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CFD ANALYSIS OF HEAT TRANSFER PHENOMENA ON FIRST WALL OF TBM WITH HIGH PRESSURIZED HELIUM GAS COOLANT

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ABSTRACT

Conventional Test Blanket Module (TBM) design concepts adopt the high pressurized helium gas as the coolant. Thus for the development of the TBM design concept and the validation of the safety and high efficiency of the power conversion system, it should be preceded to investigate the thermal-hydraulic characteristics of the high pressurized helium gas. The experimental studies on the heat transfer phenomena of helium gas at TBM condition are rare, and in consequence, few heat transfer correlations are developed for high pressurized helium gas. Therefore, the experimental investigation on the heat transfer phenomena of the helium gas under the TBM conditions is required. This study is the preliminary analysis for prepare the design of experimental facilities which is simulated the heat transfer phenomena with helium gas coolant. For this, literature survey of the conventional correlations and CFD analysis were performed. Operating pressure, inlet velocity and surface heat flux are selected for the main variable of the CFD analysis. CFD results show that helium heat transfer coefficient increases with operating pressure and inlet velocity, but remains constant with variation of surface heat flux. Comparison with the results from the CFD analysis and the conventional correlation reveals the overestimation of conventional correlation results at the high Reynolds number regime which belongs to the TBM condition. Finally, the new correlation to analyze the TBM heat transfer phenomena is required.

INTRODUCTION

One of the main functions of the Test Blanket Module (TBM) is to remove heat of the first wall and neutron wall loading energy from nuclear fusion reaction under the normal and off-normal operating conditions. The design of TBM imposes a special condition for cooling of the first wall that is one-dimensional heat flux from the fusion plasma. It can cause large temperature gradient and induce the strong thermal stress in the TBM structure. In order to ensure the thermal margin of TBM and obtain the high efficiency of the power conversion systems, it is necessary to investigate the thermal-hydraulic characteristics of the high pressurized helium gas, because it is adopted as a working fluid of the TBM cooling systems. To understand these characteristics, the evaluation of the cooling capacity of the helium gas coolant is required. Therefore, the research of the heat transfer coefficients of the helium gas under the TBM condition is essential.

In this study, the literature survey of the conventional correlations and the CFD analysis to calculate the heat transfer coefficients of the helium gas are performed to understand the TBM heat transfer phenomenon. Reflecting the Reynolds number regime of the TBM condition, standard k-ε model was selected as the turbulence model. Total length of the test section is 1070 mm including two 185 mm unheated ducts and 700 mm heated surface. Helium gas of 573 K flows into the cooling channel. Since the conventional TBM design concepts adopt 80 bar helium gas as the coolant, so the CFD analysis is conducted at 20, 40, 60, 80 bar with the helium inlet velocity of 25, 50, 75, 100 m/s and surface heat flux of 50, 100, 200, 400 kW/m^2, respectively.

NOMENCLATURE

h	[W/m^{2}K]	Convection coefficient	
k	[W/mK]	Thermal conductivity	
Nu	[-]	Nusselt number	$\mathrm{Nu}=\frac{hl}{k_f}$
Pr	[-]	Prandtl number	$\mathrm{Pr}=\frac{\nu}{\alpha}$
q''	[W/m^2]	Heat flux	
Re	[-]	Reynolds number	$\mathrm{Re}=\frac{u_\infty l}{\nu}$
T	[K]	Temperature	
Greek			
α	[m^2/s]	Thermal diffusivity	
ν	[m^2/s]	Kinematic viscosity	

Subscripts

m	Mean
w	Wall

REVIEWS ON THE HEAT TRANSFER CORRELATIONS

The coolant channel design is very important play role in the safety of the TBM structure. The cooling system is one of the key elements because it has to remove the heat generated by nuclear reactions to keep the main structure within the acceptable temperature range. It is required to withstand the heat loads, to avoid thermal damages and ensure the suitable outlet temperatures for high-efficiency power conversion systems, so the accurate prediction of heat transfer coefficient in the coolant channel of TBM is crucial. There are many correlations for the Nusselt number of the fully developed flow regime in a smooth circular pipe, most of them are not applicable to the TBM design conditions; the Prandtl number is around 0.66 and Reynolds number is over 10^5 [1]. Heat transfer correlations for helium at high pressure are uncommon, so that some experimental researches for helium heat transfer were reviewed. Then the general correlations which have been used in engineering were assessed if they can be used in the TBM coolant channel design. Some conventional correlations are tabulated in the Table 1.

McEligot's [2] correlation is valid for air, helium and nitrogen gas flow but it is valid only the regime of Reynolds number 1,500 through 45,000. Ilic [3] compared the Nusselt number obtained by the Dittus–Boelter's correlation and Gnielinski's correlation. It appears that the Dittus–Boelter's correlation overestimates the Nusselt number at least 1.15 times than Gnielinski's correlation. This overestimation is very pronounced for low Reynolds numbers. Ilic also mentioned that the heat transfer coefficient in the first wall is 15% lower than the one predicted by one-dimensional heat transfer evaluations based on Dittus-Boelter-like correlations and that satisfactory cooling of the first wall can be achieved only with hydraulically rough channels. Thus the Gnielinski's correlation may be the best choice, Lee [4] noticed that the effect of the thermal developing length term in equation is somewhat ambiguous in Gnielinski's correlation, so it can predict only the average Nusselt number and cannot predict the local value. In consequence of significant fluid property variations, some experiment data can't be predicted by the Gnielinski's correlation. Therefore in the TBM coolant channel design, Aiello[5] used a modified Gnielinski's correlation to consider the property variation of helium.

Table 1 Turbulent flow correlations

	Heat Transfer Correlation	Applicable Range
Dittus Boelter's Correlation	$\mathrm{Nu}=0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$	$10^4<\mathrm{Re}$ $0.7<\mathrm{Pr}<160$
McEligot's Correlation	$\mathrm{Nu}=0.021\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{T_w}{T_m}\right)^{-0.5}$	$\mathrm{Re}<15{,}000$
Gnielinski's Correlation	$\mathrm{Nu}=\frac{(\xi/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{\xi/8}\left(\mathrm{Pr}^{2/3}-1\right)}$ $\xi=(1.82\log\mathrm{Re}-1.64)^{-2}$	$2300<\mathrm{Re}<10^6$ $0.5<\mathrm{Pr}<1.5$
Modified Gnielinski's Correlation	$\mathrm{Nu}=\frac{(\xi/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{\xi/8}\left(\mathrm{Pr}^{2/3}-1\right)}\left(\frac{T_m}{T_w}\right)^{0.45}$	$2300<\mathrm{Re}<10^6$ $0.5<\mathrm{Pr}<1.5$ $0.5<(T_m/T_s)<1.5$

ONE-DIMENSIONAL HEATING ON THE FIRST WALL

For the TBM design, the special situation occurs in the First wall (FW) that the dominant heat flow comes from one side only. Figure 1 describes the heat transfer phenomenon from the plasma to the first wall.

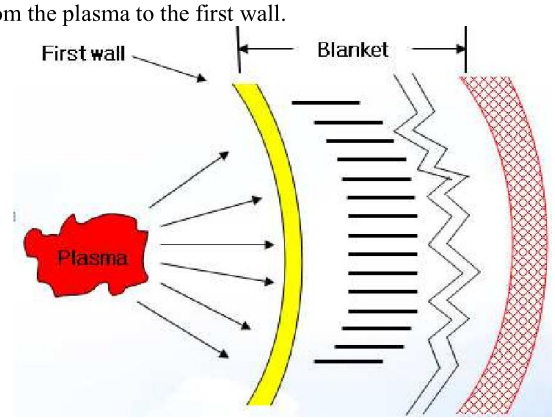

Figure 1 Schematic diagram of heat transfer phenomena

FW is a component of TBM that faces directly the fusion plasma. Due to the strong heat flux and neutron wall loading from the fusion reaction, if the high efficiency of the TBM cooling systems is not ensured, this asymmetric heat transfer condition can result in large temperature gradient and the strong thermal stress on the TBM structure. Inside the first wall, U-shaped cooling channels are equipped. TBM structure is made of Ferritic Martensitic Steel (FMS). In order to maximize the cooling capability of TBM and keep the first wall temperature below the safety limit, the rectangular cooling channels are adopted.

GEOMETRY OF THE CFD TEST SECTION

Figure 2 shows the reference geometry of test section. Total length of the reference CFD test section is 1070 mm including two 185 mm unheated ducts and 700 mm heated surface. High pressurized helium gas with 573 K flows into the rectangular channel and cools the heat transferred from the heated surface. To simulate the TBM heat transfer phenomenon, the constant heat flux condition is adopted. Four edges of rectangular channel have the radius curvature of 2 mm in order to reduce the strong pressure gradient inside the coolant channel.

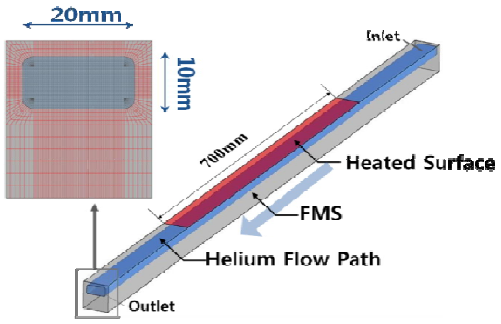

Figure 2 Test section geometry and mesh structure

ANALYSIS CONDITION

The mesh was constructed by using GAMBIT 2.3.16, and the numerical analysis was performed by FLUENT 6.3.26. The CFD analysis condition is tabulated in Table 2. The working fluid was helium gas that is same as the actual TBM coolant. Standard k-ε model was selected as the turbulence model. Material of test section is FMS and the material properties of FMS is obtained from ITER MPH and those of helium (isobaric condition) from NIST web.

Table 2. CFD analysis condition

Operating Fluid	Helium
Inlet Temperature [K]	573
Inlet Velocity [m/s]	25, 50,75,100
Operating Pressure [bar]	20, 40, 60, 80
Surface Heat Flux [kW/m^2]	50,100,200,400

MESH SENSITIVITY TEST

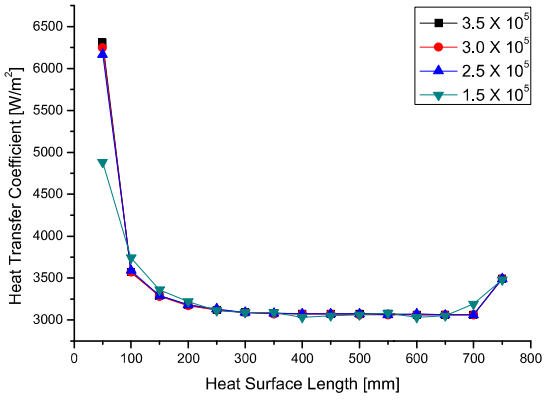

Figure 3 Mesh sensitivity test

Figure 3 shows the result of mesh sensitivity test. Mesh sensitivity tests are carried out at the 80 bar operating pressure, 25 m/s inlet velocity, 50 kW/m^2 heat flux boundary conditions. The error gets negligible over 250,000 meshes, so all CFD analysis adopts 250,000 meshes.

CFD RESULTS AND DISCUSSION

The heat transfer coefficient of helium gas is obtained from the average temperature of helium gas and the wall temperature as following:

$$h = \frac{q''}{T_w - T_m} \quad (1)$$

Figure 4 and 5 show that heat transfer coefficients increase as the operating pressure and inlet velocity increases. The increases in density due to the rise of operating pressure and in inlet velocity affect directly the Reynolds number of helium coolant, so it is found that variation of the operating pressure and inlet velocity have a significant influence on the heat transfer coefficient of helium coolant.

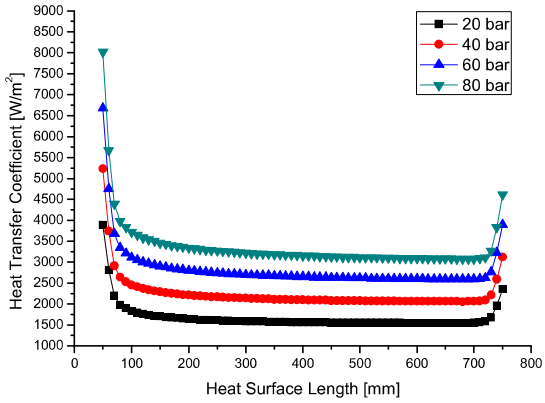

Figure 4 Heat transfer coefficient of helium gas with operating pressure variation (inlet velocity: 25 m/s, heat flux : 50 kW/m^2)

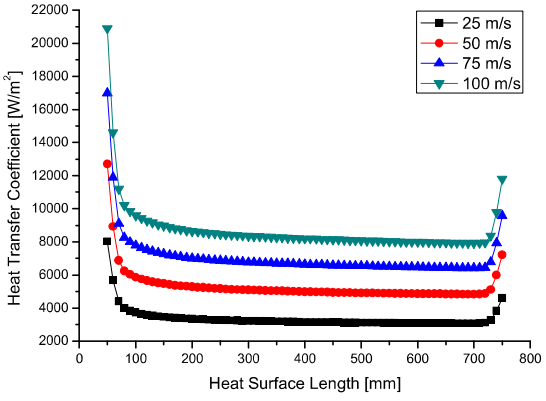

Figure 5 Heat transfer coefficient of helium gas with inlet velocity variation (operating pressure: 80 bar, heat flux: 50 kW/m^2)

Figure 6 shows the average heat transfer coefficient according to the inlet velocity and the operating pressure. The value of heat transfer coefficient in the inlet velocity of 50 m/s

is about one and half of that in 25 m/s. As a result, the heat transfer coefficient was proportional to the pressure.

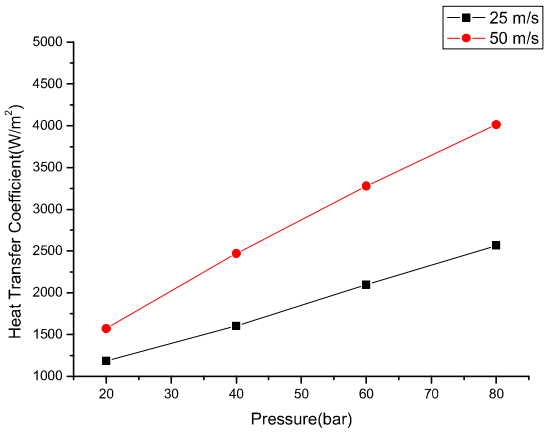

Figure 6 Heat transfer coefficient with pressure and inlet velocity

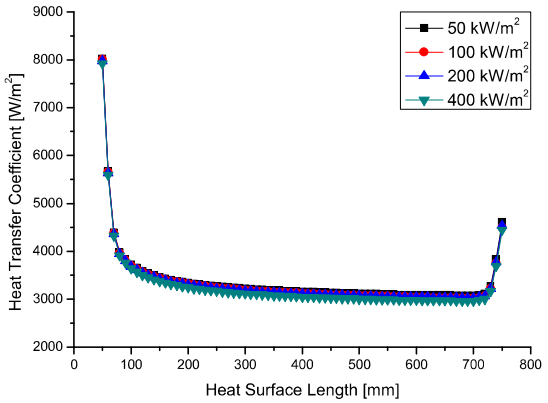

Figure 7 Heat transfer coefficient of helium gas with heat flux variation (operating pressure: 80 bar, inlet velocity: 25 m/s)

Figure 7 shows the variation of heat transfer coefficients with the heat flux variation. Calculation result shows that there is no relationship between heat transfer coefficient and heat flux. Actual heat flux of TBM condition is too high to realize in the experiment. This result implies that scale down of the heat flux could be done for experimental study.

COMPARISON WITH CFD ANALYSIS AND MODIFIED GNIELINSKI'S CORRELATION

Figure 8 and 9 show that the comparison with the CFD results and the modified Gnielinski's correlation results.

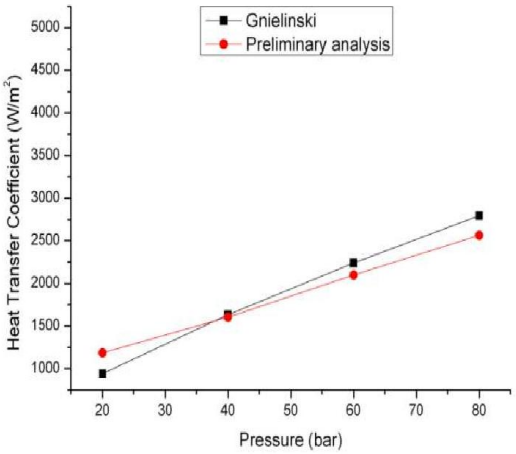

Figure 8 Comparison with the CFD results and the modified Gnielinski's correlation results (inlet velocity: 25 m/s, heat flux: 50 kW/m^2)

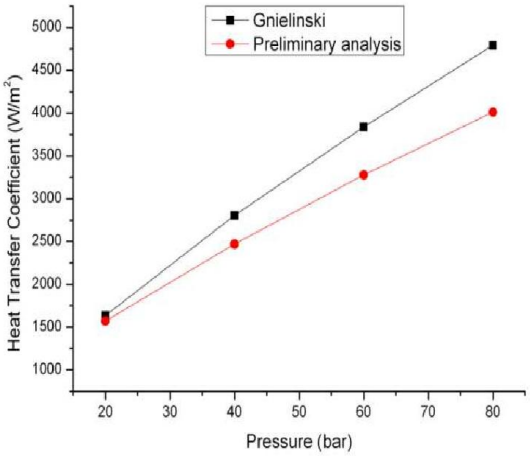

Figure 9 Comparison with the CFD results and the modified Gnielinski's correlation results (inlet velocity: 50 m/s, heat flux: 50 kW/m^2)

The modified Gnielinski's correlation estimates heat transfer coefficients well at low Reynolds number regime, but overestimates it at the high Reynolds number regime. The actual Reynolds number regime of the TBM condition is over 100,000 and this Reynolds number regime is corresponding to the 80 bar spot of Fig. 8 and Fig. 9, so this result emphasizes the necessity of new correlation.

CONCLUSION

CFD analysis was carried out to understand the heat transfer phenomena on the first wall of TBM. The analysis was conducted with varying operating pressures, the inlet velocities and the surface heat flux conditions. By the numerical calculation the heat transfer coefficients of helium gas are obtained. The heat transfer coefficients were enhanced by

increase of operating pressure and inlet velocity of helium gas, because the variations of these parameters are directly connected with the Reynolds number of helium coolant. The tendency of the heat transfer coefficient variation could be used for scaling the experimental parameter. It is confirmed that variation of surface heat flux does not dependent on the heat transfer coefficient, so scale down of surface heat flux is regarded as the reasonable choice. At last, the meaningful result was also obtained by the comparison with the results of the CFD analysis and the modified Gnielinski's correlation. Even though the modified Gnielinski's correlation is conventionally used for design the coolant channel of TBM structure, this correlation overestimates the heat transfer coefficient at the high Reynolds number regime. Therefore to validate the thermal safety of the TBM structure, new correlation should be developed to predict more accurate value of the heat transfer coefficient. All the results of this study will be applied to the design of experimental facility which simulates cooling capacity of the TBM.

ACKNOWLEDGMENT

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