Thermal design of cooler in the fuel handling pneumatic system of RDE

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Abstract. A small size reactor called Reaktor Daya Eksperimen (RDE) is being designed by BATAN. The nuclear reactor with the power of 10 MWt based on the High Temperature Gas-Cooled Reactor (HTGR) type. The helium gas with high temperature is used to remove the heat generated from the reactor core. Therefore, the helium gas as primary cooling system of reactor is high temperature. The typical of reactor cooling system is that the primary coolant system pressure should be lower than the secondary coolant pressure. In order to load a nuclear fuel pebble into the reactor core, a fuel handling system (FHS) is applied. In the FHS, a carrier gas of pneumatic system is important to blow the fuel pebbles. The objective of the research is to calculate the thermal design of cooler heat exchanger in which the high temperature of helium gas as carrier gas is reduced to be lower temperature. In this case, a cooler is used to cool the helium gas by cool water. Based on the specification data requirement to calculate the thermal design of cooler, the ChemCAD.6.1.4 software was performed. A shell-tube type of heat exchanger has been determined to reduce the temperature of helium gas from 250°C to be less than 60°C at pressure of 30 bars. The water as a coolant is passed into the shell-side at temperature of 28°C. In the design calculation, it has carried out through a various consideration on aspects of safety as well as optimization. The result of thermal design are as follows: the heat exchanger of shell-tube type using fixed tube sheet with heat duty of 0.3122 MJ/s, the coolant water mass flow rate is 3.55 kg/s, surface area for heat transfer is 51.4471 m² and Log Mean Temperature Difference (LMTD) is 81.53°C. Furthermore, the design result requirement of heat exchanger based on the specification, design tolerance and manufacture in appropriate with the TEMA standard of shell-tube type. The thermal design of cooler in the carrier gas of pneumatic system is expected to provide the design of FHS.

1. Introduction

The High Temperature Gas-Cooled Reactor (HTGR) is a Generation IV advanced nuclear reactor, which has the advantages of inherent safety features and high thermal efficiency [1-3]. It has been developed with various power capacities and can produce electricity and heat applications. The currently, a design development of small size reactor called Reaktor Daya Eksperimen (RDE) is being performed by BATAN. The fuel handling system of RDE uses a pneumatic system for loading a fuel pebble into the reactor core. Due to the hot carrier gas is applied in the pneumatic system, so a cooling system is required. The cooler is placed in the pneumatic system to keep the temperature of gas less than 60°C. It
has to prevent overheating of motor chamber and shaft bearings of compressor, likewise in maintaining the integrity of pneumatic system components [4]. Therefore, the cooler equipment plays an important role in operating of pneumatic system.

In the pneumatic system, helium gas flows from the reactor primary cooling system at temperature of 250°C. To increase the pressure in the pneumatic system the compressor is provided. Therefore, decreasing temperature of the helium gas as carrier medium absolutely conducted. By considering its availability, the operating parameters in decreasing the helium gas temperature, therefore the cooling heat exchanger of shell-tube type is selected [5]. It consists of a shell (cylindrical vessel) with a bundle tube inside. The shell-tube type has most common use and suitable for high temperature/pressure applications, more heat transfer efficiency, compact in size and relatively simple [6,7].

Meanwhile, the selection of the best heat transfer fluid for a cooling system involves consideration of performance, compatibility, and maintenance factors. Then, the water is used as the coolant medium. Water has excellent heat transfer properties with a heat capacity of around 4,200 J/kg.K, viscosity and no flash point. However, on the other hand, it has a relatively narrow range of water temperature.

In the thermal design of heat exchanger, it is usually calculated to be able to transfer heat load optimally, minimum heat transfer surface and effective operating conditions [8,9]. In which, there are limits that must be met for the heat transfer surface area and the allowable pressure drop [10]. This design methods is very well established. There are several software design and rating packages available, in order to calculate the heat exchanger design uses the ChemCAD.6.1.4 software. The ChemCAD.6.1.4 is universal software in which commonly used for simulation and optimization of the processing system [11], the software contains an integrated module CC-THERM for design and rating of heat exchanger.

Relating to the description above, the objective of this research is to calculate the thermal design on cooling heat exchanger for the pneumatic system of fuel handling in which the high temperature of helium gas as carrier medium is reduced to be lower temperature The thermal design of cooler uses the ChemCAD.6.1.4 software. From this calculation, the result of parameter design is expected to provide the specification data of cooler according to standard of Tubular Exchanger Manufacturer Association (TEMA).

2. The pneumatic of fuel handling systems

The design of the Fuel Handling System (FHS) prioritizes optimal and reliable operation, so that spherical fuel could be loaded into the reactor core, circulated and fuel burn-up detected perfectly. In the pneumatic system, the fuel lifts from the bottom to outlet of the pneumatic pipe. Due to the fuel could be loaded, discharged and reloaded continuously, therefore the fuel handling system as shown in figure 1 conducts all these processes referred above automatically.

![Figure 1. Diagram of FHS.](image-url)
The pneumatic system is one of the FHS, in which the fuel pebbles are transferred using a helium gas compressed as the conveying medium from the bottom to the reactor core. As shown in the figure 1, the cooler is installed before the carrier gas flows into the compressor. Table 1 shows the general data of pneumatic system in the FHS design of RDE.

| no. | parameter                          | value  |
|-----|------------------------------------|--------|
| 1   | pneumatic inner diameter (I.D), m  | 0.065  |
| 2   | length of straight pipe, m         | 23     |
| 3   | the densities of helium, kg/m³     | 0.179  |
| 4   | fuel pebble diameter, mm           | 0.060  |
| 5   | weight of fuel pebble, kg          | 0.200  |
| 6   | carrier gas medium                 | helium |
| 7   | helium gas temperature, ºC         | 250.0  |
| 8   | carrier medium temperature, ºC, not more than | 60.0 |
| 9   | helium gas reactor pressure, bar   | 30.0   |
| 10  | nominal helium carrier flow rate, kg/s | 0.3   |

3. Methodology
In order to calculate the thermal design of cooler, the ChemCAD.6.1.4 software is used. The ChemCAD.6.1.4™ is developed by Chemstations, Inc. The software contains an integrated module CC-THERM specifically used for designing and rating the heat exchangers in case of both single-phase and two-phase applications. Available features include all types of shell-tube, plate-frame, air-cooled and double-pipe heat exchangers respectively [15].

The following diagram as a sequence of calculations is shown in figure 2. At first, the ChemCAD.6.1.4 perform steady state mass and energy balances in which is used as the foundation for the CC-THERM calculations. In order to calculate the thermal design of shell-tube heat exchanger, it is prepare the input for stream data of water coolant and helium gas. The ChemCAD.6.1.4 calculates parameter in terms of the output temperature attained by the streams. Furthermore setting the simulation mode, selecting the calculation mode and modelling of shell-side and tube-side were carried out. In the determining of design calculation, the performance of cooler that involve temperature and mass flow rate of fluid are conducted by rating procedure. During the process of running, the ChemCAD.6.1.4 will provide a calculation when the process data input there is an unrealistic phenomenon, so this program is user friendly.
While, the ChemCAD.6.1.4 calculates the thermal parameter based on input data of design specification. Finally, the cooler design specifications consider on the heat duty, design tolerance and manufacture in appropriate with the TEMA standard. The thermal calculation uses the design requirements and the operating data as shown in table 2.

**Table 2.** Data required for the design of cooler [14].

| Operating parameter | Unit  | Value |
|---------------------|-------|-------|
| 1 temp. of coolant inlet | °C   | 28    |
| 2 temp. of coolant outlet | °C   | -     |
| 3 mass flow rate     | kg/s  | -     |

| Operating parameters | Unit  | Value |
|----------------------|-------|-------|
| 1 temp. of helium gas | °C   | 250   |
| 2 temp. of helium gas (max.) | °C   | 60    |
| 3 mass flow rate     | kg/s  | 0.3   |

Following are additional data provided to the calculation:

- the cooler is only sensible heat is transferred from tube-side to the shell-side.
- the system is under steady state, isentropic process and adiabatic conditions.
- type of cooler is specified as a shell-tube using single segmental baffle in the shell-side.

The basic layout of model for a counter-current shell and tube heat exchanger with the associated heat curve for a cooling process generated from ChemCAD.6.1.4 is shown in figure 3. From this model, fluids allocation was determined. Cooling water is passed through the shell-side (stream no.3), and the heat medium (helium gas) flows through the tube-side (stream no.1) in counter direction to transfer heat between the two fluids. In this case, the gas was determined flow into the tubes, it is to keep the pressure drop under acceptable limits. Due to the gas has a low friction, meanwhile the friction factor affects the flow pressure drop. Based on input data of mass flow rate and stream temperature no.1, no.2 and no.3 as shown in figure 3, the results of running were obtained.
Determination whether fluid through the tube or outside the tube requires special consideration. Usually this needs to evaluate various factors including the ability to be cleaned, corrosive fluid, operating pressure, fluid temperature, dangerous fluid, fluid quantity and pressure drop.

Figure 3. Model of chemstations ChemCAD.6.1.4.

However, the typical in the reactor cooling system is that the primary coolant system pressure should be lower than the secondary coolant pressure. This condition is to avoid the potential of radioactive release from the primary coolant system. In the calculation, it has carried out through a various consideration on aspects of safety as well as optimization. The equipment safety is one of the most important aspects in process engineering.

4. Results and discussion

Curve of temperature of both stream helium gas and water is depicted in Figure 4. The curve referred in this Figure uses a water mass flow rate of 3.55 kg/s. The stream temperatures depend on the amount of water mass flow rate used as cooling. Based on the heat balance calculation shows that the flow rate is able to reduce the helium temperature to 50.3 °C. From this curve also shows that there is no pinch zone in the operating of cooler. The pinch zone is condition which the smallest temperature difference occurs between the hot fluids and cold fluids in the heat exchangers.

Value of LMTD approach calculated is 81.53° C, it is applied in the design of shell and tube heat exchanger. The LMTD (log-mean temperature difference) is the effective mean temperature difference between the tube wall and the hot fluid.

Figure 4. Heat curves of flow length vs. temperature.

Meanwhile, the figure 5 shows the determination on heat exchanger specification, heat transfer type and other parameters. This design has carried out through a various consideration on aspects of safety as well as optimizations. The input data as shown in figure 5 that the heat exchanger of class B, one pass
and fixed-tubes-sheet were selected in which it has been widely used. The class B is common used for chemical process service. The cooler must consider the factors that cause leaking of tube-to-tube sheets. Furthermore, figure 5 shows also the tube specification that consist of tube diameter, length and tube configurations.

![Figure 5. General data and Tube specification.](image)

The parameter data of shell-side and baffle specifications is shown in the figure 6. Cut segmented baffle is the most popular kind and therefore to get an optimum flow pattern in shell-side, its use a single segmental baffle-cut of 25% which is standard for liquid on shell side [16].

![Figure 6. Shell and baffles specification.](image)

Figure 7 illustrates the shell-tube horizontal heat exchanger single pass 1-1 using baffles. The exchanger is divided into three parts: the front head, the shell, and the rear end. In fixed-tube heat exchanger, the tubes are welded to the shell. This is a simple construction and the tube bores can be cleaned mechanically or chemically. Fixed-tube type is suitable which has the high temperature gas inside the tubes and counter current flow arrangement is possible in this type. This exchanger is based on the TEMA standard size. As shown in figure 7, the ChemCAD.6.1.4 calculates the heat exchanger that appropriate to the standardized TEMA designs. The TEMA standard data includes tube and shell sizes, manufacturing design and recommendations for engineering designs.
Figure 7. Shell-tube heat exchanger 1-1 pass type.

Table 3 summarizes the entire design specifications of cooler in which the water is passed through the shell-side and helium gas through the tube-side respectively. The thermal design in general refers to the determination/selection of an exchanger type, diameter/length and number of tube, tube layout, fluid flow arrangement, types of tube as well as the physical size of an exchanger to meet the desired heat transfer. Data of fluid such as name, quantity and operating parameters are included in the table 3. For the heat exchangers where in both fluids are undergoing sensible heat transfer and operating under steady-state conditions, so tend to provide a better rate of heat transfer. Moreover, the ChemCAD.6.1.4 capable to simulate processes and equipment to get the highest efficiency. Nevertheless, these data specifications based on preliminary calculations that may change/revised in the final design after mechanical or thermal stress is considered.

Table 3. Cooler design specification.

|   | service of unit: cooler of pneumatic carrier gas |
|---|-----------------------------------------------|
| 1 | fluid allocation | Shell-side | Tube-side |
| 2 | fluid name | water | helium gas |
| 3 | fluid quantity, kg/s | 3.55 | 0.30 |
| 4 | helium gas inlet temperature, °C | - | 250.00 |
| 5 | helium gas outlet temperature, °C | - | 50.30 |
| 6 | water coolant inlet temperature, °C | 28.00 | - |
| 7 | water coolant outlet temperature, °C | 48.93 | - |
| 8 | LMTD, °C | 81.5341 |
| 9 | thermal duty, MJ/s | 0.3122 |
| 10 | flow current | counter current |
| 11 | type | single pass 1-1 |
| 12 | TEMA Class | B |
| 13 | tube-sheet | fixed- tube-sheet |
| 14 | number and baffle type | 6, single segmental, B.C. 25% |
| 15 | overall, W/m².K | 74.1730 |
| 16 | heat transfer area, m² | 51.4471 |
| 17 | tube type | - | plain |
| 18 | nominal tube diameter, m | - | 0.01905 |
| 19 | number of tube | - | 363 |
| 20 | tube length, m | - | 2.438 |
| 21 | shell diameter, m | 0.52 | - |
| 22 | pressure drop allowable, bar | 0.50 | - |

5. Conclusion

A calculation on the thermal design of heat exchanger for the carrier gas cooler of RDE was carried out. The cooler heat exchanger for pneumatic system of fuel handling to reduce the high temperature of helium gas to be lower temperature was obtained. The coolant water of 3.55 kg/s capable to reduce the Helium gas temperature to be 50.3 °C in which the water is passed through the shell-side. The design
calculation result including of heat exchanger of shell-tube type (class B) single pass 1-1 using 6 baffles provide by fixed tube sheet, specification of tube, heat duty, coolant water mass flow rate and surface area respectively. The design result requirement of cooling heat exchanger based on the capacity, design tolerance and manufacture in appropriate with the TEMA standard of shell-tube type. This thermal design calculation is expected to provide the design data of FHS especially for the cooling system in the carrier gas of pneumatic system.

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