Study of counter current flow limitation model of MARS-KS and SPACE codes under Dukler's air/water flooding test conditions

Won Woong Lee, Min Gil Kim, Jeong Ik Lee
Department of Nuclear and Quantum engineering, Korea Advanced Institute of Science and Technology
291 Daehak-ro, (373-1, Guseong-dong), Yuseong-gu, Daejeon 305-701, Republic of KOREA
Tel: +82-42-350-5869, Fax: +82-42-350-3810, Email: woong.aa@kaist.ac.kr, gggggtt@kaist.ac.kr, jeongiklee@kaist.ac.kr

Young Seok Bang
Safety Evaluation Department
Korea Institute of Nuclear Safety (KINS)
62 Gwahak-ro, Yuseong-gu, Daejeon 305-338. Republic of KOREA
Email: k164bys@kins.re.kr

1. Introduction

In nuclear reactor system, the counter current flow limitation (CCFL) is an important phenomenon for evaluating the safety of nuclear reactors. In two phase flow, CCFL occurs in a situation in which the liquid and gas flow in the opposite direction. Generally, if the gas flow is faster than the liquid flow, interfacial drag is generated at the interface between the gas and the liquid. If the relative velocity of two phases is increased, the interfacial drag is increased and the interface becomes chaotic. Therefore, the liquid flow can be limited by the increased interfacial drag. This is an important phenomenon which may occur during loss of coolant type accidents (LOCA) in a nuclear power plant.

In particular, CCFL occurs in components such as hot leg, downcomer annulus and steam generator inlet plenum during LOCA which is possible to have flows in two opposite directions. Therefore, CCFL is one of the thermal-hydraulic models which has significant effect on the reactor safety analysis code performance.

In this study, the CCFL model will be evaluated with MARS-KS based on two-phase two-field governing equations and SPACE code based on two-phase three-field governing equations. This study will be conducted by comparing MARS-KS code which is being used for evaluating the safety of a Korean Nuclear Power Plant and SPACE code which is currently under assessment for evaluating the safety of the designed nuclear power plant. In this study, comparison of the results of liquid upflow and liquid downflow rate for different gas flow rate from two code to the famous Dukler's CCFL experimental data are presented. This study will be helpful to understand the difference between system analysis codes with different governing equations, models and correlations, and further improving the accuracy of system analysis codes.

2. CCFL Model

MARS-KS and SPACE code have the ability to solve countercurrent flow. In order to predict the CCFL, the Bankoff correlation is implemented in MARS-KS and SPACE codes, respectively. Since the Bankoff correlation reverts to the Wallis correlation and the Kutateladze correalation depending on the scaling constant, MARS-KS and SPACE codes can accommodate three CCFL correlations with a user option specifying the scaling constant. The CCFL model can be applied to various geometries and conditions depending on appropriate value of the slope, and the gas intercept.

2.1 CCFL Correlation

Countercurrent flow is defined as one of the two phase flow patterns. CCFL correlations were derived by the dimensionless superficial velocity of phase k (k=gas or liquid). There are three types of CCFL correlations as follows:

$$j_g^{*1/2} + M\, j_f^{*1/2} = C \qquad (1)$$

$$Ku_g^{*1/2} + M\, Ku_f^{*1/2} = C \qquad (2)$$

$$H_g^{*1/2} + M\, H_f^{*1/2} = C \qquad (3)$$

where j_k^* is the dimensionless superficial velocity, Ku_k is the Kutateladze number, H_k^* is the dimensionless flux of phase k (k=gas or liquid), M is the slope and C is the gas intercept [1]. j_k^*, Ku_k, H_k^* are as follows:

$$j_k^* = j_k \left(\frac{\rho_k}{g_c D \Delta\rho}\right)^{1/2} \qquad (4)$$

$$Ku_k^* = j_k \left(\frac{\rho_k^2}{g_c \sigma \Delta\rho}\right)^{1/4} \qquad (5)$$

$$H_k^* = j_k \left(\frac{\rho_k}{g_c w \Delta\rho}\right)^{1/2} \qquad (6)$$

where j_k is the superficial velocity, ρ_k is the density of phase k, g_c is the gravity acceleration, D is the tube diameter, σ is the surface tension, w is the interpolative length determined from:

$$w = D^{1-\beta} L^{\beta} \qquad (7)$$

where L is the Laplace capillary constant and β is the scaling constant between 0 and 1 [1].

Equations (1) ~ (3) show the Wallis, the Kutateladze and the Bankoff correlations. The Wallis correlation is derived by a balance between inertial forces in the gas and hydrostatic forces to develop the following gas and liquid non-dimensional average volumetric fluxes. However, the Kutateladze correlation is derived from considerations of the stability of the liquid film or from the gas flow needed to suspend the largest stable liquid drop. The Bankoff correlation interpolates the Wallis correlation for β=0 and the Kutateladze correlation for β=1.

3. Analysis

3.1 Dukler's air/water flooding test

In this study, the CCFL model of MARS-KS and SPACE are evaluated for predicting Dukler's air/water flooding test data. This facility is designed to study the interaction between liquid downward flow and gas upward flow. This facility consists of air inlet section, test section, liquid entrance and exit sections. Figure 1 shows the schematic diagram of the Dukler's experimental facility [2].

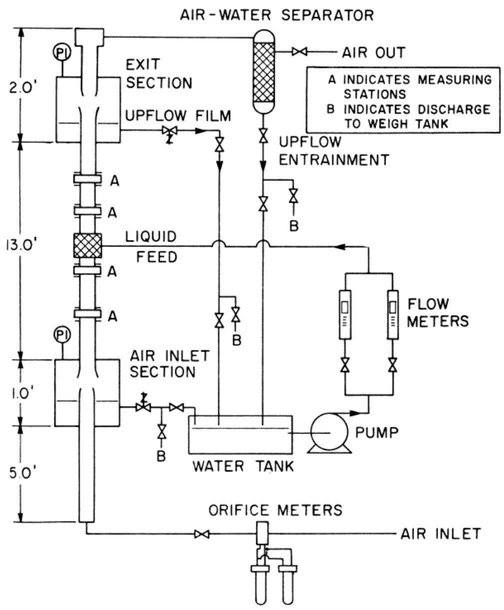

Fig. 1. Schematics of Dukler's air/water flooding experimental facility

3.2 System Code Modeling

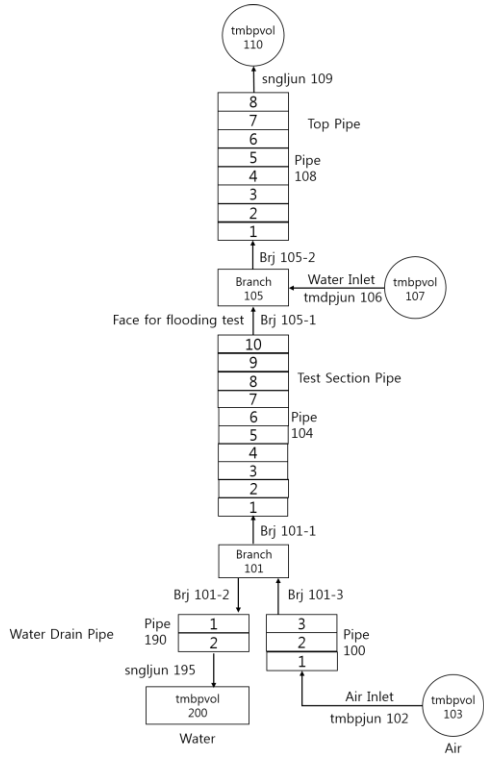

Fig. 2. Nodalization of MARS-KS code

Dukler's experiment is modeled in MARS-KS and SPACE codes respectively with the same nodalization. The liquid entrance and the air inlet section are modeled using branch component. Figures 2 and 3 show nodalization of MARS-KS and SPACE code. The pressure of 0.1MPa and the temperature of 300K are used for initial conditions and boundary conditions in all of components except for the water exit section (tmdpvol 200 and TFBC 200) and the air inlet section (tmbpvol 103 and TFBC 103). The pressure of the water exit section is at 0.104MPa, which is slightly higher than atmospheric pressure 0.1MPa. Pressure of the air inlet section is 0.102MPa. Since the air flow is injected from the air inlet (tmdpvol 103 and TFBC 103) and discharged to the exit section (tmbpvol 110 and TFBC 110). From the previous study, the Wallis correlation is appeared to be the best fitted form for the test. The user input data of 1.3 for the slope and 0.88 for the gas intercept are used [4]. These values are suggested in the SPACE assessment manual. In Dukler's experiment, air and water flow rates are control variables. Table 1 shows the air and water flow rate conditions of Dukler's experiment. MARS-KS and SPACE calculations were conducted in the range of the air flow rate from 0.016 to 0.036 kg/s at intervals of 0.002 kg/s for each case.

Table I: Air and Water flow rate conditions of Dukler's experiment

	Water flow rate [kg/s]	Air flow rate [kg/s]
Case 1	0.0126	0.03142, 0.03229, 0.03268, 0.03343, 0.03382, 0.03432, 0.03502
Case 2	0.0315	0.02743, 0.02818, 0.02857, 0.02921, 0.0298, 0.03041, 0.031, 0.03155, 0.03229, 0.03305, 0.03347, 0.003419, 0.003517, 0.03576, 0.03687
Case 3	0.063	0.02422, 0.02525, 0.02609, 0.02692, 0.0276, 0.02835, 0.02905, 0.02971, 0.03096, 0.03161, 0.03222, 0.03277, 0.03393
Case 4	0.126	0.01668, 0.0173, 0.01868, 0.02005, 0.02128, 0.02239, 0.02345, 0.02456, 0.02538, 0.02631, 0.02716, 0.02795, 0.02889, 0.0302, 0.03146, 0.03308

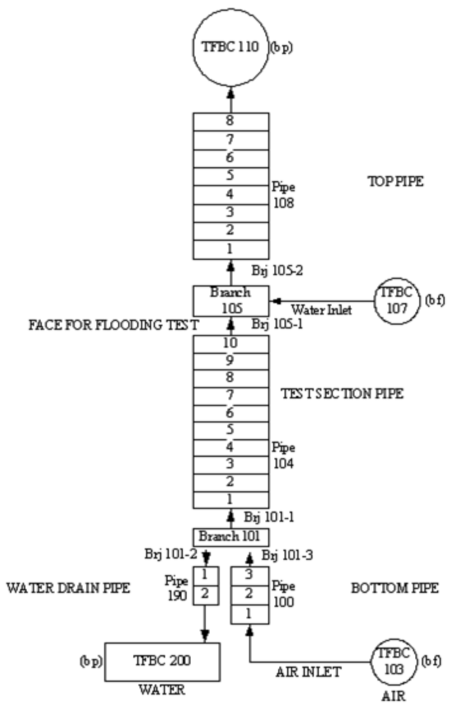

Fig. 3. Nodalization of SPACE code

4. Results

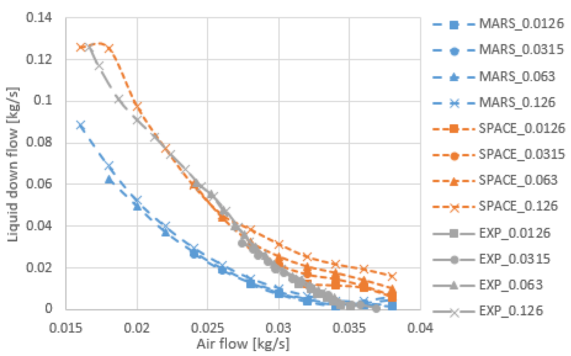

Fig. 4. Liquid down flow rate versus air flow rate

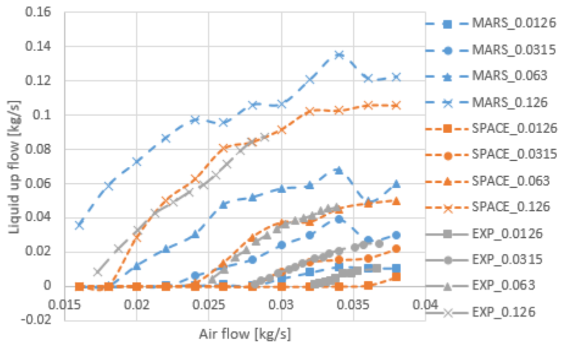

Fig. 5. Liquid up flow rate versus air flow rate

Figure 4 shows the results of MARS-KS and SPACE calculation along with the experimental data. The gray dashed line indicates the experimental data. The blue dashed line is the results of MARS-KS and the red dashed line is the results of SPACE code. Each mark indicates each case. Square mark for case 1, circle mark for case 2, triangle mark for case 3 and X-mark for case 4. As shown in Figure 4, a good agreement with SPACE results and the experimental data is observed at 1.3 slope and 0.88 gas intercept. However, in the results of SPACE, there is a slight difference of the liquid down flow rate depending on the cases when the air flow rate is fixed.

However, the results of MARS-KS show a trend contrary to the results of SPACE. A large difference with the experimental data is observed at 1.3 for the slope and 0.88 for the gas intercept. And when the air flow rate is fixed, the liquid down flow rate is constant in all cases. In other words, there is a maximum value of the liquid down flow at the fixed air flow. MARS-KS shows the trend which cannot increase the liquid down flow without decreasing the air flow rate.

Figure 5 shows results of the liquid up flow rate versus the air flow rate. In this figure, a good agreement with SPACE results and the experimental data is observed. However, there is a large difference with MARS-KS results and the experimental data. This is because interfacial drag force or entrained liquid rate of MARS-KS is calculated higher than those of SPACE.

Table 2 shows average and standard deviation of MARS-KS and SPACE calculation results over time at typical case of the liquid injection rate 0.126kg/s. In MARS-KS and SPACE, standard deviations of liquid down flow are reasonably low compared to each liquid down flow rate average value. However, in case of liquid up flow, most of standard deviation are too high compared to the liquid up flow rate average value. Several standard deviations are even higher than the average value. Therefore, it is doubtful whether calculation of the liquid up flow rate are reasonable in MARS-KS and SPACE.

Table 2 – Average and Standard deviation of MARS-KS and SPACE at the liquid injection rate of 0.126kg/s

MARS-KS			SPACE		
Air flow [kg/s]	Liquid down flow (Average) [kg/s]	Standard deviation	Air flow [kg/s]	Liquid down flow (Average) [kg/s]	Standard deviation
0.016	0.08863	0.00592	0.016	0.12549	0.00062
0.018	0.06902	0.00371	0.018	0.1233	0.00313
0.02	0.05237	0.00262	0.02	0.09813	0.01271
0.022	0.0399	0.00265	0.022	0.07771	0.01234
0.024	0.02971	0.00231	0.024	0.06028	0.00732
0.026	0.02155	0.00194	0.026	0.04643	0.00475
0.028	0.01491	0.0019	0.028	0.03937	0.0064
0.03	0.01029	0.00151	0.03	0.03212	0.00667
0.032	0.00647	0.00143	0.032	0.02638	0.00508
0.034	0.00421	0.00114	0.034	0.02244	0.00436
0.036	0.004	0.00148	0.036	0.0204	0.0037
0.038	0.00629	0.00283	0.038	0.01784	0.00287
Air flow [kg/s]	Liquid up flow (Average) [kg/s]	Standard deviation	Air flow [kg/s]	Liquid up flow (Average) [kg/s]	Standard deviation
0.016	0.03588	**0.05627**	0.016	0.00003	1.61E-08
0.018	0.0586	**0.06442**	0.018	0.00003	3.86E-06
0.02	0.07256	**0.0874**	0.02	0.02851	**0.13208**
0.022	0.08667	**0.11208**	0.022	0.04935	**0.14443**
0.024	0.09713	**0.13276**	0.024	0.06201	**0.15171**
0.026	0.09542	**0.12284**	0.026	0.07981	**0.19197**
0.028	0.10592	**0.14699**	0.028	0.08761	**0.20749**
0.03	0.10632	**0.1579**	0.03	0.09187	**0.19965**
0.032	0.12069	**0.17311**	0.032	0.09753	**0.23809**
0.034	0.13528	**0.20473**	0.034	0.1074	**0.30703**
0.036	0.12136	**0.23167**	0.036	0.10413	**0.29237**
0.038	0.12242	**0.26443**	0.038	0.10787	**0.29373**

As an example of Table 2, Figures 6~9 show the liquid down/up flow rate versus time at the liquid injection rate of 0.126kg/s and the air flow rate of 0.038kg/s in MARS-KS and SPACE codes, respectively. The air flow is injected at 250sec in MARS-KS code and 200sec in SPACE code as shown in Figures 6~9. The green dashed line indicates the liquid injection rate 0.126kg/s. These figures show fluctuation in the results and the magnitude of the fluctuation is represented as the standard deviation in Table 2. In Figures 6 and 8, the fluctuation is small and therefore the standard deviation is small in Table 2. However, the fluctuation of the liquid up flow rate is very large in Figures 7 and 9. It is noteworthy that the fluctuation magnitude is sometimes larger than the total liquid flow rate injected to the test section.

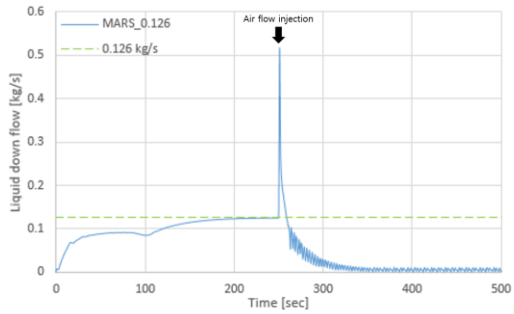

Fig. 6. Liquid down flow rate versus time of MARS-KS at liquid injection rate 0.126kg/s and air flow rate 0.038kg/s

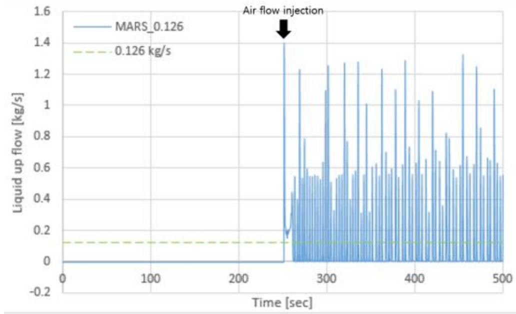

Fig. 7. Liquid up flow rate versus time of MARS-KS at liquid injection rate 0.126kg/s and air flow rate 0.038kg/s

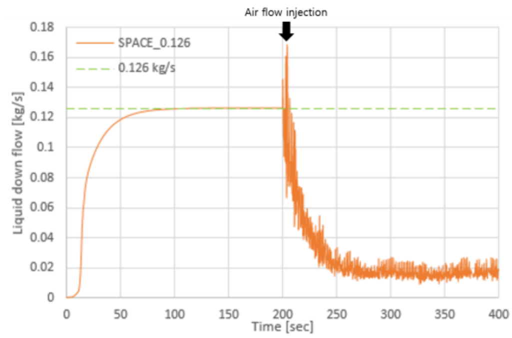

Fig. 8. Liquid down flow rate versus time of SPACE at liquid injection rate 0.126kg/s and air flow rate 0.038kg/s

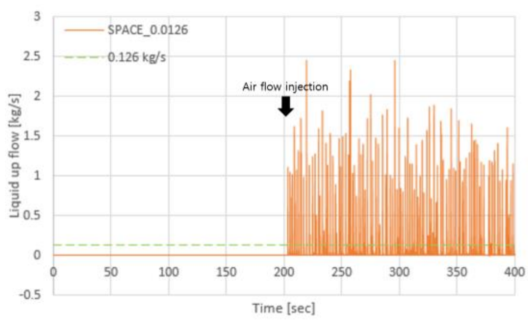

Fig. 9. Liquid up flow rate versus time of SPACE at liquid injection rate 0.126kg/s and air flow rate 0.038kg/s

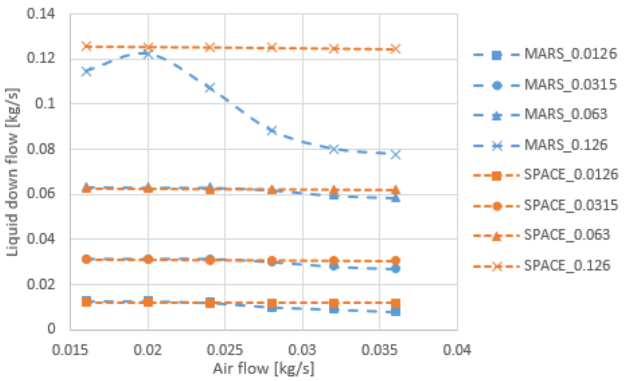

Fig. 10. Liquid down flow rate versus air flow rate without application of CCFL option

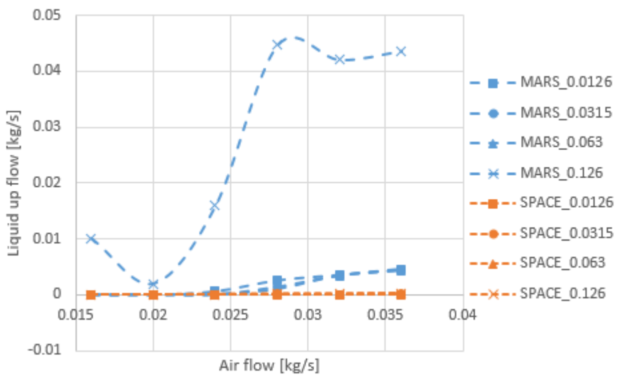

Fig. 11. Liquid up flow rate versus air flow rate without application of CCFL option

Figures 10 and 11 show the liquid down and up flow of MARS-KS and SPACE without application of CCFL option. As shown in the figures, SPACE code results show that most of the liquid injection flow reaches the water drain pipe with small amount liquid up flow. However, the results of MARS-KS without application of CCFL option show a trend that the liquid down flow rate is decreased generally at higher liquid flow rate. It means that a part of the liquid injection flows upward due to the interfacial drag force or entrained liquid. Therefore, the liquid up flow rate is increased without application of CCFL option as shown in Figure 11.

5. Conclusions

In the nuclear reactor system, the counter current flow limitation (CCFL) is an important phenomenon for evaluating the safety of nuclear reactors. This is because CCFL phenomenon can limit injection of ECCS water when CCFL occurs in components such as hot leg, downcomer annulus or steam generator inlet plenum during LOCA which is possible to flow in two opposite directions. Therefore, CCFL is one of the thermal-hydraulic models which has significant effect on the reactor safety analysis code performance. In this study, the CCFL model was evaluated with MARS-KS and SPACE codes for studying the difference between system analysis codes with different governing equations, models and correlations. This study was conducted by comparing MARS-KS and SPACE code results of liquid upflow and liquid downflow rate for different gas flow rate to the famous Dukler's CCFL experimental data.

By using 1.3 slope and 0.88 for gas intercept with user option of CCFL model, SPACE code result shows a good agreement with the Dukler's experimental data. However, there exists a slight difference in the liquid down flow rate with the experimental data and SPACE code results.

Without application of CCFL option, MARS-KS shows overestimated liquid up flow rate at the liquid injection flow rate of 0.126kg/s. This is because MARS-KS overestimates the interfacial drag force or the entrained liquid rate. In the future, these results will be analyzed in more detail to understand the reason for such discrepancy. Furthermore, the reason for high standard deviation in the liquid up flow calculation will be investigated as well.

Acknowledgments

This work was supported by the project "Feasibility assessment by SET and independent review for the SPACE code" funded by Korea Institute of Nuclear Safety (KINS).

REFERENCES

[1] Salomon Levy, Two-phase flow in complex systems, Chapter 5, JOHN WILEY & SONS INC.
[2] A. E. Dukler and L. Smith, "Two Phase Interactions in Counter-Current Flow: Studies of the Flooding Mechanism", NUREG/CR-0617 (1979)
[3] KAERI, MARS Code Manual, Volume I, II, IV (2009)
[4] KHNP, KEPCO E&C, KAERI, SPACE Manual, Volume I, II, IV (2013)
[5] Myung Taek Oh, Chan Eok Park, Jong Joo Sohn and Eun Kee Kim, "CCFL Model of the SPACE Code and Its Validation", Korean Nuclear Society Spring Meeting (2011).
[6] S. Al Issa and R. Macian, "A review of CCFL phenomenon", Annals of Nuclear Energy, 38, 1795-1819 (2011)
[7] Yi-Hsiang Cheng, Chunkuan Shih, Jong-Rong Wang and Hao-Tzu Lin, "A study of steam-water countercurrent flow model in TRACE code", 17th International Conference on Nuclear Engineering (2009)