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Temperature Control System for Ethanol Refinery Condenser in Cooking Oil Production Mini Plant

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ABSTRACT

Continuous counter-current extraction is a type of liquid-liquid extraction that utilizes a vertical column to remove impurities from raw materials by bringing them into contact with a solvent. In this study, crude palm oil (CPO) is used as the raw material and ethanol is used as the solvent to clean the impurities from the CPO. The output produced from the extraction process is safe cooking oil and impurities from CPO mixed with ethanol. The ethanol mixed with the impurities can be reused for extraction by separating it from the impurities using the distillation process. The low boiling point of ethanol allows it to evaporate and condense back into a liquid using a condenser. For the condensed ethanol to have room temperature, a condenser is required that uses water as a heat exchange medium. In this study, the design and construction of a temperature control system for the condenser are carried out using an RTD PT100 sensor with 99% accuracy. Additionally, the ethanol that has been distilled is measured by a DS18B20 temperature sensor with an accuracy of 97%. The control system in this final project successfully reduced the water temperature from 27°C to 6.5°C in 16 minutes

1. Introduction

In general, there are several stages in the production of cooking oil from palm oil, starting from crude oil, purification, fractionation, packaging and market distribution. In the stage of purifying crude oil, there are two commonly used methods, namely chemical refining and physical refining, which are known to have lengthy processes due to several stages that need to be carried out [1-4]. To refine crude palm oil, there is a purification process that needs to be conducted to remove impurities from the raw material. One of the extraction methods used is liquid-liquid extraction, which is useful for separating crude oil from its impurities by bringing the crude oil into contact with a solvent. A specific type of liquid-liquid extraction process called continuous counter current extraction is employed in this study. In this process, a vertical column is used to bring together the

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heavy liquid and the light liquid in opposite directions. The heavy liquid enters the top of the column, while the light liquid enters from the bottom. During the process, the light liquid binds to the impurities from the heavy liquid and exits through the top of the column. On the other hand, the impurity-free heavy liquid exits through the bottom of the column. The temperature of the light liquid (solvent) and heavy liquid (crude palm oil) in this method is maintained at room temperature, ranging from 25ºC to 28ºC [5]. Therefore, this method is safe to use without requiring heating to raise the temperature of the two liquids [6].

In this study, crude palm oil (CPO) serves as the heavy liquid and ethanol serves as the light liquid used to clean impurities in CPO. Ethanol is chosen as the solvent because it is a safe and non-toxic solvent. Furthermore, ethanol is a versatile solvent that can be used for filtering or extracting compounds that are polar or semi-polar, non-toxic and can be mixed with water. Additionally, ethanol is capable of extracting compounds such as flavonoids, saponins, tannins, anthraquinones, terpenoids and alkaloids [7-9].

In the process of extracting crude palm oil, there are two outputs: safe-to-consume cooking oil and impurities mixed with ethanol. The ethanol can be reused for repeated extraction processes, eliminating wastage. To separate the ethanol from the impurities mixed with crude palm oil, a distillation process is carried out. Distillation is a separation operation used to separate two or more liquid components based on their difference in boiling points [10-12]. Ethanol has a relatively low boiling point at 78.39°C [13-15]. Compared to the impurities such as free fatty acids in crude palm oil, which have a boiling point of around 220°C [16-20]. Therefore, ethanol at 78.39°C will change phase into vapor. The ethanol vapor can be condensed using a condenser that is supplied with low-temperature water. However, if the circulating water in the condenser is not replaced or continuously cooled, it will take a long time for efficient condensation of ethanol vapor. To expedite the condensation process and ensure efficiency, a cooling system is required to maintain the water at a low temperature. The condenser system includes supporting components such as a compressor, refrigerant condenser, expansion valve and evaporator. In this plant, the evaporator is installed in a water tank to cool the water inside it.

The temperature of the water in the water tank is monitored and controlled to meet the requirements of the distillation process. The water that exits the water tank is circulated towards the condenser, which is in the form of a coiled stainless-steel pipe installed directly above the distillation column. When the ethanol vapor encounters this coiled pipe, it condenses into liquid ethanol. The liquid ethanol is then directed to the ethanol storage tank to be reused as a solvent for CPO extraction. The temperature of the water in the condenser needs to be controlled effectively during the distillation process to ensure proper distillation and maintain the temperature of the ethanol used for extraction according to the requirements of CPO extraction.

Therefore, in this study, a temperature control system for the condenser is designed using an RTD PT100 sensor to measure the water temperature in the water tank. The measured results will be displayed on a Human Machine Interface (HMI) installed on the panel box door. Through the HMI interface, users can input the desired set point temperature for the water according to their needs. When the temperature reaches the set point, the controller will automatically deactivate the compressor. Thus, the implementation of this condenser temperature control system can enhance the effectiveness and efficiency of the ethanol distillation process.

CFD simulation with *Ansys Fluent* software will be used to compare the temperature distribution in the condenser pipe and walls with measurements from an RTD PT100 sensor installed in the system.

2. Methodology

2.1 Component and Control System Design

In Figure 1, the temperature control system for ethanol distillation in a mini plant for cooking oil production is presented. It consists of several equipment such as a compressor, water tank, water pump, storage tank for ethanol mixed with CPO impurities, ethanol storage tank and a distillation unit. The distillation unit comprises a boiler, which acts as a heating element to convert liquid ethanol into ethanol vapor and a condenser, which converts the ethanol vapor back into liquid ethanol for reuse in the CPO extraction process.

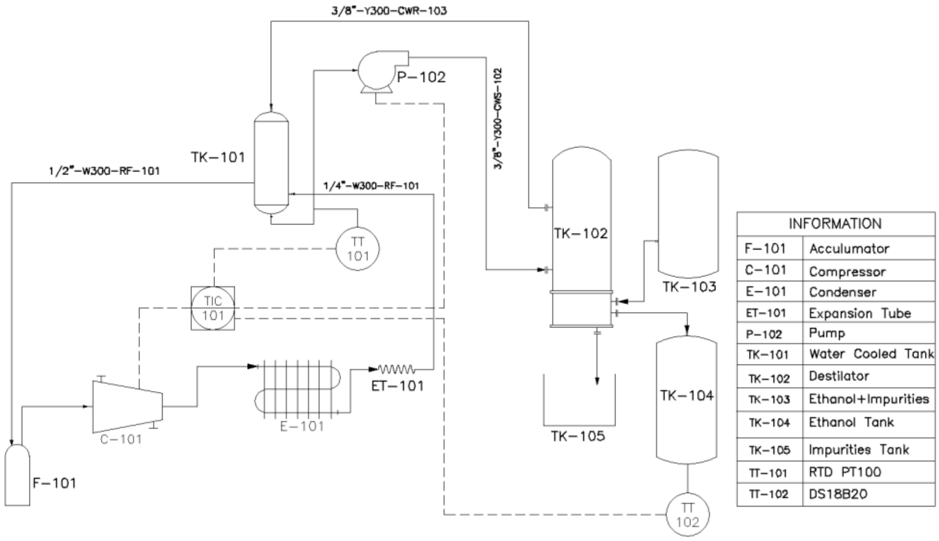

Fig. 1. Piping & instrumentation diagram

Additionally, there are temperature sensors used in the system. An RTD PT100 sensor with a 20 cm long stainless-steel probe is installed at the outlet of the water tank to measure the temperature of the water in the tank. Furthermore, there is a DS18B20 temperature sensor installed in the ethanol storage tank. This sensor is used to measure the temperature of the ethanol produced from the distillation process.

Fig. 2. Three-dimensional design components ethanol refinery condenser in cooking oil production mini plant

The materials used as the foundation for the condenser, water tank and compressor are 1.2mm thick hollow iron with dimensions of 4cm x 4cm and the base is made of 10mm thick plywood. The condenser coil is placed on top of the distillatory and at the bottom of the distillatory, there is a tank for ethanol mixed with impure palm oil (CPO), equipped with an electric heater. Additionally, there is a water tank made of acrylic with dimensions of 40 cm in height and 15 cm in diameter. Inside the water tank, there is a copper evaporator with a size of 5/16, which functions as a water cooler. Apart from that, there is a wiring design in this research, which can be seen in the following image.

In Figure 3, it depicts the wiring for the RTD PT-100 temperature sensor with the MAX31865 module, which is used to convert the analogue signal to digital. The digital signal is then transmitted to the Arduino Uno board and further relayed to the Raspberry Pi 4B through serial communication. As for the DS18B20 sensor, it consists of three cables: two for VCC and GND and one data cable that connects to a digital pin on the Arduino Uno.

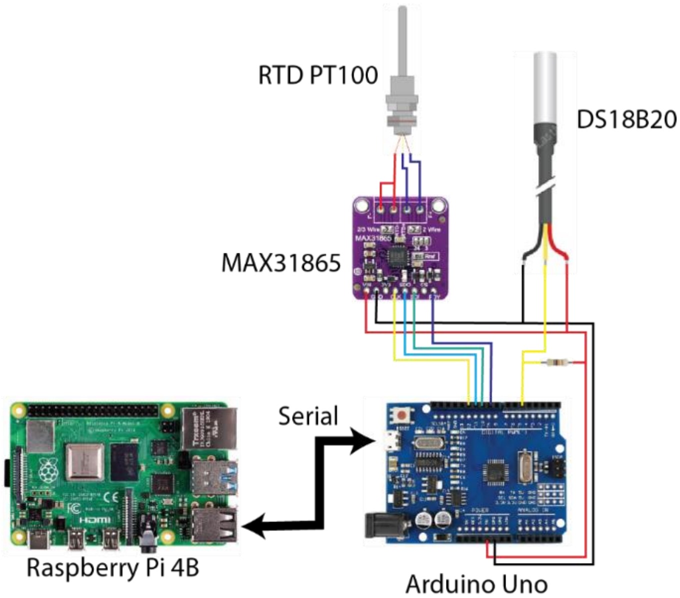

Fig. 3. Temperature sensor wiring

In Figure 4, it illustrates the wiring of the control system for the compressor and pump. There is a 5V 2-channel relay, where one channel serves as a switch to connect the 220 VAC voltage. This is used to power the Omron LY2N relay, which can handle a current of 10A. The Omron relay is used to switch the 220 VAC voltage to activate the compressor. Additionally, there is a 1-channel relay used to switch the 12V pump, which is responsible for water flow.

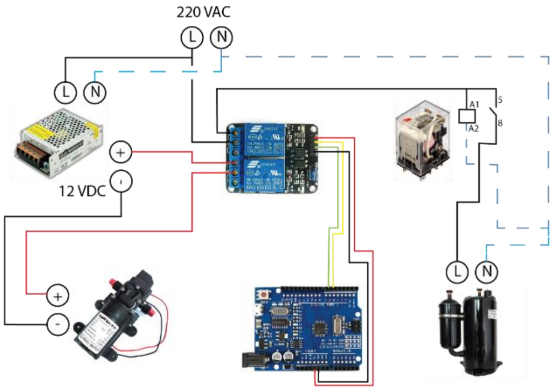

Fig. 4. Control system wiring diagram

2.2 Computational Fluid Dynamics Model

In this research, modelling begins with several stages with pays attention to the results of experiments that have been modelled on objects. Full description of the method These CFDs are as follows [21]:

2.2.1 Creation of geometry model of ethanol distiller condenser pipe

The geometric model of the plant was made using *Solidworks* software and then exported into a file in STEP format so that it could be imported into the workbench *Ansys* software. The ethanol distiller condenser pipe has dimensions of 50 cm high and a pipe diameter of 10 mm in spiral shape. The condenser pipe flows water at a temperature of 6.5°C which cools the ethanol distiller condenser pipe and outside the condenser pipe will be filled with ethanol vapor at a temperature of 79°C.

2.2.2 Meshing

CFD is run by the *ANSYS Fluent* program which has a Finite Volume concept Method. Meshing functions as a geometric control volume divider into elements smaller and smoother to get more convergent results in the analysis [21]. The model from 2.2.1 is then meshed to form a geometry with a size of 0.001. This size is used to break down and form the future net making it easier to simulate the model that has been created.

2.2.3 Setup

In determining which model is most appropriate, some variables must be considered and defined before performing calculations in the Fluent application. Like phase variables, fluid materials, boundary conditions and operating conditions. Several conditions are regulated in this CFD simulation which can be seen in Table 1.

Table 1
Boundary condition

Variable	Information
Thermal inlet	6.5°C
Multiphase	Volume of Fluid
Velocity inlet	1.2 m/s
Pressure outlet	0
Wall condition	No slip, smooth wall
Gravity	9.81 m/s^2
Wall motion	Stationary wall
Sheer condition	No slip
Temperature wall	79 °C
Material	Stainless steel

The variables specified in Table 1 are entered in each section of the *Ansys Fluent* setup. In section "general" which includes mesh, solver, time and gravitational settings acceleration. In this study, the gravity value uses a value of -9.81 m/s2 on the Y axis. Next, in the "models" section, there are several options such as: multiphase, energy and viscous. In this final assignment, we use the energy equation so that in the "energy" option, select "On", for fluid flow in this final assignment use k-epsilon which can be set to the "viscous" option, then to multiphase using the volume of fluid method. Next, choose the material used in the condenser geometry model This ethanol distillate is selected in the “Materials” section. In this research the material the condenser uses is stainless steel 304, then for the condenser pipe winding uses stainless steel 304 material. Stainless steel 304 was chosen due to the advantages of being resistant to corrosion because it contains 10.5% chromium or more. The fluid that flows in the condenser pipe is water-liquid and the fluid that fills the condenser chamber is ethyl-alcohol-vapor. Furthermore, in the boundary condition there are arrangements for the water outlet for defined variables such as the temperature of the water coming out of the condenser pipe coil, In this research, the water coming out of the condenser pipe coil has a temperature of 25°C because in the condenser experiences heat transfer from the heat of the ethanol vapor which propagates through the condenser the temperature of the water in the condenser pipe, the water at the condenser inlet which initially has a temperature of 6.5°C experiences temperature mixing with temperature ethanol vapor 79°C so that if calculated using the black principle equation then the water has outlet water with a temperature of 25°C. Then the results of the calculation of the basic black equation are input on Boundary Condition *Ansys Fluent* setup. The next step is to set the value of the fluid barrier wall as in Figure 3. Wall 1, namely condenser tube walls made of 304 stainless steel material which has momentum and does not move (Stationary Wall) and the sliding condition is No Slip. The wall temperature of the condenser pipe has a temperature of 79°C because it will be in the distillation tube filled with ethanol vapor at a temperature of 79°C. While for the second wall, the section is water in the condenser pipe which has a temperature of 6.5°C. Then the final step in the *Ansys Fluent* setup is run calculation. The purpose of this run calculation is to run numerical simulations based on initial conditions and parameters that have been determined in the previous stage. After the simulation process is run, *Ansys Fluent* will calculate a numerical solution for the given model and the parameters determined.

3. Results

3.1 Results of Ethanol Distillation Plant Construction

The results of the plant construction in this research can be seen in Figure 5. There are several components included, such as a compressor unit used to cool the evaporator located in the water tank to cool the water. There are two pans in Figure 5, the upper pan has functionality for the place of the impurities of CPO mixed with ethanol, while the lower pan is the place of the extracted CPO after being separated from the impurities. Additionally, there is a panel box containing electronic components used in this final project, including a 12VDC power supply, Raspberry Pi 4B as the controller, Arduino Uno for reading measurements from all sensors, relays used to switch voltage to activate actuators and an LCD used as the human-machine interface in this research.

Furthermore, there is a distillation unit consisting of a boiler, which is used to heat the ethanol mixed with CPO impurities to separate the ethanol from the CPO impurities. There is also a condenser used to condense the separated ethanol vapor.

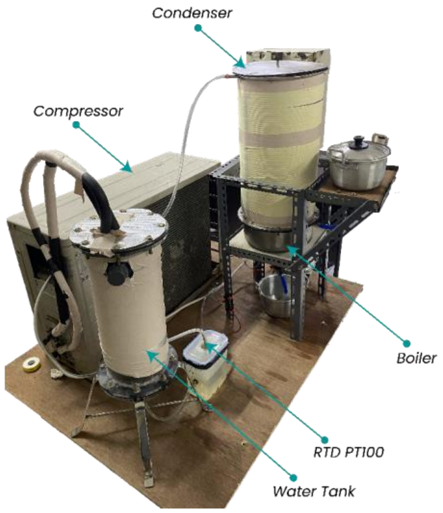

Fig. 5. Results of hardware construction

Figure 6 shows the results of creating the human-machine interface from the local computer in the laboratory, displaying the readings from the RTD PT100 and DS18B20 sensors in Celsius. There is also a real-time graph to monitor the plant's dynamic changes in water and ethanol temperatures. Additionally, there is a panel to set the setpoints for the condenser and boiler units, which also includes a dynamic response graph.

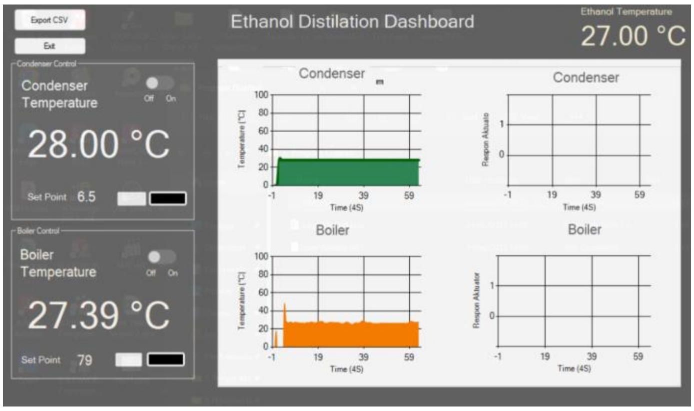

Fig. 6. Human-machine interface of distillation plant

3.2 Sensor Test Result

3.2.1 RTD PT100 temperature sensor validation

The sensor validation is performed to ensure that the readings from the RTD PT100 temperature sensor are accurate and correct. The validation is done by comparing the readings from the RTD PT100 sensor with a thermometer measuring device. During the validation process of the RTD PT100 temperature sensor, the following static characteristic parameters are error and accuracy generated by the RTD PT100 temperature sensor in this validation process.

In Figure 7, the results of the water temperature readings from the RTD PT100 temperature sensor compared to the validator thermometer can be observed. The validation process is carried out by heating the water from a low temperature to a high temperature and then cooling it back down to a low temperature. The graph shows that the RTD PT100 temperature sensor closely follows the temperature readings from the validator thermometer, with a slight error when the water temperature increases or decreases.

Based on the conducted sensor testing, it can be concluded that the RTD PT100 sensor has an average accuracy of 99% and an average error of 1%. The validation results demonstrate that the error percentage is below 5%, indicating that the RTD PT100 sensor is suitable for use in this research.

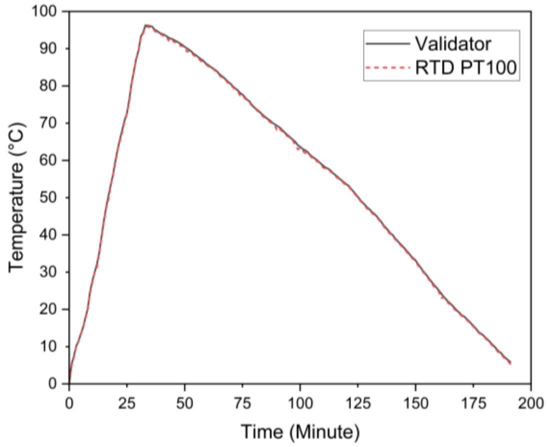

Fig. 7. RTD PT100 temperature sensor testing

3.2.2 DS18B20 temperature sensor validation

The sensor validation is performed to ensure that the readings from the DS18B20 temperature sensor are accurate and correct. The validation is done by comparing the readings from the DS18B20 sensor with a thermometer measuring device. During the validation process of the DS18B20 temperature sensor, the following static characteristic parameters are sought: error and accuracy generated by the DS18B20 temperature sensor in this validation process. These parameters will help assess how closely the DS18B20 sensor's readings align with the readings from the thermometer, indicating its precision and accuracy.

In Figure 8, the results of the water temperature readings from the DS18B20 temperature sensor compared to the validator thermometer can be observed. The validation process is carried out by heating the water from a low temperature to a high temperature and then cooling it back down to a low temperature. The graph shows that the DS18B20 temperature sensor closely follows the temperature readings from the validator thermometer, with a slight error when the water temperature increases or decreases.

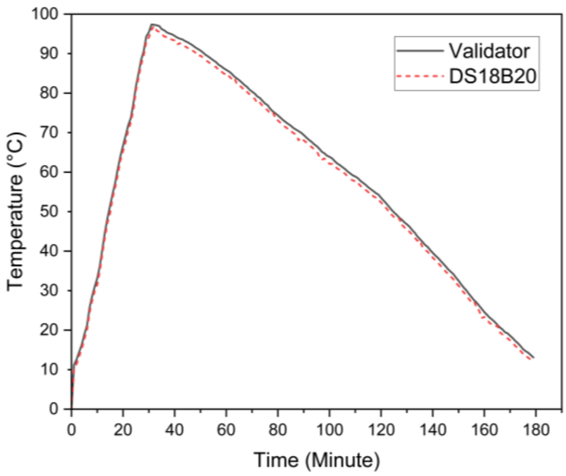

Fig. 8. DS18B20 temperature sensor testing

Based on the conducted sensor testing, it can be concluded that the DS18B20 sensor has an average accuracy of 97% and an average error of 3%. The validation results demonstrate that the error percentage is below 5%, indicating that the DS18B20 sensor is suitable for use in this research.

3.3 Performance System Test

In Figure 9, it represents the dynamic response in the form of readings from the RTD PT100 sensor and the relay condition representing the on and off state of the compressor. The graph in Figure 6 is a cut-off portion taken at the 90-minute mark to provide a clearer view of the dynamic response. It can be observed that the initial water temperature for cooling the condenser is 27°C and then the temperature decreases from 27°C towards the setpoint value of 6.5°C. The graph in the figure shows oscillation caused by the on/off control system's characteristics. It can be seen that the water temperature experiences overshoot, which is due to the temperature variable not immediately increasing when the relay is off. There is still residual cold temperature caused by the evaporator, resulting in the temperature dropping to 5.9°C. As the relay remains off for a longer duration, the water temperature gradually increases, exceeding the 6.5°C setpoint. Subsequently, the relay turns on again to activate the compressor, which functions to cool down the water in the water tank. As a result, the temperature drops back to 6.5°C. This process continues continuously.

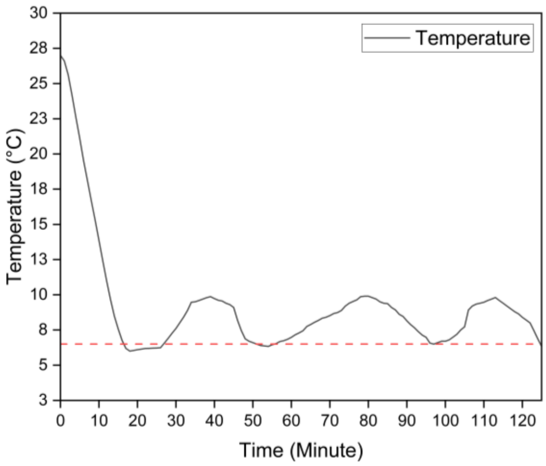

Fig. 9. Control system dynamic response

The graph indicates that the circulated water temperature within the condenser remains within the range of 6.5°C to 9.69°C. Data related to peak time, rise time, settling time and steady-state error generated by the control system are presented in Table 2.

Table 2
Control system dynamic response

Parameters	Information
Maximum Overshoot	0,6°C (9,2%)
Peak Time	18 minutes
Rise Time	16 minutes
Settling Time	51 minutes
Error Steady State	18%

Table 2 represents the dynamic response of this system in reaching the setpoint of 6.5°C, which takes 16 minutes and it takes 31 minutes to reach a steady state. The steady-state error is calculated to be 18%, as indicated in Appendix 8. The steady-state error of the control system in this final project is relatively large. However, the on/off control system used effectively maintains the condenser temperature within the range of 6.5°C to 9.7°C.

3.4 Result of Computational Fluid Dynamics (CFD) Simulation

Once all the predefined variables have been input into the CFD Fluent setup, initialization and calculation are performed to observe the results of the created simulation. The final step of the CFD simulation is to analyse the results [22]. One of the analyses includes examining the temperature contour of the simulated condenser pipe to observe the heat distribution on the condenser pipe surface. The simulation results of the condenser pipe's temperature contour can be seen in Figure 10 below.

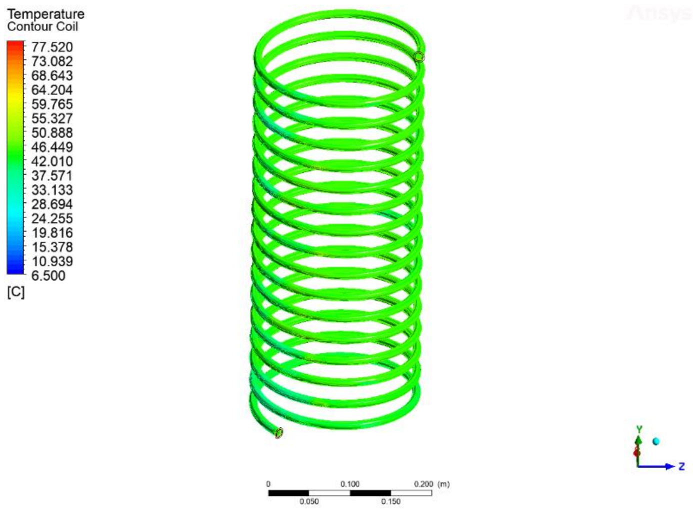

Fig. 10. Result of CFD simulation at condenser pipe

A combination of the water temperature inside the pipe and the ethanol vapor outside the pipe. Inside the condenser tube, it is filled with ethanol vapor, with a temperature ranging around 79°C. To indicate the heat distribution on the condenser pipe, a legend is provided on the left side of Figure 10, which shows the corresponding temperature of the condenser pipe when the plant is operating.

Furthermore, the CFD simulation also provides results for the water inside the condenser pipe of the ethanol distillation tube. The water inside the pipe is used to cool the condenser pipe, which is responsible for condensing the high-temperature ethanol vapor into liquid ethanol at room temperature. The simulation results for the contour of the water inside the condenser pipe can be seen in Figure 11.

In Figure 11, it can be observed that the water inside the condenser pipe undergoes a heat change from an inlet temperature of 6.5°C to 24.2°C. The temperature distribution on the condenser pipe can be seen through the colour gradient presented in the CFD result in Figure 11.

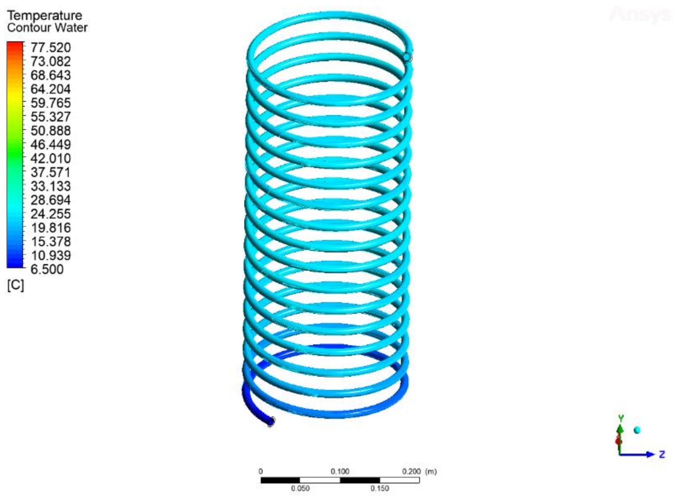

Fig. 11. Result of CFD simulation at water inside condenser pipe

Furthermore, there are also results from the CFD simulation conducted on the condenser tube, which can be seen in Figure 12 below.

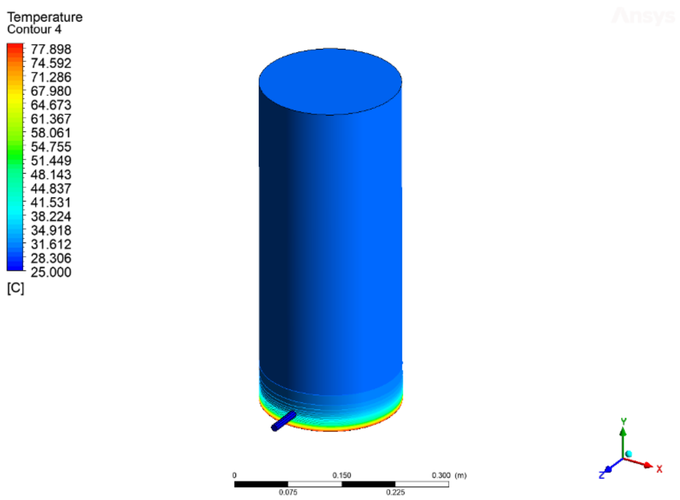

Fig. 12. Result of CFD simulation at condenser surface

In the CFD simulation, the condenser tube is observed to have a temperature ranging around 25°C. Inside the condenser tube, it is filled with ethanol vapor, which has a temperature ranging around 79°C. To indicate the heat distribution on the condenser tube, a legend is provided on the left side of Figure 12, showing the corresponding temperature of the condenser tube when the plant is operating.

Next, the simulation results in Figure 11 and Figure 12 are compared with direct measurements on the condenser tube, which can be seen in Table 3. The purpose of this comparison is to assess the agreement between the simulation results and the direct measurements. By comparing the simulation results with the direct measurements, we can evaluate the accuracy and reliability of the simulation model in representing the real-world behaviour of the condenser tube. Any discrepancies or variations between the simulated and measured values can provide insights into the performance and validity of the simulation.

Table 3
Comparison of the CFD results and real measurement

Location	CFD Simulation	Real Measurement
Shell (Surface Condenser)	25°C	26,8°C
Water Outlet	25°C	27,7°C

In the measurement during plant operation, the temperature of the condenser tube was measured using an infrared *thermogun* focused on the surface of the condenser tube's cover to determine the actual surface temperature. It is observed that the surface of the condenser tube has a temperature of 26.8°C. Furthermore, the results from the CFD simulation of the water inside the condenser pipe are compared with the measurement taken at the outlet of the water on the upper side of the condenser tube using a digital thermometer. It can be observed that the water temperature at the condenser outlet is 27.7°C. The change in temperature from the inlet to the outlet is caused by the heat transfer of ethanol vapor to the condenser pipe, resulting in a temperature increase of 21°C in the outlet water from the condenser pipe.

In Table 3, it is evident that there are temperature differences between the CFD simulation and direct measurements conducted using an infrared *thermogun* to compare the simulation results with direct measurements in the plant. The CFD simulation results show a temperature of 25°C on the condenser surface, while the measurement using the infrared *thermogun* reads 26.8°C. Furthermore, the CFD simulation results indicate a temperature of 25°C at the condenser water outlet, whereas the direct measurement shows a temperature of 27.7°C. It can be concluded that the CFD simulation for the condenser surface has a difference of 1.8°C and the simulation of the condenser water outlet has a difference of 2.7°C compared to the direct measurements. This difference is due to heat transfer Mechanisms such as Conduction, Convection and Radiation. CFD may not fully account for all heat transfer mechanisms or may simplify them. Real measurements often capture complex interactions that CFD might miss. Also, material properties with Inaccurate or variable material properties (e.g., thermal conductivity, specific heat) can lead to significant differences between simulation and measurement.

4. Conclusions

The temperature control system for the condenser utilizes an RTD PT100 sensor to measure the temperature of the water flowing through the condenser pipes. The RTD PT100 sensor has a 1% error percentage and a 99% accuracy rate. Additionally, the temperature control system for the condenser is equipped with a DS18B20 sensor, which is used to measure the temperature of the distilled ethanol. The DS18B20 sensor has a 3% error percentage and a 97% accuracy rate. The development of the ethanol condenser temperature control system using Arduino Uno has been successful in receiving sensor data from the RTD PT100 and DS18B20 sensors. In this control system, the Raspberry Pi 4B is used to regulate the condenser temperature to match the predefined setpoint. The actuator employed in this project is a compressor, which effectively cools the water in the water tank. The control system implemented in this project utilizes an on/off system that successfully lowers the water temperature from 27°C to 6.5°C within a duration of 16 minutes.

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