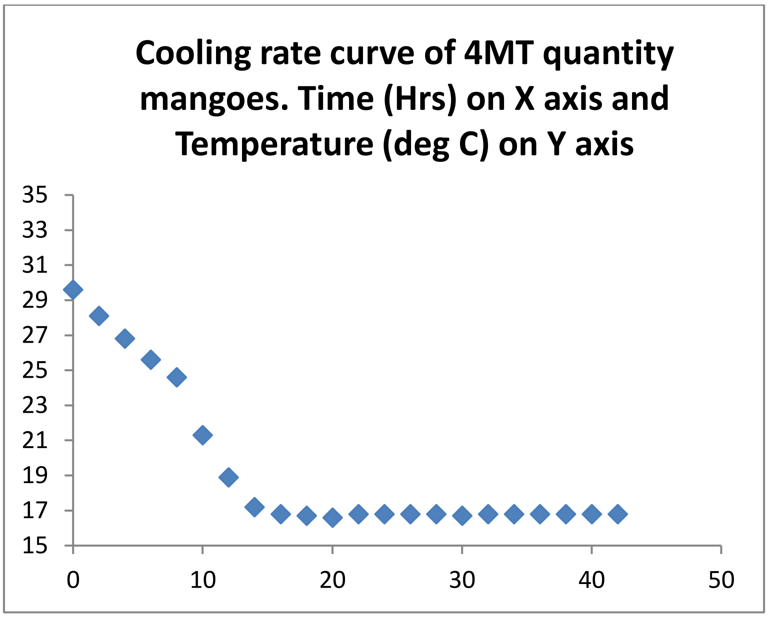

Figure 2: Cooling rate curve of 4MT quantity of mangoes in ripening chamber

It can be seen from Figure 2 that the mangoes are cooled from 30 to 16^{0}C within 16 hours of start of cooling. Further temperature is maintained at 16.8^{0}C to enable the ripening process with ethylene gas. Two distinct regions can be seen in the curve. One is the unsteady state, till the temperature reaches the set value. The second region after reaching set point temperature. The analysis of unsteady state cooling rate has been modeled with different mathematical models at figure 5, 6 and 7.

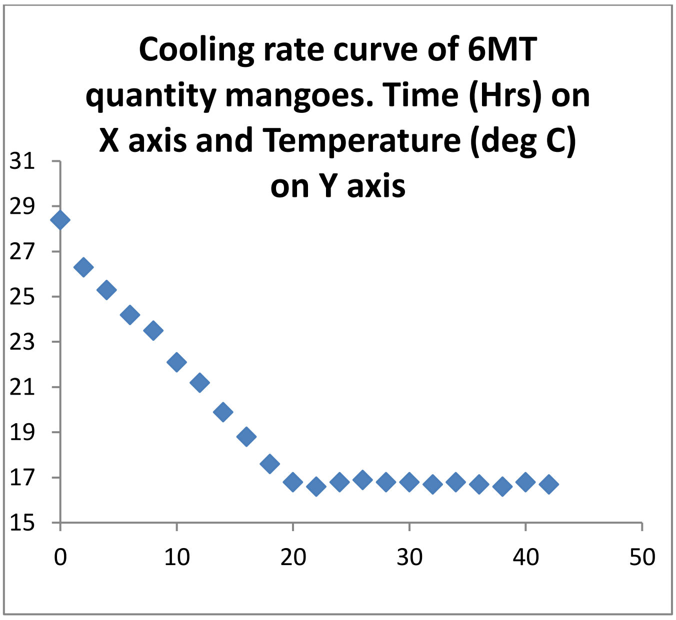

Figure 3: Cooling rate curve of 6 MT quantities of mangoes in ripening chamber

Figure 3 shows the temperature profile of mangoes when the ripening chamber is placed with 6 metric tons of mangoes. Time to achieve the set temperature of 16.8 is 20 hours. Temperature is maintained at 16.8^{0}C till the mangoes are fully ripened. As the quantity increased from 4 to 6 MT, it is seen than time taken to arrive at the set value increased from 16 to 20 hours compared to 4 MT mangoes.

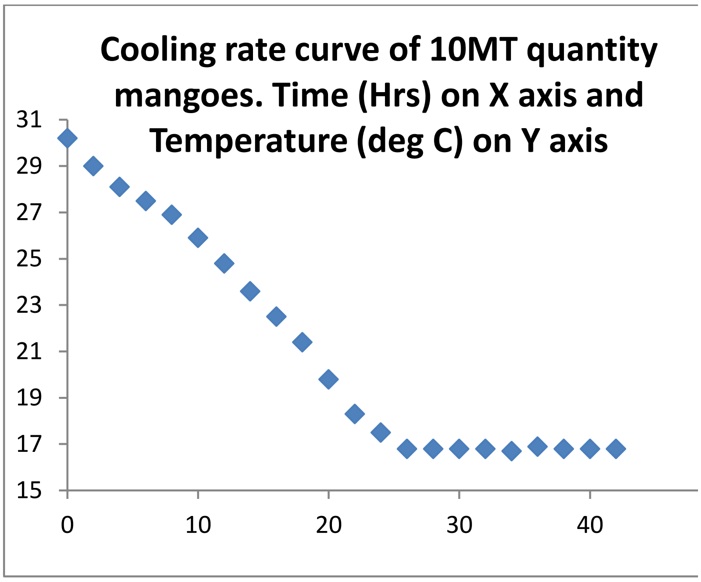

Figure 4: Temperature profile of 10 metric tons of mangoes pre-cooled in the ripening chamber.

The time to reach the set temperature of 16.8 is 26 hours. Further temperature is maintained at the same temperature till the mangoes are ripened and removed from the chamber for marketing. The time to arrive at set value is 26 hours and this is definitely expected to be more due to more sensible and latent heat from the fruits. Sensible heat is due to the fruit temperature and latent heat can be due to the moisture evaporation from the fruit apart from respiration heat.

From Figures 2, 3 and 4 it can be seen that the precooling time to the desired temperature of 16.8^{0}C took 16, 20 and 26 hours for 4, 6 and 10 metric tons quantity respectively. It can be interpreted that the ethylene ripening chambers can be successfully utilized for part loads of the chamber

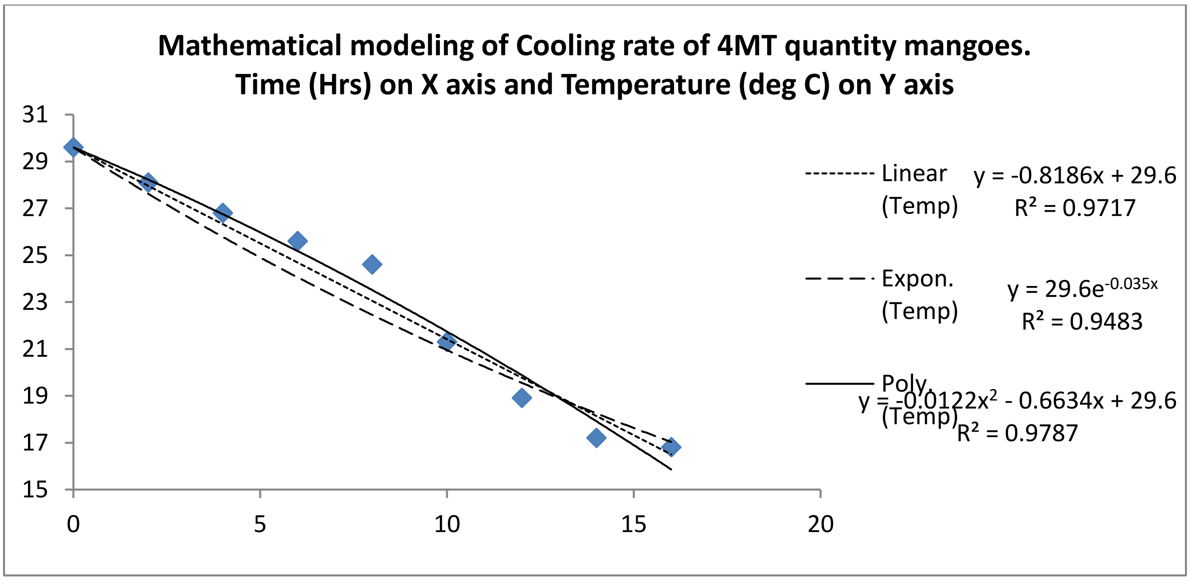

Figure 5: Application of three mathematical models (Linear, Exponential and 2nd order polynomial equations) for the cooling rate of 4 MT mangoes

The data of cooling rate 4 MT quantity during unsteady state (till the temperature reaches the set value) is plotted in figure5. Data is fitted with three equations, viz. linear, exponential and polynomial second order. The best fit equation is found to be polynomial equation of second order with R square of 0.978. The R square values for other two models found to be 0.948 and 0.971 for exponential and linear models respectively.

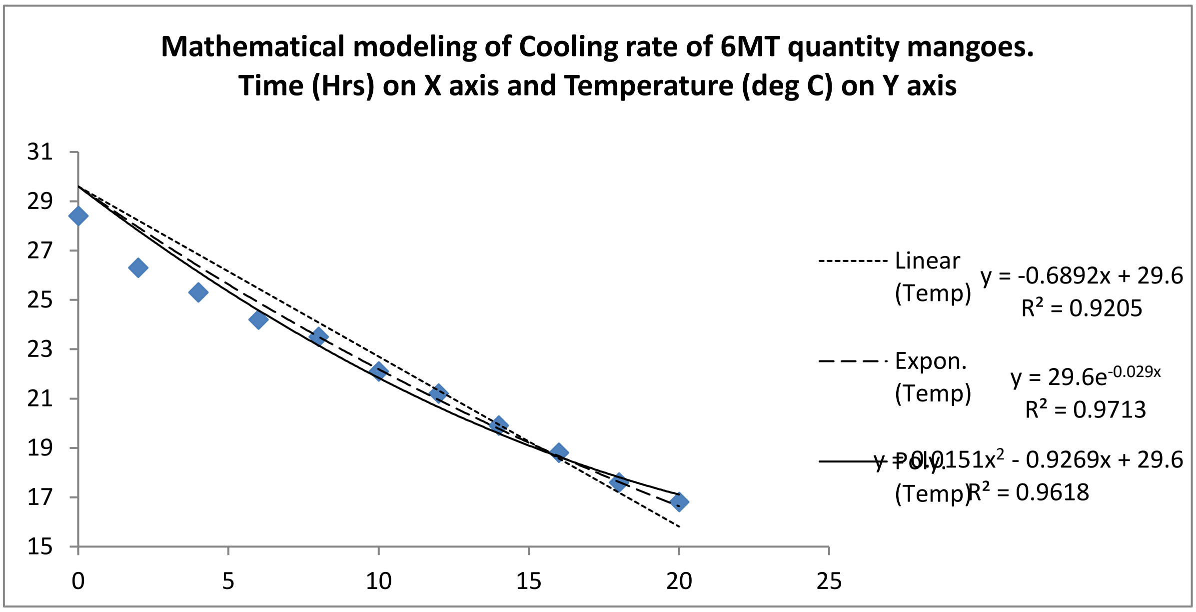

Figure 6: Application of three mathematical models (Linear, Exponential and 2nd order polynomial equation) for the cooling rate of 6 MT of mangoes

Data of cooling of 6 MT mangoes is shown in Figure 6. Cooling rate is modeled with three models equations, viz. linear, exponential and polynomial second order equations. The experimental and predicted values found to be fit with R square values of 0.920, 0.961 and 0.971 for linear, polynomial second order and exponential models. Best fit of predicted values with experimental values found to be with the exponential model with highest R square values of 0.971.

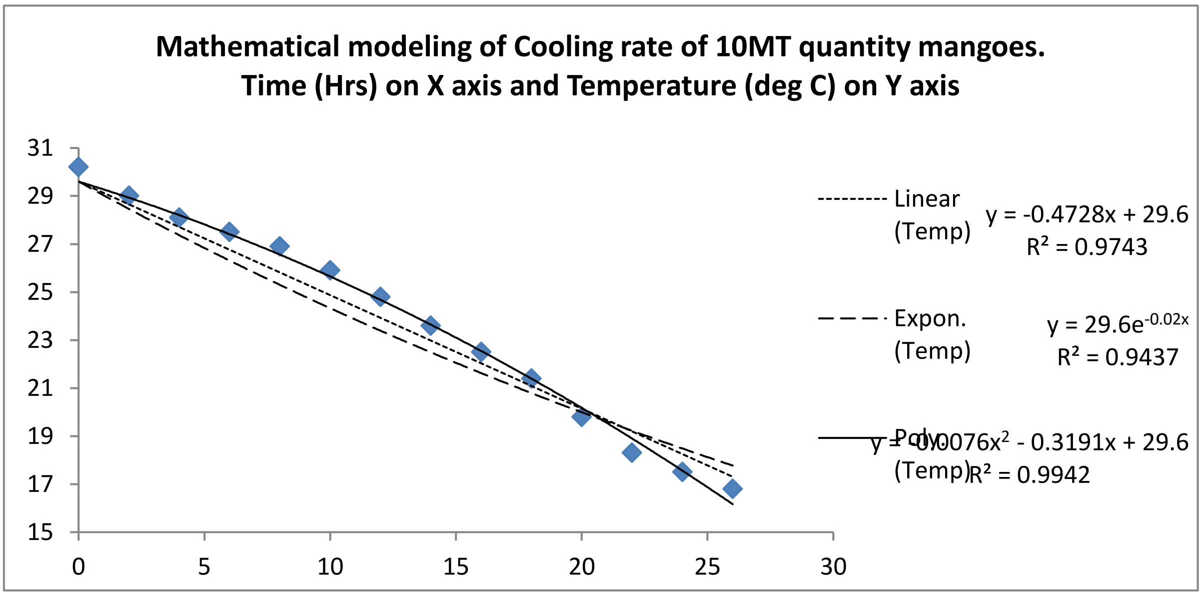

Figure 7: Application of three mathematical models (Linear, Exponential and 2nd order polynomial equations) for cooling rate of 10 MT mangoes.

The fitting of experimental values vs. predicted values with three mathematical equations for 10 MT quantity of mangoes are shown in Figure 7. The R square values are 0.943, 0.974 and 0.994 for exponential, linear and second order polynomial equations respectively. Best fit between experimental and predicted values found to be with highest R square value of 0.994 with polynomial second order equation.

V. CONCLUSIONS:

Mangoes of different quantities are subjected to pre-cooling before ripening process with ethylene gas for natural and healthy ripening. Rate of cooling is calculated for 4 MT, 6 MT and 10 MT quantities using mathematical equations, viz. linear, exponential and second order polynomial models. The cooling time for achieving steady state (set temperature for optimum ripening requirements) is found to 16, 20 and 26 hours for 4, 6 and 10 metric tons respectively. Experimental Vs predicted values of three models resulted to find the best fit equations. For 4 MT and 6 MT quantities, the exponential model fitted the best with 0.978 and 0.971 respectively. For 10 MT quantities, the polynomial second order equation fitted the best with R square value of 0.994. The results of this experiment can be used for the appropriate design of refrigeration equipment for part loads of mango ripening process. Results are also helpful to decide the timing for injection of ethylene based on reaching point of steady state temperature.

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Membership of Professional Bodies:
Dr Rao is a member of ASHRAE, ISCA, ISHMT, ISHRAE, ISTE, SAE & SESI and a Fellow of Institution of Engineers (India). **Scholarships & Awards:**

- Recipient of 'National Merit Scholarship' during 1980-85 (6 Years).
- Recipient of 'Special Rank' in Mathematics Olympiad conducted by Andhra Pradesh Association of Mathematics Teachers (APAMT), Hyderabad, A. P. at Senior Level during 1980-81.

Areas of Specialization: Energy Auditing, Energy Conservation & Management, Heat Transfer, Refrigeration and Air-conditioning and Renewable Energy Sources.

Research Guidance: Has supervised 14 M. Tech. Students and presently guiding eight PhD Scholars and four M. Tech. Students.

Important Projects handled: Was the Team Leader for the Consultancy Assignment on Energy Efficiency Services-Phase-III (3 May–30 November 1998), for the Ministry of Industry, His Majesty's Govt. of Nepal, Industrial Energy Management Component of the Power Sector Efficiency Project (PSEP) – IDA Credit No. 2347-NEP, World Bank. The activities included Demand Side Management (DSM), Furnace & Kiln and Boiler Efficiency studies, Co-generation Feasibility studies covering 65 major industries in Nepal. Trained 11 Nepalese Engineers as Certified Energy Auditors as part of the Consultancy Assignment. Dr Rao was involved in the field-testing of a number of Energy Saving Devices / Retrofits under the Energy Saving Demonstration Project, funded by GTZ, Germany. Dr Rao has developed and Demonstrated "Performance Contract for Industrial Energy Management" for Indian Scenario, sponsored by Canadian International Development Agency.

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Shaik Shareef is a post graduate student at Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur pursuing M. Tech. in Thermal Engineering. His research interests include: Thermal engineering, Pre-cooling of fruits, ripening process using ethylene gas.

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D. Ramesh Babu has over 24 years of experience in manufacturing, research, maintenance, consultancy and project management related to Refrigeration, food processing and controlled atmosphere. He was graduated in Mechanical Engineering from JNTU College of Engineering, Hyderabad in the year 2000 and obtained MBA in production and operations management from MDU, Rohtak. He also obtained his M. Tech. in Advanced Manufacturing from JNTU, Hyderabad.

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