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Evaluation of Direct Contact Condensation Models for Sonic Flow Regime using MARS 2.0

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Abstract

Direct Contact Condensation (DCC) of discharged steam in In-containment Refueling Water Storage Tank (IRWST) is of most important phenomenon affecting the temperature of Safety Injection (SI) flow and subsequent reactor safety of advanced reactors such as APR-1400. Even with such importance, current system codes are not equipped with proper DCC model. Since steam is discharged into the IRWST by sonic flow, DCC models for sonic flow regime proposed by Cumo, Liang and Kerney were investigated and implemented into the MARS 2.0, a multi-dimensional thermal-hydraulic system code. For the evaluation of original and new DCC models, MARS code was assessed using test results of a unit cell test being in progress at KAERI. Assessment results show that the interfacial heat transfer coefficients calculated by new model reach to the order of 10^6 W/m^2/K, while original MARS model results in the order of 10^1 W/m^2/K. Increase in condensation by new DCC model influences temperature distribution in quenching tank and it is shown that the calculated temperature distribution approaches closer to the experimental results by new model than by original model. Thus, we can conclude that implementation of proper DCC model for sonic flow regime should enhance the MARS capability for IRWST temperature transients.

1. INTRODUCTION

In APR1400 design, IRWST plays an important role in guaranteeing reactor safety and mitigating the severity of accident consequences. When it is necessary to depressurize reactor coolant system during the progression of accident, operator opens safety depressurization valves to discharge steam into the IRWST.

Discharged steam condenses mainly adjacent to the location of sparger holes, which affects temperature distribution in the tank. Inlet temperature of SI system depends on such temperature distribution in the tank. Since the increase in SI temperature deteriorates core decay heat removal capability and consequent reactor safety, accurate prediction of the IRWST temperature distribution is of major importance in the safety analysis.

Major phenomenon influencing the temperature distribution is DCC (direct contact condensation) of discharged steam in the tank, more specifically, interfacial heat transfer area and interfacial heat transfer coefficient. However, current existing system codes are not equipped with proper DCC model, which imposed over-conservatism in the analysis method such as use of limiting SI temperature. Thus, it is necessary to improve DCC model in the codes in order to obtain available margin through realistic safety analysis.

Since steam is discharged into the IRWST by sonic flow, DCC models for sonic flow regime proposed by Cumo [1], Kerney [2] and Liang [3] were investigated and implemented into MARS 2.0 code. For the evaluation of DCC models, MARS code was assessed using experimental data of a unit cell test being in progress at KAERI and the results by new and original models were compared.

MARS code [4] is a multi-dimensional thermal-hydraulic system code developed by KAERI by unifying RELAP5 and COBRA-TF codes and by restructuring and modernizing the code architecture. The MARS also has a coupled analysis capability of 3-D reactor kinetics and containment thermal hydraulics. Unit cell test was performed by KAERI at blowdown and condensation test facility. Test facility consists of scaled-down pressurizer, piping and quenching tank and a full-scale sparger of APR-1400. The test was performed for the investigation of dynamic load on structure as well as temperature distribution in the quenching tank during water clearing, air clearing and steam condensation phases.

2. INVESTIGATION OF THE SONIC FLOW MODEL

The flow regime related to DCC can be roughly divided into chugging, bubbling and jetting [3]. The chugging is divided into internal and external chugging. The bubbling is divided into detached and attached bubbling. And the jetting is divided into subsonic and sonic jetting. To construct the flow regime of DCC, interfacial quantities between steam and water, such as the interfacial heat transfer area and interfacial heat transfer coefficient are needed. However in the remaining flow regimes except the sonic and bubbling flow regime, the interface between steam and water is very wavy and fuzzy [3]. Thus, it is very hard to determine the shape of the interface. Whereas, for the sonic flow regime, various correlations for individual interfacial quantities are available from previous studies [1,2,4,6,7,8] because of the interface of the sonic jetting being distinct and stable.

To construct the DCC model for sonic flow regime, models for interfacial heat transfer area and interfacial heat transfer coefficient are required. Interfacial heat transfer area model of Liang [3] was adopted. Liang proposed the interfacial heat transfer area per unit length in the following form:

$$a_{i,z} = \pi D_j \sqrt{1 + (\frac{D_j}{2L_p})^2} \cdot (1 - \frac{z}{L_p}) \quad (1)$$

Eq. (1) can be rearranged into the form of the interfacial heat transfer area as follows.

$$A_i = a_{i,z} \cdot L_p = \pi D_j \sqrt{1 + (\frac{D_j}{2L_p})^2} \cdot (L_p - z) \quad (2)$$

As steam penetration length (L_p) in the Eq. (2), Kerney correlation [2] was chosen and it has the following form:

$$\frac{L_p}{D_j} = 0.3583 \frac{(G_0 / G_m)^{0.6446}}{B^{0.8311}} \quad (3)$$

where, G_m is critical steam mass flux at the atmospheric conditions having a value of $275[kg/m^2 \cdot \sec]$ and dimensionless condensation driving potential B is calculated by Eq. (4).

$$B = \frac{c_p (T_s - T_\infty)}{h_{fg}} \quad (4)$$

Applicable ranges of the Eq. (3) are given in Table. 1.

	Injector diameter $[mm]$	Pool subcooling $[^\circ C]$	Steam mass flux $[kg/m^2 \cdot \sec]$
Kerney et al	0.4~9.5	21~72	332~2050

Table 1. Experimental conditions for steam penetration length

As a correlation for interfacial heat transfer coefficient, we choose Cumo model [1]. According to Cumo et al., important parameters that determine the interfacial heat transfer coefficient are steam quality and pool subcooling. Cumo suggested the interfacial heat transfer coefficient in the form of Eq. (5):

$$h_i = (360x^2 - 530x + 250) \cdot 10^4 \cdot (T_{sat} - T_\infty)^{x/10.5 + 0.26} \quad (5)$$

Applicable ranges of Eq. (5) are given in Table. 2.

	Injector diameter $[mm]$	Pool subcooling $[^\circ C]$	Steam mass flux $[kg/m^2 \cdot \sec]$
Cumo et al	1	20~80	300~2500

Table 2. Experimental conditions for interfacial heat transfer coefficient

3. IMPLEMENTATION TO MARS 2.0

Since DCC is a local phenomenon and the subsequent temperature distribution in the tank determines inlet temperature of SI flow, it is necessary to model the tank using 3D module of the MARS. Original MARS 3D module incorporates two flow regime maps, a normal flow regime map for rod or pipe geometry in the absence of unwetted hot surface and a hot wall flow regime map. A normal flow regime map is applicable in the IRWST analysis and it consists of dispersed bubbly, slug, churn-turbulent and film flow regimes.

For the implementation of new set of DCC model for sonic flow, original flow regime map was modified to have a path to sonic flow regime. Then, MARS calculates the interfacial quantities based on new models as shown in Fig. 2. Original MARS models are applied outside the range of sonic flow regime. Since this study focuses on the evaluation of new DCC model, some of these modifications are hardwired and simplified. It is assumed that condensation length (z) in Eq. (1) is 0.9 of steam penetration length (L_P) and steam quality (x) in Eq. (5) is 1.0. These assumptions are deemed applicable to the model evaluation using unit cell test results, where steam from sparger is discharged into the quenching tank by sonic flow throughout the test.

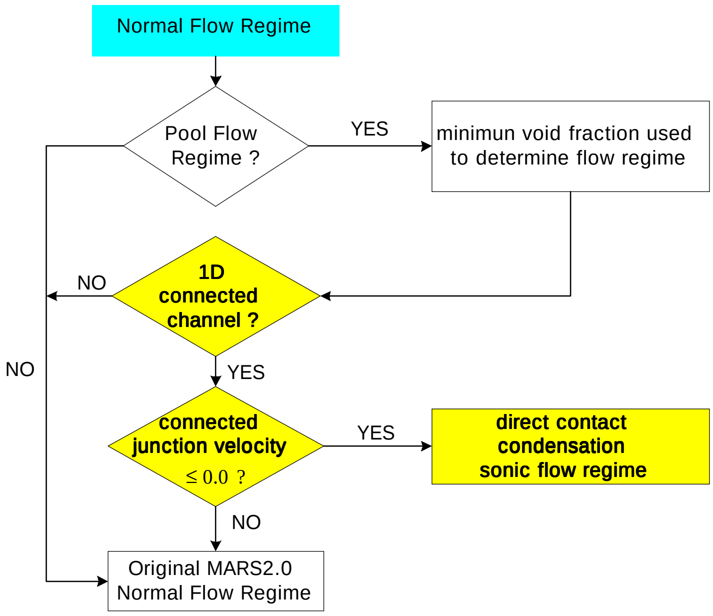


Figure 1. Sonic flow regime map implemented in MARS 2.0

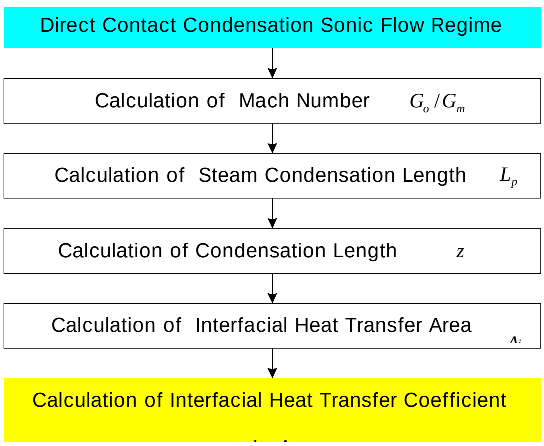


Figure 2. Calculation procedure of DCC models in sonic flow regime

4. MARS MODELLING OF UNIT CELL TEST FACILITY

To evaluate the original and new DCC models, MARS was assessed for system performance and pool temperature distribution in quenching tank using a unit cell test data. Unit cell test facility was modeled using the 1D region representing pressurizer, piping and sparger and the 3D region representing quenching tank. 1D nodalization of test facility is shown in Fig.3 and 3D quenching tank nodalization is shown in Fig.4. Quenching tank is composed of 1 channel in section 1, 5 channels and 4 axial nodes in section 2, and 1 channel in section 3.

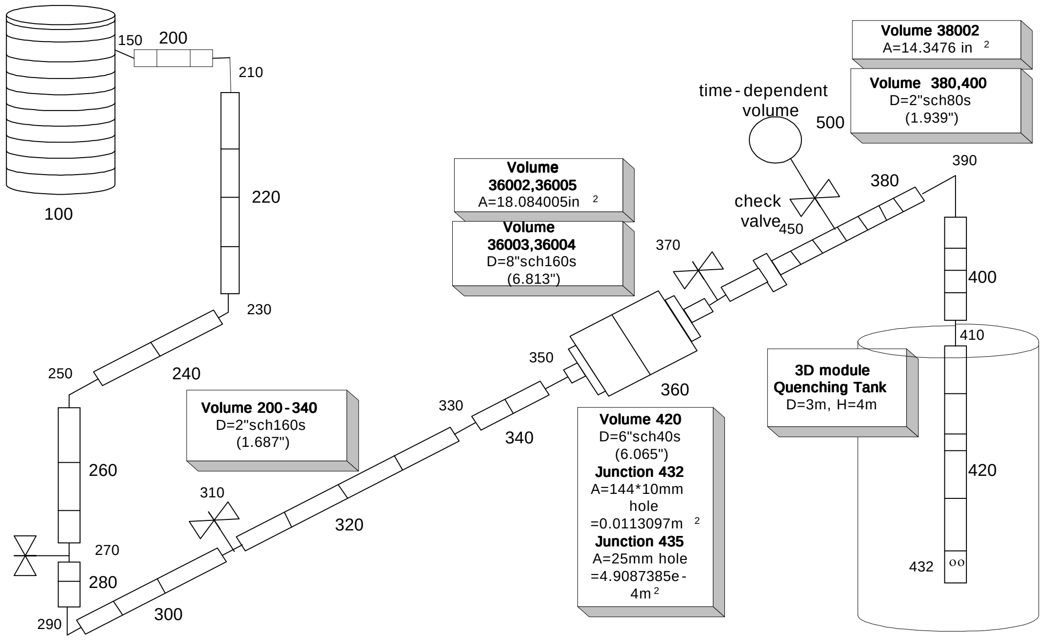


Figure 3. 1D nodalization for unit cell test facility

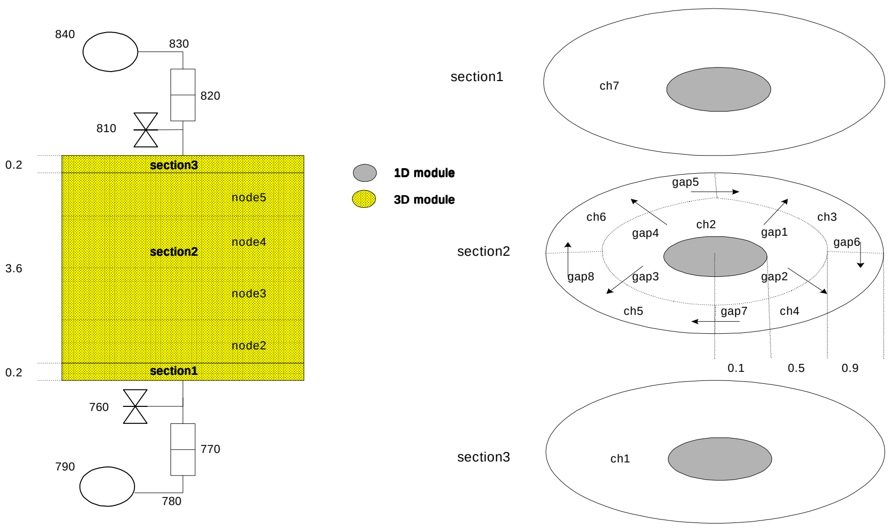


Figure 4. 3D Quenching tank nodalization

Initially, pressurizer (component 100 in Fig. 3) was pressurized at $1.527\times10^{7}[Pa]$ and its initial water level was 1.7 m. The first valve (component 270 in Fig. 3) was in open position and the second (component 310) and third (component 370) was closed. Compressed air at $3.01\times10^{6}[Pa]$ was filled in the piping between the second and third valves. Atmospheric air was in the piping from the third valve to quenching tank. Initial water temperature in quenching tank was $20.3[^{o}C]$ at atmospheric condition. A full size sparger of APR-1400 is installed in the tank and it has 144 discharge holes (component 432 in Fig.3) having 10 mm diameter at lower part, 8 holes with 38 mm diameter at load reduction ring and 1 bottom hole with 25 mm.

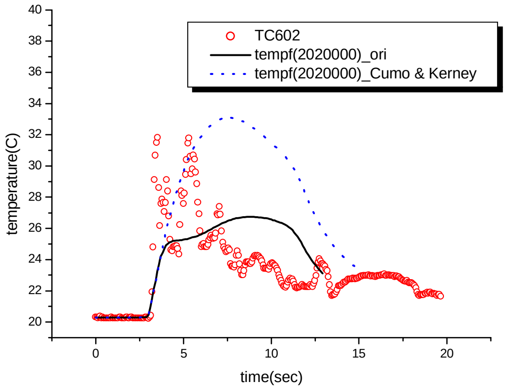
Transient was initiated by simultaneously opening the second and third valves.

5. EVALUATION RESULTS AND DISCUSSION

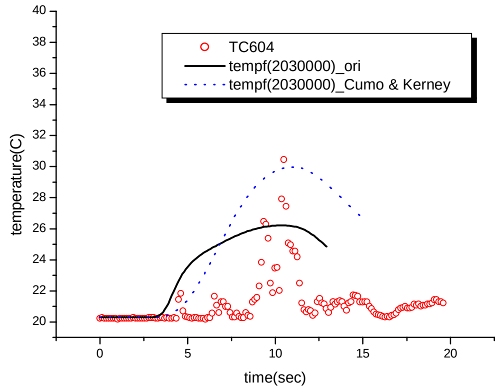
With the initiation of test, water initially in the sparger is first cleared through sparger holes, then serially, air in the piping and steam from upstream of the first valve. Steam is discharged by sonic flow and condensed in the quenching tank adjacent to sparger holes. Pool temperature tends to propagate in upper direction rather than radial direction. Such general response was qualitatively duplicated in the MARS assessment both with original and new DCC models as shown in Fig. 5. However, quantitative response of temperature distribution in the pool deviated a lot from the test results with the original DCC model.

Fig.5 compares the pool temperature distribution measured in the experiment with MARS results by original and new DCC models. In the original MARS assessment, pool temperature adjacent to sparger holes (channel 2, node 2) is largely underestimated, while temperatures in other regions are overestimated. This means that steam condensation at steam discharge location is underestimated. On the other hand, assessment results by new DCC model show better agreement with the experiment. Comparison of calculated interfacial heat transfer coefficients explains the reason such that interfacial heat transfer coefficients by new model are in the order of 10^6 W/m^2/K as reported in the references, while those by original MARS model is in the order of 10^1 W/m^2/K.

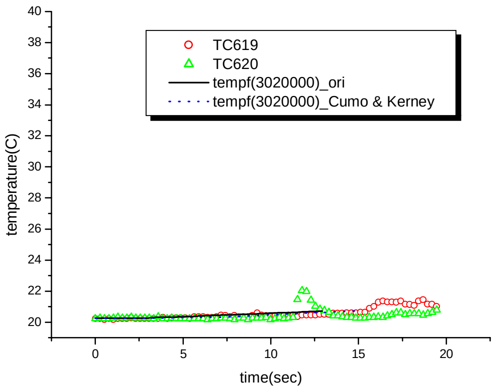
From the results of original and new MARS assessment, it is found that the MARS calculation with new DCC models based on Cumo, Liang and Kerney results in larger steam condensation adjacent to sparger holes, thus, better agreement with the experimental results. However, these results are preliminary, since some assumptions and simplifications were applied in the evaluation and the 3D nodalization of quenching tank is not fully optimized. We also need more study on literature survey and evaluation of available models.



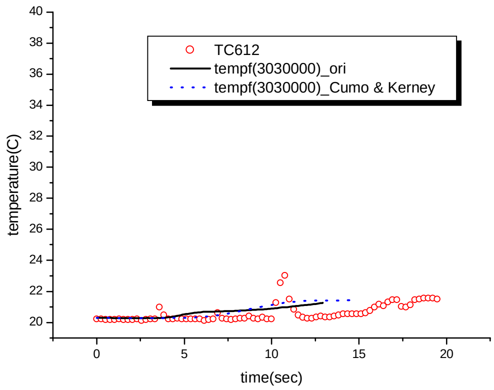
(a) channel 2, node 2



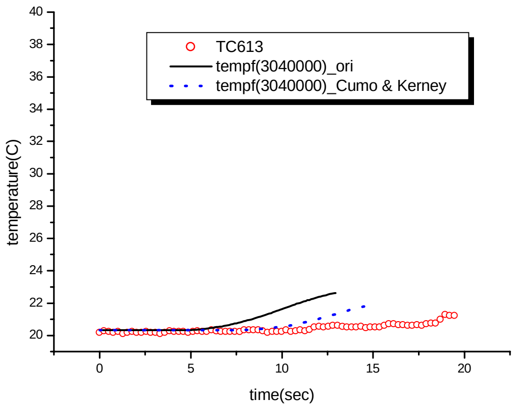
(b) channel 2, node 3



(c) channel 3, node 2



(d) channel 3, node 3



(e) channel 3, node 4

Fig. 5 Pool temperature distributions in quenching tank

6. CONCLUSIONS

DCC models for sonic flow regime were investigated and implemented into the MARS 2.0 for the purpose of enhancing the code capability in predicting the distribution of IRWST temperature. A set of new DCC models is composed of the steam condensation length proposed by Kerney et al., the interfacial heat transfer area by Liang et al. and the interfacial heat transfer coefficient proposed by Cumo, et al. For the evaluation of original and new DCC models, MARS code was assessed using the test results of a unit cell test. Unit cell test facility was modeled using the 1D region representing pressurizer, piping and sparger and the 3D region representing quenching tank. From the assessment calculation, we can obtain following results:

Interfacial heat transfer coefficients calculated by new model are in the order of 10^6 W/m^2/K, while those by original MARS model is in the order of 10^1 W/m^2/K.

Larger interfacial heat transfer by new model increases the rate of condensation adjacent to sparger holes and consequently influences the temperature distribution in the tank. In comparison with test results, it is found that the calculated temperature distribution approaches closer to the experimental results by new model than by original model.

Conclusively, it is found that the MARS calculation with new DCC models based on Cumo, Liang and Kerney results in larger steam condensation adjacent to sparger holes and subsequently better agreement with the experiment. From this, we can conclude that the implementation of proper DCC model for sonic flow regime should enhance the MARS capability in simulating the IRWST temperature transients.

As future works, we will survey and evaluate other DCC models for sonic and subsonic flow regimes. We will also perform further code assessment using recent test results in parallel with the nodalization sensitivity study on 3D modeling of quenching tank.

NOMENCLATURE

$a_{i.z}$ interfacial heat transfer area per unit length [m^2 / m]

A_i interfacial heat transfer area [m^2]

B dimensionless condensation driving potential

c_p liquid specific heat [$J / kg \cdot K$]

D_j injector diameter [m]

G_m critical steam mass flux at the atmospheric conditions [$kg / m^2 \cdot \sec$]

G_0 steam mass flux at the injector diameter [$kg / m^2 \cdot \sec$]

h_{fg} latent heat of vaporization [J / kg]

h_i interfacial heat transfer coefficient [$W / m^2 \cdot K$]

L_p steam penetration length [m]

T_s saturation temperature [^oC]

T_{sat} saturation temperature of pool water [^oC]

T_∞ bulk temperature of pool water [^oC]

z condensation length [m]

χ steam quality

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