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Evaluation of Thermal Performance and Energy Efficiency of a Continuous Milk Pasteurization System Using a PTFE Pipe and Vegetable Oil Heating Medium

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ABSTRACT

Continuous milk pasteurization systems require efficient heat transfer and energy utilization to ensure product safety and processing efficiency. However, the performance of systems utilizing alternative heating media, such as vegetable oil, is limitedly explored. This study aimed to evaluate a prototype continuous milk pasteurization system consisting of PTFE (Polytetrafluoroethylene) tubing submerged in vegetable oil heated by LPG. Experimental measurements (temperature at inlet/outlet, oil temperatures, mass flow) were combined with Computational Fluid Dynamics (CFD) using water as a surrogate fluid to analyze residence time, temperature rise, and heat-transfer performance under real operating conditions. At an oil average temperature of 131 °C, CFD and experiments showed milk reached a temperature of 72 °C after 6 m of tubing length, and then over the next 10 m. However, at an average flow speed of 0.955 m/s, the resulting residence time at ~72 °C was 10.47 s (below the HTST requirement of 15 s). Energy analysis indicated a fuel input of 1783.7 W, oil uptake of 634.4 W (35.6%), and useful heat of 139.5 W (7.8%), giving a system total efficiency of ~8.2%. Microbiological tests (Escherichia coli and Staphylococcus aureus) of treated samples complied with SNI ISO 7388:2009. Design modifications (longer tubing, alternative pipe materials, improved insulation, and heat recovery) are required to achieve HTST residence time and improve energy efficiency.

1. INTRODUCTION

Pasteurization, first discovered by the French scientist Louis Pasteur in 1863 and commercially applied in Europe in the early 1880s (Rankin *et al*., 2017), is a thermal process aimed at extending the shelf life of products by inactivating pathogenic bacteria and inhibiting enzymatic and microbial activity. It is widely used in products such as fruit juices, canned foods, and especially milk, by heating them at temperatures below 100 °C for a specific duration that exceeds microbial resistance limits to ensure safety. In milk processing, pasteurization plays a crucial role in controlling microbial growth; insufficient temperature fails to inhibit microorganisms, while excessive heat can damage nutritional content. Therefore, optimal temperature and time must be carefully controlled. According to Pazra & Wahyuningsih (2022), pasteurization is commonly classified into three types: Long Hold Pasteurization (63 °C for 30 minutes in a batch system), Low Temperature Long Time (LTLT) (62.5 °C for 30 min), and High Temperature Short Time (HTST) (72 °C for 15 s in a continuous system), each differing in processing conditions but aiming to achieve safe and high-quality milk products (Rabbani *et al.,* 2025).

In addition to microbial safety, maintaining the nutritional and functional quality of milk during pasteurization is a critical concern. High-temperature treatments with prolonged exposure may lead to denaturation of proteins and loss of bioactive components. In contrast, HTST processing has been reported to better preserve bioactive proteins, enzymatic activity, and antiviral properties of milk, making it a preferred method in modern dairy processing systems (Donalisio *et al*., 2018; Kontopodi *et al*., 2022).

Milk is a livestock commodity that provides complete nutritional value, including protein, fat, vitamins, and minerals, so it plays an important role in meeting the community's nutritional needs. The role of milk in improving nutritional status has long been recognized, making it a strategic food product. Based on data from the Central Statistics Agency (BPS, 2025), Indonesia's 2024 fresh cow milk production reached 824,273 tons, while national demand is estimated at 4.4 million tons. The gap shows that national milk production has not been able to meet domestic needs, so the milk processing industry is still dependent on imports of processed products. Processing fresh milk into ready-to-consumer products requires a series of stages to ensure product safety and quality. One of the most important stages is the pasteurization process, which aims to eliminate pathogenic microorganisms without damaging the main nutritional content of milk. Unpasteurized fresh milk has a short shelf life and is at risk of containing pathogens harmful to human health. Therefore, the application of the right pasteurization method is key to extending the shelf life and increasing the safety of milk consumption (Triwidyastuti *et al*., 2019).

The pasteurization process in fresh milk is carried out at a high temperature below the boiling point of water for a certain period of time. The pathogen elimination process will inhibit the proliferation of microorganisms, which has an impact on increasing the shelf life of cow's milk (Syarif *et al*., 2017). Cow's milk contains a wide variety of microorganisms such as *Streptococcus lactis, Escherichia coli, Staphylococcus aureus, Aerobacter aerogenes, Lactobacillus casei, Lactobacillus acidophilus, Micrococcus, Pseudomonas,* and *Bacillus* (Wijaya *et al*., 2021). Therefore, the presence of these microorganisms, both spoilage and pathogenic bacteria, necessitates the application of effective pathogen elimination methods. Without proper treatment, microbial activity can accelerate milk deterioration, leading to reduced quality, off-flavours, and potential health risks. By inhibiting or reducing microbial populations, the safety, stability, and overall shelf life of cow's milk can be significantly improved, making it more suitable for storage, distribution, and consumption (Baidhe *et al.*, 2022).

Pasteurization of milk can be done by the batch or continuous method. In this study, the continuous pasteurization system was operated at a milk mass flow rate of 1.2×10^{-2} kg/s, which is equivalent to a capacity of about 43–45 L/h. During laboratory testing, the system is run with a working volume of milk of 5 L/cycle, so that the machine used is categorized as a small–medium scale prototype that is relevant for research activities and the development of continuous pasteurization units on the scale of micro, small, and medium enterprises (MSMEs). Batch pasteurization is simple but inefficient for large volumes due to long heating times and higher energy consumption. To overcome these limitations, the High Temperature Short Time (HTST) method was developed, which is a continuous type of pasteurization carried out by heating milk at a temperature of 72 °C for at least 15 seconds (Lindsay, 2021). The HTST method is considered more efficient and able to maintain the nutritional quality of milk compared to the conventional batch method, so it is suitable to be applied to the continuous pasteurization system designed in this study (Indumathy *et al*., 2022).

Pasteurization effectiveness is strongly influenced by the thermal resistance of target microorganisms, particularly heat-resistant pathogens such as *Coxiella burnetii*, which is often used as a reference organism in defining pasteurization standards. The High Temperature Short Time (HTST) method, operating at 72 °C for at least 15 seconds, has been widely accepted as an effective approach to ensure microbial safety while minimizing nutritional degradation. Previous studies have demonstrated that HTST processing is capable of achieving significant microbial inactivation while preserving bioactive compounds and functional properties of milk better than longer heat treatments (Cerf & Condron, 2006; Escuder-Vieco *et al*., 2018; Donalisio *et al*., 2018; Kontopodi *et al*., 2022; Wittwer *et al*., 2022).

The success of continuous pasteurization is determined not only by the achievement of the target temperature but also by the uniformity of the temperature distribution, the adequacy of the residence time, and the energy efficiency of the system. In recent years, the issue of energy efficiency has become an important concern in the food processing industry as energy costs increase and demand for sustainable technology implementation increases. Recent research shows that milk pasteurization systems that have a suboptimal heat transfer design can experience significant energy loss, so a thorough evaluation of thermal performance and energy efficiency is required (Akkurt & Buyukzeren, 2024; Dabhi *et al*., 2024). One of the innovations developed in the continuous pasteurization system is the use of PTFE tubing as a milk flow medium with vegetable oil as a heating fluid. PTFE pipes have high thermal resistance, are inert, and are easy to clean, making them suitable for food processing applications. Vegetable oil as a heating medium is also considered to be able to work at high temperatures with good thermal stability and has the potential to increase the efficiency of heat distribution. However, scientific studies that specifically evaluate the performance of PTFE pipe-based continuous milk pasteurization systems with vegetable oil heaters, especially related to temperature distribution, fluid residence time, and energy efficiency, are still limited, especially at prototype scales relevant to small and medium-sized industries (Sholikhah & Moentamaria, 2022).

This study aimed to evaluate the thermal performance of a continuous milk pasteurization system using a PTFE pipe and a vegetable oil heating medium. This study examines the characteristics of milk flow, temperature distribution, fluid residence time, and heat transfer efficiency using an experimental approach and Computational Fluid Dynamics (CFD) simulation. Modeling simulation with CFD is carried out by providing assumptions on certain conditions using validation in the form of experimental data that can be used as a comparison of CFD simulations, such as on-site experiments and numerical validation (Akmal *et al*., 2019). The results of the research are expected to be a scientific basis for the development of a design of a continuous milk pasteurization system that is more energy-efficient, hygienic, and meets HTST food safety standards, while supporting the strengthening of the national milk processing industry.

2. MATERIALS AND METHODS

2.1. Time and Place

The research was carried out from April 2025 to June 2025. The research was carried out at the Renewable Energy Engineering Laboratory located in the Siswadhi Soepardjo Leuwikopo Experimental Garden, IPB Dramaga Campus.

2.2. Tools and Materials

The equipment and materials were selected according to the required experimental specifications, namely heating tanks, PTFE tubing, LPG gas, stoves, gas scales, K-type thermocouples, recorders, stopwatches, 12V DC pumps, flow meters, Arduino UNO, whole milk, and vegetable oil.

2.3. Research Procedure

2.3.1. Preparation of Tools and Materials

Before the implementation of the research, careful preparations were made, especially related to the readiness of equipment for the preliminary research process and performance testing on continuous-type pasteurization machines. This preparation aims to ensure the accuracy of the tools and the completeness of the materials used to minimize errors in data collection. The tools used include heating tanks (stainless steel cylinders), PTFE tubing, LPG burners, gas scales, K-type thermocouples with data recorders, stopwatches, 12V DC pumps, flow meters, a multimeter, and SolidWorks 2024 software for modelling. The ingredients used are whole milk as a sample and vegetable oil as a heating fluid. Inspection of all engine components, such as heating tanks, PTFE pipes, burners, pumps, and measuring instruments, to ensure their operational function. The initial mass of fuel (LPG gas) and oil is determined as a reference for energy calculations, while instrument calibration is performed to ensure accurate readings.

2.3.2. Early stages

The initial stage involved identifying problems affecting the performance of the continuous milk pasteurization system. The identification results are used as a reference in the analysis of machine performance and final product quality. Furthermore, a literature study aimed to expand the understanding of the working principle of HTST (High Temperature Short Time) pasteurization, the thermal characteristics of milk, and important parameters in the pasteurization process. Based on the results of the literature study and problem identification, the design of parameters is determined to be used as the basis for the preparation of tools, materials, and measurement instruments before the test takes place. Tool engineering drawings are created with SolidWorks 2024 based on the actual geometry of the machine to map monitoring points and support flow/heat transfer analysis.

2.4. Stages of Data Collection

Data collection begins with checking continuous type pasteurization machines, burners, PTFE pipes, DC pumps, and measurement instruments. The temperature was measured at four points, namely the oil temperature near the burner (T_{bottom}), the oil temperature at the top of the tank (T_{top}), the milk inlet temperature (T_{in}), and the milk outlet temperature (T_{out}). Figure 1 shows a milk pasteurization used in this experiment equipped with the temperature measurement positions of $\mathrm{T_{bottom}}$, $\mathrm{T_{top}}$, T_{in}, and T_{out}.

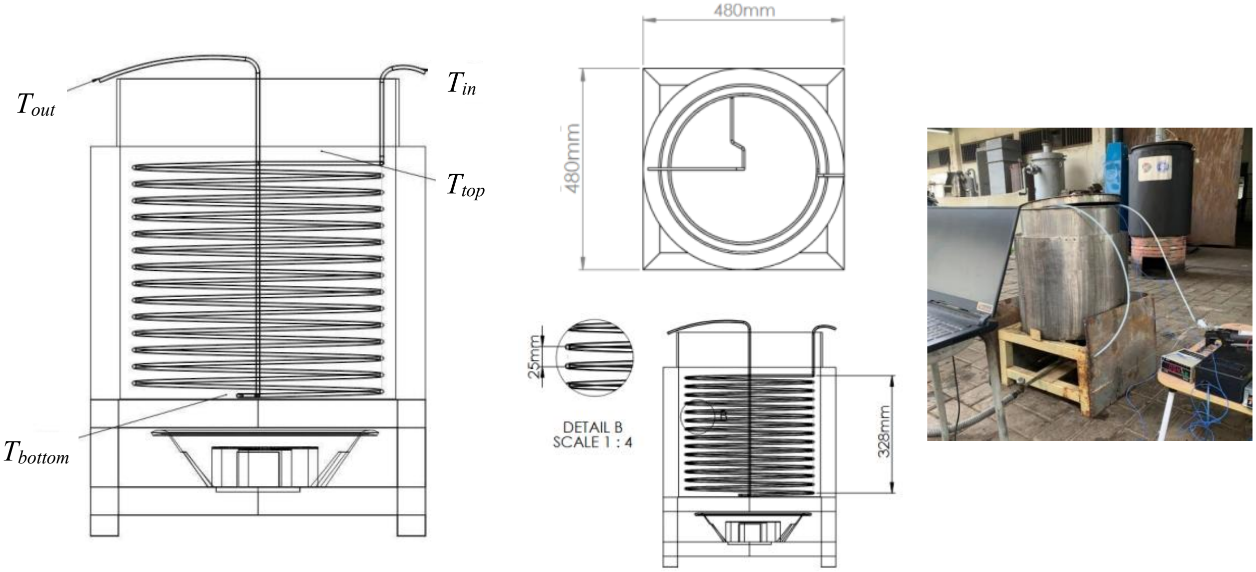

Figure 1. Design of the pasteurization machine system along with data collection set-up for measurement of temperatures

The milk flow rate is monitored using a flow meter to determine the residence time of milk on the pipeline trajectory. The pasteurization process and temperature observation are carried out for 5 minutes at a constant flow rate. This observation time is set to ensure that the continuous pasteurization system has reached a steady state, where the temperature profile and flow rate do not change significantly over time. Given that the fluid residence time in the system is only about 10.47 seconds, during the observation period of 5 minutes, the fluid has passed through the system repeatedly, so the temperature data obtained represents stable operating conditions and can be used for reliable analysis of the temperature distribution and thermal performance of the system. All temperature data is recorded using a K-type thermocouple and a data recorder. During the test with heating to a temperature of 72 °C (HTST treatment), the flow rate of the milk mass, temperatures (T_{bottom}, T_{top}, T_{in}, and T_{out}), initial mass, and consumption of LPG gas, oil mass and its temperature change, and pump voltage and current are recorded for the calculation of electrical power. The measurement data were used to calculate the rate of fuel energy transfer, the rate of oil energy transfer, and the rate of convection heat transfer to milk based on internal forced convection analysis, assuming constant surface temperature. Energy efficiency is calculated as the ratio of oil energy to fuel energy, while total energy consumption is calculated from the sum of oil energy and pump electrical power. For microbiological quality evaluation, milk samples were taken at the point of sterilization, immediately cooled, and tested to count the number of pathogenic microorganisms (*Escherichia coli* and *Staphylococcus aureus*) in four samples, namely control and three repeats. All measurement data is recapped and processed using Microsoft Excel for calculation and analysis, then compared to HTST's pasteurization standard (72 °C during the corresponding residence time).

2.5. Data Analysis

Data analysis includes the efficiency of the continuous type pasteurization machine, the energy transfer rate of the continuous type pasteurization machine, energy consumption, energy efficiency, and the microbial test of pasteurized dairy products measured according to optimal performance parameters.

2.5.1. Fuel and Oil Energy Transfer Rate

The energy of gas and oil fluid utilized in the stainless-steel frame to heat or pasteurize the milk was calculated using Equations (1) and (2).

$$Q_{fuel} = m_{gas} \times H \tag{1}$$

$$Q_{oil} = \frac{m\, C_p\, (T_{m2} - T_{m1})}{t} \tag{2}$$

where $\dot{Q}_{fuel}$ is the fuel energy transfer rate (W), m_{gas} is gas combustion rate (kg/s), H is calorific value of gas (J/kg), Q_{oil} is the oil energy transfer rate (W), T_{m1} is initial oil temperature (°C), T_{m2} is the final temperature of the oil (°C), m is the oil mass (kg), C_p is the specific heat capacity of oil (J/kg·K), and *t* is the measurement time until the target temperature is reached (s).

2.5.2. Heat Transfer Rate of Internal Forced Convection

Internal forced convection analysis with constant surface temperature conditions assumes that the temperature of the outer fluid in contact with the outermost pipe surface does not change. This analysis works based on the law of convection heat transfer defined by Equation 3, which has been adjusted as follows:

$$Q_{milk} = h \cdot A_s \cdot \Delta T_{avg} \tag{3}$$

where Q_{milk} is the rate of energy transfer of milk heat transfer (W), h is the convection heat transfer coefficient (kW/m^2), A_s is the PTFE tubing area (m^2), and ΔT_{avg} is the average temperature change (°C).

2.5.3. Heat Transfer Analysis and Visualization of Actual Data with CFDs

Heat transfer analysis was carried out to measure the rate of heat transfer energy that occurs in a continuous-type pasteurization machine using Equation (4), which has been adjusted as follows.

$$Q_{milk} = h_s \cdot A_s \cdot \Delta T_{lm} \tag{4}$$

where Q_{milk} is the rate of energy transfer of milk heat transfer (W), h_s is the milk heat transfer coefficient (W/m^2), A_s is pipe surface area (m^2), and ΔT_{lm} is logarithmic mean temperature difference (°C).

2.5.4. Efficiency Calculation

Efficiency calculation is carried out by calculating 3 efficiency parameters, namely fuel efficiency, oil efficiency, and total efficiency. The efficiency data of a continuous type pasteurization machine with a gas heater is obtained by calculating the energy values of fuel, oil fluid, and milk. The efficiency calculation represents the percentage of energy absorbed by the fluid from the fuel. The first stage in the efficiency calculation is to calculate fuel efficiency (η_{ST}) using Equation (5). The second stage of efficiency calculation is the calculation of oil efficiency (η_m) obtained by Equation (6). In the third stage of efficiency calculation, the total efficiency (η_t) was calculated using Equation (7).

$$\eta_{ST} = \frac{Q_{oil}}{Q_{fuel}} \times 100\% \tag{5}$$

$$\eta_m = \frac{Q_{milk}}{Q_{oil}} \times 100\% \tag{6}$$

$$\eta_t = \frac{Q_{milk}}{Q_{fuel}} \times 100\% \tag{7}$$

where Q_{oil} is the oil energy transfer rate (W), Q_{fuel} is the fuel energy transfer rate (W), and Q_{milk} is milk heat transfer energy transfer rate (W).

2.5.5. Gas and Electricity Energy Consumption

The pasteurization process affects the consumption of gas and electricity energy used during the pasteurization process. The electricity energy consumption was calculated using Equation (8):

$$P = V \times I \tag{8}$$

where P is active power (watts), V is voltage (volts), and I is electric current (amperes).

2.5.6. Microbial Test

Samples of milk that have been heated using a continuous-type pasteurization machine are tested in the laboratory. The test carried out was a microbial test involving the analysis of the content of *Escherichia coli* and *Staphylococcus aureus* bacteria to determine the quality of milk from continuous pasteurization. Tests were carried out on four samples, namely no treatment (control), 1 repeat, 2 repeat, and 3 repeat. Milk microbial tests were carried out at the Sea Fast Laboratory, Food Technology Science, Bogor Agricultural University.

2.6. Fluid Assumptions in CFD Simulations

In the Computational Fluid Dynamics (CFD) simulation, milk is modelled using water properties. This approach is done to simplify the numerical model and improve computational stability, while maintaining an adequate level of accuracy. The selection of water as a substitute fluid is based on the similarity of thermophysical properties between water and milk, in particular in the pasteurized temperature range (60–75 °C). Some studies report that the density, specific heat capacity, and thermal conductivity of fresh milk are similar to those of water in the 60–75 °C range at that temperature, especially at low to moderate fat content. The viscosity difference was considered not to have a dominant influence on the temperature distribution and residence time in the internal flow of pipes with similar flow regimes. Therefore, the use of water as a fluid approach in CFD simulations is considered representative enough to analyze temperature distribution, flow patterns, and residence time characteristics in continuous milk pasteurization systems. The use of water as a surrogate fluid in CFD simulation is supported by the similarity of thermophysical properties between water and milk within the pasteurization temperature range. Previous studies have shown that the density, specific heat capacity, and thermal conductivity of milk are comparable to those of water, especially at moderate temperatures and low-fat content conditions. Therefore, this assumption is considered acceptable for representing heat transfer characteristics in milk flow analysis (Minim et al., 2002).

2.7. Heat Loss to the Environment Analysis

Heat loss to the environment was analyzed through convection and radiation mechanisms from the surface of the heating tank and pipes. Heat loss due to natural convection was calculated by Equation (9):

$$\dot{Q}_{conv} = h\,A\,(T_s - T_{amb}) \tag{9}$$

where h is the air convection heat transfer coefficient (W/m²·K), A is the surface area of heat transfer (m²), T_s is the surface temperature (K), T_{amb} is the ambient temperature (K). Heat loss due to radiation was calculated as follows:

$$\dot{Q}_{rad} = \varepsilon\,\sigma\,A\,(T_s^4 - T_{amb}^4) \tag{10}$$

where ε is the surface emissivity, and σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m²·K⁴). Total heat loss to the environment was calculated as the sum of the convection and radiation components.

2.8. Heat Transfer Resistance Analysis on Pipes

Heat transfer resistance analysis was performed to evaluate the influence of the material and pipe dimensions on the heat transfer rate from the heating oil to the milk. The heat transfer model is assumed to be a layered cylindrical system consisting of an oil film, a pipe wall, and a milk film. The conduction resistance of the cylindrical pipe wall was calculated using Equation (11):

$$R_{cond} = \frac{\ln(r_o/r_i)}{2\pi k L} \tag{11}$$

where r_o and r_i each is the outer and inner radius of the pipe (m), k is the thermal conductivity of the pipe material (W/m·K), L and is the length of the pipe (m). The total heat transfer resistance is expressed as $R_{total} = R_{oil} + R_{cond} + R_{milk}$. This analysis is used to assess the contribution of each resistance to the total heat transfer resistance, as well as a basis for evaluating material selection and modification of pipe dimensions in the pasteurization system.

3. RESULTS AND DISCUSSION

3.1. Temperature Distribution

The temperature distribution in a continuous-type pasteurization machine is obtained by direct observation during the pasteurization process. Temperature observations were carried out at four observation points, recorded using a K-type thermocouple and a recorder. The four points used in this observation are 1) The oil point at the bottom of the tank (T_{bottom}), 2) The oil point at the top of the tank (T_{top}), 3) The entry point of milk into the PTFE tubing (T_{in}), and 4) The point of milk exit from the PTFE tubing (T_{out}). The results of the observation of the 4 observation points were recorded using Microsoft Excel during the observation. Temperature measurement is carried out from the beginning of the heating turned on until the completion of the pasteurization process for 5 min. This process is divided into two stages, namely heating the oil in the tank until it reaches the target temperature and entering the milk into the pipe until it reaches a temperature of 72 °C for 5 minutes. In the first stage, temperature observation was focused on two observation points, namely the oil temperature at the bottom of the tank (T_{bottom}) and the oil temperature at the top of the tank (T_{top}). The heating temperature profile of the oil up to the target temperature is presented in Figure 2.

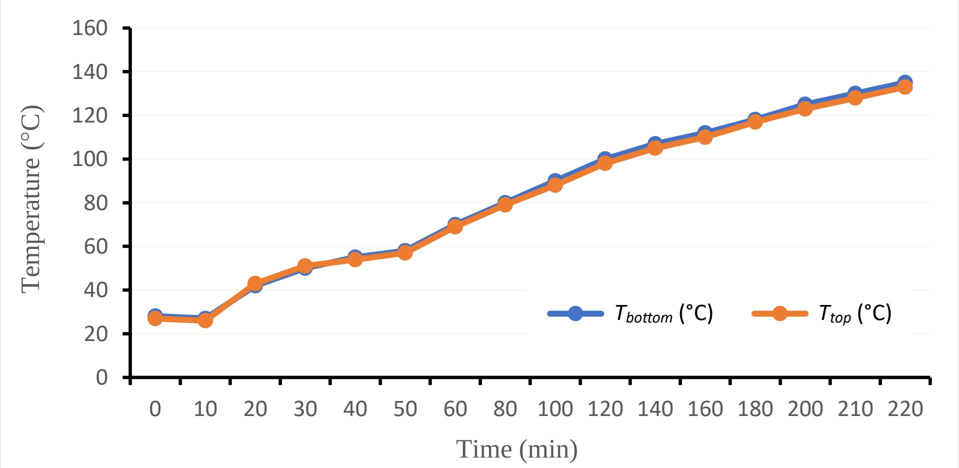

Figure 2. Temperature profile of oil at the bottom (T_{bottom}) and top (T_{top}) of the tank during the heating stage

The change in oil temperature in the first stage of heating occurred over a period of 220 min with an initial value of the bottom temperature (T_{bottom}) of 28 °C and the upper temperature (T_{top}) of 29 °C at time 0 (zero). The oil in the tank is heated using a gas stove whose heat source is located at the bottom of the tank. The temperature rise of T_{bottom} and T_{top} tends to be the same over time. Based on the graph in Figure 2, the temperature of T_{bottom} is hotter than that of T_{top} when oil heating takes place. This is because T_{bottom} is closer to the heat source than T_{top}. The temperature difference between T_{bottom} and T_{top} per unit of time ranges from 1 °C to 3 °C from the beginning to the end of the oil heating process. At the 220th minute, just before the pasteurization process was carried out, the temperature difference between T_{bottom} and T_{top} was recorded at 1 °C. It can be said that at the 220th minute, the temperature of the T_{bottom} and T_{top} oils did not differ significantly, which means that the temperature of the oil in the tank was almost uniform. The target temperature of oil heating of 135 °C is determined based on the results of several previous experiments, at which the temperature of the milk flow coming out at the outlet reaches ±72 °C. The graph in Figure 1 shows a linear trend of temperature rise with a constant gas combustion rate.

Measuring the distribution of oil temperature in the tank until it reaches the target temperature takes 220 minutes. When the oil temperature has reached the target temperature, which is at an average temperature of 134.5 °C, the pasteurization process is immediately carried out by flowing milk into PTFE tubing that has been heated by oil. Milk was pumped using a 12 V DC pump with a mass flow rate of 1.2×10^{-2} kg/s. When the pasteurization process begins, the second stage of observation is carried out by measuring the temperature at four points, namely the temperature of the oil at the bottom of the tank (T_{bottom}), the temperature of the oil at the top of the tank (T_{top}), the temperature of the milk entering the pipe (T_{in}), and the temperature of the milk coming out of the pipe (T_{out}). The pasteurization process and temperature observation during pasteurization are carried out for 5 min with a constant flow rate. The selection of observation times that are much longer than fluid residence times aims to minimize the influence of transient fluctuations and improve the reliability of temperature data used in CFD analysis and system performance evaluation. The temperature distribution in the second stage is presented in Figure 3.

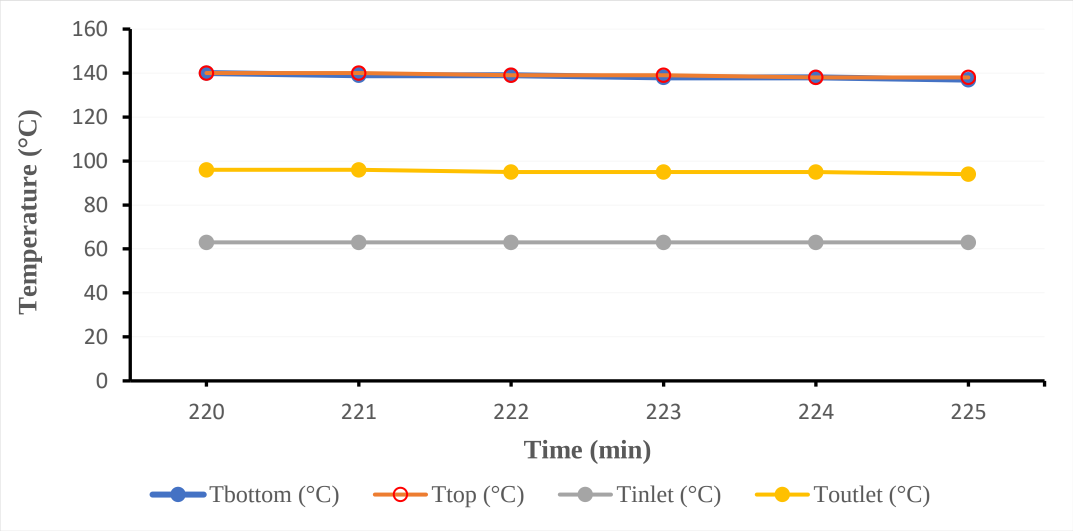

Figure 3. Temperature profiles of oil and milk at different measurement points during pasteurization

Temperature measurement in the pasteurization process was carried out for 5 min using 5 L of milk. During the measurement process, the gas combustion rate is not changed or is the same as the initial condition. The stove is kept on to maintain the oil temperature so that it does not drop because it absorbs heat from the PTFE tubing, whose temperature drops due to the flow of milk. The recording of the temperature value at each point is recorded every 10 s by the manual recording method based on the measurement results using a type K thermocouple.

At the 220th minute, the temperature of T_{bottom} and T_{top} is still the same as the heating process, which is 135 °C and 134 °C, while the milk outlet temperature is at 76 °C. Temperature changes begin to be seen in the first 1 minute after the pasteurization process is carried out. The T_{bottom} temperature decreased by 2 °C from 135 °C to 133 °C while the T_{top} temperature and milk outlet temperature did not change. At the 221st minute, after 10 seconds, the temperature of T_{bottom} dropped by 1°C from the measurement at the 220th minute to 132 °C. The temperature of the T_{top} drops by 1 °C to 133 °C, and the outlet temperature drops by 1 °C to 75 °C. The highest temperature change occurred in T_{bottom} with temperature values at the 220th and 255th minutes of 135 °C and 127 °C, or a decrease of 8°C. The temperature of T_{top} also experienced a significant decrease, which decreased from 134 °C to 130 °C, or decreased by 4°C during the 5 minutes of measurement time. It is important to pay attention to the outlet temperature or the temperature of the milk that has gone through the heating process. The parameter that has been set for the High Temperature Short Time (HTST) pasteurization process is a temperature of 72 °C, which is maintained for 15 seconds. The outlet temperature data in Figure 2 shows a temperature drop of 4 °C from 76°C to 72 °C. Outlet temperatures at lower ranges are able to be maintained longer than higher ranges. It can be seen in Figure 2 that when the outlet temperature is 76 °C, it lasts for 30 seconds, while the outlet temperature of 73 °C is able to be maintained for 200 seconds. In the temperature range of 72 °C, the outlet temperature is only recorded for 30 seconds until the process is finally completed. This phenomenon is influenced by the equilibrium factor between the temperature of the oil that provides heat and the temperature of the milk that absorbs heat.

3.2. Heat Transfer Analysis of Milk Flow in PTFE Tubing

Heat transfer analysis was carried out to obtain the value of the milk heat transfer energy transfer rate (Q_{milk}) using actual measurement data. The data that can be collected from the results of the temperature distribution analysis is a reference to obtain the value of the heat transfer coefficient of milk (h_{milk}) flowing through a PTFE tubing, the Reynolds number of milk

(*Re*), the Prandtl number of milk (*Pr*), and the Nusselt number of milk (*Nu*), and the calculation of the logarithmic mean temperature difference (ΔT_{lm}). All of the data mentioned above are used to find the rate of heat transfer in milk. Heat transfer analysis is carried out as a reference parameter to design a more optimal tool geometry by using lower energy, and saving the purchase of the materials used. The calculation of the rate of heat transfer energy refers to the calculation of internal forced convection heat transfer in a flowing fluid with constant surface temperature conditions (Çengel, 2006). The properties of milk used are based on the properties of milk from the research on thermo-physical characteristics for microwave pasteurized milk (Ali *et al.*, 2015). Temperature comparison reference data used data on the average results of the actual temperature distribution of the experiment. Temperature change is calculated using the logarithmic mean temperature difference. Pipe surface temperature conditioning is obtained from the average temperature of the upper ($\overline{T}_{top}$) and lower ($\overline{T}_{bottom}$) of the oil fluid. The distribution of milk temperature and pipe surface temperature obtained from the actual data calculation results can be seen in Table 1.

Table 1. Average milk temperature distribution and pipe surface temperature at constant $\dot{m}$

$\dot{m}$ (kg/s)	$T_{surface}$ (°C)	T_{inlet} (°C)	T_{outlet} (°C)
1.2×10^{-2}	131.3	30	73

The milk mass flow rate of 1.2×10^{-2} kg/s is affected by the pressure exerted by the 12V DC pump. The mass flow rate is the most suitable for the specification of the pasteurization machine because the milk temperature output at the outlet corresponds to the desired specification, which is ±72 °C. The results of the actual data calculation are then processed to obtain the parameters needed for the analysis of milk heat transfer. The calculation of the parameters needed for heat transfer analysis is the result of processing primary data that has been averaged and used as a reference for the calculation of logarithmic mean temperature difference, Reynolds number, Nusselt number, and Prandtl number. All parameters that have been calculated are then processed until the final result is obtained in the form of the energy transfer rate of milk heat transfer by the internal forced convection method at constant surface temperature conditions. The recapitulation of the data from the calculation of heat transfer can be seen in Table 2. The heat energy transfer rate of milk flowing along a PTFE tubing with a mass flow rate of 1.2×10^{-2} kg/s is 139.54 W. The rate of the heat energy transfer can be a reference in designing an optimal pipe geometry design in a continuous type pasteurization machine with gas heating. This heat transfer rate value will be useful for tool development, especially to make efficient, cost-effective, and increase engine capacity.

Table 2. Heat transfer calculation results

Parameter	**Symbol**	**Value**	**Units**
Inner diameter of the pipe	*Id*	4×10^{-3}	m
Pipe outer diameter	*Od*	6×10^{-3}	m
Pipe area (In)	*A*	1.26×10^{-2}	m^2
Mass flow rate	$\dot{m}$	1.2×10^{-2}	kg/s
Flow speed	v	0.96	m/s
Mean bulk temperature	T_f	51.9	°C
Density	ρ	1015.05	kg/m^3
Dynamic viscosities	μ	7.16×10^{-4}	kg/m.s
Thermal conductivity	*k*	0.61	W/m.K
Specific heat capacity	*Cp*	3951.39	J/kg. K
Prandtl number	*Pr*	4.64	-
Nusselt number	*Nu*	60.67	-
Reynolds Number	*Re*	5471.54	-
convection coefficient	*h*	9237.54	W/m^2
LMTD	ΔT_{lm}	77.09	°C
The rate of transfer of heat energy	$\dot{Q}$	139.54	W

3.3. Temperature Distribution Simulation with CFD and Design Evaluation

The application of Computational Fluid Dynamics (CFD) in food processing systems has been widely used to analyze temperature distribution, flow behaviour, and residence time in thermal processes. CFD modelling enables detailed visualization of heat transfer mechanisms and hydrodynamic characteristics that are difficult to measure experimentally.

Previous studies have successfully applied CFD to simulate milk flow and heat transfer in pasteurization systems, demonstrating its effectiveness in optimizing process design and performance (Grijspeerdt *et al*., 2003; Lakshmanan & Potter, 1990).

The simulation of temperature distribution in PTFE tubing was conducted using Computational Fluid Dynamics (CFD) through the Flow Simulation feature in SolidWorks 2024. A manual mathematical modeling approach can be further developed and supported by CFD simulation to represent the complexity of high-level heat transfer calculations (Yoon, 2018). Therefore, the heat transfer analysis based on actual data was visualized using CFD to obtain a more comprehensive understanding of temperature distribution and fluid behaviour within the system. Modeling simulation with CFD is carried out by providing assumptions on certain conditions using validation in the form of experimental data that can be used as a comparison of CFD simulations, such as on-site experiments and numerical validation (Akmal *et al*., 2019).

The simulation process was carried out through several stages, namely: (1) geometry preparation, (2) determination of the fluid and geometry domains to be analyzed, (3) mesh definition, and (4) setting of boundary conditions. In the first stage, the geometry of the system was created using the part features available in SolidWorks 2024. The second stage involved defining the computational domain, which consists of both the fluid domain and the solid (geometry) domain. This step is essential to establish the fluid flow trajectory within the pipeline and to define the computational region for analysis. The size of the simulation domain used in this study was 45 cm × 40 cm × 35 cm (D × W × H). The results of the computational domain setup are presented in Figure 3.

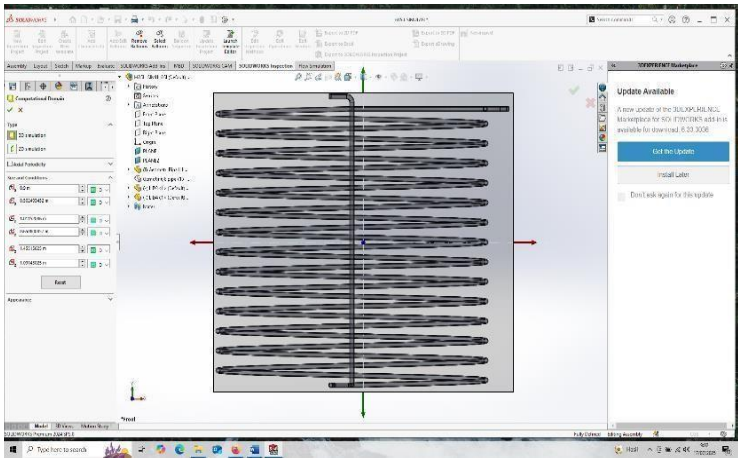

Figure 3. Analytical computing domains

The focus of the CFD analysis used in the study was the temperature distribution of the milk flowing along the PTFE tubing. The geometric dimension reference of the PTFE tubing follows the actual size of the pipe submerged in the oil fluid. The input parameters of the actual data measurement are included in the preprocessing process. This process involves determining the simulation domain and fluid domain, the physical calculation units used, and the mesh setting. The simulation domain defines the scope of the analysis on the geometry; the setup of the simulation domain should be as close as possible to the geometry. The size of the simulation domain is wide and far from the geometry, which will expand the area of the calculation and reach areas that are not important. The fluid domain setup is set by using the lids feature available in the flow simulation option. The lids cover the inlet and outlet areas of the fluid flowing on the pipe; the results of the fluid domain setup can be seen in Figure 4a. The fluid domain visualization depicts the flow trajectory from the inlet to the outlet that must be tightly sealed to prevent miscalculations, with geometric leaks being checked through the Track Leaks feature in SolidWorks 2024. Once the computational and fluid domains are defined, the next stage is the definition of the mesh on the geometry model to divide the tools into computed elements that are each calculated. The determination of the mesh must be according to the shape and size of the geometry; the smaller the size of the pipe, the higher the mesh level used, for the simulation results to be accurate. In the conjugate heat transfer analysis, it is recommended to raise one mesh level in the contact area of the pipe and fluid because it is an important point of heat transfer along the pipe. The definition of the pipe geometry mesh is shown in Figure 4b.

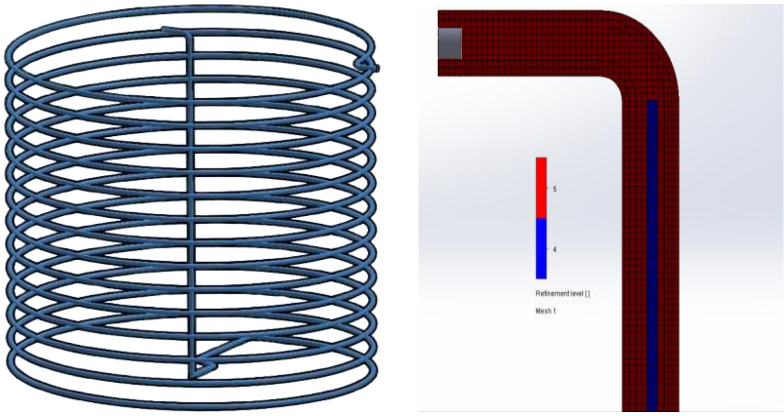

Figure 4. (a) Fluid domain, and (b) Mesh in the pipe area

Simulation of the temperature distribution of milk in a PTFE tubing using Flow Simulation is carried out by entering input parameters obtained from actual data, including mass flow rate, static pressure, thermal resistance, and heat source. The heat source is taken from the average temperature of the oil in the tank. The determination of parameter inputs must be precise to avoid analytical errors, including the selection of solid and fluid material types according to the original material. If the material is not available in the library, the material with the closest thermophysical properties is used; in this study, because the properties of milk are not available in the library, water is used as a substitute because it has thermophysical properties most similar to milk. Although the CFD simulation uses water properties, the simulation results show the conformity of temperature and residence time distribution trends with the actual experimental data using milk. This indicates that the approach to the approximation fluid is still able to adequately represent the thermal behaviour of the system. The difference in fluid type between actual and simulated data can indeed affect the results, but selecting fluids with close characteristics will minimize errors and still produce a reliable level of accuracy. The input parameters used for the CFD simulation are shown in Table 3.

Table 3. Prices, stages, and input parameters of the CFD simulation model for milk and PTFE tubing

No	Stages of the Simulation Process	Parameter	Value	Remarks
1	Wizard Flow Simulation	Unit system	-	SI (m-kg-s)
		Analysis type	-	Internal
		Default solid	PTFE	PTFE
		Default fluid	Water	Water
		Wall conditions	30 °C	Outer wall temperature
		Initial Pressure	1 atm	Pressure
		Initial Temperature	28 °C	Temperature
2	Computational Domain	x-axis	-	Covers pipe geometry
		Y-axis	-	
		Z-axis	-	
3	Fluid Subdomain	Water	-	Water on the inside of the pipe
4	Solid Materials	PTFE	-	Covers pipe geometry
5	Goals	Average fluid temperature	-	Mouth track-track fluid
		Maximum fluid temperature	-	Maximum fluid in the mouth
6	Mesh	Global mesh	Mesh level 3	Common mesh
		Local mesh	Mesh level 5	Pipe Geometry Mesh

After parameter input, the next step that needs to be done is to set up boundary conditions. Boundary conditions are required to establish the initial parameter conditions in the simulation stage. Defining boundary conditions can be done in the Input boundary settings option available in the input data tree. The parameters of the boundary conditions in this study can be seen in Table 4.

Table 4. Parameter boundary conditions for CFD simulation

Treatment	**CFD Simulation Parameter Input at the observation point**	
	Inlet	**Outlet**
Parameter Boundary conditions	Inlet mass flow rate	Static pressure
Value Input	Milk mass flow rate ($\dot{m}$) = 1.2×10^{-2} kg/s milk temperature = 30 °C	Pressure = 1 atm; Room temperature = 28 °C
Input data heat source	Pipe surface temperature = 131 °C	Pipe surface temperature = 131 °C

When all boundary condition parameters have been input, the next stage is computational running using the solver feature. The solver will continue to repeat the calculation on each mesh several times until the calculation enters the convergence stage. The repetition of the calculation on each mesh is referred to as an iteration. In this analysis, the iteration limit in the setup is 1500 iterations. The results of the simulation surface plot of the temperature distribution of milk can be seen in Figure 5, the results of the flow speed simulation of flow trajectories can be seen in Figure 6.

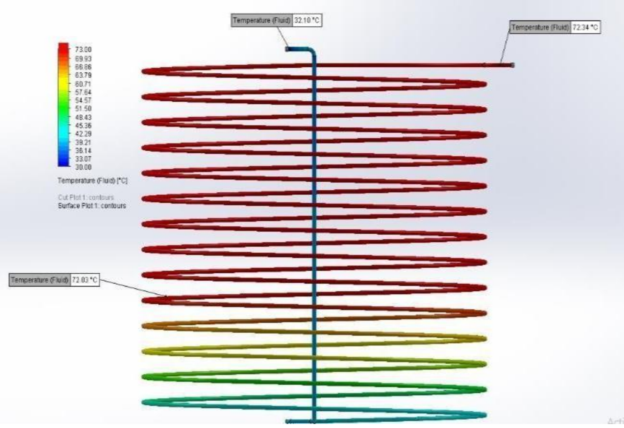

Figure 5. Surface plot results of fluid temperature distribution

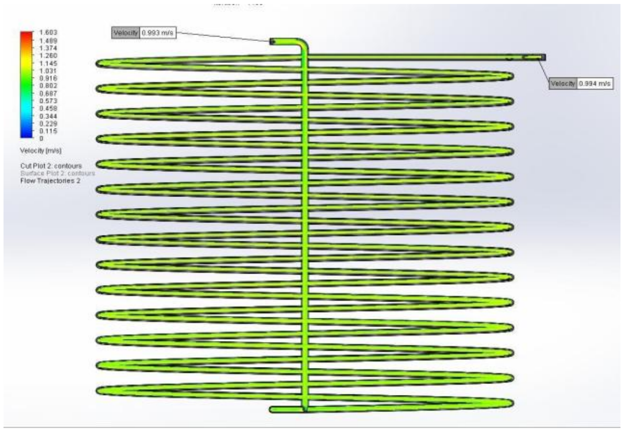

Figure 6. Results flow trajectories fluid flow velocity

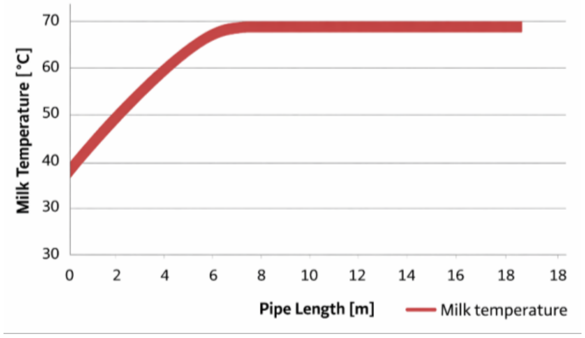

Figure 7. Distribution of milk temperature along the pipe

The results of the heat transfer analysis with CFD at constant oil temperature conditions of 131 °C, with a data reference, namely the graph in Figure 2, can be seen in the graph in Figure 7. Based on the graph in Figure 7, the temperature rises linearly along the pipeline length from the inlet (0 m) to 6 m, drastically from 32 °C to 73 °C. In this range, the process of convection heat transfer occurs intensively, and the milk temperature has not reached the equilibrium point. When the milk trajectory reaches 6 meters, the milk temperature begins to stabilize in the range of 73 °C, which indicates that there is an equilibrium of milk temperature in the pasteurization process. At this stage, the milk has reached the target temperature maintained until it reaches the end of the pipe. The equilibrium process occurs along the 10 m of the trajectory (6 to 16 m). In this condition, the milk has reached the isothermal stage, or the temperature change has not occurred. The visualization of the temperature distribution from the CFD analysis, with the surface plot seen in Figure 6, illustrates the gradient of temperature change in the pipe geometry. Figure 6 also maps the milk temperature value at the key points of the pasteurization process, namely the inlet temperature (T_{in}), the outlet temperature (T_{out}), and the point when the milk temperature reaches the equilibrium point. Temperature point mapping was carried out using the probe flow simulation display feature. Through this mapping, it can be found at which point the milk temperature begins to reach the equilibrium point. The data in the graph in Figure 8 can be used as a reference to determine how long the holding process maintains the condition of milk at a temperature of ±72 °C along the pipe. In the continuous pasteurization process using the High Temperature Short Time (HTST) method, the milk temperature needs to be maintained isothermally at a temperature of ±72 °C for 15 seconds. Figure 7 shows the velocity gradient of the fluid present in the pipeline during the pasteurization process. As can be seen, the flow rate of the fluid inside the pipe is constant, which is ± 0.995 m/s. The actual calculation and the results of the simulation calculation show the same fluid velocity value. Therefore, it can be concluded that a fluid velocity value of 0.955 m/s can be used to determine how long the fluid flows inside the pipeline during the isothermal process. The duration of the milk held at a temperature of ±72 °C with a constant speed of 0.955 m/s, based on actual data and ideal specifications, can be seen in Table 5.

Table 5. Comparison of actual and ideal specifications

Parameter	Unit	Actual	Ideal
Flow rate	m/s	0.955	0.955
Isothermal trajectory	m	10	14.3
Holding duration	s	10.47	15
Pipe length	m	16	20.3

3.4. Energy Efficiency and Consumption

Fuel efficiency is obtained by direct testing using a continuous type pasteurization machine with gas heating. The fuel efficiency value is the ratio between the oil transfer rate obtained using Equation 2 and the interpolation of liquid properties data by Çengel & Chimbala (2006). The rate of fuel energy transfer obtained from the results of Equation 1 during the test process. Fuel energy measurements are carried out from minute 0 to minute 225 or from the beginning of the stove to the end of the testing process. The results of the calculation of fuel efficiency, oil efficiency, and total efficiency can be seen in Table 6 below.

Based on Equations (5) to (7), the fuel efficiency, oil efficiency, and total efficiency of the pasteurization machine are calculated to be 35.6%, 23%, and 8.2%. This value indicates that most of the energy channelled by the fuel and oil is wasted. Relatively small efficiency values indicate that the distribution of energy from fuel to oil and oil to milk is inefficient. The amount of energy wasted can occur due to the combustion chamber that is not tightly closed, so that the heat transfer process from the burner to the tank is not optimal. In addition, this machine is also not equipped with a heat insulator in the tank, which causes the energy circulating in the tank to propagate out. Engine design evaluation needs to be carried out so that fuel efficiency values can be improved. The small value of oil efficiency is caused by suboptimal pipe design. To improve the value of oil efficiency, PTFE tubing material that has a low thermal conductivity value of 0.3 W/m.K (At 27 °C) can be replaced with pipe material with a higher thermal conductivity value with a note that does not ignore the quality of food grade in pipe materials such as stainless steel materials AISI 302 which has a thermal conductivity value of 15.1 W/m.K (At 27 °C) or at the same temperature (Çengel, 2006).

Energy consumption measurement is carried out for two parameters, namely fuel energy consumption and electrical energy consumption. Fuel energy transfer rate value (Q_{bb}) represents the energy consumption value of the gas fuel used during the testing process. The continuous system pasteurization machine utilizes fuel energy from LPG gas to heat the oil in the tank and uses electrical energy to activate the pump that flows milk along the pipe. Fuel energy is used from the beginning of the engine operation, while electrical energy is only used when the pasteurization process is carried out. The unit of energy used in both gas and electric energy is watts (W) or joules/seconds (J/s). The energy value of gas is obtained from the result of multiplying the calorific value of the gas (H) by the flow rate of the gas mass ($\dot{m}_{gas}$). According to the Ministry of Energy and Mineral Resources, the calorific value of LPG gas is 47.09 MJ/kg (Kementerian ESDM, 2020). The gas mass flow rate is calculated by dividing the mass of gas by the time.

The calculation of electrical energy consumption or pump power is carried out using a multimeter that records the current and voltage of the electrical output at the pump. A multimeter is a device that is able to measure the output voltage, current strength, and resistance of a component. The type of multimeter used in this study is a digital multimeter. Measurement of the voltage and current strength values is carried out on the 12V DC pump cable using positive probe wires and negative probe wires laid on the positive and negative axes of the pump. The placement of the positive and negative probe wires must be appropriate so that the values displayed on the LCD are not incorrect. For the display of the voltage value, the selector knob is rotated in the direction of voltage (V) DC in the desired range (in this case, it is set in the range of 0–20V DC). The pump voltage measurement results will be shown through the LCD display. The measurement of electric current is similar to that of voltage; the difference is that the positive (red) probe wire is moved to the ohm and R options, then the selector knob is turned to the ampere option (A) with a range of ±10 A. The voltage output indicated by the unit multimeter is volts (V), and the current output is amperes (A). The results of the measurement of the value of fuel energy consumption and electrical energy can be seen in Table 6.

Table 6. Fuel consumption data

Parameter	Symbols	Value	Units
Calorific value of gas	H	47089136	J/kg
Initial mass of gas	$mg1$	6	kg
Gas end mass	$mg2$	5.5	kg
Used gas mass	mgt	0.5	kg
Measurement time	t	13500	seconds
Gas combustion rate	$\dot{m}gas$	3.78×10^{-5}	kg/s
Material energy consumption	Q_{fuel}	1783.7	W

The calorific value of the gas used in the process is 47.09 MJ/kg. The initial mass of the gas before combustion is 6 kg, while the final mass of the gas after the process is 5.5 kg. Thus, the mass of gas used or consumed during the process is 0.5 kg. The burning process is carried out for 225 min. The gas combustion rate during this period was 3.78×10^{-5} kg/s. From this data, it was obtained that the fuel energy consumption produced was 1783.7 W.

The pump used in this system operates at a voltage of 12 V. The electric current flowing to operate the pump is 3 A. Based on the value of the voltage and current, the electrical power consumed by the pump is 36 W. The process of calculating this power value is the result of multiplying the voltage and current strength, which reflects the electrical energy requirement to run the pump during the process.

3.5. Pathogen Test on Pasteurized Milk

The pathogen test of pasteurized milk involves the analysis of two types of bacteria, namely *Escherichia coli* and *Staphylococcus aureus,* contained in each sample. This study used four samples, namely 1 control sample and 3 repeat samples. The control variable (without treatment) was measured as a comparison of the other three variables that went through the pasteurization process. The sampling procedure is carried out carefully to prevent any exposure of bacteria from the environment that enters the sample. The first microbial content parameter to be tested was the content of *Escherichia coli* bacteria using the SNI ISO 7251-2012 method (BSN, 2012). The microbial analysis reveals a positive result for control with *E. coli* content of 2.4×10^4 MPN/mL. The analysis, however, shows negative or zero values for three samples of milk with pasteurization treatment. According to the SNI ISO 7388:2009 standard (BSN, 2009), the maximum content value of *Escherichia coli* bacteria is <3 MPN/mL. This means that pasteurized milk passes the criteria, while untreated milk fails the requirement.

The next stage is to test the content of *Staphylococcus aureus* bacteria using the cup counting method or BAM 2001 Chapter 12 (FDA, 2019). The results of the *Staphylococcus aureus* bacteria content test are recapitulated in Table 11. The comparison of the content of *Staphylococcus aureus* bacteria in the research sample and the maximum standard of SNI ISO 7388:2009 can be seen in Table 7. The value of *Staphylococcus aureus* bacteria content in the control sample was 4.4×10^5 colony/mL. According to the SNI ISO 7388:2009 standard, the maximum content value of the number of *Staphylococcus aureus* bacterial colonies in pasteurized milk is 1×10^2 colonies /mL. This indicates that without pasteurization treatment, the milk contains a very large amount of *Staphylococcus aureus* bacteria, exceeding the maximum standard value. Meanwhile, three samples of the pasteurized milks resulted in *Staphylococcus aureus* bacteria content of less than 10 colony-forming units/mL, significantly lower than the maximum standard value. Based on the two microbial analyses, it can be concluded that the pasteurization system using PTFE pipe tubing and a hot vegetable oil medium successfully suppresses bacterial contamination in the milk. All data from the test results of *Escherichia coli* and *Staphylococcus aureus* bacteria that have been presented have been certified by the Laboratory of the Department of Food Science and Technology, Faculty of Agricultural Technology, Bogor Agricultural University.

Table 7. *Staphylococcus aureus* test results

Sample	**Units**	**Result**	**Method**	***S. aureus* maximum***	**Criteria**
Controls	Colony/mL	4.4×10^5	BAM 2001 Chapter 12	1×10^2	Not meet
Replication 1	Colony/mL	5.0×10^0	BAM 2001 Chapter 12	1×10^2	Meet
Replication 2	Colony/mL	4.5×10^0	BAM 2001 Chapter 12	1×10^2	Meet
Replication 3	Colony/mL	1.5×10^0	BAM 2001 Chapter 12	1×10^2	Meet

*) Based on SNI ISO 7388:2009 standards

3.6. Quantitative Analysis of the Inefficiency

The results of the energy balance in Table 8 show that of the total fuel energy of 1783.7 W, only about 139.5 W (7.8%) was successfully transferred to milk. The energy absorbed by heating oil is recorded at 634.4 W or 35.6% of the fuel energy, while the rest is lost at various stages of the process. These findings indicate that the energy inefficiency of the system is not caused by just one factor, but rather is the accumulation of energy loss at several stages of heat transfer.

Table 8. Energy balance of a continuous-type milk pasteurization machine

Energy Components	**Power (W)**	**Percentage of fuel energy (%)**
Fuel energy ($\dot{Q}b$)	1783.7	100
Energy absorbed heating oil ($\dot{Q}m$)	634.4	35.6
Energy transferred to milk ($\dot{Q}s$)	139.5	7.8
Energy loss of fuel → oil stage	1149.3	64.4
Energy loss of oil → milk stage	494.9	27.7
Total energy loss	1644.2	92.2

The largest energy loss occurred at the stage of conversion of fuel energy to heating oil, which was 1149.3 W or 64.4% of fuel energy. This loss is thought to have come from low combustion efficiency, heat wasted through exhaust gases, as well as heat loss from combustion chamber walls that have not been adequately insulated. This condition causes only a portion of the combustion energy to be used to heat the heating oil.

At the stage of heat transfer from oil to milk, energy loss is also still significant, which is 494.9 W or 27.7% of fuel energy. The magnitude of this loss indicates a high heat transfer resistance, especially in PTFE pipe walls that have low thermal conductivity. Heat transfer resistance analysis showed that pipe walls contributed significantly to the total heat transfer resistance, so the rate of heat transfer to milk became limited despite the relatively high oil temperature.

The results of the CFD simulation support these findings by showing that the target temperature of pasteurization can be achieved, but the energy utilization efficiency is not optimal. Therefore, improving system efficiency can be focused on reducing energy loss in two main stages, namely the combustion stage and the oil–milk heat transfer stage. Efforts that can be made include adding thermal insulation to the combustion chamber and heating tank, as well as the use of pipe materials with higher thermal conductivity or modifying pipe dimensions to reduce heat transfer resistance and increase the rate of heat transfer to milk.

The relatively low heat transfer rate observed in this study may also be influenced by thermal resistance and potential fouling effects along the heat transfer surface. Fouling formation in milk processing systems has been reported to significantly reduce heat transfer efficiency by increasing thermal resistance at the fluid–wall interface. Dynamic modeling studies have shown that fouling accumulation can alter temperature profiles and reduce overall system performance, particularly in continuous heat exchange processes (Mahdi & Mouheb, 2009).

Optimization of heat exchanger design plays a crucial role in improving energy efficiency and thermal performance. Previous studies have demonstrated that modifications in geometry, flow configuration, and heat exchanger arrangement can significantly reduce fouling and enhance heat transfer efficiency. The integration of modeling approaches in system design has also been proven effective in identifying optimal configurations and minimizing energy losses in thermal processing systems (Grijspeerdt et al., 2004).

4. CONCLUSIONS AND SUGGESTIONS

4.1. Conclusion

Based on the results of the study, the Computational Fluid Dynamics (CFD) simulation showed that milk reached an isothermal state at a temperature of 72 °C after passing along 6 m of the pipe and was able to maintain that temperature for the next 10 m. At a flow speed of 0.955 m/s, the heating time at a temperature of ±72 °C obtained is only 10.47 seconds, lower than the High Temperature Short Time (HTST) standard, which requires a minimum residence time of 15 seconds. Based on these results, the ideal pipe length to meet the HTST standard is estimated to be 20.3 m. The energy efficiency of the continuous-type milk pasteurization machine tested is still relatively low, with a fuel efficiency of 35.6%, heating oil efficiency of 23%, and total efficiency of 8.2%. This value indicates significant energy loss due to suboptimal heat transfer in the heating and thermal insulation systems. However, the results of the microbiological test showed that the quality of pasteurized milk had met the SNI ISO 7388:2009 standard, characterized by a decrease in the number of *Escherichia coli* up to <3 MPN/mL and *Staphylococcus aureus* below 1×10^2 colonies/mL in all samples.

The limitations of the system in this study include the length of the heating pipe, which is not sufficient to meet the HTST residence time, the low heat transfer efficiency, and the flow rate regulation that has not been optimized. Therefore, further research is recommended to examine pipe design optimization, thermal insulation improvement, and regulation of operating parameters to improve energy efficiency while ensuring comprehensive compliance with pasteurization standards.

4.2. Suggestions

The results indicate that improving the structural design of the continuous-type milk pasteurization machine—by enclosing the combustion chamber, adding thermal insulation to components prone to heat loss, and optimizing the heating tank geometry—can enhance fuel efficiency. In order to improve the heat transfer efficiency of the oil heating medium, it is recommended to replace the milk flow pipe material from PTFE tubing to AISI 302 stainless steel, which has a higher thermal conductivity value and still meets the requirements of food grade. The use of AISI 302 stainless steel material is expected to optimize the rate of heat transfer from the heating medium to milk so that energy consumption becomes more efficient.

Further research is recommended to examine the modification of pipe dimensions, including variations in pipe length, inner diameter, and pipe wall thickness, in order to obtain a combination of parameters that are able to meet the standard HTST residence time without increasing excessive pressure loss. Follow-up studies can also utilize CFD simulations to comprehensively evaluate the effect of changes in pipe dimensions on temperature distribution, fluid residence time, and energy efficiency before experimental testing is conducted.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
AS	✓	✓			✓							✓		✓
GR						✓		✓		✓	✓		✓	
MJ			✓	✓			✓							
DS									✓					

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

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