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Assessment of RELAP5/MOD3.2 for Reflux Condensation Experiment

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Abstract

This report describes the experimental works and the assessment of the predictability of RELAP5/MOD3.2 for the reflux condensation experiment in the presence of noncondensible gases in a vertical tube having the same outer diameter of the U-tube riser in Korean standard nuclear power plant (KSNPP). The reflux condensation experiment is performed in conditions of the low pressure, low flow and the high mass fraction of noncondensible gas representing the situation of the loss-of-residual-heat-removal (LORHR) accident during mid-loop operation.

The test facility is composed of the mixture gas generation part and the reflux condensation part. The test section in the latter part is a vertical tube with 19.05mm diameter and 2.4m length surrounded by the coolant block. Reflux condensation occurs in the range of very small flow rates because of the flooding limit. Therefore, the injected steam is completely condensed in the vertical tube.

The flooding as the upper limit of reflux condensation occurs in lower mixture upward flow rate than that of Wallis' correlation. The heat transfer coefficients near the tube inlet increase as the inlet steam flow rate and the system pressure increase. In the presence of noncondensible gas, the heat transfer capability is dramatically decreased. An empirical correlation is developed using the local data of heat transfer coefficients. The degradation factor in the correlation is expressed with four nondimensional parameters. It turns out that the Jacob number and the film Reynolds number are dominant parameters.

A non-iterative condensation model is developed to predict the steam condensation heat transfer in the presence of the noncondensible gases, which is different from the existing iterative model in the RELAP5/MOD3.2 code. The existing models, default model (Colburn-Hagen model) and alternative model (Chato-UCB model), in RELAP5/MOD3.2 are assessed with the reflux condensation data. The heat transfer coefficients estimated by the present non-iterative model and by the existing models of the standard RELAP5/MOD3.2 code are compared with the present experimental data. The default model and the alternative model under-predicts and over-predicts, respectively. The non-iterative model better predicts than the default and alternative models.

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Executive Summary

The reflux condensation in the presence of noncondensible gas in a vertical tube is performed and the existing models in the standard RELAP5/MOD3.2 code are assessed with the present experimental data and the newly developed model.

In case of the LORHR during mid-loop operation in nuclear power plants, the reflux condensation heat transfer in the riser part of the U-tube is an effective heat removal mechanism without the loss of coolant inventory. However, the previous studies of the reflux condensation are mainly interested in the flow regimes and their transitions.

The heat transfer data of the reflux condensation are very important results, which require the separate effect tests to obtain the comprehensive data for the heat transfer coefficients. The probability of the LORHR is revealed not to be negligible and the RELAP5/MOD3.2 code does not properly estimate in conditions of the mid-loop operation; the high mass fraction of noncondensible gases, and the low pressure and low flow. Therefore, the experimental study and the code analysis in this report play an important role to predict a natural heat removal capability by the primary coolant system.

The test facility is installed to perform the reflux condensation experiment. It is composed of the mixture generation part and the reflux condensation part. The latter part includes the test section. Test section has a vertical tube having the same outer diameter as the KSNPP, which is surrounded by the coolant block.

The experiments are performed with variations of three main parameters; the system pressure, the inlet steam flow rate and the inlet air mass fraction. Their ranges are 1~2.5bar, 1.348~3.282kg/hr and 11.8~55%, respectively. The experiments are also performed in pure inlet steam flow rate to compare the effects with and without the noncondensible gas.

The heat transfer data of the reflux condensation and the flooding data are obtained. The flooding is observed to know the upper limit of the reflux condensation. As a result, the onset of flooding occurs at lower upward flow rate compared to Wallis' correlation in geometric conditions of the sharp edge and the inner diameter of 16.56mm. The heat transfer coefficients near the tube inlet increase as the inlet steam flow rate and the system pressure increase. In the presence of noncondensible gas, the heat transfer capability is dramatically decreased. The empirical correlation is developed using the local data of heat transfer coefficients. The degradation factor is correlated with four nondimensional parameters. It turns out that the Jacob number and the film Reynolds number are dominant parameters.

The non-iterative model is newly developed to predict the steam condensation heat transfer in the presence of the noncondensible gases. It is applicable to engineering. The condensation models, default model and alternative model, in RELAP5/MOD3.2 are assessed with the reflux condensation data. The heat transfer coefficients estimated by the non-iterative model and with the existing models of the standard RELAP5/MOD3.2 code are compared with the present experimental data. The default model and the alternative model under-predicts and over-predicts, respectively. The non-iterative model better predicts than the present models do.

Acknowledgement

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Nomenclature

AMF	air mass fraction
FA	inlet air flow rate
FM	inlet steam-air mixture flow rate
FS	inlet steam flow rate
IET	Integral Effect Test
KSNPP	Korea Standard Nuclear Power Plant
LOCA	Loss Of Coolant Accident
LORHR	Loss Of Residual Heat Removal
NPP	Nuclear Power Plant
RCS	Reactor Coolant System
SET	Separate Effect Test
SG	Steam Generator
TB	mixture bulk temperature
TC	coolant temerature
TWo	outer wall temperature
b	blowing parameter
B	mass driving force
C	total number of node volumes
C_f	friction factor
C_p	specific heat at constant pressure
d, D	diameter
D_h	hydraulic diameter
F	degradation factor($= h_{tot} / h_f$)
g	mass transfer conductance
h	heat transfer coefficient
i	enthalpy
Ja	Jacob number
k	thermal conductivity
L	axial length of interval

$\dot{m}$	mass flow rate
$\dot{m}_{cl}$	local condensing flow rate
$\dot{m}_{ca}$	accumulated condensing flow rate
N_A, N_B	a defined arbitrary nondimensional parameter
Nu	Nusselt number
P	pressure
P_A	a defined nondimensional parameter
Pr	Prandtl number
q''	heat flux
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
St	Stanton number
T	temperature
u	velocity, internal energy
W	mass fraction
X	mole fraction
x	local axial length
y	a defined nondimensional parameter

Greek

δ	liquid film thickness
ρ	density
ε_s	sand roughness
μ	viscosity

Subscripts

AB	mass transfer
a, air	air
b	bulk
c	coolant

cd, *cond*	conductive
cv, *conv*	convective
e	entrance region
f	condensate, liquid phase, film side
g	vapor phase, mixture side
h	heat transfer
i	inner, interface
in	initial
m	mixture
o	outer
s	steam, saturated
t, *tot*	total
v	vapor phase
w	wall
0	no transpiration

Superscripts

*	dimensionless form

Chapter 1.

Introduction

1.1 Background

In case of the loss-of-residual-heat-removal (LORHR) during mid-loop operation in nuclear power plants (NPP), 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 during mid-loop operation is revealed not to be negligible when compared to the accidents during normal operation. For this reason, the integral experiments and the code analysis for the LORHR accident during mid-loop operation have been performed in several countries. In Korea, a few research groups have evaluated and analyzed the experimental results of the integral effect tests (IET) in the foreign countries using the thermal-hydraulic codes. But the separate effect tests (SET) representing the conditions of a mid-loop operation are little observed.

As the results of the thermal hydraulic code analysis for the accident of mid-loop operation, it did not properly estimates the low pressure, low temperature and low flow conditions such as mid-loop operation. This was because the models in codes were on the basis of the accidental situation in the high pressure and high temperature such as small break loss-of-coolant-accident (LOCA) or large break LOCA. Therefore, the comprehensive study of the SET is needed because the predictability of the individual models can be evaluated by the relevant experimental database and an improvement can be incorporated into the code, if needed.

A reflux condensation is the countercurrent flow between upward flow of the steam-air mixture and downward flow of the condensate, which has the upper limit by the onset of flooding. The reflux condensation heat transfer in the U-tube plays an important role of the residual heat removal to the secondary side of steam generator (SG) and has an advantage in cooling the reactor coolant system (RCS) without loss of a coolant inventory.

1.2 Objectives and Report Organization

The objective of the present study is to obtain the heat transfer data through the SET, to assess capability of the condensation model in the RELAP5/MOD3.2 code, and to develop a new non-iterative model for the reflux condensation with noncondensible gas in a vertical tube simulating the U-tube riser.

In the reflux condensation, the present experimental works are performed with the emphases on the following conditions:

- high mass fraction of noncondensible gas
- low pressure, low temperature and low flow conditions
- local measurement of heat transfer capability along a single tube.

From the above conditions, the data of the local heat transfer coefficient are obtained and the empirical correlation is developed. Additionally, the onset of flooding data is obtained to examine the upper limit of reflux condensation.

The condensation models of the RELAP5/MOD3.2 code are assessed using the present experimental data and a new condensation model is developed to improve the prediction capabilities of RELAP5/MOD3.2.

In Chapter 2, the experimental works are described; test facility, its instruments, test conditions, test results and discussion. The test results include the flooding limit to the reflux condensation, the parametric effects on the heat transfer capability, and the development of an empirical correlation. In Chapter 3, the existing condensation models in the current RELAP5/MOD3.2 code are firstly introduced briefly. The newly developed model is secondly described about its derivation and the application to the reflux condensation. Finally, the assessment results of RELAP5/MOD3.2 for reflux condensation are described. The nodalization is represented and the prediction capabilities of the existing and newly developed models are compared using the present experimental data of reflux condensation. The uncertainty analysis method, the RELAP5/MOD3.2 input deck, and the test data are attached in the Appendices.

Chapter 2.

Reflux Condensation Experiment

2.1 Objectives of the Present Works.

The objectives of the reflux condensation experiment are as follows:

- Perform an experiment of the reflux condensation heat transfer using the single vertical tube.
- Observe the flooding phenomenon in a vertical tube, and obtain the database of an onset of flooding as the upper limitations of reflux condensation.
- Obtain the database of the local heat transfer coefficients.
- Develop the empirical correlation for heat transfer coefficients using the database.

Local heat transfer coefficients are obtained through the local temperature measurements along the axial direction, which gives the distributions of the heat transfer capability and thus, the effective heat transfer regions by the reflux condensation. It can be the noticeable results that the local quantities of heat transfer in the presence of a noncondensible gas of high mass fraction. Using the data of heat transfer coefficients, an empirical correlation is developed as the function of several nondimensional parameters to show the governing factors of the reflux condensation.

2.2 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. From his results, the flooding flow rate and heat transfer rate per unit axial area decreased as the air flow rate increases. It was observed that once a tube was flooded, its heat removal capability was much less than that of the tube before flooding. Banerjee et. al. (1981) carried out the experiment of the transition from the reflux condensation 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 differences between the inlet and the outlet of the tube with the length of a single phase liquid column. According to the study, liquid column was above the reflux condensing region and occurred after flooding. Nguyen and Banerjee (1982) used the inverted U-tube test section that was directly attached to the boiler, and observed various flow patterns and oscillatory behavior. 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. They made a few steady states varying the amount of injected nitrogen gas and the secondary saturated temperature. The transition of the active to passive condensing region was observed by measuring the temperature along the axial direction. 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's 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) studied 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 newly evaluated 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 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 (55～105 bar) the empirical correlation for the heat transfer coefficient was developed using the film Reynolds number. However, the data representing the correlation was insufficient.

Table 2.1 shows the experimental conditions and the test section geometries of the previous works. In summarizing the previous works, three kinds of flow regimes exist as an increase of gas-phase upward flow in a vertical condensation.

(1) Reflux condensation

(2) Flooding and oscillation of liquid column

(3) Natural circulation of liquid

The previous works were mainly interested in the above flow regimes and their transition, and tried to modeling theoretically. These focus also make an agreement with the integral effect test (IET) considering the mid-loop operation. They distinguished the transition points using the amount of pressure drop.

Table 2.1 Previous works related to the reflux condensation

Authors	Test section geometry				Inlet steam flow [kg/hr]	NCG	Fraction or amount of NCG	Temperature measuring points
	Tube material	Tube shape	Dia. [mm]	Height [m]				
Park	Pyrex	U-tube	15.5	1.90~ 1.63	0.75~ 3.0	Air	0.~0.03	2 (in/mid.)
Banerjee & Chang	Pyrex	Vertical	17.6	4.0	~4.8	Air	0~0.05	2 (in/out)
Nguyen & Banerjee	Pyrex	U-tube	16.0	2.16	~6.1	Air	-	2 (in/out)
Hein	Stainless Steel	U-tube	20.5	1.05	~3.6	Injected N_2	0.97~ 3.4g	Local points
Tien	Copper	Vertical	20.9/9.5	0.9	1.7~2.3	None	-	3
Wan & Girard	Pyrex	Vertical	12.7~25 .4	4.0	7.0	None	-	8.
Chang & Girard & Wan	Pyrex	U-tube	12.7	1.5	18	None	-	2 (in/out)
This Exp.	Stainless Steel	Vertical	19.05	2.4	1.4~3.3	Air	0~0.55	11

※ NCG = noncondensible gas

The reflux condensation was not independently described but considered as one of the flow regimes in countercurrent flow in the previous works. It was due to the SB-LOCA specific phenomena was main interest in the transition of the flow regime. Flow regimes were visually observed using the transparent tubes, e.g. pyrex tube, which makes impossible to measure the local parameter in tube because of the manufacturing problems. Also, small concentrations of noncondensible gas were treated in the previous works. The nitrogen or air was used as a noncondensible gas, which made a vapor mixture in the ways of the pre-injected condition or the steady flow condition. The concentrations of noncondensible gases in the previous works had small fraction, which were within 10% as a vapor mass fraction unit. In some cases of the previous works, the local temperature measurements along the axial length are found, but this is not to obtain the local heat transfer coefficients but to know the in-tube condition and flow regime.

The present work treats the mixture flow with the large concentrations of the air as the noncondensible gas. Also the major characteristics in this study are to measure the temperatures at eleven local points along the stainless-steel tube such that the local heat transfer coefficient distribution can be obtained.

2.3 Facility and Instruments

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 latter includes the main test section. Test section is composed of the vertical tube, the coolant block, lower plenum and upper plenum, which has a geometry of the total length of 3.56m, and the length of effective temperature measurement of 2.4m. Figure 2.1 shows an overall schematic of the test facility.

The steam-air mixture generation part is composed of steam tank, heater, power controller, air line, air pre-heaters and flow mixer. The heater controller having the maximum power of 150kW controls a steam generator. The steam generated from the steam tank and the air from the air line individually flow into the flow mixer and mixed together. Before the air arrives at the flow mixer from the air injection line, two air preheaters heats up the cold air to have a temperature balance with saturated steam. Air preheaters have each power of 3kW and are controlled by the preheater controller. An air flow is measured by the two rotameters having different ranges: 2~20lpm, 9.4~94lpm. The air rotameters have a measuring errors of ±2.5%. The steam-air mixture from the mixer flows into the lower plenum in the reflux condensation part. All pipings are 1-inch diameter size in this part. Thermal insulating material is used to cover around the pipes and tanks to lose as low as possible. The droplet separator and the turbinemeter are located on the steam-air mixture line. A droplet generated from the mixture line by the heat loss is removed on the droplet separator and then the mixture flow rate is measured by the turbinemeter that has a maximum range of 8.1m3/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 on a vertical tube and used to measure the tube centerline temperatures and the outer wall temperatures along the same axial locations. Figure 2.2 shows the position of thermocouples' installation in a vertical tube. The coolant temperatures are also measured at the same positions. The measuring points are located closer to the tube inlet because the capability of heat transfer in this region becomes large. A vertical tube has the geometry of the outer diameter of 0.75" (equal to the U-tube diameter of KSNPP), inner diameter of 16.56 mm and effective length of 2.4m (temperature measuring region). The tube inlet has a shape of sharp edge. The coolant block is installed around the vertical tube and establishes the annular shaped flow of the coolant between the block and the tube. The outer diameter of coolant annulus is 57.15mm. The K-type 0.125" diameter thermocouples to measure the coolant temperature are installed on a coolant region penetrating into the coolant block. Figure 2.3 shows the schematic of the thermocouple attachments on the test section as a top view. Figure 2.4 shows the vertical tube and the coolant block as a side 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 lower plenum has visual windows to observe the falling condensate in tube inlet. The air-steam separator is installed on the venting line for extracting the remaining steam in a vented flow. However, the most amount of inlet steam is condensed on the inner surface of the vertical tube and no noticeable collection of the vented steam observed. Figure 2.5 shows the view from the bottom to the top. In this photograph, the lower plenum is partially shown and the coolant inlet is connected with four coolant injection hose. The thermocouples to measure the coolant temperature are shown on the right side of the vertical test section.

Total 6 pressures, 4 flow rates and 53 temperatures are measured in the reflux condensation experiment. There are two ways in the measurements of data. One is to observe or measure visually, and the other is to measure the electric signals by the measuring instruments. The air flow and coolant flow are measured by reading of the scale marks of rotameters. The steam flow is measured by the turbinemeter. The pressures are measured by the pressure transducers, and all the temperatures are measured by the K-type thermocouples. All data except the air flow rate and the coolant flow rate are collected by the data acquisition system (DAS). The DAS is made by Hewlett-Packard Co. and includes the main-frame (E1421B), MUX module (E1413C), terminal block (64 channels) and so on, and uses the GP-IB interface for communicating with the IBM 486 PC. The HP-VEE v.3.2 is used as software. The DAS collects 61 data per time interval of 0.4 ~ 1.0 second, and displays data on monitor. The tube centerline temperatures are graphically monitored to discriminate the temperature fluctuations by the onset of flooding. Table 2.2 summarizes the instruments on the components of facility and their uncertainties. The sample error analysis for the heat transfer coefficient is represented in Appendix A.

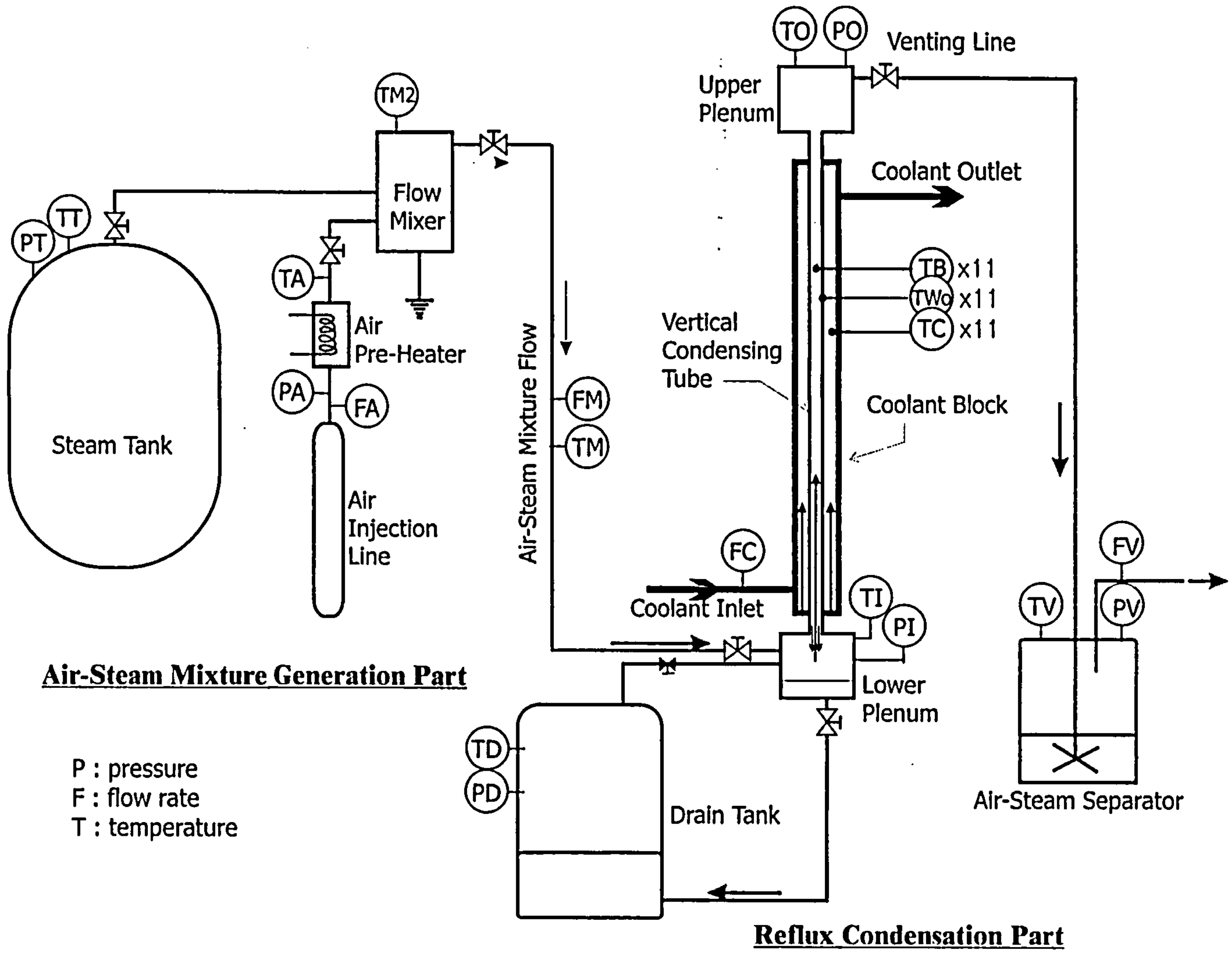

Figure 2.1 Overall schematic of reflux condensation facility

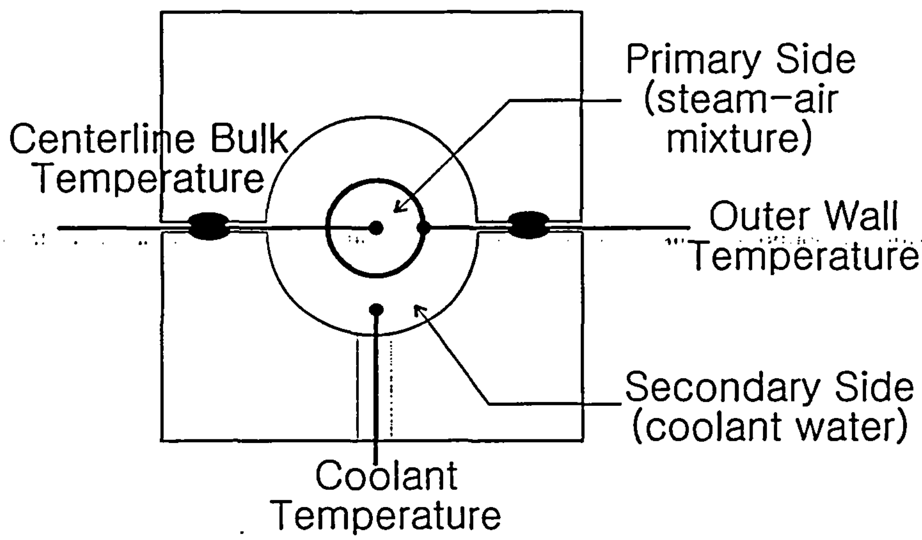

Figure 2.2 Top view of vertical tube and coolant block

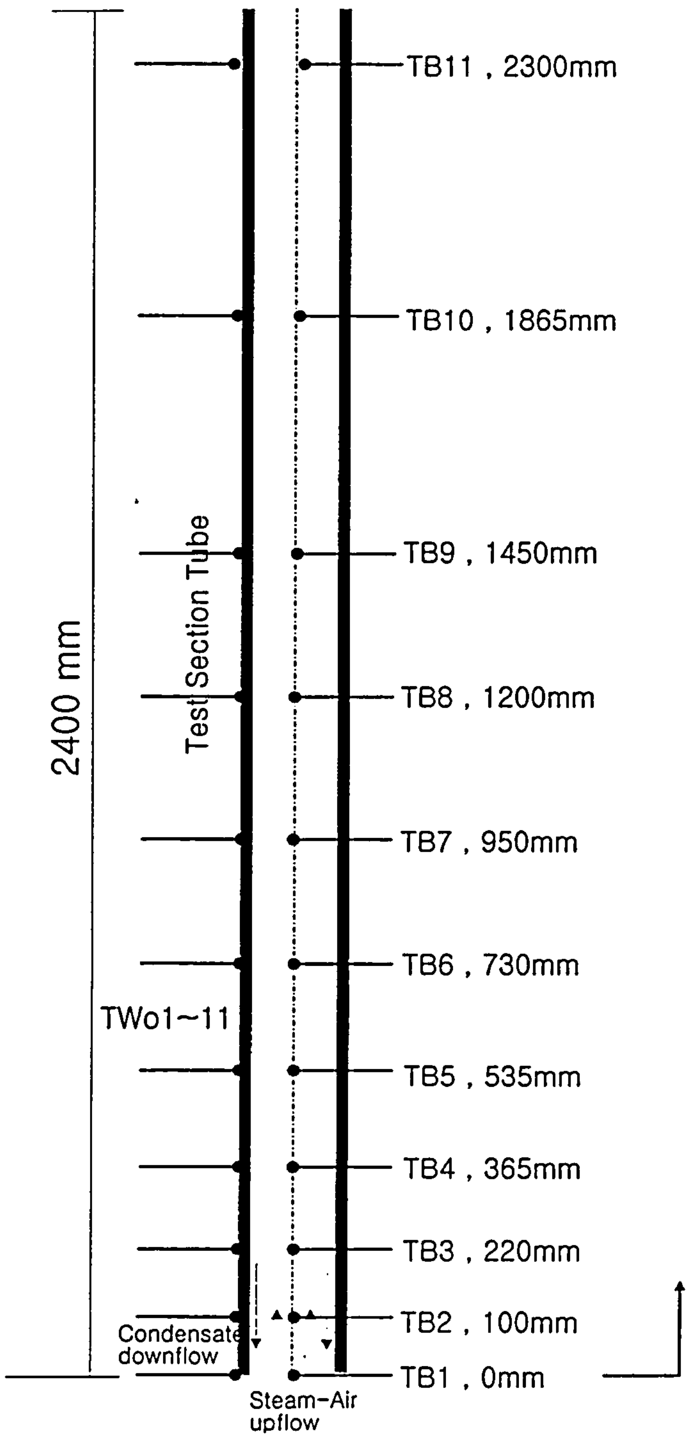

Figure 2.3 Location of temperature measurements in vertical tube

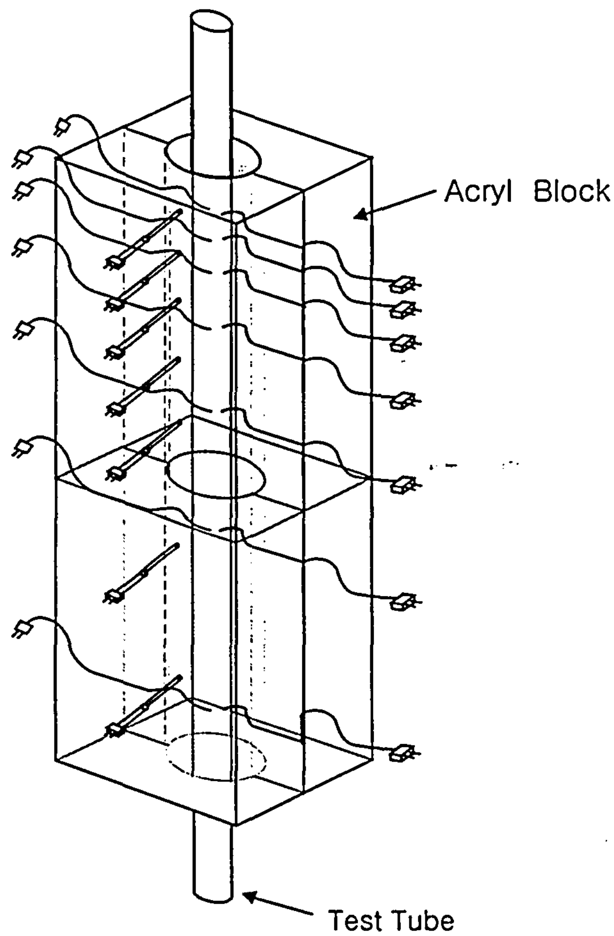

Figure 2.4 Vertical tube and coolant block

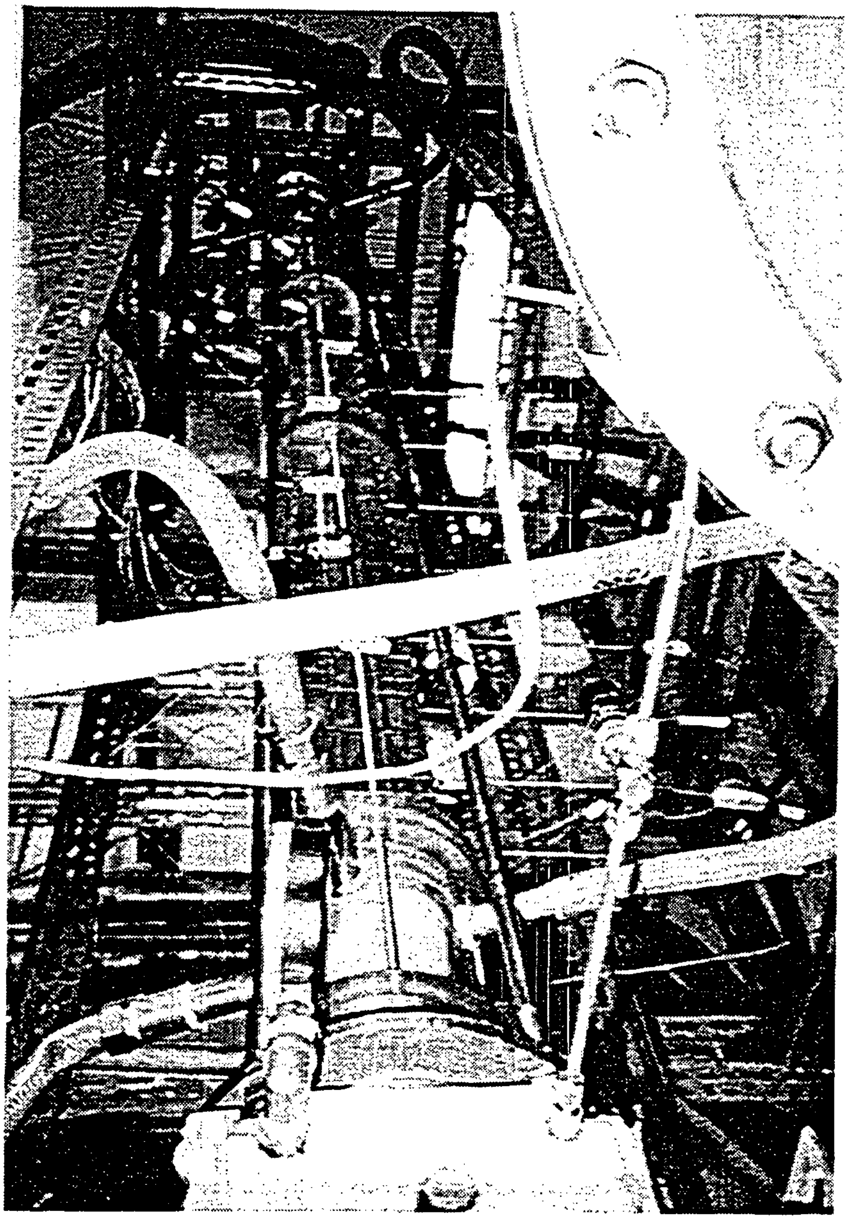

Figure 2.5 Test section of the reflux condensation experiment

Table 2.2 Instruments on the components of facility with measurement uncertainty

Component	Identifier	Parameter	Instrument	Uncertainty
Air-Steam Mixture Generation Part				(full scale)
Steam Generation Tank	PT	steam tank pressure	ABB PT-624 transducer 0~8 kgf/cm^2	0.1%
	TT	steam tank temperature	K-type T/C 0.125" Max. 1000 °C	0.5%
Air Injection Line	PA	air line pressure	PX425-100GV(Omega Co.), 0~100 psig	0.2%
	TA	air line temperature	K-type T/C 0.125" Max. 1000 °C	0.5%
	FA	inlet air flow rate	Dywer rotameters 2-20lpm, 20-200SCFH	2%
Flow Mixer	TM2	air-water mixture temperature on flow mixer	K-type T/C 0.125" Max. 1000 °C	0.5%
(on loop)	FM	air-water mixture flow rate on turbinemeter	turbinementer(Sponsler Co.) SP712-2 rev.B 1/2" max. 8.1m^3/hr	1%
	TM	air-water mixture temperature on loop	RTD4~20mA(SenTech Co.) Max. 650 °C	0.5%
Reflux Condensation Part				
Upper Plenum	TO	upper plenum temperature	K-type T/C 0.062" Max. 1000 °C	0.5%
	PO	upper plenum pressure	transducer: PX425-100GV (0~6.8)(Omega Co.) gauge: 0~5kgf/cm²	0.2%
Lower Plenum	TI	lower plenum temperature	K-type T/C 0.062"	0.5%
	PI	lower plenum pressure	transducer: PT3300/B (0~50~5kgf/cm²)(Konics Co.), gauge: 0~5kgf/cm²	0.3%
Vertical Tube	TB1 ~ TB11	air-water mixture bulk temperature in tube center	K-type T/C 0.02"(U) Max. 760 °C	0.5%
	TWo1 ~ TWo11	outer wall temperature on vertical tube	K-type T/C 0.02"(U) Max. 760 °C	0.5%
Coolant Loop	FC	coolant flow rate	Dwyer, rotameter 0.5~2.5lpm, 0.8~2.2gpm	2%
	TC1 ~ TC11	coolant temperature	K-type T/C 0.125"(U) Max. 760 °C	0.5%
Drain Tank	TD	drain tank temperature	K-type T/C 0.062" Max. 1000 °C	0.5%
	PD	drain tank pressure	pressure gauge 0~5 kgf/cm²	2%
Vented Air-Water Separator	FV	vented air flow rate	Dwyer, rotameter 10~100lpm	2%
	TV	separator temperature	K-type T/C 0.062" Max. 1000 °C	0.5%
	PV	separator pressure	pressure gauge 0~1.5kgf/cm²	2%

2.4 Data Reduction Methods

2.4.1 Local heat transfer coefficients

The calculation of the local heat transfer coefficients requires the measurement of the temperatures at the tube centerline (T_b), the tube outer wall ($T_{w,o}$), and the coolant (T_c). These three temperatures are all measured along the 11 axial points. Therefore, total 33 measurements of temperature are performed to obtain local heat transfer coefficients. In data reduction process, the inner wall temperature and the heat flux can be also calculated.

Data reduction for heat transfer coefficients is first developed from the basic heat balance concept. The heat loss by the reflux condensation from the inside of a vertical tube is transferred to the secondary side of coolant annulus through the unit tube wall area, which is the same as the heat gain by the increase of coolant temperature. This heat balance is expressed mathematically as follows:

$$q''(x)dA = \dot{m}_c C_p dT_c \quad (2\text{-}1)$$

where the $q''(x)$ is the heat flux flowing out through a unit wall area by the condensation of steam in the mixture 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:

$$q''(x) = \dot{m}_c C_p \frac{dT_c(x)}{dA} = \frac{\dot{m}_c C_p}{\pi d}\frac{dT_c(x)}{dL} \quad (2\text{-}2)$$

where the L is the axial length of interval where the adjacent two coolant temperatures are measured. The tube inner wall temperature can be calculated by the calculated heat flux and the measured outer wall temperature:

$$T_{w,i}(x) = T_{w,o}(x) + q''(x)\cdot R \quad (2\text{-}3)$$

$$R = \frac{\ln(D_o / D_i)D_h}{\pi k_{sus}} \quad (2\text{-}4)$$

where D_h is the hydraulic diameter and k_{sus} is the thermal conductivity of stainless-steel 304 as a material of vertical tube. Finally, the local heat transfer coefficient can be obtained through the heat flux divided by the difference between the tube centerline temperature and the inner wall temperature.

$$h(x) = \frac{q''(x)}{(T_b(x) - T_{w,i}(x))} \tag{2-5}$$

2.4.2 Local steam and condensate flow rates

The turbinemeter is used for measuring the steam-air mixture flow rate. However, the flow data from the turbinemeter installed on the inlet piping has some different value from the actual flow rate at tube inlet because of the heat loss in the region from the steam piping to the inlet plenum and of the falling liquid condensate. The actual flow rate can be also obtained using the local temperature data. Actual flow rate by data reduction is calculated, as results, it has a little lower value than the measured flow rate by turbinemeter.

As a results of experiment, it was found that most of the steam is condensed through the inside of vertical tube. Therefore, the amount of inlet steam flow should be the same as the amount of falling condensate at tube inlet. The inlet steam flow rate is obtained as follows:

$$\dot{m}_{s,in} = \frac{\dot{m}_c C_p (T_c(L) - T_c(0))}{i_{fg}}, \tag{2-6}$$

where L is the temperature measuring point of tube exit, and the i_{fg} denotes the latent heat of the steam. To obtain the local data for the steam flow rate ($\dot{m}_c(x)$) and the condensate flow rate ($\dot{m}_f(x)$), the following parameters are defined in the reduction process:

- local condensing flow rate ($\dot{m}_{cl}$) : the amount of condensation in a specified local interval
- local condensate flow rate ($\dot{m}_f$) : the amount of condensate flow at a local position
- accumulated condensing flow rate (m_{ca}) : the amount of condensation in the interval from inlet to the specified position

Local condensing flow rate in specified interval (i) is known as follows:

$$\dot{m}_{cl}(i) = \frac{\dot{m}_c C_p [T_c(i+1) - T_c(i)]}{i_{fg}}. \tag{2-7}$$

The local steam flow rate ($\dot{m}_s$) is the value of the inlet steam flow rate subtracted from the accumulated condensing flow rate ($\dot{m}_{ca}$) at the local point of x. Figure 2.6 shows the concept of nodes for calculating the local condensing or condensate amounts, where x and i represent the temperature measuring point and the number of interval between x and $x+1$, respectively.

The accumulated condensing flow rate at a position x is estimated as follows:

$$\dot{m}_{ca}(x) = \frac{\dot{m}_c C_p (T_c(x) - T_c(0))}{i_{fg}} = \sum_{i=1}^{x-1} \dot{m}_{cl}(i). \tag{2-8}$$

Then the local steam flow rate can be obtained as follows:

$$\dot{m}_s(x) = \dot{m}_{s,init} - \dot{m}_{ca}(x). \tag{2-9}$$

The local condensate flow rate ($\dot{m}_f$) represents the actual amount of condensate at x. In reflux condensation, the steam upward flow makes the countercurrent flow with the condensate downward flow. Therefore, the condensing flow rate ($\dot{m}_{ca}$) is different from the condensate flow rate ($\dot{m}_f$). Here, $\dot{m}_f(x)$ is the sum of the local condensing flow rate from x to L and is also the accumulated condensing flow rate from 0 to L subtracted from that from 0 to x:

$$\dot{m}_f(x) = \sum_{i=x}^{L-1} \dot{m}_{cl}(i) = \dot{m}_{ca}(L) - \dot{m}_{ca}(x). \tag{2-10}$$

By Equation (2-9), the accumulated flow rate is obtained as follows:

$$\dot{m}_{ca}(x) = \dot{m}_{s,in} - \dot{m}_s(x), \tag{2-11}$$

$$\dot{m}_{ca}(L) = \dot{m}_{s,in} - \dot{m}_s(L) = \dot{m}_{s,in}. \tag{2-12}$$

Substituting the above equation into Equation (2-10), the condensate flow rate at x is obtained as follows:

$$\begin{aligned} \dot{m}_f(x) &= \dot{m}_{ca}(L) - \dot{m}_{ca}(x) \\ &= \dot{m}_{s,in} - [\dot{m}_{s,in} - \dot{m}_s(x)] \\ &= \dot{m}_s(x). \end{aligned} \tag{2-13}$$

The inlet flow rate of air is constant along the channel when it is flowing through the tube because of its noncondensability.

$$\dot{m}_a(x) = \dot{m}_{a,in} = \dot{m}_a \tag{2-14}$$

Moreover, the local air mass fraction can be obtained as follows:

$$W_{air}(x) = \frac{\dot{m}_{a(x)}}{\dot{m}_s(x) + \dot{m}_a(x)} = \frac{\dot{m}_a}{\dot{m}_s(x) + \dot{m}_a}. \tag{2-15}$$

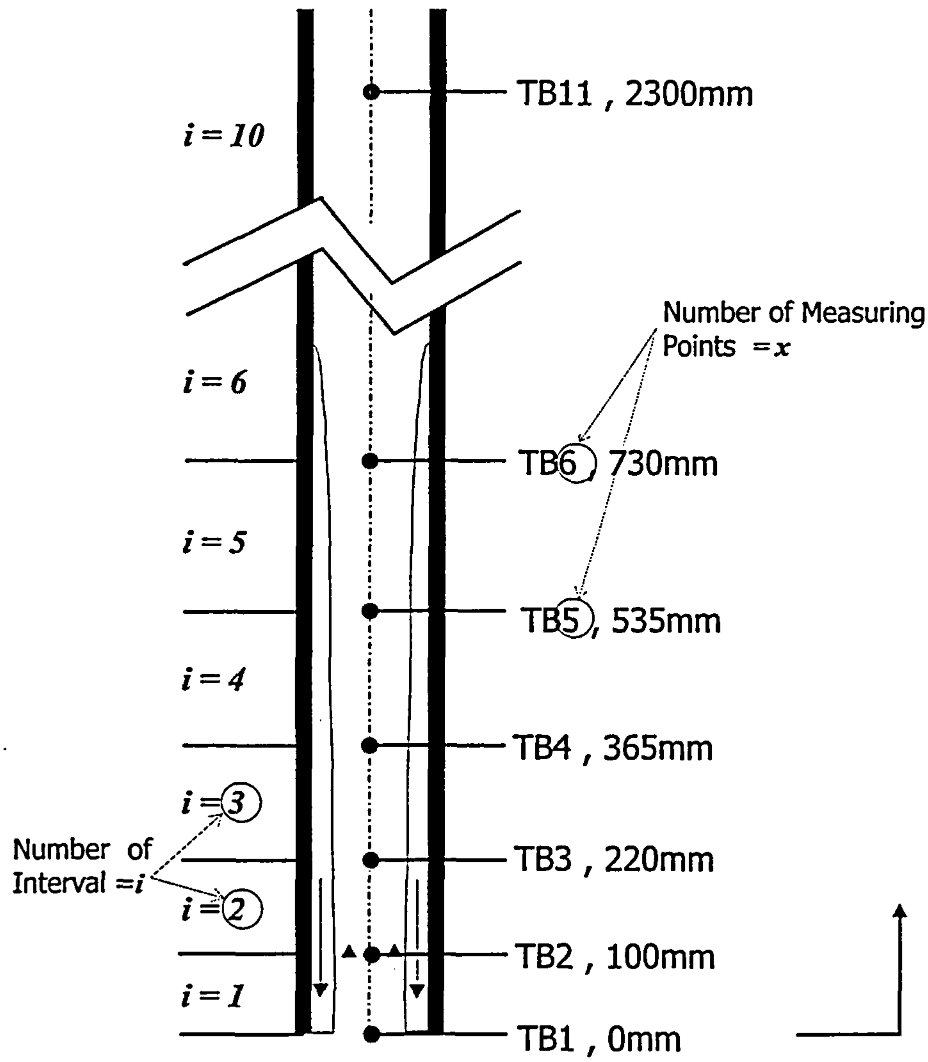

Figure 2.6 Locations of temperature measurements to calculate the local condensing flow

2.5 Results and discussion

2.5.1 Experimental Conditions

In the present experiment, 29 sets of data with variations of three main parameters are obtained and each sets have 11 data at local points. Table 2.3 represents the experimental ranges. Table 2.4 represents 29 data set of a reflux condensation experiment performed under various main parameters as a test matrix form. Total 165 of local data are available for deriving the correlation of the heat transfer coefficients, which are selected from 6 sets at 2.5 bar, 7 sets at 1.5 bar and 16 sets at 1.0-bar. Two sets at 1 bar are the cases of the inlet pure steam in the absence of the air injection.

The experimental ranges of the system pressure, the inlet steam flow rate, and the inlet air mass fraction are 1~2.5 bar, 1.348~3.282 kg/hr and 11.8~55.0 %, respectively. The inlet steam is all condensed in a vertical tube. Therefore, the amount of vented air is the same as that of injection.

Figure 2.7 shows the domain of the test conditions with respect to the inlet steam flow rate and the inlet air mass fraction. In the figure, upper and lower limit are also plotted, which represent the flooding limit proposed by Wallis (1969) and the measured range of turbinemeter, respectively. The data has a somewhat dispersed distribution because the desired data on flow rates and air mass fractions cannot be obtained as expected due to the difficulty in the control of the low flow condition.

Inlet steam is completely condensed on the inner surface of a vertical tube. The length of the active condensing region is approximately estimated to be within 1.865 m considering the local heat transfer coefficients and the temperature profiles. After the active region, it is called as the passive region, where the temperature gradients almost become zero. In reflux condensation, most of condensates smoothly flow down along the tube wall and the very small portion of the condensates falls directly. The local data used to the correlation development are attached in Appendix C.

Table 2.3 Experimental ranges

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

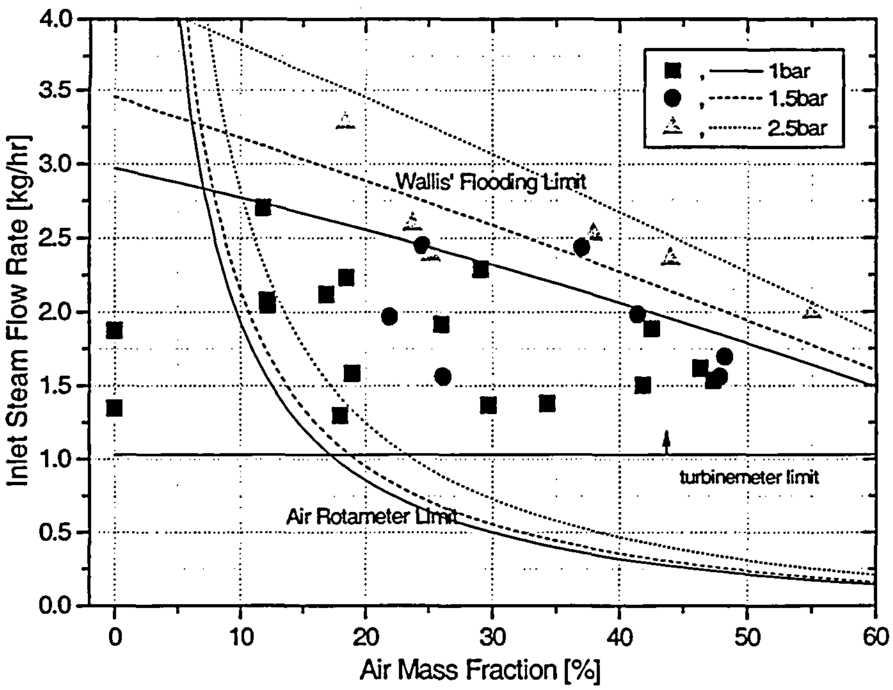

Figure 2.7 Experimental domain in terms of air mass fraction and inlet steam flow rate

Table 2.4 Test matrix for reflux condensation

I.D.	FS [kg/hr]	AMF [%]	FA [kg/hr]	FM [kg/hr]	Press [kPa]	FC [Kg/s]	TC1	Max. HF	Max. HTC
RA01	3.282	18.4	0.742	4.023	265.3	0.0333	11.1	115032	2382
RA02	2.591	23.7	0.804	3.395	266.0	0.0504	21.5	81136	1738
RA03	2.525	37.9	1.538	4.062	258.2	0.0333	9.9	51074	1044
RA04	2.384	25.2	0.804	3.187	254.5	0.0504	23.7	38719	763
RA05	2.357	44.0	1.850	4.207	260.0	0.0333	10.0	35701	709
RA06	2.000	55.0	2.443	4.443	263.3	0.0333	10.0	25908	526
RB01	2.448	24.5	0.796	3.244	157.2	0.0333	8.8	45126	1104
RB02	2.436	37.0	1.430	3.866	155.5	0.0333	8.7	40224	1024
RB03	1.985	41.4	1.403	3.388	152.0	0.0630	22.9	23195	736
RB04	1.967	21.9	0.551	2.518	156.5	0.0250	7.0	44897	1137
RB05	1.694	48.2	1.577	3.270	156.1	0.0250	6.5	25911	624
RB06	1.561	26.1	0.551	2.112	156.3	0.0250	6.7	25956	545
RB07	1.560	47.8	1.426	2.986	155.4	0.0333	8.8	21752	473
RC01	2.703	11.8	0.361	3.064	107.6	0.0333	12.0	56820	2231
RC02	2.287	29.1	0.938	3.225	107.4	0.0333	11.5	39285	1243
RC03	2.232	18.5	0.506	2.738	108.4	0.0333	11.6	39448	1243
RC04	2.119	16.9	0.432	2.550	106.9	0.0333	11.6	39316	1185
RC05	2.077	12.1	0.285	2.362	104.0	0.0504	20.1	37194	2091
RC06	2.046	12.2	0.285	2.331	104.0	0.0630	19.1	23800	805
RC07	1.916	26.0	0.672	2.588	107.0	0.0630	18.0	34596	1115
RC08	1.887	42.5	1.394	3.280	116.2	0.0333	11.2	22714	784
RC09	1.875	0.0	0.000	1.875	108.6	0.0263	13.8	121382	5645
RC10	1.618	46.3	1.392	3.010	116.1	0.0333	10.5	21666	597
RC11	1.584	18.9	0.369	1.953	107.0	0.0630	18.1	40089	1149
RC12	1.535	47.3	1.380	2.915	109.4	0.0333	10.8	27529	837
RC13	1.504	41.8	1.081	2.585	105.4	0.0250	6.5	22245	632
RC14	1.379	34.3	0.720	2.099	105.4	0.0250	6.9	23560	582
RC15	1.367	29.7	0.576	1.943	107.0	0.0333	15.6	40872	1272
RC16	1.348	0.0	0.000	1.348	107.3	0.0250	14.2	92803	3971

FS : inlet steam flow rate

FA : inlet air flow rate

HF : heat flux

TC1 : inlet coolant temperature

FM : steam-air mixture flow rate

FC : coolant flow rate

HTC : heat transfer coefficient

2.5.2. Limitation of the reflux condensation

The reflux condensation has an upper limit. When the upward flow rises over the upper limit, the condensate becomes unstable and falls with perturbation. This phenomenon is no more 'reflux' flow regime. This upper limit is called 'flooding' and the flow regime changes beyond 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 is investigated. As a result, it was found that the onset of flooding occurs at lower upward flow rate when compared to the Wallis' correlation in 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. In the present work, it is impossible to observe visually due to the use of a stainless steel tube for temperature sensor installation. Instead, the severe oscillation of the tube centerline temperature is regarded as a discrimination criterion of the onset of flooding. It is based on that the slugging or bridging of the cold condensate by the flooding cause a sudden and intermittent drop of the tube centerline temperature, and that the oscillation of the temperature can be discernable.

Figure 2.8 shows the oscillations of the temperature due to flooding as the stepwise increase of upward flow. Table 2.5 shows the flooding results. j_g^* and j_f^* represent the non-dimensional superficial velocities of the steam-air mixture and the condensate, respectively. The condensate flow rate is dependent on the inlet steam flow rate because the injected steam is condensed and becomes condensate. Therefore, the distributions of data points are in the limited range of j_f^*. The values of constant C in the Wallis' correlation are 0.6383~0.7034 in the experiments, which is lower than 0.725 suggested by Wallis (See Figure 2.9). The experimental flooding data also covers a wide range of the air mass fraction. The subsequent study of the effects of the air mass fraction may be useful.

Table 2.5 Experimental data of flooding

FS	FM	AMF	Pressure [kPa]	j_f^*	j_g^*	$j_f^{*1/2}$	$j_g^{*1/2}$	$j_{g,Wallis}^{*1/2}$	C by experiment
2.474	2.854	0.133	107	0.00828	0.3586	0.0910	0.5988	0.6340	0.6898
2.452	3.476	0.295	151	0.00816	0.3758	0.0903	0.6130	0.6347	0.7034
3.047	3.886	0.216	261	0.01031	0.3405	0.1015	0.5836	0.6235	0.6851
1.259	3.400	0.630	111	0.00415	0.3759	0.0644	0.6131	0.6606	0.6775
2.111	2.481	0.370	109	0.00700	0.3076	0.0837	0.5546	0.6413	0.6383

FS : inlet steam flow rate [kg/hr]
FM : inlet mixture flow rate [kg/hr]
AMF : air mass fraction

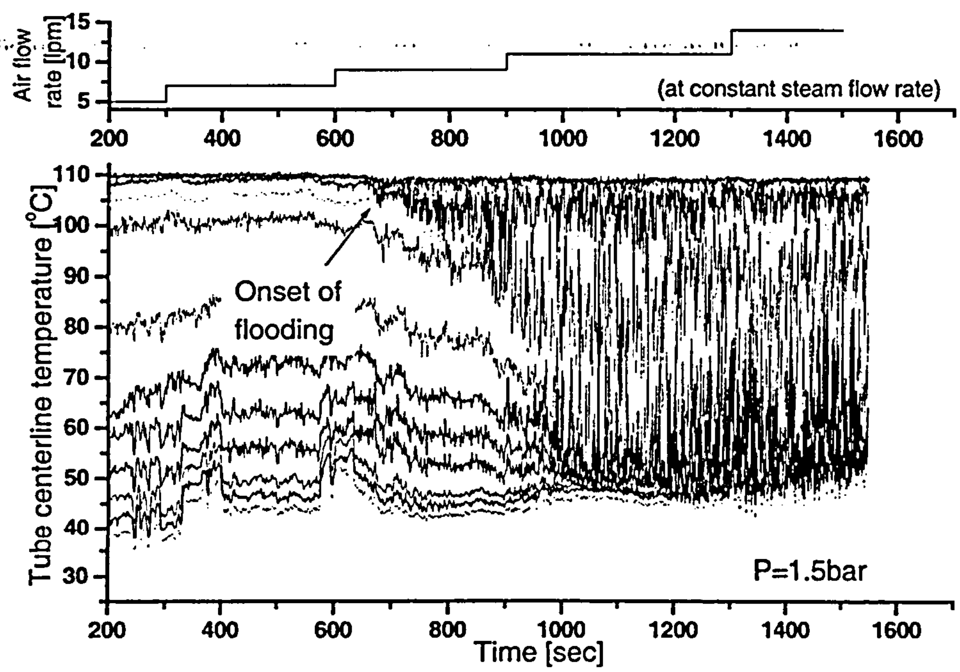

Figure 2.8 Oscillation of tube centerline temperature due to the flooding

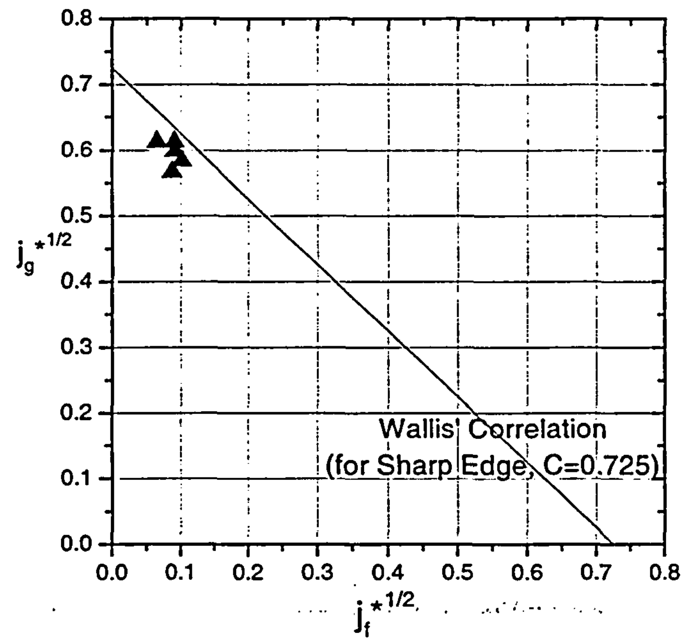

Figure 2.9 Experimental results of flooding limit and comparison with Wallis' correlation

2.5.3 Parametric Effects on the Heat Transfer Coefficients

The parametric effects in the reflux condensation are experimentally investigated that 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 active condensing lengths are roughly estimated by the curves of the heat transfer coefficient or the temperature profiles along the axial direction. The active region is enlarged or contracted according to each condition of the increase of the air mass fraction and of the system pressure.

Figures 2.10 and 2.11 show the effects of the presence and the absence of the air in the inlet flow on the temperature distributions. In case of pure steam in-flow, the injected steam is all condensed near the tube inlet and the tube centerline temperatures suddenly fall off. Instead of a short active condensing region, the heat transfer occurs intensively in this region. In case of an inlet steam-air mixture flow, the active condensing region is enlarged in the case of the air presence, which means the decrease of heat transfer capability by the presence of noncondensible gas in this region.

Figure 2.12 shows the effects of the air mass fraction. The heat transfer coefficients in the absence of the air are larger values than those in the presence of the air, which means the air plays a role of the heat transfer resistance. For the different air mass fractions (11.8~55%), the experimental results also confirm the effect of noncondensible gases on the heat transfer coefficients. As air mass fraction increases in a high concentration range, the heat transfer coefficient decreases near the tube inlet.

Figure 2.13 shows the effect of the inlet steam flow rate. An increase of steam flow causes the overall increase of the local temperatures. The local heat transfer coefficients increase over the entire active region with an increase in steam flow rate.

Figure 2.14 shows the effect of the pressure. With an increase in pressure, the active condensing region becomes shorter and the heat transfer capability is increased within this region. The distribution of heat transfer coefficients is shifted and concentrated toward the tube inlet, but its capability over the entire active region is not changed.

Therefore, it can be found that the decay power affecting the steam generation and the amount of generated noncondensible gases may be the important factors in determining the capability of heat removal through the U-tubes.

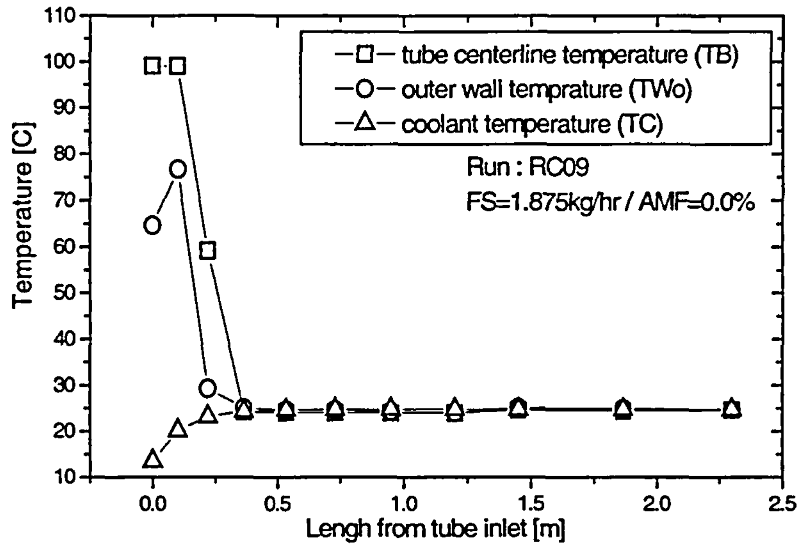

Figure 2.10 Temperature distribution in the absence of air

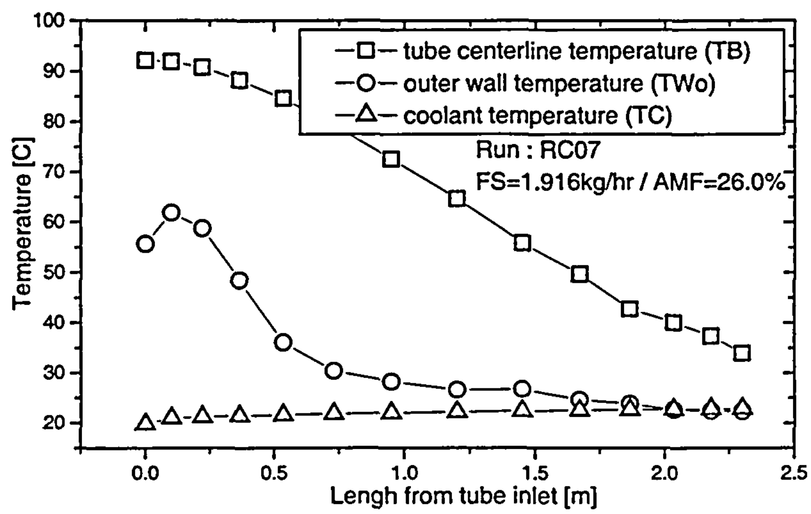

Figure 2.11 Temperature distribution in the presence of air

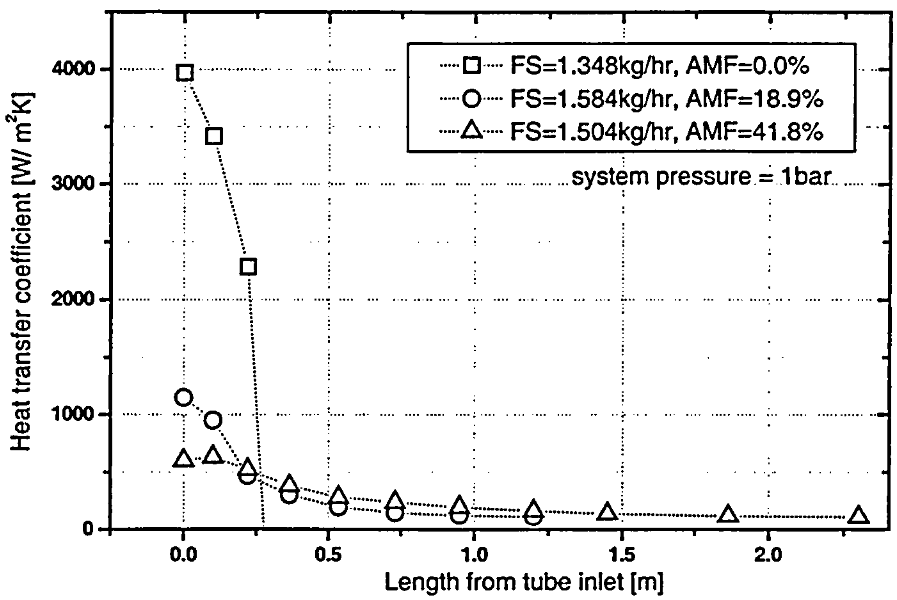

Figure 2.12 Effect of air mass fraction on heat transfer coefficient

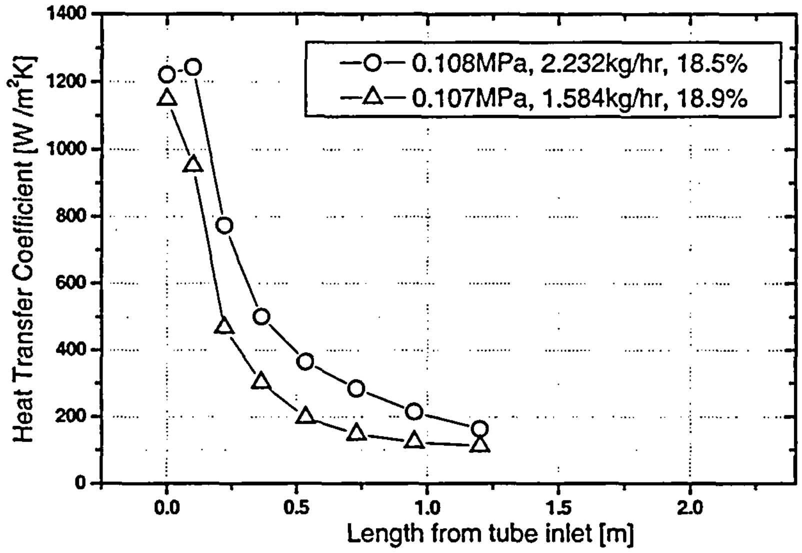

Figure 2.13 Effect of inlet steam flow rate on heat transfer coefficient

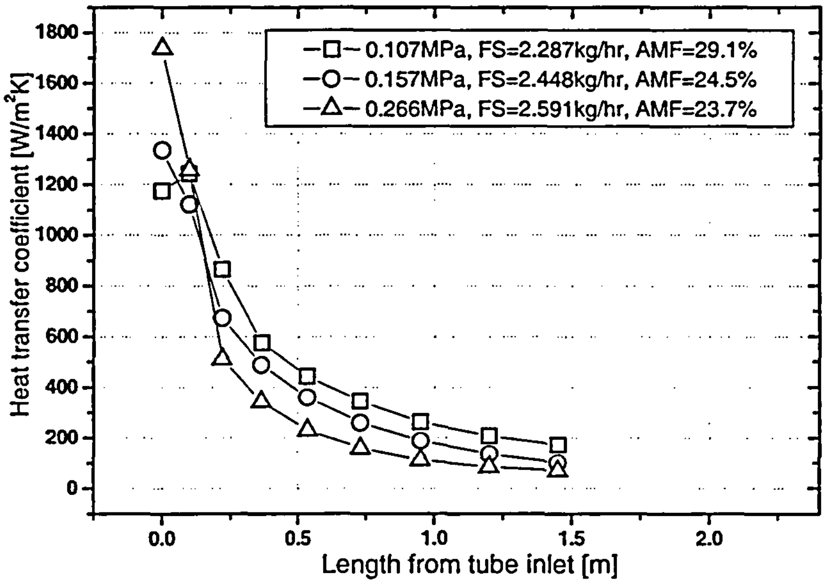

Figure 2.14 Effect of system pressure on heat transfer coefficient

2.5.4. Development of a new empirical correlation

In a vertical flow with condensation, the total heat transfer coefficient (h_{tot}) can be separated into the heat transfer coefficient of film side (h_f) and the heat transfer coefficient of steam-air mixture side (h_g) with respect to two phases, and is separated into the convective (h_{conv}) and condensation (h_{cond}) heat transfer coefficients with respect to the heat transfer mechanisms. The nondimensional parameters related to h_{conv} are Re_g, Pr_g and h_{cond} can be expressed in terms of Re_g, Re_f, W_{air} and Ja.

The degradation factor (F) is suggested for the nondimensionalization of the local heat transfer coefficients. The F represents the relative factor of the wall condensation heat transfer coefficient with noncondensible gases to that without them. 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 $q''/(T_f-T_{w,i})$. T_f is a temperature at the interface between the film layer and the mixture layer. The value of h_f may be expressed as k_f/δ according to Nusselt's classical film condensation theory (1916). k_f is thermal conductivity and δ is a film thickness as follows:

$$\delta = \left[\frac{3\mu_f^2 \mathrm{Re}_f}{4\rho_f(\rho_f-\rho_g)g}\right]^{1/3} \tag{2-16}$$

The degradation factor is developed as a function of 4 nondimensional parameters; the steam-air mixture Reynolds number and the film Reynolds number (Re_g and Re_f), the Jacob number (Ja), and the local air mass fraction (W_{air}). The Prandtl number is excluded because its effects are negligible in the present experimental condition. The least square method for multi-variables is numerically used for correlation development.

The local data in the active condensing region among the entire region are selected for developing correlation. The empirical correlation using 165 data of the local heat transfer coefficients is produced as follows:

$$F = \frac{h_{tot}}{h_f} = 2.58\times10^{-4}\,\mathrm{Re}_g^{0.200}\,\mathrm{Re}_f^{0.502}\,Ja^{-0.642}W_{air}^{-0.244} \tag{2-17}$$

$$\text{where,}\quad 6119 < \mathrm{Re}_g < 66586 \tag{2-18}$$

$$0.140 < W_{air} < 0.972 \tag{2-19}$$

$$0.03 < Ja < 0.125 \tag{2-20}$$

$$1.2 < \mathrm{Re}_f < 166.6 \qquad (2\text{-}21)$$

From this correlation, the variation of F ranging from 0.0153 to 0.3301 demonstrates that the heat transfer is severely degraded by the presence of the air. The degradation factor also decreases along the axial length. This correlation represents the reflux condensation heat transfer in the active condensing region in conditions of the low flow, low pressure and low temperature. Jacob number is the most dominant parameter: the temperature difference between the tube centerline and the inner wall is very important to heat transfer. Film Reynolds number is secondly dominant. This means that the degradation of heat transfer is low in the region of the large temperature difference and the thick condensate film. The film thickness ranges from 3.07×10^{-5} to 1.19×10^{-4} m. The root mean square error of the present correlation is 17.7 % compared with the experimental results.

Figures 2.15 and 2.16 show the comparisons of the h_{tot} results from the experiment and that from the correlation in linear-scale and log-scale. The difference between data from the correlation and the experiment is nearly same irrespective of the vertical location.

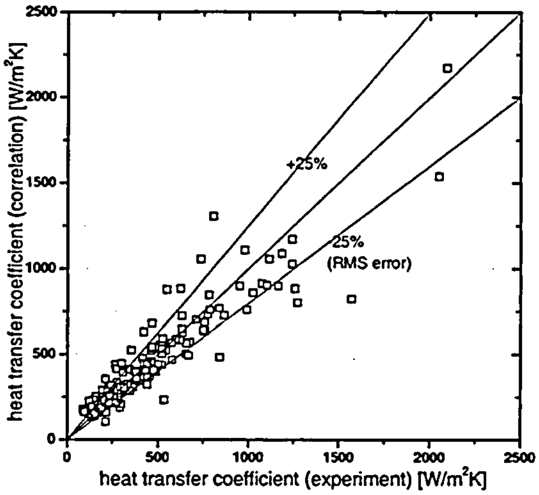

Figure 2.15 Comparison of the local heat transfer coefficients between experiment and correlation (linear-scale)

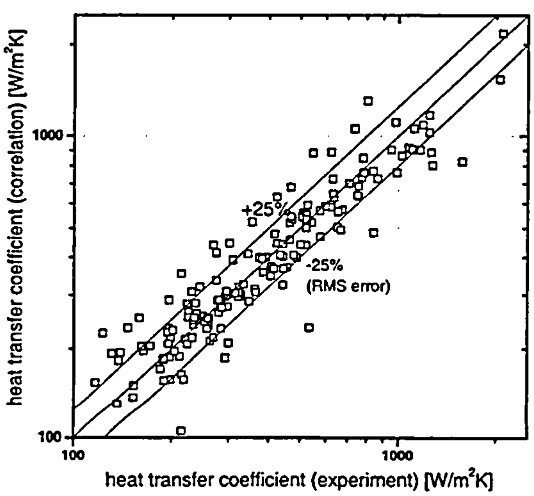

Figure 2.16 Comparison of the local heat transfer coefficients between experiment and correlation (log-scale)

Chapter 3.

Assessment of Condensation Models in RELAP5/MOD3.2

3.1. Condensation Models in the RELAP5/MOD3.2 Code

The RELAP5/MOD3.2 code is used to analyze nuclear power plant transients and loss-of-coolant accidents. Many heat transfer correlations in RELAP5/MOD3.2 are known to have many uncertainties. In particular, there is no reliable model for condensation phenomena with noncondensible gases in a vertical tube. The RELAP5/MOD3.2 condensation models can be categorized into two groups. One is wall heat transfer, which occurs when the wall comes in contact with a two-phase mixture through condensation, and the other is interfacial heat transfer, which occurs through an assumed interface as a result of differences in the bulk temperature of the liquid and vapor phases [6].

Two wall film condensation models, the default and the alternative, are used in RELAP5/MOD3.2. For an inclined surface, the Nusselt-Shah-Colburn-Hougen correlations are used as the default model, and the Nusselt-University of California-Berkeley (UCB) correlations are used as the alternative model for the wall film condensation. The default model uses Nusselt's and Shah's maxima, with Colburn-Hougen's diffusion calculation when noncondensible gases are present. The alternative model is the Nusselt model with UCB multipliers, which is revised to include the effects of interfacial shear and the presence of noncondensible gas in a vertical tube.

The detailed description of the condensation models in the standard RELAP5/MOD3.2 code are discussed in the authors' previous report [29].

3.2. New Condensation Model - Non-Iterative Model

A reference mechanistic model of vertical in-tube condensation in the original

RELAP5/MOD3.2 code, which was an iterative method, was developed for steam condensation in the presence of a noncondensible gas in a vertical tube. A non-iterative model is developed based on the reference mechanistic model to enhance its applicability to the code, which does not need iteration to find the temperature and pressure at the liquid-gas interface. The condensation heat transfer coefficient can be expressed in terms of non-dimensional bulk parameters without using any interfacial data.

In the presence of noncondensible gases the iterative model has been widely used, which was related to the heat and mass transfer analogy. The iterative model is newly developed to include the following effects:

- The high mass transfer effect by condensation;
- The entrance effect of test section;
- The interfacial waviness effect.

The non-iterative model is newly developed which includes the advantages of the above new iterative model. The non-iterative model also includes the assumption that the steam mass fraction and temperature of mixture gas have the same distribution in a gas mixture boundary layer, and the Nusselt number for condensation is derived with several mathematical derivations.

The Nusselt number for condensation is expressed as a function of air mass fraction, Jacob number, Stanton number for mass transfer, gas mixture Reynolds number, gas mixture Prandtl number and film Nusselt number on condensate surface. As a new condensation model the non-iterative model is presented.

3.2.1. Reference Modeling of Vertical In-Tube Condensation

Total heat flux can be obtained as the following:

$$q_t'' = h_t \cdot (T_b - T_w) \tag{3-1}$$

where the total heat transfer coefficient, h_t, is divided into the condensate film side heat transfer coefficient, h_f, and the mixture side heat transfer coefficient, h_g, which is composed of convective and condensation terms, h_{cv} and h_{cd}, respectively.

$$\frac{1}{h_t}=\frac{1}{h_f}+\frac{1}{h_g}=\frac{1}{h_f}+\frac{1}{h_{cd}+h_{cv}} \quad (3\text{-}2)$$

Equation (3-2) is based on the assumption that the mixture and the condensate film are at saturated state, the radiation heat transfer can be negligible, and the condensation and the sensible heat transfer rate can be calculated simultaneously using the heat and mass transfer analogy. The condensate film thickness is calculated using Munoz-Cobo et. al.(1996)'s approximate method with its accuracy and simplicity, and the condensate film heat transfer coefficient, h_f, is calculated with Blangetti et. al.(1982)'s film model. The steam -gas mixture side heat transfer coefficients, h_{cd} and h_{cv}, are calculated using the momentum, heat and mass transfer analogy. The heat flux through the condensate is balanced with the mass transfer coefficient can be expressed with the mass transfer rate as follows:

$$h_{cd}\cdot(T_b-T_i)=m_v''\cdot(i_{g,b}-i_{f,i}) \quad (3\text{-}3)$$

where $i_{g,b}$ is the bulk enthalpy and $i_{f,i}$ is the liquid enthalpy at the interface. The mass transfer rate m_v'' is expressed as follows:

$$m_v''=-g\cdot\frac{W_{v,i}-W_{v,b}}{1-W_{v,i}}=-g\cdot B \quad (3\text{-}4)$$

where g is the mass transfer conductance, B is mass transfer driving force, and $W_{v,b}$ are the steam mass fraction of the steam at the interface and at the tube centerline, respectively.

From Equations (3-3) and (3-4), the condensation heat transfer coefficient, h_{cd}, can be derived.

$$h_{cd}=g\cdot\frac{i_{g,b}-i_{f,i}}{1-W_{v,i}}\cdot\frac{W_{v,i}-W_{v,b}}{T_i-T_b} \quad (3\text{-}5)$$

The convective heat transfer, h_{cv}, in Equation (3-2) and mass transfer conductance, g, in Equation (3-5) can be calculated together using the heat and mass transfer analogy.

$$St=\frac{h_{cv}}{\rho_g u_g}=\frac{Nu}{\mathrm{Re}_g\,\mathrm{Pr}_g} \quad (3\text{-}6)$$

$$St_{AB}=\frac{g}{\rho_g u_g}=\frac{Sh}{\mathrm{Re}_g\,Sc_g} \quad (3\text{-}7)$$

where St and St_{AB} are Stanton numbers for heat transfer and mass transfer, respectively, and. Sh and Sc are Sherwood number and Schmidt number, respectively. There are several methods to calculate the Stanton number, St. Gnielinski(1976)'s calculation method can be used for smooth tubes and Dipprey and Sabersky(1963)'s calculation method can be used for rough tubes, which is applied to the present model.

For Stanton number for heat transfer,

$$St = \frac{C_f/2}{1.0 + \sqrt{C_f/2}\cdot\left(5.19\left[\mathrm{Re}_g\cdot\sqrt{C_f/2}\cdot\varepsilon_s/D\right]^{0.2}\cdot\mathrm{Pr}^{0.44} - 8.48\right)}, \tag{3-8}$$

where ε_s is defined as follows:

$$\varepsilon_s/D = e^{3.0-0.4/\sqrt{C_f/2}}, \tag{3-9}$$

As the heat transfer coefficient strongly depends on the interfacial shear stress, it is very much important to adopt the appropriate interfacial friction factor. The friction factor, C_f, is calculated using Wallis(1969)'s correlation for the interfacial friction factor in the vertical annular flow as follows:

$$C_f/2 = C_{f,s}/2\cdot\left(1 + 300\cdot\frac{\delta}{D}\right) \tag{3-10}$$

where $C_{f,s}$ is the friction factor for the smooth tube and δ is the film thickness.

Using the heat and mass transfer analogy, the Stanton number for mass transfer, St_{AB}, is calculated similarly.

$$St_{AB} = \frac{C_f/2}{1.0 + \sqrt{C_f/2}\cdot\left(5.19\left[\mathrm{Re}_g\cdot\sqrt{C_f/2}\cdot\varepsilon_s/D\right]^{0.2}\cdot Sc^{0.44} - 8.48\right)} \tag{3-11}$$

where Sc is Schmidt number. The high mass transfer effect is also considered. The Stanton number with blowing, $St_{AB,b}$, can be expressed with the Stanton number for no transpiration, $St_{AB,0}$, and the blowing parameter, b_h:

$$St_{AB} = St_{AB,0}\cdot\frac{b_h}{e^{b_h} - 1}, \tag{3-12}$$

where b_h is the alternative heat transfer blowing parameter, which has explicit relation for $St_{AB,0}$ rather than the implicit equation. b_h is theoretically derived and it can be expressed with several nondimensional parameters as follows:

$$\begin{aligned} b_h &= \frac{m_v''/G_\infty}{St_{AB,0}} \\ &= -\frac{Ja}{St_{AB,0}\cdot\mathrm{Pr}_g\cdot\mathrm{Re}_g}\cdot\frac{Nu_f}{\left[Nu_f + \left(Nu_{cd} + Nu_{cv}\right)\cdot k_g/k_f\right]} \end{aligned} \tag{3-13}$$

where m_v'' is the mass transfer rate of the vapor, G_∞ is the mass flux of the free stream and Ja is Jacob number.

The entrance effect on heat transfer should also be considered. For short tubes, where the region of fully developed flow is a small percentage of the total length, the local value of the Nusselt number of uniform velocity and temperature profile in the entrance region is given based on the experimental data for gas (Bonilla, 1964).

$$Nu_e = 1.5 \cdot \left[\frac{x}{D}\right]^{-0.16} \cdot Nu_0, \quad for \quad 1 < \frac{x}{D} < 12 \tag{3-14}$$

and

$$Nu_e = Nu_0, \quad for \quad \frac{x}{D} > 12 \tag{3-15}$$

where Nu_0 is the Nusselt number which the entrance effect is not considered.

3.2.2. Solution Scheme of Non-Iterative Model

Based on the description above, the condensation heat transfer coefficient can be determined without any liquid-gas interface information such as the interface temperature. The condensate film heat transfer coefficient, h_f, can be calculated by the empirical correlation, and both convective and condensation heat transfer coefficients, h_{cv} and h_{cd}, can be calculated by the analogy between heat and mass transfer without using the interface temperature, T_i.

From the energy balance, the amount of heat transferred by the condensing vapor to the liquid-vapor interface through the steam-noncondensible gas mixture boundary layer is equal to that transferred through the condensate film. The heat flux through the condensate film layer is calculated by

$$q_f'' = h_f \cdot (T_i - T_w). \tag{3-16}$$

The heat flux through the mixture boundary layer is

$$q_v'' = (h_{cd} + h_{cv}) \cdot (T_b - T_i). \tag{3-17}$$

The heat fluxes are balanced at the interface.

$$h_f \cdot (T_i - T_w) = (h_{cd} + h_{cv}) \cdot (T_b - T_i), \tag{3-18}$$

and

$$(h_f + h_{cd} + h_{cv}) \cdot (T_b - T_i) = h_f \cdot (T_b - T_w). \tag{3-19}$$

Using the Equations (3-18) and (3-19), the temperature difference between the bulk and the interface is expressed with the temperature difference between the bulk and the condensing wall.

$$T_b - T_i = \frac{h_f}{h_{cd} + h_{cv}} \cdot (T_i - T_w) = \frac{h_f}{h_f + h_{cd} + h_{cv}} \cdot (T_b - T_w) \tag{3-20}$$

The mass fraction of steam at the interface, $W_{v,i}$, can be expressed in terms of the bulk mass fraction of steam, $W_{v,b}$, by Taylor expansion.

$$W_{v,i} = W_{v,b} + \left.\frac{\partial W_v}{\partial T}\right]_b \cdot (T_i - T_b) + \left.\frac{\partial W_v}{\partial T}\right]_b^2 \cdot (T_i - T_b)^2 + \cdots \tag{3-21}$$

Equation (3-21) can be approximated by taking the first order differential term only. The properties of temperature and concentration are assumed to be changed proportionally in the gas mixture boundary layer. This is another expression of heat and mass transfer analogy. The terms of $W_{v,i} - W_{v,b}$ and $1 - W_{v,i}$ can be calculated as follows:

$$W_{v,i} - W_{v,b} \approx \left.\frac{\partial W_v}{\partial T}\right]_b \cdot (T_i - T_b), \tag{3-22}$$

$$\begin{aligned} 1 - W_{v,i} &\approx 1 - W_{v,b} - \left.\frac{\partial W_v}{\partial T}\right]_b \cdot (T_i - T_b) \\ &= 1 - W_{v,b} + \frac{h_f}{h_f + h_{cd} + h_{cv}} \cdot (T_b - T_w) \cdot \left.\frac{\partial W_v}{\partial T}\right]_b, \end{aligned} \tag{3-23}$$

and using these two equations, the Equation (3-5) can be expressed as follows:

$$h_{cd} = g \cdot i_{fg} \cdot \frac{\partial W_v / \partial T]_b}{1 - W_{v,b} + h_f / (h_f + h_{cd} + h_{cv}) \cdot (T_b - T_w) \cdot (\partial W_v / \partial T]_b)}. \tag{3-24}$$

When Equation (3-24) is rearranged, a simple quadratic equation for the condensation heat transfer coefficient, h_{cd}, is derived as follows:

$$A \cdot h_{cd}^2 + B \cdot h_{cd} + C = 0, \tag{3-25}$$

where

$$A = 1 - W_{v,b}, \tag{3-26}$$

$$B = (h_f + h_{cv}) \cdot (1 - W_{v,b}) + \left[h_f \cdot (T_b - T_w) - g \cdot i_{fg} \right] \cdot \frac{\partial W_v}{\partial T} \bigg]_b , \tag{3-27}$$

and

$$C = -g \cdot i_{fg} \cdot (h_f + h_{cv}) \cdot \frac{\partial W_v}{\partial T} \bigg]_b . \tag{3-28}$$

If the unknown variable, $\partial W_v / \partial T \big]_b$, is constant, calculated solutions should be exact. The term $\partial W_v / \partial T$ can be determined as follows: The vapor mole fraction and the vapor mass fraction is expressed in terms of the pressure ratio as follows:

$$X_v = P_v / P_t , \tag{3-29}$$

where P_v and P_{tot} are vapor partial and total pressures, respectively, and

$$W_v = \frac{M_v \cdot P_v / P_t}{M_g \cdot (1 - P_v / P_t) + M_v \cdot P_v / P_t} . \tag{3-30}$$

The partial differentiation of vapor mass fraction with respect to temperature is derived and approximated to be expressed with the bulk properties using the Clausius-Clapeyron equation as follows:

$$\frac{\partial W_v}{\partial T} = \frac{\partial W_v}{\partial P_v} \cdot \frac{\partial P_v}{\partial T} = \frac{1}{P_t} \cdot N_A \cdot \frac{\partial P_v}{\partial T} \approx \frac{i_{fg} \rho_v}{P_t T} \cdot N_A \tag{3-31}$$

where

$$N_A = \frac{M_v \cdot M_g}{\left[M_g \cdot (1 - X_v) + M_v \cdot X_v \right]^2} . \tag{3-32}$$

Using the Equations (3-31) and (3-32), the coefficients, B and C, in Equations (3-27) and (3-28) can be rewritten as follows:

$$B = H_1 \cdot A + H_2 \cdot B_{2T} - B_{3T} \tag{3-33}$$

and

$$C = -H_1 \cdot B_{3T} \tag{3-34}$$

where

$$H_1 = h_f + h_{cv} , \tag{3-35}$$

$$H_2 = h_f , \tag{3-36}$$

$$B_{2T} = (i_{fg} \cdot \rho_v)/(P_t \cdot T) \cdot (T_b - T_w) \cdot N_A \tag{3-37}$$

and

$$B_{3T} = (g \cdot i_{fg}^2 \cdot \rho_v) \cdot (P_t \cdot T) \cdot N_A. \tag{3-38}$$

As the coefficients A and C are always positive and negative, respectively, Equation (3.25) has the following unique positive solution:

$$h_{cd} = \frac{-B + |B| \cdot \sqrt{1 - 4AC/B^2}}{2A}. \tag{3-39}$$

Equation (3-39) can be nondimensionalized using Equations (3-26), (3-33) and (3-34) as follows:

$$Nu_{cd} = \frac{1}{2}\frac{k_f}{k_g}\frac{Nu_f}{div1} \cdot \left[-div + |div| \cdot \sqrt{1 + 4 \cdot \frac{div1 \cdot div3}{div^2}} \right], \tag{3-40}$$

where

$$div = div1 + div2 + div3, \tag{3-41}$$

$$div1 = N_B \cdot P_A, \tag{3-42}$$

$$div2 = Ja, \tag{3-43}$$

and

$$div3 = 1/Nu_f \cdot k_g / k_f \cdot \mathrm{Pr}_g \cdot St_{AB} \cdot \mathrm{Re}_g. \tag{3-44}$$

The nondimensional parameters in Equations (3-40) through (3-44) are defined as follows:

$$W_{g,b} = 1 - W_{v,b}; \tag{3-45}$$

$$X_{g,b} = 1 - X_{v,b}; \tag{3-46}$$

$$Nu_{cd} = h_{cd} D_h / k_g; \tag{3-47}$$

$$Nu_f = h_f D_h / k_f; \tag{3-48}$$

$$St_{AB} = g / \rho_g u_g; \tag{3-49}$$

$$\mathrm{Re}_g = \rho_g u_g D_h / \mu_g; \tag{3-50}$$

$$\mathrm{Pr}_g = C_{p_g} \mu_g / k_g; \tag{3-51}$$

$$P_A = P_t^2 / (\rho_v^2 - i_{fg}^2) \cdot C_{p_g} / R_v; \quad (3\text{-}52)$$

$$N_B = X_{g,b} \cdot (1 - X_{g,b}) \cdot [1 + X_{g,b} \cdot (M_g / M_v - 1)]. \quad (3\text{-}53)$$

As the term div is always positive and the second term in the square root of Equation (3-40) is a very small value compared with 1, the square root term of Equation (3-40) can be expanded and approximated from the expansion of the Taylor series as follows:

$$\sqrt{1+y} \approx 1 + \frac{1}{2} y, \quad (3\text{-}54)$$

where

$$y = 4 \cdot (1 + h_{cv} / h_f) \cdot \frac{div1 \cdot div3}{div^2}. \quad (3\text{-}55)$$

Using the approximation of Equation (3-54), Equation (3-40) can be simplified as follows:

$$Nu_{cd} = \left(1 + \frac{h_{cv}}{h_f}\right) \cdot \frac{\Pr_g \cdot St_{AB} \cdot \mathrm{Re}_g}{N_B \cdot P_A + Ja - \Pr_g \cdot St_{AB} \cdot \mathrm{Re}_g \cdot \frac{1}{Nu_f} \cdot \frac{k_g}{k_f}}. \quad (3\text{-}56)$$

St_{AB} and h_{cv} in Equation (3-40) are corrected to consider the effects of high mass transfer and entrance using Equation (3-12) and Equations (3-14) and (3-15), respectively. As the convective heat transfer coefficient, h_{cv}, is negligibly small compared with the film side heat transfer coefficient, h_f, Equation (3-56) can be further simplified as follows:

$$Nu_{cd} = \frac{\Pr_g \cdot St_{AB} \cdot \mathrm{Re}_g}{N_B \cdot P_A + Ja - \Pr_g \cdot St_{AB} \cdot \mathrm{Re}_g \cdot \frac{1}{Nu_f} \cdot \frac{k_g}{k_f}}. \quad (3\text{-}57)$$

Now, the Nusselt number for condensation can be calculated by those parameters of St_{AB}, Re_g, $\Pr_g$, Nu_f, k_g / k_f, Ja, N_B, and P_A. Several nondimensional parameters used in Equation (3-57) are parameters used in empirical correlations proposed by several investigators, e.g., Kuhn (1995), Araki et. al. (1995), Hasanein et. al. (1994), Vierow (1990), Vierow and Schrock (1991), and Siddique et. al. (1993).

3.3. Calculation Procedures of the Modified Model

The calculation procedures are explained in Figures 3.1 and 3:2 for the reference model and the present non-iterative model, respectively. The default model of the original RELAP5/MOD3.2 code also has an iterative solution scheme similar to the reference model. Calculation procedures are quite different between the reference model and the non-iterative model. The reference model separately calculates the heat flux through the liquid film and through the mixture boundary layer with an assumed interface temperature. It needs iteration to get reasonable heat transfer coefficients by modifying the interface temperature until the heat fluxes converge within a specified accuracy. The reference model separately calculates the heat flux through the liquid film and through the air-vapor boundary layer.

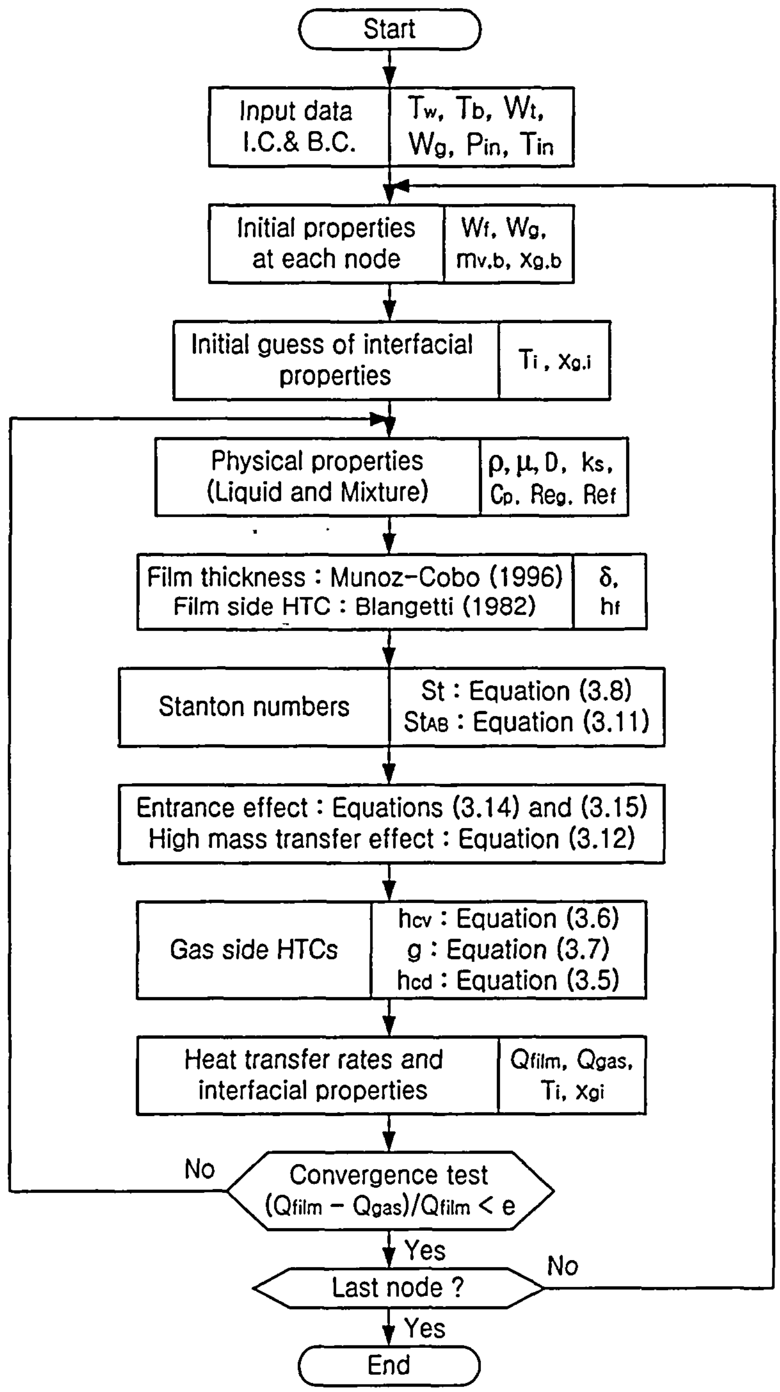

Figure 3.1 Calculation procedure of reference iterative model

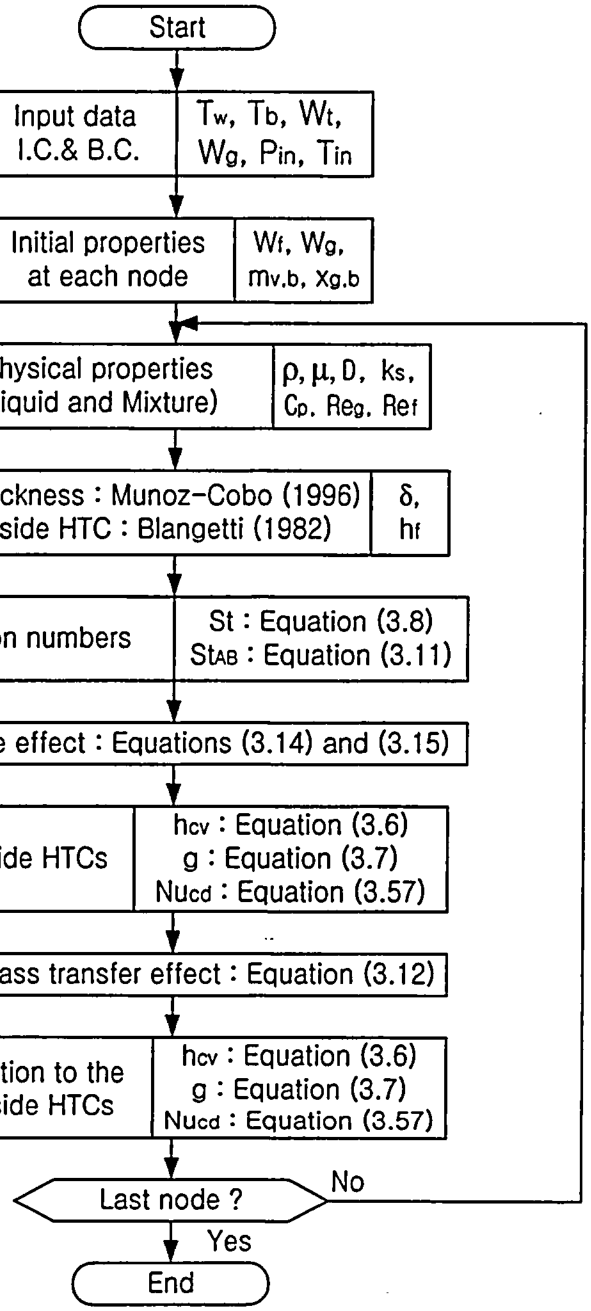

Figure 3.2 Calculation procedure of the present non-iterative model: the modified model

3.4. Simulation of Reflux Condensation Experiments

The RELAP5 calculation is performed for the experiments discussed in Chapter 2. The simulation results by two wall-film condensation models of the RELAP5/MOD3.2 code and the modified condensation model are compared with the experimental data.

3.4.1. RELAP5/MOD3.2 Nodalization

Figure 3.3 shows the nodalization scheme of RELAP5/MOD3.2 for the reflux condensation experiments. The present RELAP5/MOD3.2 nodalization used for this simulation contains 43 control volumes, 10 junctions, a valve and a heat structure.

The steam-air mixture is injected upward into the riser part of the U-tube of steam generator as boundary conditions at various air mass fractions and steam flow rates. Both the steam-air mixture and the coolant are injected at constant flow rates upward into the condensing tube and into the annulus of the coolant jacket, respectively. In the RELAP5/MOD3.2 calculation, this behavior is simulated using a time-dependent volume and a time-dependent junction to specify flow and pressure boundary conditions. Time-dependent volumes acting as infinite sources or sinks are used to represent boundary conditions both for the steam-noncondensible gas mixture flow in a condensing tube and for the coolant flow in a coolant jacket.

For the simulation of the coolant jacket, two time-dependent volumes 200 and 280 are connected to the annulus 240 via a time-dependent junction 210 and a single junction 270. Similarly, for the simulation of the test section, two time-dependent volumes 100 and 180, a time-dependent junction 105 and a single junction 165 are also used. A pipe volume 130 is used to simulate an upper plenum and three pipe volumes 150, 160 and 157 are used to simulate a lower plenum, a drain tank and a connecting pipe between the lower plenum and the drain tank, respectively. The above three pipes are connected using single junctions 155, 156 and 158. A valve 175 is used to regulate the venting of the mixture of the residual steam and the noncondensible gas. A heat structure 140 with 11 sub-volumes is used to represent the heat transferred from the steam-noncondensible gas mixture to the coolant through the condensing tube.

3.4.2. Base Case Calculation

Four reflux condensation experiments are simulated using the RELAP5/MOD3.2 code. Before 200 sec, the steady state conditions are achieved. Their steady state test conditions are listed in Table 3.1.

Table 3.1 Steady state test conditions of reflux condensation experiments

I.D.	T_{sat} [℃]	AMF	P_{tot} [kPa]	FS [kg/h]	FA [kg/h]
RC16	101.6	0	107.3	1.35	0
RC13	91.0	0.418	105.4	1.50	1.08
RC02	95.3	0.291	107.4	2.29	0.94
RA02	123.7	0.237	266.0	2.59	0.80

Two tests of RC16 and RC13 have different inlet air mass fractions under the similar inlet saturated steam temperatures and inlet steam flow rates. Two tests of RC02 and RA02 have different inlet saturated steam temperatures under the similar air mass fractions and inlet steam flow rates. The calculated local heat transfer coefficients are compared for the tests with different air mass fractions and different system pressures or inlet saturated steam temperatures. Therefore, the effects of inlet air mass fraction and of inlet saturated steam temperature on the local heat transfer coefficient can be investigated through the comparison of those tests.

Figures 3.4 through 3.7 show the local heat transfer coefficients along the tube length for the reflux condensation experiments RC16, RC13, RC02, and RA02, respectively.

Figure 3.4 shows that the modified model gives accurate prediction over the experimental data along the test section. However, both the default model and the alternative model of the RELAP5/MOD3.2 code give much higher predictions than the experimental heat transfer coefficient in the entrance region of the test section.

Figure 3.5 shows the simulation results of experiment RC13 with high inlet air mass fraction. The calculated heat transfer coefficient from the default model is always lower than the experimental data, while the calculated one from the alternative model is always higher than the experimental data. The heat transfer coefficient calculated from the modified model shows reasonable agreement with the experimental data in the entrance region.

Figures 3.6 and 3.7 shows the simulation results with different inlet steam temperatures. The calculated heat transfer coefficients from the modified model are always between two predictions from the alternative and the default models in RELAP5/MOD3.2, and they show good agreement with the experimental data throughout the condensing tube.

In the atmospheric conditions (RC16, RC13, RC02), the under-predictions of the default model become larger as the air mass fraction increases. With the increased system pressure (RA02), the non-iterative model better predicts the experimental data, while the default model under-predicts the experimental data.

From the aforementioned simulation results, we conclude that the local heat transfer coefficients are well predicted with the modified RELAP5/MOD3.2 code but they are under-predicted by the default model and over-predicted by the alternative model. Also the modified RELAP5/MOD3.2 code better predicts the experimentally obtained active condensing region and its length than the original codes.

3.4.3. Run Statistics

The computer used in the calculation is a Pentium III personal computer with Window 98 operating system. The random access memory is 128Mbyte and the clock speed of CPU is 500Mhz. The CPU time, the time step size, and the grind time are compared between three calculation results. Table 3.2 shows the required CPU time and the grind time for the base case calculation of RC02.

Table 3.2 The CPU time and the grind time of experiment RC02

Condensation model used	Node number	Problem time (second)	CPU time (second)	Number of time step	Grind time
Default model	41	200	5485.3	25519	5.00
Alternative model	41	200	2235.4	14526	3.58
Modified model	41	200	2753.7	12866	4.98

Figure 3.8 shows the required CPU times with respect to the real problem time for the base calculation of RC02. The required CPU times increase linearly for three calculation results,

except for the initial transient situation. The default model needs the highest CPU time and the alternative model needs the lowest. The modified model needs lower CPU time than the default model and slightly higher CPU time than the alternative model except for the initial transient situation.

Figures 3.9 through 3.11 show the time step sizes with respect to the real problem time for the default model, the alternative model and the modified model, respectively. The time step sizes of the default model are 0.00781 sec except for the initial 0.0156 sec. The time step sizes of the alternative model fluctuate between 0.00781 sec and 0.0156 sec during the initial transient situation and they become 0.0156 sec after the problem time becomes approximately 40sec. The time step sizes of the modified model are 0.0156 sec except for the initial 0.00781 sec.

The grind time is expressed as follows:

$$Grind\ time = \frac{CPU \times 10^3}{C \times \Delta T} \tag{3-58}$$

where CPU is the CPU time, C is the total number of model volumes, and ΔT is the number of time steps. The grind times are 5.00, 3.58 and 4.98 for the default model, the alternative model and the modified model, respectively. The grind time of the modified model is slightly lower than that of the default model but it is 28.1% higher than that of the alternative model.

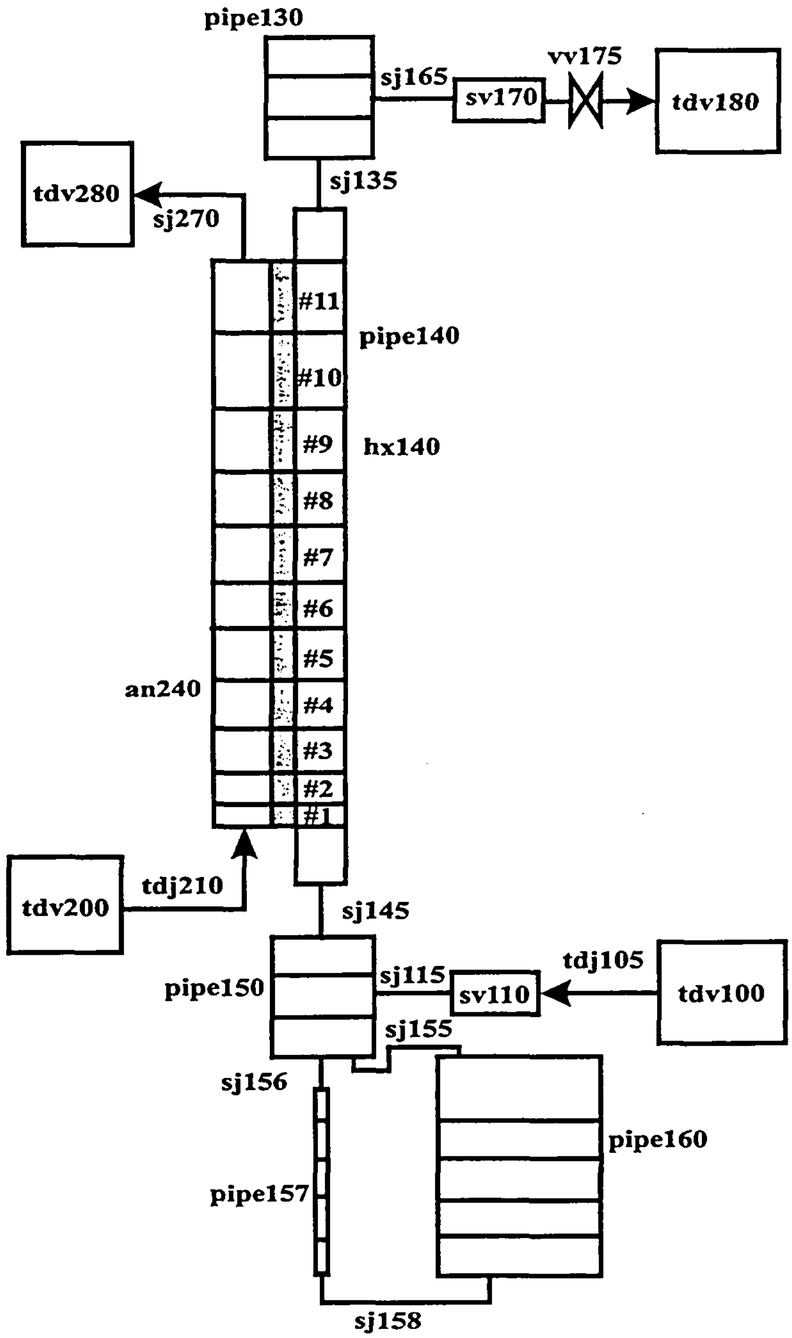

Figure 3.3 RELAP5/MOD3.2 nodalization for reflux condensation experiment

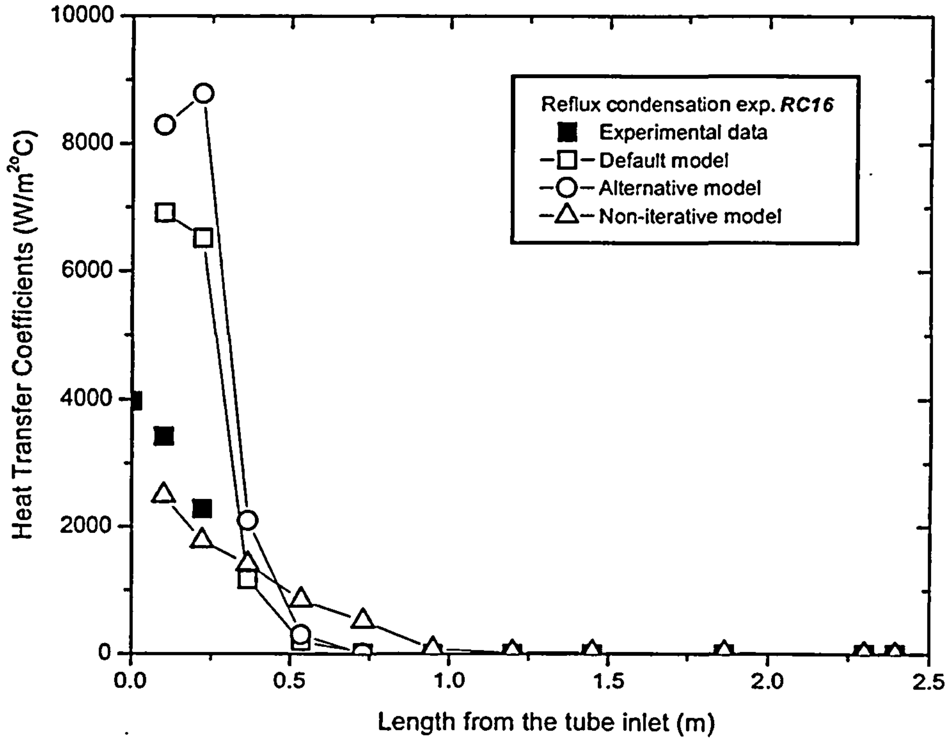

Figure 3.4 Heat transfer coefficients of reflux condensation: #RC16

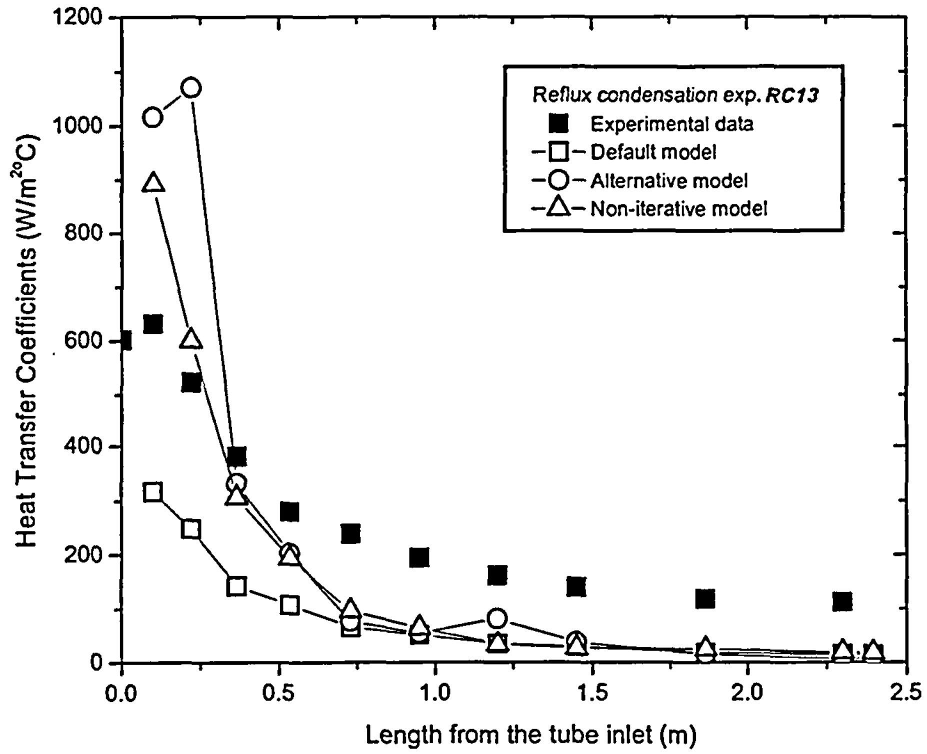

Figure 3.5 Heat transfer coefficients of reflux condensation: #RC13

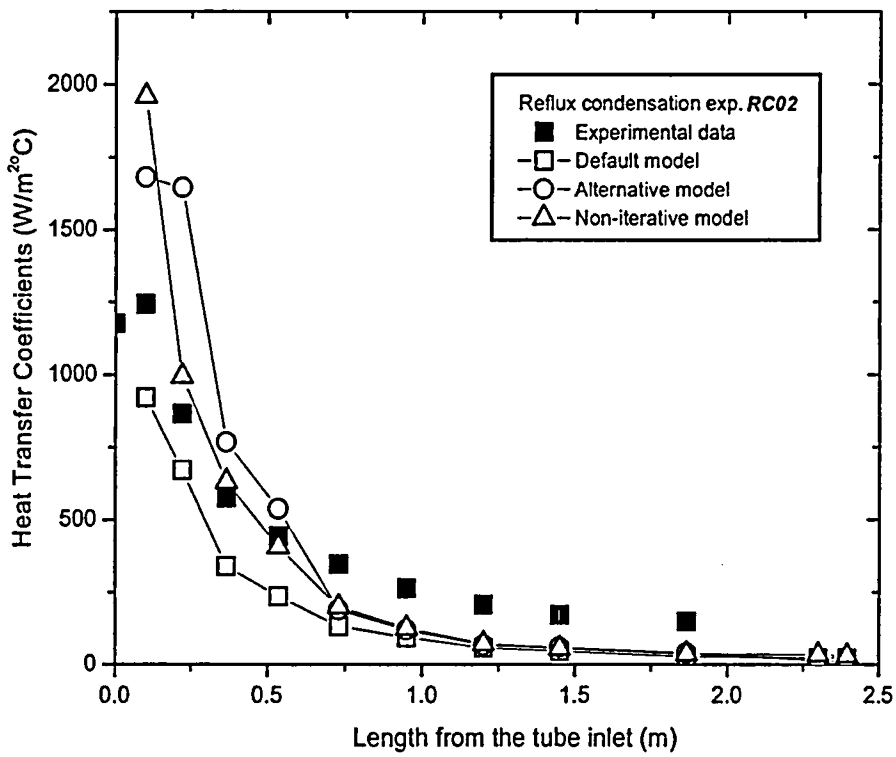

Figure 3.6 Heat transfer coefficients of reflux condensation: #RC02

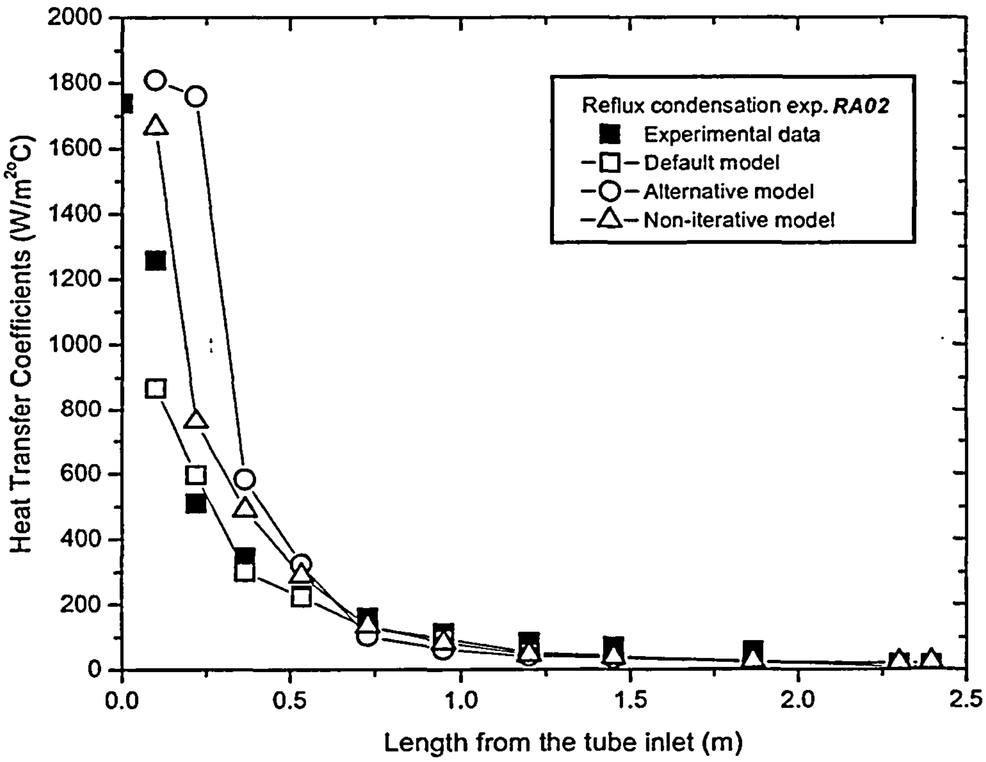

Figure 3.7 Heat transfer coefficients of reflux condensation: #RA02

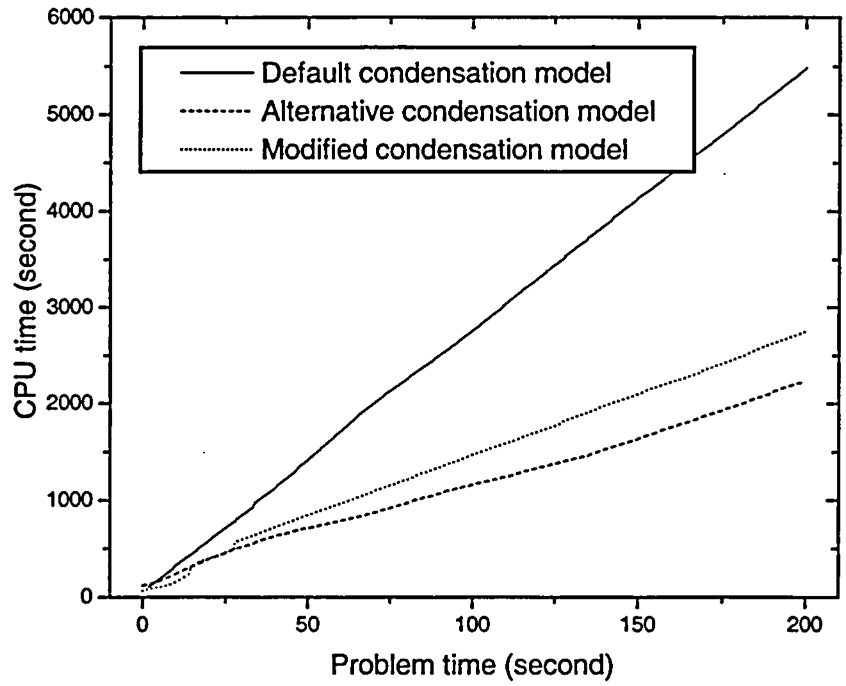

Figure 3.8 Comparison of required CPU times of three condensation models

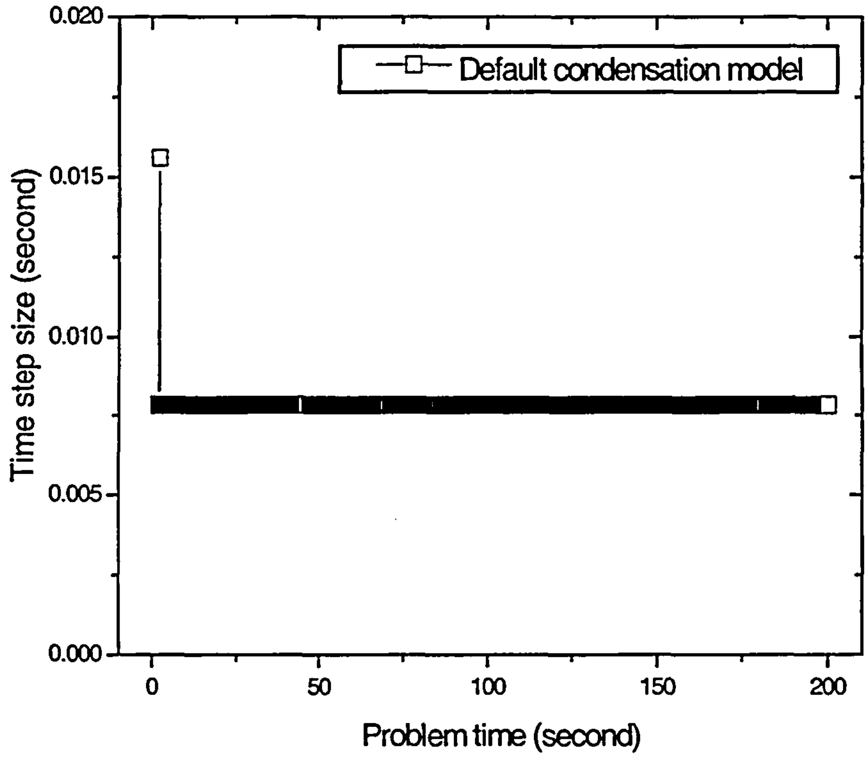

Figure 3.9 Time step sizes of the default condensation model

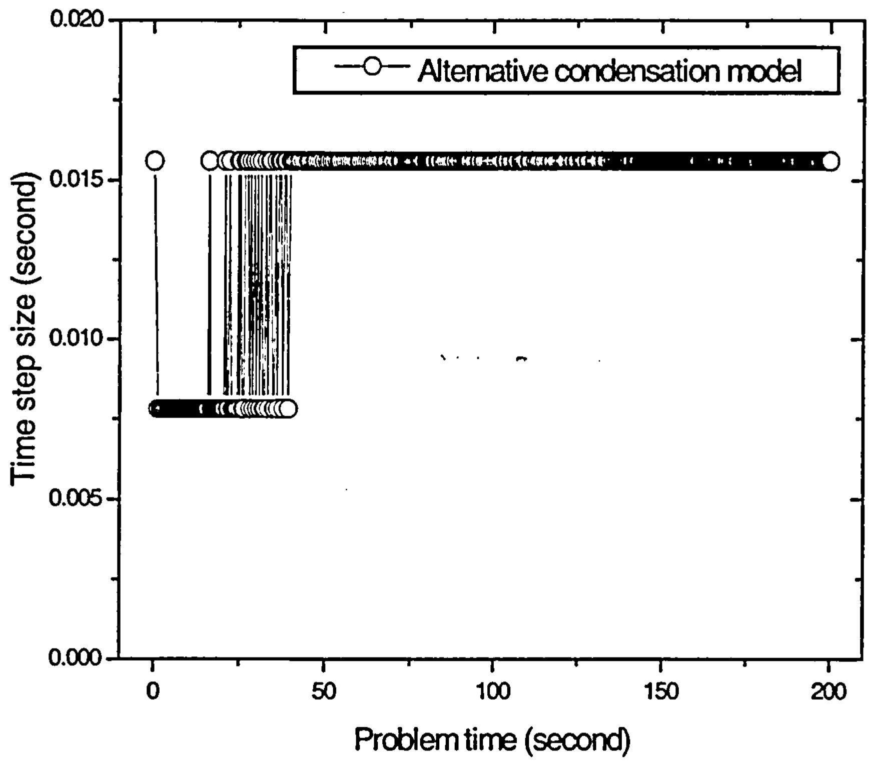

Figure 3.10 Time step sizes of the alternative condensation model

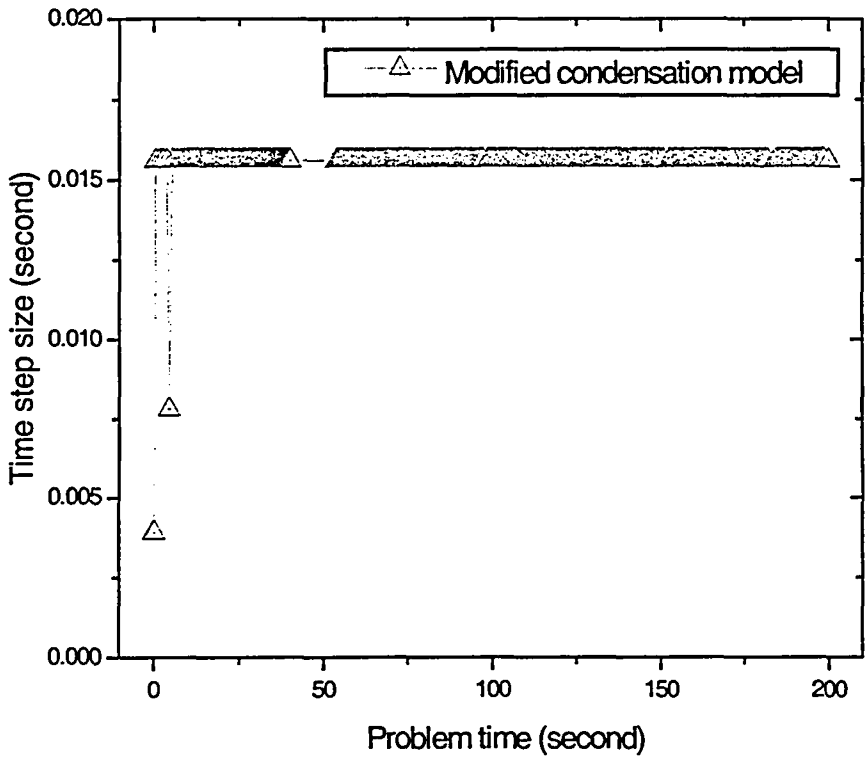

Figure 3.11 Time step sizes of the modified condensation model

Chapter 4.

Conclusions and Recommendations

The reflux condensation experiment in the presence of noncondensible gas is performed. The flooding limit to the reflux condensation is firstly obtained in several air mass fractions. 29 data sets of the heat transfer coefficients are obtained, which represent the characteristics of several parametric effects. The empirical correlation is developed using total 165 local data of the heat transfer coefficients, where the degradation factor, F is described as a function of four nondimensional parameters.

The standard frozen RELAP5/MOD3.2 code is assessed for the existing two condensation heat transfer models. Also a new non-iterative condensation model is developed and implemented into the RELAP5/MOD3.2 code, and the result of the new model is compared to the experimental data and the code results for the two existing condensation models of the standard RELAP5/MOD3.2 code.

From the above studies of the experiments and the code analysis, the conclusions are listed as follows:

- The onset of flooding in conditions of the reflux condensation is lower than that of Wallis' correlation. It may be resulted from the condensation effect on the film interface and the presence of noncondensible gas.

- The heat transfer coefficients are affected by several parameters. The heat transfer capability in the presence of noncondensible gas is dramatically decreased. For the range of air mass fraction of 10~55 %, the heat transfer coefficient is decreased with an increase of the air mass fraction. As the pressure increases, the heat transfer capability is enhanced near the tube inlet. As the steam flow rate increases, the local heat transfer coefficients are all increased in the active condensing region.

- The empirical correlation is developed using four nondimensional parameters. The Jacob number and the film Reynolds number are dominant parameters. However, the effect of the mixture gas Reynolds number is relatively low. The correlation covers the local heat transfer coefficients for the active condensing region up to about 1.5m from the tube inlet.

- The existing condensation models in the standard RELAP5/MOD3.2 code are assessed for the reflux condensation. It shows that the default model under-predicts and the alternative model over-predicts the experimental data, respectively. The under-prediction of the default model becomes larger as the air mass fraction increases in the atmospheric conditions.

- A non-iterative model is newly developed to be implemented into RELAP5/MOD3.2. The non-iterative model predicts better the experimental data than the existing default model and alternative model. It has good predictability especially in high pressure conditions.

- The flooding data are obtained in the condition of the reflux condensation with noncondensible gas, but is not enough to represent the effect of the air mass fraction on flooding. The effects of detailed noncondensible gas on the flooding limit may be useful as part of the CCFL study. In this report, the experiment is performed about reflux condensation before the onset of flooding. After flooding, the liquid column is formed and the reflux condensation also occurs below the liquid column. The characteristics of the reflux condensation may be different according to the conditions with or without the liquid column.

- The local heat transfer data, especially with high air mass fraction, are comprehensively obtained for reflux condensation and an empirical correlation is developed. With its simplicity and mechanistic modeling, the non-iterative model can be used to improve the condensation models in the presence of noncondensible gases in various thermal hydraulic codes.

Bibliography

[1] Araki, H., Kataoka, Y. and Murase, M, "*Measurement of Condensation Heat Transfer Coefficient inside a Vertical Tube in the Presence of Noncondensible Gas*," J. of Nuclear Science and Technology, Vol. 32, No.6, pp.517-526, June 1995.

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

[3] Blangetti, F., Kerbs, R. and Schlunder, E.U., "*Condensation in Vertical Tubes - Experimental Results and Modeling*," Chemical Engineering Fundamentals, Vol.1, No. 2, pp.20-63, 1982.

[4] Bonilla, C.F., "*Heat Transfer*," New York: Interscience, 1964.

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

[6] Choi, K.Y., Park, H.S., Kim, S.J., NO, H.C., and Bang, Y.S., "*Assessment and Improvement of Condensation Models in RELAP5/MOD3.2*," Nuclear Technology, Vol.124, No.2, p.103-117, 1998.

[7] Colburn, A.P. and Hougen, O.A., "*Design of Cooler Condensers for Mixtures of Vapors with Non-condensing Gases*," Industrial and Engineering Chemistry, Vol.26, No.11, p.1178, 1934.

[8] Collier, J.G. and Thome, J.R., "*Convective Boiling and Condensation*", 3rd Edition, Oxford university press, 1994.

[9] Dipprey, D.F. and Sabersky, R.H., "*Heat and Momentum Transfer in Smooth and Rough Tubes at Various Prandtl Numbers*," Int. J. Heat Mass Transfer, vol.6, pp.329-353, 1963.

[10] Dittus, F.W. and Boelter, L.M, "*Heat Transfer in Automobile Radiators of the Tubular Type*," Publications in Engineering, U.C.B., Vol.2, p.443, 1930.

[11] Dumont, D., Lavialle, G., Noel, B. and Deruaz, R., "*Loss of Residual Heat Removal during Mid-loop Operation : BETHSY Experiments*," Nuclear Eng. and Design, Vol.149, pp.365-3374, 1994.

[12] El-Wakil, "Nuclear Heat Transport", McGraw-Hill, 1978

[13] Girard, R., and Chang, J.S., "*Reflux Condensation Phenomena in Single Vertical Tubes*," Int. J. of Heat Mass Transfer, Vol.35, No.9, pp.2203-2218, 1992.

[14] Gnielinski, V., "*New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow*," Int. Chem. Eng., Vol.16, No.2, pp.359-368, 1976.

[15] Hassanein, H.A., Golay, M.W. and Kazimi, M.S., "*Steam Condensation in the Presence of Noncondensable Gases under Forced Convection Conditions*," MIT-ANP-TR-024: M.I.T., 1994.

[16] Hassan, Y.A. and Raja, L.L., "*Analysis of Experiments for Steam Condensation in the*

Presence of Noncondensable Gases using the RELAP5/MOD3 Code," Nuclear Technology, Vol.104, p.76, 1993.

[17] Hein, D., Rippel, R., Weiss, P., "*The Distribution of Gas in a U-tube Heat Exchanger and its Influence on the Condensation Process*", Proc. 7th Int. Heat Transfer Conf., 1982.

[18] Kageyama, T., Peterson, P.F. and Schrock, V.E., "*Diffusion Layer Modeling for Condensation in Vertical Tubes with Noncondensable Gases,*" Nuclear Engineering and Design, Vol.141, pp.289-302, 1993.

[19] Kays, W.H. and Leung, E.Y., "*Heat transfer in annular passages-hydrodynamically developed turbulent flow with arbitrarily prescribed heat flux,*" Int. J. Heat Mass Transfer, Vol.6, p.537, 1963.

[20] Kuhn, S.Z., "*Investigation of Heat Transfer from Condensing Steam-Gas Mixtures and Turbulent Films Flowing Downward Inside a Vertical Tube,*" Ph.D. thesis, M.I.T., 1995.

[21] Lee, C.H., Liu, T.J., Way, Y.S. and Hsia, D.Y., "*Investigation of Mid-loop Operation with Loss of RHR at INER Integral System Test (IIST) Facility,*" Nuclear Eng. and Design, Vol.163, pp.349-358, 1996.

[22] Mills, A.F., "*Heat and Mass Transfer,*" Richard D. IRWIN Inc., UCLA, 1995.

[23] Munoz-Cobo, J.L., Herranz, L., Sancho, J., Tkachenko, I. and Verdu, G., "*Turbulent Vapor Condensation with Noncondensable Gases in Vertical Tubes,*" Int. J. Heat Mass Transfer, Vol.39, No.15, pp.3249-3260, 1996.

[24] Nakamura, H., Anoda, Y. and Kukita, Y., "*Loss of Residual Heat Removal(RHR) during PWR Mid-loop Operation : Experiments in ROSA-IV/LSTF,*" Int. Topical Meeting "Safety of Thermal Reactors" of ANS Nuclear Reactor Safety Division, USA, July 21-25, 1991.

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

[26] NO, H.C., "*Iterative and Non-Iterative Condensation Models for Steam Condensation with Noncondensable Gas in a Vertical Tube,*" Proc. of NTHAS: First Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, p.313, 1998.

[27] Noel, -B. and Deruaz, R., "*Reflux Condensation with Nitrogen in Steam Generator U-tubes Analysis of BETHSY Test 7.2c Using CATHARE Code,*" 3rd Int. Symposium on Multiphase Flow and Heat Trasfer, XI'AN, China, Sept. 19-21, 1994.

[28] Nusselt, W.A., "*The Surface Condensation of Water Vapor,*" Z. Ver. Deutsch. Ing., Vol.60, pp.541-546, 1916.

[29] Park, H.S., NO, H.C. and Bang, Y.S., "*Assessment of RELAP5/MOD3.2 for Steam Condensation Experiments in the Presence of Noncondensables in a Vertical Tube of PCCS*", USNRC, NUREG/IA-0147, 1998.

[30] Park, H.S. and NO, H.C., "*A Condensation Experiment in the Presence of Noncondensables in a Vertical Tube of PCCS and Its Assessment with RELAP5/MOD3.2,*" Nuclear Technology, Vol.127, pp.160-169, 1999.

[31] Park, J.W., "*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.

[32] Peterson, P.F., Schrock, V.E. and Kageyama, T., "*Diffusion Layer Theory for Turbulent*

Vapor Condensation with Noncondensable Gases," J. Heat Transfer, Trans. of ASME, Vol.115, pp.998-1003, 1993.

[33] Ransom, V.H., Trapp, J.A., and Wagner, R.J., "*RELAP5/MOD3 Code Manual, Volume IV: Models and Correlations,*" USNRC NUREG/CR-5535, INEL-95/0174, INEL, June 1995.

[34] Shah, M.M., "*A General Correlation for Heat Transfer during Film Condensation Inside Pipes,*" Int. J. Heat Mass Transfer, Vol.22, pp.547-556, 1979.

[35] Siddique, M., Golay, M.W. and Kazimi, M.S., "*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.

[36] Siddique, M., Golay, M.W. and Kazimi, M.S., "*Theoretical Modeling of Forced Convection Condensation of Steam in a Vertical Tube in the Presence of a Noncondensable Gas,*" Nuclear technology, Vol.106, pp.202-214, 1994.

[37] Tien, C.L., Fukano, T., Hijikata, K., and Chen, S.J., "*Reflux Condensation and Operation Limits of Countercurrent Vapor-Liquid Flows in a Closed Tube,*" EPRI/NP2648, Nov. 1982.

[38] Venugopalan, D., Girard, R. and Kirkaldy, J.S., "*Optimal Staionary States in Thermalhydraulics : Total Reflux Condensation,*" Canadian J. of Chemical Eng., Vol. 70, Aug, 1992.

[39] Vierow, K.M. and Schrock, V.E., "*Condensation in a Natural Circulation Loop with Noncondensable Gases: Part I - Heat Transfer,*" Proc. of the Int. Conf. on Multiphase Flows '91, pp.183-186, 1991.

[40] Vierow, K.M., "*Behavior of Steam-Air Systems Condensing in Concurrent Vertical downflow,*" M.S. Thesis, U.C.B., 1990.

[41] Wallis, G.B., "*One-dimensional Two-phase Flow*", McGraw-Hill Book Co., 1969

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

Appendices

Appendix A.
Uncertainty Analysis of the Reflux Condensation Experiment

Sample error analysis for the heat transfer coefficient are performed as follows:

The local heat transfer coefficient is defined as

$$h(x) = \frac{q''(x)}{(T_b - T_{w,i})} \tag{A-1}$$

By the above equation, the total error of heat transfer coefficient is expressed as the composite error in partially differentiated terms.

$$\sigma_h^2 = \left(\frac{\partial h}{\partial q''} \sigma_{q''} \right)^2 + \left(\frac{\partial h}{\partial (T_b - T_{w,i})} \sigma_{(T_b - T_{w,i})} \right)^2 \tag{A-2}$$

where T_b is directly measured and h and q'' are calculated from the measured parameters. The measured parameter has a measurement error and the calculated parameter has a composite error. Differentiating Equation (A-1) partially with respect to q'' and $(T_b - T_{w,i})$, and substituting into the Equation (A-2), we obtain

$$\frac{\sigma_h}{h} = \left[\left(\frac{\sigma_{q''}}{q''} \right)^2 + \left(\frac{\sigma_{(T_b - T_{w,i})}}{(T_b - T_{w,i})} \right)^2 \right]^{\frac{1}{2}} \tag{A-3}$$

The heat flux is given as the following:

$$q''(x) = \frac{\dot{m}_c C_p}{\pi d} \frac{dT_c}{dL}(x) \tag{A-4}$$

In the similar derivation with the above Equation (A-3), the relative error for heat flux is obtained as the following:

$$\frac{\sigma_{q''}}{q''} = \left[\left(\frac{\sigma_{\dot{m}_c}}{\dot{m}_c} \right)^2 + \left(\frac{\sigma_{(dT_c/dL)}}{(dT_c/dL)} \right)^2 \right]^{\frac{1}{2}} \tag{A-5}$$

The tube inner wall temperature is given as the heat flux and the tube outer wall temperature.

$$T_{w,i} = q''(x) \cdot R + T_{w,o} \tag{A-6}$$

The error for $(T_b - T_{w,i})$ is obtained as follows:

$$\sigma_{T_{w,i}} = \left[\left(\frac{\partial T_{w,i}}{\partial q''} \sigma_{q''} \right)^2 + \left(\frac{\partial T_{w,i}}{\partial T_{w,o}} \sigma_{Tw,o} \right)^2 \right]^{\frac{1}{2}} \tag{A-7}$$

$$= \left((R\sigma_{q''})^2 + (\sigma_{T_{w,o}})^2 \right)^{\frac{1}{2}}$$

$$\sigma_{(T_b - T_{w,i})} = (\sigma_{T_b}{}^2 + (R\sigma_{q''})^2 + \sigma_{T_{w,o}}{}^2)^{\frac{1}{2}} \tag{A-8}$$

The error of measuring parameter is given by the instrument error. The flowmeter accuracy is within $\pm 2.5\%$ of the full scale reading.

$$\sigma_{\dot{m}_c} = 0.025\, \dot{m}_c \text{ (full scale)} \tag{A-9}$$

All temperatures in test section are measured by the K-type thermocouples whose error limits are 1℃. The minimum temperature difference between the surface inner wall and mixture bulk is 7.2℃. The coolant temperature gradient, (dT_c / dL), is within 10% maximum.

$$\sigma_{T_b} = \sigma_{T_{w,i}} = \sigma_{T_{w,o}} = \sigma_{T_c} = 1.0 \tag{A-10}$$

$$(T_b - T_{w,i}) = 7.2 \tag{A-11}$$

$$\sigma_{(dT_c/dL)} = 0.1\,(dT_c / dL) \tag{A-12}$$

The maximum heat flux from experiment is 115,023W/㎡ and the relative error from Equation (A-5) is 0.103. Therefore the heat flux error of $\sigma_{q''}$ is 11,848.

The temperature difference error of $\sigma_{(T_b - T_{w,i})}$ is 1.7619. Finally, the relative maximum error for heat transfer coefficient is as the following:

$$\left(\frac{\sigma_h}{h} \right)_{\max} = 0.266 \tag{A-13}$$

Appendix B.
Input Deck for Reflux Condensation Experiment: #RC11

```
=RELAP5/MOD3.2 Simulation
*
******************************************************************
*          Reflux Condensation in the presence
*          of noncondensible gas in a Vertical Tube
* Test #RC11: Reflux condensation experiment
* steam-air mixture, countercurrent
* Ptot=0.106Mpa, Tsat=96.5C,
* Wg,in=0.00044kg/s, air mass fraction=18.9%
* D=0.01656m, L=2.4m
*
*     experimented by Young Min Moon
*     coded by HSPARK
* Nov. 9. 1998
******************************************************************
*
*
***********************************
*  miscellaneous control cards
***********************************
*
*
100    new    transnt
101    run
*
105    10.    20.
110    air
*
*
***********************************
* time step cards
***********************************
*
* original time step
*     end     min.st   max         ctrl minor major    rstplt
203  200.    1.0e-8   0.5   3     2500 10000 10000
*
*201   50.0    1.0e-7    0.05    3     100      1000      1000
*
*
*minor editor cards
*     alp      num        min       max
*
301   voidg     140020000   0.99    1.0
302   voidg     140030000   0.99    1.0
*
306   p     140020000    0.    10.e5
*
301   velgj    140020000    0.    ·5.0
302   velgj    140030000    0.     5.0
*
310   quala    140020000   0.     1.0
311   quala    140030000   0.     1.0
312   quala    140050000   0.     1.0
313   quala    140070000   0.     1.0
314   quala    140090000   0.     1.0
315   quala    140110000   0.     1.0
*
341    hthtc       140000100     0.0   1.e4
342    hthtc       140000200     0.0   1.e4
343    hthtc       140000300     0.0   1.e4
344    hthtc       140000400     0.0   1.e4
345    hthtc       140000500     0.0   1.e4
346    hthtc       140000600     0.0   1.e4
347    hthtc       140000700     0.0   1.e4
348    hthtc       140000800     0.0   1.e4
349    hthtc       140000900     0.0   1.e4
```

```
350    hthtc      140001000    0.0   1.e4
351    hthtc      140001100    0.0   1.e4
*
365    htrnr      140000100     -1.e6   0.0
*
***********************************
* trip logic
***********************************
*
*
502    time   0    lt     null   0.    0.    n     0.0
506    time   0    gt     null   0.    0.    n     -1.0
508    quala     130010000   gt    null   0.    0.8    n     0
*
*
***********************************************
* hydrodynamic data : steam-air mixture tube
***********************************************
*
*
* component 100 : S/G using time dependent volume
*     name       type
1000000 tdv100   tmdpvol
*     area     length    vol    x       angle    elev    rough     dhydr    vflag
1000101 2.0         2.0      0.0    0.0    0.0        0.0       1.e-4    0.0        00000
* noncondensible gas(air)
*     cntrl
1000200 004
*     var       pressure       temp.    eq.quality
1000201 0.0        0.106e6    0.37065e3    1.0
*
*
* component 105 : Steam flow initiation in kg/s
*     name         type
1050000 tdj105    tmdpjun
*     from        to        area
*     ccc000000      cccvv000n
1050101 100000000       110010001      0.00051
*     cntrl      trip
1050200 1       502
*     var waterflow steamflow        interface vel.
1050201    -1.0    0.0      0.00044        0.0
1050202       0    0.0      0.00044        0.0
*
*
* component 110 : single volume near mixture inlet
*     name          type
1100000      sv110       snglvol
*     area        length         vol        x        angle
1100101      0.00051 0.2         0.0        0.0        0.
*     elev        rough       dh        vflag
1100102      0.00          1.e-4    0.0          00000
*     cntrl       pressure     temp.
1100200      003      0.106e6     0.37065e3
*
*
* component 115 : single volume to lower plenum
*     name          type
1150000 sj115     sngljun
*     from        to        areav       kforw       kbackw     jflag
1150101 110010002      150010001 0.00051 11.783    7.608 0001000
*     cntrl      waterflow      steamflow       x
1150201 1      0.0      0.00044       0.0
*
*
* component 130 : upper plenum
*     name      type
1300000    pipe130        pipe
*     nv
1300001    3
*     area        nv
1300101    0.04       3
*     length       vn
1300301    0.06       1
1300302    0.08       2
```

```
1300303  0.06    3
*     volume     nv
1300401   0.0     3
*     angle      nv
1300601   -90.0     3
*     rough    dhydr     nv
1300801   1.e-4    0.0    3
*     vflag    nv
1301001   00000     3
*     jflag     nj
1301101   000000      2
*     cntrl   pressure temp.     eq.quality     vn
1301201   004       0.106e6   0.37065e3      1.0     0.0     0.0     1
1301202   004       0.106e6   0.37065e3      1.0     0.0     0.0     2
1301203   004       0.106e6   0.37065e3      1.0     0.0     0.0     3
*   cntrl
1301300    1
*     waterflow     steamflow int.vel    nj
1301301   0.0       0.00044       0.0    2
*
*
* component 135 : upper plenum to condensing tube
*     name        type
1580000 sj135   sngljun
*     from        to      areav     kforw     kbackw   jflag
1580101 140130002     130030001 0.0002154 117.83e-3     76.08e-3 0001000
*    cntrl     waterflow      steamflow     x
1580201 1     0.0     0.00044       0.0
*
*
* component 140 : condensing tube
*     name       type
1400000   pipe140        pipe
*     nv: no. vol
1400001    13
*     area      nv
1400101   0.0002154    13
*     length      vn
* ccc0301 - ccc0399
1400301   0.370     1
1400302   0.200     2
1400303   0.040     3
1400304   0.250     4
1400305   0.090     5
1400306   0.300     6
1400307   0.140     7
1400308   0.360     8
1400309   0.140     9
1400310   0.690     10
1400311   0.180     11
1400312   0.010     12
1400313   0.370     13
*     volume       nv
*     angle      vn
1400601   90.0     13
*     rough     dhydr      no. vol
1400801   1.e-4   0.0      13
*     vflag     no. vol
1401001   00000      13
*     jflag      no. jun
1401101   000000        12
*     cntrl   pressure      temp.       nv
1401201   004     0.106e6   0.37065e3     1.0     0.0     0.0     1
1401202   004     0.106e6   0.37065e3     1.0     0.0     0.0     2
1401203   004     0.106e6   0.37065e3     1.0     0.0     0.0     3
1401204   004     0.106e6   0.37065e3     1.0     0.0     0.0     4
1401205   004     0.106e6   0.37065e3     1.0     0.0     0.0     5
1401206   004     0.106e6   0.37065e3     1.0     0.0     0.0     6
1401207   004     0.106e6   0.37065e3     1.0     0.0     0.0     7
1401208   004     0.106e6   0.37065e3     1.0     0.0     0.0     8
1401209   004     0.106e6   0.37065e3     1.0     0.0     0.0     9
1401210   004     0.106e6   0.37065e3     1.0     0.0     0.0     10
1401211   004     0.106e6   0.37065e3     1.0     0.0     0.0     11
1401212   004     0.106e6   0.37065e3     1.0     0.0     0.0     12
1401213   004     0.106e6   0.37065e3     1.0     0.0     0.0     13
```

```
*      cntrl
1401300   1
*      water flow   steam flow int.vel jn
1401301   0.0     0.0     0.0     12
*
*
* component 145 : condensing tube to lower plenum
*      name        type
1450000 sj145    sngljun
*    from         to         area       kforw        kbackw    jflag
1450101 150010002     140010001     0.0002154 117.83e-5    76.08e-5    0001000
*    cntrl     waterflow      steamflow      x
1450201 1      0.0      0.0      0.0
*
*
* component 150 : lower plenum
*      name      type
1500000   pipe150       pipe
*      nv
1500001   3
*      area       nv
1500101   0.04     3
*      length      vn
1500301   0.06     1
1500302   0.08     2
1500303   0.06     3
*      volume      nv
1500401   0.0        3
*      angle        nv
1500601   -90.0       3
*      rough      dhydr      nv
1500801   1.e-4    0.0     3
*      vflag      nv
1501001   00000      3
*      jflag      nj
1501101   000000      2
*      cntrl    pressure temp.    eq.quality       vn
1501201   004       0.106e6   0.37065e3      1.0      0.0      0.0      1
1501202   004       0.106e6   0.37065e3      1.0      0.0      0.0      2
1501203   004       0.106e6   0.37065e3      1.0      0.0      0.0      3
*    cntrl
1501300   1
*      waterflow      steamflow int.vel    nj
1501301   0.0        0.0        0.0     2
*
*
************************************
* hydrodynamic data : venting line
************************************
*
*
* component 155 : lower plenum to drain tank
*      name        type
1550000 sj155    sngljun
*    from       to        areav        kforw        kbackw    jflag
1550101 150030002    160050002    0.00001    923317.24 923317.24 0001000
*    cntrl     waterflow      steamflow      x
1550201 1      0.0      0.0      0.0
*
*
* component 156 : lower plenum to drain pipe
*      name        type
1560000 sj156    sngljun
*    from         to         areav        kforw        kbackw    jflag
1560101 150030002      157050002     0.00012    2109.13    4153.80    0001000
*    cntrl     waterflow      steamflow      x
1560201 1      0.0      0.0      0.0
*
*
* component 157 : drain pipe
*      name      type
1570000   pipe157       pipe
*      nv
1570001   5
*      area       nv
```

```
1570101  0.00012    5
*     length    vn
1570301  0.20    5
*     volume    nv
1570401  0.0     5
*     angle      nv
1570601  90.0    5
*     rough     dhydr     nv
1570801  1.e-4    0.0     5
*     vflag     nv
1571001  00000     5
*     jflag     nj
1571101  000000       4
*     cntrl  pressure    temp.    eq.quality        vn
1571201  004    0.106e6  0.37065e3    1.0    0.0    0.0    1
1571202  004    0.106e6  0.37065e3    0.5    0.0    0.0    2
1571203  004    0.106e6  0.37065e3    0.0    0.0    0.0    3
1571204  004    0.106e6  0.37065e3    0.0    0.0    0.0    4
1571205  004    0.106e6  0.37065e3    0.0    0.0    0.0    5
*    cntrl
1571300   1
*     waterflow    steamflow int.vel    nj
1571301   0.0       0.0       0.0    4
*
*
* component 160 : drain tank
*     name    type
1600000  pipe160      pipe
*     nv
1600001   5
*     area     nv
1600101  0.7854     5
*     length    vn
1600301  0.20    5
*     volume    nv
1600401  0.0     5
*     angle      nv
1600601  90.0    5
*     rough     dhydr     nv
1600801  1.e-4    0.0     5
*     vflag     nv
1601001  00000     5
*     jflag     nj
1601101  000000       4
*     cntrl  pressure    temp.    eq.quality        vn
1601201  004    0.106e6  0.37065e3    1.0    0.0    0.0    1
1601202  004    0.106e6  0.37065e3    0.5    0.0    0.0    2
1601203  004    0.106e6  0.37065e3    0.0    0.0    0.0    3
1601204  004    0.106e6  0.37065e3    0.0    0.0    0.0    4
1601205  004    0.106e6  0.37065e3    0.0    0.0    0.0    5
*    cntrl
1601300   1
*     waterflow    steamflow int.vel    nj
1601301   0.0       0.0       0.0    4
*
*
* component 165 : upper plenum to single volume
*    name       type
1650000 sj165   sngljun
*    from     to     areav      kforw     kbackw    jflag
1650101 130010002   170010001   0.0001267   2109.13e-8   4153.80e5 0001000
*    cntrl    waterflow     steamflow      x
1650201 1     0.0     0.0      0.0
*
*
* component 170 : single volume near mixture outlet
*    name        type
1700000     sv170     snglvol
*    area       length       vol       x     angle
1700101     0.0001267 0.2      0.0      0.0     0.
*    elev      rough     dh     vflag
1700102     0.     1.e-4   0.0      00000
*    cntrl     pressure   temp.
1700200     003     0.106e6   0.29965e3
*
```

```
*
* componet 175 : valve for venting
*      name       type
1750000   vv175      valve
*      from        to        areav    kforw kback jflag
1750101   170010002     180000000 0.0001267 2109.13e-5     4153.80e-5     000100
*      cntrl waterflow      steamflow interface velocity
1750201     1     0.0        0.0     0.0
*    valve type
1750300      trpvlv
*    trip number(open when true)
1750301      506
*
*
* component 180 : venting simulation using tdv
*    name       type
1800000 tdv180    tmdpvol
*    area     length     vol     x    angle    elev    rough    dhydr   vflag
1800101 2.0      2.0      0.0    0.0    0.0      0.0     0.0       0.0   00000
*    cntrl
1800200 004
*    var       pressure       temp.     eq.quality
1800201 0.0       0.106e6    0.29965e3      1.0
*
*
*********************************************
* hydrodynamic data : coolant water annulus
*********************************************
*
*
* component 200 : coolant source simulation using tdv
*    name       type
2000000 tdv200    tmdpvol
*    area     length     vol       x       angle    elev    rough    dhydr    vflag
2000101 2.0      2.0      0.0      0.0    0.0      0.0     0.0      0.0      00000
*    cntrl
2000200 003
*    var      p(1atm)        temp.
2000201 0.0       0.1013e6       0.29125e3
*
*
* component 210 : coolant water flow initiation -> 0.13kg/s
* component 210 *
*    name        type
2100000 tdj210    tmdpjun
*    from        to        area
2100101 200000000      240010001      0.00049
*    cntrl      trip
2100200 1      502
*    var      waterflow      steamflow      x
2100201 -1.0      0.063      0.0      0.0
2100202   0.       0.063      0.0      0.0
*
*
* component 240 : outer tube for coolant water
*      name       type
2400000   out_tube       annulus
*      nv
2400001    11
*      area       nv
2400101   0.00228       11
*      length      vn
2400301   0.200     1
2400302   0.040     2
2400303   0.250     3
2400304   0.090     4
2400305   0.300     5
2400306   0.140     6
2400307   0.360     7
2400308   0.140     8
2400309   0.690     9
2400310   0.180     10
2400311   0.010     11
*      volume      nv
2400401   0.0      11
```

```
*      angle      nv
2400601   90.0        11
*      rough        hd        nv
2400801   1.e-4        0.0      11
*      vflag      nv
2401001   00010       11
*      jflag      nj
2401101   000020        10
*      cntrl    pressure temp.          vn
2401201   003     0.1013e6     0.29125e3     0.0     0.0     0.0     1
2401202   003     0.1013e6     0.29125e3     0.0     0.0     0.0     2
2401203   003     0.1013e6     0.29125e3     0.0     0.0     0.0     3
2401204   003     0.1013e6     0.29125e3     0.0     0.0     0.0     4
2401205   003     0.1013e6     0.29125e3     0.0     0.0     0.0     5
2401206   003     0.1013e6     0.29125e3     0.0     0.0     0.0     6
2401207   003     0.1013e6     0.29125e3     0.0     0.0     0.0     7
2401208   003     0.1013e6     0.29125e3     0.0     0.0     0.0     8
2401209   003     0.1013e6     0.29125e3     0.0     0.0     0.0     9
2401210   003     0.1013e6     0.29125e3     0.0     0.0     0.0     10
2401211   003     0.1013e6     0.29125e3     0.0     0.0     0.0     11
*      cntrl
2401300   1
*      waterflow    steamflow    int.vel nj
2401301   0.063     0.0     0.0        10
*
*
* component 270 : outer tube to coolant outlet
*    name        type
2700000 sj270    sngljun
*    from       to       area       kforw      kbackw   jflag
2700101 240110002     280000000     0.00049   50.0       90.48     0001000
*    cntrl    waterflow     steamflow     x
2700201 1     0.063        0.0      0.0
*
*
* component 280 : coolant water dumping
*    name      type
2800000 tdv280    tmdpvol
*    area      length       vol     x    angle     elev    rough    dhydr    vflag
2800101 2.0       2.0      0.0    0.0    0.0       0.0     0.0       0.0    00000
*    cntrl
2800200 003
*    var       p(1atm)        temp.
2800201 0.0        0.1013e6        0.29125e3
*
*
*****************************************************************
* heat structure input : pipe140 <-> annulus240
* (condensing tube simulation)
*****************************************************************
*
*
* heat structure 140 : heat transfer simulation through pipe
11400000   11   4   2   1   0.00828
11400100   0   1
11400101   3   0.009525
11400201   5   3
11400301   0   3
11400401   373.0   4
*
11400501   140020000   0    101   1   0.200   1
11400502   140030000   0    101   1   0.040   2
11400503   140040000   0    101   1   0.250   3
11400504   140050000   0    101   1   0.090   4
11400505   140060000   0    101   1   0.300   5
11400506   140070000   0    101   1   0.140   6
11400507   140080000   0    101   1   0.360   7
11400508   140090000   0    101   1   0.140   8
11400509   140100000   0    101   1   0.690   9
11400510   140110000   0    101   1   0.180 10
11400511   140120000   0    101   1   0.010 11
*
11400601   240010000   0    101   1   0.200   1
11400602   240020000   0    101   1   0.040   2
11400603   240030000   0    101   1   0.250   3
```

```
11400604  240040000  0   101  1  0.090  4
11400605  240050000  0   101  1  0.300  5
11400606  240060000  0   101  1  0.140  6
11400607  240070000  0   101  1  0.360  7
11400608  240080000  0   101  1  0.140  8
11400609  240090000  0   101  1  0.690  9
11400610  240100000  0   101  1  0.180 10
11400611  240110000  0   101  1  0.010 11
*
11400701  0  0.0   0.0   0.0   11
11400801  0  10.0  10.0  10.0  10.0  0  0  1.0  11
11400901  0  10.0  10.0  10.0  10.0  0  0  1.0  11
*
*
**************************************************************
* heat structure thermal property data : SUS (005)   18cr-8ni
**************************************************************
*
*
20100500   tbl/fctn   1   1
*
*          temp(k)          thermal conductivity(w/m.k)
20100501   0.2732611e+03   0.1489124e+02
20100502   0.2942611e+03   0.1489124e+02
20100503   0.3109278e+03   0.1505739e+02
20100504   0.3664834e+03   0.1609584e+02
20100505   0.4220389e+03   0.1696813e+02
20100506   0.4775945e+03   0.1800657e+02
20100507   0.5331500e+03   0.1885809e+02
20100508   0.5887056e+03   0.1956423e+02
20100509   0.6442611e+03   0.2041575e+02
20100510   0.8109278e+03   0.2297030e+02
20100511   0.9220389e+03   0.2423029e+02
20100512   1.9220389e+03   0.2423029e+02
*
*          temp(k)          volumetric heat capacity(j/m3.k)
20100551   0.2742611e+03   0.3831330e+07
20100552   0.3109278e+03   0.3831330e+07
20100553   0.3664834e+03   0.3985580e+07
20100554   0.4220389e+03   0.4105300e+07
20100555   0.4775945e+03   0.4224090e+07
20100556   0.5331500e+03   0.4308800e+07
20100557   0.5887056e+03   0.4359790e+07
20100558   0.6442611e+03   0.4410320e+07
20100559   0.8109278e+03   0.4561910e+07
20100560   0.9220389e+03   0.4625250e+07
20100561   1.9220389e+03   0.4625250e+07
*
. end of file
```

Appendix C.
Local Data of Reflux Condensation Experiment

Nomenclature (for Appendix C)

Characters

Twi	: inner wall temperature(°C)
TB	: centerline temperature in tube(°C)
TC	: coolant temperature(°C)
mu	: viscosity(N·s/m^2)
Rho	: density(kg/m^3)
F	: flow rate(kg/hr)
FA	: air flow rate(kg/hr)
FS	: steam flow rate(kg/hr)
FM	: steam-air mixture flow rate(kg/hr)
Delta	: film thickness(m)
Re	: Reynolds number
Ja	: Jacob number
W_air	: air mass fraction
HTC	: heat transfer coefficient(W/m^2·°C)
F	: degradation factor ($= h_{tot} / h_f$)
RMS	: root mean square error ($= \sqrt{\left\|(h_{exp} - h_{corr}) / h_{exp}\right\|}$)

Subscripts

mix, g	: steam-air mixture
in	: inlet
f	: film
exp	: by experiment
corr	: by correlation
cond	: condensate

Table C.1. 165 local data for correlation development (inlet steam-air mixture flow)

	Exp. No.	Length [m]	Twi	TB(x)	TC_fit	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
1	RA01	0.1	68.9	120.2	16.1	11.1	4186.2	4.045E-04	1.35348E-06	942.4	1.4058	1.141	0.742	0.0333	3.282
2	RA01	0.22	59.5	118.3	18.4	11.1	4184.9	4.719E-04	1.35911E-06	944.0	1.3998	1.665	0.742	0.0333	3.282
3	RA01	0.365	50.8	114.8	20.5	11.1	4183.8	5.502E-04	1.36389E-06	946.9	1.3938	2.143	0.742	0.0333	3.282
4	RA01	0.535	43.6	109.0	22.2	11.1	4183.0	6.281E-04	1.36495E-06	951.6	1.3916	2.530	0.742	0.0333	3.282
5	RA01	0.73	38.3	100.2	23.5	11.1	4182.5	6.938E-04	1.35897E-06	958.2	1.3995	2.826	0.742	0.0333	3.282
6	RA01	0.95	33.4	89.0	24.4	11.1	4182.1	7.612E-04	1.34437E-06	966.1	1.4237	3.031	0.742	0.0333	3.282
7	RA01	1.2	30.3	76.2	24.9	11.1	4181.9	8.074E-04	1.31657E-06	974.2	1.4663	3.145	0.742	0.0333	3.282
8	RA02	0.1	76.1	121.7	23.9	21.5	4182.3	3.634E-04	1.37021E-06	941.2	1.3965	0.816	0.804	0.0504	2.591
9	RA02	0.22	62.3	119.6	25.0	21.5	4181.9	4.504E-04	1.37509E-06	942.9	1.3908	1.212	0.804	0.0504	2.591
10	RA02	0.365	54.0	115.9	26.0	21.5	4181.5	5.197E-04	1.37758E-06	946.0	1.3864	1.569	0.804	0.0504	2.591
11	RA02	0.535	46.1	110.2	26.9	21.5	4181.2	5.997E-04	1.37511E-06	950.6	1.3864	1.864	0.804	0.0504	2.591
12	RA02	0.73	40.1	100.7	27.6	21.5	4181.0	6.710E-04	1.36024E-06	957.9	1.3985	2.091	0.804	0.0504	2.591
13	RA03	0.1	64.5	111.0	11.4	9.2	4189.1	4.340E-04	1.35828E-06	950.0	1.3952	0.497	1.538	0.0333	2.525
14	RA03	0.22	52.5	108.1	13.5	9.2	4187.7	5.336E-04	1.36186E-06	952.3	1.3932	0.970	1.538	0.0333	2.525
15	RA03	0.365	44.4	104.2	15.4	9.2	4186.6	6.188E-04	1.3646E-06	955.3	1.3937	1.399	1.538	0.0333	2.525
16	RA03	0.535	39.2	98.9	17.1	9.2	4185.6	6.821E-04	1.3655E-06	959.2	1.3991	1.782	1.538	0.0333	2.525
17	RA03	0.73	34.3	91.4	18.5	9.2	4184.8	7.483E-04	1.36018E-06	964.5	1.4152	2.097	1.538	0.0333	2.525
18	RA03	0.95	30.2	82.9	19.5	9.2	4184.3	8.089E-04	1.34912E-06	970.1	1.4424	2.322	1.538	0.0333	2.525
19	RA03	1.2	27.9	73.6	20.2	9.2	4184.0	8.451E-04	1.33177E-06	975.7	1.4809	2.480	1.538	0.0333	2.525
20	RA04	0.1	74.0	121.7	27.1	24	4181.2	3.747E-04	1.38506E-06	941.1	1.3864	1.073	0.804	0.0504	2.384
21	RA04	0.22	57.5	119.5	27.8	24	4180.9	4.887E-04	1.38826E-06	943.0	1.3821	1.325	0.804	0.0504	2.384
22	RA05	0.1	60.5	107.7	10.3	8.7	4189.9	4.639E-04	1.35701E-06	952.6	1.3955	0.360	1.85	0.0333	2.357
23	RA05	0.22	51.7	104.9	11.9	8.7	4188.8	5.413E-04	1.35739E-06	954.7	1.3962	0.719	1.85	0.0333	2.357
24	RA05	0.365	41.4	100.8	13.5	8.7	4187.7	6.545E-04	1.35532E-06	957.8	1.4001	1.079	1.85	0.0333	2.357
25	RA05	0.535	35.6	95.4	15.1	8.7	4186.7	7.301E-04	1.35158E-06	961.7	1.4086	1.438	1.85	0.0333	2.357
26	RA05	0.73	32.4	87.8	16.6	8.7	4185.9	7.758E-04	1.34261E-06	966.9	1.4271	1.774	1.85	0.0333	2.357
27	RA05	0.95	28.4	79.3	17.9	8.7	4185.1	8.371E-04	1.33194E-06	972.3	1.4555	2.066	1.85	0.0333	2.357
28	RA05	1.2	26.1	70.4	19.0	8.7	4184.6	8.745E-04	1.32078E-06	977.6	1.4947	2.313	1.85	0.0333	2.357
29	RA06	0.1	52.1	98.9	9.9	8.8	4190.2	5.374E-04	1.34657E-06	959.2	1.4050	0.245	2.443	0.0333	2
30	RA06	0.22	48.1	95.5	11.1	8.8	4189.3	5.780E-04	1.34244E-06	961.6	1.4107	0.512	2.443	0.0333	2
31	RA06	0.365	39.9	91.5	12.4	8.8	4188.4	6.732E-04	1.338E-06	964.4	1.4188	0.801	2.443	0.0333	2

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Wair(x)	HTC_exp	HTC_corr	F_exp	F_corr	RMS
1	RA01	2.141	2.1413	2.8833	1.1689E-04	5628.7	45497.8	113.06	0.09762	0.2573	1570.4	826.7	0.27900	0.14688	0.4736
2	RA01	1.617	1.6171	2.3591	1.1193E-04	5802.0	37072.0	73.19	0.11186	0.3145	674.0	573.8	0.11617	0.09889	0.1487
3	RA01	1.139	1.1387	1.8807	1.0459E-04	6123.6	29451.0	44.20	0.12172	0.3945	442.7	402.4	0.07229	0.06571	0.0910
4	RA01	0.752	0.7516	1.4936	9.4864E-05	6665.7	23370.6	25.56	0.12436	0.4968	292.2	296.2	0.04384	0.04444	0.0137
5	RA01	0.456	0.4556	1.1976	8.2606E-05	7577.1	18821.9	14.03	0.11769	0.6196	196.6	234.2	0.02595	0.03091	0.1913
6	RA01	0.251	0.2508	0.9928	6.9442E-05	8923.2	15771.5	7.04	0.10571	0.7474	131.4	192.7	0.01473	0.02160	0.4667
7	RA01	0.137	0.1369	0.8789	5.7566E-05	10692.5	14258.2	3.62	0.08726	0.8442	90.3	178.1	0.00845	0.01665	0.9720
8	RA02	1.775	1.7746	2.5786	1.0604E-04	6258.9	40192.0	104.28	0.08680	0.3118	1258.0	886.0	0.20099	0.14156	0.2957
9	RA02	1.379	1.3791	2.1831	1.0459E-04	6234.1	33907.9	65.39	0.10924	0.3683	510.2	559.1	0.08185	0.08969	0.0958
10	RA02	1.022	1.0223	1.8263	9.9064E-05	6499.2	28314.6	42.01	0.11804	0.4402	344.6	410.2	0.05302	0.06311	0.1904
11	RA02	0.727	0.7267	1.5307	9.2427E-05	6872.8	23773.3	25.88	0.12207	0.5253	230.3	307.9	0.03351	0.04479	0.3368
12	RA02	0.500	0.4998	1.3038	8.4270E-05	7453.5	20470.9	15.91	0.11550	0.6167	159.3	252.9	0.02138	0.03393	0.5872
13	RA03	2.028	2.0284	3.5664	1.1689E-04	5595.6	56077.6	99.82	0.08756	0.4312	990.3	761.1	0.17698	0.13601	0.2315
14	RA03	1.555	1.5547	3.0927	1.1442E-04	5613.5	48501.2	62.23	0.10466	0.4973	651.8	503.9	0.11611	0.08977	0.2269
15	RA03	1.126	1.1264	2.6644	1.0774E-04	5877.7	41700.0	38.87	0.11253	0.5772	455.8	372.1	0.07755	0.06330	0.1837
16	RA03	0.743	0.7433	2.2813	9.6630E-05	6489.0	35680.9	23.27	0.11232	0.6742	327.6	296.7	0.05049	0.04572	0.0943
17	RA03	0.428	0.4279	1.9659	8.2604E-05	7515.7	30868.3	12.21	0.10740	0.7823	233.3	239.7	0.03104	0.03189	0.0274
18	RA03	0.203	0.2027	1.7407	6.5831E-05	9348.0	27556.3	5.35	0.09912	0.8836	164.0	196.9	0.01754	0.02106	0.2006
19	RA03	0.045	0.0451	1.5831	4.0313E-05	15187.1	25387.6	1.14	0.08594	0.9715	116.8	155.0	0.00769	0.01021	0.3272
20	RA04	1.311	1.3114	2.1154	9.6851E-05	6835.6	32619.7	74.75	0.09097	0.3801	630.1	726.0	0.09218	0.10621	0.1522
21	RA04	1.059	1.0589	1.8629	9.8402E-05	6579.2	28660.0	46.28	0.11815	0.4316	269.2	438.8	0.04092	0.06669	0.6300
22	RA05	1.997	1.9973	3.8473	1.1869E-04	5479.5	60550.4	91.95	0.08852	0.4809	708.9	702.2	0.12937	0.12816	0.0094
23	RA05	1.638	1.6377	3.4877	1.1678E-04	5492.8	54876.8	64.61	0.09975	0.5304	542.5	522.9	0.09877	0.09520	0.0361
24	RA05	1.278	1.2784	3.1284	1.1430E-04	5509.3	49297.3	41.72	0.11134	0.5914	406.5	374.0	0.07378	0.06788	0.0800
25	RA05	0.919	0.9192	2.7692	1.0591E-04	5877.4	43758.0	26.89	0.11207	0.6681	328.0	302.1	0.05581	0.05140	0.0790
26	RA05	0.583	0.5826	2.4326	9.2503E-05	6684.4	38695.5	16.04	0.10380	0.7605	279.4	263.2	0.04180	0.03938	0.0579
27	RA05	0.291	0.2909	2.1409	7.4993E-05	8173.2	34329.1	7.42	0.09535	0.8641	231.7	218.5	0.02835	0.02673	0.0570
28	RA05	0.044	0.0442	1.8942	4.0459E-05	15070.2	30629.7	1.08	0.08298	0.9767	198.3	158.8	0.01316	0.01054	0.1992
29	RA06	1.755	1.7552	4.1982	1.1885E-04	5400.7	66586.2	69.75	0.08687	0.5819	526.4	593.3	0.09747	0.10985	0.1270
30	RA06	1.488	1.4883	3.9313	1.1505E-04	5540.8	62544.6	55.00	0.08797	0.6214	463.7	520.8	0.08369	0.09400	0.1232
31	RA06	1.199	1.1992	3.6422	1.1243E-04	5584.7	58138.0	38.05	0.09574	0.6707	372.9	399.7	0.06677	0.07157	0.0719

	Exp. No.	Length [m]	Twl(x)	TB(x)	TC_fit	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
32	RA06	0.535	30.8	86.3	13.7	8.8	4187.6	7.998E-04	1.33073E-06	967.9	1.4322	1.090	2.443	0.0333	2
33	RA06	0.73	29.8	78.9	15.0	8.8	4186.8	8.151E-04	1.31729E-06	972.6	1.4558	1.379	2.443	0.0333	2
34	RA06	0.95	26.5	71.2	16.1	8.8	4186.2	8.679E-04	1.30239E-06	977.1	1.4858	1.623	2.443	0.0333	2
35	RA06	1.2	24.3	63.2	17.2	8.8	4185.5	9.049E-04	1.28843E-06	981.5	1.5238	1.867	2.443	0.0333	2
36	RB01	0.1	62.6	100.7	10.2	8.2	4189.9	4.478E-04	1.29179E-06	957.9	0.9377	0.446	0.796	0.0333	2.448
37	RB01	0.22	54.4	99.2	12.2	8.2	4188.6	5.158E-04	1.29765E-06	959.0	0.9476	0.891	0.796	0.0333	2.448
38	RB01	0.365	42.3	96.3	14.1	8.2	4187.4	6.435E-04	1.30268E-06	961.1	0.9630	1.314	0.796	0.0333	2.448
39	RB01	0.535	37.6	91.7	15.7	8.2	4186.4	7.030E-04	1.30537E-06	964.3	0.9858	1.670	0.796	0.0333	2.448
40	RB01	0.73	31.6	85.2	17.1	8.2	4185.6	7.877E-04	1.30715E-06	968.6	1.0214	1.981	0.796	0.0333	2.448
41	RB01	0.95	27.3	77.5	18.2	8.2	4185.0	8.548E-04	1.30913E-06	973.4	1.0715	2.226	0.796	0.0333	2.448
42	RB01	1.2	24.5	69.8	19.0	8.2	4184.6	9.015E-04	1.31286E-06	977.9	1.1335	2.404	0.796	0.0333	2.448
43	RB02	0.1	59.9	96.2	9.6	7.9	4190.4	4.687E-04	1.3018E-06	961.1	0.9627	0.377	1.43	0.0333	2.436
44	RB02	0.22	52.6	94.4	11.4	7.9	4189.1	5.326E-04	1.30624E-06	962.4	0.9742	0.776	1.43	0.0333	2.436
45	RB02	0.365	42.6	91.5	13.2	7.9	4187.9	6.400E-04	1.30984E-06	964.4	0.9908	1.175	1.43	0.0333	2.436
46	RB02	0.535	38.7	86.9	14.8	7.9	4186.9	6.886E-04	1.30958E-06	967.5	1.0143	1.529	1.43	0.0333	2.436
47	RB02	0.73	33.4	80.3	16.3	7.9	4186.0	7.612E-04	1.30587E-06	971.7	1.0494	1.861	1.43	0.0333	2.436
48	RB02	0.95	29.6	73.1	17.5	7.9	4185.4	8.182E-04	1.30086E-06	976.0	1.0927	2.127	1.43	0.0333	2.436
49	RB02	1.2	25.9	65.2	18.5	7.9	4184.8	8.778E-04	1.29469E-06	980.4	1.1470	2.348	1.43	0.0333	2.436
50	RB03	0.1	72.4	103.9	23.5	23	4182.5	3.836E-04	1.33506E-06	955.5	0.9578	0.197	1.403	0.063	1.985
51	RB03	0.22	68.0	102.1	24.1	23	4182.3	4.103E-04	1.33666E-06	956.8	0.9659	0.453	1.403	0.063	1.985
52	RB03	0.365	58.2	99.4	24.7	23	4182.0	4.829E-04	1.33626E-06	958.9	0.9770	0.710	1.403	0.063	1.985
53	RB03	0.535	44.9	95.0	25.3	23	4181.8	6.130E-04	1.33146E-06	962.0	0.9928	0.951	1.403	0.063	1.985
54	RB03	0.73	39.7	88.9	25.8	23	4181.6	6.758E-04	1.32085E-06	966.1	1.0142	1.166	1.403	0.063	1.985
55	RB04	0.1	62.2	99.7	8.1	5.5	4191.5	4.508E-04	1.27733E-06	958.6	0.9301	0.435	0.551	0.025	2.27
56	RB04	0.22	49.8	97.9	10.5	5.5	4189.7	5.603E-04	1.28068E-06	959.9	0.9389	0.835	0.551	0.025	2.27
57	RB04	0.365	37.0	94.7	12.8	5.5	4188.2	7.110E-04	1.28314E-06	962.2	0.9531	1.219	0.551	0.025	2.27
58	RB04	0.535	32.6	90.2	14.7	5.5	4187.0	7.729E-04	1.28455E-06	965.3	0.9738	1.536	0.551	0.025	2.27
59	RB04	0.73	27.3	83.1	16.2	5.5	4186.1	8.548E-04	1.28014E-06	970.0	1.0051	1.786	0.551	0.025	2.27
60	RB04	0.95	23.7	74.8	17.3	5.5	4185.5	9.152E-04	1.27294E-06	975.0	1.0466	1.970	0.551	0.025	2.27
61	RB04	1.2	22.1	66.5	18.1	5.5	4185.0	9.434E-04	1.26602E-06	979.7	1.0965	2.103	0.551	0.025	2.27
62	RB05	0.1	48.3	87.2	6.6	5.1	4192.6	5.758E-04	1.29256E-06	967.3	0.9960	0.247	1.577	0.025	1.694

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Wair(x)	HTC_exp	HTC_corr	F_exp	F_corr	RMS
32	RA06	0.910	0.9103	3.3533	1.0836E-04	5686.5	53818.2	24.31	0.10296	0.7285	296.0	299.4	0.05205	0.05265	0.0115
33	RA06	0.621	0.6215	3.0645	9.5714E-05	6423.8	49684.5	16.28	0.09107	0.7972	278.3	288.1	0.04332	0.04485	0.0353
34	RA06	0.377	0.3771	2.8201	8.2490E-05	7398.4	46246.1	9.28	0.08289	0.8663	249.0	256.8	0.03366	0.03471	0.0312
35	RA06	0.133	0.1329	2.5759	5.8903E-05	10308.1	42698.2	3.14	0.07213	0.9484	228.4	218.5	0.02216	0.02119	0.0435
36	RB01	2.002	2.0023	2.7983	1.1694E-04	5578.1	46264.5	95.49	0.07083	0.2845	1101.7	905.6	0.19750	0.16234	0.1780
37	RB01	1.557	1.5569	2.3529	1.1264E-04	5719.9	38724.8	64.46	0.08325	0.3383	757.9	635.7	0.13250	0.11114	0.1612
38	RB01	1.134	1.1340	1.9300	1.0895E-04	5790.0	31642.1	37.63	0.10032	0.4124	488.1	398.8	0.08430	0.06887	0.1830
39	RB01	0.778	0.7780	1.5740	9.8742E-05	6330.0	25753.0	23.64	0.10048	0.5057	361.6	314.8	0.05712	0.04974	0.1293
40	RB01	0.467	0.4667	1.2627	8.6234E-05	7158.0	20630.8	12.65	0.09954	0.6304	260.2	237.3	0.03635	0.03315	0.0880
41	RB01	0.222	0.2221	1.0181	6.8961E-05	8866.0	16609.7	5.55	0.09321	0.7818	188.6	184.2	0.02127	0.02077	0.0234
42	RB01	0.044	0.0443	0.8403	4.0883E-05	14858.5	13669.6	1.05	0.08410	0.9473	136.5	131.2	0.00919	0.00883	0.0390
43	RB02	2.059	2.0589	3.4889	1.1957E-04	5434.2	57239.2	93.82	0.06717	0.4099	1024.3	863.5	0.18849	0.15891	0.1569
44	RB02	1.660	1.6599	3.0899	1.1603E-04	5536.4	50520.7	66.56	0.07732	0.4628	749.8	640.6	0.13543	0.11570	0.1457
45	RB02	1.261	1.2611	2.6911	1.1240E-04	5615.2	43878.8	42.09	0.09043	0.5314	520.1	438.8	0.09262	0.07815	0.1563
46	RB02	0.907	0.9068	2.3368	1.0297E-04	6083.6	38109.0	28.12	0.08911	0.6120	413.5	368.2	0.06797	0.06052	0.1096
47	RB02	0.575	0.5747	2.0047	9.1190E-05	6795.1	32786.9	16.12	0.08669	0.7133	321.2	295.9	0.04727	0.04355	0.0786
48	RB02	0.309	0.3091	1.7391	7.5747E-05	8113.5	28553.1	8.07	0.08039	0.8222	252.8	246.2	0.03116	0.03035	0.0261
49	RB02	0.088	0.0879	1.5179	5.0839E-05	11987.9	25039.5	2.14	0.07262	0.9421	197.4	187.9	0.01647	0.01567	0.0481
50	RB03	1.788	1.7875	3.1905	1.0712E-04	6168.5	51040.2	99.52	0.05873	0.4397	735.8	1057.2	0.11929	0.17138	0.4367
51	RB03	1.532	1.5321	2.9351	1.0397E-04	6320.8	46897.7	79.75	0.06358	0.4780	623.3	887.5	0.09861	0.14041	0.4238
52	RB03	1.275	1.2755	2.6785	1.0311E-04	6285.2	42810.4	56.42	0.07673	0.5238	422.8	631.3	0.06727	0.10044	0.4931
53	RB03	1.034	1.0339	2.4369	1.0388E-04	6102.0	39088.8	36.02	0.09337	0.5757	274.8	414.0	0.04503	0.06784	0.5064
54	RB03	0.819	0.8189	2.2219	9.9000E-05	6339.8	35926.6	25.88	0.09174	0.6314	213.7	354.2	0.03371	0.05588	0.6576
55	RB04	1.835	1.8354	2.3864	1.1380E-04	5729.2	39901.5	86.95	0.06965	0.2309	1074.4	916.3	0.18753	0.15994	0.1471
56	RB04	1.435	1.4346	1.9856	1.1260E-04	5678.4	33112.9	54.68	0.08930	0.2775	654.3	565.1	0.11523	0.09952	0.1363
57	RB04	1.051	1.0508	1.6018	1.0971E-04	5690.0	26660.7	31.56	0.10708	0.3440	405.2	347.5	0.07121	0.06108	0.1423
58	RB04	0.734	0.7339	1.2849	9.9872E-05	6193.9	21362.5	20.28	0.10686	0.4288	286.7	275.0	0.04629	0.04440	0.0408
59	RB04	0.484	0.4838	1.0348	8.9601E-05	6823.7	17263.9	12.09	0.10350	0.5325	198.3	216.8	0.02906	0.03177	0.0933
60	RB04	0.300	0.3004	0.8514	7.7936E-05	7779.7	14285.4	7.01	0.09477	0.6471	137.9	182.7	0.01773	0.02348	0.3248
61	RB04	0.167	0.1671	0.7181	6.4542E-05	9358.3	12114.6	3.78	0.08233	0.7673	96.5	163.8	0.01031	0.01750	0.6976
62	RB05	1.447	1.4467	3.0237	1.1337E-04	5625.1	49961.6	53.66	0.07126	0.5215	624.0	596.5	0.11093	0.10604	0.0441

	Exp. No.	Length [m]	Twi(x)	TB(x)	TC_fit	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
63	RB05	0.22	43.9	84.3	8.2	5.1	4191.4	6.246E-04	1.29215E-06	969.2	1.0110	0.511	1.577	0.025	1.694
64	RB05	0.365	34.7	81.0	9.8	5.1	4190.2	7.427E-04	1.29227E-06	971.3	1.0301	0.774	1.577	0.025	1.694
65	RB05	0.535	27.7	76.5	11.4	5.1	4189.1	8.483E-04	1.29064E-06	974.0	1.0566	1.038	1.577	0.025	1.694
66	RB05	0.73	25.9	70.1	12.8	5.1	4188.2	8.778E-04	1.28308E-06	977.8	1.0922	1.268	1.577	0.025	1.694
67	RB05	0.95	22.8	63.1	14.1	5.1	4187.4	9.310E-04	1.27532E-06	981.5	1.1372	1.482	1.577	0.025	1.694
68	RB05	1.2	21.0	56.1	15.2	5.1	4186.7	9.633E-04	1.26796E-06	985.1	1.1889	1.663	1.577	0.025	1.694
69	RB06	0.1	49.6	96.0	7.0	5.5	4192.3	5.623E-04	1.27785E-06	961.3	0.9436	0.250	0.551	0.025	1.561
70	RB06	0.22	41.3	93.5	8.6	5.5	4191.1	6.557E-04	1.2792E-06	963.0	0.9546	0.516	0.551	0.025	1.561
71	RB06	0.365	30.7	89.3	10.1	5.5	4190.0	8.013E-04	1.27743E-06	965.9	0.9712	0.765	0.551	0.025	1.561
72	RB06	0.535	24.4	83.8	11.6	5.5	4189.0	9.032E-04	1.2766E-06	969.5	0.9976	1.015	0.551	0.025	1.561
73	RB06	0.73	21.3	76.4	12.9	5.5	4188.1	9.578E-04	1.27444E-06	974.1	1.0381	1.231	0.551	0.025	1.561
74	RB06	0.95	18.3	67.6	14.0	5.5	4187.4	1.014E-03	1.27418E-06	979.1	1.0993	1.413	0.551	0.025	1.561
75	RB07	0.1	46.4	90.0	9.0	8.5	4190.8	5.967E-04	1.29764E-06	965.4	0.9869	0.120	1.426	0.0333	1.56
76	RB07	0.22	43.5	86.9	10.1	8.5	4190.0	6.291E-04	1.29543E-06	967.5	1.0006	0.355	1.426	0.0333	1.56
77	RB07	0.365	37.9	83.3	11.1	8.5	4189.3	6.993E-04	1.29237E-06	969.8	1.0166	0.568	1.426	0.0333	1.56
78	RB07	0.535	27.7	78.5	12.0	8.5	4188.7	8.481E-04	1.28582E-06	972.8	1.0379	0.772	1.426	0.0333	1.56
79	RB07	0.73	24.2	71.7	13.0	8.5	4188.1	9.071E-04	1.27432E-06	976.8	1.0691	0.982	1.426	0.0333	1.56
80	RB07	0.95	22.5	64.3	14.0	8.5	4187.4	9.356E-04	1.2647E-06	980.9	1.1117	1.208	1.426	0.0333	1.56
81	RB07	1.2	20.8	57.1	15.1	8.5	4186.7	9.672E-04	1.2632E-06	984.6	1.1715	1.460	1.426	0.0333	1.56
82	RC01	0.1	71.4	97.6	13.1	10.5	4188.0	3.893E-04	1.25257E-06	960.1	0.6758	0.577	0.361	0.0333	2.703
83	RC01	0.22	60.5	96.8	15.6	10.5	4186.4	4.639E-04	1.25835E-06	960.7	0.6897	1.131	0.361	0.0333	2.703
84	RC01	0.365	46.9	94.7	17.9	10.5	4185.1	5.909E-04	1.26477E-06	962.2	0.7130	1.641	0.361	0.0333	2.703
85	RC01	0.535	39.5	91.2	19.8	10.5	4184.2	6.783E-04	1.2742E-06	964.6	0.7519	2.062	0.361	0.0333	2.703
86	RC01	0.73	33.3	85.1	21.4	10.5	4183.4	7.627E-04	1.29217E-06	968.7	0.8288	2.416	0.361	0.0333	2.703
87	RC01	0.95	28.9	75.8	22.6	10.5	4182.9	8.292E-04	1.33463E-06	974.5	0.9934	2.682	0.361	0.0333	2.703
88	RC02	0.1	61.4	90.7	11.9	10.2	4188.8	4.569E-04	1.26618E-06	965.0	0.7417	0.374	0.938	0.0333	2.287
89	RC02	0.22	53.7	89.2	13.6	10.2	4187.7	5.223E-04	1.27096E-06	966.0	0.7603	0.749	0.938	0.0333	2.287
90	RC02	0.365	42.9	86.4	15.4	10.2	4186.6	6.364E-04	1.27558E-06	967.8	0.7890	1.145	0.938	0.0333	2.287
91	RC02	0.535	38.3	82.9	17.0	10.2	4185.6	6.938E-04	1.28145E-06	970.1	0.8270	1.497	0.938	0.0333	2.287
92	RC02	0.73	33.7	77.1	18.5	10.2	4184.8	7.569E-04	1.28585E-06	973.7	0.8852	1.826	0.938	0.0333	2.287
93	RC02	0.95	28.7	70.7	19.7	10.2	4184.2	8.323E-04	1.29284E-06	977.4	0.9606	2.090	0.938	0.0333	2.287

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Wair(x)	HTC_exp	HTC_corr	F_exp	F_corr	RMS
63	RB05	1.183	1.1830	2.7600	1.0879E-04	5815.8	45619.4	40.45	0.07399	0.5714	521.1	501.7	0.08960	0.08627	0.0371
64	RB05	0.920	0.9195	2.4965	1.0582E-04	5871.9	41260.6	26.44	0.08477	0.6317	383.9	358.7	0.06538	0.06109	0.0656
65	RB05	0.656	0.6562	2.2332	9.8658E-05	6202.9	36954.4	16.52	0.08932	0.7062	297.5	275.4	0.04796	0.04441	0.0741
66	RB05	0.426	0.4258	2.0028	8.6177E-05	7072.0	33338.1	10.36	0.08088	0.7874	260.6	252.6	0.03685	0.03572	0.0306
67	RB05	0.212	0.2120	1.7890	6.9477E-05	8708.1	29960.4	4.86	0.07373	0.8815	220.1	215.1	0.02528	0.02470	0.0228
68	RB05	0.031	0.0312	1.6082	3.6998E-05	16281.5	27087.8	0.69	0.06421	0.9806	189.5	157.6	0.01164	0.00968	0.1683
69	RB06	1.311	1.3113	1.8623	1.0930E-04	5847.5	31124.9	49.80	0.08583	0.2959	520.5	553.8	0.08901	0.09470	0.0639
70	RB06	1.045	1.0450	1.5960	1.0654E-04	5909.6	26647.2	34.04	0.09654	0.3452	391.8	400.3	0.06630	0.06773	0.0216
71	RB06	0.796	0.7956	1.3466	1.0380E-04	5935.3	22513.5	21.21	0.10834	0.4092	285.8	273.1	0.04815	0.04601	0.0446
72	RB06	0.546	0.5462	1.0972	9.5060E-05	6388.8	18356.6	12.92	0.10979	0.5022	223.5	207.5	0.03498	0.03248	0.0715
73	RB06	0.330	0.3302	0.8812	8.1712E-05	7377.5	14767.9	7.36	0.10183	0.6253	184.8	172.1	0.02505	0.02333	0.0685
74	RB06	0.148	0.1475	0.6985	6.3436E-05	9432.4	11708.2	3.11	0.09109	0.7888	152.8	138.3	0.01620	0.01466	0.0948
75	RB07	1.440	1.4402	2.8662	1.1470E-04	5541.0	47173.0	51.55	0.08007	0.4975	473.2	534.4	0.08540	0.09644	0.1293
76	RB07	1.205	1.2053	2.6313	1.0985E-04	5755.2	43382.2	40.92	0.07955	0.5419	416.9	478.1	0.07244	0.08307	0.1467
77	RB07	0.992	0.9924	2.4184	1.0649E-04	5872.8	39965.4	30.31	0.08342	0.5897	309.9	392.2	0.05278	0.06678	0.2654
78	RB07	0.788	0.7881	2.2141	1.0495E-04	5831.2	36775.8	19.85	0.09324	0.6441	236.6	282.2	0.04058	0.04839	0.1925
79	RB07	0.578	0.5781	2.0041	9.6531E-05	6288.1	33588.5	13.61	0.08723	0.7115	233.6	251.9	0.03714	0.04006	0.0786
80	RB07	0.352	0.3522	1.7782	8.2458E-05	7332.6	30029.6	8.04	0.07666	0.8019	257.2	232.7	0.03508	0.03174	0.0952
81	RB07	0.100	0.1000	1.5260	5.4657E-05	11015.4	25800.1	2.21	0.06668	0.9345	293.2	186.8	0.02662	0.01696	0.3628
82	RC01	2.126	2.1261	2.4871	1.1368E-04	5805.9	42407.0	116.64	0.04849	0.1451	2049.2	1539.0	0.35295	0.26508	0.2490
83	RC01	1.572	1.5718	1.9328	1.0893E-04	5970.3	32804.1	72.36	0.06716	0.1868	1165.0	902.6	0.19513	0.15118	0.2253
84	RC01	1.062	1.0621	1.4231	1.0351E-04	6145.8	24031.4	38.39	0.08842	0.2537	666.6	494.1	0.10847	0.08039	0.2588
85	RC01	0.641	0.6413	1.0023	9.1453E-05	6860.4	16799.8	20.19	0.09561	0.3602	441.3	324.7	0.06433	0.04733	0.2643
86	RC01	0.287	0.2870	0.6480	7.2543E-05	8540.0	10710.9	8.04	0.09577	0.5571	300.0	208.9	0.03513	0.02446	0.3037
87	RC01	0.021	0.0214	0.3824	3.1272E-05	19622.2	6119.3	0.55	0.08670	0.9440	214.7	104.8	0.01094	0.00534	0.5119
88	RC02	1.913	1.9126	2.8506	1.1537E-04	5644.6	48082.5	89.40	0.05383	0.3291	1243.0	1028.2	0.22021	0.18216	0.1728
89	RC02	1.538	1.5384	2.4764	1.1210E-04	5740.7	41613.4	62.91	0.06520	0.3788	865.2	727.6	0.15071	0.12675	0.1590
90	RC02	1.142	1.1424	2.0804	1.0829E-04	5831.6	34831.9	38.34	0.07988	0.4509	576.4	468.0	0.09884	0.08026	0.1880
91	RC02	0.790	0.7905	1.7285	9.8429E-05	6359.0	28807.9	24.33	0.08188	0.5427	443.3	367.9	0.06971	0.05786	0.1700
92	RC02	0.461	0.4607	1.3987	8.4434E-05	7343.5	23232.1	13.00	0.07966	0.6706	346.3	287.2	0.04716	0.03911	0.1707
93	RC02	0.197	0.1970	1.1350	6.5489E-05	9365.5	18749.7	5.05	0.07708	0.8264	262.7	212.0	0.02805	0.02263	0.1931

	Exp. No.	Length [m]	Twl(x)	TB(x)	TC_fit	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
94	RC03	0.1	66.0	95.1	12.0	10.3	4188.7	4.235E-04	1.25812E-06	961.9	0.6997	0.376	0.506	0.0333	2.232
95	RC03	0.22	55.0	93.8	13.7	10.3	4187.6	5.103E-04	1.2619E-06	962.8	0.7140	0.752	0.506	0.0333	2.232
96	RC03	0.365	42.2	91.1	15.4	10.3	4186.6	6.448E-04	1.26459E-06	964.7	0.7363	1.128	0.506	0.0333	2.232
97	RC03	0.535	34.5	87.4	17.0	10.3	4185.6	7.455E-04	1.26947E-06	967.2	0.7707	1.482	0.506	0.0333	2.232
98	RC03	0.73	30.1	81.7	18.4	10.3	4184.9	8.105E-04	1.27551E-06	970.8	0.8258	1.791	0.506	0.0333	2.232
99	RC03	0.95	25.8	74.8	19.6	10.3	4184.3	8.795E-04	1.29146E-06	975.0	0.9175	2.056	0.506	0.0333	2.232
100	RC04	0.1	63.5	94.0	12.1	10.4	4188.6	4.412E-04	1.25117E-06	962.7	0.6951	0.376	0.432	0.0333	2.119
101	RC04	0.22	53.1	92.9	13.8	10.4	4187.5	5.279E-04	1.2558E-06	963.4	0.7096	0.751	0.432	0.0333	2.119
102	RC04	0.365	39.7	89.9	15.4	10.4	4186.6	6.757E-04	1.25727E-06	965.5	0.7319	1.104	0.432	0.0333	2.119
103	RC04	0.535	33.0	86.0	17.0	10.4	4185.6	7.670E-04	1.26302E-06	968.1	0.7696	1.458	0.432	0.0333	2.119
104	RC04	0.73	28.8	79.4	18.3	10.4	4184.9	8.307E-04	1.26757E-06	972.3	0.8299	1.744	0.432	0.0333	2.119
105	RC04	0.95	25.1	69.5	19.4	10.4	4184.4	8.912E-04	1.27675E-06	978.1	0.9392	1.987	0.432	0.0333	2.119
106	RC05	0.1	80.4	96.8	20.4	19.3	4183.9	3.426E-04	1.24931E-06	960.7	0.6753	0.365	0.285	0.0504	2.077
107	RC05	0.22	67.1	96.0	21.5	19.3	4183.4	4.160E-04	1.25305E-06	961.3	0.6858	0.723	0.285	0.0504	2.077
108	RC05	0.365	49.3	93.9	22.5	19.3	4182.9	5.650E-04	1.25523E-06	962.8	0.7027	1.073	0.285	0.0504	2.077
109	RC05	0.535	36.6	90.0	23.5	19.3	4182.5	7.166E-04	1.25668E-06	965.4	0.7303	1.393	0.285	0.0504	2.077
110	RC05	0.73	32.7	83.1	24.3	19.3	4182.2	7.708E-04	1.25601E-06	970.0	0.7786	1.668	0.285	0.0504	2.077
111	RC05	0.95	28.8	71.3	24.9	19.3	4181.9	8.304E-04	1.25239E-06	977.1	0.8709	1.892	0.285	0.0504	2.077
112	RC06	0.1	66.5	94.2	19.2	18.5	4184.5	4.204E-04	1.23992E-06	962.5	0.6754	0.295	0.285	0.063	2.046
113	RC06	0.22	57.5	92.7	19.9	18.5	4184.1	4.888E-04	1.23961E-06	963.6	0.6841	0.592	0.285	0.063	2.046
114	RC06	0.365	43.8	89.4	20.6	18.5	4183.8	6.259E-04	1.2356E-06	965.8	0.6977	0.898	0.285	0.063	2.046
115	RC06	0.535	30.4	84.4	21.4	18.5	4183.4	8.064E-04	1.22849E-06	969.2	0.7192	1.194	0.285	0.063	2.046
116	RC06	0.73	28.0	74.7	22.0	18.5	4183.1	8.428E-04	1.21063E-06	975.1	0.7571	1.466	0.285	0.063	2.046
117	RC06	0.95	25.3	60.9	22.6	18.5	4182.9	8.879E-04	1.18637E-06	982.7	0.8255	1.705	0.285	0.063	2.046
118	RC07	0.1	64.6	91.9	18.8	17.9	4184.7	4.333E-04	1.26497E-06	964.1	0.7316	0.367	0.672	0.063	1.916
119	RC07	0.22	60.8	90.8	19.5	17.9	4184.3	4.614E-04	1.27075E-06	964.9	0.7489	0.670	0.672	0.063	1.916
120	RC07	0.365	50.1	88.2	20.2	17.9	4184.0	5.577E-04	1.27414E-06	966.6	0.7729	0.956	0.672	0.063	1.916
121	RC07	0.535	37.3	84.6	20.8	17.9	4183.7	7.073E-04	1.27618E-06	969.0	0.8038	1.204	0.672	0.063	1.916
122	RC07	0.73	31.3	79.3	21.3	17.9	4183.5	7.915E-04	1.27377E-06	972.3	0.8426	1.407	0.672	0.063	1.916
123	RC08	0.1	54.5	88.3	11.6	10.4	4189.0	5.149E-04	1.28451E-06	966.6	0.7904	0.264	1.394	0.0333	1.887
124	RC08	0.22	50.0	86.0	12.9	10.4	4188.1	5.583E-04	1.28603E-06	968.1	0.8107	0.549	1.394	0.0333	1.887

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Walr(x)	HTC_exp	HTC_corr	F_exp	F_corr	RMS
94	RC03	1.856	1.8558	2.3618	1.1160E-04	5873.0	40092.3	93.58	0.05372	0.2142	1243.0	1173.6	0.21165	0.19983	0.0558
95	RC03	1.480	1.4797	1.9857	1.1005E-04	5860.0	33608.0	61.92	0.07161	0.2548	773.5	732.4	0.13200	0.12498	0.0532
96	RC03	1.104	1.1039	1.6099	1.0776E-04	5852.6	27188.6	36.57	0.09023	0.3143	501.2	440.8	0.08564	0.07532	0.1204
97	RC03	0.750	0.7503	1.2563	9.9274E-05	6256.2	21135.3	21.49	0.09759	0.4028	363.9	307.2	0.05817	0.04910	0.1559
98	RC03	0.441	0.4410	0.9470	8.5292E-05	7213.5	15856.3	11.62	0.09517	0.5343	284.1	232.9	0.03938	0.03229	0.1801
99	RC03	0.176	0.1759	0.6819	6.4341E-05	9470.0	11277.6	4.27	0.09037	0.7420	214.5	165.0	0.02265	0.01742	0.2309
100	RC04	1.743	1.7433	2.1753	1.1073E-04	5898.5	37132.0	84.39	0.05623	0.1986	1185.3	1090.3	0.20095	0.18485	0.0801
101	RC04	1.368	1.3678	1.7998	1.0837E-04	5932.7	30608.7	55.34	0.07336	0.2400	755.2	687.2	0.12729	0.11583	0.0900
102	RC04	1.015	1.0145	1.4465	1.0636E-04	5901.1	24571.9	32.07	0.09250	0.2987	477.4	406.4	0.08090	0.06887	0.1488
103	RC04	0.661	0.6614	1.0934	9.6034E-05	6446.9	18488.9	18.42	0.09764	0.3951	348.2	286.4	0.05401	0.04443	0.1774
104	RC04	0.375	0.3746	0.8066	8.1364E-05	7539.9	13590.1	9.63	0.09320	0.5356	269.4	217.6	0.03573	0.02886	0.1923
105	RC04	0.132	0.1319	0.5639	5.8595E-05	10381.7	9433.7	3.16	0.08177	0.7660	217.9	158.7	0.02099	0.01529	0.2715
106	RC05	1.712	1.7121	1.9971	1.0131E-04	6581.6	34141.0	106.73	0.03023	0.1427	2091.4	2172.9	0.31777	0.33014	0.0389
107	RC05	1.354	1.3544	1.6394	9.9922E-05	6569.0	27941.9	69.53	0.05340	0.1738	978.8	1111.4	0.14900	0.16920	0.1355
108	RC05	1.004	1.0040	1.2890	1.0004E-04	6386.4	21931.2	37.95	0.08222	0.2211	506.4	543.1	0.07930	0.08504	0.0724
109	RC05	0.684	0.6838	0.9688	9.5106E-05	6558.5	16465.6	20.38	0.09864	0.2942	323.3	319.8	0.04930	0.04877	0.0108
110	RC05	0.409	0.4088	0.6938	8.1834E-05	7561.4	11797.9	11.33	0.09302	0.4108	252.6	245.9	0.03340	0.03252	0.0265
111	RC05	0.185	0.1854	0.4704	6.4148E-05	9564.0	8022.4	4.77	0.07850	0.6058	211.7	189.1	0.02213	0.01978	0.1065
112	RC06	1.751	1.7513	2.0363	1.0914E-04	6009.0	35074.4	88.97	0.05109	0.1400	804.8	1306.2	0.13393	0.21737	0.6230
113	RC06	1.454	1.4540	1.7390	1.0778E-04	6006.4	29961.2	63.53	0.06488	0.1639	547.6	881.8	0.09117	0.14682	0.6104
114	RC06	1.148	1.1481	1.4331	1.0802E-04	5856.0	24771.6	39.18	0.08410	0.1989	354.8	524.4	0.06059	0.08955	0.4780
115	RC06	0.852	0.8519	1.1369	1.0617E-04	5798.4	19765.3	22.56	0.09945	0.2507	244.5	319.3	0.04217	0.05506	0.3058
116	RC06	0.580	0.5796	0.8646	9.4379E-05	6489.1	15253.1	14.69	0.08596	0.3296	223.7	280.9	0.03448	0.04329	0.2556
117	RC06	0.341	0.3408	0.6258	8.0035E-05	7604.1	11265.0	8.20	0.06554	0.4555	224.9	254.3	0.02958	0.03344	0.1306
118	RC07	1.549	1.5495	2.2215	1.0573E-04	6187.1	37507.1	76.37	0.05017	0.3025	1115.2	1058.2	0.18025	0.17103	0.0512
119	RC07	1.246	1.2461	1.9181	1.0034E-04	6484.3	32236.9	57.68	0.05504	0.3504	781.1	849.6	0.12047	0.13102	0.0876
120	RC07	0.960	0.9605	1.6325	9.7892E-05	6534.3	27363.7	36.78	0.07013	0.4116	468.0	544.0	0.07162	0.08325	0.1624
121	RC07	0.712	0.7116	1.3836	9.5725E-05	6525.2	23155.0	21.49	0.08694	0.4857	275.1	335.6	0.04215	0.05144	0.2202
122	RC07	0.509	0.5092	1.1812	8.8684E-05	6956.5	19804.9	13.74	0.08808	0.5689	225.3	264.4	0.03239	0.03801	0.1735
123	RC08	1.623	1.6234	3.0174	1.1355E-04	5675.1	50169.3	67.34	0.06194	0.4620	784.9	760.8	0.13831	0.13405	0.0308
124	RC08	1.338	1.3379	2.7319	1.0925E-04	5854.4	45369.2	51.18	0.06596	0.5103	634.7	628.3	0.10841	0.10733	0.0101

	Exp. No.	Length [m]	Twl(x)	TB(x)	TC_flt	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
125	RC08	0.365	41.7	83.0	14.2	10.4	4187.3	6.508E-04	1.28719E-06	970.0	0.8368	0.834	1.394	0.0333	1.887
126	RC08	0.535	32.4	78.8	15.4	10.4	4186.6	7.758E-04	1.28569E-06	972.6	0.8697	1.098	1.394	0.0333	1.887
127	RC08	0.73	29.9	73.0	16.6	10.4	4185.9	8.136E-04	1.28179E-06	976.1	0.9153	1.361	1.394	0.0333	1.887
128	RC08	0.95	26.7	66.7	17.6	10.4	4185.3	8.646E-04	1.2768E-06	979.6	0.9680	1.580	1.394	0.0333	1.887
129	RC08	1.2	24.9	60.1	18.5	10.4	4184.8	8.946E-04	1.27286E-06	983.1	1.0318	1.778	1.394	0.0333	1.887
130	RC10	0.1	47.1	85.0	11.1	10	4189.3	5.887E-04	1.28096E-06	968.7	0.8094	0.241	1.392	0.0333	1.618
131	RC10	0.22	45.2	82.5	12.2	10	4188.6	6.097E-04	1.28158E-06	970.3	0.8305	0.482	1.392	0.0333	1.618
132	RC10	0.365	40.6	79.1	13.3	10	4187.9	6.644E-04	1.28084E-06	972.5	0.8578	0.722	1.392	0.0333	1.618
133	RC10	0.535	30.5	75.1	14.3	10	4187.2	8.043E-04	1.27902E-06	974.9	0.8900	0.941	1.392	0.0333	1.618
134	RC10	0.73	25.2	69.2	15.3	10	4186.6	8.896E-04	1.27299E-06	978.3	0.9343	1.159	1.392	0.0333	1.618
135	RC10	0.95	23.6	62.7	16.2	10	4186.1	9.170E-04	1.26626E-06	981.8	0.9876	1.356	1.392	0.0333	1.618
136	RC10	1.2	22.3	56.2	16.9	10	4185.7	9.398E-04	1.25836E-06	985.0	1.0435	1.509	1.392	0.0333	1.618
137	RC11	0.1	62.0	92.7	19.0	18.1	4184.6	4.525E-04	1.25363E-06	963.6	0.7072	0.366	0.369	0.063	1.584
138	RC11	0.22	55.9	91.4	19.5	18.1	4184.3	5.019E-04	1.25626E-06	964.5	0.7201	0.575	0.369	0.063	1.584
139	RC11	0.365	44.8	88.3	20.0	18.1	4184.1	6.140E-04	1.25504E-06	966.5	0.7387	0.779	0.369	0.063	1.584
140	RC11	0.535	32.9	83.8	20.4	18.1	4183.9	7.690E-04	1.25087E-06	969.5	0.7642	0.964	0.369	0.063	1.584
141	RC11	0.73	27.1	76.7	20.8	18.1	4183.7	8.588E-04	1.24005E-06	973.9	0.7990	1.122	0.369	0.063	1.584
142	RC11	0.95	25.1	66.6	21.1	18.1	4183.5	8.907E-04	1.21991E-06	979.7	0.8458	1.249	0.369	0.063	1.584
143	RC12	0.1	56.9	87.5	11.4	10.3	4189.1	4.936E-04	1.29255E-06	967.1	0.8106	0.242	1.38	0.0333	1.535
144	RC12	0.22	50.8	85.6	12.7	10.3	4188.2	5.502E-04	1.2981E-06	968.4	0.8354	0.527	1.38	0.0333	1.535
145	RC12	0.365	41.7	82.6	13.9	10.3	4187.5	6.508E-04	1.30156E-06	970.3	0.8666	0.790	1.38	0.0333	1.535
146	RC12	0.535	35.1	78.5	15.1	10.3	4186.7	7.371E-04	1.30481E-06	972.8	0.9091	1.053	1.38	0.0333	1.535
147	RC12	0.73	31.4	72.9	16.1	10.3	4186.2	7.907E-04	1.30361E-06	976.2	0.9605	1.272	1.38	0.0333	1.535
148	RC12	0.95	27.9	66.5	16.9	10.3	4185.7	8.451E-04	1.29925E-06	979.7	1.0186	1.448	1.38	0.0333	1.535
149	RC13	0.1	47.3	82.5	6.6	6.5	4192.6	5.865E-04	1.25586E-06	970.3	0.7830	0.016	1.081	0.025	1.504
150	RC13	0.22	43.6	80.4	8.0	6.5	4191.6	6.281E-04	1.25662E-06	971.7	0.8009	0.246	1.081	0.025	1.504
151	RC13	0.365	34.7	77.0	9.5	6.5	4190.5	7.427E-04	1.25524E-06	973.7	0.8263	0.491	1.081	0.025	1.504
152	RC13	0.535	26.0	72.9	10.9	6.5	4189.5	8.761E-04	1.253E-06	976.2	0.8577	0.721	1.081	0.025	1.504
153	RC13	0.73	23.7	67.3	12.2	6.5	4188.6	9.152E-04	1.24729E-06	979.3	0.8984	0.933	1.081	0.025	1.504
154	RC13	0.95	20.5	61.5	13.4	6.5	4187.8	9.724E-04	1.24308E-06	982.4	0.9483	1.130	1.081	0.025	1.504
155	RC13	1.2	18.8	55.5	14.4	6.5	4187.2	1.004E-03	1.23879E-06	985.3	1.0049	1.293	1.081	0.025	1.504

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Walr(x)	HTC_exp	HTC_cor r	F_exp	F_corr	RMS
125	RC08	1.053	1.0525	2.4465	1.0601E-04	5943.7	40593.5	34.54	0.07565	0.5698	463.7	456.5	0.07802	0.07680	0.0155
126	RC08	0.789	0.7892	2.1832	1.0193E-04	6066.1	36266.7	21.73	0.08498	0.6385	334.3	325.8	0.05511	0.05371	0.0254
127	RC08	0.526	0.5260	1.9200	9.0245E-05	6814.6	31990.7	13.81	0.07892	0.7261	284.0	288.9	0.04168	0.04240	0.0174
128	RC08	0.307	0.3067	1.7007	7.6751E-05	7955.2	28447.2	7.58	0.07324	0.8197	232.7	248.3	0.02925	0.03121	0.0670
129	RC08	0.109	0.1093	1.5033	5.4916E-05	11072.1	25224.1	2.61	0.06444	0.9273	195.7	208.2	0.01768	0.01880	0.0637
130	RC10	1.377	1.3772	2.7692	1.1223E-04	5670.3	46170.7	49.97	0.06921	0.5027	597.6	587.2	0.10539	0.10355	0.0175
131	RC10	1.136	1.1365	2.5285	1.0639E-04	5961.0	42137.2	39.81	0.06810	0.5505	522.7	534.4	0.08769	0.08965	0.0224
132	RC10	0.896	0.8959	2.2879	1.0099E-04	6226.0	38149.1	28.80	0.07028	0.6084	423.3	444.8	0.06799	0.07144	0.0508
133	RC10	0.677	0.6772	2.0692	9.7885E-05	6291.0	34551.7	17.98	0.08140	0.6727	295.5	308.9	0.04697	0.04910	0.0453
134	RC10	0.459	0.4586	1.8506	8.8687E-05	6860.7	31047.5	11.01	0.08029	0.7522	235.5	253.1	0.03433	0.03689	0.0746
135	RC10	0.262	0.2618	1.6538	7.4150E-05	8174.9	27894.6	6.10	0.07134	0.8417	201.5	230.3	0.02465	0.02817	0.1430
136	RC10	0.109	0.1089	1.5009	5.5679E-05	10853.1	25473.4	2.47	0.06185	0.9275	172.0	204.4	0.01585	0.01883	0.1882
137	RC11	1.218	1.2179	1.5869	9.9027E-05	6581.6	27034.9	57.48	0.05653	0.2325	951.0	903.0	0.14449	0.13719	0.0505
138	RC11	1.009	1.0086	1.3776	9.6204E-05	6713.5	23419.6	42.92	0.06521	0.2679	467.7	681.2	0.06967	0.10147	0.4563
139	RC11	0.805	0.8047	1.1737	9.5290E-05	6650.9	19972.8	27.99	0.08003	0.3144	301.8	444.8	0.04538	0.06688	0.4738
140	RC11	0.620	0.6196	0.9886	9.3957E-05	6587.5	16880.0	17.21	0.09362	0.3732	196.2	289.4	0.02979	0.04393	0.4745
141	RC11	0.462	0.4619	0.8309	8.8121E-05	6934.4	14310.3	11.49	0.09131	0.4441	147.0	234.3	0.02120	0.03379	0.5938
142	RC11	0.335	0.3349	0.7039	7.9820E-05	7621.7	12322.9	8.03	0.07633	0.5242	123.3	225.0	0.01617	0.02952	0.8256
143	RC12	1.293	1.2935	2.6735	1.0376E-04	6234.1	44175.5	55.97	0.05604	0.5162	836.6	770.6	0.13420	0.12361	0.0789
144	RC12	1.008	1.0082	2.3882	9.8922E-05	6474.5	39292.6	39.14	0.06372	0.5778	621.3	585.3	0.09596	0.09039	0.0580
145	RC12	0.745	0.7449	2.1249	9.4456E-05	6670.6	34868.4	24.45	0.07487	0.6494	433.7	407.4	0.06502	0.06107	0.0606
146	RC12	0.482	0.4818	1.8618	8.4996E-05	7316.3	30473.9	13.96	0.07944	0.7412	322.5	306.1	0.04408	0.04183	0.0509
147	RC12	0.263	0.2625	1.6425	7.0908E-05	8701.4	26910.1	7.09	0.07595	0.8402	257.9	252.3	0.02964	0.02900	0.0217
148	RC12	0.087	0.0872	1.4672	5.0082E-05	12224.6	24117.8	2.20	0.07063	0.9406	204.4	196.6	0.01672	0.01608	0.0382
149	RC13	1.488	1.4876	2.5686	1.1488E-04	5541.3	43682.3	54.17	0.06411	0.4209	631.6	648.2	0.11398	0.11698	0.0263
150	RC13	1.258	1.2582	2.3392	1.1106E-04	5693.9	39756.5	42.78	0.06701	0.4621	523.1	551.6	0.09187	0.09688	0.0546
151	RC13	1.013	1.0125	2.0935	1.0908E-04	5696.4	35620.1	29.12	0.07700	0.5164	381.3	396.2	0.06694	0.06955	0.0391
152	RC13	0.783	0.7833	1.8643	1.0563E-04	5771.0	31777.2	19.09	0.08535	0.5798	280.1	288.9	0.04854	0.05005	0.0313
153	RC13	0.571	0.5706	1.6516	9.6229E-05	6300.8	28280.1	13.31	0.07933	0.6545	238.8	261.6	0.03790	0.04152	0.0956
154	RC13	0.374	0.3743	1.4553	8.5141E-05	7066.5	25003.2	8.22	0.07459	0.7428	194.6	226.7	0.02754	0.03208	0.1650
155	RC13	0.211	0.2107	1.2917	7.0921E-05	8447.6	22270.4	4.48	0.06675	0.8369	162.1	203.7	0.01919	0.02412	0.2568

	Exp. No.	Length [m]	Twl(x)	TB(x)	TC_fit	TC1	Cp(x) [J/kgK]	mu_film	mu_mix	Rho_f	Rho-mix	F_cond [Kg/hr]	FA [Kg/hr]	FC [Kg/s]	FS_in [Kg/hr]
156	RC13	1.45	18.6	48.8	15.1	6.5	4186.7	1.008E-03	1.22909E-06	988.4	1.0617	1.408	1.081	0.025	1.504
157	RC14	0.1	47.7	85.9	7.1	5.8	4192.3	5.822E-04	1.26005E-06	968.2	0.7650	0.214	0.72	0.025	1.379
158	RC14	0.22	42.1	84.1	8.5	5.8	4191.2	6.460E-04	1.26433E-06	969.3	0.7862	0.444	0.72	0.025	1.379
159	RC14	0.365	32.4	80.6	9.9	5.8	4190.2	7.758E-04	1.26589E-06	971.5	0.8168	0.675	0.72	0.025	1.379
160	RC14	0.535	24.3	76.2	11.3	5.8	4189.2	9.049E-04	1.26932E-06	974.2	0.8608	0.905	0.72	0.025	1.379
161	RC14	0.73	21.8	70.4	12.4	5.8	4188.4	9.488E-04	1.26928E-06	977.6	0.9146	1.085	0.72	0.025	1.379
162	RC14	0.95	18.9	63.1	13.4	5.8	4187.8	1.002E-03	1.26888E-06	981.5	0.9891	1.250	0.72	0.025	1.379
163	RC15	0.1	63.6	93.2	12.1	10.3	4188.6	4.404E-04	1.28373E-06	963.2	0.7541	0.397	0.576	0.0333	1.367
164	RC15	0.22	54.8	92.0	13.9	10.3	4187.5	5.122E-04	1.30561E-06	964.1	0.7992	0.795	0.576	0.0333	1.367
165	RC15	0.365	42.4	89.4	15.6	10.3	4186.4	6.423E-04	1.34533E-06	965.8	0.8872	1.170	0.576	0.0333	1.367

	Exp. No.	FS(x) [Kg/hr]	F_f(x) [Kg/hr]	FM(x) [Kg/hr]	Delta	h_f	Re_g	Re_f	Ja	Wair(x)	HTC_exp	HTC_corr	F_exp	F_corr	RMS
156	RC13	0.096	0.0963	1.1773	5.4581E-05	10971.0	20457.4	2.04	0.05493	0.9182	139.6	194.2	0.01272	0.01770	0.3909
157	RC14	1.165	1.1650	1.8850	1.0579E-04	6021.7	31950.4	42.74	0.06986	0.3820	574.2	569.2	0.09536	0.09453	0.0086
158	RC14	0.935	0.9347	1.6547	1.0169E-04	6201.0	27951.5	30.90	0.07679	0.4351	441.2	442.2	0.07115	0.07131	0.0022
159	RC14	0.704	0.7045	1.4245	9.8218E-05	6295.5	24032.9	19.39	0.08811	0.5055	314.7	304.3	0.04999	0.04833	0.0331
160	RC14	0.474	0.4744	1.1944	9.0453E-05	6712.6	20096.0	11.20	0.09485	0.6028	231.3	217.1	0.03446	0.03234	0.0615
161	RC14	0.294	0.2936	1.0136	7.8136E-05	7724.5	17055.6	6.61	0.08880	0.7103	189.0	186.0	0.02447	0.02408	0.0161
162	RC14	0.129	0.1294	0.8494	6.0390E-05	9923.2	14296.1	2.76	0.08075	0.8477	153.3	151.4	0.01545	0.01525	0.0126
163	RC15	0.970	0.9695	1.5455	9.0979E-05	7180.3	25712.5	47.01	0.05453	0.3727	1272.5	804.1	0.17722	0.11199	0.3681
164	RC15	0.572	0.5722	1.1482	8.0206E-05	8038.0	18782.8	23.86	0.06851	0.5016	840.0	483.2	0.10450	0.06011	0.4248
165	RC15	0.197	0.1972	0.7732	6.0570E-05	10416.2	12274.7	6.56	0.08653	0.7450	533.3	235.0	0.05120	0.02256	0.5593

Table C.2 Local data without noncondensible gas (inlet pure steam flow)

Exp.No	Length	TB	TWo	Twi	TO	HF	HTC
RC16	0	99.3	67.7	75.9	14.2	92,803.5	3,971.3
	0.1	98.3	74.4	80	19.5	62,663.3	3,416.4
	0.22	35.2	24.2	26.1	21.7	20,882.7	2,282.8
	0.365	21.2	22.3	22.8	22.5	5,656.7	-
	0.535	21.1	21.9	22	22.7	-	-
	0.73	21.1	21.8	21.8	22.7	-	-
	0.95	21	21.5	21.5	22.8	-	-
	1.2	21.2	21.3	21.3	22.8	-	-
	1.45	21.6	22.4	22.4	22.8	-	-
	1.865	21.6	22.3	22.3	22.8	-	-
	2.3	21.8	22	22	22.8	-	-
RC09	0	99.1	64.7	75.5	13.5	121,382.6	5,134.8
	0.1	99	76.7	84.1	20.1	83,882.4	5,645.0
	0.22	59.2	29.3	32	23.2	30,518.5	1,122.3
	0.365	24.2	25.1	25.9	24.3	9,173.2	-
	0.535	24.1	24.7	24.9	24.7	2,234.3	-
	0.73	24.1	24.7	24.7	24.8	-	-
	0.95	24	24.3	24.3	24.8	-	-
	1.2	24	24.1	24.1	24.8	-	-
	1.45	24.6	25.2	25.2	24.8	-	-
	1.865	24.4	25	25	24.8	-	-
	2.3	24.6	24.7	24.7	24.8	-	-

(The unreasonable calculations of heat flux and heat transfer coefficient are represented as blank cells.)

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report describes the experimental works and the assessment of the predictability of RELAP5/MOD3.2 for the reflux condensation experiment in the presence of noncondensible gases in a vertical tube having the same outer diameter of the U-tube riser in Korean standard nuclear power plant (KSNPP). The reflux condensation experiment is performed in conditions of the low pressure, low flow and the high mass fraction of noncondensible gas representing the situation of the loss-of-residual-heat-removal (LORHR) accident during mid-loop operation. The test facility is composed of the mixture gas generation part and the reflux condensation part. The test section in the latter part is a verticle tube with 19.05mm diameter and 2.4m length surrounded by the coolant block. Reflux condensation occurs in the range of very small flow rates because of the flooding limit. Therefore, the injected steam is completely condensed in the vertical tube.

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