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Local Heat Transfer Coefficients for Reflux Condensation Experiment in a Vertical Tube in the Presence of Noncondensible Gas

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Abstract

The local heat transfer coefficient is experimentally investigated for the reflux condensation in a countercurrent flow between the steam-air mixture and the condensate. A single vertical tube has a geometry which is a length of 2.4m, inner diameter of 16.56mm and outer diameter of 19.05mm and is made of stainless steel. Air is used as a noncondensible gas. The secondary side is installed in the form of coolant block around vertical tube and the heat by primary condensation is transferred to the coolant water. The local temperatures are measured at 15 locations in the vertical direction and each location has 3 measurement points in the radial direction, which are installed at the tube center, at the outer wall and at the coolant side. In three different pressures, the 27 sets of data are obtained in the range of inlet steam flow rate 1.348~3.282kg/hr, of inlet air mass fraction 11.8~55.0%. The local heat transfer coefficient increases as the increase of inlet steam flow rate and decreases as the decrease of inlet air mass fraction. As an increase of the system pressure, the active condensing region is contracted and the heat transfer capability in this region is magnified. The empirical correlation is developed represented with the 165 sets of local heat transfer data. As a result, the Jacob number and film Reynolds number are dominant parameters to govern the local heat transfer coefficient. The rms error is 17.7% between the results by the experiment and by the correlation.

1. Introduction

In case of the loss of residual heat removal during midloop operation in nuclear power plant, it is estimated that the safety of the reactor may be severely threatened by the boiling of a coolant inventory when the decay heat is not properly removed. Such a probability of accident inducing the core damage in the case of midloop operation is revealed not to be negligible compared to the case of normal operation.

The integral experiment and the code analysis of the loss of residual heat removal accident during midloop operation have been performed in several countries. In Korea, a few research groups have evaluated and analyzed the experimental results of the foreign integral test facility using the thermal-hydraulic code.

A reflux condensation is the countercurrent flow between the steam-air mixture upward flow and the condensate downward flow, and has the upper limit by the onset of flooding. The reflux condensation in the U-tube plays an important role of the residual heat removal to the secondary side of steam generator and has an advantage not to be the loss of a coolant inventory.

The present experimental study has two characteristics compared to the previous works. One is to obtain the local heat transfer coefficients by the measurement of local temperatures along the axial length of the vertical tube. The other is to perform an experiment in the range of the high air mass fraction that is similar to the conditions of midloop operation.

2. Previous Works

J.W. Park(1984) carried out several experiments on reflux condensation and flooding limits with the low concentrations of noncondensible gas in pyrex tubes. He obtained the following results. The flooding flow rate and heat transfer rate per unit axial area decreases as the air flow rate increases. Once a tube is flooded, its heat removal capability is much less than that of the tube before flooding.

Banerjee et. al.(1981) carried out the experiment of the transition from the reflux con- densation to natural circulation and the behavior of condensing region and liquid column. Also they performed the theoretical analysis of heat removal and the stability of flow regime. They related the pressure difference between the inlet and outlet of the tube with the length of a single phase liquid column.

Nguyen and Banerjee(1982) used the inverted U-tube test section which was directly attached to the boiler, and observed various flow patterns and oscillatory behavior. And they described the pressure drop of the test section as the parameter representing the flow regimes.

Hein et. al.(1982) carried out the experiments using the inverted U-tube made of stainless steel and the saturated secondary coolant pool. And they made a few steady states varying the amount of injected nitrogen gas and the secondary saturated temperature. The locations about the transition of the active to passive condensing region are observed by measuring the temperature at axial locations. The active length became short as the amount of injected nitrogen gas increased.

Tien et. al.(1982) performed the 2-D analysis of the condensation in a tube with the Nusselt film condensation theory and the condensation experiments using the copper tube evaporator that leads to the thermosyphoning and the collapse of liquid column at the head of tube.

Wan et. al.(1983) studies the formation of liquid column after flooding using the single long tubes which are different from each other. And the constants, C and m, in Wallis' flooding formula were represented newly from the experimental results. The diameter of the tube was considered as an important factor in their study.

Chang et. al.(1983) used four tubes for their experiments and predicted that the multi-tube effects according to the fluctuation of liquid column exist. The fluctuation was magnified in the multi-tube to the single tube. The heat removal capability was increased as the inlet pressure increases.

Marcolongo(1987) measured the local temperatures and investigated for the reflux condensation and the flooding limit using the inverted U-tube. The experimental flooding results were compared to a few correlations and it was concluded that Wallis' correlation is most similar to the prediction of the experiments. In the range of high pressure(55~105bar) the empirical correlation for the heat transfer coefficient was developed using the film Reynolds number. However, the data representing the correlation was insufficient.

In the previous works the reflux condensation is described not independently but partly as one of the flow regimes in countercurrent flow. Such a separate test related to the SB-LOCA has a main interest in the transition of the flow regime and to the visual observation by the pyrex tube. Small concentrations of noncondensible gases like the air or the nitrogen are treated in the previous works. The present work treats the mixture flow with the large concentrations of the air as the noncondensible gas. Also the major characteristic in this study is to measure the local points of temperature and to obtain the data for the local heat transfer coefficient.

3. Experimental Works

3.1 Facility Description

A test facility is installed for the reflux condensation experiments. The test facility is composed of two parts. One is the steam-air mixture generation part and the other is the reflux condensation part. The main test section is composed of the vertical tube, the coolant block and upper/lower plenums, which has a geometry of the total length 3.56m, the height 4.3m. Figure 1 shows the overall schematic of the test facility

The steam-air mixture generation part is composed of steam generator, heater, power controller, air line, air pre-heaters and flow mixer. The steam generated from the steam generator is mixed with the air heated on the air pre-heaters in the flow mixer. The two air pre-heaters having each power 3kW heat up air to make a temperature balance with the saturated steam. The air flow is measured by the two rotameters that have different ranges; 2−20lpm, 9.4−94lpm. The air rotameters have a measuring errors of ±2.5%. The steam-air mixture from the flow mixer flows into the lower plenum in the reflux condensation part. The droplet separator and the turbinemeter are located on the steam-air mixture line. The droplet generated from the mixture line is removed on the droplet separator and then the mixture flow rate is measured by the turbinemeter which has a maximum range of 8.1m^3/hr.

The reflux condensation part is composed of vertical tube, coolant block, lower and upper plenum, drain tank, venting line and air-steam separator. K-type 0.5mm-dia. thermocouples are attached by the silver soldering on the vertical tube and measure the tube centerline temperatures and the outer wall temperatures along the same axial locations. Figure 2 shows the position of thermocouples in a vertical tube. They are located more closely near the tube inlet because of the importance of heat transfer in this region. A vertical tube has a geometry of the outer diameter of 0.75"(equal to the U-tube dia. of Korea standard NPP), inner diameter of 16.56mm and effective length of 2.4m(surrounded by the coolant block). The tube inlet shape is a sharp edge. The coolant blocks are installed around the vertical tube and make the annular shaped flow of the coolant between the block and the tube. The outer diameter of coolant annulus is 57.2mm. The K-type 0.125"-dia. thermocouples to measure the coolant temperature are installed penetrating into the coolant block. Figure 3 shows the schematic for the attachment of thermocouples on the test section as a sheared view. For the stable inlet and outlet conditions the upper and lower plenums are installed at both ends of a vertical tube. They have a shape of 20×20×20cm cubic. The air-steam separator is installed on the venting line for extracting the remaining steam in a vented flow. However, the nearly entire amount of inlet steam was condensed on the inner surface of the vertical tube and no noticeable collection of the vented steam occurred.

3.2 Experimental Conditions

The experimental ranges of the system pressure, the inlet steam flow rate, and the inlet air mass fraction in the experiment; 1~2.5bar, 1.348~3.282kg/hr and 11.8−55.0%. The inlet steam is all condensed in a vertical tube and the amount of the vent of air is the same as that of injection. The city water used as the coolant and the steam is made of the mineralized water. Figure 4 shows the graph of the test results with respect to the inlet steam flow rate and the inlet air mass fraction. Table

1 represents the experimental conditions for the present work.

Table.1 Experimental Conditions

Parameter	Units	Conditions	Remarks
FS	kg/hr	1.348 ~ 3.282	inlet steam flow rate
FA	kg/hr	0, 0.551 ~ 2.443	inlet air flow rate
FM	kg/hr	1.875 ~ 4.443	inlet mixture flow rate
P	bar	1, 1.5, 2.5 *(approx.)*	system pressure
AMF	%	0, 11.8 ~ 55.0	inlet air mass fraction
FC	kg/s	0.0250 ~ 0.0630	coolant flow rate

3.3 Data Reduction and Instruments

The calculation of the local heat transfer coefficients requires the measurement of the temperatures at the tube centerline(T_b), at the tube outer wall($T_{w,o}$) and at the coolant(T_C). Data reduction for heat transfer coefficients is first developed from the basic heat balance concept. The rate of heat loss by the reflux condensation is transferred to the secondary side through the infinitesimal tube area, which is the same as the rate of heat gain by the increase of coolant temperature. This heat balance is expressed mathematically as follows:

$$q''(x)\ dA = \dot{m}_C C_p dT_c\ , \tag{1}$$

where $q''(x)$ is the heat flux flowing out through unit wall area by the mixture condensation and $\dot{m}_C$ is the coolant flow rate. If the coolant flow rate and the coolant temperature are known the local heat flux can be calculated using the following relationship:

$$q''(x) = \dot{m}_C C_p \frac{dT_C(x)}{dA} = \frac{\dot{m}_C C_p}{\pi d} \frac{dT_C(x)}{dL}\ , \tag{2}$$

where L is axially the length of interval that the adjacent two T_Cs are measured. The tube inner wall temperature can be calculated by the heat flux and by the measured outer wall temperature

$$T_{w,i}(x) = T_{w,o}(x) + q''(x) \cdot R\ , \tag{3}$$

$$\text{where } R = \frac{\ln(D_o/D_i)D_h}{\pi k_{ss}}\ . \tag{4}$$

where D_h is the hydraulic diameter and k_{ss} is the thermal conductivity in a vertical tube. Finally, the local heat transfer coefficient is estimated through the heat flux divided by the difference between the tube centerline temperature and the inner wall temperature.

$$h(x) = \frac{q''(x)}{(T_b(x) - T_{w,i}(x))} \tag{5}$$

In the present experiments the data is measured and collected at the points of 6 in pressure, 4 in flow rate and 53 in temperature. Among these measurements the points of 2 in pressure, 2 in flow rate and 36 in temperature are represented importantly to analyze the experimental results. The gauges and transducers are used for the pressure measurements. The rotameters and turbinemeter are used for the flow rate. The 1 RTD and 52 thermocouples are used for the temperature. Data acquisition system is required to collect about 60 data points per 0.5–1.0 second. A set of 486 PC and data acquisition unit(HP E1421B) having a 64 channel terminal box is used for the data collection and the experiments are monitored using the software for windows, HP VEE v.3.2. The values of measuring parameter varying with each run time can be checked on monitor and the transition of temperature profiles due to flooding is discernable in a graphic display.

4. Results and Discussion

4.1 General Description

As a result of the reflux condensation experiment the 29 sets of data with variations of three main parameters and total 165 sets of data at local points are used to derive the correlation for the heat transfer coefficients. In conditions of pressure, the 6 data at 2.5bar, the 7 data at 1.5bar and the 16 data at 1.0bar are obtained. Among the 1bar experiments the two data is performed with inlet pure steam in the absence of the air injection. Nearly entire amount of inlet steam are condensed on the inner surface of a vertical tube. The length of the active condensing region is estimated to be within 1.865m considering the local heat transfer coefficients and the temperature profiles.

4.2 Limitations of the Reflux Condensation

The reflux condensation has an upper limit in a rate of upflow in the countercurrent flow. This upper limit is called 'flooding' and the flow regime changes in the upflow over the flooding. The flooding itself is an important phenomenon in countercurrent flow and gives a limitation of the reflux condensation. Therefore, the experimental study of the onset of flooding was preceded. As a result, the experimental values are below the value of Wallis' correlation in the geometric conditions of the sharp edge and the inner diameter of 16.56mm.

The flooding discrimination in the previous works depends on the visual observation of the transparent pyrex tube or the pressure drop between both ends of the test tube. In the present work, it's impossible to observe visually due to the use of a stainless steel tube. Therefore, the onset of the oscillation of the tube centerline temperatures is used for discriminating the flooding. Figure 5 shows the oscillations of the temperature due to flooding.

Figure 6 shows the flooding results. $j_g^*$and j_f^* represents the nondimensional superficial velocities of the steam-air mixture and the condensate. As the condensate flow rate is dependent on the inlet steam flow rate, the distributions of data points are in the limited range of j_f^* . The values of constant C in the Wallis' correlation are 0.6543−0.7034 in the experiments, which is lower than 0.725 suggested by Wallis.

4.3 Parametric Effects on the Heat Transfer Coefficient

The heat transfer coefficient increases with an increase in the system pressure and in the inlet steam flow rate, and decreases with an increase in the inlet air mass fraction. The effects on the active condensing length can be estimated by the curves of the heat transfer coefficient and the heat flux along the axial direction. The active region is enlarged and contracted at each condition of the increase in the air mass fraction and the system pressure.

Figures 7 and 8 show the effects of the presence and the absence of the air in the inlet flow on the temperature distributions. In the same case for air injection but different for air mass fraction(11.8−55%) the experimental results confirm the effect of noncondensible gases on the heat transfer coefficients. Figure 9 shows the effect of the air mass fraction. The heat transfer coefficients in the absence of the air have very large values compared to the presence of the air. Figure 10 shows the effect of the inlet steam flow rate. The local heat transfer coefficients increases over the active region with an increase in steam flow rate. Figure 11 shows the effect of the pressure. With an increase in pressure, the active condensing region becomes short and the heat transfer coefficients magnify within this region. The heat transfer distribution is shifted and concentrated to the tube inlet, but its capability over the active region does not change as the pressure increase. Therefore the decay power effecting the steam generation and the amount of generated noncondensible gases are important factors to the heat removal through the U-tubes.

4.4 Development of Experimental Correlation

In vertical condensation flow, the total heat transfer coefficient(h_{tot}) is separated into the film heat transfer coefficient(h_f) and the mixture upflow heat transfer coefficient(h_g) with respect to the geometry, and is separated into the convective(h_{conv}) and condensation(h_{cond}) heat transfer coefficients. h_{conv} is related to Re_g, Pr_g and h_{cond} can be expressed in terms of Re_g, Re_f, W_{air}, Ja.

The degradation factor(F) is introduced for the nondimensionalization of the local heat transfer coefficients. F is defined as the ratio of h_{tot}/h_f, where h_{tot} is $q''/(T_b - T_{w,i})$ and h_f is $q''/(T_f - T_{w,i})$. h_f is the same as k_f/δ according to Nusselt(1916)'s classical film theory. k_f is a thermal conductivity and δ is a film thickness.

$$\delta = \left[\frac{3\mu_f^2 Re_f}{4\rho_f(\rho_f - \rho_g)g} \right]^{\frac{1}{3}} \tag{6}$$

The degradation factor is expressed as a function of 4 nondimensional numbers. The Re_g and Re_f is the steam-air mixture Reynolds number and the film Reynolds number. Ja is the Jacob number and W_{air} is the local air mass fraction. The Prandtl number reveals to be negligible in this consideration. Least square method for multi variables is numerically used for the correlation development.

The result of the developed empirical correlation using the 165 sets of the local heat transfer coefficient data is as the following.

$$F = \frac{h_{tot}}{h_f} = 2.58\times10^{-4} Re_g^{0.200} Re_f^{0.502} Ja^{-0.642} W_{air}^{-0.244} \tag{7}$$

$$where,\ 6119 < Re_g < 66586 \tag{8}$$

$$0.140 < W_{air} < 0.972 \tag{9}$$

$$0.03 < Ja < 0.125 \tag{10}$$

$$1.2 < Re_f < 166.6 \tag{11}$$

The F has values from 0.0153 to 0.3301. This results represent the heat transfer is severely disturbed by the presence of the air on the high percentage. The local air mass fraction along the axial length increases with the condensation of steam and F decreases axially. This correlation describes the reflux condensation heat transfer in the active condensing region. Jacob number is the most dominant parameter; the temperature difference between the tube centerline and the inner wall is very important to heat transfer. The film thickness is $3.07\times10^{-5} - 1.188\times10^{-4}$m. The rms error is 17.7% between the experimental results and the correlation results.

Figures 12 and 13 show the comparisons of the h_{tot} results by the experiment and by the correlation in normal and log scales. The rms errors have a similar values along the vertical length. Figures 14–16 show the effects of the Jacob number, the film Reynolds number and the air mass fraction on the heat transfer coefficients.

5. Conclusions

For the determination of an upper limit of the reflux condensation, the flooding experiment was preceded. The flooding limits are lower than that of Wallis' correlation. The data for heat transfer coefficient is obtained by measuring the 11 local temperatures. The presence of the air causes a remarkable decrease of the heat transfer coefficients compared to the inlet pure steam. The heat transfer coefficient decreases with the increase of the air mass fraction, the decrease of the inlet steam flow, and the decrease of the system pressure. The empirical correlation is developed using four nondimensional parameters; film Reynolds number, gas Reynolds number, Jacob number and air mass fraction. Among them Jacob number and film Reynolds number are the most dominant parameters, which represent the thermal driving potential and the growth of a liquid film.

References

[1] Hyun Sik Park and Hee Cheon NO, "A Condensation Experiment in the Presence of Noncondensables in a Vertical Tube of PCCS and Its Assessment with RELAP5/MOD3.2", Accepted to Nuclear Technology, 1999.

[2] J.W. Park, "An Experimental Investigation of Condensation Phenomena In A Vertical U-tube With and Without Noncondensible Gas", M.S. Thesis, Dept. of Nuclear Engineering, Korea Advanced Institute of Science and Technology, 1984.

[3] S. Banerjee, J.S. Chang, R. Girard and V.S. Krishnan, "Reflux Condensation and Transition to Natural Circulation in a Vertical U-tube", ASME Winter Annual Meeting, Nov. 15-20, Washington D.C., 1981.

[4] Q. Nguyen and S. Banerjee, "Flow Regimes and Removal Mechanisms in a Single Inverted U-tube Steam Condenser", ANS Trans. Vol. 43, 1982.

[6] D. Hein et al., "The Distribution of Gas in a U-tube Heat Exchanger and its Influence on the Condensation Process", Proc. 7th Int. Heat Transfer Conf., 1982.

[7] C.L. Tien, T. Fukano, K. Hijikata and S.J. Chen, "Reflux Condensation and Operation Limits of Countercurrent Vapor-Liquid Flows in a Closed Tube," EPRI/NP-2648, Nov. 1982.

[8] P.T. Wan, R. Girard and J.S. Chang, "The Role of Flooding Phenomena in Reflux Condensation in a Vertical Inverted U-tube," 3rd Multiphase Flow and Heat Transfer Symposium Workshop, April, 1983.

[9] J.S. Chang, R. Girard, S. Revankar and P.T. Wan, "Heat Removal Capability of Steam Generators under Reflux Cooling Modes in a CANDU-PHT System," 4th Canadian Nuclear Soc. Conf., 1983.

[10] G.B. Wallis, "One-dimensional Two-phase Flow", McGraw-Hill Book Company.

[11] M. Siddique, M.W. Golay and M.S. Kazimi, "Local Heat Transfer Coefficients for Force-Convection Condensation of Steam in a Vertical Tube in the Presence of a Noncondensible Gas," Nuclear Technology, Vol. 102, pp. 386-402, June , 1993.

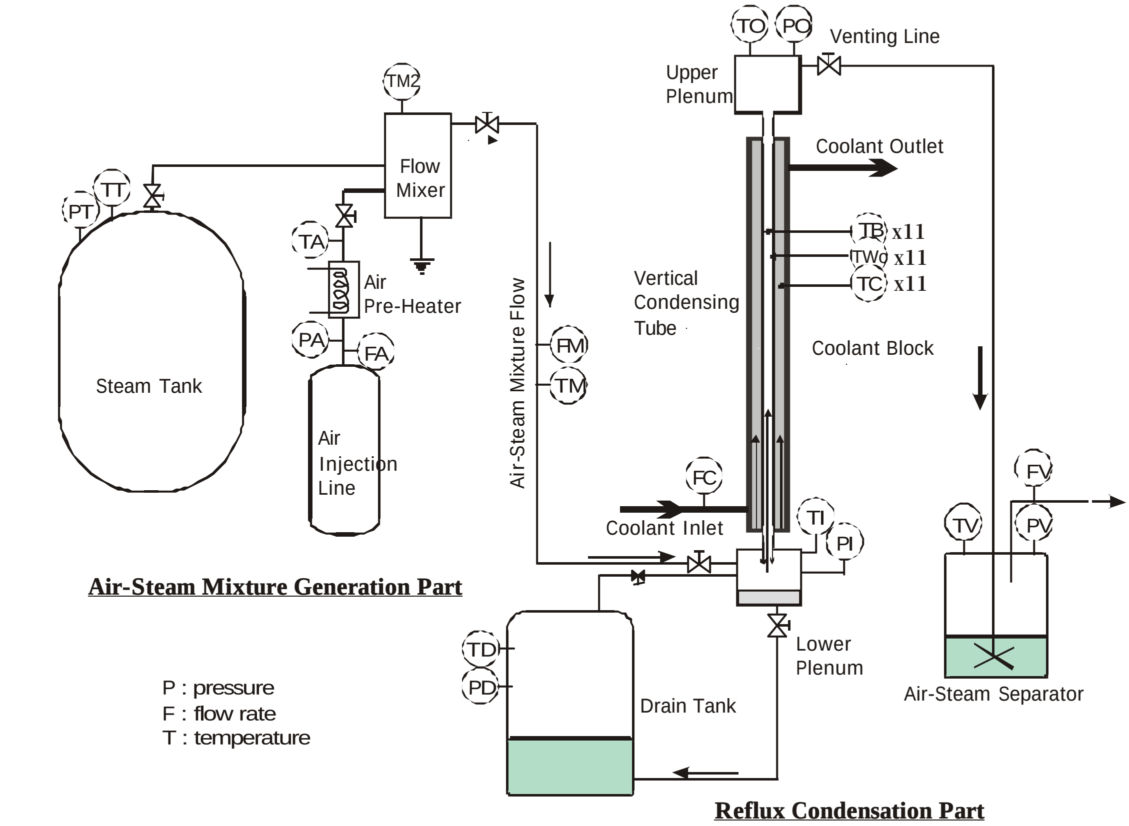

Fig.1 Schematic Diagram of Test Facility

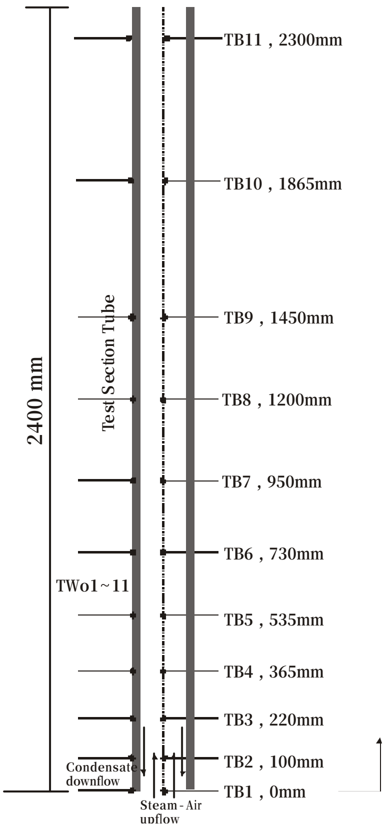

Fig.2 Location of Temperature Measurements in a Vertical Tube

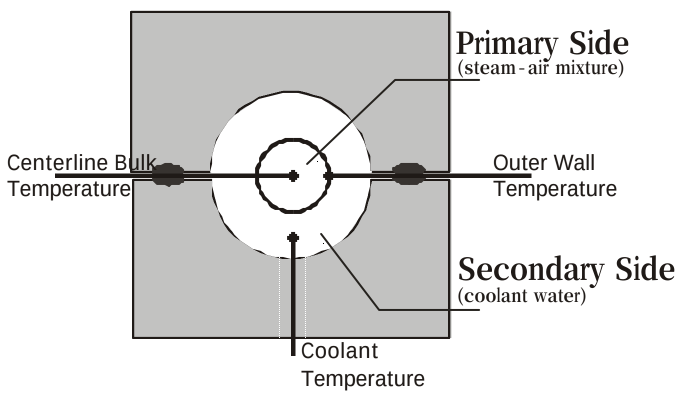

Fig.3 Sheared View of Test Section

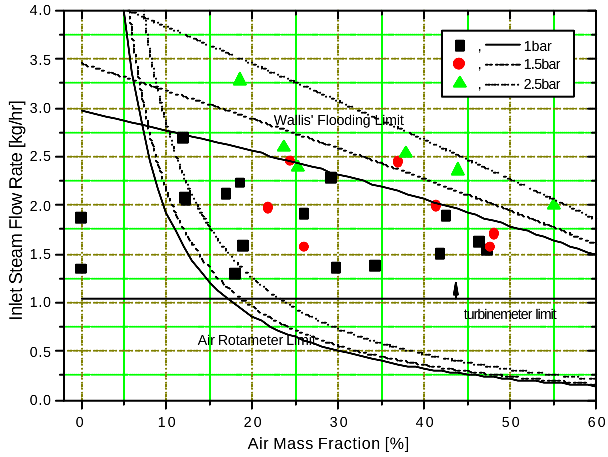

Fig.4 Range of Experimental Results

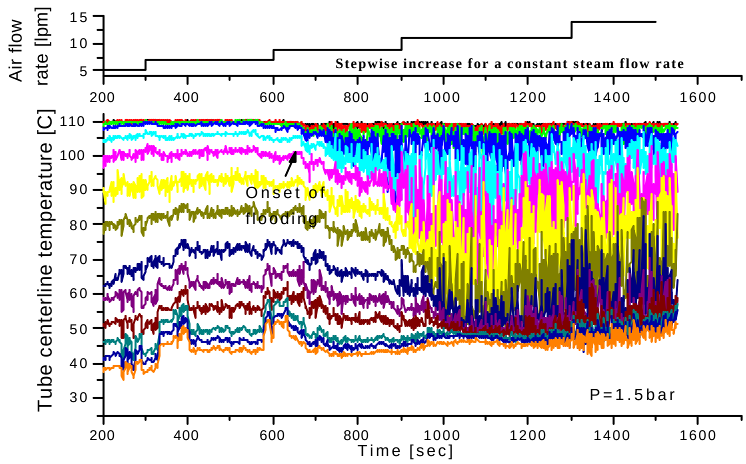

Fig.5 Tube Centerline Temperature Fluctuation

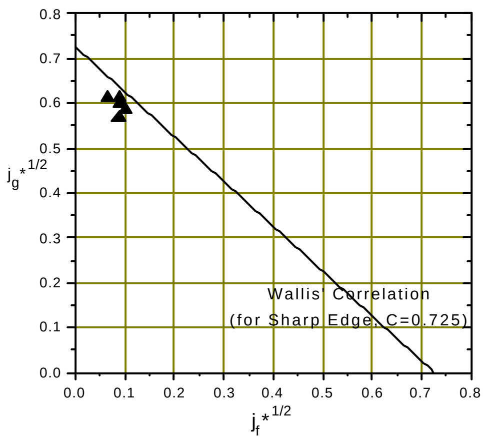

Fig.6 Experimental Results of Flooding Limit

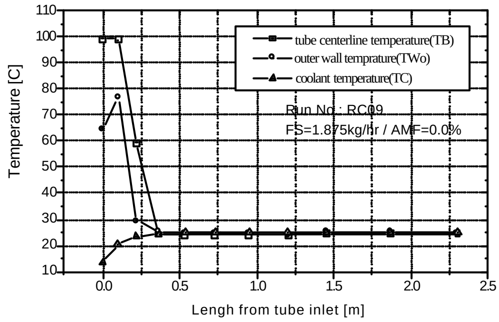

Fig.7 Temperature distribution
in the Absence of Air

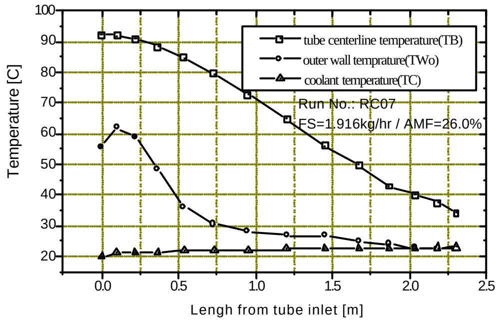

Fig.8 Temperature distribution
in the Presence of Air

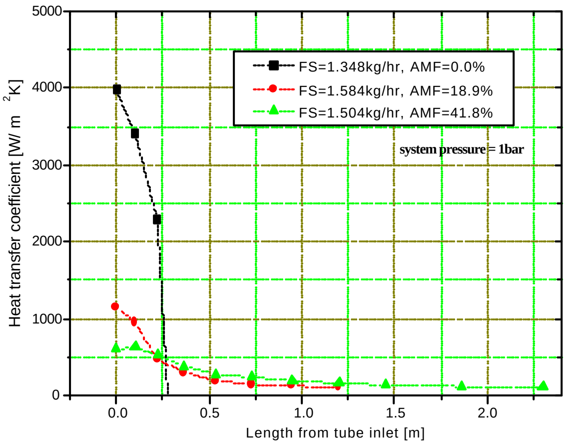

Fig.9 Air Mass Fraction Effect on
Heat Transfer Coeficient

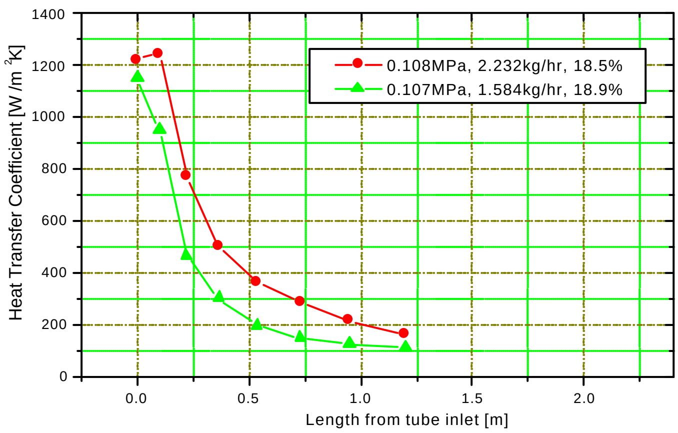

Fig.10 Inlet Steam Flow Rate Effect on
Heat Transfer Coeficient

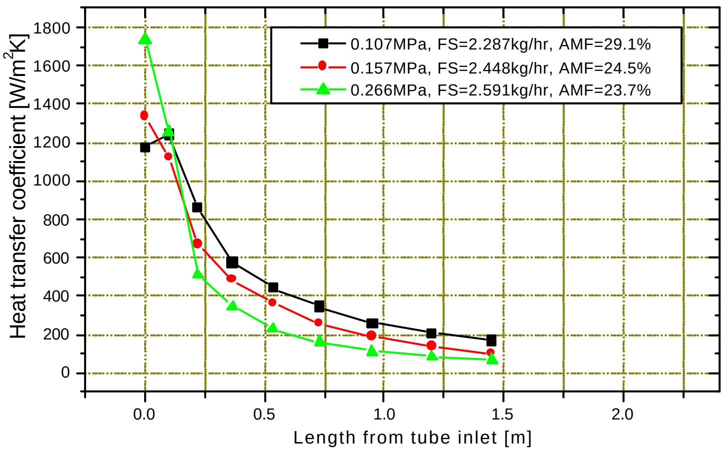

Fig.11 System Pressure Effect on
Heat Transfer Coefficient

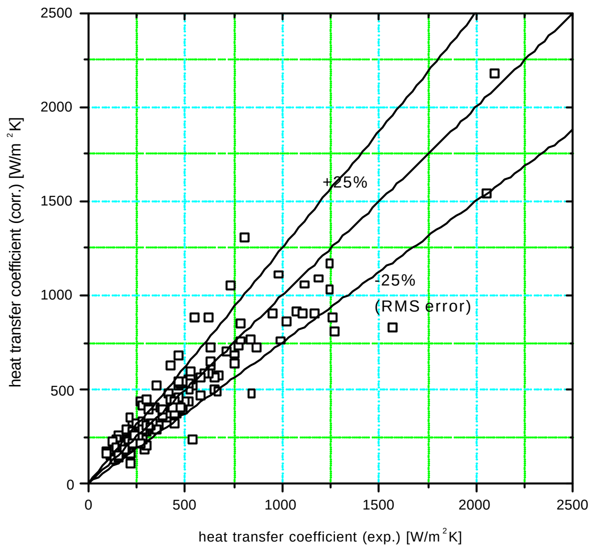

Fig.12 Comparison of the Local Heat Transfer Coefficients
between Experiment and Correlation (normal scale)

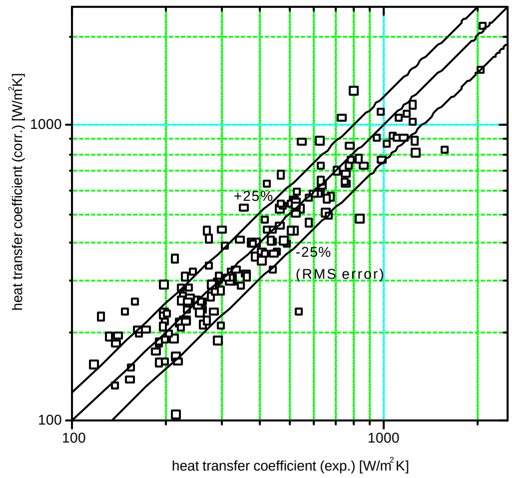

Fig.13 Comparison of the Local Heat Transfer Coefficients between Experiment and Correlation (log scale)

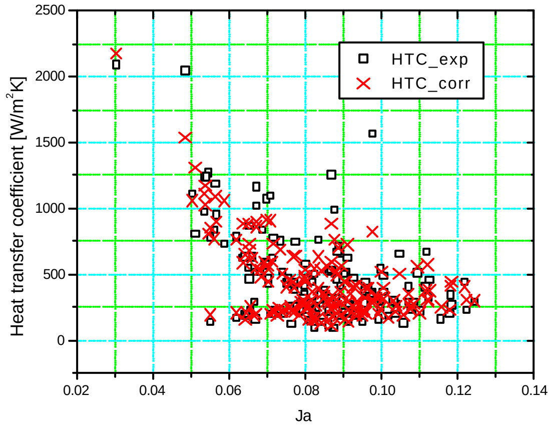

Fig.14 Heat Transfer Coefficients along the Jacob Number

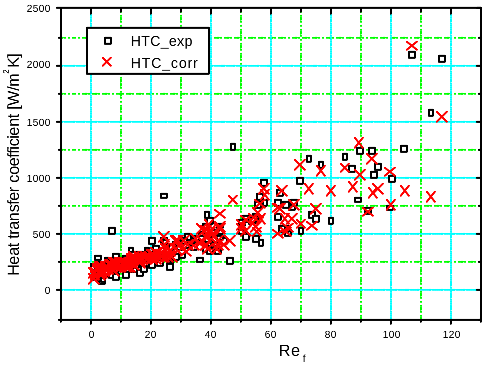

Fig.15 Heat Transfer Coefficients along the Film Reynolds Number

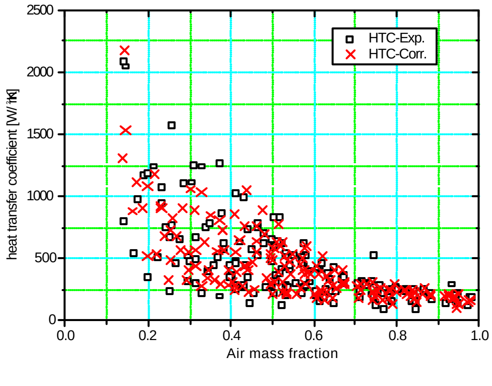

Fig.16 Heat Transfer Coefficients along the Air Mass Fraction