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Assessment of TRACE VESSEL component with DVI direct bypass test

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1. Introduction

The direct ECC bypass phenomenon was one of the main safety issue related to the Direct Vessel Injection (DVI) system of APR1400 with the steam condensation rate, the ECC penetration rate and the subcooled margin of injection flow. Unlike the cold-leg injection of other plant design, the direct bypass is the main safety injection bypass mechanism rather than sweep out from water surface of downcomer.

The foremost experimental investigation for direct bypass phenomenon was conducted by Upper Plenum Test Facility (UPTF). As the UPTF was designed for full-scale simulation of the 4-loop PWR, specifically Siemens-KWU type, various thermal hydraulic phenomena related to LBLOCA were investigated for PWR. The UPTF-21 was the only test with UPTF for downcomer direct injection conducted with water and steam as working fluids. [1] Yun et al. conducted the direct ECC bypass test with MIDAS (Multi-Dimensional Investigation in Downcomer Annulus Simulation) test facility which is scaled down from APR1400 and uses water/steam as working fluids. [2,3] For taking account of the scale and design effects, Cho et al. conducted the direct vessel injection test using DIVA (Direct vessel Injection Visualization and Analysis) test facility with water and air. [4]

Owing to the importance of the direct ECC bypass, NRC system code TRACE has adopted UPTF in the assessment matrix since former version TRAC-M. [5] With VESSEL component which is developed for simulating multidimensional phenomena, the results of UPTF-21 were reproduced well. However, some of the calculation result shows different results such as system pressure due to the complicated design and phenomena similar to real PWR plant. For the assessment of the system code simulating the direct ECC bypass phenomenon, it is recommended that the reference test is designed only for separate effect for the phenomenon. The MIDAS test facility and the DIVA test facility has proper design and devices only for the direct ECC bypass. Even if the DIVA test produced more data points and detailed results, the MIDAS test is regarded as reference test for the code assessment due to simplicity and the working fluids which could occur condensation.

In this study, the assessment results of TRACE V5 patch5 for the DVI direct bypass with MIDAS test are presented. To simulate multidimensional flow, the test section is modeled by the VESSEL component. The effects of (1) the VESSEL nodalization, the optional interfacial friction model and the CCFL model for VESSEL component are investigated.

2. Reference test and assessment methods

The MIDAS test facility is steam-water separate effect test facility could be simplified to five components; (1) boiler (steam supply system), (2) safety injection simulator (two activated SI lines; broken leg (#2) side & intact leg side (#4)), (3) test section (scaled down downcomer, cold-legs), (4) separator & containment simulator (sump for discharge flow from broken cold-leg of test section), (5) core barrel (sump for flow to lower part from outlet of test section). The maximum allowable operating conditions are 10 bars and 300 Celsius degrees.

The test data with 15 steady-state conditions with different flow rates and different DVI modes are selected from the MIDAS test for this study. Five tests are conducted with DVI line 4 (broken cold-leg side) and one test is conducted with DVI line 2 (opposite side). Nine tests are conducted with both DVI lines together. There are two major results of MIDAS test which are (1) the condensation fraction of steam flow and (2) the bypass fraction of SI flow.

$$Condensation\ fraction = \left(1 - \frac{\dot{m}_{steam,broken\ leg}}{\sum \dot{m}_{steam,intact\ leg}}\right) \times 100 \quad (1)$$

The result of condensation fraction of steam flow is presented in figure 1. It shows linear characteristics to the ratio of SI flow to steam flow rate with 0.999547 as the correlation coefficient for all test data. As the SI flow rate increases comparison to steam flow rate, the condensation fraction of steam flow increases.

$$Bypass\ fraction = \frac{\dot{m}_{liquid,broken\ leg}}{\sum \dot{m}_{SI} + \dot{m}_{condensation}} \times 100 \qquad (2)$$

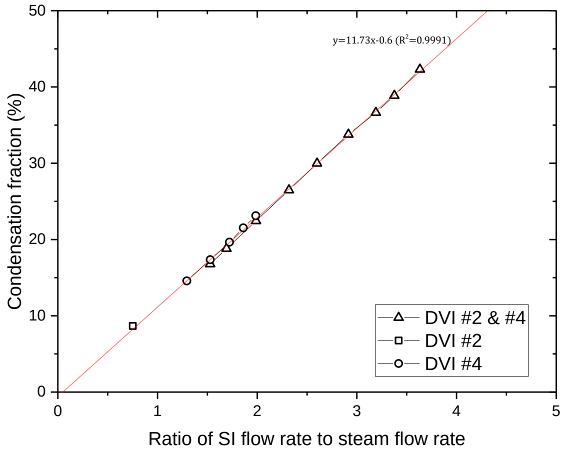

Fig. 1 Test result [3]: Condensation fraction to the water/steam flow rate ratio

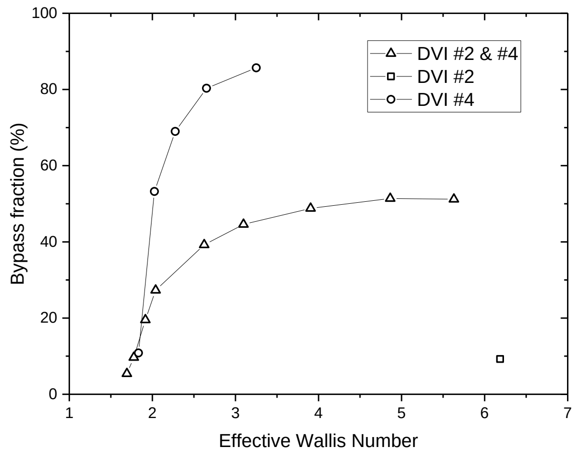

Fig. 2 Test result [3]: Bypass fraction to the effective Wallis number

The result of bypass fraction of SI flow is presented in figure 2 with the effective Wallis number which is calculated from the effective steam mass flow rate of broken cold-leg. The bypass fraction increases with effective Wallis number increase but the increase rate is different for each DVI mode. SI flow with DVI line 4 shows the largest bypass fraction while SI flow with DVI line 2 shows the smallest bypass fraction.

The MIDAS facility could be simplified with VESSEL, PIPE, FILL and BREAK components without heat structure as figure 3. The DVI lines and steam injection lines, intact cold-legs, are modeled with FILL and PIPE components. The broken cold-leg and the water sump are modeled with PIPE and BREAK components. The test section is modeled by VESSEL component with 15 axial cells and 2 radial cells. All faces of the first radial cells are blocked for representing downcomer shape. The mass flow rate and temperature of FILL components are assigned according to each test conditions.

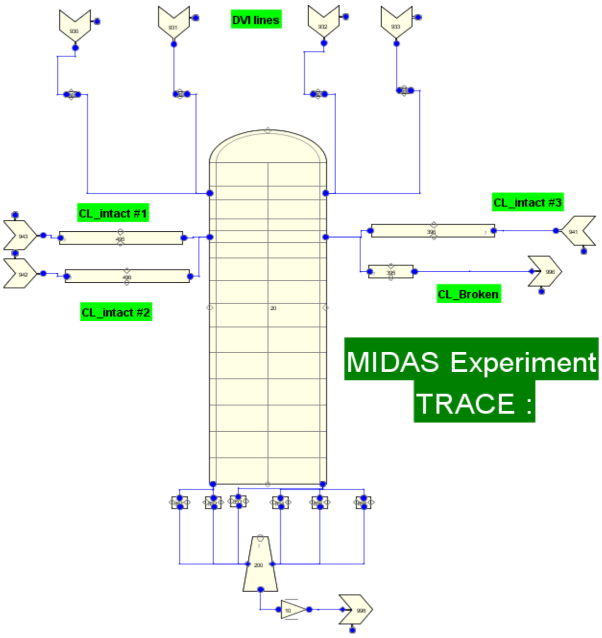

Fig. 3 TRACE input model for MIDAS test facility

The direct ECC bypass phenomenon is consequence of energy and momentum interaction of steam and water. The interfacial heat transfer and the interfacial friction should be assessed. However, there is no specific interfacial heat transfer model for VESSEL component except option for sensitivity analysis purpose. The effect of interfacial heat transfer would be assessed indirectly with other options. First of all, the effect of azimuthal VESSEL nodalization is considered. Modeling with 4-channel, 6-channel and 12-channel were investigated. Two optional interfacial friction model for VESSEL component are investigated also which are IBLAUS option and LBDRAG option. Finally, effect of adopting CCFL models, the Kutateladze model and Wallis model, is investigated. [6,7]

3. Assessment results

3.1 VESSEL nodalization

The number of node of VESSEL component could affect the calculated flow regime for specific flow condition and the concomitant closure models. Determination of channel number could be one of the most significant parameters for MIDAS test as the main flow direction for steam is azimuthal. As presented in figure 4, interfacial heat transfer rate was lower than test results. Reducing channel number could decrease the error of heat transfer because of enhancing mixing effect. Despite the low condensation fraction of TRACE results, the bypass fraction generally shows lower value than test results as in figure 5. The bypass fraction of steam flow was well reproduced in partial effective Wallis number range while detailed division in azimuthal direction causes the higher bypass fraction with VESSEL component. For low effective Wallis number condition, the calculation result couldn’t reproduce increasing bypass fraction with increasing effective Wallis number. Two modeling methods showed similar level of error except 12-ch. Modeling method. With the VESSEL component, six channel modeling method is considered as suitable method for Downcomer as the critical condition for direct bypass is high steam flow condition.

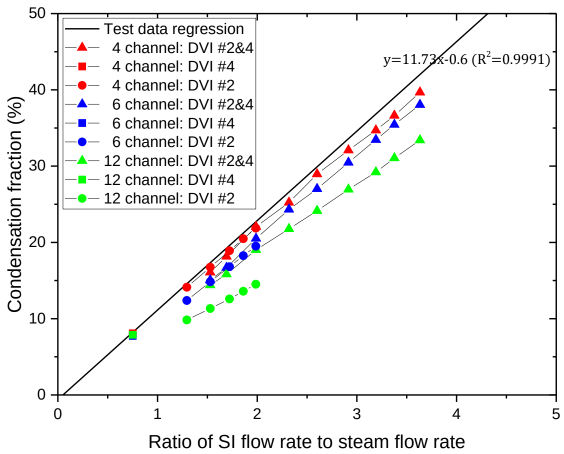

Fig. 4 Condensation fraction with various channel number

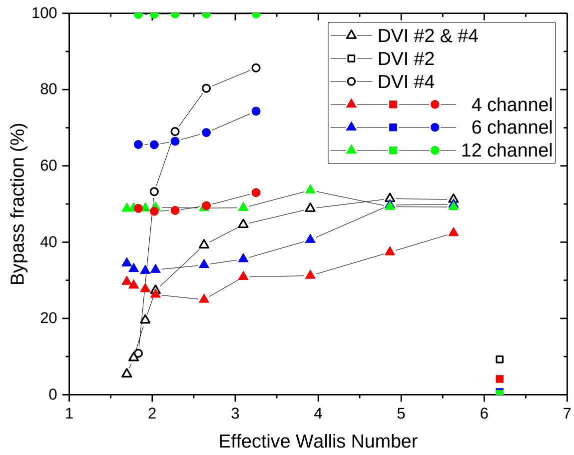

Fig. 5 Bypass fraction with various channel number

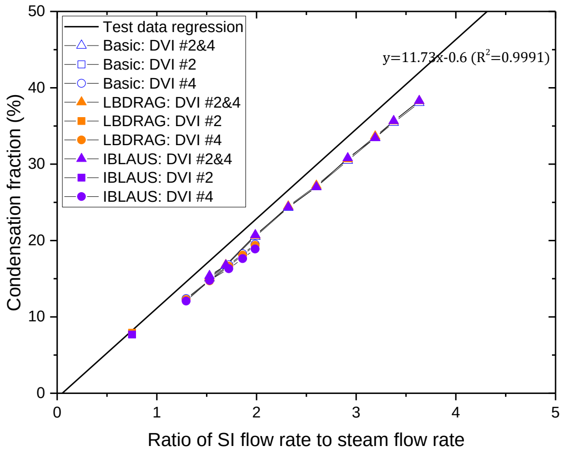

Fig. 6 Condensation fraction for each optional interfacial friction model

3.2 optional interfacial friction model

TRACE code is providing two optional interfacial friction model which are LBDRAG option and IBLAUS option. The results for two model are presented in figure 6 and figure 7. The two options couldn't affect the calculation result of condensation fraction that much. (lower than 0.5%p error in average) With the LBDRAG model, which showed more stable bypass fraction (6.67E-4 as average of standard deviation) than basic model (9.46E-4 as average of standard deviation), affects 0.02%p for the error of bypass fraction in average. However, the calculation data with IBLAUS model in one second period showed the unstable bypass fraction with 0.53189 of the average of standard deviation.

3.3 CCFL model

The Wallis form and the Kutateladze form and the Bankoff form are available for CCFL model. In this study, the pure Wallis form and the pure Kutateladze form are attempted for simulating MIDAS. The Wallis form reduces the average of condensation error 0.06%p and reduces the bypass fraction 0.64%p lower than non-CCFL case in average with 2.28E-2 as average of standard deviation. The Kutateladze form reduces the condensation fraction 2.5%p with nearly full bypass and 7.01E-2 as average of standard deviation.

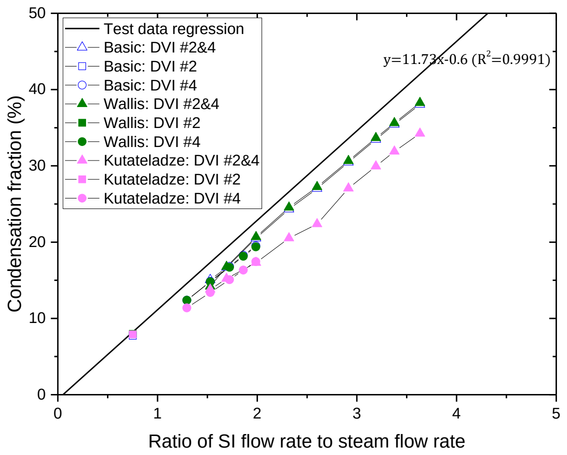

Fig. 8 Condensation fraction for each CCFL model

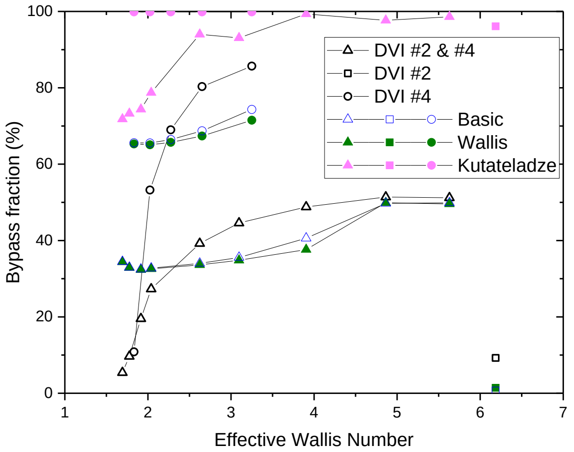

Fig. 9 Bypass fraction for each CCFL model

4. Conclusions

The assessment for the VESSEL component in TRACE V5 Patch5 is conducted using MIDAS test data. Effects of nodalization method and interfacial friction models and CCFL models are investigated in this study.

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