Studies on MHD Pressure Drop and Heat Transfer of Helium-Lithium Annular-Mist Flow in A Transverse Magnetic Field*

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Pressure drop and heat transfer coefficient of helium-lithium annular-mist flow in a rectangular duct were investigated experimentally under a transverse magnetic field at system pressure of 0.2 MPa. A ratio of MHD pressure drop to that of non-magnetic field increases with magnetic flux density and a mass flow rate ratio of lithium to helium in low helium velocity region. However, as increasing the helium velocity, the increment of MHD pressure drop with the magnetic flux density is much reduced and then becomes almost zero. At this condition, the MHD pressure drop of the annular-mist flow becomes much smaller than that of lithium single phase flow with the same lithium mass flow at the high magnetic flux density. Heat transfer coefficient ratio of the helium-lithium annular-mist flow to helium single phase in the non-magnetic field is well correlated by a ratio of the mass flow rate of lithium to helium. The heat transfer coefficient in the magnetic field increases with the magnetic flux density and then terminates at a certain value depending on the mass flow rate ratio and the helium velocity. These characteristics of the MHD pressure drop and the heat transfer in the magnetic field suggest that the helium-lithium annular-mist flow is effectively applicable to cooling of the high heat flux wall in a strong magnetic field like a first wall of a magnetic confinement fusion reactors.

Key Words: Magnetohydrodynamic(MHD) flow, Two-phase liquid metal flow
Helium-lithium annular-mist flow, MHD pressure drop, Magnetic field,
Fusion blanket cooling

1. Introduction

In a magnetic confinement fusion reactor, the first wall and the blanket surrounding the fusion plasma will be exposed to severe conditions of strong magnetic field, high neutron flux and high heat flow. Several methods using high pressure helium gas, pressurized water or liquid lithium have been proposed for cooling of such severe parts in the fusion reactor.

However, it has been pointed out that these cooling methods have several definite disadvantages, respectively.

For the gas cooling, temperature of the structure becomes too much high at high heat flux surfaces of the first wall and the divertor because of low heat

capacity and low heat transfer coefficient of the helium flow.

For the water cooling, a tritium breeding ratio decreases by several percents for every millimeter thickness of water channel.

A possibility of the vapor explosion due to violent vaporization when water is injected into the high temperature solid blanket material being kept at high temperature between 400~800°C at break of the coolant channel may be severe for the fusion blanket safety.

For the liquid lithium cooling, large magnetohydrodynamic (MHD) pressure drop under the strong magnetic field is the most severe problem from the view point of engineering feasibility.

For TOKAMAK fusion reactor conditions of the magnetic flux density, $B_T=10$ Tesla, the electric conductivity of lithium, $\sigma_{Li}=10$ mho/m and the wall conductance ratio $C=0.05$, the MHD pressure drop is predicted to be more than 5 MPa/m at lithium velocity of $U_{Li}=1$ m/s. Therefore, the flow velocity of the liquid lithium has to be limited normally less than 0.1

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m/s in such strong magnetic field. The heat transfer coefficient at such low velocity becomes rather low too.

Newly proposed cooling method here using a helium-lithium annular-mist flow has a possibility of large reduction of the MHD pressure drop and rather high heat transfer coefficient due to much reduced electric conductivity of the two-phase mixture and then high attainable velocity.

Several works for a gas-liquid metal two-phase MHD flow have been reported mainly as fundamental studies for liquid metal MHD power generators⁽¹⁾⁽²⁾.

Saito⁽³⁾ investigated the slip ratio and the MHD pressure drop of NaK-N₂ two-phase flow in a vertical duct and got that the slip ratio was little influenced by the magnetic field and that the MHD pressure drop of the two-phase flow became a little higher than that of single phase liquid flow.

Dobran⁽⁴⁾ proposed a generalized method to analyze two-phase MHD flow and got the good correlations for Saito's data.

Michiyoshi et al. investigated experimentally the effects of a transverse magnetic field on the void profile⁽⁵⁾ of cross section and the heat transfer characteristics⁽⁶⁾ in the mercury-nitrogen two-phase flow. They made clear that the void fraction profile in the plane normal to the magnetic flux shifted to one side with increase in the magnetic flux density but did not shifted in the parallel direction and the Nusselt number decreased with increase in the magnetic flux density.

Owen⁽⁷⁾ and Dunn⁽⁸⁾ investigated theoretically the two-phase MHD pressure drop for both the homogeneous and the annular flow models and showed that these models did not result in any big difference for MHD pressure drop between them. However, in all above studies, the two-phase flows were limited to the bubble flow regime or low quality region.

For the liquid metal MHD power generators, only the bubble flow with high electric conductivity is worthwhile to be used.

However, for an application to a fusion reactor, how reduced electric conductivity of lithium can be attainable is important to reduce the MHD pressure drop.

In the present study, the MHD pressure drop and the heat transfer characteristics are investigated experimentally in the helium-lithium annular-mist flow under a transverse magnetic field.

2. Experimental Systems

As shown in Fig. 1, the helium-lithium two-phase flow loop is composed of two flow lines of helium and lithium, respectively.

Helium is circulated by two roots blowers connected in series to get large circulation pressure. The line is composed of a flow meter, an expansion tank served as an economizer in which heat is transferred from the lithium flow to the helium one and a preheater with max. 16 kW.

On the other hand, the lithium is initially charged up from a dump tank to the expansion tank at every experiment series and then circulated by an electro-magnetic pump.

An electromagnetic flow meter and a lithium preheater are installed in the lithium line. Two fluids are smoothly introduced to a test section through an entrance nozzle in which they are joined at angle of 5 degree. At the outlet of the test section three cyclone separators and a mesh one are settled in series to separate fully lithium droplets from helium gas.

Helium gas is cooled down to normal temperature by an air cooler, passed through the mesh filter to eliminate the lithium particles completely and returned to the blower again.

A zirconium getter, a molecular sieve and a cold trap are connected to both fluid lines to eliminate oxygen, nitrogen and other impurities.

The lithium line except for the test section is constructed inside a steel container for the safety point of view.

The test section, in which the helium-lithium annular-mist flow is formed, is also installed in the guard vessel as shown in Fig. 2. In the guard vessel, argon gas is charged to mitigate a lithium fire when the liquid lithium happens to leak from the section. Two kinds of 1 620 mm long rectangular ducts with different cross sections of 20 mm high $\times$ 50 mm wide (duct 1) and 10 mm high $\times$ 40 mm wide (duct 2), respectively, are used for the test ducts. As shown in the figure, six pressure taps in every 200 mm distance are mounted to measure the MHD pressure drop along

Fig. 1 Helium-lithium two-phase flow loop

Fig. 2 Test section and pressure measurement system

Fig. 3 Cross section of test duct 2 with heater blocks

the duct.

There is no high precision pressure transducer to be workable in the high temperature lithium. Therefore, the following measurement method is used. Helium stream less than 1 cc/sec is introduced from the outlet of the blower to the each pressure tap of the test duct and then the back pressure of the stream were measured by the high precision differential pressure transducer (accuracy: ± 1 Pa).

By this method, highly accurate and reproducible data of the pressure drop can be obtained in the annular-mist flow regime.

As shown in Fig. 3 the test duct is heated uniform-

Table 1 Experimental condition

Pressure at the test section	0.2 MPa
Flow rate Helium	7.70, 13.9, 20.8, 27.8 kg/m ² s
Lithium	20.0 ~ 280 kg/m ² s
Helium velocity at 0.2 MPa	44.0, 88.7, 132.7, 177.5 m/s
Inlet temperature	
Helium	350 °C
Lithium	350 °C
Magnetic flux density	0 ~ 1.4 T
Wall conductance ratio	0.07, 0.08
Hartman number (Lithium flow)	0 ~ 3300

ly at one side (downward) wall over 1 000 mm distance of the center region to simulate the first wall coolant channel situation of the fusion reactor.

To get uniform heat flux over whole heating area, seven sheath heaters are mounted parallel in the stainless duct block and two thermocouples settled in a distance of 12.5 mm are employed to get the heat flux and the temperature at the heated wall.

A transverse magnetic field up to 1.5 Tesla with a pole piece of 300 mm width and 960 mm length is imposed from outside of the guard vessel in the horizontal direction.

The experimental conditions are shown in Table 1.

3. Experimental Results

3.1 Pressure drop

1) Pressure drop of the annular-mist flow under non-magnetic field.

Figure 4 shows relation between the pressure drop ratio, $\phi_g^2 = \Delta P_{TPF} / \Delta P_{HE}$, of two-phase flow to that

of single phase helium flow at the same gas flow rate and the mass flow rate ratio of lithium to helium, G_{Li}/G_{He} .

In contrast to the Chisholm's correlation expressed by unique function of the mass flow rate ratio based on the experiment of air-water or steam-water flow, ϕ_g^2 is correlated by both the mass flow rate ratio and the helium Reynolds number.

The following correlation is obtained.

$$\phi_g^2 = 1 + 1.5 \times 10^{-5} Re_{He} [(1-X)/X]^{1.32} \quad (1)$$

where, Re_{He} is Reynolds number of the helium flow defined by the superficial helium velocity, U_{He} , hydrodynamic equivalent diameter of the channel and X is quality of helium.

Fig. 4 Relatio between pressure drop ratio ϕ_g^2 and mas flow rate ratio, G_{Li}/G_{He}

2) MHD pressure drop in a magnetic field

Figures 5(a), (b) and (c) show ratios, R_B , of total MHD pressure drop over the magnetic field to that under non-magnetic field in the duct 1 at the same flow condition. The ratio R_B is influenced by the magnetic flux density, B , the mass flow rate ratio of lithium to helium, G_{Li}/G_{He} , and the superficial helium velocity, U_{He} .

MHD pressure drop in the lithium single phase flow generally increases with a square of $B^{(9)}$.

At the low helium velocity of Fig. 5(a), R_B increases with $B^{2.0}$ in the same tendency as the lithium single phase flow and also with the mass flow rate ratio, G_{Li}/G_{He} . However, when the helium velocity increases, the effect of the mass flow rate ratio on R_B terminates in the region above a certain value of the flow rate ratio, that is, $G_{Li}/G_{He} > 6.0$ in Fig. 5(b) and 4.5 in Fig. 5(c) and R_B increases in proportion to $B^{0.5} - B^{1.0}$ instead of $B^{2.0}$ at the low helium velocity. These tendencies to mitigate the effect of the magnetic flux density on the MHD pressure drop become more remarkable for the experimental results measured in the conditions of higher helium flow velocity using the duct 2 with smaller cross section as shown in Figs. 6(a), (b) and (c).

At the low helium flow velocity of Fig. 6(a), R_B shows the same tendency with Fig. 5(c). As the velocity increases as shown in Fig. 6(b), the increment of R_B with B is much reduced and terminates at about 0.5 Tesla. At the highest helium velocity of Fig. 6(c), R_B has a small peak value of 1.2 at 0.4 Tesla for

Fig. 5 Ratio of total MHD pressure drop to that under non-magnetic field in low and middle helium flow velocity (duct 1)

every mass flow ratio and then decreases less than unity in the higher magnetic flux region.

To know the trend of the MHD pressure drop in more detail, the local pressure drop were investigated along the channel. Fig. 7 indicates local value of R_B in

the duct 2 obtained from the pressure drop in the distance of 400 mm length at the inlet, the center and the exit parts of the magnetic field, respectively. Therefore, both the inlet and the exit parts include the end effect of the magnetic field.

Duct 2

Fig. 6 Ratio of total MHD pressure drop to that under non-magnetic field in middle and high helium flow velocity (duct 2)

Fig. 7 Local MHD pressure drop ratio in the regions of inlet, center and exit of magnetic field

The upper row in Fig. 7 is the local MHD pressure drops at the low helium velocity of $U_{He}=44.5$ m/s and the lower one is at the high velocity of $U_{He}=177$ m/s. The MHD pressure drop is the largest at the inlet region and gradually decreases along flow direction.

At the low helium velocity, the R_B is larger at lower quality, that is, higher lithium flow rate ratio in the local section.

At the high helium velocity, the same trend of R_B is obtained in the inlet region but in the center and the exit sections, R_B has small peak at about 0.4 Tesla and decreases less than unity in the higher magnetic flux region. The R_{Bs} are smaller at lower quality in these conditions on the contrary.

MHD pressure drop of the annular-mist flow was compared with that of the lithium single phase flow which was calculated by Carlson's correlation⁽⁹⁾ derived for the rectangular duct with conducting wall.

As shown in Fig. 8, a ratio, ϕ_{LiB}^2 , of MHD pressure drop of two-phase flow to that of the single phase lithium flow with the same lithium mass flow rate decreases with the increase of the magnetic flux density in almost proportion to B^{-2} at the high helium velocity of $U_{He}=177.0$ m/s. The ϕ_{LiB}^2 becomes less than unity at 0.5 Tesla and less than 0.1 in the region more than 1.0 Tesla.

If it is confirmed that these relations are applicable to the fusion magnetic condition of about 10 Tesla, the MHD pressure drop of the annular-mist flow would be almost 0.1 percent of that of the lithium single phase flow.

Fig. 8 Ratio of MHD pressure drop of helium-lithium annular mist flow to that of lithium single phase flow at the same lithium mass flow rate

3.2 Heat transfer characteristics

1) Heat transfer under non-magnetic field

A ratio, h_{TPF}/h_{He} , of heat transfer coefficient of the helium-lithium annular-mist flow to the helium single phase flow at the same helium flow rate is shown in Fig. 9. All data of the ratio at the location of $L/D_h=40.6$ are expressed by a simple function of the mass flow rate ratio, $G_{Li}/G_{He}=(1-X)/X$.

When the mass flow rate ratio is 10, the heat transfer coefficient becomes about 13.5 times larger than that of the helium single phase flow. This means that if total mass flow rate is equal, the heat transfer coefficient of the annular-mist flow is larger than that of the helium single phase flow.

As the density ratio of lithium to helium is about 3000 at 0.2 MPa, the volumetric flow rate ratio of lithium to helium is about 1/300. Large improvement of heat transfer coefficient compared with the helium flow is caused by 1) enhancement due to lithium film flow with high heat capacity and conductivity near the wall region, 2) heat transport by entrainment and deposition of the droplets, and 3) enhancement of turbulent mixing due to the interfacial wave.

Although high heat transfer rate can be attainable by the two-phase annular-mist flow, the shortcoming of the flow is that the local ratio of the heat transfer coefficient gradually decreases along the channel as shown in Fig. 10.

Finally the local value of the heat transfer ratio, $h_{TPF}(x)/h_{He}(x)$, is correlated as follows.

$$\frac{h_{TPF}}{h_{He}} = 4.4 \left[1 + 1.85 \left(\frac{1-X}{X} \right)^{0.85} \right] \left(\frac{L}{D_h} \right)^{-0.4} \quad (2)$$

where, L is the distance from the entrance of the magnetic field and D_h is the thermal equivalent diameter.

Deterioration of the local heat transfer coefficient along the channel compared with that of single phase flow is explained by decrement of deposition rate of

Fig. 9 Heat transfer coefficient ratio of helium-lithium two-phase flow to helium single phase flow

the droplets to the liquid film.

To improve this point and to enhance the heat transfer coefficient, it may be proposed to use the evaporation heat transfer by mixing of volatile composition like potassium or cesium.

2) Heat transfer coefficient under the magnetic field

A ratio of heat transfer coefficient under the magnetic field to that of the non-magnetic field at the location of $L/D_h=40$ is shown in Figs. 11(a), (b) and (c).

The ratio, $(h_{TPF})_B / (h_{TPF})_{B=0}$, increases steeply with B up to about 0.8 Tesla at $U_{He}=44.5$ m/s and about 0.5 Tesla at $U_{He}=88.6$ m/s and then terminates at a certain value depending on the quality.

The increasing rate with B depends on the helium flow velocity and the quality. The increment of the

Fig. 10 Local heat transfer coefficient ratio

ratio with B becomes smaller with increase in the helium velocity and larger with increasing the quality except for the highest quality in which continuous liquid film may not be formed.

4. Considerations

The most interesting points of the helium-lithium annular-mist flow are that the MHD pressure drop is much reduced under the strong magnetic field compared with the lithium single phase flow at the same lithium mass flow rate and that the enhancement of the heat transfer coefficient is urged by the transverse magnetic field.

The reduction of the MHD pressure drop becomes larger as the helium flow velocity increases. Lorentz force due to the magnetic field works on the lithium film of the annular-mist flow and gives it the following effects; 1) increment of the liquid film thickness, 2) suppression of the interfacial wave and then reduced entrainment rate from the lithium film, and 3) suppression of the turbulent motion in the lithium film flow.

On the other hand, the increment of the liquid thickness causes the increase of the helium gas velocity flowing in the core region and then the shear stress at the interface. This stimulates the interfacial wave, the entrainment generation rate and consequently the turbulent motion in the liquid film.

The increment of the liquid film thickness becomes maximum at the inlet section of the magnetic field.

According to Steen & Wallis's correlation⁽¹⁰⁾, a criterion of the entrainment generation in the annular flow is estimated as follows.

Fig. 11 Effect of magnetic field on heat transfer coefficient of helium-lithium annular-mist flow

Fig. 12 Surmised flow patterns of helium-lithium annular mist flow under transversal magnetic field

$$U_{He} > 2.46 \times 10^{-6} \left(\frac{\tau_{Li}}{\mu_{He}} \right) \left(\frac{\rho_{Li}}{\rho_{He}} \right)^{0.5} = 137.0 \text{ m/s} \quad (3)$$

(at 350°C)

where, τ_{Li} is surface tension coefficient of lithium, and μ and ρ are viscosity and density, respectively.

Considering the suppression of the interfacial wave by the Lorentz force, the value may be shifted to larger value for the lithium film flow under the magnetic field.

Figures 12(a) and (b) express the presumed flow patterns under the magnetic field in both low and high helium velocities.

In the low helium velocity of $U_{He} = 44 \text{ m/s}$, the shear stress at the interface is not enough large to generate entrainment even if both the liquid film thickness and then the helium velocity increase. The increments of both the liquid film flow rate due to reduction of the entrainment rate and the film thickness by the Lorentz force result in the increment of the MHD pressure drop and the heat transfer in this case.

However, at the high helium velocity of $U_{He} = 177 \text{ m/s}$, when the liquid film increases at the inlet region of the magnetic field, the generation rate of the entrainment increases there and then the liquid film flow rate in the magnetic field region decreases consequently. This effect makes the increment of the MHD pressure drop mitigate. The mild increment of the heat transfer coefficient may be caused by the increment of the deposition rate and the disturbance induced by deposition of the cold droplets in the core region.

5. Conclusions

For the helium-lithium annular-mist flow in the rectangular ducts, the MHD pressure drop and the

heat transfer coefficient were measured under the transverse magnetic field and obtained the following results.

(1) The pressure drop ratio of the helium-lithium annular-mist flow to the helium single phase flow is correlated as Eq.(1) under the non-magnetic field.

(2) A ratio of the MHD pressure drop to that in non-magnetic field increases with a square of the magnetic flux density and with the flow rate ratio of lithium to helium at the low helium flow rate.

(3) As the helium flow rate increases, the increment rate of R_B with B is reduced and at the high helium flow rate, the MHD pressure drop shows a small peak at 0.4-0.5 Tesla and then decreases with the increasing magnetic field less than the value of the non-magnetic field.

(4) Local MHD pressure drop is the largest at the inlet region and then reduces along the flow direction.

(5) The MHD pressure drop in the annular-mist flow becomes less than 10% of that of the lithium single phase flow at the same lithium flow rate when B is more than 1.0 Tesla.

(6) A ratio of the heat transfer coefficient of the annular-mist flow to that of single phase flow is correlated in the non-magnetic field as Eq.(2).

(7) The heat transfer coefficient ratio under the magnetic field increases with B in the region of $B < 0.5$ but terminates in the higher region at a certain value depending on the helium flow rate and the quality.

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