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Original Article

Assessment of ECCMIX component in RELAP5 based on ECCS experiment

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ABSTRACT

ECCMIX component was introduced in RELAP5/MOD3 for calculating the interfacial condensation. Compared to other existing components in RELAP5, user experience of ECCMIX component is restricted to developmental assessment applications. To evaluate the capability of the ECCMIX component, ECCS experiment was conducted which included single-phase and two-phase thermal mixing. The experiment was carried out with test sections containing a main pipe (70 mm inner diameter) and a branch pipe (21 mm inner diameter) under the atmospheric pressure. The steam mass flow in the main pipe ranged from 0 to 0.0347 kg/s, and the subcooled water mass flow in the branch pipe ranged from 0.0278 to 0.1389 kg/s. The comparison of the experimental data with the calculation results illuminated that although the ECCMIX component was more difficult to converge than Branch component, it was a more appropriate manner to simulate interfacial condensation under two-phase thermal mixing circumstance, while the two components had no differences under single-phase circumstance.

1. Introduction

Under the condition of Loss of Coolant Accident (LOCA) in the Pressurized Water Reactor, the Emergency Core Cooling (ECC) system is put into use. The subcooled water from the ECC system and the high-temperature coolant or steam-water mixture in the cold leg are mixed in the vicinity of the ECC injection pipe. The location of the ECC injection tube is closely related to the type of PWRs. In the second generation reactors, the ECC injection tube is generally arranged on the primary circuit.

In the small break Loss of Coolant Accident (SBLOCA), thermal mixing of the cold water and hot water and direct contact condensation might occur after the injection of subcooled water into the cold leg. With the decreasing of the system pressure and the start of the accumulator injection, a higher subcooled water flow makes the direct contact condensation easier to occur. And in the large break Loss of Coolant Accident (LBLOCA), the condensation during the ECC injection is a key factor which influences the core reflooding especially under the condition of low pressure safety injection (LPSI). However, this phenomena of the condensation during the ECC injection is so complicated that it has not been fully understood so far.

RELAP5 code was used principally by Idaho National Engineering Laboratory (INEL) analysts for understanding Loss-of -Fluid Test (LOFT) and Semiscale experimental behavior initially. Since then, the code has become widely accepted throughout the world for analyzing commercial and experimental light-water reactor (LWR) systems together with their related scaled systems. And after numbers of assessment and evolution, RELAP5 has become a reliable system analysis code in the thermal hydraulic field [1]. However, the results of the experiments made by Tandon et al. [2] pointed out that RELAP5 is not capable to predict the condensation when the ECCS injects subcooled water into a two-phase flow properly. So in the version of RELAP5/MOD3.1, a new component was built in to simulate the phenomena associated with subcooled ECC injection into a reactor coolant system, which was the ECCMIX component. Because of the restricted user experience of the ECCMIX component, necessary assessment is crucial before applying the new component to the condensation of the ECC injection in PWRs.

In the present study, ECCS experiment was carried out for evaluating the capability of the ECCMIX component (RELAP5/MOD3.4). The experiment contained single-phase and two-phase thermal mixing between the high temperature water or steam-

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water mixture in the main pipe and the subcooled water in the branch pipe. The experiment was under the atmospheric pressure (0.1 MPa). The steam mass flow in the main pipe ranged from 0 to 0.0347 kg/s, while in the branch pipe ranged from 0.0278 to 0.1389 kg/s. In contrast to the calculation results of the ECCMIX component, the branch component calculation was also performed.

2. Previous work

There are various experimental and numerical investigations of the ECC injection in the published literature.

McFarland [3] conducted single-phase thermal mixing experiment with three different configuration of T-junctions. And the pressure and fluid temperature analysis were performed under the transient and steady conditions. By visualizing the experimental section, the mixing process at the T-junction was observed. They concluded that under the condition of $L/D < 10$, a good mixing of the same fluid could be obtained with an inapparent pressure losses.

Maruyama [4] experimentally investigated the temperature distribution in the cold leg before and after thermal mixing by using air as the mixture medium, and derived the deflected jet trajectory equations for T-junction. They pointed out that the angle of 45°between the main pipe and branch pipe was the optimal value for obtaining rapid mixing.

Zughbi [5] investigated the flow regime of the ECC injection experimentally and numerically. The conclusions indicated that the injection of cold water would affect the temperature of the main wall in the direction of incidence directly, and the angle of inclination would affect the length of the mixed area. Besides the angle of inclination, the velocity ratios and the diameter ratios of the main pipe and branch pipe also effected the single-phase thermal mixing notably.

Seyed [6] analyzed the jet flow patterns using dimensionless number of MR. Based on different value of MR, jet attaching the wall, deflected jet and impinging jet were distinguished.

Due to the absence of phase change during single-phase thermal mixing, the mechanism was relatively simple. The temperature and pressure distribution after thermal mixing are mainly caused by the temperature difference between cold and hot fluids. So the main purpose of the single-phase thermal mixing was to obtain the temperature distribution in the main pipe.

Kim [7] conducted an interfacial heat transfer experiment of stratified flow. And derived a interfacial heat transfer correlation caused by the temperature differences between the steam and water. He also studied the flow state of the steam and water during the thermal mixing in the horizontal pipe.

Based on Kim, Segev [8] experimentally studied the interfacial heat transfer between the steam and subcooled water in a rectangular pipe, and finally summed up the heat transfer relationship based on Nusselt number and Reynolds number.

After above interfacial condensation investigations, a number of studies have also been carried out on the relevant phenomena in the T-junction of the cold leg of the Pressurized Water Reactor. Damerell [9] carried out a 2D/3D experiment system for PWR which included the important experiment of two-phase flow thermal hydraulic phenomenon in the primary circuit and core of the reactor in the case of LBLOCA and SBLOCA. And the dimensionless thermodynamic ratio (RT) was first proposed to analyze the condensation and heat transfer phenomena of the thermal mixing in ECC injection, which was the ratio of the potential condensation rate to the steam.

Mayinger [10] analyzed the influence of geometric structure on the phenomenon of ECC injection based on UPTF experiment, and concluded that different value of RT would cause different condensation effectiveness. When $RT < 1$, the mass flow of steam would play a decisive role in the thermal mixing condensation; and when $RT > 1$, the mass flow of subcooled water was more important in thermal mixing.

Jun Liao [11] published the theoretical analysis of the UPTF 8 experiment, which focused on the direct contact condensation of steam with subcooled water under LOCA accident conditions, and derived the heat transfer correlation based on D-B correlation which was more applicable for two-phase thermal mixing.

Mingjun Wang [12] used the CFD method to simulate the thermal mixing phenomenon, and the flow patterns of impact jet flow, deflection flow and upper wall jet flow were defined. The focus was on the structure stress distribution characteristics during the thermal mixing process. Tangtao Feng [13] also used the CFD method to simulate the thermal mixing phenomenon, but paid more attention to the two-phase thermal mixing characteristics such as temperature field, velocity field, volume fraction and local steam condensation characteristics. The results show that the condensation rate was closely related to the coolant thermodynamic ratio between the main pipe and branch pipe.

Although there were many of investigations of ECC injection existed, few of them focused on the separate effects tests just as direct condensation heat transfer in cooling system. XJTU-ECCS was a separate effects test facility which was focused on researches of thermal mixing phenomena based on Chinese PWR design.

As for the evaluation of the ECCMIX component of RELAP5, few literature have been published. Most researchers are more concerned with the calculation capability of RELAP5 on the overall system, and less on the calculation errors of individual components. For example, Jeong et al. [14] used the experimental data of LOFT L2-3 large water loss accident to evaluate the accident analysis capability of RELAP5. The ECCMIX components were used in the system modeling, but the ECCMIX components were not evaluated separately. The analysis of the composition of calculation errors could not be performed, which was not conducive to the improvement of the calculation. Guba et al. [15] was one of the few researchers to evaluate ECCMIX components using experimental data. The results showed that the ECCMIX component was suitable for simulating HPIS of VVER-440 plants, but it was not capable to simulate the direct injection of the accumulator. Because of the few evaluation of the calculation capability of ECCMIX components, the work of this paper is of great significance.

3. Experiment description

3.1. Experimental system

The Emergency Core Cooling System (ECCS) experiment was performed at Xi'an Jiaotong University, and Fig. 1 is the schematic diagram of the system. The experiment system was constructed in November 2013 and completed in March 2014. The experiment system included a main circuit system, a steam system, and a safe injection system. In the single-phase thermal mixing experiment, the check valve of the steam system was closed, and the liquid with a certain degree of subcooling in the main circuit system flowed into the head of the experimental section, and was mixed with the supercooled liquid in the branch pipe of the experimental section from the safety injection system. After entering the weighing tank, it flowed into the circulation of the main circuit system through the circulation pump. During the two-phase thermal mixing experiment, the steam from the steam system was thoroughly mixed with the high temperature fluid of the main circuit system to form a two-phase flow, and then entered the experimental section, and then mixed with the supercooled liquid in the branch pipe, and the mixed fluid flowed into the weighing tank. The experimental

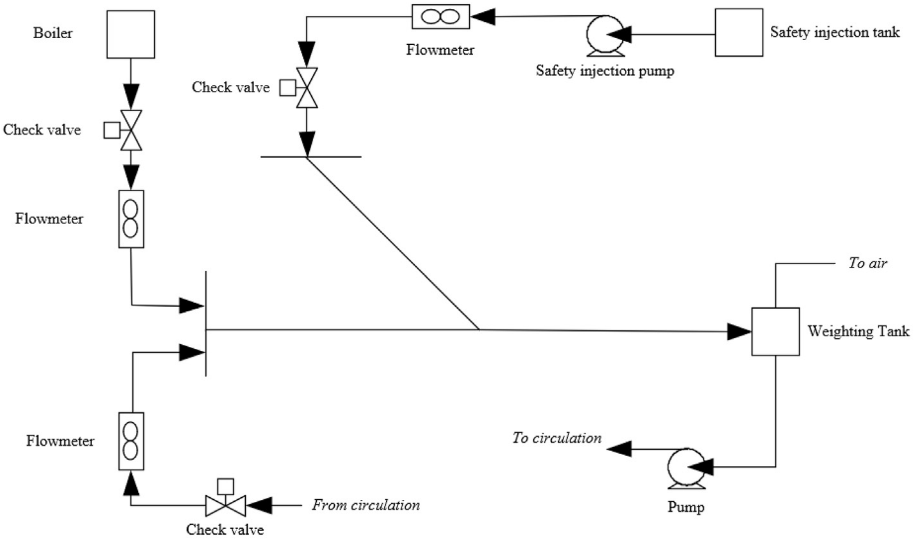


Fig. 1. Schematic diagram of experiment system.

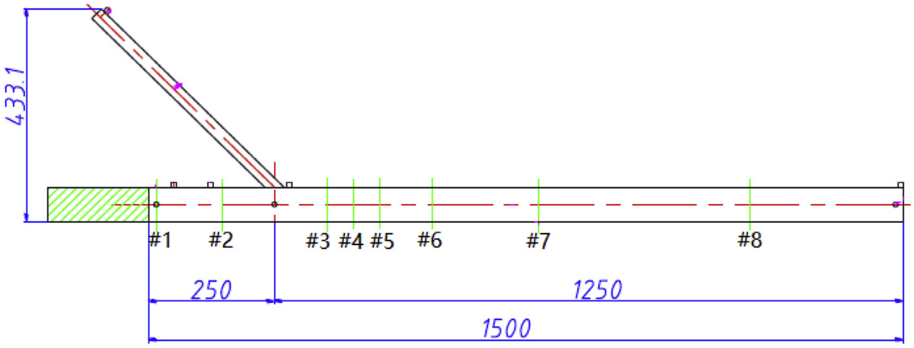


Fig. 2. T-junction geometric parameter diagram.

section and the whole test loop were covered by the thermal insulation material for reducing heat losses, and the calculation results in Section 4.2 illustrated that it had no significant effect on the experimental results without considering the heat losses.

The main geometric parameters of the T-junction experimental section are shown in Fig. 2, and more details of the T-junction experimental section are shown in Table 1.

The experimental section was designed with 8 temperature measuring sections whose locations are shown in Table 2. In order to accurately measure the temperature change during single-phase thermal mixing, the temperature inside the tube was monitored by a 6-point temperature measurement section in the area of the obvious thermal mixing phenomenon (temperature measurement section #2, #3, #4). In the case where the phenomenon was not obvious (temperature measurement section #1, #5, #6, #7, #8), the temperature measurement of the top and bottom of the tube is performed using a 2-point temperature measurement section.

The 6-point and 2-point temperature measurement sections are shown in Figs. 3 and 4, respectively. The 6-point temperature measurement section measures the temperature at the top, bottom, two horizontal positions, and two positions of the line at a 45-degree angle from the horizontal line. And the 2-point temperature measurement section only measures the temperature at the top and bottom of the section.

The measurement instruments and the accuracy of them are shown in Table 3, and refer to Jing Zhang [16]for the parameter

Table 1
Geometric and initial condition of T-junction experimental section.

	Main pipe	Branch pipe
Outer diameter (mm)	76	25
Inner diameter (mm)	70	21
Length (mm)	250 (Before thermal mixing) 1250 (After thermal mixing)	433.1 (Vertical height) 612.5 (Actual length)
Pressure (MPa)	0.1	
Inlet subcooling (K)	0 (for two-phase mixing) 26 (for single-phase mixing)	60
Mass flow (kg/s)	0–0.278 (water from circulation) 0–0.0347 (steam from boiler)	0.0278–0.1389

Table 2
Temperature measurement section position coordinates (point 0 at the main pipe entrance).

Section number	Position coordinates (mm)
#1	30.0
#2	145.0
#3	355.0
#4	407.5
#5	460.0
#6	565.0
#7	775.0
#8	1195.0

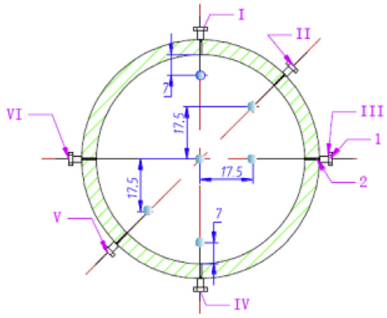


Fig. 3. 6-point temperature measurement section.

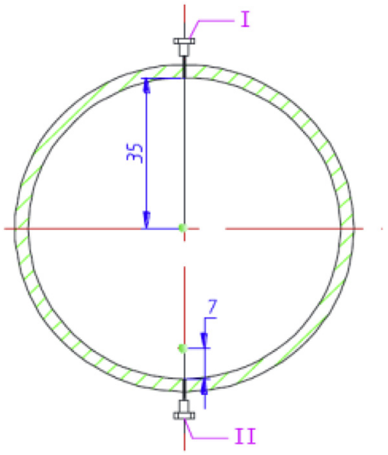


Fig. 4. 2-point temperature measurement section.

Table 3
Measurement instruments and the accuracy.

Measurement item	Measurement instruments	Accuracy
Pressure	Pressure Transmitters	0.25%
Temperature	K-type thermocouples	0.75%
Mass flow	Coriolis mass flowmeter	0.2%

transmission error.

The two-phase thermal mixing experiment was to simulate the phenomenon of thermal mixing between steam and cold water in the main pipe under the conditions of accumulative pressure and low pressure injection. The steam in the main pipe is provided by the steam boiler. For two-phase thermal mixing experiments, the most important measurement parameter was the condensation. After the hot and cold mixing of the outlet, the fluid flows into the weighing water tank. Based on the quality of the water tank under stable conditions, the increase rate of the water tank quality was obtained by the least squares method, which was the liquid phase flow after the ECC injection, minus the liquid flow rate in the main pipe and in the branch pipe, and then the two-phase ECC injection condensation were obtained.

Janicot [17] summed up the expression for the interfacial condensation of two-phase flow as follows:

$$Q_{cond} = h_i A_i \Delta T \tag{3-1}$$

where h_i is the heat transfer coefficient, A_i is the interfacial heat transfer area, ΔT is the temperature difference between the steam in the main pipe and the subcooled water in the branch pipe.

The interfacial condensation heat transfer coefficient is calculated by the following formula:

$$Nu = \frac{Q_{cond}}{D_b k \Delta T} \tag{3-2}$$

where k is the thermal conductivity of the subcooled water, D_b is the diameter of the branch pipe.

The flow characteristics of the fluid in the branch pipe Re_b could be expressed by the following formula:

$$Re_b = \frac{4W_b}{\pi \mu D_b} \tag{3-3}$$

where W_b is the subcooled water mass flow in the branch pipe, μ is the dynamic viscosity of the subcooled water in the branch pipe.

The two-phase thermal mixing condensation model was built based on Equations (3-1) and (3-2). Ren WY et al. [18] conducted detailed description of the condensation model. This paper only focused on the condensation value after two-phase thermal mixing, which was the basis for the model verification of RELAP5.

3.2. Single-phase thermal mixing experimental results

For the influence of single-phase thermal mixing on the temperature field distribution in the tube, Hosseini [19] pointed out that the single-phase thermal mixed flow pattern was mainly determined by the jet coefficient MR, and the impinging jet was when MR < 0.35; 0.35 < MR < 1.35 was the deflected jet; when MR > 1.35, it was the wall attached jet. MR definition is as follows:

$$M_R = \frac{\rho_m V_m^2 D_m D_b}{\frac{\pi}{4} D_b^2 \rho_b V_b^2} \tag{3-4}$$

where V_m and V_b represent the main flow rate and the branch flow rate, respectively, D_m and D_b represent the main pipe diameter and the branch pipe diameter, respectively; ρ_m and ρ_b represent the main fluid density and the branch pipe fluid density, respectively.

The impinging jet indicated that the branching injection fluid directly impacted the single-phase fluid in the main pipe, mainly affecting the temperature of the lower wall surface in the horizontal pipe of the thermal mixing area. The deflected jet indicated that the branching fluid had an impact on the single-phase fluid in the main pipe, but due to the large fluid momentum in the main pipe, it only partially affected the temperature of the lower wall surface in the horizontal pipe of the thermal mixing area. The wall attached jet indicated that due to the large momentum of the single-phase fluid in the main pipe, the subcooled fluid of the branch pipe mainly affected the temperature of the upper wall surface in the horizontal pipe of the thermal mixing area.

After single-phase thermal mixing whose condition are shown in Table 4, the temperature changed at the top and bottom of each

Table 4
Single-phase thermal mixing condition.

	Main pipe	Branch pipe
Pressure (MPa)	0.1	
Inlet temperature (K)	347.15	313.15
Mass flow (kg/s)	0.0278–0.278	0.0278

temperature measurement section are shown in Fig. 5.

It can be seen from Fig. 5(a) that when MR > 3.0, the temperature at the top of the main pipe decreases slightly, indicating that the top temperature is affected by the cooling of the cold water and the temperature is lowered. When the MR number is gradually increased, the branch jet is affected by the larger momentum of the main pipe and flows near the upper wall surface, indicating that the injection flow is converted from the deflected jet to the upper wall attached jet.

It can be found from Fig. 5(b) that when MR < 0.5, the temperature at the bottom of the main pipe is low, indicating that the bottom temperature is greatly affected by the cooling of the cold water. When the MR number is increased, the bottom temperature rises at a higher rate, and the temperature of the inner and lower wall of the main pipe approaches the temperature of the main inlet, that is, the cooling capacity of the subcooled water of the branch pipe decreases for the bottom regions of the main pipe, indicating that the jet from the branch pipe cannot directly impact the lower wall of the main pipe with the fluid momentum in the main pipe increasing, and the injection flow is converted from the impinging jet to the deflecting jet, which is similar to the findings of Seyed et al.

In addition, it can be seen from Fig. 5 that there is a significant thermal stratification. When the MR is small, that is, the main flow is small, the temperature of the lower wall gradually increases and the temperature of the upper wall changes little along the main flow direction, indicating that the injection flow mainly affects the temperature change of the fluid in the lower half of the main pipe, which proves that the injection flow is an impinging jet, and the flow of the branch pipe immediately affects the temperature of the lower wall surface whose temperature gradually rises again after thermal mixing. When the MR is large, that is, the main flow rate is large, the temperature of the lower wall surface gradually decreases and the temperature of the upper wall surface gradually increases along the main flow direction, indicating that the injection flow is the upper wall jet, in which the branch pipe flow immediately affects the temperature of the upper wall surface, and the temperature of the upper wall gradually rises after thermal mixing. And due to heat conduction, the influence of the injection flow on the temperature of the lower wall surface is delayed, resulting in the lower wall surface temperature gradually decreases after mixing.

In summary, it can be seen that the thermal stratification proves that as the MR becomes larger, the injection flow from the impinging jet to the deflecting jet eventually becomes the upper wall jet. And the correspondence between the MR number and the jet flow pattern can be obtained: when the MR > 3.0 is the upper wall attached jet; 0.5 < MR < 3.0 is the deflecting jet; and MR < 0.5 is the impinging jet.

3.3. Two-phase thermal mixing experimental results

In the two-phase thermal mixing experiment, when the main pipe is full of steam, the change of the condensation with the branch pipe flow is shown in Fig. 6. When the steam-water mixture in the main pipe is used, the change of the condensation with the branch pipe flow is shown in Fig. 7. The relationship between the

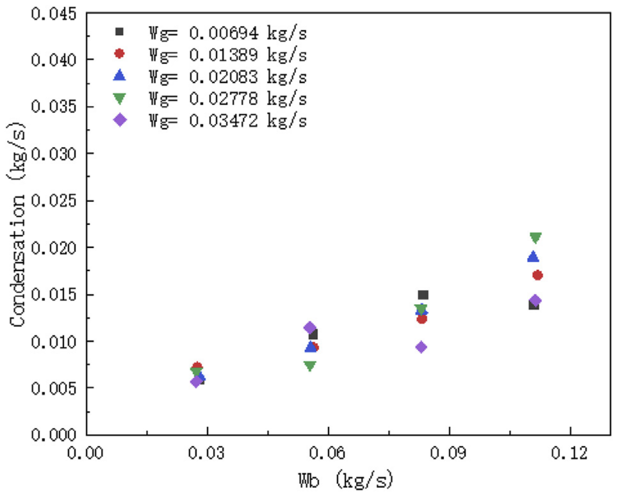
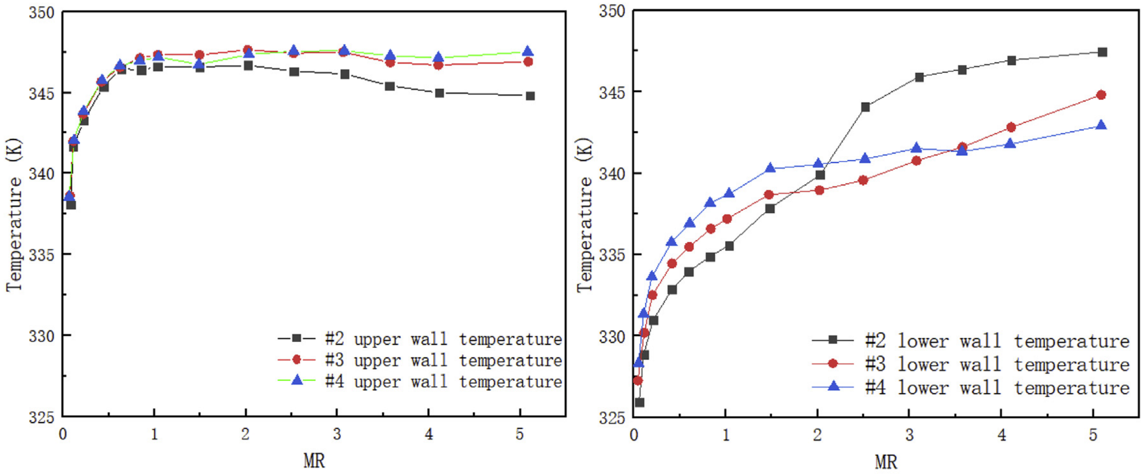


Fig. 6. Condensation with the flow of the branch pipe (pure steam in main pipe).



(a) Upper wall temperature curve (b) Lower wall temperature curve

Fig. 5. Single-phase thermal mixing results.

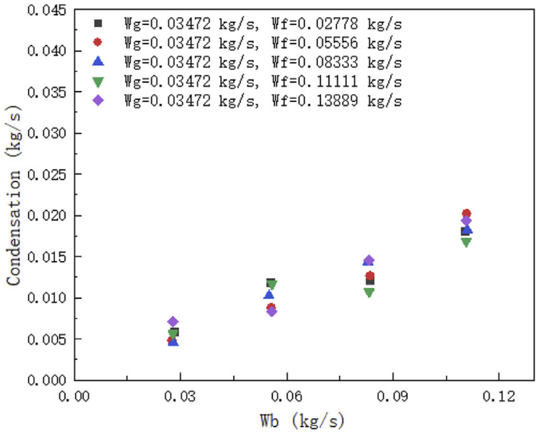


Fig. 7. Condensation with the flow of the branch pipe (steam-water mixture in main pipe).

Reynolds number and the Nusselt number is shown in Fig. 8.

It can be seen from Figs. 6 and 7 that the larger the branch pipe flow rate, the larger the condensation. And the linear relationship is existed between the branch pipe flow rate and the condensation. When the branch pipe flow is small, the cooling capacity to the main fluid is limited, so when the main flow rate is different, the condensation difference is small. When the branch pipe flow becomes larger, the difference in the amount of condensation caused by the different main flow rates gradually increases, and the overall trend is that the main flow rate is larger and the amount of condensation is larger. When the main pipe is full of two-phase mixture, the effect of liquid flow on the condensation is small at the same steam flow rate. By comparing Figs. 6 and 7, it can be seen that two important factors affecting the condensation are the steam flow in the main pipe and the subcooled water flow in the branch pipe.

It can be seen from Fig. 8 that under the lower steam flow rate, the cooling water has a larger cooling capacity. When Reynolds number reaches a certain critical value, the Nusselt number gradually stabilizes, indicating that the condensation is no longer accompanied by the cooling water Reynolds number. When the steam flow rate is high, the condensation is proportional to the flow rate of the cold water, indicating that the condensing phenomenon is more obvious as the flow rate of the cold water is increased, and the condensing amount is larger.

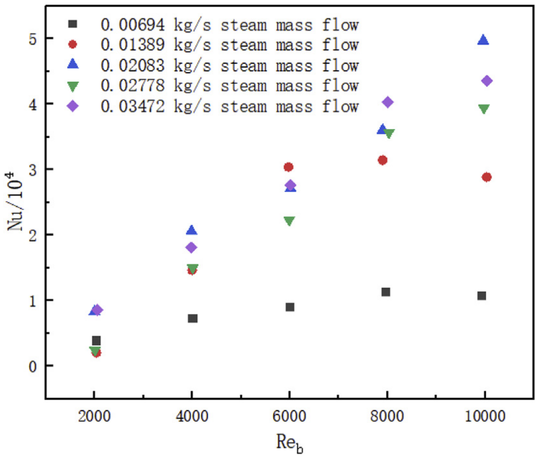


Fig. 8. Safe injection direct contact condensation heat transfer relationship curve.

4. RELAP5 calculation

4.1. Model building

According to the geometric parameters of the ECC thermal mixing experimental section, the simulation calculation was carried out by using RELAP5. The RELAP5 node diagram is shown in Fig. 9.

In Fig. 9, 100 is a Time-Dependent Volume Component for a given inlet temperature and pressure boundary of the main pipe; 105 is a Time-Dependent Junction Component for a given entrance flow boundary of the main pipe; 110 is a Single-Volume Component which are set up for the fluid being fully developed before mixing; 120 is the thermal mixing area, which is the main part of the simulation calculation; 130 is a Single-Volume Component which is the fully developed section of the outlet fluid after mixing; 140 is a Time-Dependent Volume Component, which is used to give the outlet pressure boundary of the main pipe. 200 is a Time-Dependent Volume Component for a given inlet temperature and pressure boundary of the branch pipe; 205 is a Time-Dependent Junction Component for a given entrance flow boundary of the branch pipe; 210 is a Single-Volume Component, which allows the fluid in the branch pipe to be fully developed before mixing.

Before the calculation, sensitivity analysis of the model is needed to verify the correctness of the model. First, set 120 to Single-Volume Component (1 control volume), and take any working condition to calculate; then set 120 to Branch Component (1 control volume), calculate the same working condition; and then, set 120 as Pipe Components, two and three control volumes are respectively calculated for the same working condition, and last the calculation results are compared.

When the flow rate is 0.0347 kg/s in the main pipe (pure steam) and the flow rate is 0.0278 kg/s in the branch pipe, the calculation results of different component types of 120 are shown in Table 5.

Three conclusions can be obtained from Table 5:

1. When the number of control volumes is the same, the calculation result is independent of the module type;
2. When the component types are the same, the calculation result is independent of the number of control volumes;
3. As shown in Fig. 6, the condensation experiment results under the same working conditions was about 0.006 kg/s, indicating that some components in RELAP5 such as Single-Volume, Branch, and Pipe were significant deficiencies in the condensation calculation. Therefore, the ECCMIX component dedicated to the calculation of condensation was introduced in RELAP5/MOD3.

Overall, in the model shown in Fig. 9, 120 can be calculated by using any type of component and arbitrary number of control volumes, which proves that the modeling method is correct.

4.2. Assessment of branch component

The temperature distribution after mixing is mainly analyzed in the single-phase thermal mixing experiment. As a system analyzing program, RELAP5 can only give one temperature to the same section. Therefore, when comparing the calculation results and experimental results to verify the accuracy of the RELAP5 component, the temperature data of the temperature sections of #3 and #4 are mainly averaged. The temperature of the fluid after mixing is analyzed by comparing with the temperature of the control volume of the corresponding location in RELAP5 model.

120 was set to the Branch component with the flow rate in the main pipe 0.0306 kg/s, the fluid temperature in the main pipe

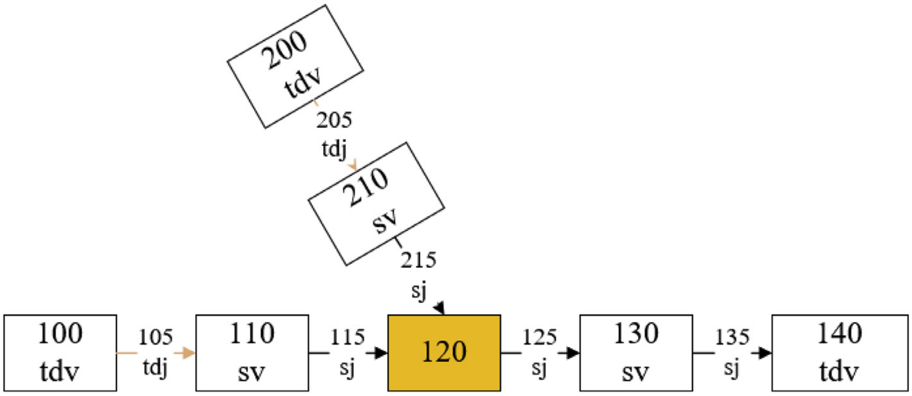


Fig. 9. RELAP5 node diagram of ECC simulation.

Table 5
Model sensitivity analysis results.

Component Type of 120	Number of control volume	Condensation (kg/s)
Single-Volume	1	0.0031
Branch	1	0.0031
Pipe	2	0.0031
Pipe	3	0.0031

347 K, the branch flow rate 0.0278 kg/s, and the temperature change after mixing with the branch pipe fluid temperature was shown in Fig. 10(a). The flow rate in the main pipe was changed to 0.0431 kg/s with the remaining conditions unchanged, and the temperature change after mixing with the temperature of the branch pipe fluid was shown in Fig. 10(b).

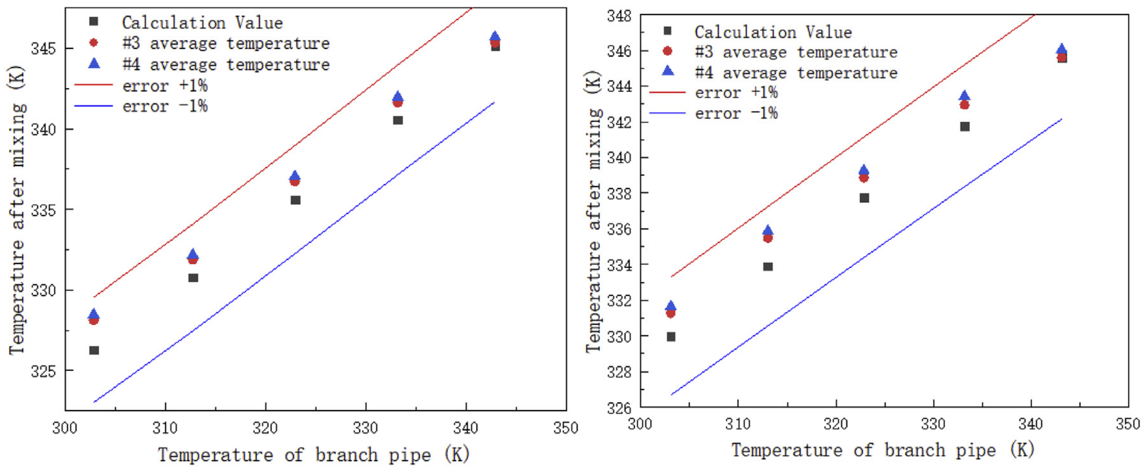
It can be seen from Fig. 10 that the calculation of single-phase thermal mixing by the Branch component is pretty accurate, and the calculated value of the mixed temperature and the experimental value are within ±1%.

The condensation after mixing is mainly analyzed in the two-phase thermal mixing experiment. 50 sets of working conditions were simulated by the RELAP5 code, and the steam flow rate range in the main pipe was 0.00694–0.0347 kg/s, the liquid flow rate range in the main pipe was 0–0.139 kg/s, the supercooled water flow rate range in the branch pipe was 0.0278–0.139 kg/s, and the fluid temperature in the main pipe was the saturation temperature under the atmospheric pressure, the fluid temperature in the branch pipe was normal temperature.

The comparison between the calculated value of the condensation and the experimental value is shown in Figs. 11 and 12. Fig. 11 is a comparison chart of experimental and calculated values of 50 sets of working conditions, and Fig. 12 is an error analysis diagram of experimental and calculated values.

It can be seen from Fig. 11 that the calculated values of most working conditions are not in good agreement with the experimental values, and the half calculation errors are outside the ±30% error lines. It can be further seen from the error distribution of Fig. 13 that the calculated value is smaller than the experimental value as a whole, and the absolute value of the error reaches a maximum of about 80%. This is similar to the calculation results of Ren Wuyue [20,21], which proves that the Branch component has the problem of inaccurate calculation when calculating the two-phase thermal mixing.

Through the modeling calculation of the Branch component and comparison with the experimental values, the Branch component in RELAP5 has good applicability in calculating single-phase thermal mixing, but the error is large and most calculation values are smaller than experimental values when calculating the two-phase



(a) 0.0306 kg/s in the main pipe

(b) 0.0431 kg/s in the main pipe

Fig. 10. Effect of branch pipe temperature on temperature after mixing. (Single phase in Branch component).

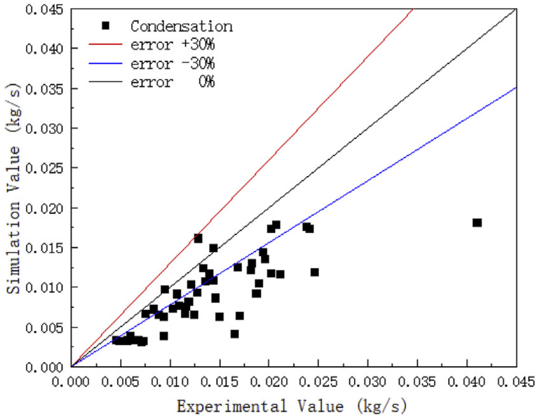


Fig. 11. Two-phase thermal mixing condensation.(Two phase in Branch component).

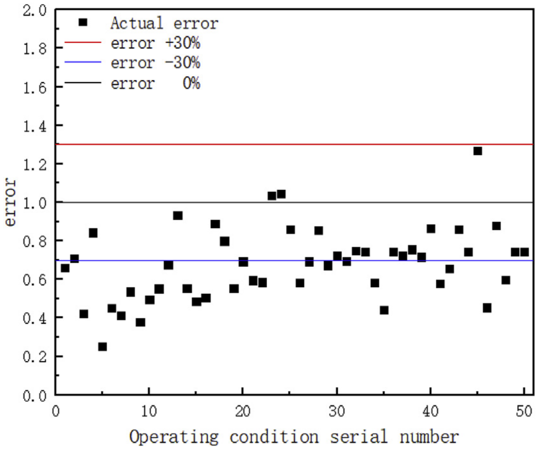


Fig. 12. Error distribution.(Two phase in Branch component).

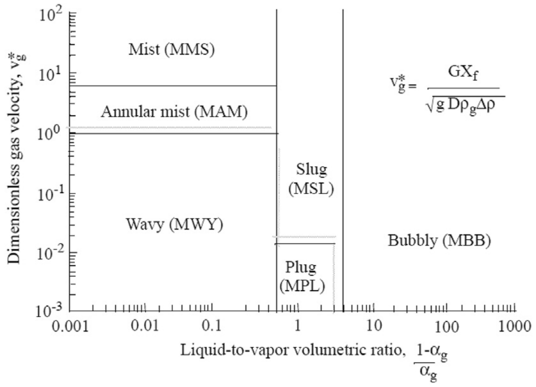


Fig. 13. Schematic of ECCMIX component flow regime map.

thermal mixing. To further accurately calculate the condensation in the two-phase thermal mixing, the ECCMIX component was introduced specifically for the two-phase thermal mixing condensation calculation in the new version of RELAP5.

4.3. Assessment of ECCMIX component

Prior to the introduction of the ECCMIX component, RELAP5 included three flow regime maps, which would not apply specifically to the condensation process in a horizontal pipe near the ECC injection point. Tandon et al. [2] reported a flow regime map for condensation inside horizontal tubes, which was considered a more suitable basis for the interfacial heat transfer calculation in condensation for this geometry. And the flow regime map was shown as Fig. 13. It could be seen that there were six basic flow patterns, which were wavy flow, plug flow, slug flow, bubbly flow, annular/annular-mist flow and dispersed droplet flow. For each flow pattern above, there were different correlations to calculate the interfacial area and heat transfer coefficient. Due to space limitations, calculation correlations under each flow pattern were not described in detail.

120 was set as the ECCMIX component, and the same single-phase thermal mixing working condition was calculated. The temperature changes after mixing with the temperature of the branch pipe fluid was shown in Fig. 14.

Comparing Figs. 14 and 10, it can be seen that for single-phase thermal mixing, the calculation results using the Branch component and the ECCMIX component are the same. This result indicates that the ECCMIX component in the RELAP5 code is deal as the Branch component when there is no two-phase thermal mixing, which is consistent with the statement in Relap5/MOD3 code manual [22].

120 was set as the ECCMIX component and the same two-phase thermal mixing condition was calculated. The comparison between the calculated value of the condensation after mixing and the experimental value is shown in Figs. 15 and 16.

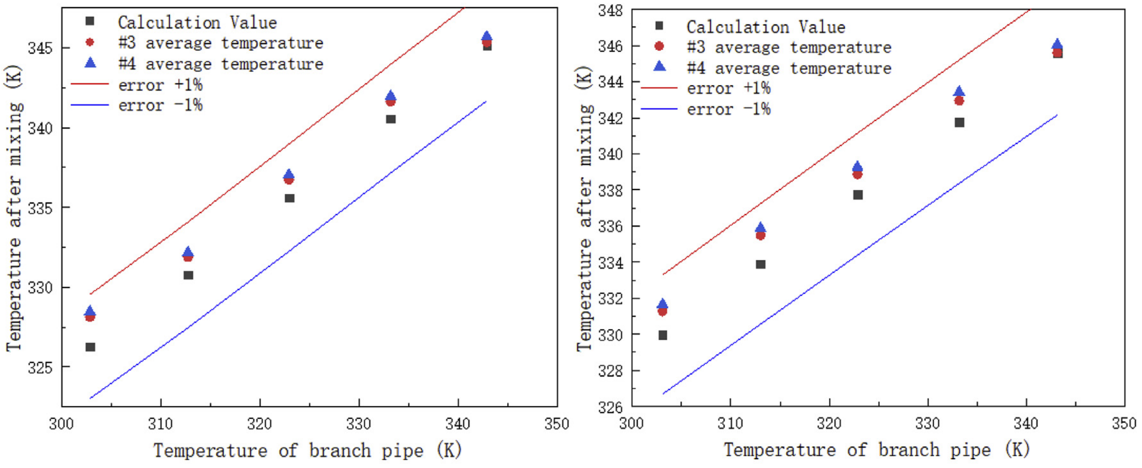
It can be seen from Fig. 15 that the calculated values of most working conditions are in good agreement with the experimental values, and the overall error is within 30%. It can be further seen from the error distribution of Fig. 16 that there is no tendency for the overall value to be larger or smaller than the experimental value, and the absolute value of the error is about 50%, which is more in line with the experimental data than the calculation result of the calculation with Branch component.

Although the calculation of the two-phase thermal mixing condensation is more accurate than the Branch component of the ECCMIX component, there is also a problem that it is difficult to converge. When the ECCMIX component is used to calculate the two-phase thermal mixing condensation, it is necessary to strictly pay attention to the setting of the geometric parameters and the initial thermal parameters, otherwise the calculation is not easy to converge.

5. Conclusions

The temperature field data of the single-phase thermal mixing experiment and the condensation data of the two-phase thermal mixing experiment were obtained. And based on this data, the RELAP5 code was used for modeling calculation, and the original Branch component and the newly introduced ECCMIX component in RELAP5 were evaluated. The main conclusions are as follows.

1. In the single-phase thermal mixing experiment, the correspondence between the MR number and the jet flow pattern suitable for the experimental conditions was obtained: impinging jet when MR < 0.5; deflecting jet with 0.5 < MR < 3.0; and upper wall attached jet with MR > 3.0.
2. Two important factors affecting the two-phase thermal mixing condensation were the steam flow rate in the main pipe and the injection flow rate in the branch pipe. The influence of the liquid flow rate in the main pipe on the condensation under the same steam flow rate could be neglected.
3. In the two-phase thermal mixing, the condensation and the subcooled water flow rate in the branch pipe was proportional,



(a) 0.0306 kg/s in the main pipe

(b) 0.0431 kg/s in the main pipe

Fig. 14. Effect of branch pipe temperature on temperature after mixing. (Single phase in ECCMIX component).

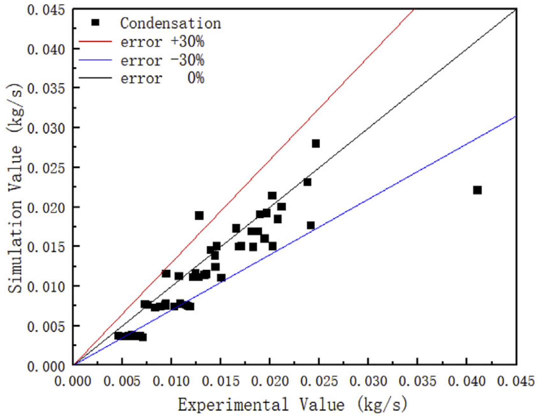


Fig. 15. Two-phase thermal mixing condensation.(Two phase in ECCMIX component).

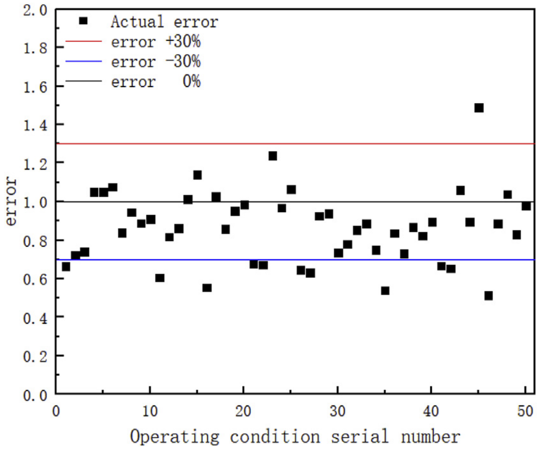


Fig. 16. Error distribution.(Two phase in ECCMIX component).

but when the flow rate of the subcooled water reached a certain critical value, the condensation gradually became stable.

4. The calculation capacity of the Branch component was the same as that of the ECCMIX component when calculating the single-phase thermal mixing with RELAP5 code, and the error between the calculated and experimental value was less than 1%.
5. When calculating the two-phase heat mixing with RELAP5, the calculation efficiency of the Branch component was poor, and the overall result was smaller than the experimental value. Meanwhile the ECCMIX component had a better applicability to this situation, and the calculated value was within the experimental value of 30% error band. And the distribution of positive and negative errors is more uniform than the Branch component.
6. Though the ECCMIX component had higher calculation accuracy, it was more difficult to converge than the Branch component in calculation, and more accurate geometric parameters and initial thermal parameters were needed.

Idaho National Engineering Laboratory (INEL) explained that the ECCMIX component had not been verified by a large amount of experimental data, and it should be used with caution. However, through the work of this paper, it was found that the ECCMIX component was more applicable than the Branch component for the two-phase thermal mixing condensation calculation, which provided the basis for model validation for future simulation calculations of RELAP5.

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Abbreviations

LOCA	Loss of Coolant Accident
ECC	Emergency Core Cooling
PWR	Pressurized Water Reactor
SBLOCA	Small Break Loss of Coolant Accident
LBLOCA	Large Break Loss of Coolant Accident
LPSI	Low Pressure Safety Injection
INEL	Idaho National Engineering Laboratory
LOFT	Loss of Fluid Test
LWR	Light Water Reactor

Nomenclature and Units

Q	total heat transfer, W
h	heat transfer coefficient, $w/(m^2 \cdot k)$
A	heat transfer area, m^2
ΔT	temperature difference, k
Nu	Nusselt number
D	diameter, m
k	thermal conductivity of the subcooled water, $w/(m \cdot k)$
Re	Reynolds number
W	mass flow, kg/s
μ	dynamic viscosity of the subcooled water, $N \cdot s/m^2$
ρ	density, kg/m^3
V	flow velocity, 11

Subscripts

cond	condensation
i	interface between vapor phase and liquid phase
g	vapor phase
f	liquid phase
m	main pipe
b	branch pipe

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