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SEED RECOVERY FOR INERT GAS MHD POWER GENERATION

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ABSTRACT

The condensation of low concentration potassium vapor (10-100 ppm) in helium flow onto the boiler tubes is investigated to clarify whether we can expect a boiler to work as a seed recovery device for inert gas MHD. A cold model experiment has demonstrated that low concentration ethylene glycol vapor (about 100 ppm) contained in a helium flow can effectively condense onto water-cooled copper tubes, and this condensation is well explained by a mass transfer analysis based on the heat transfer analogy. This same analysis predicts that the potassium vapor can condense onto the boiler tubes so well that there is no need for an extra seed recovery device in an inert gas MHD power generation system.

NOMENCLATURE

C_p	specific heat
g	gravitational acceleration
h	heat transfer coefficient
h_m	mass transfer coefficient
J	homogeneous nucleation rate
Le	Lewis number
Nu	Nusselt number
n	particle number distribution
P	pressure
Pr	Prandtl number
Re	Reynolds number
r	particle radius
$\dot{r}$	rate of particle growth
S	supersaturation ratio
T	temperature
t	time
u	velocity
W	mass flux
y	axial distance normal to the wall surface

<u>Greek Characters</u>

$\delta(r)$	Dirac delta function
δ_l	film thickness
μ	viscosity
ρ	density

<u>Subscripts</u>

g	gas
im	impingement
l	liquid
p	particle
s	saturated
th	thermophoresis
v	vapor
w	wall

INTRODUCTION

Recent experiments of our blow-down facility FUJI-1 have demonstrated a high enthalpy extraction in the disk MHD generator by employing argon seeded with cesium as a working gas.[1] We are planning to conduct continuous power generation experiments by newly installing a closed loop facility, FUJI-2, whose main objective is the engineering demonstration of inert gas MHD power generation.

From the engineering point of view, many components for inert gas MHD need further developments, but our feasibility study has shown that all of them except for the seed recovery device are technically feasible for the case of clean fuels. In the case of inert gas MHD, seed recovery is basically unnecessary because the working gas containing the seed material circulates in a closed loop. But from the technical point of view, it is desirable to remove the seed material between the MHD generator and the inert gas compressor, because the seed material may condense in the inert gas compressor and may also chemically attack the high temperature inert gas heaters.

At the exit of the MHD generator, the temperature of the working gas (helium or argon) is still sufficiently high (well above 1000K) so that the seed material (metallic potassium or cesium) contained therein is considered to be in the vapor phase. This seed vapor may condense in the boiler located downstream of the MHD generator where the working gas is cooled almost to room temperature. If there is sufficient condensation, we can expect that the boiler will work as a seed recovery device as well as a heat exchanger.

In this study, the performance of the boiler located downstream of the MHD generator as a seed recovery device is predicted by considering a simple mass transfer mechanism. Our predictions are then verified by a cold model experiment using ethylene glycol as a simulated seed material.

CALCULATIONS

Within the range of the working gas temperature expected at the inlet of the boiler, the seed material is considered to exist in the vapor phase. Therefore, two mechanisms are considered to predict the seed condensation onto the boiler tubes. One mechanism is that the seed vapor condenses directly onto the boiler tubes with cooling of the working gas, and the other mechanism is that the seed vapor nucleates first within the working gas, and then the nucleated seed droplets deposit on the boiler tubes. In this study, the first type of condensation is evaluated by a mass transfer mechanism based on the heat transfer analogy, while the second type is evaluated by assuming that the vapor phase seed turns to the liquid phase droplets by homogeneous nucleation and that they deposit on the boiler tubes by way of thermophoresis and inertial impingement.

Seed Vapor Condensation

In the case of inert gas MHD, the seed fraction is so small compared with unity that the transport of seed vapor onto the boiler tubes can be evaluated quantitatively by the following equation based on the heat transfer analogy.

$$W_v = h_m(\rho_v - \rho_{vw}) \tag{1}$$

If we assume here that the Lewis number Le=1, then the mass transfer coefficient h_m is related to the heat transfer coefficient h by the following equation.

$$h_m = \frac{h}{\rho C_p} \tag{2}$$

Then given the following expression for h,[2] we can obtain an equation for h_m.

$$N_u = 0.35 R_e^{0.6} P_r^{0.36} \tag{3}$$

In this case of very small seed fraction, the physical properties of the mixed gas (the working gas + seed vapor) are well approximated by those for the pure working gas.

Nucleation of the Seed Vapor

The homogeneous nucleation of the seed vapor in the course of cooling the working gas and the size distribution of the seed droplets formed by this nucleation are described by the so-called Spray-Equation.[3]

$$\frac{\partial n(r,t)}{\partial t} + \frac{\partial}{\partial r}[\dot{r} n(r,t)] = J(r,t) \cdot \delta(r) \tag{4}$$

This equation describes the change with time of the particle size distribution caused by the growth and shrinkage of droplets as well as by their nucleation. Here, the splitting or the agglomeration of droplets are not taken into account. The nucleation and growth of droplets are driven by the supersaturation ratio S of the vapor phase seed and they can be expressed as a function of this variable.

Deposition of the Seed Droplets

The deposition of the seed droplets formed by the nucleation on the boiler tubes is evaluated by considering the following two transport mechanisms: inertial impingement and thermophoresis. The mass flux of the seed droplets W_p which deposits on the boiler tubes is given as the sum of the mass flux due to inertial impingement W_{im} and that due to thermophoresis W_{th}. Here, W_{im} and W_{th} are calculated from the formulae described in Ref.(4). Inertial impingement of the seed droplets onto the boiler tubes depends on the flow field and the droplet size, and is expressed by the Stokes number. On the other hand, the transportation of the seed droplets to the boiler tubes by the thermophoresis is caused by collisional momentum exchange between the seed droplets and the atoms of the working gas, and is mainly expressed by the Knudsen number and the temperature field.

Determination of the Seed Film Thickness on the Boiler Tubes

The liquid phase seed material condensed on the boiler tubes is assumed to form thin films with uniform thickness, and the value of which is determined by the balance of the downward film flow due to gravity and the rate of condensation W.

$$\frac{d}{dx}\int_0^{\delta_l(j)} \rho_l u_l dy = W \tag{5}$$

where, W is the sum of W_v and W_p, and the velocity distribution u_l within the liquid seed film can be obtained by integrating the following momentum equation.

$$\frac{\partial}{\partial y}\left(\mu_l \frac{\partial u_l}{\partial y}\right) = -\rho_l g \tag{6}$$

The boundary conditions for this equation are as follows:

$$\begin{aligned} y = \delta_l &: \ \mu_l \frac{\partial u_l}{\partial y} = 0 \\ y = 0 &: \ u_l = 0 \end{aligned} \tag{7}$$

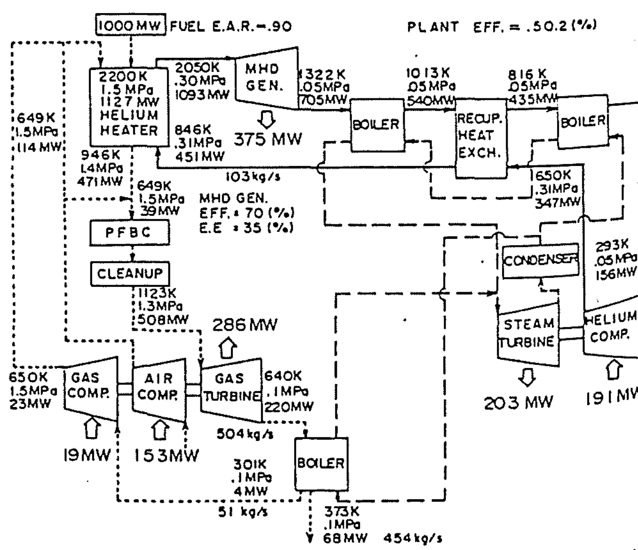

Fig.1 System of a direct coal fired inert gas MHD triple combined cycle (thermal input to the plant is 1000MW)

PREDICTION OF THE SEED CONDENSATION IN THE BOILER

Conditions Assumed in the Calculation

In this prediction, a direct coal fired inert gas MHD triple combined cycle[5] (thermal input to the plant is 1000 MW) is employed, whose schematic system is shown in Fig.1. In this system, the working gas and the seed material are assumed to be helium and potassium respectively, and two boilers are located downstream of the MHD generator. The helium temperature throughout the high temperature boiler and at the inlet of the low temperature boiler is above the saturation temperature of potassium. Thus the potassium contained in the helium flow coming from the MHD generator is in the vapor phase at the inlet of the low temperature boiler, and the condensation of this potassium vapor in the low temperature boiler is evaluated below.

The physical dimensions of the boiler and the assumed conditions are summarized in Table 1. As the molecular impurities (such as H_2O and CO_2) in the helium, originating from the combustion gas residue in the high temperature helium heater, are predicted to be removed rapidly by chemical reaction with the seed material[6], it is assumed that the helium flow contains only vapor phase potassium at the inlet of the boiler. Temperature distributions of the helium gas and the boiler tubes are provided by the curves shown in Fig.2, which is obtained by a simple heat transfer calculation. One-dimensional steady state condensation calculations are performed for two seed fractions (10^{-4} and 10^{-5}).

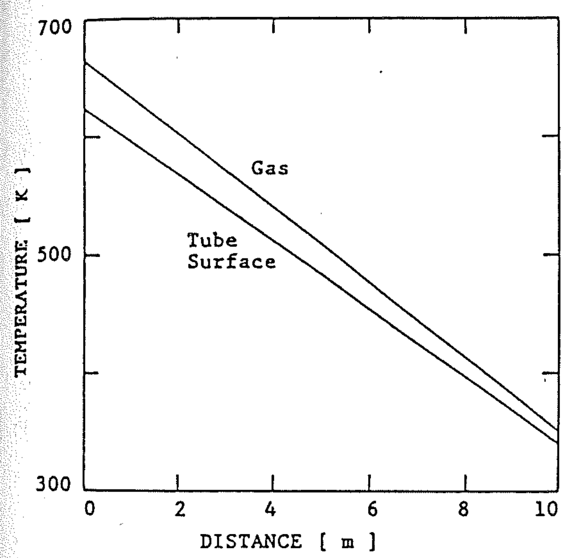

Fig. 2 Temperature distributions of helium gas and boiler tubes in the boiler

Table 1 Physical dimensions of the boiler and assumed conditions in the calculation

Cross section of the boiler	15 × 15 m²
Diameter of a boiler tube	31.75 mm
Longitudinal pitch of the tube array	63.50 mm
Lateral pitch of the tube array	63.50 mm
Arrangement of the tube array	Staggered
Helium mass flow rate	100 kg/s
Helium pressure	0.05 Mpa
Helium temperature	665 - 350 K
Boiler tube wall temperature	625 - 340 K
Seed fraction	1×10^{-4}, 1×10^{-5}

Results and Discussions

Figure 3 shows how the partial pressure of the vapor phase potassium in helium and the saturated pressure of potassium at the boiler tube wall temperature change along the flow direction in the boiler for the two values of seed fraction. The saturated pressure is above the partial pressure until about 4m and 6m from the entrance of the boiler in the cases of high seed fraction (10^{-4}) and low seed fraction (10^{-5}) respectively, where neither the condensation nor the nucleation of the potassium

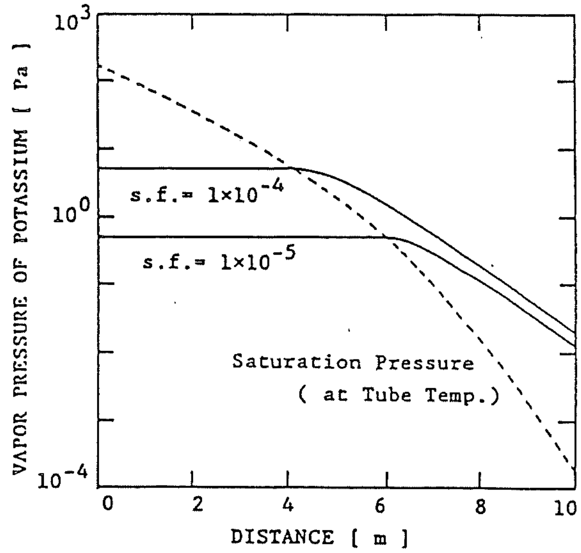

Fig.3 Changes of the saturated pressure at the boiler tube wall temperature and the partial pressure of potassium vapor along the flow direction in the boiler

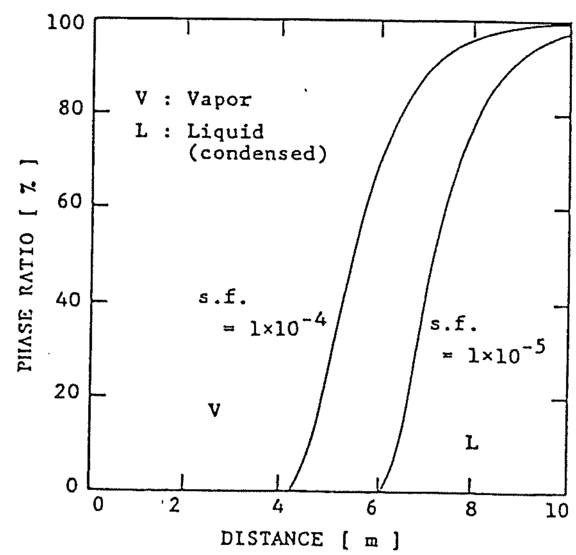

Fig.4 Phase change of potassium vapor along the flow direction in the boiler

vapor occurs. Thus the vapor pressure is held constant. However, as soon as the cooling of the helium flow causes the saturated pressure to become less than the partial pressure, the partial pressure begins to decrease rapidly. This decrease is mainly caused by the direct condensation of potassium vapor onto the boiler tubes but not by nucleation, as the supersaturation ratio of the potassium vapor is not large when compared with unity.

Figure 4 shows how the vapor phase potassium changes to liquid phase along the flow direction in the boiler. The regions of vapor phase and condensed liquid phase potassium are denoted by V and L respectively. The diameter of potassium droplets formed by nucleation is extremely small, about 10^{-3} μm, and their total mass fraction is in the range of 10^{-30}-10^{-40}%, which is too low to be seen in this figure. This figure shows that almost all of the potassium vapor condenses directly onto the boiler tubes and the potassium content in the helium flow exiting the boiler is very small. Thus we can expect the boiler to act perfectly as a seed recovery device, and we will not require any further seed recovery devices for inert gas MHD.

Figure 5 shows the variation of film thickness of the liquid potassium condensed on the boiler tubes. It can be seen from this figure that film thickness grows steeply at the start of the condensation of the potassium vapor. However, the thickness is less than 20 μm for the case of the high seed fraction and less than 2 μm for the case of the low seed fraction. In this case of such a small seed fraction, the condensation may occur as dropwise or as the combination of dropwise and filmwise condensations rather than simple filmwise condensation. Thus further investigation on this problem is required to establish an efficient way of recovering the condensed liquid potassium from the boiler.

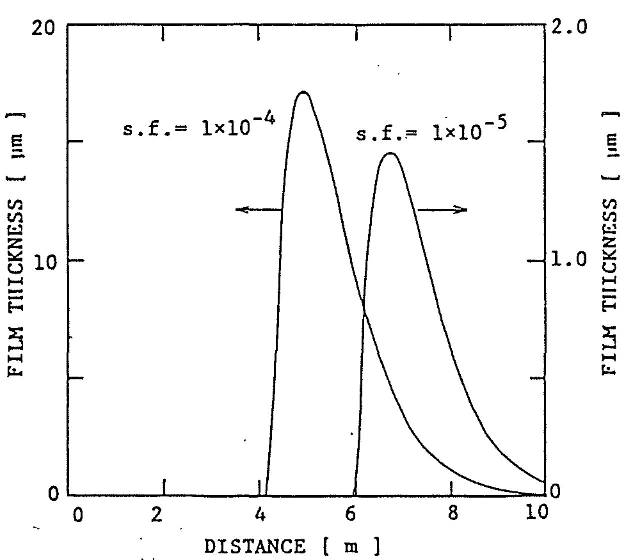

Fig.5 Change of the film thickness of the condensed potassium on the boiler tubes along the flow direction in the boiler

COLD MODEL EXPERIMENT FOR SEED RECOVERY

In the case of inert gas MHD, the seed fraction is so small (10^{-5}-10^{-4}) that the vapor pressure of the seed is very low (0.5-5 Pa). Therefore, the above prediction needs to be experimentally verified because there are few experimental works on the condensation of vapor in such a low vapor pressure region. Thus we have carried out an cold model experiment, where ethylene glycol is used as a simulated seed material. We used ethylene glycol because its saturated vapor pressure at room temperature lies within the above low pressure region.

Experimental Equipment and Procedure

The schematic system of the equipment used in the experiment is shown in Fig.6. Ethylene glycol is injected into the helium flow by bubbling with heating, and then droplets of ethylene glycol are removed from the helium flow in a packed bed mist separator, where the helium flow is cooled to room temperature at the same time. In this way, a room temperature helium flow containing the saturated ethylene glycol vapor is generated. This helium flow is introduced to the test channel and samples of

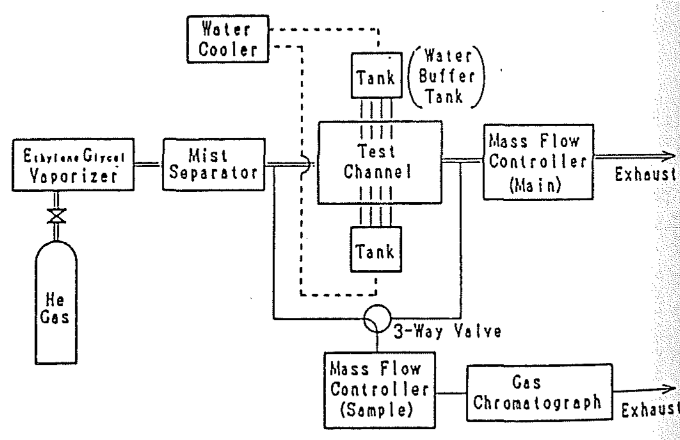

Fig.6 System of the equipment for the cold model experiment

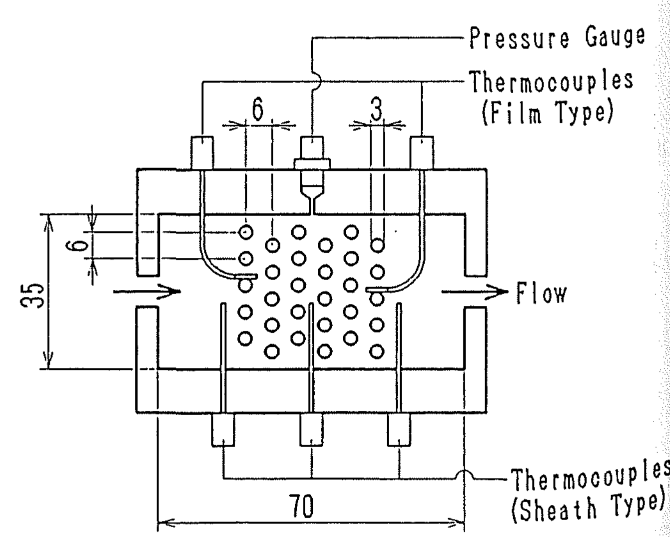

Fig.7 Test channel used in the cold model experiment

helium are taken at the inlet and outlet of the test channel. The concentration of ethylene glycol vapor contained in these samples are measured by a gas chromatograph apparatus.

Figure 7 shows the test channel used in the experiments, in which a 5x6 array of water-cooled copper tubes are installed for simulating the boiler tubes. These copper tubes can be set at fixed temperature by controlling the temperature of the cooling water.

The experimental conditions and the physical dimensions of the test channel are shown in Table 2. The maximum helium velocity in the test channel is about 0.2m/sec, which is one order smaller than the value expected in the actual boiler. During the experiments, the concentration of ethylene glycol at the exit of the test channel is measured while changing the helium velocity and the copper tube wall temperature but keeping the mole fraction of ethylene glycol at the inlet of the test channel constant. The mass flow rate of the sampled helium is kept so low (up to about 5% of the main helium flow) that there should be no significant effect on the main flow conditions caused by sampling.

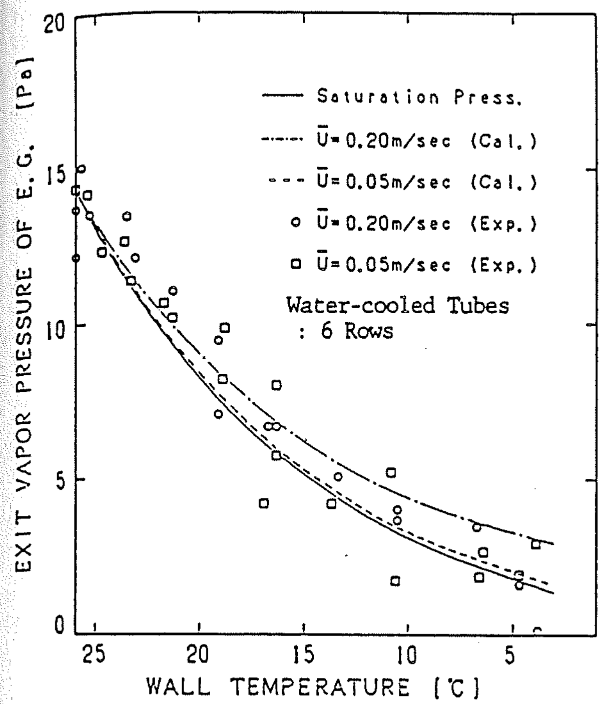

Fig.8 Vapor pressure of ethylene glycol at the exit of the test channel as functions of the copper tube wall temperature and the velocity of helium flow in the test channel (6 rows of copper tubes along the flow direction are water -cooled)

Table 2 Physical dimensions of the test channel and conditions for the cold model experiment

Cross section of the test channel	35 × 35 mm²
Diameter of a copper tube	3.0 mm
Longitudinal pitch of the tube array	6.0 mm
Lateral pitch of the tube array	6.0 mm
Arrangement of the tube array	Staggered
Average helium velocity	0.05 m/s, 0.20 m/s
Helium pressure	0.135 Mpa
Wall temperature of water-cooled copper tubes	5 - 25 °C
Helium temperature at the inlet of the test channel	26 - 27 °C
Mole fraction of ethylene glycol at the inlet of the test channel	about 1.1× 10⁻⁴

Experimental Results and Discussions

The experiments are carried out with all the 6 rows of the copper tubes along the flow direction cooled and with only 4 rows of the copper tubes cooled. The results for these two cases are shown in Figs.8 and 9, respectively. Both figures show the change of the vapor pressure of ethylene glycol at the exit of the test channel as functions of the copper tube wall temperature and the helium flow velocity in the test channel. In these figures, the experimental results are compared with the results of the calculations described above. Here, the saturated vapor pressure is expressed by the following equation[7], and is shown in both figures by a solid line.

$$\log P_s = 8.2621 - \frac{2197.0}{t + 212.0} \qquad P_s\,[\,\mathrm{mm\,Hg}\,],\ t\,[\,^\circ\mathrm{C}\,] \quad (8)$$

In both figures, the measured exit vapor pressure of ethylene glycol decreases as the copper tube wall temperature and the helium flow velocity

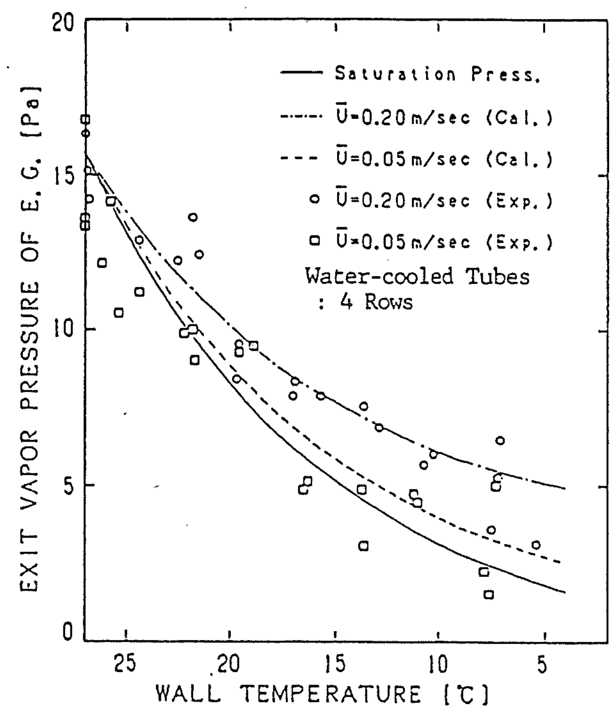

Fig.9 Vapor pressure of ethylene glycol at the exit of the test channel as functions of the copper tube wall temperature and the velocity of helium flow in the test channel (4 rows of copper tubes along the flow direction are water -cooled)

decrease and as the number of water-cooled coppe tubes increases, and these data are well explained by the calculation. In Fig.8, the measured data and their corresponding calculated curves are quite near to the saturated vapor pressure curve irrespective of the helium flow velocity, which means that condensation occurs in the test channel almost to the theoretical maximum limit. But when the number of water-cooled copper tubes is reduced from 6 rows to 4 rows as shown in Fig.9, the effect of the helium flow velocity begins to appear more clearly, and the amount of condensation decreases as the velocity increases.

These experiments demonstrate that a vapor with a very low partial pressure can effectively condense onto a cold wall and this condensation is well explained by the same calculation as that used for predicting the seed condensation in the boiler. This validates our conclusion that the boiler can be used as a seed recovery device for inert gas MHD power generation.

DESIGNING OF A BOILER AS A SEED RECOVERY EQUIPMENT

Figure 5 shows the condensed film thickness distribution along the flow direction in the boiler, which we know corresponds to the distribution of the condensation rate. From this figure we can see that the condensation occurs in a rather narrow region in the boiler while the heat flux is almost evenly distributed. The reason for this is that the driving force term (T_g-T_w) for the heat flux does not change much along the flow direction, but that for the mass flux ($_v$- $_{vw}$) shows significant change. This change occurs because the saturated vapor pressure decreases as an exponential function of the boiler tube wall temperature. This results in a limited boiler region involved in the seed condensation, and which suggests that there is an optimum designing for the boiler

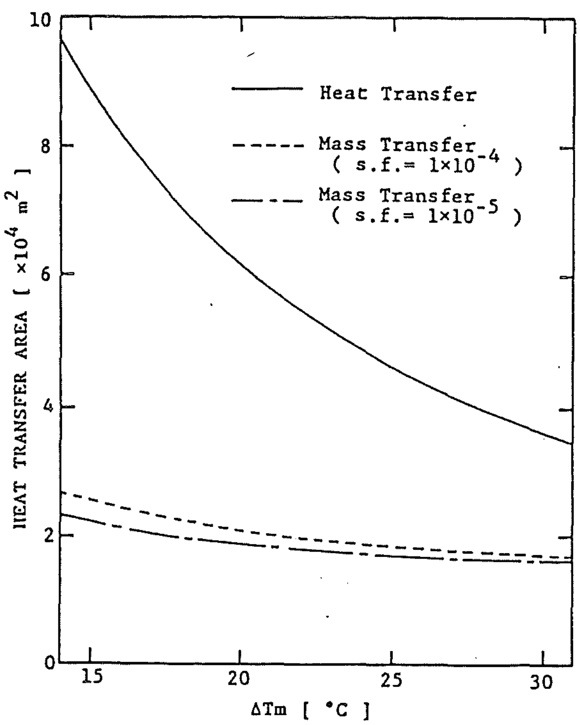

Fig.10 Total heat transfer area required for the heat transfer and the mass transfer as a function of the logarithmic mean temperature difference between helium gas flow and boiler tube wall

working as a seed recovery device simultaneously.

Therefore, finally, Fig.10 shows the total heat transfer area required for the heat transfer (the solid line) and for the mass transfer (the short dashed line and the alternate long and short dashed line for the two seed fractions) as a function of the logarithmic mean temperature difference T_m between the helium gas flow and the boiler tube wall. Here, the area required for the mass transfer refers to the area required for the 95%. condensation of the potassium contained in the helium flow and the same conditions as summarized in Table 1 are assumed to hold. This figure demonstrates that the area required for the mass transfer is much less than that for the heat transfer. This fact suggests the designing strategy of dividing the boiler into two parts; one for the heat transfer augmentation (by the use of fins, etc.) and the other for promoting the seed condensation as well as for facilitating the recovery of the condensed seed. This enables us to make the boiler compact while maintaining a high performance as a seed recovery device.

CONCLUSIONS

The condensation of very diluted seed material (metallic potassium) contained in helium flow in a boiler located downstream of an MHD generator is investigated. The mass transfer analysis based on the heat transfer analogy predicts that most of the seed vapor present at the inlet of the boiler directly condenses onto the boiler tubes as a liquid film, and no extra seed recovery device is required for inert gas MHD power generation. A cold model experiment using ethylene glycol as a simulated seed material is performed, which demonstrates that the low concentration vapor of ethylene glycol (about 100 ppm) contained in the helium flow at the room temperature almost completely condenses on water-cooled copper tubes. This experiment is well explained by the above mass transfer analysis and validates our prediction for an efficient seed condensation in the boiler.

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