PERFORMANCE ANALYSIS OF RECUPERATOR OF RGTT200K CONCEPTUAL DESIGN USING CHEMCAD

Piping Supriatna, Sriyono

Center for Nuclear Reactor Technology and Safety (CNRTS)-BATAN

ABSTRACT

PERFORMANCE ANALYSIS OF RECUPERATOR OF RGTT200K CONCEPTUAL DESIGN USING CHEMCAD. RGTT200K is a high temperature gas cooled reactor with 200 MW thermal powers, designed with cogeneration concept to produce hydrogen, electricity generation and potable water by desalination process. RGTT200K uses helium gas as a coolant with core inlet temperature of 615 °C and outlet temperature about 950 °C. The coolant is circulated at 120 kg/sec mass flow rate at initial pressure of 5 MPa. To keep material integrity of RGTT200K structure, the recuperator performance of RGTT200K must be maintained due to its double function. Those main functions are to reduce the output temperature coolant from the turbine and transfer it back to the main primary circuit using a compressor and to increase the coolant gas from the compressor before entering the core again. This paper describes an analysis to evaluate the recuperator performance by modelling using ChemCAD computer code. The calculation results showed that to obtain the core inlet temperature of 615 °C with the recuperator effectiveness of 0.95, the value of the logarithmic mean temperature difference (LMTD) should be 2.51, and the recuperator heat load (BPR) of 264.7 and the heat exchanger coefficient and heat exchange (UA) of 10.546 are needed. Based on those values, the difference between the inlet and outlet temperature of reactor core is not so big and still in stable condition to maintain the material structure integrity of the core.

Keywords: RGTT200K, recuperator, turbine, compressor, ChemCAD Code

ABSTRAK

ANALISIS KINERJA REKUPERATOR PADA DESAIN KONSEPTUAL RGTT200K MENGGUNAKAN CHEMCAD. *RGTT200K merupakan salah satu jenis reaktor Generasi IV dengan daya 200MWth, yang didesain dengan konsep kogenerasi untuk produksi hidrogen, pembangkitan listrik dan produksi air bersih melalui proses desalinasi. RGTT200K menggunakan gas helium sebagai pendingin dengan temperatur di bagian inlet teras adalah 615 °C dan pada bagian outlet 950 °C. Pendingin reaktor disirkulasikan dengan debit 120 kg/detik pada tekanan sebesar 5 MPa. Untuk menjaga integritas material struktur RGTT200K, perlu dijaga kinerja rekuperator yang berfungsi ganda yaitu untuk menurunkan temperatur gas pendingin keluaran dari turbin yang kemudian diteruskan ke kompresor, dan menaikkan temperatur gas pendingin dari kompresor sebelum diteruskan ke dalam teras reaktor. Dalam penelitian ini dilakukan analisis kinerja rekuperator melalui pemodelan dengan menggunakan perangkat lunak Chemcad. Hasil analisis menunjukkan bahwa untuk memperoleh kondisi temperatur inlet teras RGTT200K sebesar 615 °C, maka diperlukan kinerja rekuperator dengan efektivitas 0,95; LMTD 2,51; BPR 264,7; dan UA 10,546. Dengan demikian beda temperatur antara inlet dengan outlet pada teras reaktor tidak begitu jauh dan tetap stabil, sehingga diharapkan tidak terjadi ketegangan material pada struktur teras RGTT200K .*

Kata kunci *: RGTT200K, rekuperator, turbin, kompresor, software ChemCAD*

INTRODUCTION

RGTT200K is a helium gas-cooled reactor with 200 MWth power, designed using cogeneration concept for electricity generation, hydrogen production, and seawater desalination. The core inlet temperature is 520 °C and the outlet is 950 °C [1]. The reactor coolant is circulated with mass flow rate of 120 kg /sec at 5 MPa of pressure. The electricity in RGTT200K is generated through turbines, compressors and generators with a single shaft system. This one axis configuration makes the power generation system becoming much simpler, because the rotation of the generator will provide high efficiency [2,3]. RGTT200K is designed with pebble fuel, which has 3 MWth/m^3 of power density and 66.67 m^3 of reactor core volume. Based on the power density and the core volume, a reactor power of 200 MWth can be obtained.

The function of recuperator inside HTGR is to take benefit of residual heating from the turbine, which thermal energy can be used for industrial needs such as desalination, compressor rotating and helium reheating, before circulated back into the reactor. The aim of this study is to determine the optimal effectiveness and the maximum efficiency of the recuperator. RGTT200K is designed using fuel element of pebble bed, with power density of 3 MWth/m^3 and core volume of 66.67 m^3. Based on the dimension of core power density and volume, a power reactor of 200 MWth is obtained. The performance of RGTT200K design is depend on the performance of intermediate heat exchanger (IHX), turbines and precooler, and also is determined by the use of the heat from the cogeneration system through the heat exchanger (popular known as recuperator). The success of RGTT200K design is determined by IHX, turbine and precooler performance. A good recuperator design is also the key success of cogeneration system. Recuperator performance is influenced by heat transfer efficiency from the hot part to the cold part. The purposes of this paper are to validate the effectiveness of recuperator heat transfer using the ChemCAD software. A specific method to calculate the heat transfer effectiveness on the recuperator is by using the LMTD method

THEORY

The Energy Conversion System and Recuperator of RGTT200K

The RGTT200K produced heat energy from the fission reaction can be used for various purposes such as the hydrogen production, electricity generation and sea water desalination through the cogeneration system [4]. The concept of reactor multifunction is not suitable termed again as nuclear power plants, but more suitable termed for the National Nuclear Energy System (NES) which focus on reactor thermal energy utilization in various industries [1]. The thermal energy for hydrogen production facilities are taken by a heat exchanger (IHX) mounted on the reactor coolant. It is located before the turbine with 950 °C temperature operation. The cooling gas coming out from the IHX with 850 °C temperature and 50 bars pressure is used to drive the gas turbine that are connected to the compressor and electrical generator system on one axis shaft. The amount of electrical energy generated is affected by turbine power and and compressor [4,5]. The cogeneration concept and helium inventory control system of RGTT200K are shown in Figure 1 [6,7].

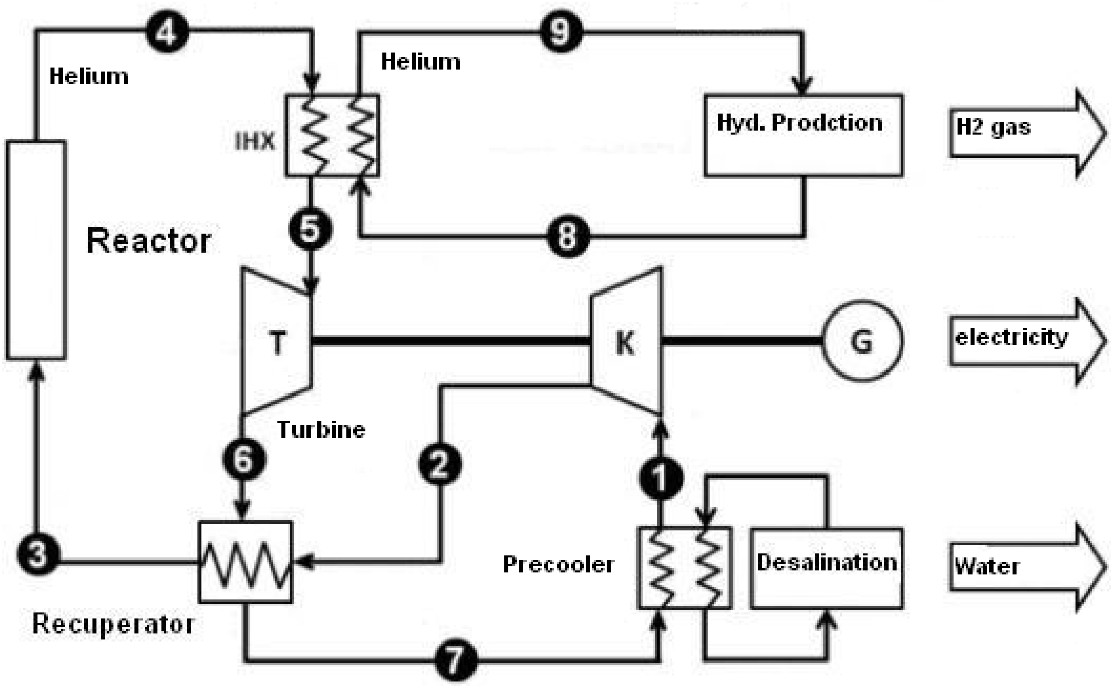

Fig. 1. The cogeneration concept and helium inventory control system of RGTT200K [1]

The power reactor is 200 MWth and the helium coolant is circulated through the reactor core with 520 °C inlet and 950 °C outlet. The core inlet pressure is at 5.0 MPa resulting in the pressure drop in the core of 0.1 MPa. The helium coolant is circulated at 120 kg/sec mass flow rate in to the Intermediate System Heat Exchanger (IHX) to obtain heat for hydrogen production process[4]. From the IHX, the helium gas is passed to the turbine to generate electricity. The helium gas out from the turbine is used to increase the helium temperature coming out from the precooler through the recuperator.

In many types of processes, combustion is used to generate heat, and the recuperator serves to recuperate, or reclaim this heat, in order to reuse or recycle it. By design, the recuperator and the IHX have similar design in term of shell and tube part. The shell side is for the hot part and the other is for cold part. These components transfer the heat from the hot part the cold one. Recuperators are often used in association with the burner portion of a heat engine, to increase the overall efficiency. In RGTT200K, helium is compressed and used to drive the gas turbine engine. The recuperator transfers some of the waste heat in the exhaust to the compressed air, thus preheating it before entering the reactor core[7,8]. Since the gases have been pre-heated, less energy is needed to heat the gases up to the turbine inlet temperature. By recovering some of the energy usually lost as waste heat, the recuperator can make a heat engine or gas turbine significantly more efficient.

Thermodynamic parameter of recuperator

The effectiveness of recuperator depends on the hot gas mass flow rate entering the recuperator from the turbine and the cold gas mass flow rate from the compressor. By using equation (1), the effectiveness of recuperator can be determined [9].

$$\varepsilon = \frac{\dot{m}_h.(T_{h,in} - T_{h,out})}{\dot{m}_c.(T_{h,in} - T_{c,in})} \qquad \text{.....................} (1)$$

Where:

ε : effectiveness of recuperator

$\dot{m}_h$., $\dot{m}_c$. : mass flow rate from turbine and from compressor

$T_{h,in}$: gas hot temperature entering the recuperator

$T_{h,out}$: gas hot temperature leaving the recuperator

$T_{c,in}$: cold temperature from the compressor

On other hand, the IHX efficiency can be calculated by following equation:

$$\eta = \frac{\dot{m}_c.(T_{c,out} - T_{c,in})}{\dot{m}_h.(T_{h,in} - T_{h,out})} \qquad \text{..............} (2)$$

Where η is IHX efficiency. By determining the outlet temperature of the cold part of the recuperator in to the reactor, and by using the equation (2), the efficiency of recuperator can be determined. The heat energy transferred on the recuperator, which is required for the hydrogen production process, can be determined by equation (3)[8].

$$Q_h = \dot{m}.c_p.(T_{h,in} - T_{h,out}) \qquad \text{.................} (3)$$

Where Q_h is the amount of calorie transferred in hot fluid $T_{h,in}$ and $T_{h,out}$ is inlet and outlet hot temperature from the turbine.

The coolant fluid, temperature, and pressure will determine C_P and C_V value. The heat capacity ratio $\gamma = C_P / C_V$ for helium gas is 1.66. By using equation (4) the outlet temperature can be determined. To maintain the integrity of turbine structure, the GTR (Gas Turbine Ratio) is limited not more than 2.0. Based on the GTR curve, the GTR value is determined to be 1.85 for RGTT200K turbine [10] assuming an adiabatic process approximation[8,10].

$$\frac{T_2}{T_1} = (\frac{P_2}{P_1})^{(\gamma-1)/\gamma} \qquad \text{.............................} (4)$$

Where γ is ratio value of coolant heat capacity, T is temperature, P is pressure. The GTR is calculated by P_2/P_1 to be used to calculate the pressure in the turbine inlet or outlet. Furthermore, the power required to run the turbines and compressors can be determined using equation (5).

$$Q_L = (Q_{turbine} - Q_{compressor}).Eff_{Ge} \qquad \text{...........} (5)$$

Where Q_L is electrical power generation, $Q_{turbine}$ is total power for the turbine (power from turbine to be used for compressor movement), $Q_{compressor}$ is electrical compressor power, and Eff_{Ge} is generator efficiency.

The logarithmic mean temperature difference (also known as log mean temperature difference or simply by LMTD) is used to determine the temperature driving force for heat transfer in flow systems, most notably in heat exchangers. The LMTD is a logarithmic average of the temperature difference between the hot and cold feeds at each end of the double pipe exchanger. The larger the LMTD, the more heat is transferred. The use of the LMTD arises straight forwardly from the analysis of a heat exchanger with constant flow rate and fluid thermal properties. It is assumed that a generic heat exchanger has two ends (which we call "A" and "B") at which the hot and cold streams enter or exit on either side; then, the LMTD is defined by the logarithmic mean as follows:

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left[\frac{\Delta T_A}{\Delta T_B}\right]} = \frac{\Delta T_A - \Delta T_B}{\ln \Delta T_A - \ln \Delta T_B} \quad .(6)$$

Where ΔT_A is the temperature difference between the two streams at the A end, and ΔT_B is the temperature difference between the two streams at the B end. With this definition, the LMTD can be used to find the exchanged heat in a heat exchanger:

$$Q = U.A.LMTD \quad \text{.....(7)}$$

Where Q is the exchanged heat duty (in Watts), U is the heat transfer coefficient (in Watts per Kelvin per square meter) and A is the exchange area.

METHODOLOGY

For the simulation of thermodynamic parameters on the recuperator, this component is modelled using ChemCAD 6.1.4 and shown in Fig. 2. There are 4 important streams should be analysed: stream no. 6 is the helium gas from the turbine outlet and directly goes to the stream no 7 (precooler inlet), stream no. 2 is the helium gas from the compressor outlet and is reenergized by the recuperator and to be fed in to the reactor core. The recuperator function will increase overall efficiency, recycle the helium gas from the turbine and optimize the overall energy balance system. The helium mass flow rate is 120 kg/second, and the pressure of 50 bars.

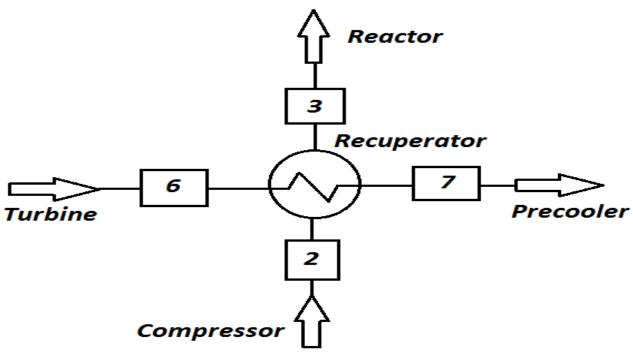

Fig. 2. Recuperator configuration related to coolant flows[9]

RESULTS AND DISCUSSION

The results of mass and energy balance calculation of the energy conversion system in the recuperator using the ChemCAD software are shown in Table 1.

Table 1. Thermodynamic calculation results of RGTT200K recuperator using ChemCAD.

No.	T6 °C	T2 °C	T7 °C	T3 °C	P6	P2	P7	P3	Ef-fect.	LMTD	BPR	U.A.	Power (P)
1.	600.0	110.0	165.0	545.0	27	50	27	50	0.89	55.1	242.4	4.40	243.0
2.	620.0	125.0	165.0	580.0	27	50	27	50	0.92	40.1	253.5	6.32	222.0
3.	640.0	140.0	165.0	**615.0**	27	50	27	50	0.95	25.1	264.7	10.55	**201.0**
4.	660.0	160.0	165.0	655.0	27	50	27	50	0.99	5.08	275.8	54.30	177.0
5.	680.0	130.0	165.0	645.0	27	50	27	50	0.94	35.1	287.0	8.18	183.0
6.	700.0	150.0	165.0	685.0	27	50	27	50	0.97	15.1	298.0	19.74	159.0
7.	720.0	130.0	165.0	685.0	27	50	27	50	0.94	35.1	309.1	8.81	159.0
8.	740.0	160.0	165.0	715.0	27	50	27	50	0.99	25.1	320.4	12.77	141.0

From the above results, following particular relationships can be reviewed in between:

1. Turbine outlet temperature $T_{h,in}$ (T6) against recuperator heat load (BPR).
2. Recuperator heat load (BPR) against recuperator effectiveness (effect.)
3. Core inlet temperature $T_{c,out}$ (T3) against recuperator effectiveness (effect.)
4. Turbine outlet temperature $T_{h,in}$ (T6) against compressor outlet temperature $T_{c,in}$ (T2).
5. Recuperator effectiveness (effect.) against recuperator LMTD.
6. Recuperator effectiveness (effect.) against recuperator UA.
7. Core inlet temperature $T_{c,out}$ (T3) against reactor thermal power (P).

From Table 1, a correlation between the turbine outlet temperatures (T6) and recuperator heat load BPR can be obtained as shown in Figure 3. If the turbine outlet temperature increases, the recuperator heat load will also increase because no energy is needed to support the process to increase the fluid temperature. The fluid will turn back to the main primary circuit and enter the core.

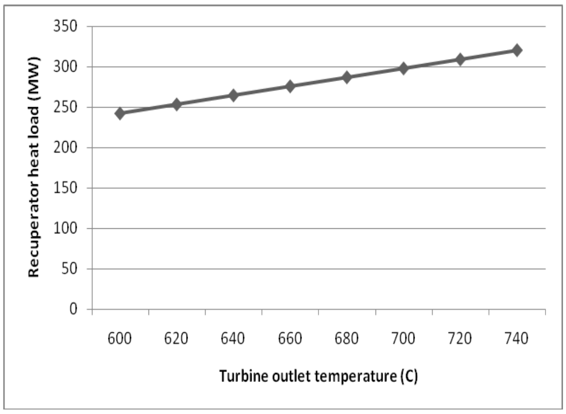

Fig. 3. Correlation between the turbine outlet temperatures (T6) and recuperator heat load BPR

The recuperator effectiveness value is calculated to follow the curve in Figure 4, in which the maximum operational effectiveness of 99 % is achieved at the recuperator heat load (BPR) of 275,8 MW. The recuperator effectiveness will affect the reactor core inlet temperature [2] to increase the core thermal generation caused by the fission reaction.

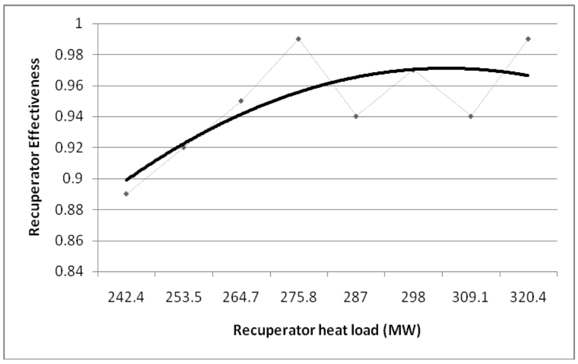

Fig. 4. Correlation between the recuperator heat load (BPR) and recuperator effectiveness (Effect.)

The relationship between the recuperator effectiveness and the compressor outlet temperature is shown in Figure 5. The figure indicates that an increase in the compressor outlet temperature will affect the effectiveness of recuperator to decrease.

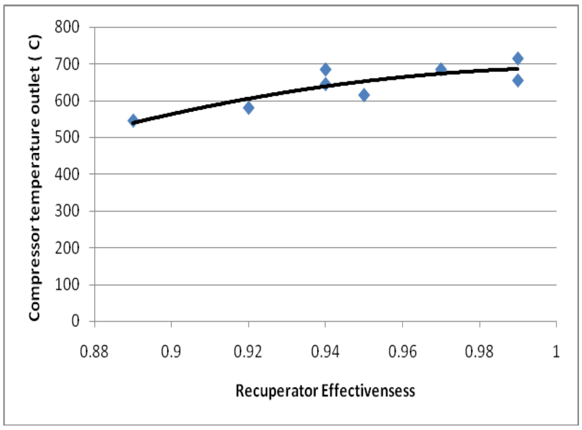

Fig. 5. Correlation between the compressor outlet temperature (T2) and the recuperator effectiveness

The relationship between the turbine outlet temperatures (T6) and the compressor outlet temperature (T2) is shown in Figure 6 having characteristic of a polynomial curve [3].

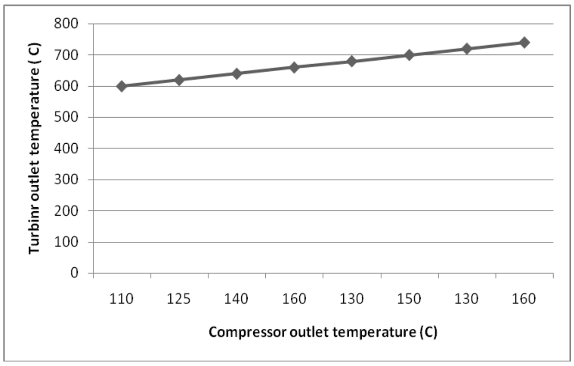

Fig. 6. Correlation between the turbine outlet temperature (T6) and the compressor outlet temperature (T2)

As shown in Figure 6, the increase of the turbine outlet temperature (T6) follow a polynomial curve related to the compressor outlet temperature (T2), in which the compressor outlet temperature reachs the maximum temperature of 160 ^{o}C.

The relationship between the recuperator effectiveness and LMTD is shown in Figure 7. The LMTD value will clearly decrease as the recuperator effectivess value increases.

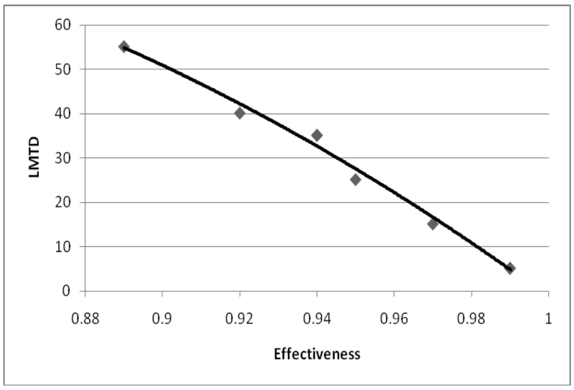

Fig. 7. Correlation between the recuperator effectiveness and LMTD.

Figure 8 shows the relationship between the recuperator effectiveness and the UA factor. The curve follows an exponential charateristic, in which the UA factor is 17,500 for the recuperator effectiveness of 99%.

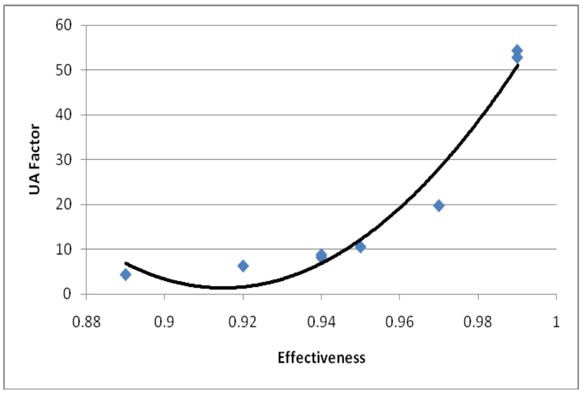

Fig. 8. The correlation between recuperator effectiveness and the UA factor.

The relationship between the reactor power and the outlet compressor temperature is shown in Figure 9. The curve shows that the higher the reactor power, the lower the compressor temperature will be. To achieve the required reactor power of 200 MWth, the compressor outlet temperature should be 615 °C.

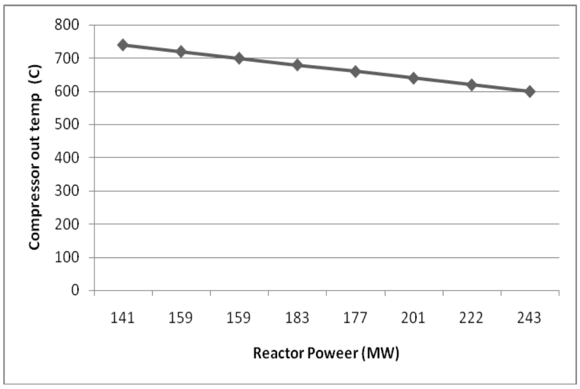

Fig. 9. The correlation between reactor power vs compressor outlet temperature.

From Figure 3 until Figure 9, it shows that the recuperator effectivenesss value used in RGTT200K will clearly affect the working parameter value changes of reactor components. Based on Figure 3 and Figure 4, the value range of the turbine outlet temperature between 600-740 °C have a positive linear correlation on the recuperator heat load (MWth) and the recuperator heat load has a polynomial first order correlation with the recuperator effectiveness. The recuperator performance will result in the 99% of effectiveness based on the recuperator heat load of 275.8 MWth. The same value has been shown also in Figure 4 on the 655°C of core inlet temperature. Figure 7 and Figure 8 show the recuperator effectiveness are in range between 0.89 to 0.99, in which the 99% effectiveness results in the 5.08 of LMTD and UA factor of 12.765. To obtain the RGTT200K core inlet conditions of 615oC as designed and recuperator effectiveness of 0.95, the LMTD value should be 25.1, the recuperator heat load is 264.7 and the UA factor is 10.55. Based on those values, the difference between the inlet and outlet temperature of reactor core is not so big and still in stable condition to maintain the material structure integrity of the core.

CONCLUSIONS

Recuperator is one of the key components in RGTT200K reactor design. Its function is to take benefit of residual heating from turbine, which thermal energy was able to be used for industrials needs, like desalination, compressor rotating and reheating helium in the recuperator, before to be circulated into the reactor. Based on the ChemCAD calculation to obtain the RGTT200K core inlet conditions of

615 ^{o}C and recuperator effectiveness of 0.95, the LMTD value should be 25.1, the recuperator heat load is 264.7 and the UA factor is 10.55. Based on those values, the difference between the inlet and outlet temperature of reactor core is not so big and still in stable condition to maintain the material structure integrity of the core.

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