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IMPROVEMENT OF THE CCFL MODEL OF THE RELAP5/MOD3.2.2B CODE IN A HORIZONTAL PIPE

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ABSTACT

To demonstrate the applicability of RELAP5 to the prediction of the onset of flooding in the hot leg at the reflux condensation phase during mid-loop operation, numerical analysis is performed for the counter-current flow in a horizontal pipe with the inclined riser using the RELAP5/MOD3.2.2b code. It is found that the RELAP5, simulating the CCFL phenomena using interfacial friction along with the flow regime map in the horizontal pipe, produces unsatisfactory results. Under the CCFL condition, it is observed that large oscillation exists in the flow rate, void fraction, and etc. and the liquid flow rate is much lower than that predicted by the CCFL model measured in the experiment. The CCFL model of RELAP5 for the vertical volume is extended to the model for the horizontal and inclined volumes. The horizontal volume flow regime map and interfacial friction model coupled to the CCFL model are modified. And a new correlation developed from Kang's experiment is implemented to the CCFL model of RELAP5. With this modified RELAP5, the analysis of CCFL phenomena in the horizontal pipe and hot leg geometry is performed, and produces reasonable results in comparison with experimental data.

1. INTRODUCTION

If we increase the gas or liquid flow rate in a countercurrent flow system, a limit is reached where the flow rate of neither the gas nor the liquid phase can be increased further without altering the flow pattern. This limiting condition is called ‘flooding’ or ‘countercurrent flow limitation (CCFL)’. Flooding occurrence in a gas-liquid countercurrent flow system is an important phenomenon in numerous engineering applications such as tubular reflux condenser, boiler, refrigerator tubes, oil and natural gas pipelines, and so on. Especially, it is a very important phenomena in the safety of a nuclear power plant. In the transient condition such as reflux condensation cooling mode during a mid-loop operation or ECC injection phase following a loss of coolant accident (LOCA) in the pressurized water reactor, flooding can occurs in the U-tube of a steam generator, the downcomer annulus of a reactor vessel and hot leg, and it limits water from flowing into the reactor vessel and affects the inventory of the coolant in the reactor vessel and the safety of the nuclear power plant.

The old RELAP5 codes used the interfacial friction to simulate the CCFL phenomena. The CCFL model for the vertical volume is added to the RELAP5/MOD3 to simulate the flooding at the rod bundle and upper tie plate in the reactor vessel and U-tubes of the steam generator.

Wallis[1] proposed the CCFL correlation widely used for predicting the flooding in vertical pipes with the relative small diameter from the relation between a momentum flux and a hydrostatic force. And Kutateladze suggested a CCFL correlation derived by taking the hydrodynamic instability into consideration in dimensional analysis. Then, Bankoff et al. [2] proposed a general CCFL model that allows the user to select the wallis form, the Kutateladze form, or a form in between the Wallis and Kutateladze forms:

$$H_g^{*1/2} + mH_f^{*1/2} = c \qquad (1)$$

where $$H_k^* = j_k \left[\frac{\rho_k}{g w (\rho_f - \rho_g)} \right]^{1/2} \qquad k = j, g \qquad (2)$$

$$w = D_j^{1-\beta} L^{\beta} , \qquad L = \left[\frac{\sigma}{g(\rho_f - \rho_g)} \right]^{1/2} \qquad (3,4)$$

There are some important experiments about the CCFL phenomena in a horizontal pipe and a hot leg geometry. Table 1 summerizes the geometries and results of these tests. Dillistone[8] simulated the CCFL phenomena in the hot leg of Upper Plenum Test Facility(UPTF), a full-scale simulation of a four-loop German PWR, using RELAP5/MOD2. One of main conclusions in this study is that standard RELAP5/MOD2 fails to predict the flooding curve and void fraction in the test section.

2. RELAP5 NODALIZATION OF CCFL EXPERIMENTS

To validate the availability of the present RELAP5 code on the CCFL phenomena in the hot leg under the condition such as the reflux condensation phase during the mid-loop operation, the CCFL phenomena are simulated in the horizontal pipe and hot leg geometry of various geometry using the standard RELAP5/MOD3.2.2b code.

There are four reference experiments, LDH3 and LDH2BI by Seong-Kwon Kang[7], MHYRESA R-351 by G. Geffraye[5], and UPTF separate effects test 11(steam-water countercurrent flow in the broken loop hot leg) at 15 bar (UPTF-15) by Weiss[6]. Figure 2 shows the schematic diagram of the experimental facility of Kang. Information about the geometry and fluid condition in these tests is given in Table 2.

Figure 1 shows the broken loop hot leg of UPTF test facility and Figure 3 shows its RELAP5 ndodalization. In the other tests, the geometry and dimension of test section is somewhat different, but the basic configuration of the nodalization is similar.

Water is injected to 'B 320' from the time-dependent volume, 'TDV 310' using the time-dependent junction, 'TDJ 315'. 'TDV 310' controls the properties of water, and 'TDJ 315' controls the injection rate. Water pass along 'B 320' and 'B 350', flow in the test section 'P 100' from right to left, and is accumulated in steam generator (P 270). Air (or steam) is injected to 'B 270' from 'TDV 210' using 'TDJ 315', pass along 'B 320' and 'B 350', flow in the test section 'P 100' from the left of the test section to the right side, and is vented to 'TDV 390' through 'J 385'. 'TDV 390' works as the pressure boundary condition and the venting line. It controls the overall system pressure.

3. ANALYSIS OF CCFL USING STANDARD RELAP5 CODE

To validate the applicability of the RELAP5 code, which predicts the flow condition after the onset of flooding, several simulations are performed for various geometry and flow condition. The water injection rate is fixed, and air(or steam) injection rate increases gradually from the initial value to the final one. One of these tests is performed for the geometry of the Test LDH2BI. The injection rate of water is fixed, and the injection rate of air gradually increases. It is shown in Figures 4 and 5.

Figure 6 shows the mass flow rate at the bend in the test section. Before the onset of flooding, the mass flow rate is equal to the injection rate. But if once the CCFL occurs, there is a large vibration and transition in the mass flow rate, void fraction, pressure and etc. At the moment, the liquid flow can be reversed, but the flow regime remains in the horizontally stratified regime. In a real situation, as the air flow rate further increases at a constant injection rate of water, the flow rate of water does not oscillate so much, but just decreases. And the flow rate of water in the RELAP5 simulation is much lower than the flow rate obtained from the experiment.

Figure 7 shows the square root of the nondimensional superficial velocities which is used in the correlation of the Wallis form and Figure 8 shows the liquid levels in the reactor vessel (P270) and steam generator (P370). It shows that the amount of the water passing through the hot leg under the flooding condition is much lower. Figure 9 shows the liquid fraction in the hot leg. Before the onset of flooding, liquid fraction is lower than that of experiment, increases as air flow increases and oscillates after the flooding occurs.

Figures 10, 11, 12 and 13 show the experimental flooding results of the LDH3, LDH2BI, R-351 and UPTF-15, respectively. These points present the flow rate of air that flooding occurs at a given flowrate of water, i.e. the point of the onset of flooding. Also, the results of RELAP5 simulations are compared with these of these experiments in the figures. Generally, RELAP5 overpredicts the flooding points for the LDH3, LDH2BI and R-351, but underpredicts the steam flow rate by a factor of more than three for UPTF-15.

In tests above, we know that the standard RELAP5/MOD3.2.2b produces the poor predictions of the air flow rate where the CCFL occurs for given flow rate of water, a large transient occurs after the onset of flooding and the water flow rate is lower than that in the experiment.

4. MODIFICATION OF RELAP5/MOD3.2.2B

The CCFL model of RELAP5/MOD3 is used for the vertical volume only. And this model is modified so as to be applied to the horizontal volume. Figure 14 shows the flow chart of the original CCFL subroutine. In this subroutine, the part checking if the volume is vertically oriented is removed. And the CCFL correlation developed by Kang[7] is added to the horizontal CCFL model. Kang correlation for the CCFl phenomena in the hot leg geometry is expressed as

$$\left(j_g^*\right)^{1/2} + m\left(j_f^*\right)^{1/2} = c \qquad \text{; Wallis form} \qquad (5)$$

where m=0.397, $c = 0.603 - 0.00234\left(\frac{L}{D}\right)$, (6)

and L/D is the length-to-diameter raio. It is done by modifying the R-level input processing subroutines, such as RPIPE, RSNGJ and RBRNCH, as shown in the Figure 15. If one wish to use the CCFL correlation, he must specify the diameter, flag(2.0) and L/D at the junction data card in place of diameter, β and c(gas intercept). It is explained in Table 3.

Since the CCFL model of the RELAP5 is applied only in the case which the liquid or gas flow rate is higher than that of flooding curve, if the flow limitation occurs due to the interfacial friction, which is the process that RELAP5 simulates the CCFL phenomena without the CCFL model, the CCFL model cannot be applied. That is, in the cases that RELAP5 under-estimates the flooding point, CCFL model is not used. The ratio of the relative velocity to critical velocity, $|v_g - v_f|/v_{crit}$ lies between 0.5 and 1.0 and it is the transition region of the flow regime map of RELAP5 where flooding occurs in the standard RELAP5. To avoid the under-prediction, the transition region is lies between 0.9 and 1.0 of the ratio. It is done by altering the old stratification factor into the new factor, as follows;

$$F_{28} = \min\left[1.0,\ \max\left[0.0,\ 10\left(1 - \frac{|v_g - v_f|}{v_{crit}}\right)\right]\right] \qquad (7)$$

5. TEST PROBLEM OF THE MODIFIED RELAP5 CODE

To demonstrate the performance of the modified CCFL model, two test problems are selected, one is simulation of the CCFL phenomena in the horizontal pipe at 5 bar and the other is application of the CCFL correlation to the Test UPTF-15.

At first, in order to test the modified CCFl model, analysis is performed using the modified CCFL model. The CCFL user constants (form selector(β), gas intercept(c) and slope(m) is provided by user. The geometry and boundary conditions are the same as these of Test LDH3 except that the pressure is 5 bar. The flow rate of water is 0.5 Kg/s and that of air linearly increases form 0.0 Kg/s at the start to 0.1 Kg/s at the end. And the slope is 1.0 and the gas intercept is 0.6 or 0.55 for the Wallis form of CCFL model.

Figure 16 shows the mass flow rates of the water and air at the left end of the test section. At about 440 sec, the flooding occurs and the air flow limits the water flow, and the mass flow rate of water decreases gradually as the flow rate of air increases. Figure 17 shows the flooding curves of Wallis form. The dot lines present the limitation induced by the CCFL model and the user input(c and m). The CCFL model prevents the flow rates from exceeding counter-current flow limitation and well predicts the mass flow rate under the flooding condition.

Next, in order to test the performance of CCFL correlation, a test is performed using Kang's CCFL correlation. The reference test is UPTF-15 and the geometry and boundary conditions are the same. For the CCFL correlation, the value of L/D is 25 and the values of gas intercept (c) and slope (m) is computed in the code using the CCFL correlation.

Figure 18 shows the mass flow rate of the water ansd steam at the position that a flooding occurs and Figure 19 shows the flooding curve of this test result. In spite of the fact that Kang's correlation is derived from the experiemental data of small diameter, it is found out that the modified RELAP5 well predicts the onset of flooding and the flow condition in the hot leg of the large diameter.

6. CONCLUSIONS

The standard RELAP5 produces the poor predictions of air flow rates where a CCFL occurs for given water flow rate and the properties of the fluid oscillates. The CCFL model of RELAP5/MOD3.2.2b code is modified in order to be applied to the horizontally oriented volume with angle below 45 degrees and Kang's CCFL correlation is added to the code. With this modified RELAP5, the analysis of CCFL phenomena in a horizontal pipe and a hot leg of real scale is performed, and produces reasonable results in comparison with experimental data. And, it is certain that the modified RELAP5 is applicable to the simulation of CCFL phenomena in the Pressurized Water Reactor.

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[2] S. G. Bankoff, R. S. Tankin, M. C. Tuen, and C. L. Heish, "Countercurrent Flow of Air/Water and Steam/Water Through a Horizontal Perforated Plate", *Int. J. of Heat and Mass Transfer*, 24, 1981, pp. 1381-1385.

[3] A. Ohnuki, "Experimental Study of Counter-Current Two-Phase Flow in Horizontal Tube Connected to Inclined Riser", J. of Nuclear Science and Technology 23(3), pp. 219~232, 1986.

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[5] G. Greffraye, P. Bazin, P. Pichon and A. Bengaouer, "CCFL in Hot Legs and Steam Generators and Its Prediction with the CATHARE Code", NURETH-7, 1995.

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[7] S.K. Kang, "Geometrical Parametric Effects on CCFL in a Nuclear Reactor Hot Leg", M.S thesis, KAIST, 1999.

[8] M. J. Dillistone, "Analysis of the UPTF Separate Effects Test 11 (Steam-Water Countercurrent Flow in the Broken Loop Hot Leg) Using RELAP5/MOD, *NUREG/IA-0071*, 1992.

Table 1. Summery of the experiment tests and results

	Geometry	Correlation Form	Result
Ohnuki[3] (1985)	Horizontal +inclined riser	Wallis form	$m = 0.75$ $c = \ln\left[\frac{L}{D}\frac{1}{l}\right] + 0.88$
Choi[4] (1995)	Nearly horizontal	Modified Wallis form	m=0.64, c=0.58
MHYRESA R-351[5]	Horizontal +inclined riser	Kutatelaze/Wallis form	m=0.549, c=0.549
UPTF[6], 15bar	PWR lot leg	-	m=0.653, c=0.534
Kang[7] (1998)	Horizontal +inclined riser	Wallis Form	M=0.397, c=0.603-0.00234(L/D)

Table 2. Summery of the geometry and condition for the CCFL test

	Geometry	Dia [cm]	Length [m]	Angle [Deg]	Fluid	Pressure [bar]
Kang (LDH3)	Horizontal	8	3.388	-	Air-Water	1 bar
Kang (LDH2BI)	Horiz+Riser	8	2.0 +0.623	35	Air-Water	1 bar
MHYRESA (R-351)	Horiz+Riser	35.1	2.645 +1.06	50	Air-Water	1 bar
UPTF SET11 (15 bar)	Hot leg	75	7.086 +1.188	50(44)	Steam-Water	15 bar

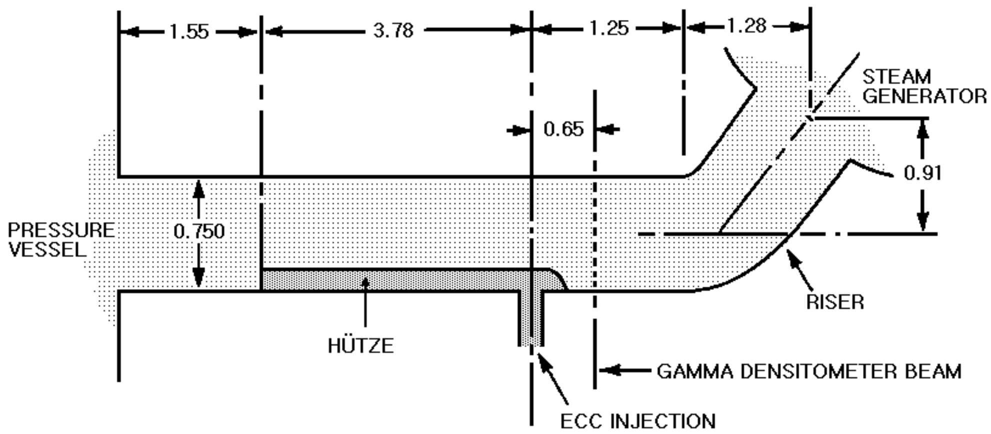

Figure 1. UPTF broken loop hot leg

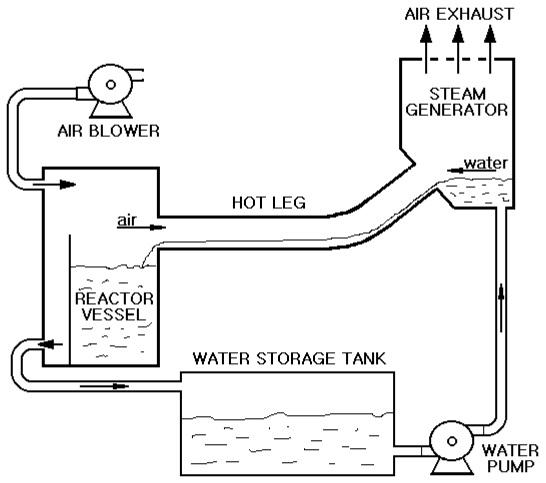

Figure 2. Schemetic diagram of the Kang's experimental facility

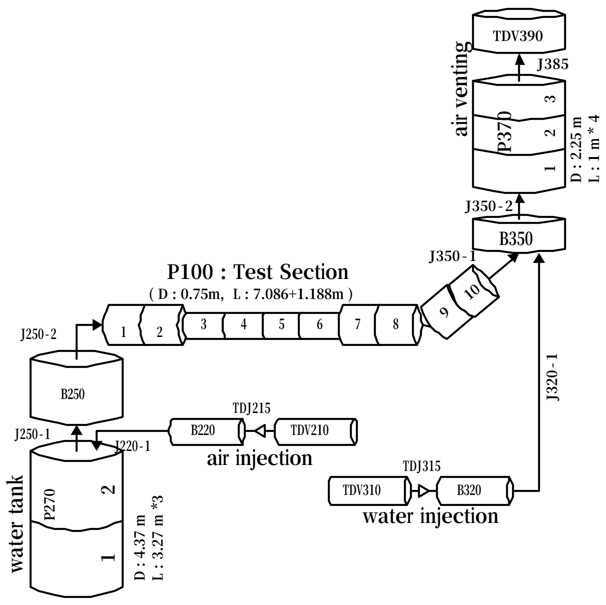

Figure 3. RELAP5 nodalization of test UPTF-15

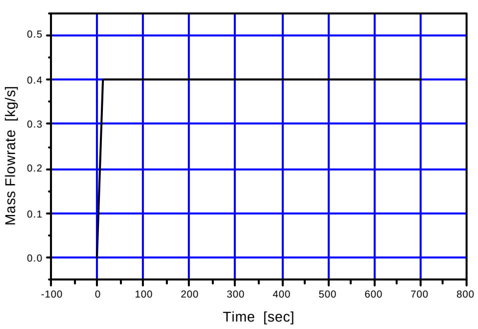

Figure 4. Injection rate of water

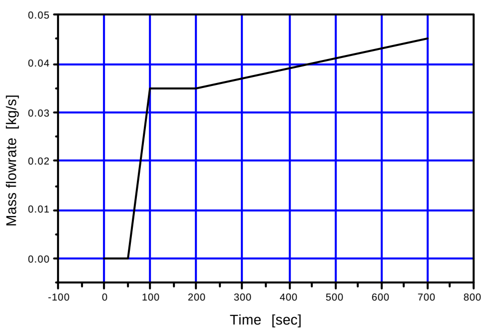

Figure 5. Injection rate of air

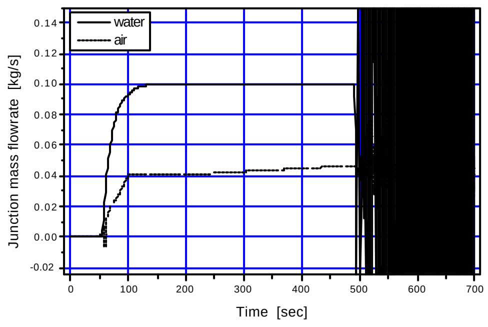

Figure 6. Mass flow rate of water and air

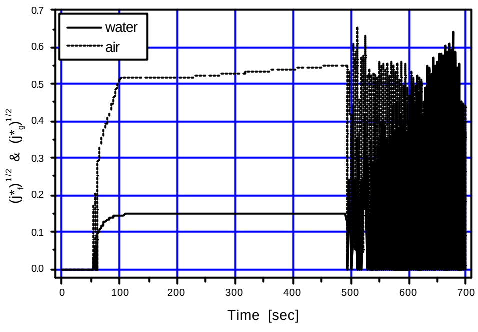

Figure 7. Square roots of nondimensional superficial velocity

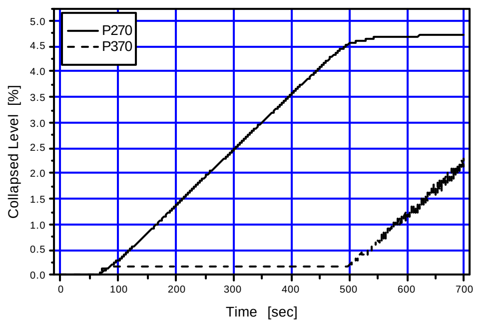

Figure 8. Liquid levels in the Vessel and S/G

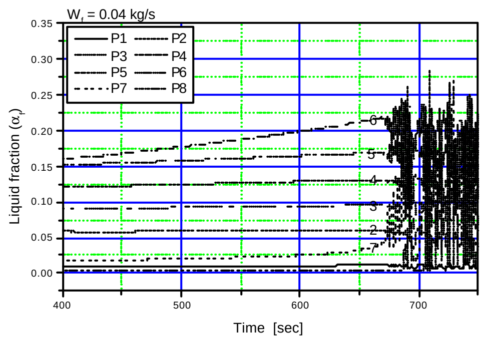

Figure 9. Liquid fraction in the test section

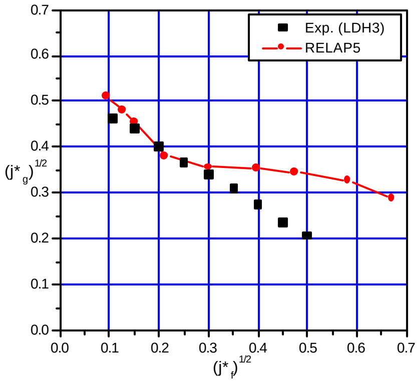

Figure 10. Flooding curve of LDH3

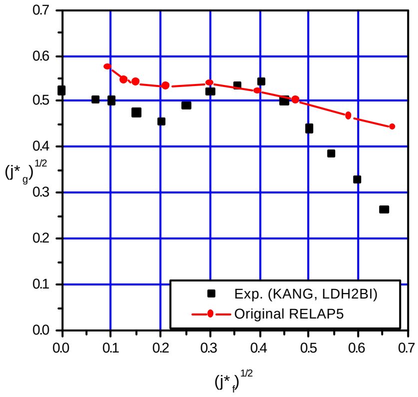

Figure 11. Flooding curve of LDH2BI

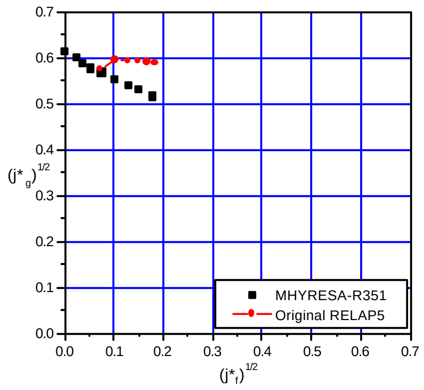

Figure 12. Flooding curve of MHYRESA R-351

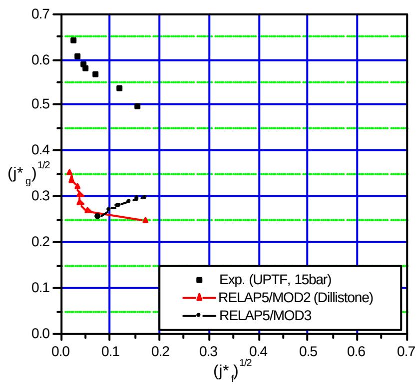

Figure 13. Flooding curve of UPTF-15

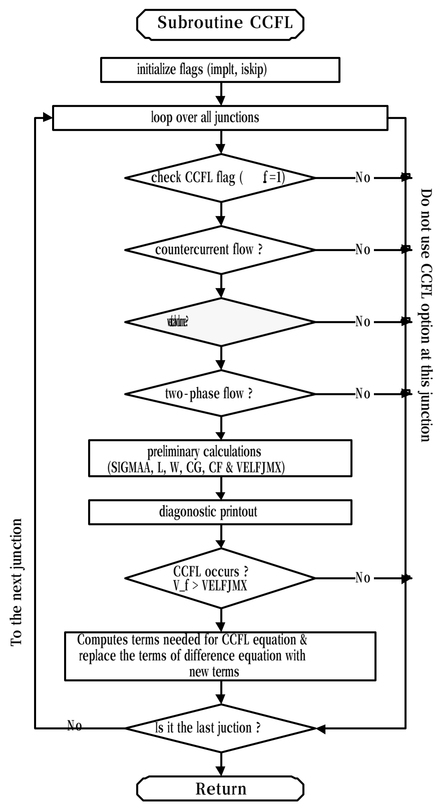

Figure 14. Flow chart of the subroutine CCFL

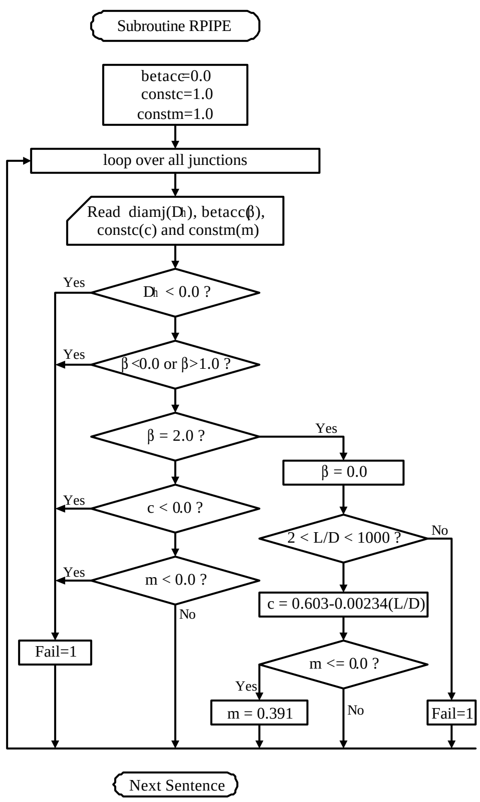

Figure 15. Flow chart of the modified subroutine RPIPE

Table 3. Input requirement for the CCFL correlation (junction data card)

	Word #1	Word #2	Word #3	Word #4
Original Input	Diameter	Form selection (β)	Gas intercept(c)	Slope(m)
CCFL correlation	Diameter	2.0 (flag)	L/D	0.0 (or slope)

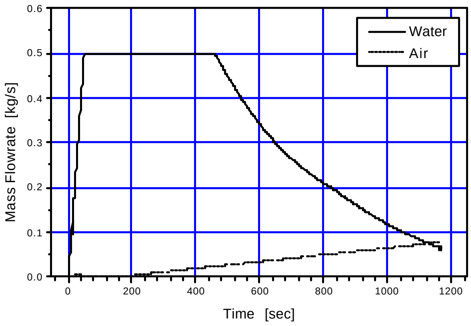

Figure 16. Mass flow rate of the water & air

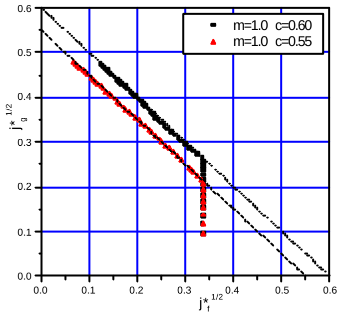

Figure 17. Flooding curve

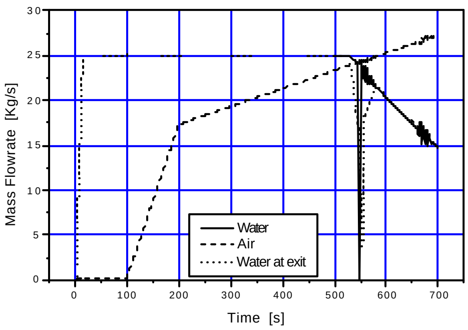

Figure 18. Mass flow rate of water and steam

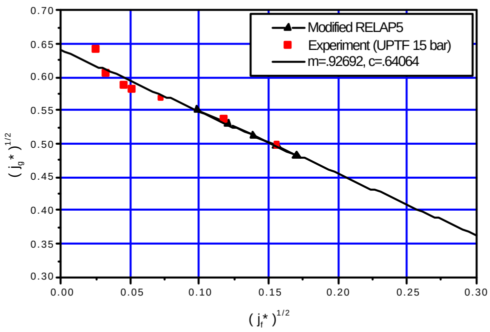

Figure 19. Flooding curve