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HEAT TRANSFER CHARACTERISTICS OF FOAM FLOW AT TEMPERATURE UP TO 373K OF HEATING SURFACE

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ABSTRACT An experimental study on heat transfer of water-air foam was conducted under forced convection conditions. A cylindrical heating surface whose temperature was lower than 373K, i.e., less than the boiling temperature of water, was employed. Heat transfer coefficient was obtained for various combinations of foam density, foam velocity, and temperature of the heating surface. The coefficients were found to increase with increasing the density and the velocity of the foam. Abrupt increase in the coefficient was also obtained as the temperature of the heater rises to 373K. A numerical analysis based on a lubricated plug flow model shows that one of the reason of the increase in the coefficient is latent heat transfer due to vapor diffusion in void space in the foam.

Keywords: Water-Air Foam, Heat Transfer Coefficient, Cylindrical Heating Surface, Forced Convection, Non-Newtonian Fluid

1. INTRODUCTION

Liquid-gas foam consists of many bobbles, i.e., discrete gaseous phase is enclosed in continuous thin liquid film. Foam of soap and shampoo is the example of the foam in our every day life. Liquid-gas foam has been used in rather limited area such as food industry, fire extinguishing, floating separation of ores in mine industries, and insecticide under house floor. Recently, foam will be planned to apply as a coolant for heat treatment of steel products in iron and steal industries[1]. Foam is a two phase mixture of gas and liquid. We can obtain, therefore, intermediate cooling rates between gas cooling and liquid cooling by using foam as a coolant. In addition, it is expected that the cooling rate will be controlled by changing content ratio of liquid and gas in the foam. Foam is a new material for coolant in future and its rheological and thermal properties must be clarified.

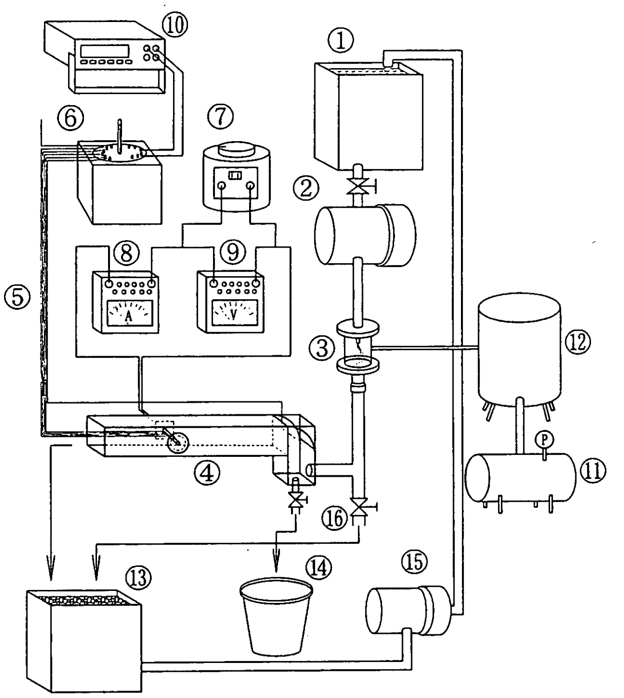
Studies of foam flow have been reported by many investigators. Most of them are analytical ones considering foam as a non-Newtonian fluid[2,3,4]. Foam's rheological property is different from those of usual two-phase flow. A few experimental studies have been carried out on pressure drop for foam flow through pipes[5,6,7]. It has been reported that a flow of foam shows much higher pressure drop than that of water or the air. These high apparent viscosity of foam can be predicted by a model of lubricated plug flow, in which foam flows rigidly over a layer of thin liquid film on pipe wall[5,7].

Few studies have been presented on heat transfer properties of liquid-gas foam. The only available one was reported by Saito et al.[8], they measured heat transfer rates to foam flow from a heating surface of high temperature, i.e., from 373K to 1000K.

In this study, heat transfer experiments of water-air foam were conducted under forced convection condition by using a cylindrical heating surface. Mean heat transfer coefficient for relatively lower temperature of a heating surface, i.e., from room temperatures to 373K, was obtained because no date is available for that temperature range up to now. The experiment was conducted for various combination of foam velocity, foam density and temperature of heating surface. A numerical analysis based on a simple flow model is also presented to evaluate a role of vapor diffusion in foam.

2. EXPERIMENTAL METHOD

Experimental apparatus is schematically shown in Fig.1. Water-air foam was generated by a foam generator. The foam liquid was a 1% aqueous solution of Kao MX-968 which is the one of raw ma-



1. Liquid Tank,
2. Pump,
3. Foam Generator,
4. Rectangular Channel,
5. Thermocouples,
6. Cold Junction,
7. Transformer,
8. Ammeter,
9. Voltmeter,
10. Digital Multimeter,
11. Air Compressor,
12. Air Tank,
13. Foam Reservoir,
14. Liquid Reservoir,
15. Pump,
16. Bypass Valve

Fig.1 Illustration of Experimental apparatus.

terials for commercially available shampoo. The foaming liquid was pumped up to a nozzle in the foam generator and sprayed over a metal net to form a thin liquid layer. The liquid layer was forced through the metal net by compressed air and liquid-gas foam was continuously generated. The foam was directly introduced to a horizontal aluminum channel of 1000mm in length, 70mm×75mm in cross section. Flow rate and density of the foam were measured at the exit of the channel by receiving the foam by a container.

Expansion ratio, E, is used to specify the state of the foam. Foam density ρ_F is a function of E.

$$E=\frac{(\text{volume of foam})}{(\text{volume of liquid contained in foam})} \tag{1}$$

$$\rho_F=\rho_w\frac{1}{E}+\rho_a\left(1-\frac{1}{E}\right) \tag{2}$$

where ρ_w and ρ_a are density of foam liquid and the air, respectively. E is the multiple factor to the volume of a liquid, which yields the volume of foam expanded by the air. In this experiment, E ranged from 12 to 48, which correspond to ρ_F is from 84kg/m^3 to 22kg/m^3, and mean diameter of bubbles is from 0.5 to 0.8mm. The mean velocity of the foam ranged from 16mm/s to 140mm/s.

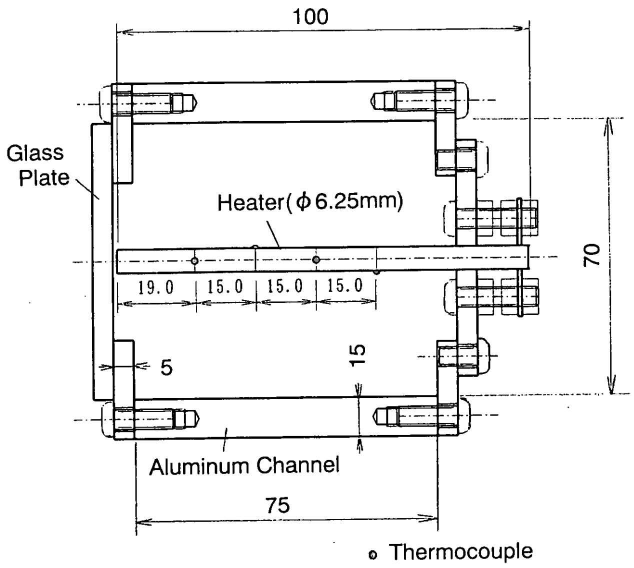


Fig.2 Heater configuration.

A commercially available cylindrical heater (Watlow Co., E4A30, 300Wmax, 6.25mm in diameter and 100mm long) was set at 600mm from the inlet of the rectangular channel. Sheath material of the heater is an alloy of Ni, Cr and Fe. Four thermocouples of type T, 0.1mm in diameter, were soldered to the heater to measure the surface temperature. Locations of these thermocouples were every 90° angle on the surface of the cylinder(see Fig.2). The local surface temperature was not uniform along the circumference of the heater. There was a tendency that the surface temperature at the front stagnation point is lower than that at the rear one, especially in a high heat flux and high foam velocity conditions. The mean surface temperature of the heater T_w was evaluated as an arithmetic mean value of these four temperatures. Foam was maintained at a room temperature T_F, which was measured by a thermocouple at the inlet of the channel. Heat transfer rate to the foam Q was obtained by electric input power to the heater subtracting heat losses. The heat losses were estimated by another series of experimental runs using water and the air, which was figured out to be 3% to 10% of the total input power to the heater.

The mean heat transfer coefficient α_m is defined by

$$Q=A\alpha_m(T_w-T_F) \tag{3}$$

where A is surface area of the heating cylinder, Q is heat transfer rate, T_F and T_w are foam temperature and surface temperature of the cylinder, respectively.

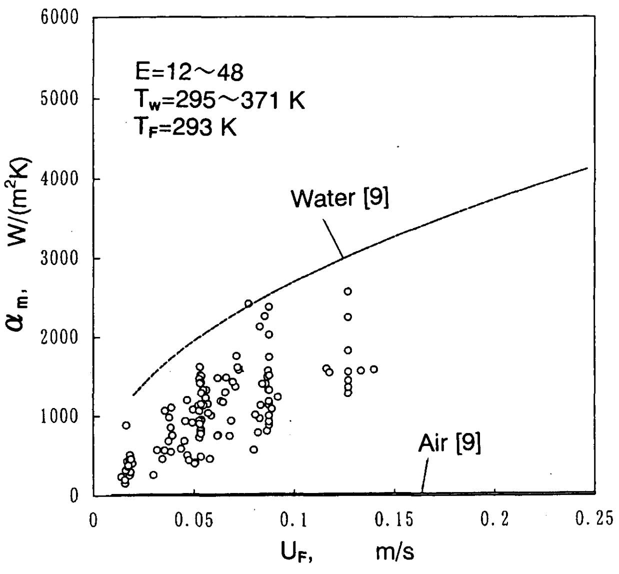


Fig.3 Heat transfer coefficient versus foam velocity.

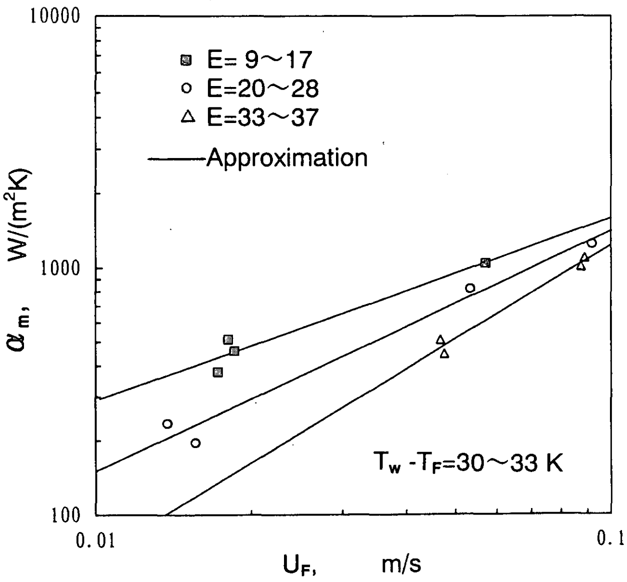


Fig.4 Heat transfer coefficient versus foam velocity. ($T_w - T_F$=30～33K)

3. RESULTS AND DISCUSSION

3.1. Mean Heat Transfer Coefficient

Experimental values of mean heat transfer coefficient for the foam flow are shown in Fig.3 as a function of foam velocity. Various data, different in the expansion ratio of the foam and in temperature of the heating surface, are included in Fig.3. Predicted values[9] for water and the air are also indicated in the same figure for comparison. The values for the foam flow falls between those for water and the air flows, which indicate that the foam possesses intermediate cooling ability between water cooling and air cooling.

Change in the heat tranfers coefficient with foam velocity is shown in Fig.4 for a constant value of $(T_w - T_F)$. The solid lines are approximations of the data. The coefficient increases with increasing foam velocity. However, its rate of increase is different depending upon the values of E. It can be shown that foam with high E, i.e., foam of high void ratio, possesses poor heat transfer ability in a lower velocity range.

Figure 5 indicates the heat transfer coefficient as a function of E for a constant value of $(T_w - T_F)$. The solid lines are the approximations of the data. The coefficient is high when E is low. This experimental result is predictable because a low E value means a high ratio of liquid content in foam. The heat conducted through the liquid phase, therefore, will increase with decreasing E.

The effect of the surface temperature on the heat transfer coefficient is shown in Fig.6 for the case of E =27. It is indicated that the increasing rate of the coefficient goes higher when $(T_w - T_F)$ is greater than 50K. This result is much different from heat transfer characteristics of usual one-phase fluid. One reason of the increase in the coefficient is that, in void spaces in foam, there will exist latent heat transfer due to water-vapor diffusion in addition to the heat conduction.

3.2. Numerical Evaluation of Heat Transfer Mechanism in Foam

Studies on pressure drop for foam flow showed that lubricated plug flow model can be applied when foam velocity is low[cf. 5,6,7]. In the following, we will calculate the heat transfer coefficient by using the flow model and evaluate the effect of latent heat transfer by vapor diffusion in foam.

Heat transfer mechanism in water-air foam can be classified as follows; (1) conduction of heat in liquid films and in void space of bubbles, (2)latent heat transfer by water vapor diffusion in void space of bubbles, (3)Marangoni convection of thin liquid films due to temperature difference. To evaluate the above (1) and (2), simple analysis of convection heat transfer for foam flow was conducted by assuming a lubricated plug flow model. In this model, we assume that foam is lubricated by a thin liquid layer on a heat transfer surface. Foam is considered as a rigid body and flows at a constant velocity U_F. This assumption is acceptable for a foam flow of low velocity because apparent viscosity of the foam is very high[cf. 6,7]. To simplify the analysis, a two-dimensional flat wall was employed as a heat transfer surface. The length of the wall is one half of perimeter of the heating cylinder used in the experiment. Marangoni effect and boiling

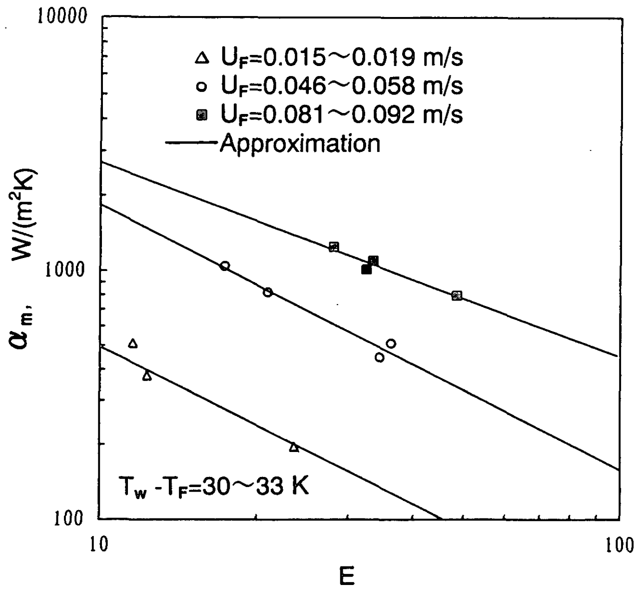


Fig.5 Heat transfer coefficient versus expansion ratio.($T_w - T_F$ =30~33K)

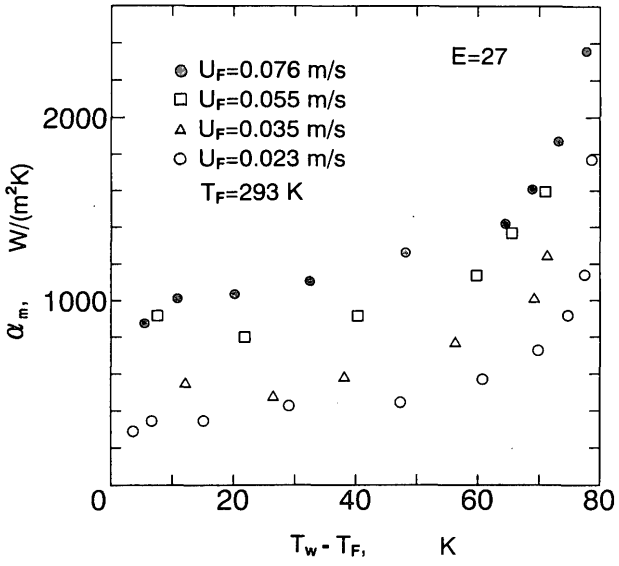


Fig.6 Heat transfer coefficient versus $T_w - T_F$. (Experiment)

of foam liquid are excluded in this analysis. With above assumptions, velocity changes linearly in the thin liquid layer from zero at the wall to a constant value U_F of the rigid foam flow at the upper border of the liquid layer(see Fig.7).

The energy equation in steady state is represented by

$$\rho c U \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial t}{\partial y}\right). \quad (4)$$

U: velocity of foam/foam liquid[m/s],
x: coordinate parallel to heating wall[m],
y: coordinate perpendicular to heating wall[m],
λ: thermal conductivity of foam/foam liquid [W/(mK)],
ρc: heat capacity of foam/foam liquid[J/(m^{3}K)]

The specific heat of foam c is represented as

$$c = \frac{\rho_w c_w + (E-1)\rho_a c_a}{\rho_w + (E-1)\rho_a} \quad (5)$$

where c_a and c_w are specific heat of the air and foam liquid, respectively.

The boundary conditions for Eq.(4) are $T = T_F$ at x=0(left boundary), $\partial T/\partial y = 0$ at upper boundary, $\partial T/\partial x = 0$ at right boundary and $T = T_w$ at $y = 0$(heat transfer surface). The velocity distribution is assumed to be a function of y and independent of x according to the lubricated plug flow model, i.e.,

$$U = \frac{y}{\delta} U_F, \quad at \quad 0 \le y \le \delta \quad (6)$$

$$U = U_F, \quad at \quad y > \delta \quad (7)$$

where δ is the thickness of a liquid layer on the heat transfer surface.

The effective thermal conductivity of foam λ is calculated by

$$\frac{\lambda}{\lambda_w} = \frac{1-(1-\lambda_a/\lambda_w)\varepsilon^{2/3}}{1-(1-\lambda_a/\lambda_w)\varepsilon^{2/3}(1-\varepsilon^{1/3})}. \quad (8)$$

ε: void ratio of foam[$\equiv (1-1/E)$],
λ_a: effective thermal conductivity of void space [W/(mK)],
λ_w: thermal conductivity of foam liquid[W/(mK)]

Above equation is derived for a single bubble in foam by assuming a one-dimensional heat conduction model[10]. The effective thermal conductivity of wetted void space λ_a can be expressed as[11]

$$\lambda_a = \lambda_{a0} + \frac{D_v L}{R_v T}\left(\frac{P}{P - p_v}\right)\frac{dp_v}{dT}. \quad (9)$$

D_v: diffusion coefficient of water vapor[m^2/s],
L: latent heat of evaporation[J/kg],
P: atmospheric pressure[Pa],
p_v: partial pressure of water vapor[Pa],
R_v: gas constant of water vapor[Nm/(kgK)],
T: temperature[K],
λ_{a0}: thermal conductivity of dry air[W/(mK)]

The second term on the right-hand side of Eq.(9) represents latent heat transfer by vapor diffusion.

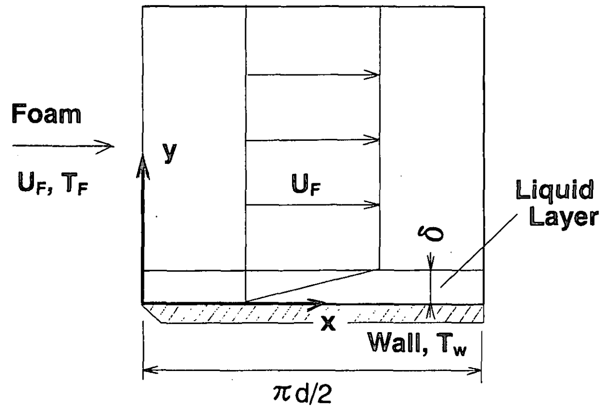


Fig.7 Analytical model.

In this analysis, it was assumed that water vapor in the void space is saturated at the local temperature in the foam. Krischer[11] proposed following correlation for the diffusion coefficient D_v of saturated water vapor in a wet cavity.

$$D_v = \frac{2.34}{P_T}\left(\frac{T}{273}\right)^{2.3} \quad \left[\frac{m^2}{s}\right] \tag{10}$$

where P_T is total pressure in Pa.

Equation (4) can be solved numerically by a finite difference method[12]. 17×14 control volumes are set in a flow field of 9.83mm×9.82mm. The calculation was iterated until $|T_{new} - T_{old}|$ of all the control points converge to less than $(T_w - T_F)\times10^{-5}$ in successive calculation process.

An example of the numerical result is shown in Fig.8. The solid curve represents mean heat transfer coefficient obtained by taking the vapor transfer into account and the broken line is that neglecting the vapor diffusion. This figure shows that the vapor diffusion in foam greatly increases heat transfer in higher temperature range of heat transfer surface. The quantitative value of the coefficient is not agree with the experimental ones(cf. Fig.6) because of difference in the form of the heat transfer surface and of many other unknown factors. The qualitative tendency, however, that the heat transfer coefficient increases in the higher temperature range of T_w is the same with the experiment. The saturation vapor pressure of water greatly increases at high temperature, and this will result in the increase in the vapor transfer in foam. From this numerical analysis, therefore, it is concluded that the latent heat transfer by vapor diffusion is an important mechanism of heat transfer in water-air foam.

4. CONCLUSIONS

Heat transfer to water-air foam from a heated cylinder, whose surface temperature is less than

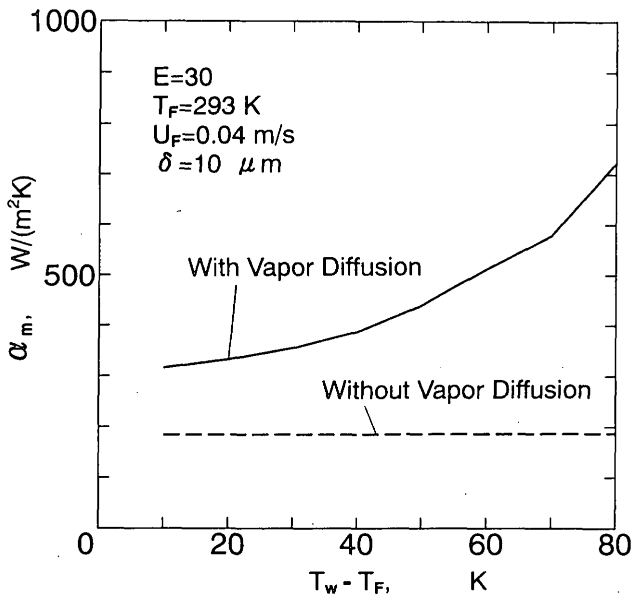


Fig.8 Heat transfer coefficient versus $T_w - T_F$. (Numerical calculation)

373K, was experimentally studied. The conclusions are summarized as follows.

(1) The value of mean heat transfer coefficient for foam flow ranges between those for water and the air flows.

(2) The heat transfer coefficient increases with increasing foam velocity and with decreasing the expansion ratio of the foam.

(3) Numerical analysis shows that latent heat transfer by vapor diffusion in the foam is the one of the important factors that increases the heat transfer coefficient at higher temperature range.

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