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Heat Transfer Analysis of Helical Coil Condenser for Bioethanol Purification

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ABSTRACT

Bioethanol purification requires efficient condensation systems to improve phase change and energy transfer in separation processes. This study analyzes heat transfer characteristics of a helical coil condenser and its effect on steam condensation at different reactor temperatures. The experiment used a 20 L bioethanol system with reactor temperatures of 58°C and 71°C, testing durations of 1800–7200 s, and data collection every 100 s. Parameters observed included inlet steam temperature, total heat energy, heat transfer rate, steam mass flow rate, condensate film mass rate, and percentage of condensed steam. Results show that at 58°C, condensation reached 20.26%, while at 71°C it increased to 32.66%, indicating higher heat transfer efficiency. The study concludes that higher reactor temperature improves condenser performance and provides optimization insight for bioethanol purification systems.

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INTRODUCTION

The increasing global demand for energy is driven by rapid population growth, industrial expansion, and rising transportation activities. At the same time, the depletion of fossil fuel reserves and environmental concerns related to greenhouse gas emissions have intensified the need for sustainable energy alternatives. Bioethanol (C_2H_5OH) has emerged as one of the most promising renewable fuels due to its biodegradability, carbon neutrality potential, and ability to be produced from biomass resources (International Energy Agency, 2023; Gupta & Verma, 2022).

Bioethanol production generally involves fermentation followed by separation and purification processes to increase ethanol concentration. One widely applied method is vacuum distillation, which enables separation based on differences in boiling points under reduced pressure conditions. In this process, the liquid mixture is vaporized, and the resulting vapor is subsequently condensed back into liquid form. Efficient condensation is critical to ensure high recovery rates and purity levels of ethanol (Kumar et al., 2021; Singh & Patel, 2023).

Within the distillation system, the condenser plays a crucial role as the main heat transfer component responsible for phase change from vapor to liquid. The performance of the condenser directly influences the efficiency and reliability of the overall purification system. Among various condenser designs, the helical coil condenser has gained significant attention due to its enhanced heat transfer characteristics. The curved geometry induces secondary flow and turbulence, which improves convective heat transfer compared to conventional straight tube configurations (Wang et al., 2020; Zhang & Li, 2022).

Previous studies have extensively investigated the thermal performance of helical coil heat exchangers under different operating conditions. Moawed (2020) reported that curved pipe geometries significantly enhance natural convection heat transfer. Elsaid et al. (2021; 2023) demonstrated that coil inclination, tube geometry, and working fluid properties strongly affect thermal-hydraulic performance. Furthermore, recent studies have confirmed that helical configurations outperform straight tubes due to improved mixing and higher Nusselt numbers (Inyang & Uwa, 2022; Rahman et al., 2024). However, most existing studies focus on general heat exchanger applications rather than specific bioethanol purification systems.

Despite extensive research, a clear gap remains in understanding the heat transfer performance of helical coil condensers applied specifically to bioethanol purification at controlled operational capacities. In particular, limited experimental data are available regarding the influence of reactor temperature variations on condensation efficiency, energy transfer rate, and steam mass flow behavior in a 20-liter scale system. This limitation restricts optimization of condenser design for industrial bioethanol production systems.

Therefore, this study aims to analyze the heat transfer characteristics of a helical coil condenser in a 20-liter bioethanol purification system under different reactor temperatures (58°C and 71°C). The analysis focuses on inlet steam temperature, total heat energy, heat transfer rate, steam mass flow rate, and condensation efficiency. This research contributes theoretically to the advancement of heat transfer studies in curved geometries and practically provides design optimization insights for improving bioethanol purification efficiency in industrial applications.

LITERATURE REVIEW

Bioethanol Production and Purification Systems

Bioethanol is widely recognized as a sustainable alternative fuel that can reduce dependence on fossil-based energy and mitigate greenhouse gas emissions. The production of bioethanol generally involves fermentation of biomass followed by separation and purification processes to increase ethanol concentration. Among various purification methods, distillation remains the most commonly applied technique due to its simplicity and scalability in industrial applications. However, the final purity of bioethanol strongly depends on the efficiency of phase separation and condensation processes during distillation (Kumar et al., 2021; Gupta & Verma, 2022). Recent studies emphasize that optimization of purification systems is essential to improve energy efficiency and product yield. According to Singh and Patel (2023), vacuum distillation systems provide better control of boiling points and reduce thermal degradation of ethanol. Nevertheless, the performance of downstream equipment such as condensers plays a decisive role in determining the overall efficiency of the purification process.

Heat Transfer Mechanism in Condensation Systems

Heat transfer during bioethanol purification is dominated by phase change processes, particularly condensation of ethanol vapor into liquid form. This process involves latent heat removal, where thermal energy is transferred from vapor to cooling medium through conduction and convection mechanisms. The efficiency of this process depends on temperature gradients, fluid velocity, and heat exchanger design. According to Wang et al. (2020), condensation heat transfer is significantly influenced by surface geometry and flow turbulence, which enhance the heat transfer coefficient. Similarly, Zhang and Li (2022) explain that improved mixing in the vapor phase enhances thermal energy dissipation, leading to higher condensation rates. Experimental studies also confirm that condensation inside curved geometries generates secondary flow structures that intensify heat transfer performance (Moawed, 2020; Inyang & Uwa, 2022).

Helical Coil Heat Exchanger Configuration

Helical coil heat exchangers are widely used due to their compact structure and superior heat transfer performance compared to straight tube configurations. The curvature of the coil induces centrifugal forces that generate secondary flow (Dean vortices), which enhances fluid mixing and increases convective heat transfer rates. This phenomenon results in higher Nusselt numbers and improved thermal efficiency. Research by Elsaid et al. (2021) demonstrates that helical coil configurations significantly outperform conventional heat exchangers in terms of thermal-hydraulic performance. In addition, Rahman et al. (2024) report that geometric parameters such as coil diameter, pitch, and tube curvature directly affect heat transfer enhancement. A comparative study by Flayyih et al. (2025) further confirms that helical coils provide 8–12% higher thermal performance compared to straight tubes under identical operating conditions. A detailed experimental investigation by Sánchez et al. (2025) highlights that helical coil heat exchangers are particularly effective for ethanol cooling applications due to their ability to maintain high heat transfer coefficients in compact systems.

Thermal-Hydraulic Performance and Flow Behavior

The performance of helical coil heat exchangers is strongly influenced by the interaction between thermal and hydraulic phenomena. The curvature of the coil induces pressure drop due to increased flow resistance, which must be balanced against the gain in heat transfer efficiency. The trade-off between heat transfer enhancement and pumping power requirement is a key consideration in system design. Flayyih et al. (2025) report that although helical coils increase pressure drop, the overall thermal performance remains superior due to enhanced turbulence and secondary flow formation. Similarly, CFD and experimental studies confirm that Nusselt number increases with Reynolds number, while friction factor decreases gradually at higher flow rates due to flow stabilization effects. A recent CFD-validated study also shows that helical coil systems achieve more uniform temperature distribution and improved energy transfer compared to straight tubes, confirming their suitability for phase-change-based applications such as condensation (Flayyih et al., 2025; Wang et al., 2020).

METHODOLOGY

This study employed a quantitative experimental research design to analyze heat transfer characteristics in a helical coil condenser used for bioethanol purification. The experimental approach was selected to determine causal relationships between reactor temperature and thermal performance parameters under controlled conditions. Experimental research is widely used in thermal engineering to evaluate energy transfer behavior in phase change systems (Creswell & Creswell, 2021).

The experimental system consisted of a 20-liter bioethanol purification unit equipped with a helical coil condenser. The condenser geometry and cooling system were designed to enhance heat transfer through secondary flow formation and increased turbulence. A continuous cooling water system was maintained using a Yamamax Pro DB 402 pump. The working fluid was bioethanol with physicochemical properties listed in Table 2.

Table 1. Geometric Characteristics of Helical Coil Condenser

Parameter	Symbol	Value (m)
Inner diameter	di	0.0214
Outer diameter	do	0.0254
Coil helical diameter	dhk	0.2346
Pitch	P	0.0800
Distance inlet-outlet	f	0.4440
Helical coil height	Hc	0.4500
Shell height	Hs	0.5000
Shell diameter	Ds	0.3350
Shell inner diameter	Dis	0.0254

Table 1 presents the geometric configuration of the helical coil condenser used in this study. The inner and outer diameters (di and do) determine the internal flow area and influence vapor velocity during condensation. The coil diameter (dhk) and pitch (P) define the curvature and spacing of the coil, which directly affect secondary flow formation and turbulence intensity. The shell dimensions (Hs, Ds, Dis) define the external cooling region, which influences heat removal capacity. Overall, these geometric parameters are critical in determining the overall heat transfer coefficient and condenser efficiency.

Table 2. Cooling Water Pump Specifications

Brand	Yamamax Pro DB 402
Power	1.5 HP
Voltage	220 V / 50 Hz
Flow head	15 m
Suction head	7 m
Flow rate	417 L/min

Table 2 describes the specifications of the cooling water pump used to maintain continuous heat removal in the condenser system. The pump power (1.5 HP) ensures sufficient energy to circulate cooling water through the system. The flow rate (417 L/min) determines the cooling water velocity, which directly influences convective heat transfer on the shell side. The flow head and suction head indicate the pump’s capability to maintain stable circulation under operational pressure losses. These parameters are essential to ensure steady-state heat transfer conditions during the experiment.

Table 3. Physicochemical Properties of Bioethanol

Property	Unit	Value
Oxygen content	Mass %	34.7
Cetane number	-	5.8
Octane number	-	110
Density (15°C)	kg/m^3	790
Water content	mg/kg	2024
Viscosity (40°C)	mm^2/s	1.13
Auto-ignition temperature	°C	332–366
Stoichiometric air-fuel ratio	-	1/9.01
Latent heat of vaporization	MJ/kg	0.91
Lower calorific value	MJ/kg	25.22–26.70
Flash point	°C	13

Table 3 summarizes the physicochemical properties of bioethanol used as the working fluid in this study. Density and viscosity influence flow behavior and vaporization rate inside the reactor. The latent heat of vaporization determines the energy required for phase change, which directly affects condenser load. The octane number reflects combustion characteristics, although in this study it relates to fuel quality stability. Water content affects purity and condensation efficiency, while thermal properties such as calorific value and ignition temperature provide context for energy performance during heating and evaporation processes.

The experimental setup of the helical coil condenser system is illustrated in Figure 1, where vapor from the reactor enters the condenser and cooling water flows counter-currently to enhance heat transfer performance. The system operates under controlled reactor temperatures of 58°C and 71°C with testing durations of 1800 s, 3600 s, 5400 s, and 7200 s. Data were recorded every 100 seconds using a calibrated digital data logger.

Figure 1. Condenser Coil Helical Pipe

During operation, vapor generated from the bioethanol reactor flows into the helical coil condenser, where it is cooled and condensed into liquid form. Cooling water circulates continuously through the shell side to remove latent heat of vaporization. Heat transfer occurs through convection between vapor and tube wall, conduction through the metal wall, and convection between cooling water and tube surface. This mechanism is consistent with phase-change heat transfer theory in curved tube systems (Wang et al., 2020; Zhang & Li, 2022).

Data collection involved measurement of inlet steam temperature (Tin), total heat energy (qtot), heat transfer rate (Q), steam mass flow rate ($\dot{m}$), condensate mass rate (mkf), and condensation efficiency. Measurements were conducted for each experimental run under steady-state conditions. The governing energy balance was applied to quantify heat transfer performance.

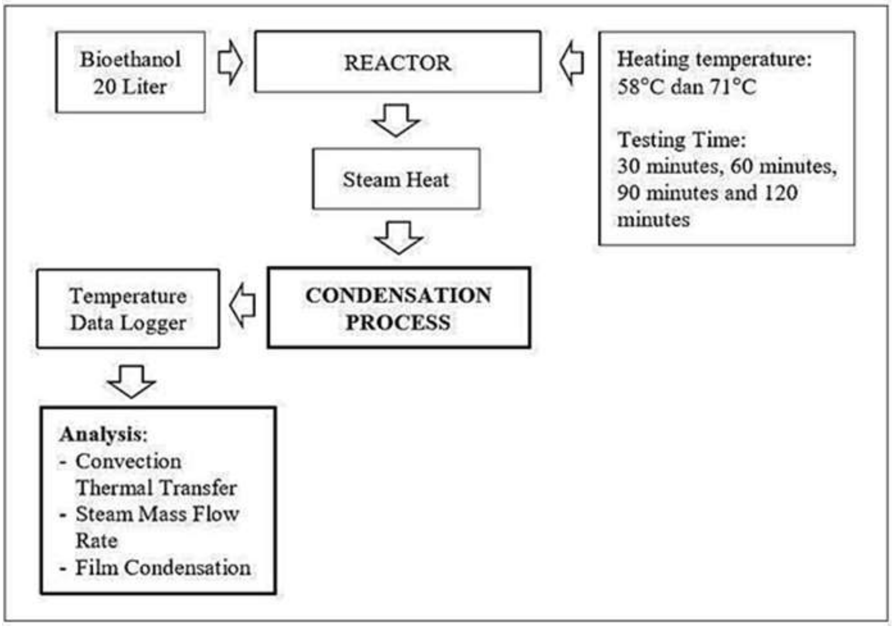


Figure 2. Experimental Test Scheme

Data analysis was performed using quantitative descriptive methods and thermodynamic energy balance calculations. Heat transfer rate was determined based on energy conservation principles, while condensation efficiency was calculated from the ratio of condensed mass to total vapor mass. Microsoft Excel and engineering calculation tools were used for processing and visualization of experimental trends. To ensure data reliability, each experiment was repeated under identical conditions, and results were averaged. Instrument calibration was conducted prior to testing to minimize measurement error. This approach follows standard experimental validation procedures in thermal system research (Elsaid et al., 2023; Rahman et al., 2024).

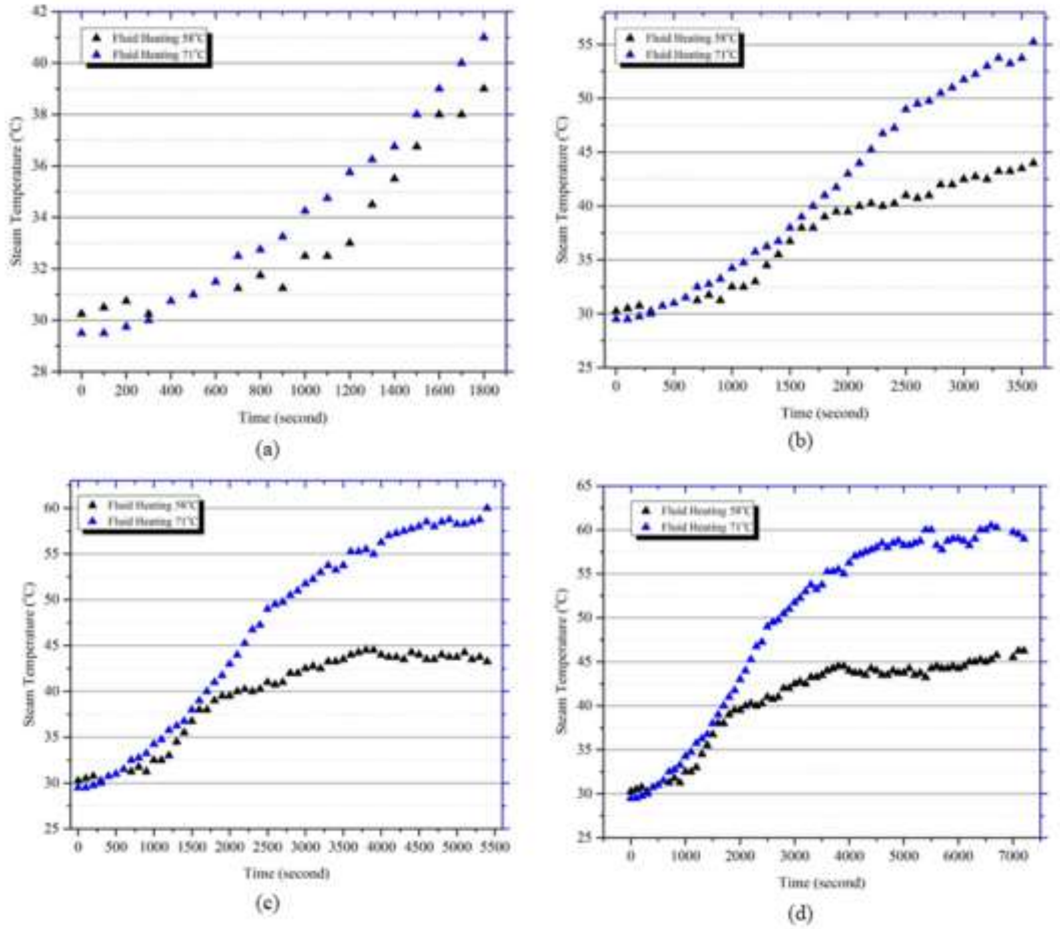
RESEARCH RESULT

Inlet Steam Temperature Characteristics (Tin)

The experimental results show that the inlet steam temperature (Tin) is strongly influenced by the reactor heating temperature. Two operational conditions were evaluated: 58°C and 71°C. The data indicate that higher reactor temperature produces higher inlet steam temperature entering the helical coil condenser system.

Table 4. Inlet Steam Temperature (Tin) Results

Reactor Temperature	Tin (°C)	Observation
58°C	46.25	Lower vapor energy condition
71°C	59.00	Higher vapor energy condition



(a) Test Time 1800 seconds; (b) Test Time 3600 seconds; (c) Test Time 5400 seconds; and (d) Test Time 7200 seconds

Figure 3. Steam Temperature Entering the Helical Coil Condenser

These results confirm that increasing reactor temperature leads to an increase in steam thermal energy entering the condenser system.

Heat Transfer Energy and Rate (qtot and Q)

The analysis of heat transfer performance shows variation in total heat energy (qtot) and heat transfer rate (Q) between the two reactor conditions.

Table 5. Heat Transfer Results

Reactor Temperature	qtot (kJ)	Q (kJ/s)
58°C	3992.86	0.55
71°C	3223.16	0.45

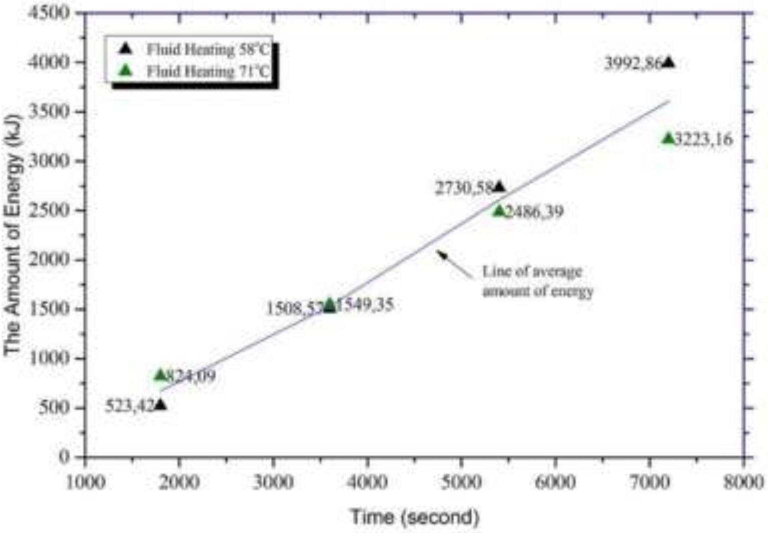


Figure 4. Amount of Heat Energy in a Helical Coil Condenser

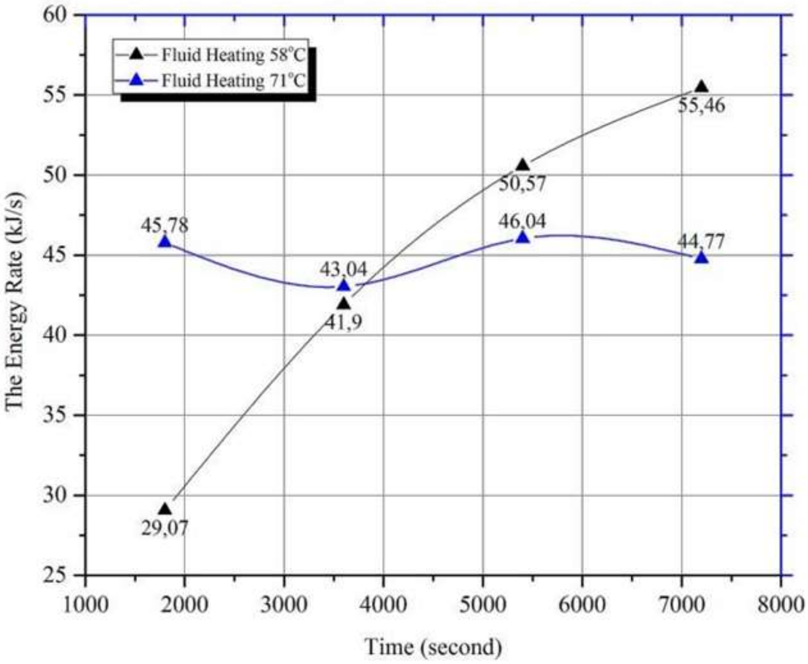


Figure 5. Rate of Heat Energy

The results indicate that the 58°C condition produces higher total accumulated heat energy, while the 71°C condition shows different energy distribution characteristics in the system.

Steam Mass Flow Rate (ṁ)

The steam mass flow rate increases with reactor temperature, indicating higher vapor generation at elevated heating conditions.

Table 6. Steam Mass Flow Rate Results

Reactor Temperature	ṁ (kg/s)
58°C	1.5×10^{-4}
71°C	1.9×10^{-4}

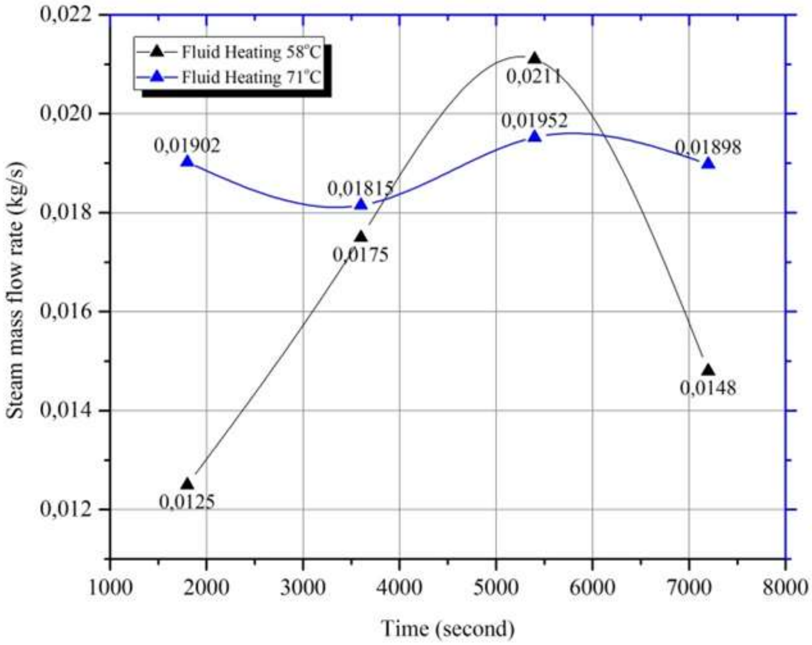


Figure 6. Steam Mass Flow Rate

The data show that the 71°C condition produces a higher mass flow of steam compared to 58°C.

Condensate Film Mass Rate (MKF)

The condensate film mass rate reflects the amount of vapor successfully condensed on the helical coil surface.

Table 7. Condensate Film Mass Rate Results

Reactor Temperature	mkf ($\times 10^{-4}$ kg/s)
58°C	30
71°C	62

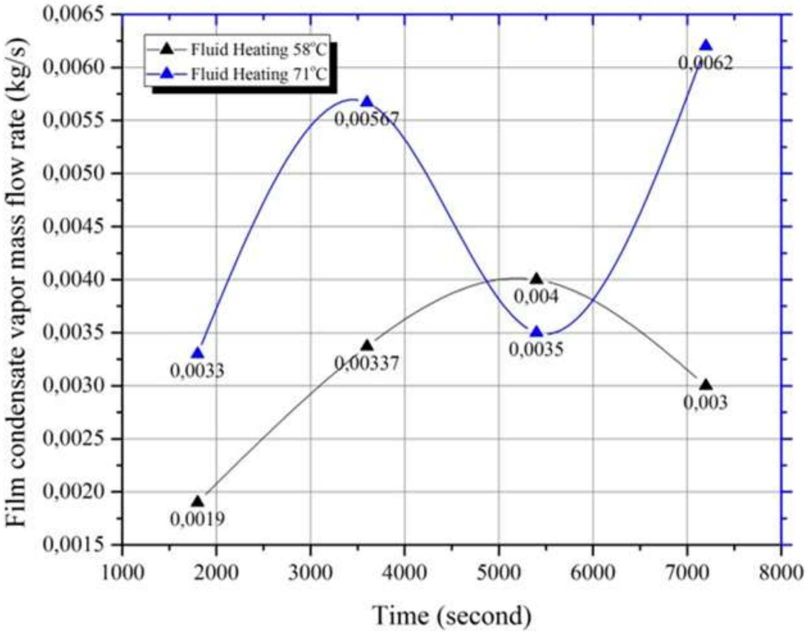


Figure 7. Film Condensate Flow Rate

The results demonstrate a significant increase in condensate formation at higher reactor temperature.

Condensed Vapor Percentage (Condensation Efficiency)

The condensation efficiency is used to evaluate the effectiveness of vapor-to-liquid conversion in the system.

Table 8. Condensation Efficiency Results

Reactor Temperature	Condensed Vapor (%)
58°C	20.26%
71°C	32.66%

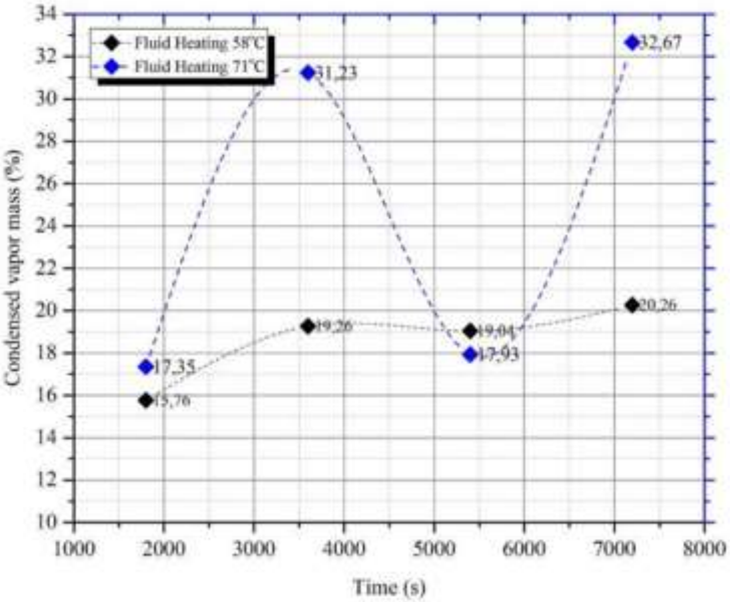


Figure 8. Condensed Steam Mass

The results indicate that the 71°C operating condition produces higher condensation efficiency compared to 58°C.

Summary of Experimental Findings

The overall performance comparison between the two reactor conditions is summarized as follows.

Table 9. Summary of Key Experimental Results

Parameter	58°C	71°C	Higher Performance
Tin (°C)	46.25	59.00	71°C
qtot (kJ)	3992.86	3223.16	58°C
Q (kJ/s)	0.55	0.45	58°C
$\dot{m}$ (kg/s)	1.5×10^{-4}	1.9×10^{-4}	71°C
mkf ($\times 10^{-4}$ kg/s)	30	62	71°C
Condensation (%)	20.26	32.66	71°C

The experimental data confirm that reactor temperature variation significantly affects heat transfer and condensation performance in the helical coil condenser system. The 71°C condition results in higher steam generation, greater condensate formation, and improved condensation efficiency compared to the 58°C condition.

DISCUSSION

The experimental results demonstrate that reactor temperature significantly influences the thermal performance of the helical coil condenser in bioethanol purification. At a reactor temperature of 58°C, the system produced a maximum inlet steam temperature (Tin) of 46.25°C, total heat energy (qtot) of 3992.86 kJ, heat transfer rate (Q) of 0.55 kJ/s, steam mass flow rate ($\dot{m}$) of 1.5×10^{-4} kg/s, condensate film mass rate (mkf) of 30×10^{-4} kg/s, and condensation efficiency of 20.26%. In contrast, at a reactor temperature of 71°C, the system produced Tin of 59°C, qtot of 3223.16 kJ, Q of 0.45 kJ/s, $\dot{m}$ of 1.9×10^{-4} kg/s, mkf of 62×10^{-4} kg/s, and a higher condensation efficiency of 32.66%. These results indicate that increasing reactor temperature enhances vapor generation and condensation performance, despite variations in total heat energy distribution. This also suggests that the system performance is more strongly influenced by vapor formation rate and flow dynamics rather than total accumulated energy alone.

The improvement in condensation efficiency at 71°C confirms that higher thermal input strengthens phase-change intensity and vapor transport toward the helical coil condenser. This behavior is consistent with classical heat transfer theory, where an increased temperature gradient enhances the driving force for heat exchange (Incropera et al., 2021). The helical coil geometry further contributes to this enhancement through secondary flow (Dean vortices), which improves turbulence and convective heat transfer efficiency (Wang et al., 2020; Zhang and Li, 2022). In practical terms, this means that higher temperature not only increases vapor production but also improves contact between vapor and cooling surface.

Interestingly, although qtot and Q are higher at 58°C, the condensation efficiency is lower compared to 71°C. This indicates that total energy input is not directly proportional to system performance. Instead, energy utilization efficiency and flow dynamics play a more dominant role in determining condensation effectiveness. This phenomenon can be explained by the fact that excess heat at lower temperature conditions may not be fully converted into effective phase change, leading to less efficient condensation. Similar behavior was reported by Elsaid et al. (2023), who emphasized that heat exchanger performance depends not only on energy magnitude but also on flow distribution and thermal resistance characteristics.

The increase in steam mass flow rate (ṁ) and condensate film mass rate (mkf) at 71°C further supports stronger phase-change activity under higher temperature conditions. This indicates that more vapor is actively generated and successfully transported into the condenser, resulting in increased condensate formation. This finding aligns with Zhang and Li (2022), who explained that higher thermal gradients accelerate evaporation and improve vapor transport toward the cooling surface. In this system, higher mkf values also indicate more effective surface condensation, meaning that heat removal is occurring more efficiently along the coil surface.

From a physical mechanism point of view, the helical coil structure plays an important role in improving heat transfer. The curved shape of the coil creates a swirling flow that increases fluid mixing and reduces thermal resistance near the wall. This condition reduces the thickness of the thermal boundary layer, allowing faster heat transfer from vapor to cooling water (Moawed, 2020; Inyang and Uwa, 2022). At higher temperatures, this effect becomes stronger because the increased vapor velocity intensifies turbulence, making the heat transfer process more effective and stable during operation.

In addition, the results indicate that system performance is not only determined by energy input but also by how efficiently that energy is utilized in the phase-change process. This explains why the 71°C condition performs better even though it does not have the highest total heat energy value. In real application terms, this shows that an efficient condensation system should prioritize effective energy conversion rather than maximum energy accumulation.

Overall, the experimental findings confirm that the use of a helical coil condenser in a 20-liter bioethanol purification system is most effective at a reactor temperature of 71°C with a 7200-second operation period. Under these conditions, the system achieved optimal performance with Tin = 59°C, qtot = 3223.16 kJ, Q = 0.45 kJ/s, $\dot{m} = 1.9 \times 10^{-4}$ kg/s, mkf = 62×10^{-4} kg/s, and condensation efficiency of 32.66%. This shows that higher reactor temperature provides more favorable thermodynamic conditions for vapor generation, heat transfer, and condensation efficiency, making it the most optimal operating condition among those tested.

Despite these positive results, several limitations must be considered. The study assumes steady-state conditions, which may not fully represent real industrial operations where temperature and flow fluctuate dynamically over time. Heat losses to the environment were not directly measured, which may introduce minor deviations in energy balance calculations. In addition, the system was tested only at laboratory scale (20 liters), so scale-up effects such as pressure drop and flow instability may not yet be fully represented. The absence of Computational Fluid Dynamics (CFD) analysis also limits detailed understanding of internal flow patterns and turbulence distribution inside the helical coil condenser.

For future research, it is recommended to combine experimental work with CFD simulation to visualize flow behavior and secondary vortex formation in detail. Larger-scale experiments are also required to evaluate industrial feasibility and energy efficiency under real operating conditions. Furthermore, optimization of coil geometry such as pitch, diameter, and curvature ratio should be conducted to further enhance heat transfer performance and reduce energy losses in the system.

CONCLUSIONS AND RECOMMENDATIONS

The study confirms that increasing reactor temperature from 58°C to 71°C improves helical coil condenser performance in bioethanol purification, as shown by higher vapor generation, increased condensate flow, and improved condensation efficiency (20.26% to 32.66%). However, system efficiency is not solely dependent on total heat energy, but more on flow behavior and heat transfer interactions on the coil surface. The helical coil enhances performance through secondary flow formation that strengthens turbulence and heat transfer. These findings can be applied to optimize industrial bioethanol distillation by adjusting reactor temperature and improving condenser design for higher energy efficiency.

ADVANCED RESEARCH

This study has several limitations that should be considered. First, the experiment was conducted under steady-state conditions, which do not fully represent transient behavior in real industrial systems. Second, heat losses to the environment were not analyzed in detail, which may affect the accuracy of the energy balance results. Third, the study was limited to a 20-liter laboratory scale, so the findings cannot be directly generalized to industrial-scale applications. In addition, no Computational Fluid Dynamics (CFD) analysis was performed to visualize internal flow patterns in the helical coil condenser. Therefore, future research is recommended to integrate CFD simulations with experimental work to better understand secondary flow mechanisms, temperature distribution, and turbulence characteristics, as well as to conduct larger-scale studies to evaluate system scalability in industrial bioethanol production.

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