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Analysis of Heat Transfer and Cooling Characteristics in Jaggery Cooling and Aeration Phase

by

Prashidda Kharel

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The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a thesis entitled **'Analysis of Heat Transfer and Cooling Characteristics in Jaggery Cooling and Aeration Phase'** submitted by Prashidda Kharel (075MSREE012), in partial fulfillment of the requirements for the degree of Master of Science in Engineering in Renewable Energy Engineering.

Supervisor, Dr. Hari Bahadur Darlami
Associate Professor
Department of Mechanical and Aerospace Engineering

External Examiner, Er. Malesh Shah
Assistant Professor, Department of Mechanical
Engineering, Kathmandu University

Committee Chairperson, Assistant Prof. Dr. Sudip Bhattarai
Head of Department
Department of Mechanical and Aerospace Engineering

Date: 12 January 2026

ABSTRACT

Jaggery or Gur is one of the important food elements all over the world including Nepal. It is mainly obtained from sugarcane juice. The process of solid Jaggery preparation includes obtaining juice, purification, evaporation, cooling, moulding and storing. During the cooling phase, slow cooling and aeration of Jaggery at higher temperature is important as it affects the crystal structure of Jaggery and effectively its quality.

The study focused on the analysis of cooling characteristics and the rate of temperature decrease of mechanically stirred Jaggery in the crystallization pot at different rotational speeds and insulation. First, mathematical calculation of heat losses was done, assuming steady state process. The first experiment was conducted on water by heating up to its boiling point and studying the temperature while cooling. Then heated Jaggery was cooled up to a striking point at different rotational speeds for two setups: one without insulation and another with 50 mm rockwool insulation available easily on the market. Then, simulation was conducted for the same pot with and without insulation on ANSYS Student 2025R2 software for validation. Heat losses from all the surfaces of crystallization pot were determined from simulation.

Evaporation heat loss was the dominant heat loss followed by convection and radiation according to calculations and simulation. Initial testing on water determined the introduction of insulation decreased the rate of heat loss with fastest cooling at 75 rpm without insulation and slowest cooling rate at 25 rpm with insulation. For the uninsulated crystallization pot, the temperature of Jaggery reached 75 °C in 38 minutes for 25 rpm rotation, 32 minutes for 50 rpm rotation and 28 minutes for 75 rpm. After the addition of insulation, the same temperature reached 53 minutes at 25 rpm, 45 minutes at 50 rpm and 40 minutes at 75 rpm. Final experimental testing at 75 rpm with and without insulation showed time required to reach 75 °C was 30 minutes and 43 minutes respectively. The results from simulation show that time required to reach 75 °C was 28 minutes without insulation and 40 minutes with insulation. Future iterations could extend the test to different sizes and types of insulation.

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CHAPTER ONE: INTRODUCTION

1.1 Background

Popular all around the world with various names, Jaggery or Gur (Gud in Nepali Hilly region) is a product obtained from concentrating sweet juices of sugarcane or palm extract. It is produced in South Asia, South America, and Southeast Asia in large quantities (Shrivastava & Singh, 2020). It is used in different countries as a sugar alternative because of the belief that it has medicinal as well as health benefits. It is believed to have various health benefits in the past as well as in the present because of its vitamins and mineral contents (Ukey, et al., 2024). The manufacturing process of Jaggery starts when sugarcane is crushed to get juice or extracts from palm trees. Initially, the juice has low sugar content and high in water content. This juice is heated under open pans to facilitate evaporation. The concentration reaches to semi solid or solid level with the help of heat applied to the sweet juice to remove moisture. Jaggery with 70% sucrose, glucose and fructose content of less than 10%, minerals under 5% and moisture under 3% are considered as quality. It is golden yellow with hard texture and crystalline structure (Hirpara, Thakare, Kele, & Patel, 2020).

In context of Nepal, Jaggery holds a significant importance in Nepali way of life and celebrations. It has its various forms and names among the diverse cultural practices of Nepal. It has names like gud, chaku, veli, khudo and so on and it is used in celebrations, beverages and food products and sometimes simply as a sweet treat. In the past, it was a way of preserving the high quantity of sugarcane produced during the season for future consumption. It was done by traditional methods and in small quantities in local households. People used to collect small amounts of sugarcane juice from their own farms and process it to obtain liquid or solid Jaggery. Nowadays, the sugarcane plantation and Jaggery manufacture has gained some commercial dimension. Nepal produces around 3 - 4 million tons of sugarcane per year (Aryal, 2025). Jaggery is one of the products that is obtained from sugarcane juice other than sugar and unprocessed sugarcane juice. The popularity of Jaggery as a healthy alternative to processes white sugar has made the demand of Jaggery higher in Nepal and other parts of the world more than ever before.

1.2 Jaggery Manufacturing Process

The process of Jaggery production goes through multiple steps and sugarcane is the most common source of Jaggery in context of Nepal. Figure 1.1 (Ukey, et al., 2024) provides a schematic diagram of Jaggery processing.

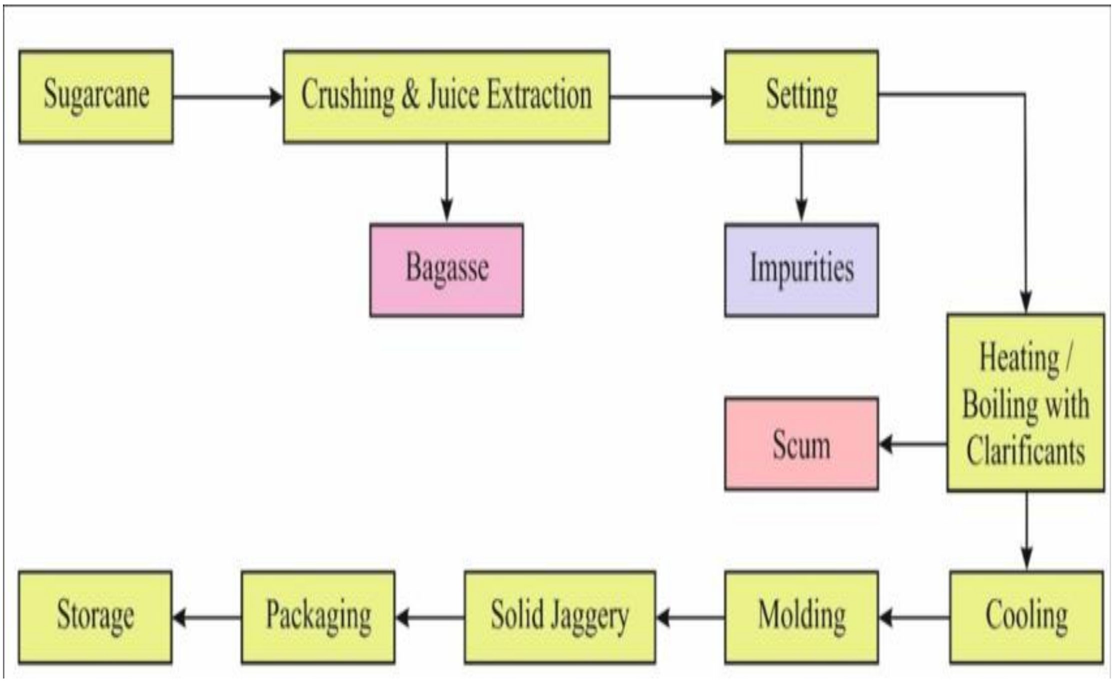

Figure 1.1: Solid Jaggery Manufacturing Process

The process of making solid Jaggery goes through many steps starting with juice extraction, evaporation, sitrring and aeration, molding and packaging.

i. Juice Extraction

Sugarcane takes usually 12-18 months to mature, and it is harvested after maturing. The stalks are cut and they are collected. The sugarcane stalks are cleaned to make them free from dust and other debris. They are then fed into a crusher to extract the juice. Sugarcane juice is obtained after this crushing process. The moisture content of sugarcane juice is between 70-80% (Sankhla, Chaturvedi, Aparna, & Dhanlakshmi, 2012).

ii. Heating and Clarification

After clean juice is obtained, it is transferred to a large, open pan and it is heated over furnace or direct lame. The main job of this process is to reduce the moisture content of the juice. The juice is continuously stirred, and it thickens with time. Single pan, two pan and three pan boiling systems are utilized during this process. Additionally, some additives like lime is added to the syrup for clarification.

iii. Concentration

After boiling the juice for some time, the juice goes from watery liquid to a thick syrup. The boiling process continues until the syrup reaches the desired concentration called as striking point which is 118 degrees for sugar Jaggery. This striking point is determined by an experienced worker in traditional Jaggery plants. The color of the syrup ranges from light brown to dark brown, depending on the sugar content and processing time. The moisture content of molten Jaggery while at striking point is around 15 % (Pathak, et al., 2024).

iv. Stirring and Aeration

Once the syrup reaches the desired consistency, it is removed from the heat. Then the syrup is stirred continuously and aerated. This step is critical in determining the quality of Jaggery. In traditional methods of Jaggery production, stirring is done with metal or wooden paddles. This requires a lot of manual labor and it is done for a long period of time. For large batches, it requires 3-4 people simultaneously in this step. The purpose of stirring in this phase is to allow moisture to evaporate from Jaggery. Additionally, when air is introduced in the Jaggery through constant stirring, its porosity increases increases and smooth crystalline structure is obtained in Jaggery increasing its quality. At the end of stirring and aeration phase, the concentration of sugar increases because moisture content decreases to 5-7% (Selvi, Mathialagan, & Mohan, 2022). The stirring process is continued till the temperature of Jaggery cools down to 60-75 °C. Usually, in traditional methods, observation is carried out by experienced personnel who determines that Jaggery is ready for molding.

v. Moulding

The thick syrup is then poured into wooden, metal or concrete moulds to be shaped into blocks or cakes if solid Jaggery is the end-product. The Jaggery is shaped round, rectangular or smaller individual pieces, depending on market demands.

vi. Cooling and Solidification

The poured syrup is left to cool and solidify in the moulds. This cooling process can take several hours to a day, depending on the ambient temperature. The size of the

Jaggery pieces also determines the cooling rate. Some amount of moisture is also lost in this step.

vii. Packaging and Storage

Once solidified, Jaggery is ready for storage. For packaging, Jaggery blocks or pieces are wrapped in plastic wraps or edible wraps and stored in a dry place to prevent moisture absorption.

The traditional method of Jaggery production is labor intensive. To mechanize this process a Jaggery Production Machine has been fabricated which replaces the labor intensive cooling and aeration process with a automated stirring provided by an impeller. Once Jaggery reaches upto crystallization point, it can be transferred to crystallization pot of the machine. The impeller is rotated with the robotic arm that allows for different rotational speeds. The main focus of the study was the heat loss and temperature decrease during this stirring process.

1.3 Problem Statement

Good Jaggery has large crystallization structure and porosity. The amount of air trapped inside the Jaggery during stirring and molding process gives the indication of uniform crystallization structure leading to its superior quality (Ramya, Ashwini, & Mirajkar, 2018). For this, during the cooling phase, the Jaggery needs to be continuously stirred and aerated requiring a slow cooling rate (Thorat, et al., 2023). This cooling rate is directly affected by the heat lost from the crystallization pot. Additionally, cooling rate is also higher due to the movement of impeller arm that is in constant rotation. However, by introducing insulation around the cylinder, the cooling process slows down effectively and the good quality Jaggery will be obtained.

Moreover, most of the research conducted in the Jaggery production process focuses on the evaporation phase of sugar syrup and on the efficiency of the heating equipment. Additionally, study on the heat loss, physical measurement and simulation of sugarcane juice evaporating equipment is extensive. Although, the study of heat loss during evaporation and heating facilitates the design of energy efficient system, the crystallization or the aeration phase is important for Jaggery quality. However, there is a lack of comprehensive study on the cooling and aeration phase of Jaggery making process. Study of the heat loss process from the crystallization pot during aeration phase results in the quantitative characterization of the process. As a result, the uniformity and the quality of Jaggery would be determined empirically rather than depending on the experience of Jaggery makers.

1.4 Objectives

The main objective of the study is to analyze the heat loss characteristics of Jaggery making process during cooling and aeration phase.

Specific objectives of the study are as follows:

- To calculate heat loss from crystallization pot during cooling phase.
- To simulate heat profile and temperature curve of Jaggery during crystallization process using ANSYS Fluent.
- To determine the effect of insulation on heat transfer from crystallization pot.
- To compare experimental and simulation data for different rotational speed.

1.5 Scope and Limitations

1.5.1 Scope of the Study

The study focused on cooling and aeration phase of Jaggery production on the fabricated machine which happens after evaporation and before moulding. The project started with calculation of heat losses from the crystallization pot. Experiment was conducted on Jaggery initially to find the effect of insulation just by cooling it down from the elevated temperature. Similarly, the effect of different rotational speed on the cooling rate was characterized in the study. The final experimental testing was conducted for different setups by cooling Jaggery from crystallization temperature to molding temperature. Later, simulation was conducted on ANSYS Fluent software to study temperature profile and conduction and convection losses form the surfaces. Simulation and experimental data were compared with each other.

1.5.2 Limitations

- The initial mathematical calculation assumed steady state heat transfer. The calculations were done for initial benchmark setup. In realty, cooling occurs in transient conditions.
- The student version of ANSYS software only allows for 1 million elements which constrained the minimum element size to 7 mm.

- To decrease the processing time and computational load, the steel crystallization pot was not modelled in ANSYS. The properties of steel were directly applied to Jaggery fluid.
- Insulation type and thickness used in the experiment was selected on the basis of market availability and cost. Because of the contaminating nature of rock wool, the physical application should be avoided since Jaggery is food product.

CHAPTER TWO: LITERATURE REVIEW

2.1 Properties of Jaggery

The study by Shau, Kumar, Patel, Shau, & Painkra (2024) systematically evaluates the physico-chemical properties of Jaggery – both solid and molten -- produced from the cane variety CoLk94184. The authors conducted the measurement of essential attributes such as °Brix, color, density, moisture content, pH, hardness, reducing sugars, and importantly, viscosity, using standardized analytical methods. Their findings indicate that molten Jaggery exhibits a very high viscosity—averaging 2519.79 mPa·s—as measured across a range of spindle speeds (50 – 190 rpm). Their study reinforces the ideas presented in earlier literature that concentrated sugar products act as highly viscous, potentially non-Newtonian fluids. The findings of °Brix (around 79.8°), true density (1.36 g/cc), and moisture contents for both solid and molten forms of Jaggery align with previously published values. Through detailed experimental values and measurement conditions, this study adds valuable empirical data for food scientists, who are modeling Jaggery flow behavior or developing Jaggery processing equipment. The viscosity dataset obtained from the experiment offers a foundation for further rheological modeling as well as temperature-dependent and shear-dependent behavior of Jaggery. These are the areas where existing literature is still limited.

Rao, Das, & Das (2008) provide experimental study on how temperature, viscosity, density, thermal conductivity, specific heat, and color change as the concentration process of Jaggery occurs. Their work not only studies sugarcane juice (commonly used in Jaggery), but also studies palmyra-palm and date-palm, which behave differently while reducing sugar content, heating and caramelization. The study identifies three processing zones I–III, where viscosity and boiling point increase slowly at first and then rise rapidly as total soluble solids rise beyond 60% w/w. The study of this nonlinear behavior is especially important because Jaggery quality depends heavily on conditions in Zone III, where temperatures reach 105 – 121 °C and sharp increases in viscosity (from 4.5 to 988 mPa·s for sugarcane juice) make heat transfer more difficult and promote caramelization. The research also shows that juices with higher reducing sugar levels like palmyra-palm and date-palm experience higher boiling point rise and darken faster, owing to composition’s effects on thermophysical changes.

In another study by the same researchers, they investigated the thermophysical properties of granular Jaggery prepared from the same three sources: sugarcane, palmyra palm, and date-palm, with a focus on the influence of moisture content on bulk density, thermal conductivity, thermal diffusivity, and specific heat. Results showed that bulk density and thermal conductivity increased linearly with moisture content, while specific heat followed a nonlinear rising trend, with saturation at higher moisture levels. However, thermal diffusivity showed minimal changes across moisture ranges, remaining relatively constant. The research was conducted employing a line heat-source transient method to measure conductivity and diffusivity, and specific heat was estimated using derived values along with bulk density. This study shows a strong dependence of thermophysical properties on moisture (Rao, Das, & Das, 2008).

A study analyzes the physicochemical and phytochemical characteristics of liquid jagger using the CO86032 sugarcane variety. The authors measured key physical properties and found out Total Soluble Solid (TSS) to be 73 °Brix, specific gravity was 1.4, and viscosity 807 cP. Similarly, chemical analysis showed moisture content of 21%, 0.87% protein, 0.45% fat, a pH of 5.03 a slightly acidic nature, and non-reducing sugars were predominant. Mineral profiling revealed various elements necessary for human nutritional value like potassium, calcium, magnesium, iron, and zinc. They concluded that liquid Jaggery is not only a natural sweetener but also a nutritionally healthy option for sugar with broad potential application in Ayurveda, beverages, and food products (Aralkar, Kshirsagar, Lande, & Agarkar, 2023).

Existing literature study describes that viscosity, density, thermal conductivity, and heat capacity in sugarcane liquids are strongly dependent on soluble solids (°Brix) and temperature. In the prior study, viscosities ranged widely-from ~1.8 to 105 mPa·s for syrups of 50 – 70 °Brix at 35 – 55 °C, yet lacked characterization across full processing ranges. Similarly, prior estimates of thermal properties Specific heat (Cp) were between 1.5 – 3.5 kJ/kg·K and thermal conductivity (k) was 0.38–0.52 W/m·K, which were based on narrow temperature intervals and often neglected process-induced chemical changes such as sucrose inversion, Maillard reactions, or polymer formation. The study adds to previously studied parameters an the present study characterizes juices and syrups collected directly from two NCCS factories using steam versus direct combustion heating. Viscosity increases from 1.4 mPa·s in 31 °Brix juice at 75 °C to more than 165 mPa·s in 71 °Brix syrup at 35 °C, while densities increase from around

1.12 to 1.35 g/mL over 30 –70 °Brix. Thermal conductivity decreases from approximately 0.46 to 0.26 W/m·K with concentration. Measured specific heat capacities ranged from 2.4 –3.8 kJ/kg·K, decreasing consistently with solids content. Property correlations are regressed as functions of temperature and concentration, yielding the most complete and process-relevant dataset to date that can help to predict more accurately the heat transfer behavior-such as nucleate boiling coefficients of 160–290 W/m²·K. It supports the improved design of both evaporation and mixing operations in Jaggery production (Alarcon, Orjuela, Narvaez, & Camacho, 2020).

Molasses displays shear-thinning, flow behavior indices being typically < 1, for instance, $n = 0.80 – 0.93$ over 30 – 60 °C, and that viscosity increases with total solids and decreases with temperature. However, the interactive effect of additives like ethanol had not yet been systematically assessed. The article by the researchers contributes to the literature by providing comprehensive rheological parameters for molasses with 0 – 5% added ethanol in the temperature range 45–60 °C, and shear rates equivalent to 4.8 – 60 rpm. The authors demonstrate that the consistency coefficient decreases significantly with ethanol addition-from 19.51 Pa·s at 45 °C with zero ethanol to 3.61 Pa·s at 5% ethanol-while the value of n increases from 0.756 to 0.938 over the same range, confirming lower viscosity with reduced shear sensitivity (Togrul & Arslan, 2004).

2.2 Technologies for Preparation of Jaggery

The review by Kuruba and team provides an overview of traditional and modern technologies adopted for solid and granular Jaggery production, elaborating on the need to improve processes with regard to meeting increasing market and export demands. The article covers all steps concerning Jaggery production: juice extraction, clarification, boiling, striking point determination, cooling, and molding-while explaining variations in production methodologies in terms of open pan, multi-pan, steam-based, and vacuum evaporation systems. It notes that technological improvements such as furnace design improvement, fins and baffles, multi-pan heating, freeze concentration, steam boiling, and vacuum pan evaporators may lead to high improvement in thermal efficiency, bagasse consumption reduction, and improved product quality and hygiene. Comparing the three different forms of Jaggery: solid, liquid, and granular on the basis of moisture content, striking temperature, and shelf life, the paper has pointed out that the storability and export prospects of granular Jaggery are higher (Kuruba, Rao, Khokhar, & Patel, 2020).

Shiralkar, Kancharla, Shah, & Mahaja (2014) studied the energy efficiency of Jaggery evaporation process in two single pan systems. The objective of their study was to study heat provided for pan during evaporation phase and the quantity of bagasse utilization in respect to the weight of Jaggery produced. The field data measurement found the efficiency of single pan Jaggery ranging from 45-60% equivalent to 1-1.5 kg of bagasse used to 1 kg of Jaggery made. The efficiency of the system can be increased by controlling the air flow through blocking inlet holes in the present setup. An alternative to provide air dampers was also proposed. They concluded the study by pointing out the need for further testing and analysis of multi-pan systems. This study provides a starting point for further increasing the efficiency of the systems.

The molding process of solid Jaggery production uses various kinds of molds such as wooden, aluminum, concrete, and steel. In research conducted about the study of cooling during molding process, the researchers compared the cooling of Jaggery in wooden molds sprinkled with water and aluminum molds. Both molds were rectangular in shape with size of 5×5×10 cm. The readings were taken every minute using thermocouples and the results show decrease in temperature from 105 °C to 62.5 °C in 25 minutes for wooden box and at the same time the temperature was 83 °C for aluminum. Hardness measured for Jaggery obtained from both molds had shown the considerable hardness of wooden box cooled Jaggery only after 25 minutes, whereas aluminum only reached after 18 hours (B, T, & CV, 2018).

There were few research works conducted about the computational fluid dynamics (CFD) application to study heat transfer process in the process of making Jaggery. Kulkarni & Ronge (2018) studied CFD modelling and simulated the heat transfer in open pan Jaggery furnace and compared the obtained data with data measured in the field. They studied a single pan Jaggery furnace with 2.77 m diameter and 1.52 m height and the dimension of the pan was 3 m bottom diameter and 3.4 m top diameter with 0.91 m height. In addition to that, 3 m×3 m trays were used for cooling. For the CFD part, the boundary conditions were set for flue gas and ambient temperature, and the mixed type of thermal conditions were applied with a combination of convection and radiation. The results obtained from the CFD simulation and field measurement agreed with each other with a variation of 8.68% for sugarcane and 5.67% on average for flue gases. This study concluded that CFD simulation tool could be used for analysis of Jaggery making furnaces.

2.3 Cooling and Aeration

In a investigation conducted by (Thorat, et al., 2023), the storage stability of solid Jaggery made from mechanical Jaggery cooling machine was done. The study mainly emphasized on the effect of stirring speed, stirring time, and batch size on the physico-chemical quality and shelf life of solid Jaggery. The stirring speeds for fresh Jaggery preparation were 18, 20, and 22 rpm and the stirring times were 20, 25, and 30 minutes long. The batch sizes taken were 50 and 75 kg which showed 12.57% to 9.53% moisture content, 15.72% to 8.85% reducing sugars, 65.19% to 76.52% non reducing sugars, pH values found between 6.11 and 6.77, and colour absorbance values ranging from 0.34 to 0.15. Improved crystallization and quality was indicated with 22 rpm stirring speed with 30 minutes stirring time for a 75 kg batch, making it the optimum operating condition. In that operating condition, the lowest moisture content of 9.53%, higher non-reducing sugars of 76.40%, and desirable colour (0.16 absorbance units) were observed. When the produced Jaggery was stored for 90 days in a storage study room at temperature 25–28 °C, during which moisture content reduced from 10.45% to 7.69%, pH went down from 6.35 to 6.04, percentage of reducing sugars rose from 8.85% to 9.86%, and percentage of non-reducing sugars declined from 75.51% to 71.01%, meanwhile colour absorbance decreased from 0.182 to 0.153 as a result of oxidation and enzymatic reactions. The product was found to have acceptable quality for up to 3 months. This study demonstrates that mechanically cooled Jaggery improves shelf life, consistency in quality, and reduced physical labour and hygiene issues in comparison to traditional cooling methods.

The effect of stirring time and stage (stirring) temperature has a huge effect on the crystal formation and crystal structure in solid Jaggery making process. With the help of microscopic analysis (SEM), differential scanning calorimetry (DSC) analysis, moisture sorption isotherms, and laboratory-scale experiments, the authors have determined that the crystallization of Jaggery is a process governed by stirring time, cooling rate strategy (stage temperature), and the amount of reducing sugar (RS). According to the study, sucrose crystals are produced effectively when stirring occurs with optimal crystallization observed after 6 minutes of stirring. However, less or over-stirring leads to instabilities in the structural properties or moldability. Moreover, cooling stage temperature strongly promotes the size of the crystals with higher stage temperature values around 90 °C producing larger crystals with longer growth times but lower yields in crystallization. However, rapid cooling assists in the production of small crystals. On the other hand, an increase in the amount of RS from 5.9% to 11.6% substantially lowers the crystallization of sucrose with lower yields from 82% to 69%, along with the development of smaller crystals (Verma, Iyer, Shah, & Mahajani, 2021).

The literature study done above have been summarized in the following table.

Table 2.1: Literature Summary

Authors	Objectives	Study Methods	Results
(Shau, Kumar, Patel, Shau, & Painkra, 2024)	Evaluation of physical and chemical properties of solid and molten Jaggery	Rotatioonal Viscometer at different spindle speeds	Jaggery showed high viscosity acting as potentially non newtonian fluid
(Rao, Das, & Das, 2008)	Investigation of thermophysical properties of granular Jaggery	Experimental measurement	Viscosity and Boiling point slowly increase with temperature
(Rao, Das, & Das, 2008)	Investigation of change in thermophysical properties with moisture	Heat line source transient method for measured data	Bulk density and thermal conductivity increased linearly, specific heat increases non linearly and thermal diffusivity remained constant

(Aralkar, Kshirsagar, Lande, & Agarkar, 2023)	Measurement of physicochemical and phytochemical properties	Experimental measurement	Key physical properties found Presence of minerals
(Alarcon, Orjuela, Narvaez, & Camacho, 2020)	Characterization of juices and syrups obtained from two factories	Experimental measurement and regression analysis	Viscosity increases with brix and decreases with temperature, thermal conductivity decreases, specific heat decreases with brix
(Kuruba, Rao, Khokhar, & Patel, 2020)	Review of technology, methods, improvements and types of Jaggery	Literature study	Storability of granular Jaggery are higher Advances in technology make the process efficient
(Shiralkar, Kancharla, Shah, & Mahaja, 2014)	Study of energy efficiency of Jaggery evaporation process	Field measurement	Efficiency can be increased by controlling air flow
(B, T, & CV, 2018)	Study of cooling during molding process	Experimental observation	Water sprinkled wooden mold had faster molding and hardness than aluminum molds

(Kulkarni & Ronge, 2018)	Modelling and simulation of heat transfer in open pan Jaggery making system	Simulation followed by experimentation	CFD simulation and field measurement agreed CFD applicable to analyse Jaggery making process
(Thorat, et al., 2023)	Study of the effect of stirring speed, stirring time and batch size on storability of Jaggery	Varying time and speed of stirring Property study after 90 days	30 minute stirring at 22 rpm for 75 kg batch had best results
(Verma, Iyer, Shah, & Mahajani, 2021)	Study the effect of stirring time and stage temperature	Laboratory Experiments	Stirring and higher temperature aids crystallization

The process of Jaggery making and the technology used in Jaggery helped understand the role of stirring and aeration in quality of Jaggery. The study has helped determine that the viscosity of Jaggery is temperature and sugar concentration dependent which was useful during simulation phase. Additionally, Jaggery crystal formation, quality and storageability are determined by cooling and stirring phase. The literature study also helped in including CFD anslysis of Jaggery as the objective of the study.

CHAPTER THREE: RESEARCH METHODOLOGY

The goal of this research is to study the heat loss characteristics and the effect of insulation on heat flow characteristics on the crystallization pot used during aeration, stirring and cooling process of solid Jaggery making. The steps involved in methodology of the study tenure are listed in the figure and described in detail.

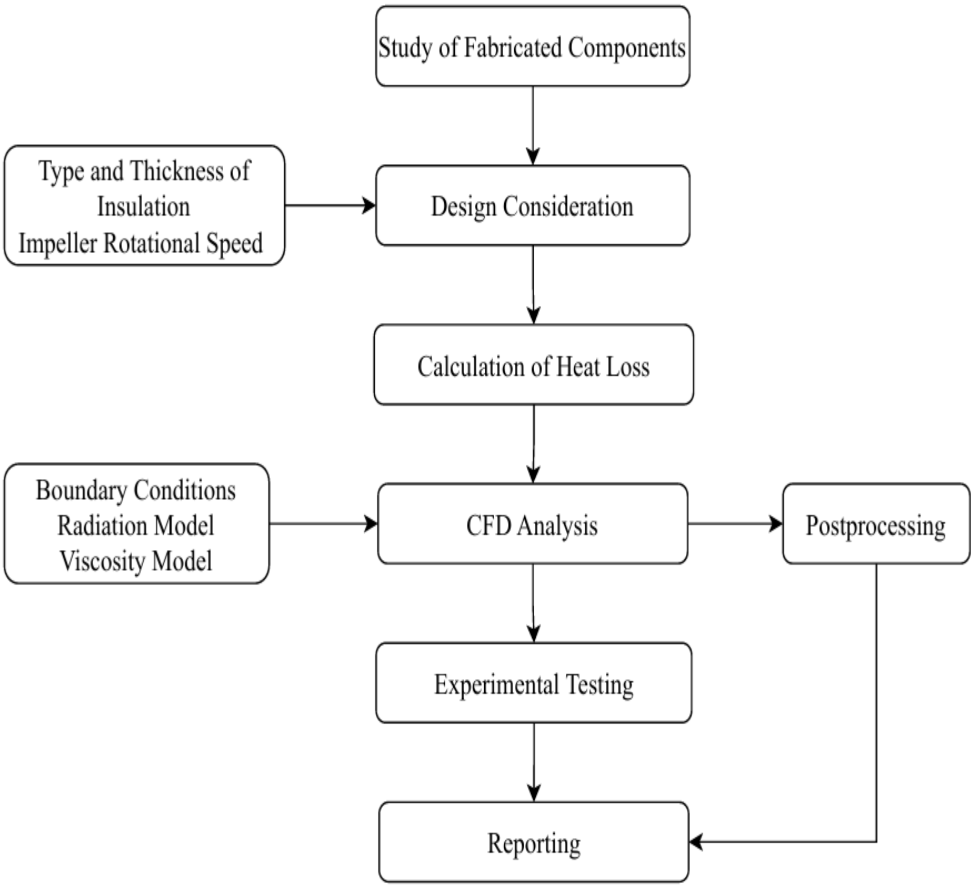

Figure 3.1: Methodology

3.1 Study of Fabricated Components

The study was conducted on a prefabricated setup of Jaggery Processing Machine. Fabrication of Jaggery Processing Machine involved precise cutting, welding, and integration of structural and mechanical components. Then, surface treatments such as heat-resistant and anti-corrosion coatings were performed to enhance durability and ensure food safety.

3.1.1 Description of Jaggery Processing Machine

Key fabricated components in the Jaggery processing machine included (Darlami, 2026):

- Support table: It has a curved-edge top surface mounted on four cylindrical legs, designed with bolted fixtures to securely mount key subsystems. It interfaces with the mould-holding table and provides efficient flow and handling of molten Jaggery during discharge. Additionally, it supports the flat tray through a connecting bush.
- Robot arm: It has a digital control unit for monitoring and adjusting of rotational speed (RPM) and torque. This ensures uniform mixing throughout the cooking process.
- Impeller: It is designed to stir the Jaggery mixture and to maintain uniform consistency during the cooking process. It is attached to the robotic arm and optimized for torque and rotational speed to handle varying viscosities of the molten Jaggery.
- Pouring mechanism: The mechanism includes a crystallization pot with a 20-liter capacity for holding Jaggery and a handle system that manages the tilting and pouring of the Jaggery mixture. It is supported by a ball and bearing for smooth and controlled movement during tilting and pouring.
- Cylinder lock plate assembly: This assembly includes a precisely designed lock plate and a locking bush that securely holds the stirrer in place. This keeps it properly aligned with the crystallization pot’s centre during operation.
- Mould: An appropriate mould size is selected based on market demand and is suitable for packaging and distribution.
- Flat tray: The flat tray is a two-layered structure. The upper layer includes a circular platform that rotates relative to the lower flat surface. The bottom layer is a square base supported by two diagonal braces for structural stability. A central bush connects the tray to the leg of the support table, allowing it to rotate smoothly along the bush's radius.
- Insulation: Insulation used in the setup is a commercially available rock wool with a thickness of 50 mm. This insulation covers the bottom and the side portion of crystallization pot. It is wrapped with food grade aluminium foil to ensure food safety.

The entire system was assembled on a support table constructed using welded joints and bolted fixtures. All critical components, such as the robotic arm and cooking pot, were securely fixed to this frame to maintain stability during operation. Strict adherence to the design specifications was maintained throughout the fabrication process. Quality control protocols were applied at every stage to ensure compliance with mechanical, thermal, and hygiene standards.

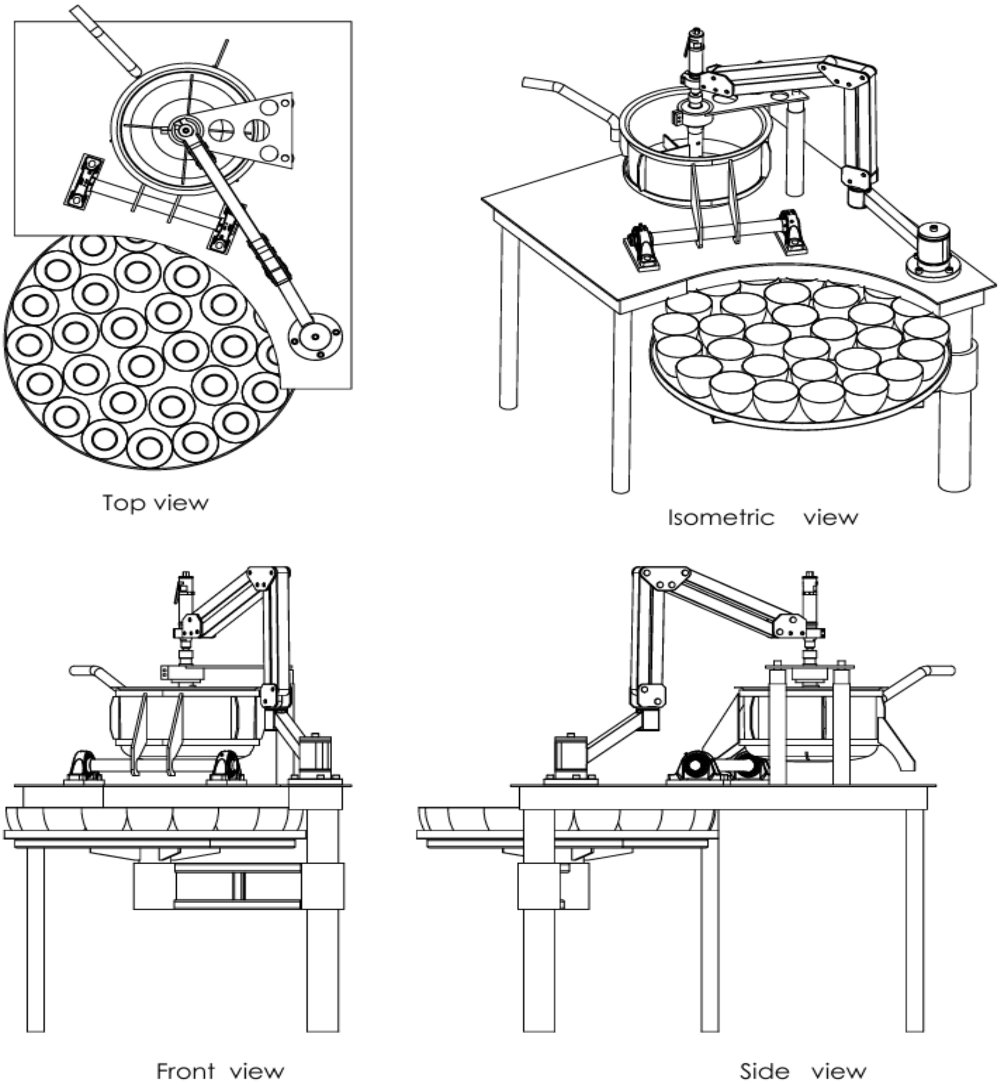

Figure 3.2: Schematic Diagram of Jaggery Processing Machine

3.1.2 Dimensions of the Crystallization Pot

The crystallization pot is the chamber where aeration and stirring of molten Jaggery occurs. The pot is a food grade stainless steel cylinder available in the market.

Table 3.1: Dimensions of Crystallization Pot

Diameter	376 mm
Thickness	3 mm
Height(H)	243.50 mm
Diameter of the Top Ring	432 mm

3.2 Design Considerations

In this study, rock wool insulation of 50 mm was used to insulate the crystallization pot on the outer surface area and the bottom side. The choice of rockwool and the thickness was done according to market availability of the insulation material. The effect on heat loss due to this insulation was studied. To ensure the safety of food material, the rock wool was wrapped by food grade aluminium foil. Additionally, the molten Jaggery is rotated at different speeds for aeration. The maximum speed available from the robotic arm is 150 rpm.

3.3 Calculation of Heat Loss

The heat loss occurs from the crystallization pot and the open surface where Jaggery is exposed to the air. Conductive, convective, radiation and evaporative heat loss need to be calculated to study the rate of cooling after the striking point is achieved in the Jaggery and it is transferred to the crystallization pot. To make the study and calculation simple, various assumptions were made so as these assumptions did not significantly affect the end results.

3.3.1 Heat Loss in the Crystallization Pot

After the sugar syrup is heated, the moisture present in the syrup evaporates and the temperature keeps on increasing. After this temperature increase and moisture loss, there comes a point where heat addition is not necessary. This point is called striking point. The striking point for sugarcane Jaggery is 118 °C to 120 °C (391 K to 393 K) (Aralkar, Kshirsagar, Lande, & Agarkar, 2023). After this point, the molten Jaggery is transferred to the crystallization pot where it is continuously and vigorously stirred. This step is crucial for the quality of Jaggery as incorporation of air in Jaggery is dependent on this step. During this stirring and aeration step, various heat losses occur and the temperature of the molten mass decreases.

The heat transfer from the Jaggery and steel crystallization pot to the ambient environment happens through three surfaces. These three surfaces are the bottom of the pot, the top part of the pot and the cylindrical surface area. At the bottom of the pot, the heat transfer process occurs first from the Jaggery to the steel surface by convection, from steel inner surface to the outer surface by conduction and the outer steel surface from the bottom to the air through convection and radiation. Same thing happens at the side of the cylindrical surface.

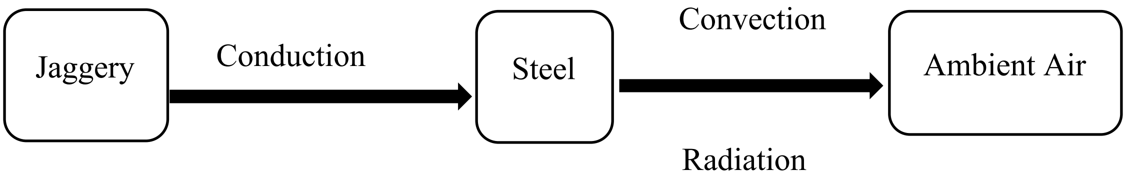

Figure 3.3: Heat loss through bottom and side

The heat transfer or heat loss process on the top open part of the pot is different. In this part, heat loss occurs through evaporation from Jaggery and air and through radiation from the Jaggery surface. Additionally, since the Jaggery is in constant motion, forced convective heat transfer occurs in that surface area.

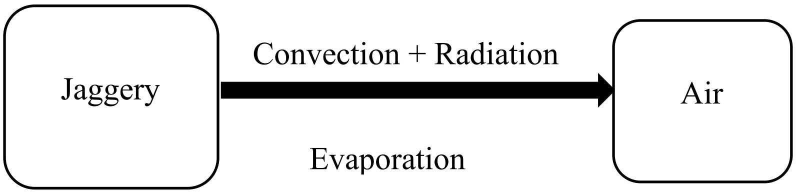

Figure 3.4: Heat Flow from Top Surface

3.3.2 Heat Loss due to Conduction

Fourier's law of heat conduction states that "The rate of heat flow through a simple homogenous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change in temperature with respect to the length of the path of heat flow" (Rajput, 2014).

Mathematically,

$$Q = -kA\frac{dt}{dx} \qquad \text{...(3.1)}$$

where,

Q = Heat flow through a body per unit time (in watts)

A = Surface area of heat flow which is perpendicular to the direction of flow

dt = Temperature difference between two faces of the body

dx = Thickness of the body in the direction of heat flow

k = Thermal conductivity of the body (W/mK)

The negative sign indicates that the temperature decreases in the direction of heat flow.

3.3.3 Heat Lost due to Convection

Heat transfer by convection between a surface and an adjacent fluid is quantified with the help of Newton's law of cooling (Rajput, 2014).

$$Q = hA(t_s - t_f) \qquad ...(3.2)$$

where,

Q = Rate of convective heat transfer

A = Area exposed to the heat transfer

t_s = Surface temperature

t_f = Fluid temperature

h = Coefficient of convective heat transfer (W/m^2K)

i. Convection heat loss from the top

The heat transfer occurring in the open surface of the crystallization pot is more complex than the steel surface. Since the Jaggery inside the crystallization pot is rotating, convective heat transfer coefficient is determined only after knowing if the flow is laminar or turbulent. The flow regime is a function of the velocity of the fluid and the geometry of the surface. By considering Jaggery rotation inside a crystallization pot as external fluid flow on a rotating cylinder with zero axial velocity (Taylor-Couette flow) the rotational Renyolds Number is determined by formula

$$\mathrm{Re}\omega = \frac{\rho \mathrm{VD}}{\mu} \qquad ...(3.3)$$

where,

Re_ω= Rotational Reynolds Number

D = Diameter of the surface

V = upstream velocity (velocity of rotating Jaggery)

μ = Viscosity of Jaggery

For a laminar flow, the convective heat transfer coefficient is a function of Nusselt number (Nu) which is obtained through the correlation of Reynolds number (Re) and Prandtl number (Pr) (Incropera, DeWitt, Bergman, & and Lavine, 2007). The correlation is from the equation

$$Nu = 0.3 + \frac{\mathrm{Re}\omega^{\frac{1}{2}} Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}} \left[1 + \left(\frac{\mathrm{Re}\omega}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \qquad ...(3.4)$$

The convective heat transfer coefficient can be calculated by using the equation (Incropera, DeWitt, Bergman, & and Lavine, 2007)

$$h = \frac{Nu * k}{L} \qquad ...(3.5)$$

where,

k= thermal conductivity of Jaggery (0.0471 W/mK (Meshram, 2017))

ii. Convection heat loss from bottom

The Nusselt number (Nu) for circular flat plate with hot surface up is a characteristics of another dimensionless number known as Rayleigh number (Ral) which is obtained by relation:

$$Nu = 0.27 Ral^{\frac{1}{4}} \qquad ...(3.6)$$

The Rayleigh number is the product of two dimensionless numbers Grashoff number (Gr) and Prandtl number (Pr)

$$Ra = \frac{Gr \times Pr}{D} \qquad \text{...(3.7)}$$

Inserting formula for Grashoff number, the equation becomes

$$= \frac{g \times \beta \times (Ts - T\infty)L^3 \times Pr}{v^2} \qquad \text{...(3.8)}$$

where,

g = acceleration due to gravity (9.81 m/s^2)

β = volumetric expansion rate (1/T$_{abs}$)

T$_s$ = Temperature of hot surface (118 °C)

T$_\infty$ = Ambient Temperature (25 °C)

v = Kinematic viscosity of air at ambient temperature (1.55 × 10^{-5} m^2/s)

iii. Convection heat loss from side

Similarly, for the cylindrical side of the crystallization pot, the value of Rayleigh number is obtained from equation 3.8. For cylindrical surface, the Nusselt number comes form the expression (Incropera, DeWitt, Bergman, & and Lavine, 2007):

$$Nu = 0.60 + \frac{0.387 Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.599}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \qquad \text{...(3.9)}$$

3.3.4 Heat Lost due to Radiation

Among the laws of radiation, Stefan-Boltzann law is used to calculate radiation heat transfer from a body. The law states that "The emissive power of a black body is directly proportional to the fourth power of its absolute temperature (Rajput, 2014).

$$Q = \varepsilon \sigma A(T_1^4 - T_2^4) \qquad \text{...(3.10)}$$

where,

ε = Emissivity of the surface

σ = Stefan Boltzmann Constant ($5.67*10^{-8}$ W/m^2K^4)

A = Surface area

T_1 = Temperature of heat source in kelvin

T_2 = Temperature of receiver in kelvin

3.3.5 Heat lost by Jaggery

Heat is lost by Jaggery as sensible heat and heat loss due to the evaporation of moisture.

i. Sensible Heat Loss

The total amount of heat energy lost by mass of Jaggery ($Heat_{Jaggery}$) going from 118 °C to 75 °C can be calculated by using the formula

$$Heat_{Jaggery} = M_J S_J (T_1 - T_2) \qquad ...(3.11)$$

where,

M_j = Mass of Jaggery

S_j = Specific heat of Jaggery at 118 °C (2970 KJ/kgK) (Kuruba, Rao, Khokhar, & Patel, 2020)

T_1 = Temperature of Jaggery when it is transferred from open pan to crystallization pot (118 °C)

T_2 = Temperature of Jaggery after heat loss (75 °C)

ii. Heat Lost due to Evaporation

When the water changes its phase from liquid to vapor, it carries some amount of heat to change its phase (Rajput, 2014). It is given by formula:

$$Q = m \times h_{fg} \qquad ...(3.12)$$

where,

Q = Heat loss due to evaporation

m = mass of water lost due to evaporation

h_{fg} = Latent heat of vaporization of water

3.4 Experimental Testing and Analysis

A test setup in the machine was prepared after the completion of calculations. Firstly, preliminary testing was done in water for the ease and availability. This test was extended for Jaggery at different rotational speeds. When this test was completed, another setup introduces the insulation around the crystallization pot, and the heat losses will be measured. After getting the values from the measurement, calculation was done, and the data was compared to the values achieved from experiment and CFD analysis.

3.4.1 Experimental Setup

The Jaggery Processing Machine has been fabricated. To conduct the performance testing of the machine as well as cooling characteristics of the crystallization pot, the experiment was done in three different speeds. By varying the speed, Jaggery was cooled from the striking point to 75 °C and temperature was noted for each minute. In addition to that, another experimental setup introduces 50 mm rock wool insulation on the bottom of the pot and at the cylindrical part, while there was no change in the top open part of the cylindrical pot. After Jaggery reached striking point, it was transferred to the crystallization pot with insulation.

3.4.2 Measuring Process

After the liquid Jaggery was transferred to the crystallization pot when it attains striking point, the measurement of temperature is done. The temperature was continuously monitored in a few intervals for consistent value by a contact thermometer. Additionally, the speed of rotating impeller was varied using the robotic arm which has a touch screen hub and a display screen attached to the arm.

3.4.3 Measuring Instruments

Following measuring instruments will be utilized to measure temperature and time of the cooling.

i. Contact Thermometer

The contact thermometer used in the experimental measurement process is a FLUKE 53 II Temperature thermometer. It has a precision on 0.1 units and allows temperature measurement of solids as well as liquids. The front panel is backlit and makes it easy to view results. This thermometer has a measurement range of -200 to 1372°C.

ii. Stopwatch

The stopwatch used during experimentation was a mobile digital stopwatch with a precision of 0.1 second. It had start and stop functions and lap function.

3.5 Computational Fluid Dynamics Analysis

A CFD analysis of the system was done for both with and without insulation. A student version of ANSYS Fluent software which is ANSYS Student 2025R2 was selected for this study. The construction of the system was done in designmodeler and the meshing was done in meshing. The setup was performed in fluent with CFD solution. The analysis contains following steps:

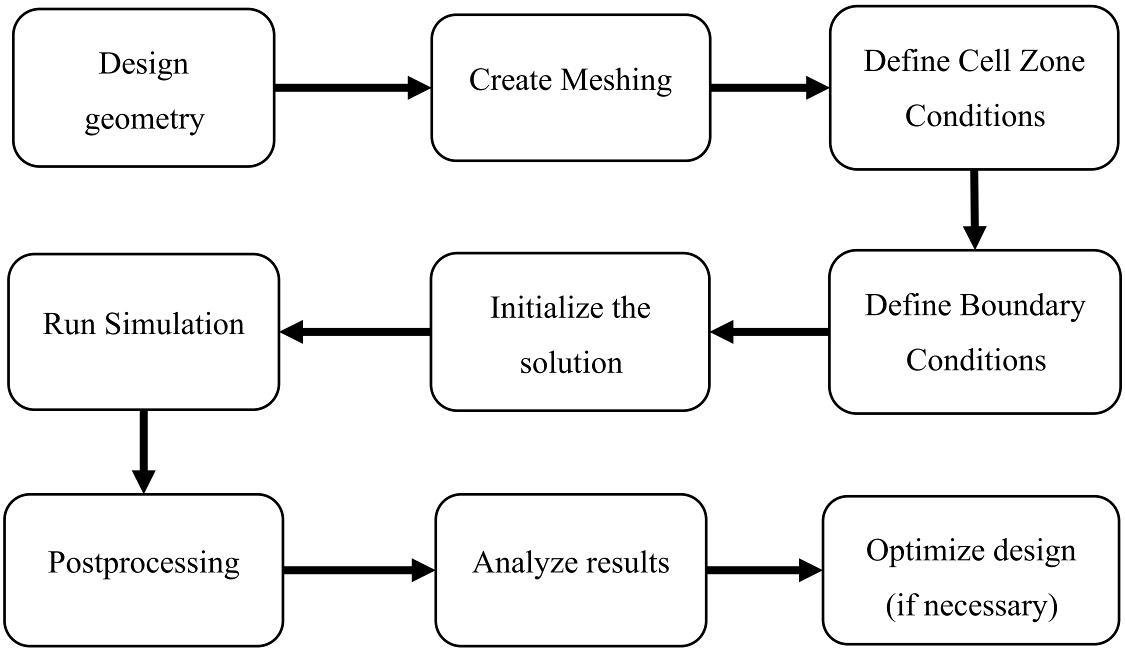

Figure 3.5: Step-by-step procedure of the CFD analysis

3.6 Reporting

The reporting step is an ongoing process from the beginning of the study to the end. The reporting began with the literature review to the calculation, analysis of the obtained results from the calculation, simulation and testing. A final report was made after the completion of project.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Heat Energy Carried by Jaggery

An initial mathematical calculation of heat loss provided the scale of heat loss from the Jaggery system. When heated Jaggery is transferred to the crystallization pot after the striking point, the temperature of Jaggery is around 118 °C. Although the ambient temperature is assumed to be 12 °C , the pouring of the molten Jaggery occurs earlier. Let the temperature at which Jaggery is poured in the molds is 75 °C. At that time, the total amount of heat energy lost by mass of Jaggery ($\text{Heat}_{\text{Jaggery}}$) going from 118 °C to 70 °C with density 1440 kg/m^3 (Pathak, et al., 2024) and the volume of Jaggery is 20 L, mass of Jaggery is 28.8 kg is 4,961,088 J. This heat is the basic estimation of how much heat is carried by Jaggery that provides an initial way calculating heat losses.

4.2 Heat Transfer from the Crystallization Pot

When considering the heat transfer by conduction from Jaggery to steel plate, the thickness of steel plate is 3 mm resulting in almost no resistance by the steel plate. The steel was able to reach thermal equilibrium with Jaggery in few seconds. As a result, for simplification purposes, it is assumed that the outside layer of crystallization pot is in the same temperature as Jaggery. So, now only the heat transfer by convection and radiation were considered during the calculation. The temperature of Jaggery is 118 °C while the ambient temperature is assumed to be 12 °C. The area of the top and bottom surfaces of the cylindrical pot is 0.111 m^2 and the cylindrical surface is 0.287 m^2. The convective and radiative heat losses are tabulated. The coefficient of convection for the to surface is 35 W/m^2K, while for the cylindrical side and bottom surface are 6.21 W/m^2K and 4.09 W/m^2K obtained after calculation (Annex 1). The emissivity of steel is 0.35 and Jaggery is 0.95 (Transmetra).

The heat transfer or heat loss process on the top open part of the pot is different. In this part, heat loss occurs through convection from Jaggery and air and through radiation from the Jaggery surface. Moreover, evaporative heat loss due to loss of moisture during aeration is another major heat loss in the open side. Additionally, since the Jaggery is in constant motion, forced convective heat transfer occurs in that surface area.

Table 4.1: Sensible Heat Loss from Crystallization Pot

Heat Loss	From Top	From Side	From Bottom
Convection	411.81 W	159.95 W	48.12 W
Radiation	100.29 W	80.89 W	36.95 W
Total	512.10 W	240.84 W	85.07 W

ii. Heat Transfer due to Evaporation of Moisture

When the water changes its phase from liquid to vapor during stirring and aeration, it carries some amount of heat to change its phase. This water escapes from the open part of crystallization pot. At the initial phase of stirring process, the moisture content of the mixture is 15% (Pathak, et al., 2024). This moisture level decreases to 5-7% while preparing solid Jaggery (Selvi, Mathialagan, & Mohan, 2022). The evaporated mass of moisture is 2.48 kg (Annex 1). Therefore, heat loss due to evaporation with latent heat of vaporization of water 2260 KJ/kg becomes 5608.52 KJ (Annex 1).

4.3 Experimental Testing

The experimental testing phase evaluates the actual performance of the Jaggery making machine and the cooling characteristics of the crystallization pot. The testing was done for different setups and for different rotational speed of the impeller. Initial performance testing was conducted on water with and without thermal insulation at different rotational speeds. This experiment was then duplicated with Jaggery. At the last stage of experimental testing, one specific rotational speed was selected and the cooling charagteristics of Jaggery was observed with and without the presence of rock wool insulation.

4.3.1 Performance Testing in Water

As a baseline and approximation of cooling characteristics of Jaggery, the cooling test was first performed in water. Water is freely available and the properties of water are measured and known. Additionally, water does not go through increased viscosity at reduced temperature and does not show non-Newtonian behavior. Conducting the experiment in water provided a starting point for understanding the experimental procedure for Jaggery. For this, cooling test was performed for the same crystallization pot where Jaggery would be cooled. First, the test was done for three different rotation speeds of the impeller 25 rpm, 50 rpm and 75 rpm without insulation. This test was again repeated with same rotating speeds after the introduction of 50 mm rockwool insulation.

i. At 25 rpm

15 liters of water was heated to its boiling point in a separate container, and it was transferred to the crystallization pot. Then, the impeller rotation started at 25 rpm. Temperature was noted each minute with the help of contact thermometer which had a precision of 0.1 °C. The process was continued until the temperature reached 60 °C. Same process was repeated for the same rotational speed after the introduction of insulation of 50 mm.

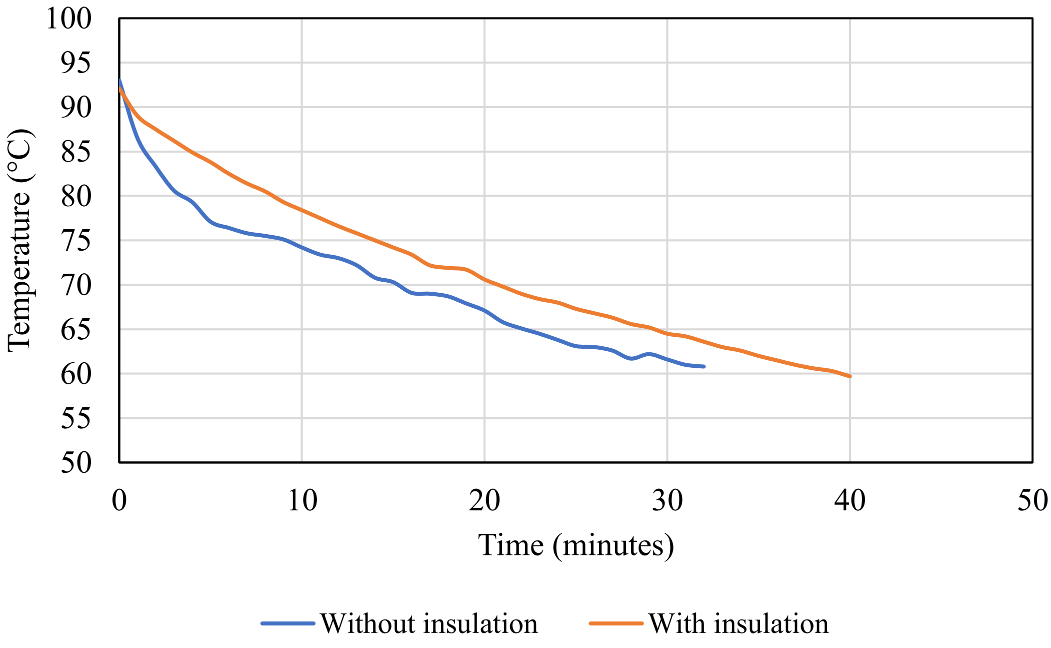

Figure 4.1: Temperature at 25 RPM before and after insulation

The Figure 4.1 compares the transient cooling characteristics of 15 liters of water in the crystallization pot with and without 50 mm rock wool insulation under identical operating conditions. For both cases, the temperature decreased linearly with time from an initial value. When the crystallization pot was not insulated, the temperature decline was less than the insulated pot. While the water from uninsulated pot reached 60 °C in 33 minutes from 98 degree initially, the water inside the insulated pot was able to attain the same temperature from 92.1 degree at around 40 minutes. This shows the rate of cooling 0.81 °C per minute with insulation and 1.13 °C per minute with insulation. The temperature is consistently higher when insulated when it is not insulated.

ii. At 50 rpm

Similar to 25-rpm rotational speed, the experiment was repeated for the impeller speed of 50 rpm for both with and without insulation of crystallization pot.

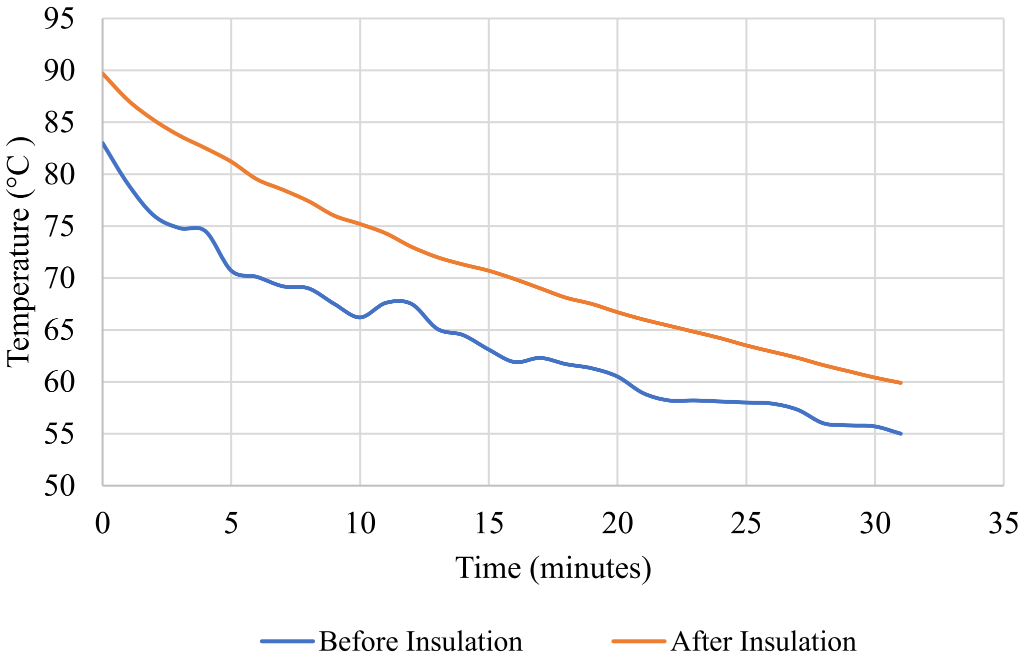

Figure 4.2: Temperature at 50 RPM before and after insulation

From the Figure 4.2, it is evident that the insulated cooling rate shows a steeper downward trend than that of uninsulated cooling rate for the crystallization pot. Before the introduction of insulation, the temperature of water reached 60 °C in 20 minutes. This time has increased to 30 minutes after insulation was introduced. Temperature of water in the insulated system remains higher than the uninsulated system throughout the observed time.

iii. At 75 rpm

The rotating speed was further increased to 75 rpm from 50 rpm for another set of experiments. Like previous two setups, cooling rate was determined with and without insulation.

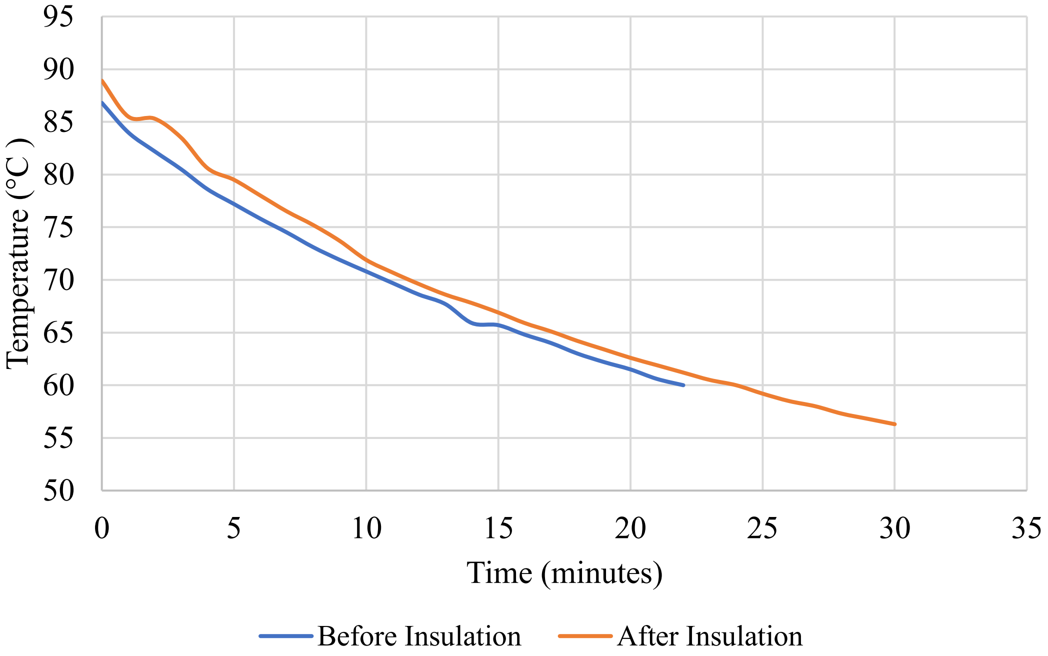

Figure 4.3: Temperature at 75 RPM before and after insulation

Like the cooling rate at 25 and 50 rpm, introduction of insulation slows down the cooling rate of water. The graphs show that the cooling rate was 1.21 ° C per minute without insulation, the rate dropped down to 1.08 °C per minute after the introduction of insulation.

When the rate of cooling with and without insulation was compared, it was observed that introduction of insulation slowed down the rate of cooling. Insulation can be an effective way of regulating cooling and aeration behavior during Jaggery crystallization. Additionally, slower cooling rates were observed in lower rotating speeds than higher rotating speeds. The slowest cooling rate was observed at 25 rpm rotation with insulation while the fastest cooling was at 75 rpm without insulation. Higher speed results in continuous surface renewal as well as mixing resulting in higher rates of convection as well as evaporation from the surface. This phenomenon can be attributed to the faster rate of cooling at higher rotational speed.

4.3.2 Experimental Testing in Molten Jaggery

After the cooling characteristics were obtained from water, the same experimental testing was done in Jaggery with and without the insulation. Molten Jaggery (khudo) was heated up to 118 °C, its striking point, and it was allowed to cool to 75 °C at different rotating speeds.

i. At 25 RPM

The molten Jaggery was heated with the help of gas burner and the heated Jaggery was poured into the crystallization pot. Then the heated Jaggery was rotated with the help of impeller. The rotational speed was set at 25 rpm with the help of the robotic arm connected to the impeller.

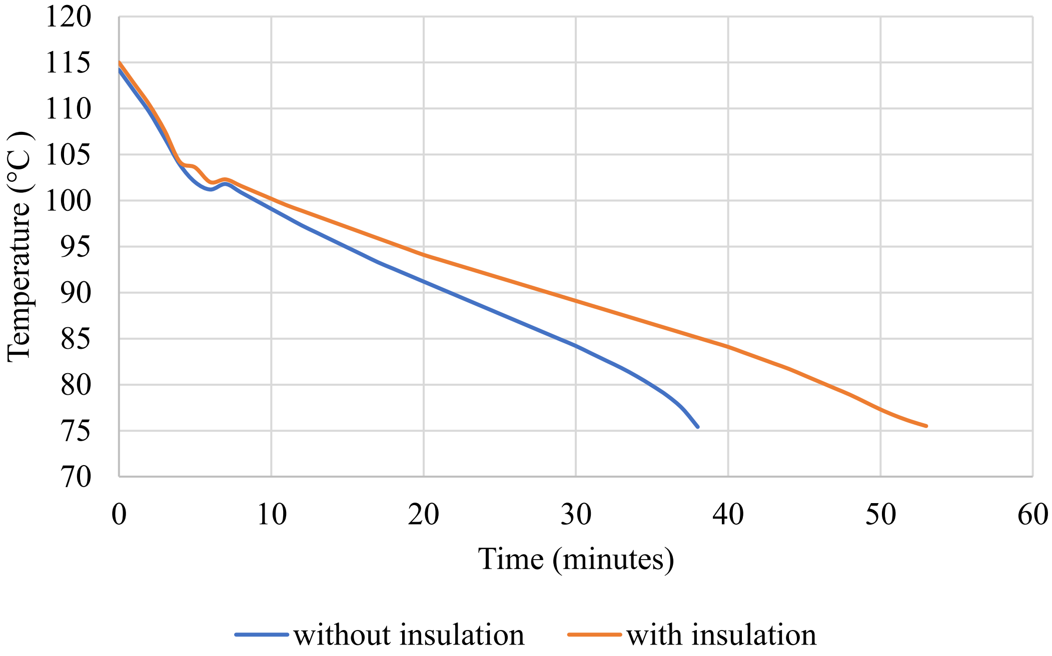

Figure 4.4: Temperature of molten Jaggery at 25 RPM before and after insulation

At the rotational speed of 25 rpm, the cooling curve of the molten Jaggery without insulation is steeper than the cooling curve with insulation. The temperature of the Jaggery without insulation and the temperature of Jaggery after insulation at the initial phase are similar in characteristics. This trend deviates as the temperature of the system decreases. Without insulation, 75 °C was achieved in 38 minutes. The same temperature of Jaggery can be observed at 52 minutes when thermal insulation was achieved around the crystallization pot.

ii. At 50 rpm

For the next set of testing, the rotational speed was increased to 50 rpm with the help of the robotic arm. Same experiment was repeated for this increased speed.

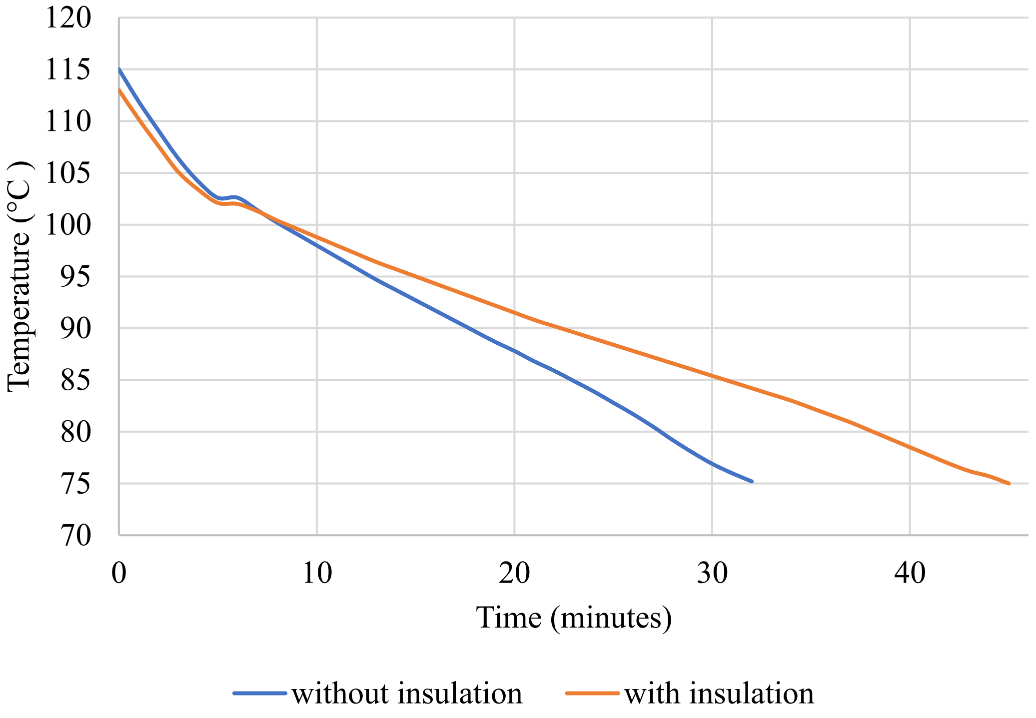

Figure 4.5: Temperature of molten Jaggery at 50 RPM before and after insulation

At 50 rpm, the cooling characteristics with and without insulation show similar characteristics as that of 25 rpm. The temperature of uninsulated system is higher than insulated system initially. After some time, the temperature of insulated system becomes higher than uninsulated system. The reverse trend is observed once the insulation that is initially in ambient temperature gains heat from Jaggery and comes in thermal equilibrium with the system. Although the cooling curves show similar nature, cooling rate is faster at 50 rpm speed. Molten Jaggery reached 75 °C in 45 minutes with insulation and 32 minutes without thermal insulation.

iii. At 75 rpm

For the third time, experiment was repeated from repeated for 75 rpm rotational speed of the impeller.

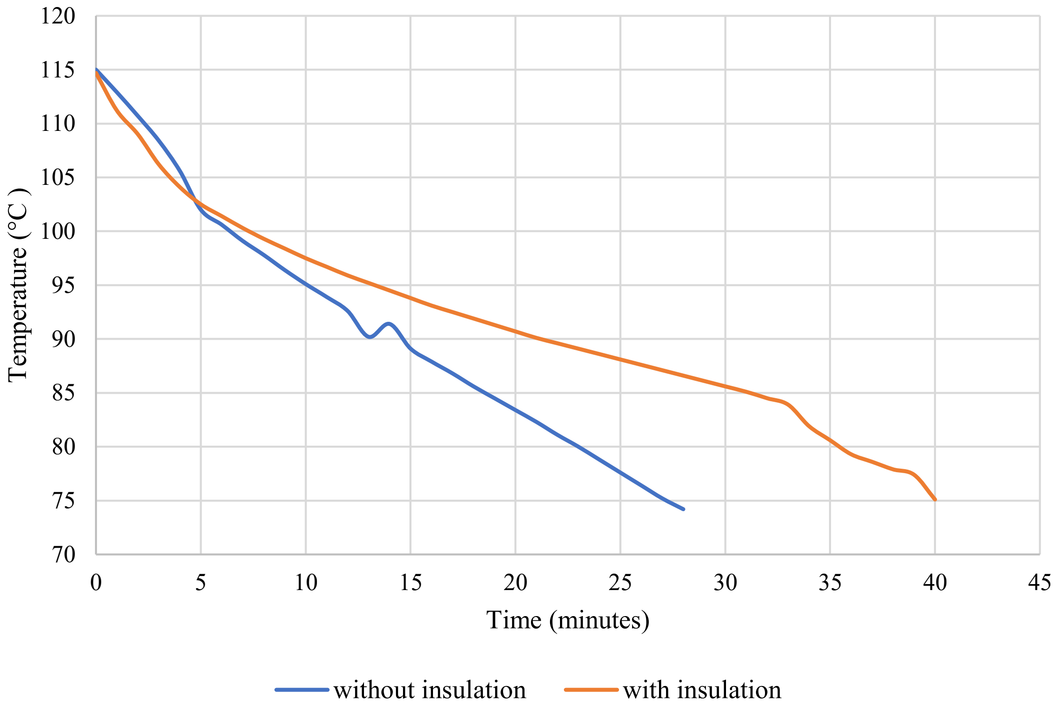

Figure 4.6: Temperature of molten Jaggery at 75 RPM before and after insulation

The temperature declines as well as subsequent the cooling rate was similar in characteristics to the previous setups. However, the temperature difference at the end was less pronounced than at lower rpm. It takes time for the insulation and Jaggery to reach thermal equilibrium. Since the temperature decreases faster with higher rotational speed, this result is as expected. At 28 minutes, the uninsulated system reached 75 °C, meanwhile, the insulated Jaggery took 40 minutes for the same temperature.

Comparison between insulated and non-insulated cases

When comparing the effect of insulation on cooling characteristics, the cooling rate is higher in insulated system than the uninsulated system at the beginning. This trend becomes reverse after some time. While the pot is insulated, heat is lost by the Jaggery faster because the temperature of the insulation is at ambient temperature. As it comes in contact with hotter Jaggery, the temperature of the insulation increases first. As a result, the temperature of the insulated system is lower than the uninsulated system initially. After the Jaggery and insulation reach thermal equilibrium, the rate of cooling of Jaggery is slower than the uninsulated system. Thermal insulation provides effective resistance against heat loss from the sides and bottom reducing the effective cooling rate. The effect of insulation was more pronounced at lower rotational speeds than at higher speed. At 25 rpm, Jaggery cooled to 75 °C 15 minutes slower when insulated while the difference was 13 minutes for 50 rpm and just 12 minutes for 75 rpm.

Regarding the effect of rotational speed, the higher rotational speed cools the system faster than the lower rotational speed as expected. For the uninsulated crystallization pot, the temperature of Jaggery reached 75 ° C in 38 minutes for 25 rpm rotation, 32 minutes for 50 rpm rotation and 28 minutes for 75 rpm. After the addition of insulation, the same temperature reached 53 minutes at 25 rpm, 45 minutes at 50 rpm and 40 minutes at 75 rpm. The effect of rotation in cooling is higher because higher speed results in continuous surface renewal as well as mixing resulting in higher rate of evaporation and convection from the top surface.

Higher stirring time has been observed when insulation was introduced around the crystallization pot. At 75 rpm, the stirring time is enough so that aeration occurs effectively. However, this time is not very long since the quality of the Jaggery declines due to over stirring. As a result, the longer stirred time at 75 rpm with insulation results in better quality of Jaggery which is also supported by existing literature (Thorat, et al., 2023). In addition to that, when the stage temperature or stirring temperature is higher, smaller and more uniform crystals are formed indicating high quality Jaggery (Verma, Iyer, Shah, & Mahajani, 2021). Introducing insulation around the crystallization pot effectively helps keep the system at higher temperature as indicated by both simulation and experimentation.

4.3.3 Final Experimental Testing

Again, the molten Jaggery was heated up to 118 °C and poured into the crystallization pot to study the heat loss characteristics for insulated and uninsulated system. The ambient temperature was 12 °C for all the experiments. For this final stage, rotational speed was fixed at 75 rpm. The experiment was repeated three times to achieve consistent results. The same experimental procedure was repeated with 50 mm rock wool insulation. Jaggery was heated up to 118 °C and cooled down to 75 °C. Figure 4.7 illustrates the variation of temperature with time for the system with and without insulation.

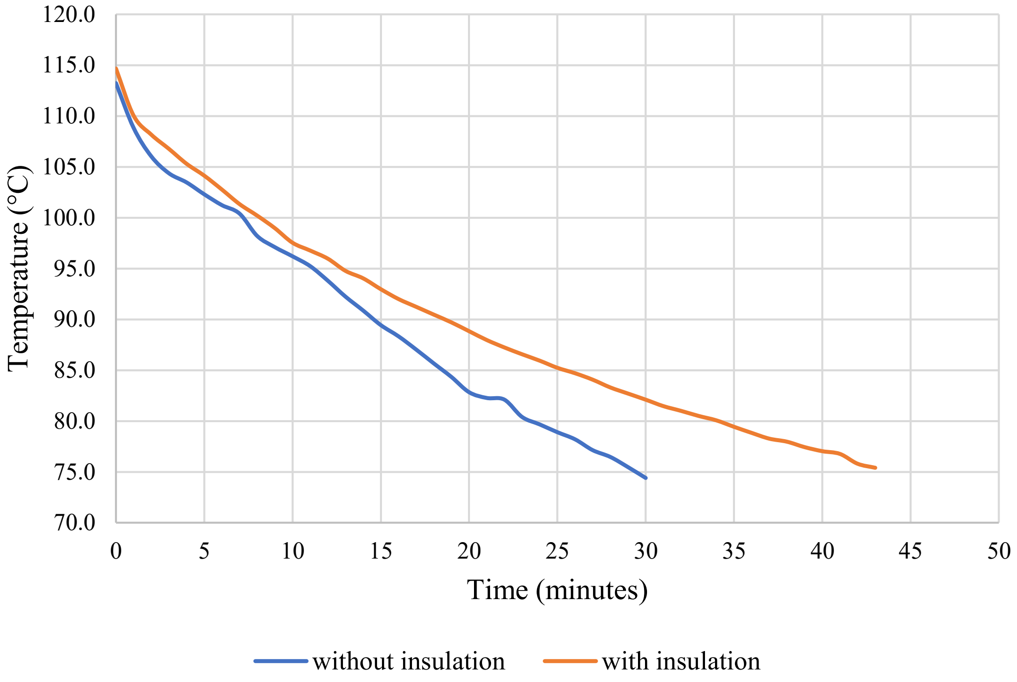

Figure 4.7: Temperature of Jaggery at 75 rpm with and without insulation

In both graphs, the temperature decreases gradually from the initial value, indicating a reduced rate of heat loss due to the insulating effect. The similar downward trends in both cases confirm that insulation effectively limits heat transfer to the surroundings and helps maintain higher temperatures for a longer duration. Similar characteristics were observed earlier when the experiment was conducted at 75 rpm.

The repetition of the experiment shows consistent results, thereby confirming the reliability of the observations and the effectiveness of insulation in improving thermal retention and overall system efficiency. Although minor variations in the temperature profiles can be seen, these differences are negligible and may be attributed to experimental conditions or measurement uncertainties. The repetition of the experiment under insulated conditions produces consistent results, which strengthens the reliability and reproducibility of the observations.

4.4 Computational Fluid Dynamics Analysis

A simulation study or Computational Fluid Dynamics (CFD) of heat loss characteristics analyses how thermal energy is lost from a system and temperature changes under different operating conditions and boundary conditions using numerical models. It helps to identify the dominant modes of heat transfer (evaporation, conduction, convection, radiation) and understand the processes that cannot be measured through experiment. For CFD analysis of the crystallization pot, ANSYS Student 2025 R2 software student version was used which is freely available for download. Ansys Workbench was used to create a system and Designmodeler for geomety. Later Meshing was used for meshing and Fluent for the setup. The simulation setup was run for two different systems: one without insulation and one with insulation.

4.4.1 Geometry

The geometry was designed with Designmodeler according to the dimensions of the body. It contains a steel cylinder of thickness of 3 mm. The cylinder was filled with molten Jaggery and this Jaggery was rotated with the help of impeller at 75 rpm. The geometry setup of pot, Jaggery and the impeller is as as shown in the figure. Later, a 50 mm rock wool insulation was also modelled on the walls of the system leaving the top part open.

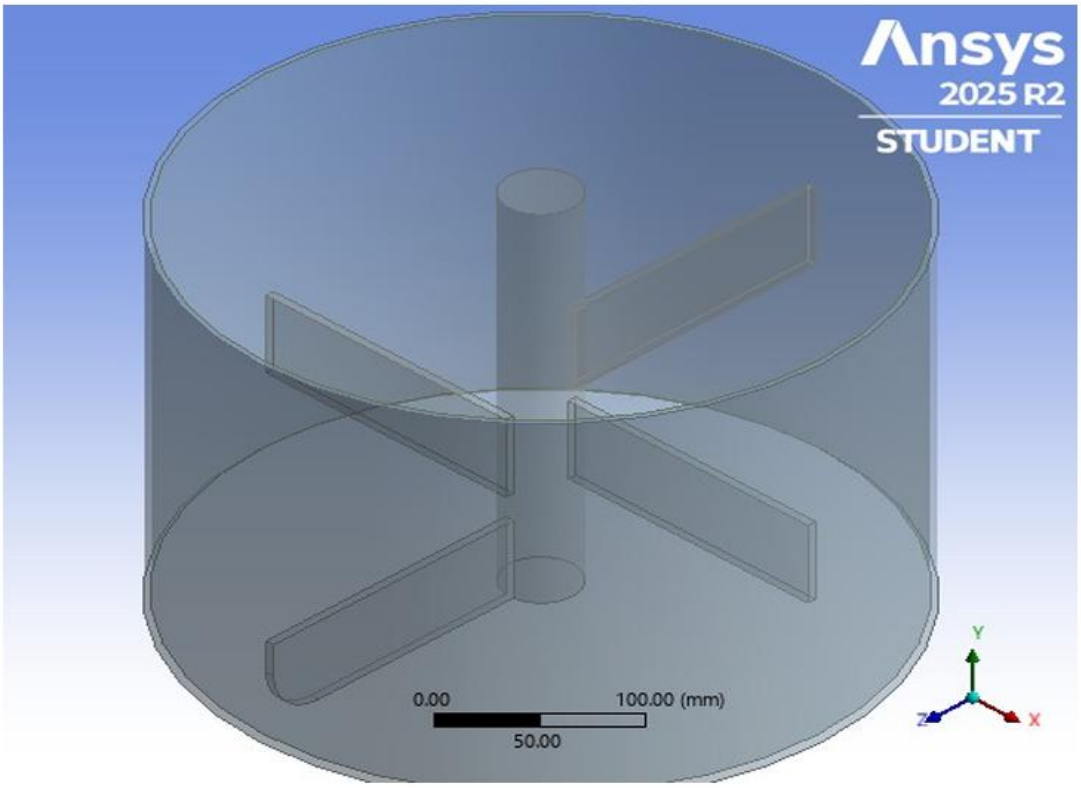

Figure 4.8: System Geometry

To simplify CFD and meshing, some assumptions have been made that have no significant impact on the overall values obtained for heat loss and temperature profile. The assumptions are:

i. The heat is lost from the top portion as the moisture leaves the system. This heat loss has been applied as an overall coefficient of convection from the top portion.
ii. The impeller rotation has been removed and the rotational motion has been directly provided to the Jaggery which produces same results as impeller rotation.
iii. Although insulation has been wrapped with aluminium foil, the effect of heat loss due to aluminium foil has been neglected due to its very small thickness.

The simplified geometry of the system has a rotating Jaggery body nested inside stationary body of Jaggery. The rotating part was named impeller and the remaining portion was named Jaggery. The rotating body has the radius and the height of the impeller that produce rotational motion. The rotational body and the Jaggery body were assigned two different materials to seperate their rotating and non rotating motion. The non-rotating body has been provided with default material and the rotating body is assigned frozen material from the geometry setting of ANSYS. The simplified version of the system shows a body with the rotational motion inside a Jaggery body.

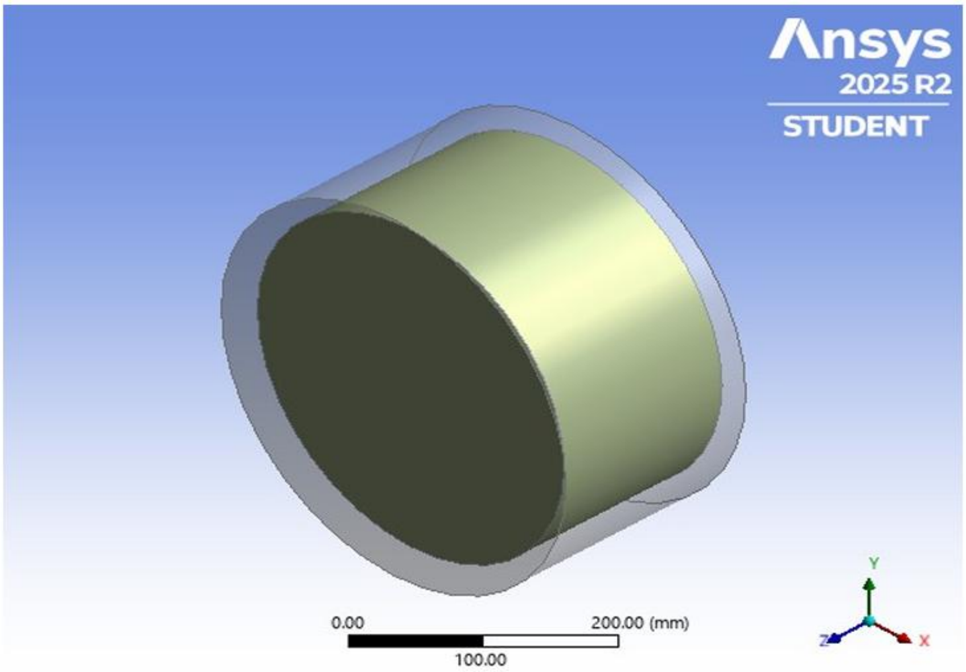

Figure 4.9: Simplified Geometry of the Uninsulated System

For insulated system, 50 mm rock wool was modelled around the bottom and cylindrical side of the crystallization pot.

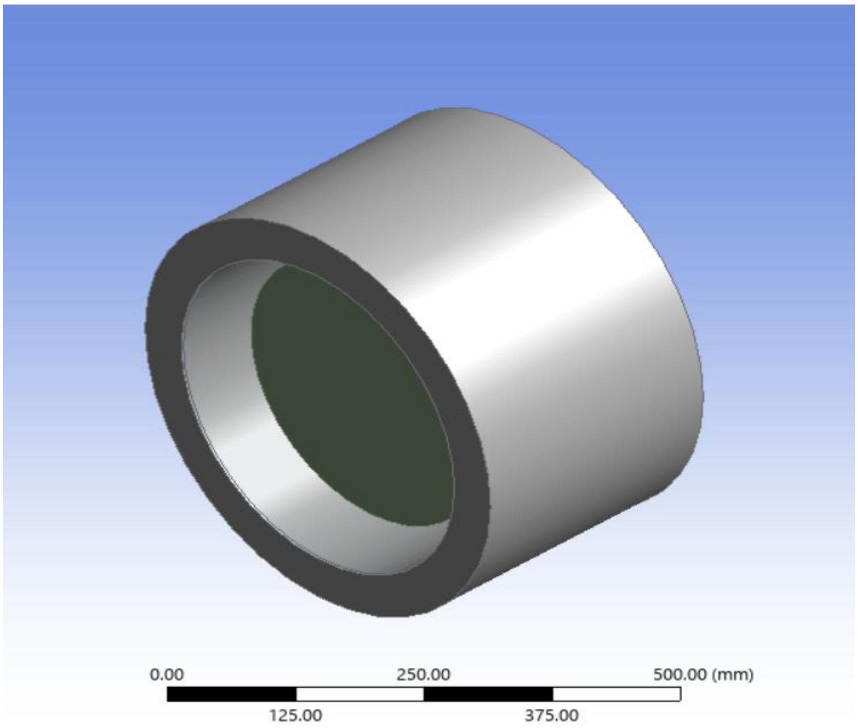

Figure 4.10: Geometry of the Insulated Crystallization Pot

4.4.2 Meshing

Meshes were created for the geometry using ANSYS Meshing tool. The separate bodies were provided with tetrahedron volume meshes. While the rotating body was meshed from automatic mesh method, the outer body was meshed using patch confirming method with tetrahedron meshes. The boundary layers were provided with inflation layers to properly simulate the heat transfer through the walls. The element size was 6 mm. The meshing structure of the system is as follows with 227891 nodes and 498290 elements with separate meshing for rotating body and Jaggery.

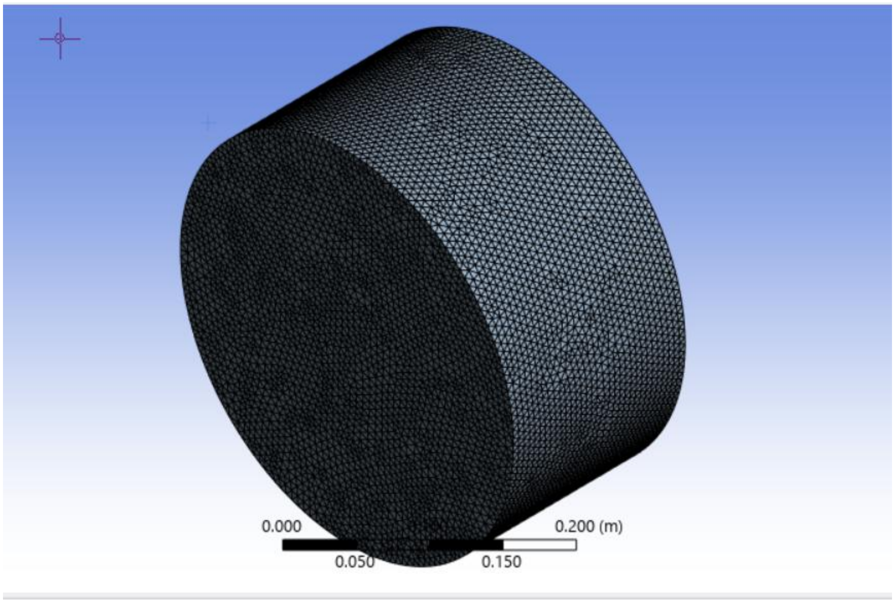

Figure 4.11: Mesh Structure of Impeller

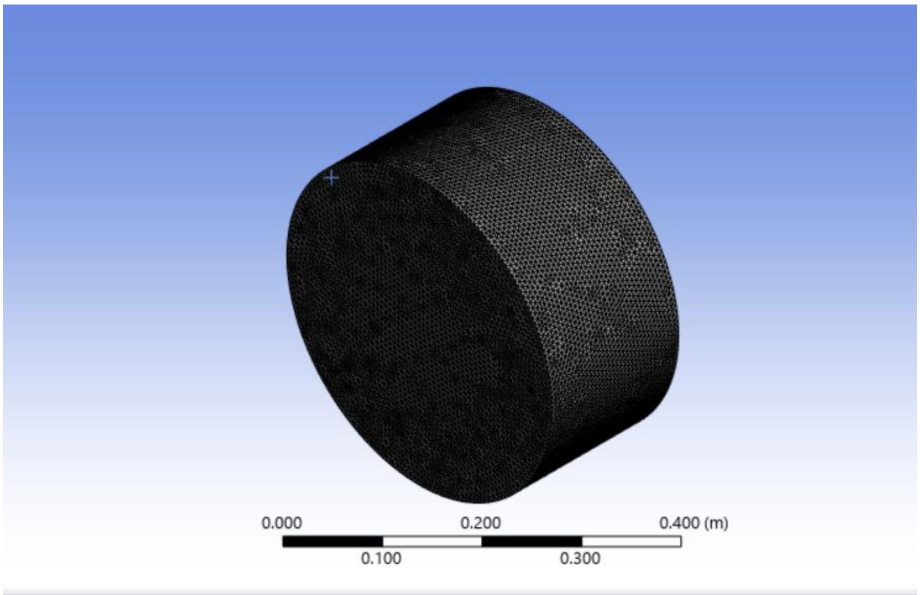

Figure 4.12: Mesh Structure Jaggery

For the insulated system, tetrahedral meshes were created with 7 mm element size. Altogether, 261,140 nodes and 914,895 elements were created. Inflation layers were introduced in the Jaggery-insulation interface and insulation surface for accurate calculations.

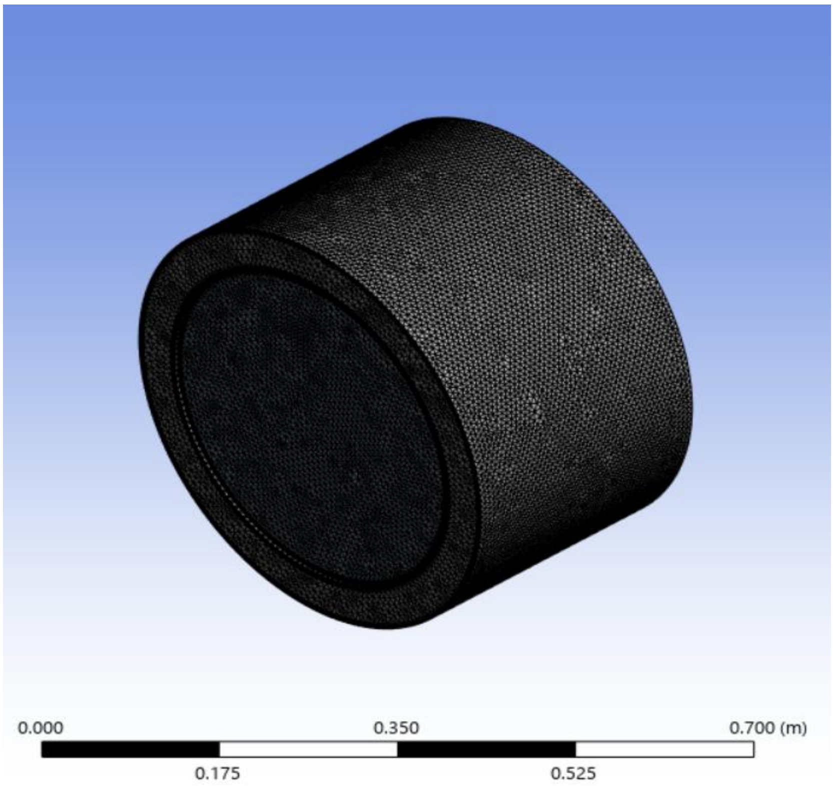

Figure 4.13: Mesh of Insulated System

4.4.3 Setup and Solution

This conducts the actual calculations inside the ANSYS Fluent. The CFD solution was selected to solve the equation. The boundary conditions and cell zone conditions are listed in Annex 4. The energy equation was turned because it is necessary for heat transfer solution. Viscosity profile was sst-ω and the radiation heat was selected to be discrete ordinate. Density, specific heat, thermal conductivity and viscosity were assigned for Jaggery. The rotating part was assigned a roating speed of 75 rpm along Z-axis. For boundary conditions, the ambient temperature was fixed at 285 K (12 °C) and the emissivity of Jaggery and steel were assigned 0.95 and 0.35. The effect of gravity along Z-axis was turned on and the system was sloved for transient characteristics. For the solution, the initialization was started with temperature of 113 °C or 386 K. The time step was 10 s and each time step had 5 iterations. The solution was started and all the values converged.

For the insulated system analysis, the Jaggery and impeller temperature were patched at 114 °C or 387 K. However, the outside insulation was exposed to the ambient temperature with other convective heat loss coefficients remaining the same and emissivity changed accordingly. Other parameters remained the same for insulated system as the uninsulated system.

4.4.4 Post Processing

The heat loss from different surfaces, as well as the overall heat loss of the pot, was observed in case of insulation and without insulation. Additionally, temperature versus time plot, total heat loss, convection and radiation heat loss plots were also obtained.

4.5 Jaggery Temperature

Temperature of Jaggery was measured experimentally and compared with the data obtained from simulation.

4.5.1 Without insulation

Initially, simulation was conducted for the system without insulation, the decline in temperature with time was studied. This data was compared with data obtained from the experiment.

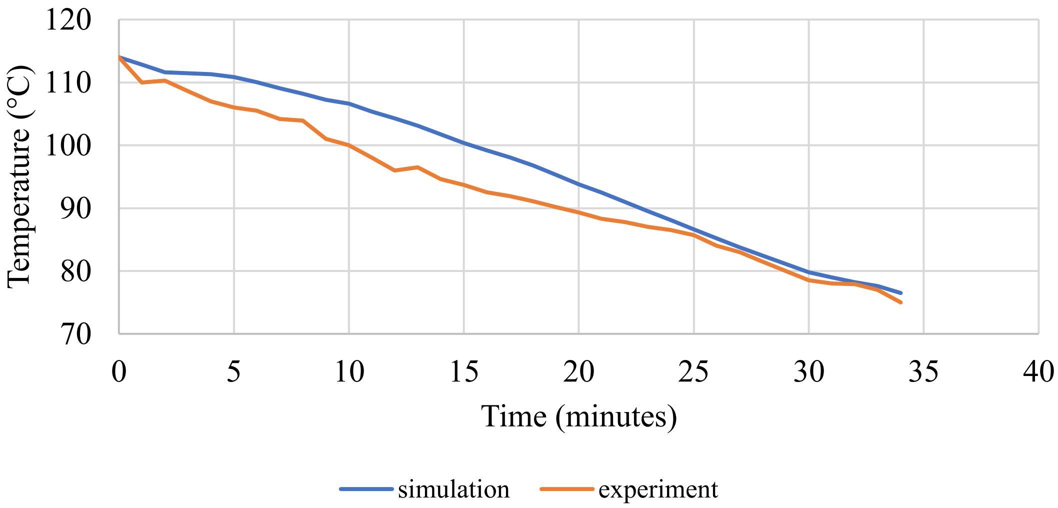

Figure 4.14: Temperature comparison without insulation

Ansys simulation indicates that the temperature of system decreases almost linearly with time. Assuming the whole body, steel crystallization pot included, is at 387 K, it reached 361 K (88 °C) in 20 minutes. The body was able to reach 75 °C in 30 minutes. The rate of temperature decline gets very small in long run because the temperature difference between the system and the ambient air decreases as well as the rate of heat transfer. When the experimental data was compared with simulated data, the rate of temperature decline was similar. After 30 minutes, the temperature ranged between 73-74 °C. While the temperature profile is similar at the beginning as well as at the end, temperature obtained from simulation remained comparatively higher. This discrepency can be the result of errors in measurement and losses that were not considered during the experiment. While simulation solves the transient heat loss without any losses other than given in the boundary conditions, in real life such perfect cooling does not occur. These errors can lead to some difference in experimental and simulated data.

4.5.2 With Insulation

Later, a 50 mm rock wool insulation has been modelled around the uninsulated system, and the properties have been changed accordingly. Other things have been kept the same. Now the heat loss occurs from insulated surface on side and bottom whereas top part has additional 50 mm ring around it.

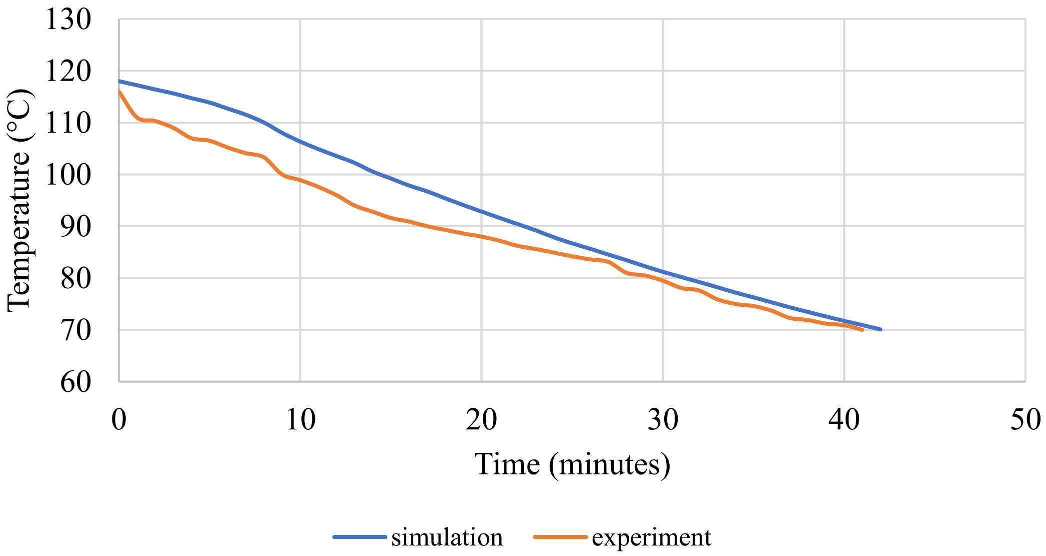

Figure 4.15: Temperature comparison with insulation

After the introduction of insulation, temperature of Jaggery inside the crystallization pot declined less rapidly in comparison to the time before insulation, although the nature of decline is the same. The temperature of Jaggery was 357 K (84 °C) in around 30 minutes. After 35 minutes, the temperature dropped down to around 80 °C and it took around 43 minutes to reach 348 K (75 °C). Introduction of insulation at the bottom and side of the crystallization pot slows down the rate of cooling resulting in lower rate of temperature decline. This slow decline in temperature allows for more aeration and stirring time. Similar discrepency in temperature data of simulated and experimental data can be observed for insulated setup for similar reasons as the insulated system.

While the temperature of system is consistent throughout the system without insulation, temperature distribution is different once thermal equilibrium is introduced around the crystallization pot. The temperature of Jaggery, temperature of insulation and the average temperature of the system are different.

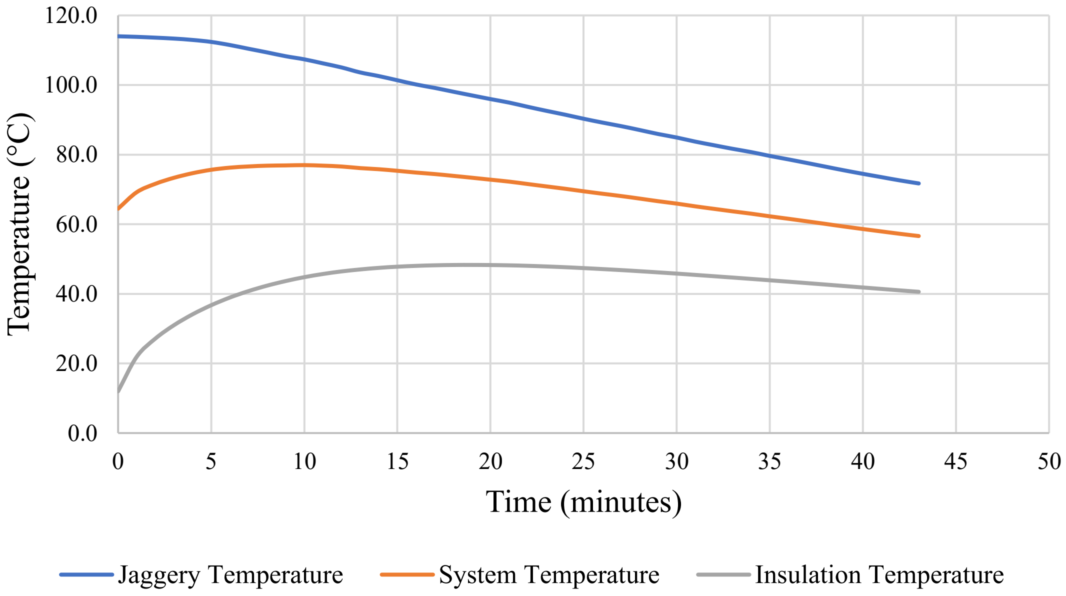

Figure 4.16: Temperature Comparison

Figure 4.16 compares the temperature of Jaggery, temperature of the system and temperature of the insulation. While the temperature of Jaggery decreases linearly after insulation, the average temperature of the system and insulation first increase and then decrease linearly. The insulation was able to reach the highest temperature of 48 °C. When Jaggery is poured to the crystallization pot, the temperature is high, however the temperature of insulation is at the ambient temperature. This results in heat being transferred from Jaggery to the insulation. After thermal equilibrium is reached between insulation and Jaggery, the temperature starts to decline and at one point the temperature of the system, Jaggery and insulation becomes equal.

4.6 Heat losses from Jaggery

Regarding the heat losses from the Jaggery body, three types of losses occur namely convection, radiation and evaporation. Natural convection occurs from side of the side and bottom of the system, meanwhile forced convection and evaporation occurs from the top open surface because of the rotation of the impeller. Additionally, radiation heat loss occurs from all the surfaces exposed to ambient air assumed at 285 K.

4.6.1 Convective heat loss

In the Jaggery system, heat loss due to convection occurs from three different surfaces. From the top, forced convection occurs while from the bottom and side natural convection occurs to the ambient air.

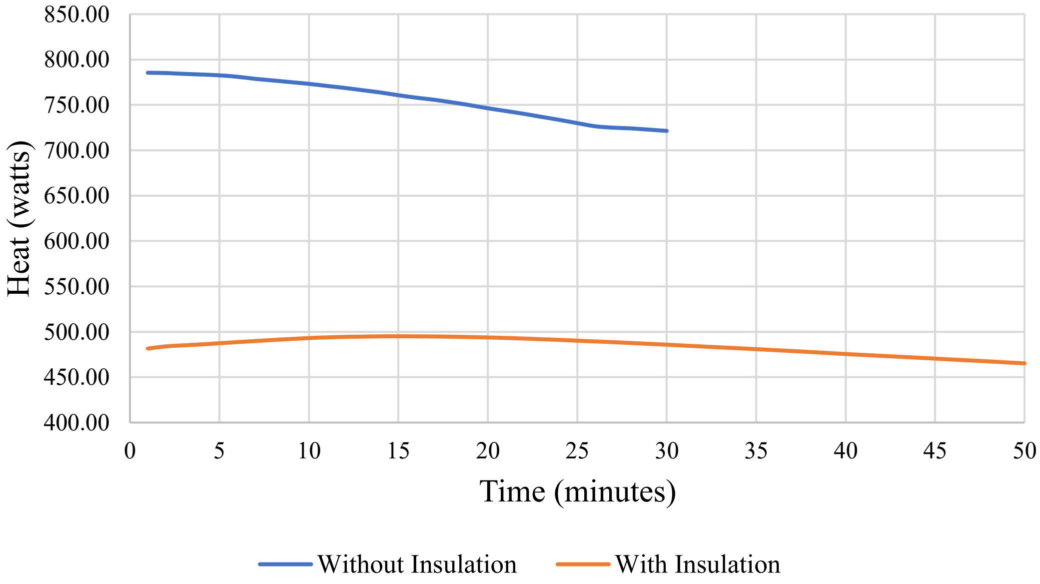

Figure 4.17: Convective heat loss

Heat loss due to convection is decreasing linearly from the system. For the uninsulated system, the highest value occurs at the beginning, which was around 780 W, and the graph is very slowly decreasing to reach the value of around 720 W after 30 minutes. However, as thermal insulation is installed, the convective heat loss at the beginning is around 480 W. This value increases slightly to almost 500 watts and declines very slowly after that. The initial incline upwards trend is because the insulation is gaining heat from the Jaggery. So, with increasing temperature, convection also increases. However, once thermal equilibrium is reached, the temperature starts to decline and subsequently the total convective heat loss. As the system cools down, the rate of convection decreases because the temperature gradient also starts to decline.

The characteristics of convection from the top Jaggery surface does not change after the addition of insulation. However, the rate of heat loss is lowered from the side and the bottom portion as the resistance increases because of insulation. This reduction is due to the decrease in temperature gradient with the surrounding after insulation is introduced. Rockwool provides resistance due to its low thermal conductivity. The inner face in contact with crystallization pot is in high temperature, meanwhile, the outer face exposed to surrounding sees a very small temperature rise.

i. From the top

The top part has forced convection because of the rotating Jaggery. Although the speed is present, the flow of the fluid is laminar, and the convective heat transfer applied was 35 W/m^2K. Convection heat loss from the top surface does not change significantly after the addition of insulation. As the top surface of the crystallization pot is open, Jaggery is directly exposed to the air surface. The characteristics of heat loss is almost similar from the top before and after insulation.

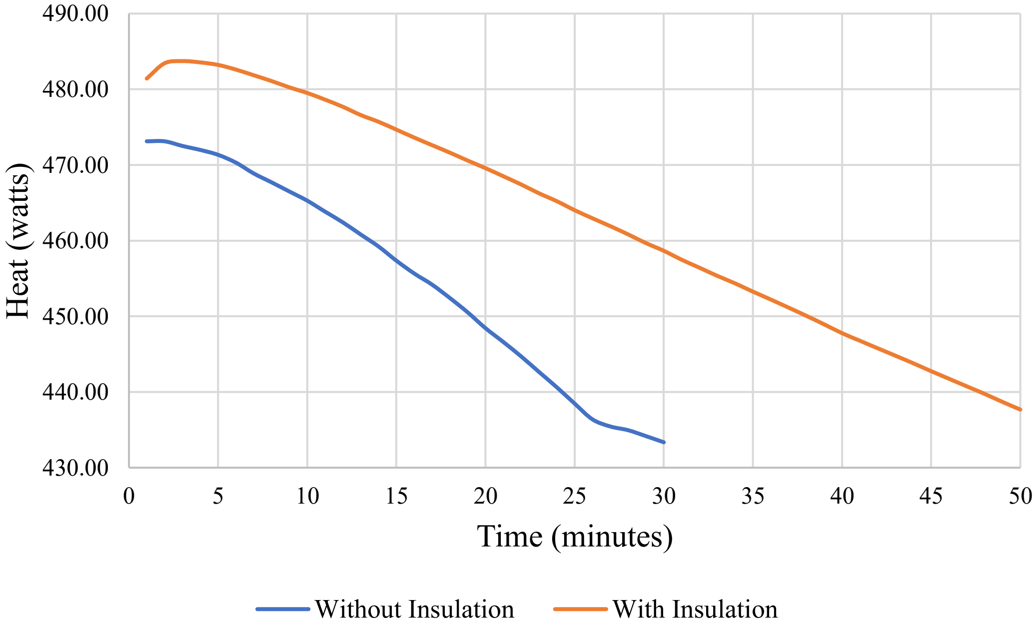

Figure 4.18: Convective heat loss from top of the pot

Among all the surfaces exposed to air, the top part has the largest convection heat transfer rate. The forced convection makes the convective heat transfer coefficient higher than the bottom with equal area. It is significant when all the sensible heat transfers are compared with the initial value of around 470-480 watts for both setups. Both graphs show a constant decline with time. The only difference on the convection heat loss from top is because of the rapidly decreasing temperature gradient of the uninsulated system with surrounding. This temperature gradient decline is relatively slower for the insulated system.

When compared with total convection of the system, Figure 4.18 indicates that convection from top is dominant. The graph indicates similar characteristics of convective heat transfer between top surface area and the whole system. The convection heat transfer throughout the time is slightly smaller in value than the whole system.

ii. From the walls

The walls of the pot were exposed in air initially the heat loss trend was studied and after that the insulation was applied to the pot and again the heat loss characteristics was observed. The side portion of crystallization pot has the largest surface exposed to ambient air. Natural convection occurs from this cylindrical surface. The cylindrical side of the crystallization pot is also insulated by rock wool, and the convective heat transfer coefficient is almost similar to that of uninsulated case. In the same way as side wall, the bottom portion of the crystallization pot is a steel surface exposed to ambient air. It also has heat loss due to natural convection like the sides. Before insulation, the heat was lost from the side of the crystallization pot because of the interaction between air and steel. After insulation, the interaction occurs between rock wool and ambient air. The natural convection from the bottom of crystallization pot does not change and the convective heat transfer coefficient does not change as well.

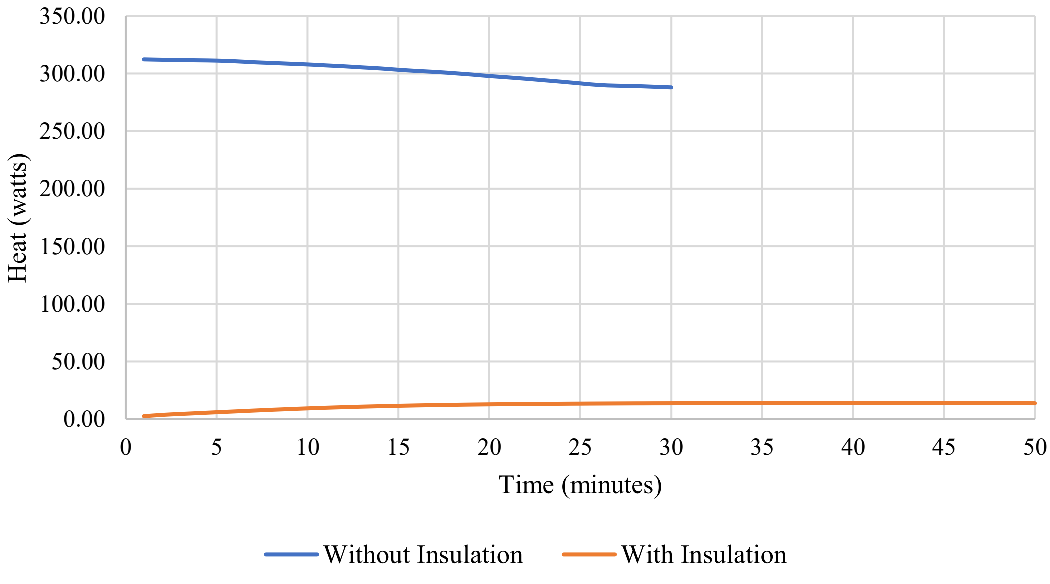

Figure 4.19: Convective heat loss from walls of the pot

While convection from the side is not as high as the top surface, the rate is higher than the bottom part because of the larger surface area as well as the convection occurring on the side. The total convection loss from the walls is around 300 watts in the beginning with a slow downward trend.

After insulation, Figure 4.19 indicates the convective heat loss from the walls is slowly increasing with time. It starts with 1 watt at the beginning and increases to around 13 watts after 30 minutes. Once the thermal equilibrium has been reached, the heat loss starts to decline as the temperature of the system declines.

4.6.2 Radiation heat loss

Radiation heat loss is comparatively lower than convective heat loss in the system. The radiation occurs from all three surfaces: Jaggery top surface, steel side surface and steel bottom surface. The emissivity values of Jaggery and steel surface are different resulting in different rates of heat loss. While the total radiation heat loss from the surfaces is not as high as convective heat loss, it is in the range of 200 Watts at the beginning. Later, the rate is declining with a slow linear rate. Even after 30 minutes, the rate of radiation heat loss is around 200 Watts.

Radiation of the insulated system is significantly less than the radiation of uninsulated system. It is almost half of the uninsulated system. The main reason for this lower value is due to the smaller temperature gradient between the insulated surface and the surrounding.

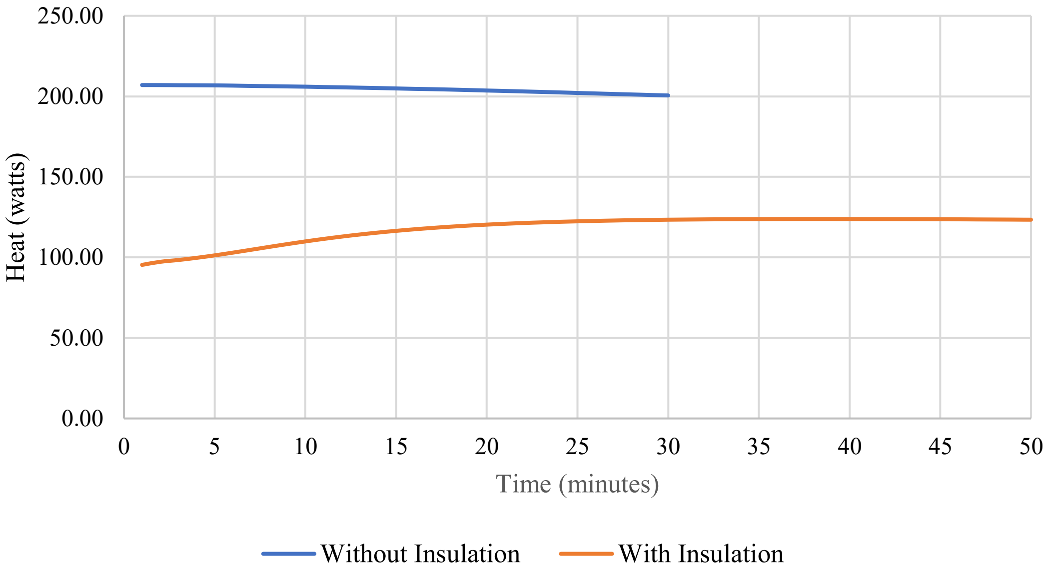

Figure 4.20: Radiation heat loss

According to the graph, radiation heat loss is increasing with time up to a certain time and starts to decline slowly after that. It reached the high of 123 watts and had a very slow downward trend.

i. From top

The top surface of the crystallization pot is open which causes the Jaggery being exposed to the ambient air and losing heat through radiation. Radiation heat loss from the top is higher than sides and bottom because emissivity of Jaggery is higher than steel.

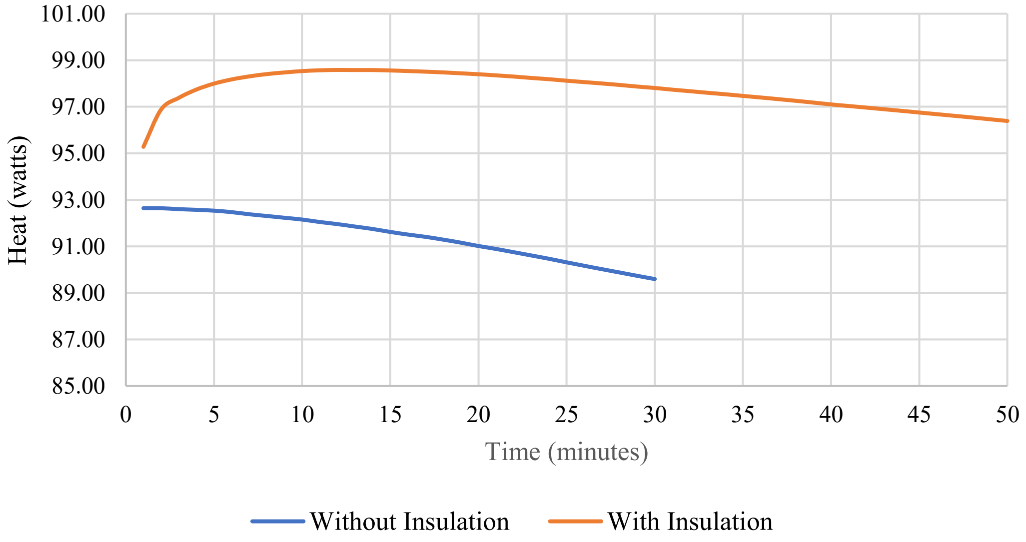

Figure 4.21: Radiation heat loss from top

In the beginning, for uninsulated system, around 93 Watt of heat is lost through top in the from of radiation. This value is decreasing linearly with time but at a very slow rate. For the insulated system, radiation heat loss started with around 96 watts at the beginning which quickly climbed to 99 watts. After that, the radiation heat loss declined linearly at a leisurely pace. The Figure 4.21 indicates that the radiation heat loss from the top is highest. The emissivity of Jaggery is 0.95, higher than rock wool, and the temperature is high which results in greater heat loss. Around 90 watts of heat leaves from the top as radiation which declines slowly as temperature decreases with time.

ii. From walls

The walls of pot were initially exposed to room temperature and later on wall was insulted and heat characterics was studied. The surface area of side is greater than the bottom part and the material is made up of steel. The radiation heat loss is between 115 watt with a linear decline with time fro the uninsulated system. Later, the side surface of the crystallization pot was insulated with rock wool with emissivity of 0.9.

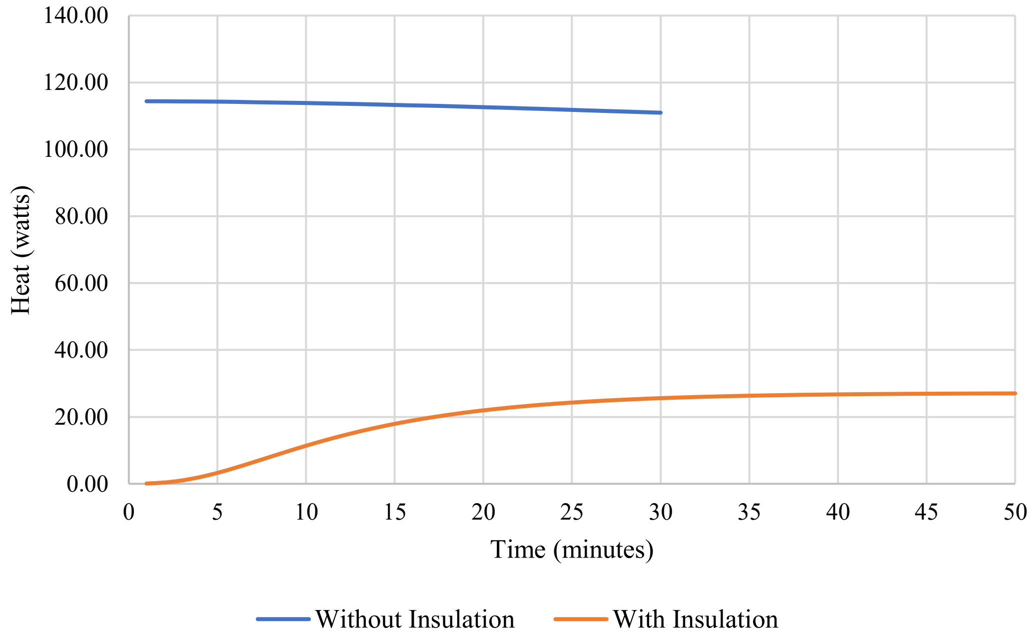

Figure 4.22: Radiation heat loss from walls of the pot

As shown in the Figure 4.22, radiation heat loss from wall is increasing first and reaches highest of 27 watts. This is because of conduction heat transfer dominating radiation until insulation and crystallization pot reach thermal equilibrium. Later the rate declines slowly for a long time. The bottom surface of the crystallization pot has the smallest surface area and emissivity resulting in the lowest rate of radiation heat transfer while the side is in middle because of its larger surface area.

When insulation was introduced around the side and bottom of crystallization pot, it was able to effectively reduce the rate of temperature decline. In addition to that, the rate of heat loss also declined effectively slowing down the cooling rate. The radiative and convective heat losses from the side and bottom were less after insulation was introduced. However, there was a minimal effect on the evaporation, convection and radiation losses form the top surface of Jaggery. When all the surfaces are compared, the top surface remains the dominant contributor to heat loss. On the top surface, the evaporative heat loss is higher than convection and radiation.

4.6.3 Total heat loss

Convective and radiative heat losses occur from all the surfaces of Jaggery and steel befor insulation. After insulation, heat is lost from the insulation walls. Evaporative heat loss occurs from the top surface due to the loss of moisture. The total heat transfer of the system with time shows a significant decrease over time. At the beginning, the rate of heat transfer becomes above 6000 W. The graph shows a linear decline with time, however, the rate of heat loss decreases with time. This is a clear indication of slow heat transfer rate due to decreased temperature. So, the simulation of the system indicates a fast rate of heat transfer with time because of high temperature followed by a slow decline at lower temperature.

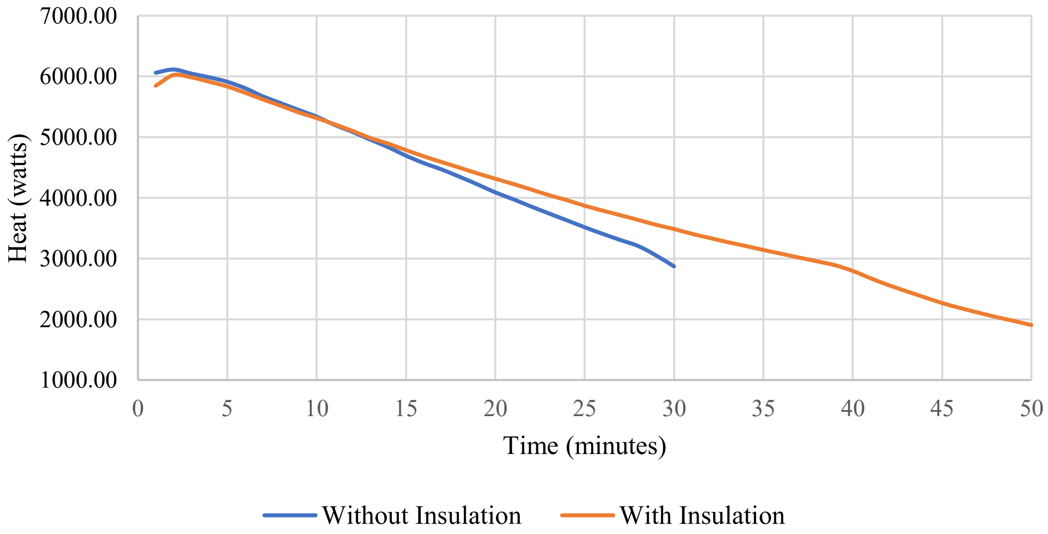

Figure 4.23: Total heat loss

After insulation, total heat loss from the system is due to convection heat loss from the insulation sides and bottom as well as Jaggery surface exposed to air, radiation heat loss from all the faces and evaporation of moisture from the top surface. The total heat transfer rate at the beginning for few minutes is almost similar for insulated as well as non-insulated system. But over time, the rate of heat loss is higher for the insulated system. This can be attributed to the fact that the initial temperature of the body is high at the beginning. With time, the rate of heat loss from the uninsulated system becomes lower because the temperature of the system is lower. This smaller temperature gradient causes the system to lose less heat than the insulated system. Meanwhile, for the insulated system, the bulk heat is retained due to insulation and temperature remains elevated. The higher temperature gradient attributes to higher rate of heat loss. The total heat lost by the body is around 2000 Watts even after 40 minutes.

In comparison to the heat loss due to convection and radiation, heat loss due to evaporation is significant. As moisture carries the heat as latent heat of vaporization of water, the heat is lost when the moisture from Jaggery evaporates. This latent heat of vaporization dominates the insulated system too whereas convective and radiative heat losses decline in comparison to the uninsulated system. Therefore, the heat loss is decreasing at a slow speed with time.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Good quality Jaggery is obtained from adequate stirring time and higher stirring temperature. The study successfully led to the study of cooling characteristics and temperature curve during cooling phase of a fabricated Jaggery Processing Machine. The study started by conducting a mathematical analysis at steady state condition. This was followed by experimental testing that provided the cooling characteristics of Jaggery and crystallization pot at different rotational speeds with and without insulation. In addition to that, ANSYS simulation of temperature curve and heat losses was conducted for the machine.

- Evaporative heat loss (5608 KJ) was dominant in comparison to convection (620 W) and radiation heat loss (218 W).
- Cooling test conducted in water depicted slower cooling rates in lower rotating speeds than higher rotating speeds. The slowest cooling rate was observed at 25 rpm rotation with insulation while the fastest cooling was at 75 rpm without insulation.
- Experimental tests in Jaggery showed the introduction of insulation resulted in higher rate of temperature decline until thermal equilibrium was reached between insulation and Jaggery. At 25 rpm, Jaggery cooled 15 minutes slower when insulated while the difference was 13 minutes for 50 rpm and just 12 minutes for 75 rpm.
- Final experiment at 75 rpm and 12 °C ambient temperature indicated insulation slows down cooling. Temperature reached 75 °C in less than 30 minutes without insulation and more than 40 minutes with insulation.
- Time required to reach 75 °C for uninsulated system was 28 minutes and more than 40 minutes for insulated system with a linear temperature decline from simulation. Simulation and experimental data are similar in nature.
- At the beginning, convective heat loss was 700-800 W for uninsulated system and 480-500 W for insulated system. This was higher than radiative heat loss at almost 200 W for uninsulated system and 120 W for insulated system according to simulation. The top part of the crystallization pot has the highest heat losses in terms of both radiation and convection.

In conclusion, the cooling rate of Jaggery is higher at higher rotational speed than at lower rotational speed. Thermal insulation was able to slow down the cooling rate and keep Jaggery in consistent higher temperature than uninsulated system allowing for better crystal formation and aeration.

5.2 Recommendations

After the completion of the project, certain research gaps can be recommended for further adoption of the Jaggery machine. The following recommendations are proposed:

- Future iterations could simulate the system by adding mass transfer to study evaporative effect on cooling rate
- Conduct cooling test for different types and thickness of insulation

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ANNEXES

1. Calculations

i. Heat lost by Jaggery from 118 °C to 75 °C

$\text{Heat}_{\text{Jaggery},75} = 28.8 \times 2970 \times (118-75)$ (equation 3.11)

$\text{Heat}_{\text{Jaggery},75} = 3{,}678{,}048$ J

ii. Convective heat transfer coefficient for top open surface

$D = 0.376$m

$\omega = 75$ rpm $= 7.8$ rad/sec $= 1.25$ m/s

$v = 0.0289$ m^2/s (Alarcon, Orjuela, Narvaez, & Camacho, 2020)

$Re_\omega = 23{,}512$ (equation 3.3)

For a Reynolds number (Re_ω) of 23,512 for cross flow across cylinder, the flow remains in the laminar flow regime. The Nusselt number is obtained from equation 3.4.

$Pr = 3.97$ for organic compounds (Meshram, 2017)

$Nu = 213.28$

$h_{top} = 35$ W/m^2K (From equation 3.5)

iii. Convective heat transfer coefficient for side

Rayleigh number = 154,732,330 (equation 3.7)

Nusselt number (Nu) = 58.15 (From equation 3.9)

Characteristic Length = 0.27

Convective heat transfer coefficient = 6.21 W/m^2K.

iv. Convective heat transfer coefficient for bottom

The characteristics length for a circular horizontal plate is the ratio of area and perimeter.

Characteristic length = 0.094 m

Prandtl number = 0.7 at room temperature and pressure

From equation 3.7 and 3.8, Rayleigh number = 8,956,653

Nusselt number = 14.77 (equation 3.6)

From equation 3.5,

Convetive heat transfer coefficient of bottom = 4.09 W/m^{2}K.

v. Mass of moisture lost by Jaggery while going from 15% to 7%

The mass of solid Jaggery in 28.8 kg mixture is = 0.85×28.8 = 24.48 kg

Mass of moisture in the mixture = 0.15×28.8 = 4.32 kg

After aeration and stirring, the mass of solid remains constant,

$$\text{total mass of the mixture} = \frac{\text{Mass of solid Jaggery}}{(1 - \text{final moisture content})}$$

$$= \frac{24.48}{(1 - 0.07)}$$

= 26.32 kg

Mass of moisture = 26.32 - 24.48 = 1.84 kg

Mass of water lost in the form of vapor = 4.32 - 1.84 = 2.48 kg

vi. Evaporative Heat Loss

The evaporative heat loss given by formula:

$$Q = m * h_{fg}$$

Heat loss due to evaporation= 2.48 kg × 2260 KJ/kg = 5608.52 KJ

2. Experimental Data

Temperature vs Time without Insulation

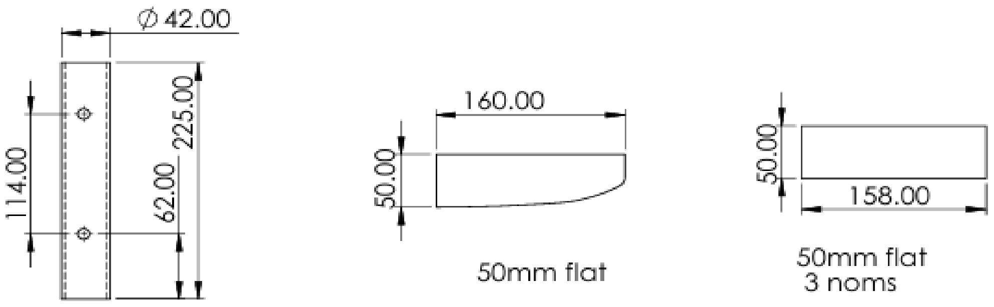
Time (minutes)	Test 1 (°C)	Test 2 (°C)	Test 3 (°C)	Average
0	110	112.5	117.2	113.2
1	107	105.1	114.4	108.8
2	105.2	104.8	108.1	106.0
3	104	104.2	104.9	104.4
4	103.9	103.5	103	103.5
5	101.5	102.9	102.5	102.3
6	100.2	102.5	101	101.2
7	99.5	101	100.7	100.4
8	97.5	99.6	97.5	98.2
9	96.8	98.1	96.4	97.1
10	96	96.9	95.7	96.2
11	95.1	95.7	94.9	95.2
12	93.6	94.5	93.3	93.8
13	91.5	93.1	92.1	92.2
14	90.4	91.2	91	90.9
15	87.5	90.9	89.9	89.4
16	86.5	89.7	88.8	88.3
17	85	88.2	87.9	87.0
18	82.5	87.8	86.7	85.7
19	81.9	85.5	85.6	84.3
20	80.1	83.8	84.6	82.8
21	80.2	82.9	83.7	82.3
22	81.3	82.1	82.9	82.1
23	78.5	80.8	81.9	80.4
24	78	80	81	79.7
25	77.3	79.2	80.2	78.9
26	76.6	78.6	79.4	78.2
27	75	77.8	78.6	77.1
28	74.2	77.6	77.6	76.5
29	73.2	76.6	76.6	75.5
30	72.2	75.5	75.5	74.4

Temperature vs Time with Insulation

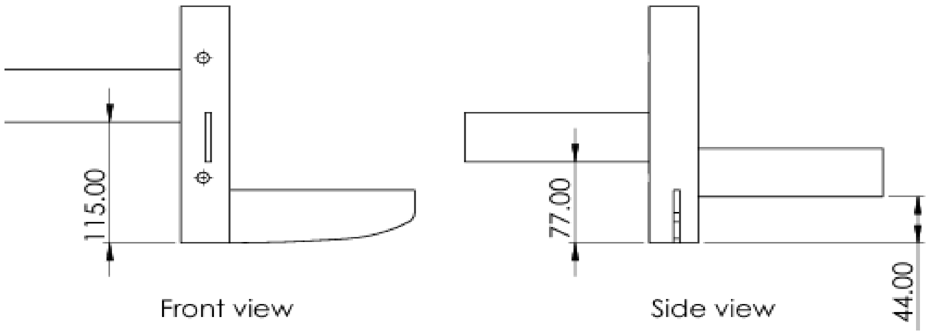
Time (minutes)	Test 1 (°C)	Test 2 (°C)	Test 3 (°C)	Average (°C)
0	114	114	116	114.7
1	110.1	110	110	110.0
2	110.2	110.3	104	108.2

3	108.7	108.6	103	106.8
4	106.9	107	102	105.3
5	105.3	105.4	101.7	104.1
6	103.8	103.7	100.8	102.8
7	102.2	102.3	99.5	101.3
8	100.9	101	98.7	100.2
9	99.6	99.5	97.8	99.0
10	98.5	98.6	95.5	97.5
11	97.4	97.3	95.6	96.8
12	96.4	96.5	95	96.0
13	95.2	95.3	93.8	94.8
14	94.7	94.6	92.8	94.0
15	93.6	93.7	91.6	93.0
16	92.6	92.5	90.9	92.0
17	91.8	91.9	90	91.2
18	91	91.1	89.3	90.5
19	90.3	90.2	88.6	89.7
20	89.2	89.3	88	88.8
21	88.4	88.3	87.2	88.0
22	87.7	87.8	86.2	87.2
23	87.1	87	85.6	86.6
24	86.4	86.5	84.9	85.9
25	85.8	85.7	84.2	85.2
26	85.2	85.3	83.6	84.7
27	84.5	84.6	83.1	84.1
28	83.9	83.8	82.2	83.3
29	83.2	83.3	81.6	82.7
30	82.6	82.7	81	82.1
31	82	81.9	80.5	81.5
32	81.4	81.5	80.1	81.0
33	81	80.9	79.6	80.5
34	80.5	80.6	79.1	80.1
35	79.9	79.8	78.6	79.4
36	79.2	79.3	78	78.8
37	78.9	78.8	77.1	78.3
38	78.5	78.6	76.8	78.0
39	78	77.9	76.4	77.4
40	77.6	77.5	76	77.0
41	77.3	77.4	75.6	76.8
42	76.1	76.2	75.1	75.8
43	75.8	75.9	74.5	75.4

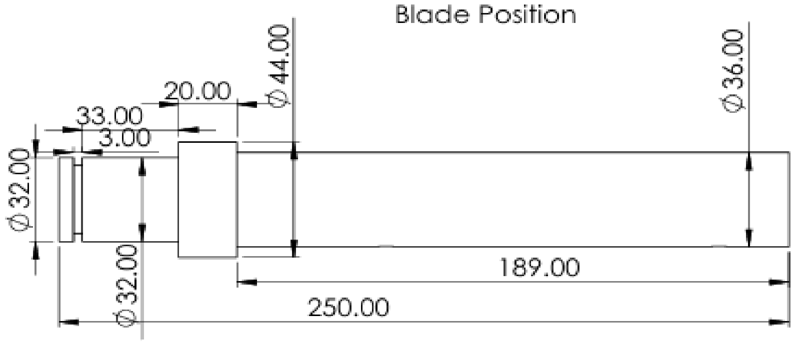
3. Schematic Diagram of Impeller



Blade Holding pipe

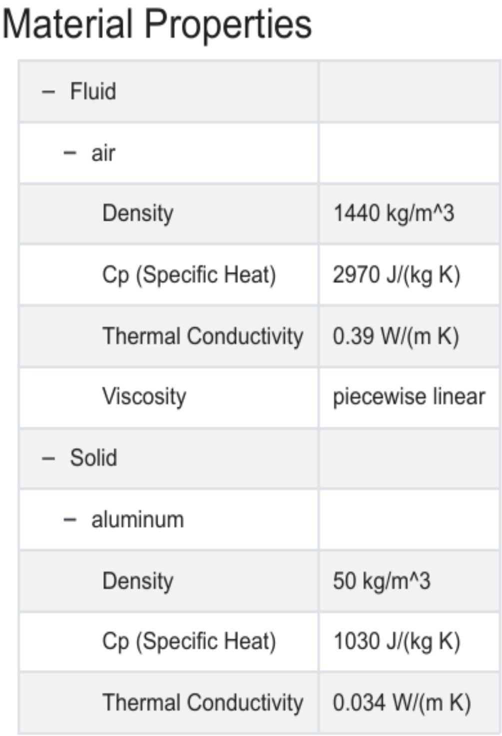


Blade Position



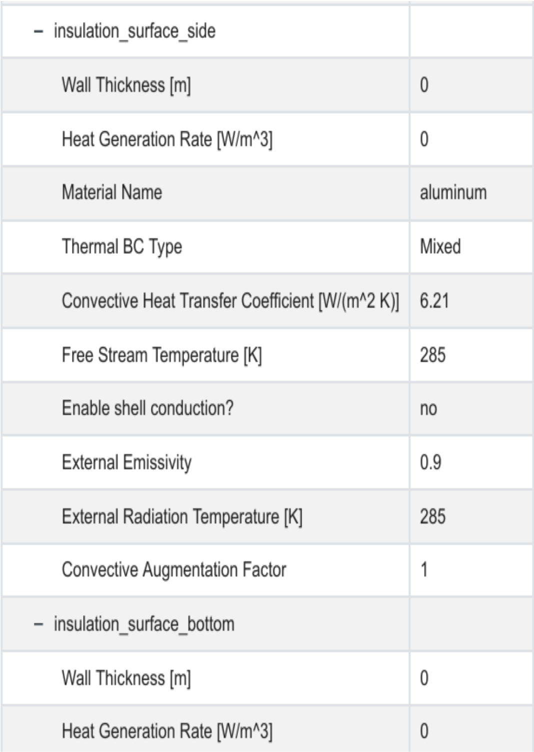
Dimensions of the Impeller

4. ANSYS Backend

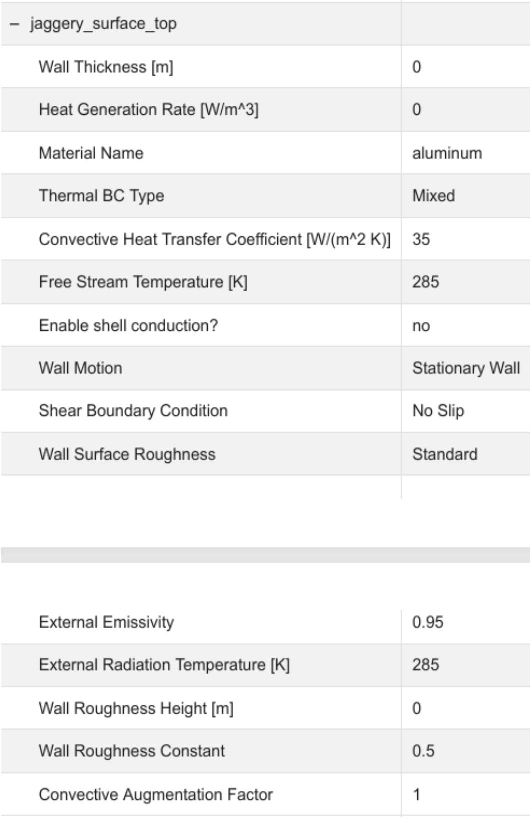


Material Properties

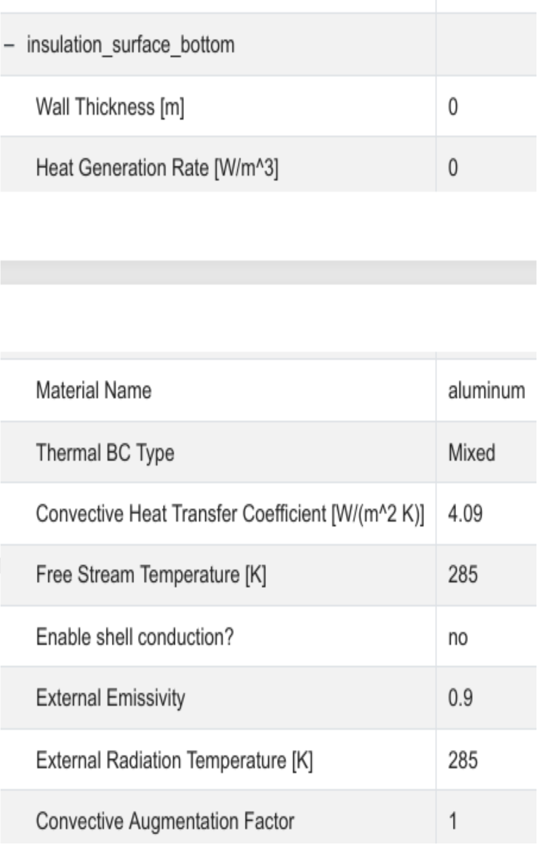
− Fluid	
− air	
Density	1440 kg/m^3
Cp (Specific Heat)	2970 J/(kg K)
Thermal Conductivity	0.39 W/(m K)
Viscosity	piecewise linear
− Solid	
− aluminum	
Density	50 kg/m^3
Cp (Specific Heat)	1030 J/(kg K)
Thermal Conductivity	0.034 W/(m K)



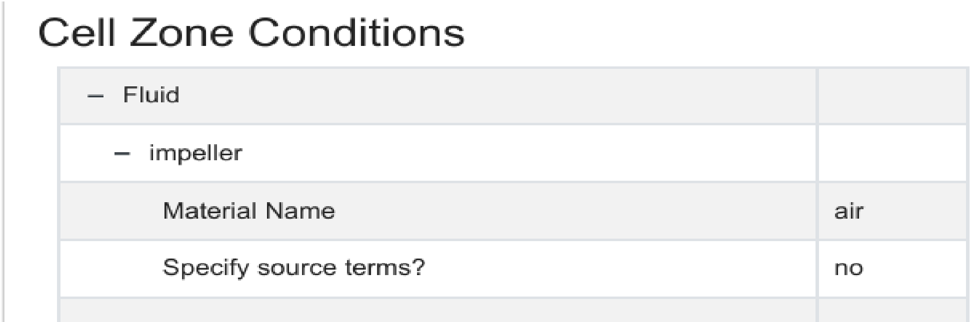
− insulation_surface_side	
Wall Thickness [m]	0
Heat Generation Rate [W/m^3]	0
Material Name	aluminum
Thermal BC Type	Mixed
Convective Heat Transfer Coefficient [W/(m^2 K)]	6.21
Free Stream Temperature [K]	285
Enable shell conduction?	no
External Emissivity	0.9
External Radiation Temperature [K]	285
Convective Augmentation Factor	1
− insulation_surface_bottom	
Wall Thickness [m]	0
Heat Generation Rate [W/m^3]	0



− jaggery_surface_top	
Wall Thickness [m]	0
Heat Generation Rate [W/m^3]	0
Material Name	aluminum
Thermal BC Type	Mixed
Convective Heat Transfer Coefficient [W/(m^2 K)]	35
Free Stream Temperature [K]	285
Enable shell conduction?	no
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Surface Roughness	Standard
External Emissivity	0.95
External Radiation Temperature [K]	285
Wall Roughness Height [m]	0
Wall Roughness Constant	0.5
Convective Augmentation Factor	1

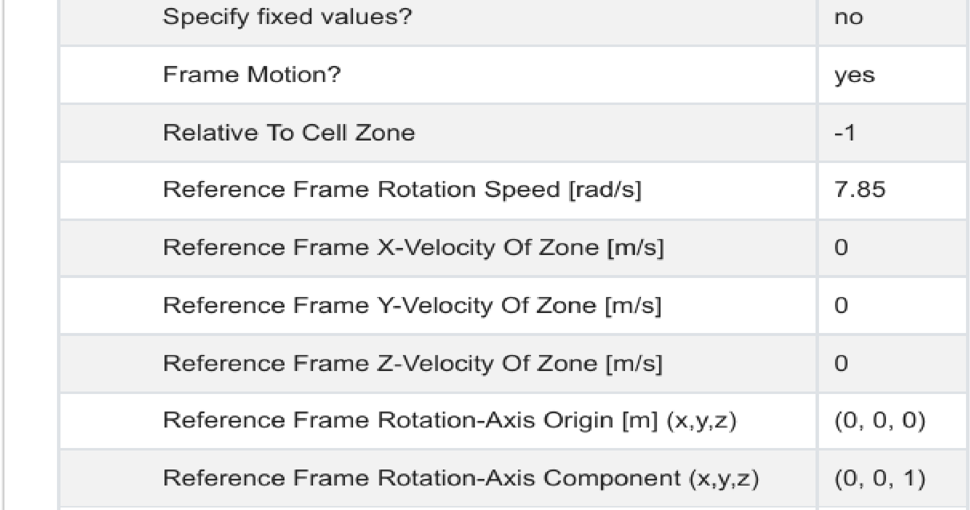


− insulation_surface_bottom	
Wall Thickness [m]	0
Heat Generation Rate [W/m^3]	0
Material Name	aluminum
Thermal BC Type	Mixed
Convective Heat Transfer Coefficient [W/(m^2 K)]	4.09
Free Stream Temperature [K]	285
Enable shell conduction?	no
External Emissivity	0.9
External Radiation Temperature [K]	285
Convective Augmentation Factor	1

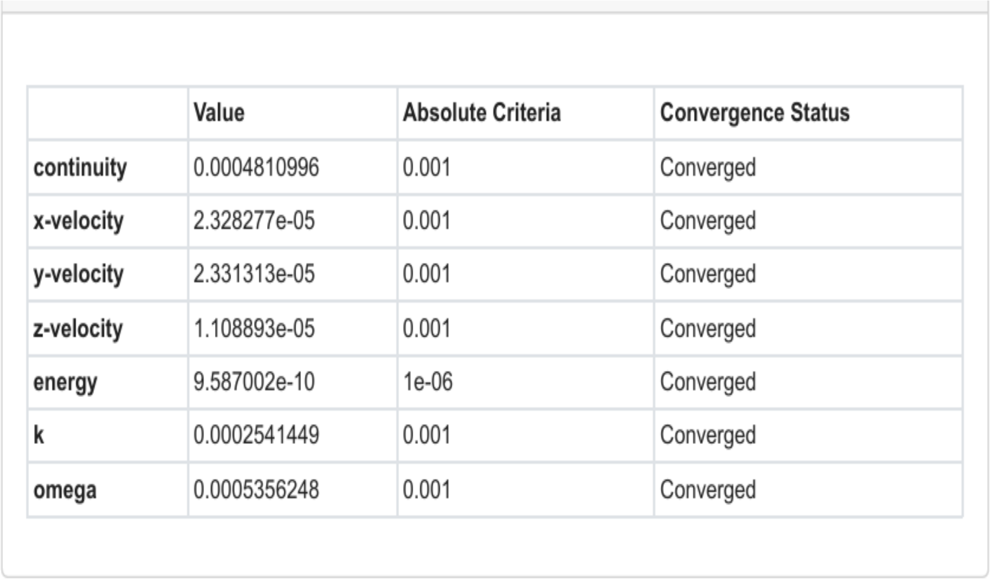


Cell Zone Conditions

– Fluid	
– impeller	
Material Name	air
Specify source terms?	no



Specify fixed values?	no
Frame Motion?	yes
Relative To Cell Zone	-1
Reference Frame Rotation Speed [rad/s]	7.85
Reference Frame X-Velocity Of Zone [m/s]	0
Reference Frame Y-Velocity Of Zone [m/s]	0
Reference Frame Z-Velocity Of Zone [m/s]	0
Reference Frame Rotation-Axis Origin [m] (x,y,z)	(0, 0, 0)
Reference Frame Rotation-Axis Component (x,y,z)	(0, 0, 1)



	Value	Absolute Criteria	Convergence Status
continuity	0.0004810996	0.001	Converged
x-velocity	2.328277e-05	0.001	Converged
y-velocity	2.331313e-05	0.001	Converged
z-velocity	1.108893e-05	0.001	Converged
energy	9.587002e-10	1e-06	Converged
k	0.0002541449	0.001	Converged
omega	0.0005356248	0.001	Converged

5. Photographs

Setup Without Insulation

Setup with Insulation

Robotic Arm

Moulding Flat Plate

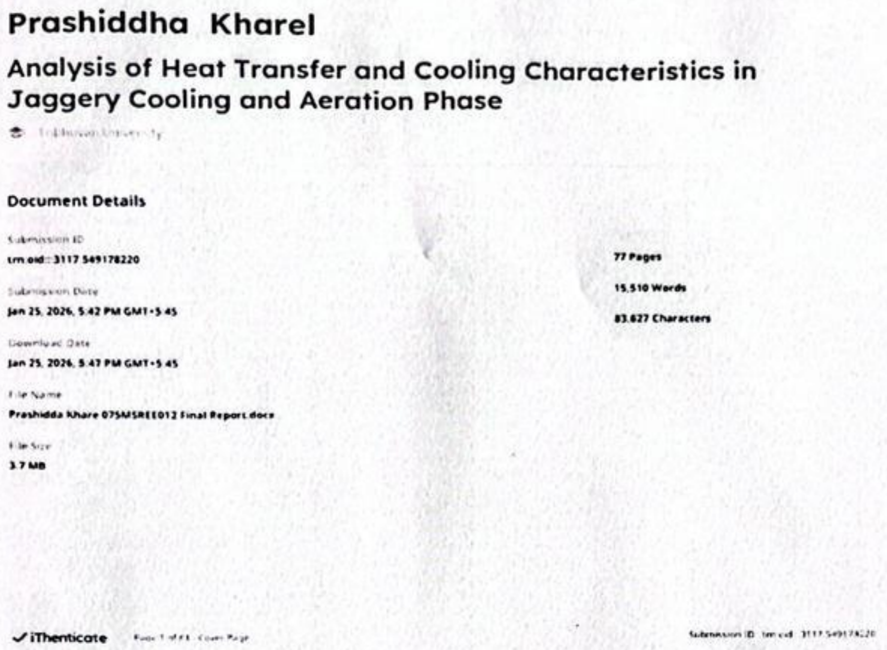
Crystallization Pot

Impeller

Pouring Mechanism

Cylinder Lock Plate Assembly

6. Plagiarism Report



Prashiddha Kharel

Analysis of Heat Transfer and Cooling Characteristics in Jaggery Cooling and Aeration Phase

Tribhuvan University

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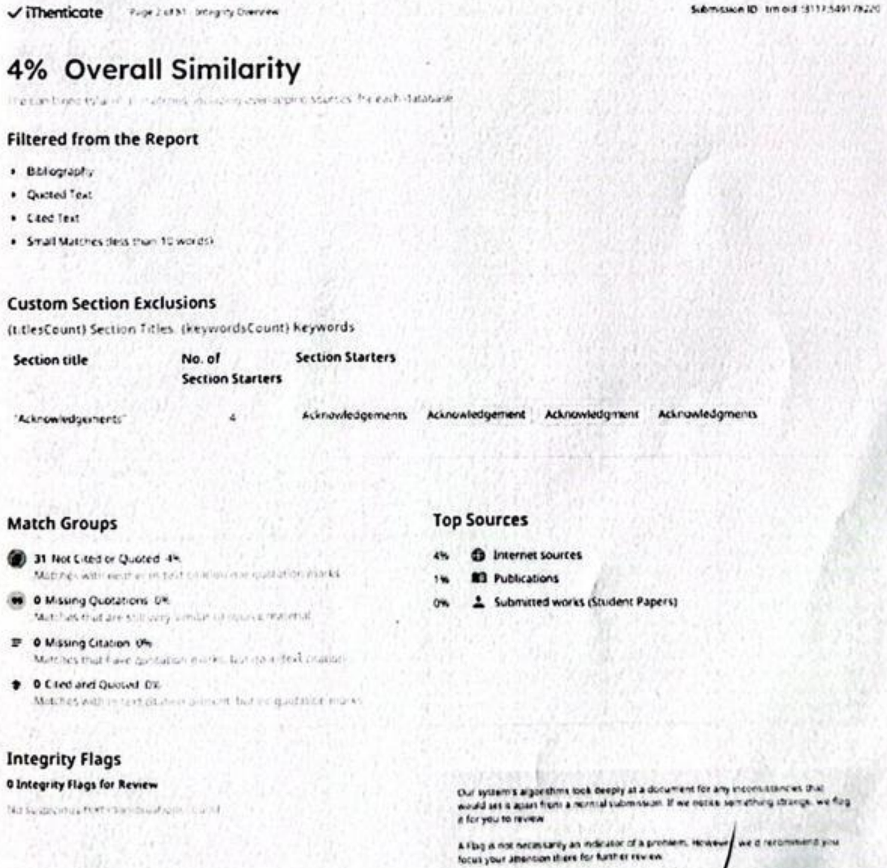

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