Thermo-hydraulic Analysis for the Steam Generator Subsystem of a HTR

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1. Introduction

A High Temperature Reactor(HTR) is one of the 4th generation reactor concepts, particularly using graphite moderator and helium coolant. The HTR is designed to be a high efficiency system, which can supply electricity as well as a broad range of process heat, while retaining the desirable safety characteristics. In the HTR, a Steam Generator Subsystem(SGS) is installed to generate steam for energy conversion [1]. The SGS includes the heat exchanger facilitating transfer of heat from helium to feed water, and helium guidance structures. The SGS is connected to a main circulator which provides momentum necessary for forced circulation of the helium flow [2]. In order to utilize the HTR safely and effectively, it is essential to calculate pressure rise in the circulator required for various operating conditions. Moreover, it should be verified whether the SGS was properly designed for providing flow path to the helium or not.

In this study, thermo-hydraulic characteristics of the SGS were investigated using Computational Fluid Dynamics(CFD) for various operating conditions. Particularly the full-scale steam generator model was applied to the analyses. At normal operating condition, the result was compared to that of the concept design report for the HTR by General Atomics(GA)

2. Modeling and Schematic of Steam Generator

2.1 Steam Generator Subsystem Model

A SGS model is shown in Fig. 1. The SGS is composed of a helical type heat exchanger, shrouds directing the flow of the shell-side helium and support systems. The hot helium gas emerging from the reactor core flows to the SGS through a hot gas duct and enters the top of the heat exchanger through a vertical helium inlet duct and an inlet flow distribution cone. The gas flow downward through the heat exchanger, nominally perpendicular to the tubes within the helical coils and countercurrent to the steam flow. The cooled helium leaves at the end of the heat exchanger, turns 180 degrees, and flows upward through an annular region between the outer shroud of the SGS and the inner wall of the steam generator vessel, leading to the inlet of main circulator system.

The commercial CFD codes, Fluent was applied to the analysis and the Reynolds Stress Model(RSM) with standard wall treatment was used. The helical type heat exchanger was modeled as porous media and the resistance parameters of the porous media were determined by preliminary CFD analyses based on the GA's report. All boundary conditions in the GA's report were adopted in this study as shown in Table I [3]. The thermal conductivity and viscosity of the helium were calculated from Refprop 8.0 made by NIST(National Institute of Standards and Technology). The adiabatic boundary condition was applied to all walls in the domain.

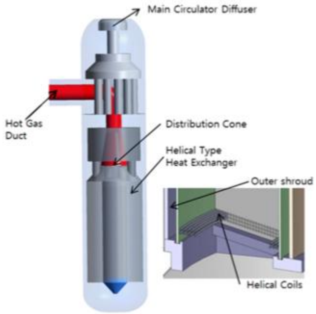


Fig.1 Steam Generator Subsystem

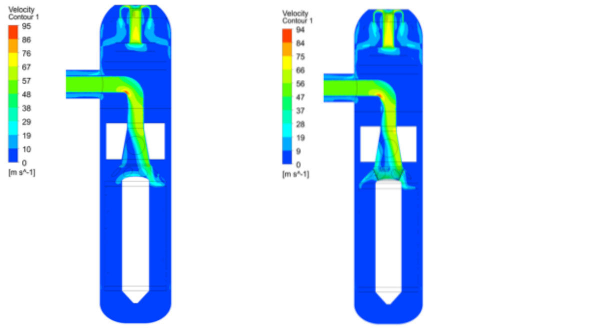
2.2 Analysis Results

The velocity contour was represented at normal operating condition(100%) as shown in Fig. 2(a). The 10% of total helium flow was biased to the right side at the inlet of the heat exchanger due to excessively high velocity of the helium at the inlet of the hot gas duct. If the helical heat exchanger is influenced by the large amount of high temperature helium, the heat exchanger can be damaged due to excessive heat [4]. Most of the feed water will be vaporized at the end of the heat exchanger and changed into steam. Because the steam has low thermal conductivity compared to the water, the heat transfer degradation occurs, which causes localized overheating of the surface of the heat exchanger. Moreover, the biased helium flow had bad effects on the mechanical integrity and thermal effectiveness of the heat exchanger.

In order to keep the helium flow uniform, a screen was installed in front of the heat exchanger. From

Table I: Boundary conditions for CFD analysis

Operating Condition	100%	75%	50%
Inlet Velocity(kg/s)	155	116	77
Inlet Temperature(℃)	724	712	697
Inlet Pressure(MPa)	6.94	6.93	6.93



(a) Without screen (b) With screen

Fig. 2 Velocity contours for the SGS at normal operating condition

several CFD analyses, the specific screen model was proposed and made the helium flow approximately equal within ±1% difference as shown in Fig. 2(b).

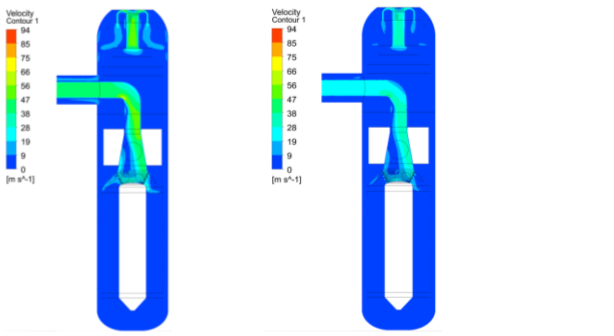
The CFD analyses were carried out for various operating conditions as shown in Fig 3. At normal operating condition, the value of pressure drop in the SGS was in good agreement with that of GA's results within 6% difference if the screen was not installed. However, due to the pressure drop caused by the screen, it was necessary that the helium circulator selected by GA have sufficient margins for safe operation of the HTR as shown in Table II.

The heat transfer effect in the porous media on the pressure calculation was investigated at normal operating condition, because the values of helium viscosity decrease with temperature drop as shown in Fig. 4. The pressure drop in the SGS was 32% higher without heat transfer effect.

3. Conclusions

In this study, CFD analyses of the SGS were conducted for various operating conditions. The helical type heat exchanger was modeled as porous media and the RSM turbulence model was used.

(1) At the inlet of the heat exchanger, non-uniform helium flow was founded. In order to keep the helium flow uniform, a screen model was proposed. The screen made the helium flow approximately uniform within ±1% difference at the inlet of the heat exchanger.

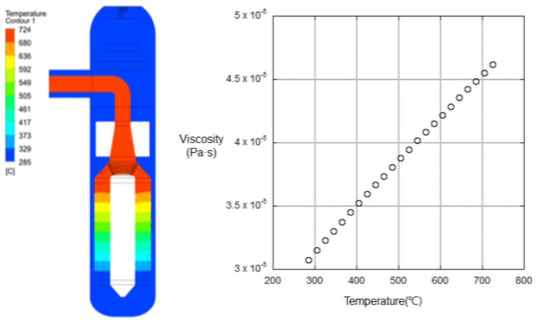


(a) 75% (b) 50%

Fig. 3 Velocity contours for the SGS at various operating condition(75%, 50%)

Table II: Analysis Results of CFD analysis

Operating Condition	100%	75%	50%
ΔP_{GA} (kPa)	35	-	-
$\Delta P_{\text{without screen}}$ (kPa)	37	21	9
$\Delta P_{\text{with screen}}$ (kPa)	41	23	10



(a) Temperature Contour (b) Viscosity

Fig. 4 Temperature contour the for SGS at normal operating condition and viscosity variation of the helium with temperature

(2) Without the screen, the calculated pressure drop in the SGS was in good agreement of that of GA's result at normal operating condition. However, due to the pressure drop in the screen, it was concluded that the helium circulator designed by GA should have more circulation capacity for safe and effective operation of the HTR.

(3) At normal operating condition, CFD analyses were conducted for two cases, whether the heat transfer in the porous media occurred or not. It was concluded that the effects of viscosity variation caused by temperature change should be considered in case of investigating the thermo-hydraulic characteristics of helium in the SGS.

Acknowledgements

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REFERENCES

[1] Guido Baccaglini, "Next Generation Nuclear Plant (NGNP): Steam Generator Subsystem Design Description", General Atomics, December, 2010.

[2] Karl Swanson, "Next Generation Nuclear Plant(NGNP): Main Circulator Subsystem Design Description", General Atomics, December, 2010.

[3] D. Allen, "Next Generation Nuclear Plant(NGNP): Plant Design Requirements Document Steam-Cycle Modular Helium Reactor(SC-MHR) Demonstration Plant", General Atomics, December 2010.

[4] Liang Zhao, Liejin Guo, Convective boiling heat transfer and two-phase flow characteristics inside a small horizontal helically-coiled tubing once-through steam generator, International Journal of Heat and Mass Transfer, Vol. 46, pp. 4779-4788, 2003