DESIGN ANALYSIS ON OPERATING PARAMETER OF OUTLET TEMPERATURE AND VOID FRACTION IN RDE STEAM GENERATOR

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ABSTRACT

DESIGN ANALYSIS ON OPERATING PARAMETER OF OUTLET TEMPERATURE AND VOID FRACTION IN RDE STEAM GENERATOR. HTGR is one of the next generation reactor types. HTGR is currently considered as one of the leading reactors for the future nuclear power plant. The steam generator is one of the main components in HTGR as well as in RDE. In the steam generator, the heat is transferred by high temperature helium gas in the shell side to water in the tube side to generate the superheated steam. The purpose of this work is to design the operating parameter of outlet temperature and void fraction of steam based on feed water mass flow rate and inlet temperature variations in RDE steam generator. In this work, the ChemCAD program was used. Both inlet and outlet temperature of helium gas have been set up as boundary conditions. The result shows that using the mass flow rate of 4.3 kg/s - 4.8 kg/s and water inlet temperature of 110 ^oC - 160 ^oC, the superheated steam outlet temperature (void fraction = 1.0) is obtained in the range of 275.5 ^oC – 600 ^oC. This analysis is beneficial to assess 10 MW RDE design especially in the steam generator system operating parameters.

Keywords: outlet temperature, void fraction, superheated steam, RDE steam generator

ABSTRAK

ANALISIS DESAIN PARAMETER OPERASI UNTUK TEMPERATUR KELUARAN DAN FRAKSI UAP PADA PEMBANGKIT UAP RDE. *Reaktor daya HTGR adalah salah satu tipe reaktor generasi lanjut. HTGR saat ini merupakan desain reaktor yang dipertimbangkan untuk pembangkit listrik unggulan dimasa mendatang. Pembangkit uap merupakan salah satu komponen utama pada HTGR begitu pula pada RDE. Di dalam pembangkit uap, panas dari gas helium temperatur tinggi pada sisi shell di transfer ke air pada sisi tube pembangkit uap untuk menghasilkan uap lewat jenuh. Tujuan analisis ini adalah mendesain parameter operasi terhadap temperatur keluaran dan fraksi uap berdasarkan variasi laju alir massa air umpan dan temperatur masuk pada RDE. Dalam analisis digunakan program ChemCAD, temperatur gas helium masuk dan keluar ditentukan sebagai kondisi batas. Hasil menunjukkan bahwa dengan menggunakan laju alir massa 4,3 kg/detik - 4,8 kg/detik dan temperatur masukan air umpan dari 110 ^oC -160 ^oC dapat diperoleh uap lewat jenuh (fraksi uap= 1,0) pada temperatur keluaran dalam rentang 275,5 ^oC - 600 ^oC. Analisis ini berguna untuk memberikan kajian desain RDE 10 MW khususnya parameter operasi sistem pembangkit uap.*

Kata-kata kunci: temperatur keluaran, fraksi uap, uap lewat jenuh, pembangkit uap RDE

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INTRODUCTION

Energy supplies are highly required to meet the amount of energy necessary for the global industrialization. The primary application of nuclear energy is to generate electricity. In addition to that, it is also used for cogeneration applications, in the integration with other systems and applications [1]. One particular type of advanced power reactors expected to meet such energy demand is the high temperature gas-cooled reactor (HTGR) [2]**.** This reactor can be operated with the outlet temperature up to 900 ^{o}C. Moreover, higher gas outlet temperature can be reached whenever the reliable advanced materials discovered [3].

The HTGR is one of the future generation reactor types. Therefore, its design and inherent safety features are currently considered as one of the leading reactor for the future nuclear power plant [4]. It has been developed with variation of power capacities [5]. Helium gas, reactor coolant, is used to heat the water which flows through the steam generator in a closed cycle. Some advantages of using helium gas as a coolant are due to its non-reactive, inert and single-phase, non-corrosive and it does not absorb neutrons. Therefore, those properties have given additional safety aspects of the reactor [6]**.**

Currently, HTR-10, the small size of HTGR, is operated in China [7-8]. Referring to that, Indonesia plan to build a small size of HTGR called RDE (Reaktor Daya Eksperimental) that has a thermal power of 10 MW. To support the plan, the design of steam generator (SG) operating parameters is required.

The steam generator is used to produce steam and to separate primary coolant (helium) and steam, therefore there is no leak to the secondary coolant. In the steam generator, the high temperature helium in the shell side transfer heat to water in the tube side of SG to generate the superheated steam. The secondary coolant (water) is passed through the helical tube of the steam generator with the steam pressure about 4.0 to 6.0 MPa [9]. Therefore, the steam generator is one of the main components in HTGR due to its function.

However, there is a further development to be considered in the HTGR steam generator, which is performance optimization of its thermal parameters. In general, the parameters related to the thermal design of steam generator system are temperature, mass flow rate, coolant pressure and heat transfer coefficient. Meanwhile, the outlet temperature and steam quality produced from the steam generator are attributed with operating parameters which are mass flow rate and inlet temperature. In the thermal calculation model of steam generator, the heat exchanger feature of ChemCAD program is applied. It provides the library data of heat exchanger. The ChemCAD.6.1.4 version is one of programs that can be used to analyze the thermal parameter of steam generators. Furthermore, the results are beneficial to assess the design parameters of steam quality.

The objective of this work is to design the operating parameters such as outlet temperature, steam quality and void fraction of steam based on feed water mass flow rate and inlet temperature variations in RDE steam generator by utilizing the ChemCAD program. This analysis is worthwhile to support the RDE design especially for the steam generator system operating parameter.

HTGR STEAM GENERATOR (HTGR-SG)

In general, the steam generator consists of pressure vessel and blower pressure vessel portion which are joined to steam generator vessel. Fig. 1 shows the cross section view of the HTR-10 steam generator [9]. The configuration of installed steam generator is in the vertical position, once-through, helically boilers tube side and counters flow circulation. The hot helium flows through the hot gas duct at the bottom, then the steam flows out from the steam nozzle at the upper of the steam generator.

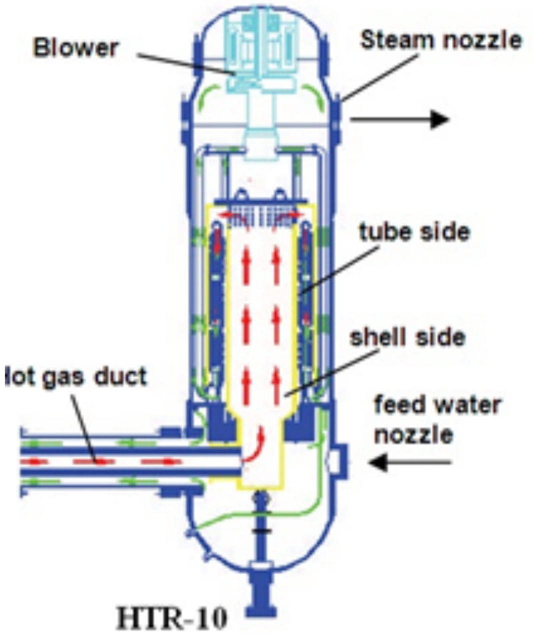

Fig. 1. Cross section view of HTGR-SG [9]

As a heat exchanger, the steam generator transfers heat of high temperature helium gas to the secondary coolant system. The heat passes through shell side to the tube side to generate the superheated steam as shown in Fig. 1 [10]. The helium gas flow is generated by the blower at the top regions. For the secondary coolant, the water enters to the helical tubes at the bottom side and flows out from the steam generator through the nozzle steam. Prior to leaving steam generator, the steam passes through the heat transfer tube that has three sections, which are the warm-up section, phase-change section and superheated section. Fig.2 illustrates the steam quality or mass fraction as a function of flow distance. The steam quality remains at zero until the two-phase section [10].

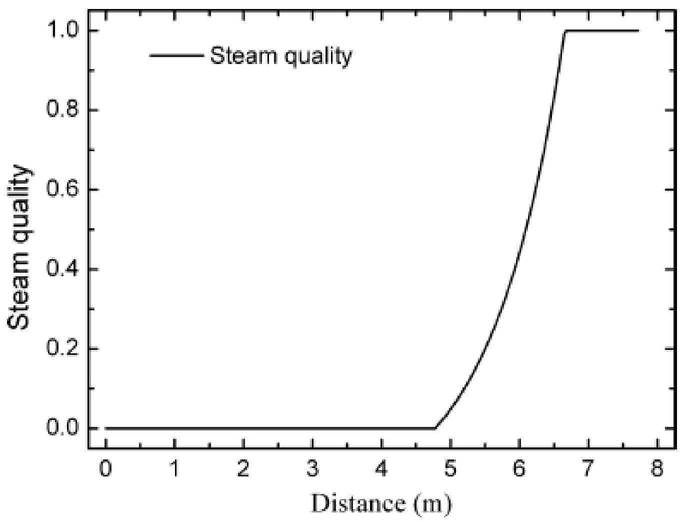

Fig. 2 Variation of steam quality of water as a function of distance [10]

In general, the small size HTGR is designed with the helium gas temperature from the reactor outlet of 700 ^{o}C [11]. Fig.3 illustrates the simple block diagram of primary and secondary coolant system of the HTGR.

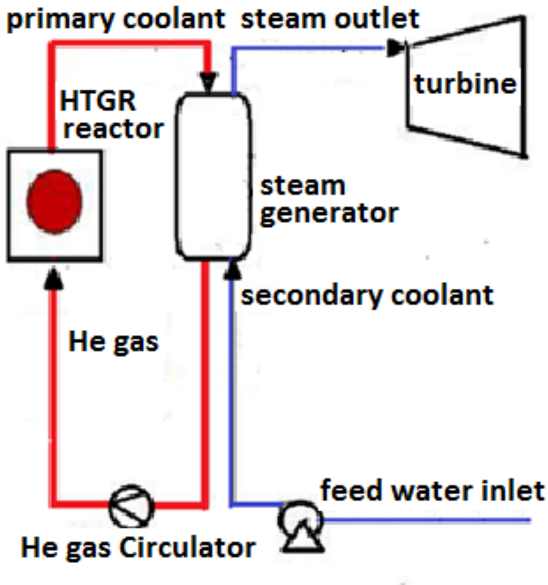

Fig. 3 Block diagram of primary and secondary coolant system

METHODOLOGY

The ChemCAD program is commonly used for simulation and optimization of the processing system [12]. In the thermal analysis of steam generator, the both inlet and outlet helium gas temperatures are used as boundary conditions. The calculation is based on the feed water inlet temperature. A change in the flow rate for feed water results in a change of steam temperature [10].

Fig. 4 shows the model diagram which is used for the thermal calculation of steam generator performance. The diagram was created by using the feature of the ChemCAD program. It provides basic symbol component units for the process flow diagram. Meanwhile, Table 1 shows the input data which is obtained from references [7,13]. The operating parameter calculations are based on the thermal calculation concept, which is 10.0 MW.

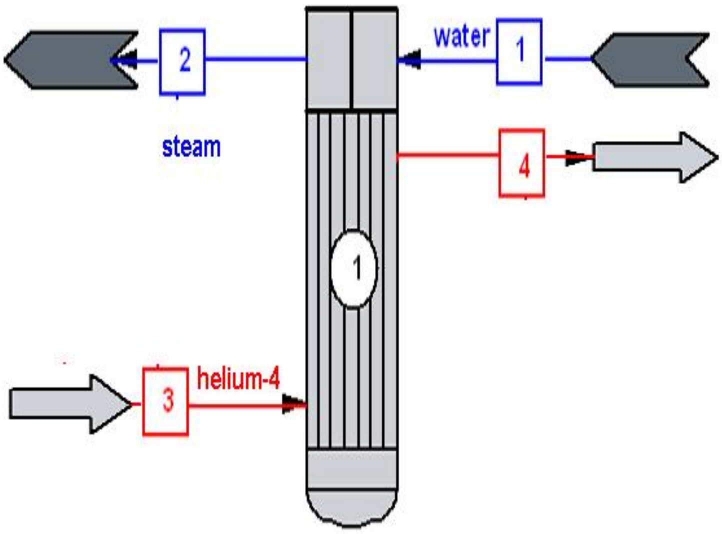

Fig. 4 The heat exchanger model of ChemCAD

Table 1. Input data [7,13]

No.	Parameter	Values
1	Thermal power, MW	10.0
2	Primary coolant mass flow of He, kg/s	4.4
3	Helium gas inlet temperature, ^oC	700
4	Helium gas outlet temperature, ^oC	250
5	Steam pressure, MPa	6.0
6	Range of feed water inlet temperature, ^oC	110-160

The calculation of heat transfer requirement, thermodynamic equilibrium on the two-phases condition of thermal heat exchanger are basic principle in design. The enthalpy calculation in the ChemCAD uses the SRK (Soave-Redlich-Kwong) and Peng-Robinson equation. The following equation is the latent heat of vaporization used in the ChemCAD [14],

$$H = H_f - H_{ov}(25^o C) + \int_{25}^{Tb} Cp.dT + H_{ov}(Tb) + \int_{Tb}^{Ts} Cpv.dT \quad (1)$$

for liquid,

$$H = (H_f - H_{ov}) + \int_{25}^{Ts} C_P.dT \quad (2)$$

where

H : flow enthalpy (kJ),
H_{ov} : heat of vaporization (kJ/kg),
Ts : system temperature (^oC),
Tb : boiling temperature (^oC),
C_p : specific heat (J/g K).

In the thermal calculation of steam generator, the CC-Therm module of ChemCAD.6.1.4 was used. With this model, the calculations can be obtained faster. The ChemCAD will display a running list of input error and warning messages when the current file is opened. Therefore, the input data must be filled in accordance with the parameters required for calculation.

In the method of thermal calculation of steam generator, the helium gas flows through the shell side, meanwhile, the water and vapor flow through the helical tube side. The heat transfer performance of the helical tube does not match exactly with the straight tube. However, in the calculation using ChemCAD, the helical tube can be modeled as a straight tube with the same dimensions and heat transfer surface area. The preparation of model, determination of boundary condition and input data option was conducted. Furthermore, the diagram of calculation steps is described in Fig. 5.

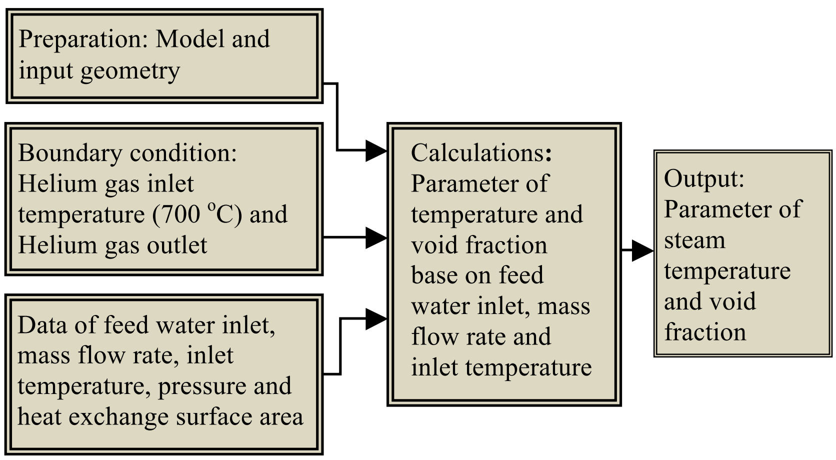

Fig. 5. Diagram of calculation steps

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RESULT AND DISCUSSIONS

Fig. 6 shows the void fraction of steam against the feed water mass flow rate for various inlet temperatures (in the range of 110 ^{o}C to 160 ^{o}C). The production of steam at temperature higher than saturation temperature is obtained when the void fraction equals 1.0. The superheat degree is the temperature added to the steam saturation. Therefore, in the steam generator design, the superheated steam no longer contains moisture. It is less erosive and less corrosive than wet saturated steam that is carrying droplets. In order to have a sustainable turbine operation, the steam cannot contain any moisture at all. In general, the superheated steam increases the efficiency of the steam turbine [15]. Dry steam is superheated steam which is formed at a certain pressure and at different temperatures. In this design analysis, the outlet steam pressure of RDE-SG is 6.0 MPa. Therefore the saturation steam temperature in the steam generator is 275.5 ^{o}C [16]. Furthermore, as shown in Fig.7, the outlet temperature of superheated steam is more than 275.5 ^{o}C depends on the utilized mass flow rate.

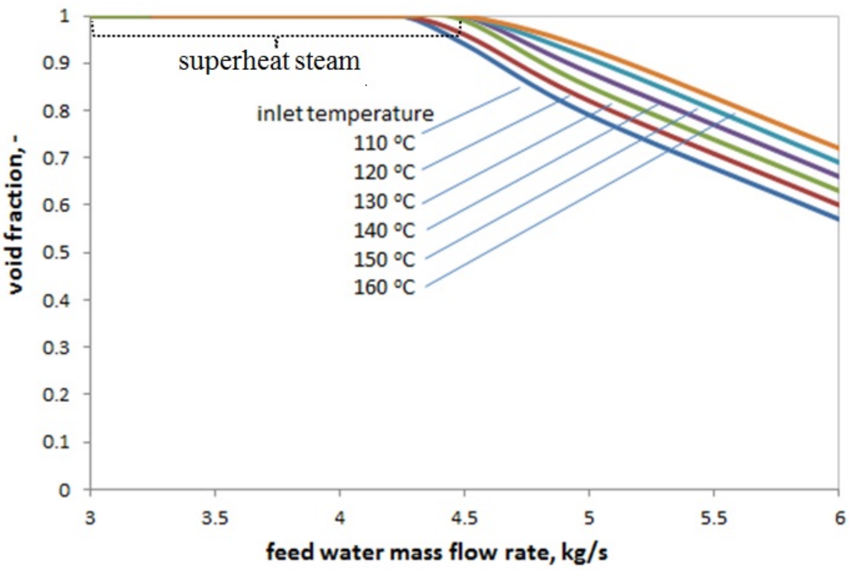

Fig. 6. Variation of void fractions of steam as a function of feed water mass flow rates

The steam dryness fraction is used to quantify the amount of water within steam. Therefore, the steam dryness is important because it has a direct effect on the total amount of transferable energy (latent heat) contained within the steam.The temperature of water flowing on the tube side of steam generator is increased by the heating steps. Those steps are sensible heat, latent heat of evaporation, and heating toward superheated steam.

In the analysis, the outlet steam temperature is affected by the heat transfer coefficient, feed water temperature, and mass flow rate [17]. Therefore, the principle in the steam generator thermal analysis is to specify fluid temperature, pressure and mass flow rate in order to determine steam production with the lowest possible content on droplets and at highest possible pressure and mass flow rate.

Fig. 7 depicts the variation of outlet steam temperatures as a function of feed water mass flow rates. In case of inlet temperature of 110 ^{o}C, it is shown that to obtain the superheated steam temperatures, the flow rate of feed water should not more than 4.3 kg/s. Meanwhile, when mass flow rate is higher than 4.3 kg/s, the void fraction of steam produced will be less than 1.0. It means the steam generator will produce the steam that carrying droplets. Therefore, by applying the mass flow rate of 4.3 kg/s - 4.8 kg/s and feed water inlet temperature from 110 ^{o}C - 160 ^{o}C, the superheated steam (void fraction equals to 1.0) can be obtained in the range of 275.5 ^{o}C - 600^{o}C.

Furthermore, the use of steam superheated at higher temperatures is an advantage for the application of cogeneration system. However, in another hand, the increase of steam temperature depends on the degree of material stress in the steam generator components. Temperature condition above the design limit of tube materials can cause strain, buckle, crack, and rupture.

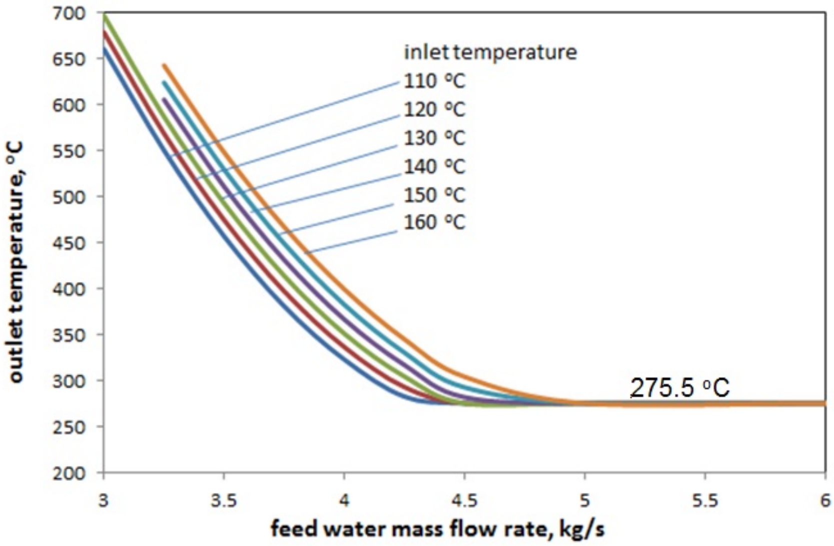

Fig. 7. Variation of Outlet temperature as a function of feed water mass flow rates

CONCLUSION

Design analysis of operating parameter for the RDE steam generator at the power of 10 MW was carried out. The result shows that using the mass flow rate of 4.3 kg/s - 4.8 kg/s and water inlet temperature of 110 ^{o}C - 160 ^{o}C, the superheated steam outlet temperature (void fraction = 1.0) is obtained in the range of 275.5 ^{o}C - 600 ^{o}C. The principle in the steam generator thermal design is to specify fluid temperature, pressure and mass flow to determine a vapor production with the lowest possible content on droplets and at highest possible pressure and mass flowrate. This work is beneficial to assess the operating parameter design of RDE steam generator.

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