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Investigation of quenching phenomena during the relooding phase against the FLECHT-SEASET experiment by using RELAP5/MOD3.3

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Abstract: The reflood model of RELAP5/MOD3.3 (patch 4) was assessed by using the FLECHT-SEASET tests. The tests were conducted to have a better understanding of the postulated loss of coolant accident in a light water reactor (LWR). The best-estimate system analysis code was used to simulate these accident scenarios, especially in Design Basic Accident such as Loss-Of-Coolant-Accident (LOCA). The primary purpose of this report was to assess the accuracy of a computer system analysis code by using RELAP5/MOD3.3 in comparison to actual test results taken from the FLECHT-SEASET tests in which the reflood model was built in. In RELAP5's simulation cases, the various boundary and initial conditions, such as power supplied and reflooding rate were selected. As a result, the RELAP5 looked to be accurate in predicting the quenching time and rod surface temperature for this particular case. However, the RELAP5 code under-estimated the rod surface temperature in comparing with the experimental data of the FLECHT-SEASET tests. Accordingly, for this high flooding rate and particular reactor power level that the reflooding model in RELAP5 could be possible used for predicting the reflooding phenomena during the LOCA accident.

Keywords: *RELAP5, reflooding, FLECHT-SEASET, light water reactor.*

I. INTRODUCTION

In an effort to better understand some of the thermal-hydraulics within nuclear reactors, FLECHT SEASET tests were conducted back in the early 1980's in which a pressurized water reactor was put through various loss of coolant accidents and then flooded with emergency coolant. These accidents differed from each other by various flooding rates and peak reactor power levels. The main goal of these tests was to observe how various flooding rates and power levels effect temperature changes within the reactor and the time at which the reactor has reached a safe temperature.

As we begin to go deeper into the technology age, more advanced computational programs are coming into existence. These programs can allow engineers to model reactor accidents without performing these tests on actual reactors. The RELAP5 is one of the best-estimate code which was widely used within the nuclear industry. This computer code can model all the systems within a reactor and have been proven to be effective tools. One of the important phenomena of light water reactor is loss of coolant accident (LOCA) in which the reflooding phase is occurred. In order to apply the system code for whole system of nuclear reactor, the RELAP5 need at first to be verified

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with this phenomenon by comparing with experimental data, called Separate Effect Test (SET) [1, 2, 3]. Chung, B.D. et al. [4] has found the weakness the reflooding model in the RELAP5/MOD3.1 by lacking of quenching temperature model and the shortcoming of Chen transition boiling model. Koszela [5] has used the interim version (RELAP5/MOD3.2.2 Gamma) to verify the reflooding model and he found that the quench times were significantly too short due to the over prediction of the heat transfer coefficients for post-critical heat flux flow regimes. Therefore, Choi et al. [6] has used the RELAP5/MOD3.3 (patch 3) to verify that model and found that the quenching times were still unsatisfactory. This group has proposed the film boiling wall-to-fluid heat transfer needed to divide into three different sub-regimes. Therefore, in this report, the RELAP5/MOD3.3.3 (patch 4) was applied to verify the reflooding model with some available FLECHT-SEASET experimental data by changing of reflooding rate.

II. FLECHT-SEASET MODELLING USING RELAP5

The reflooding phase occurred as a sequence of phenomena during the LOCA accident such as Blowdown, Refill and Reflooding. For the reflooding phase, when lower plenum was filled, the reflood started with the fuel element being rewetted from the bottom upwards. As the fuel element was already rewetted, the thermal-hydraulic phenomena were complicated such as steam forming and the entrainment of liquid droplets flow before the rewetting front and going to the upper plenum. Therefore, various experiment [1, 2, 3] tests have been built up to understand these phenomena and also obtain the experimental data for validation and verification of thermal-hydraulic computer code, including the best-estimate system code such as RELAP5/MOD3.

A. Reflooding Phenomena

Reflooding phenomena occur in the loss of coolant accident (LOA) after the core has been uncovered and then emergency core cooling system inject water to refill the core. When the water level of the core increases, water will contact with hot fuel rod and steam formed. However, the fuel rods were not cooled down uniformly then many of heat transfer regimes exists in reflooding phase as presented in the Fig.1**Fig.** . Fig.2 depicted the different in heat transfer and hydraulic flow regimes in reflooding phase between low and high flooding rate [1]. Thus, the thermal-hydraulic behavior was investigated by focusing the changing of reflooding model (coolant injection).

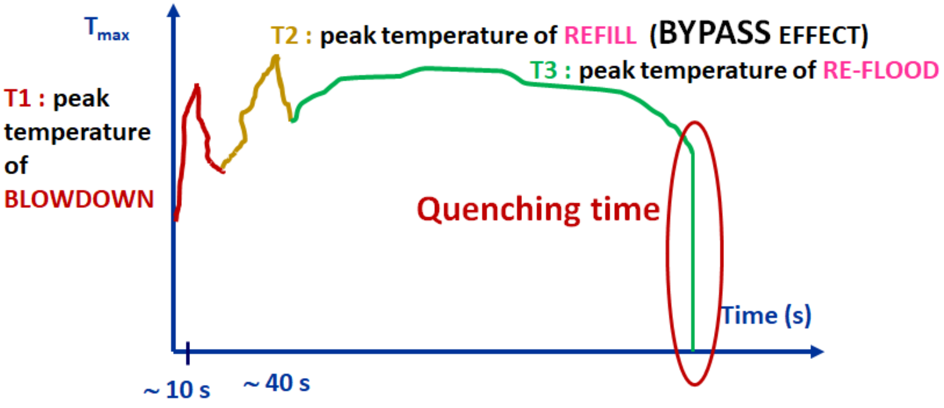


Fig. 1. The LOCA transient in PWR type

B. FLECHT-SEASET Tests

FLECHT-SEASET was forced reflood test facility. It used electrically heated rod to simulated a full-length Westinghouse 17 x 17 rod bundle. The main component of FLECHT-SEASET was a test section which consisted lower and upper plenum connected to a cylindrical with diameter 3.89 m. The initial average power of FLECHT-SEASET was 2.3 kW/m [6]. The test conditions were based on the reference assumptions applicable for the reflood transient of a hypothetical large break LOCA (LBLOCA) of a PWR type. These assumptions were as follows:

- The core hot assembly was simulated in term of peak power (kW/m) and initial temperature at the time of bottom of core recovery (BOCREC);
- The initial rod cladding temperature depended primarily on the full-power linear heating rate at the time of core recovery. For the period from 30 seconds after the initiation of a hypothetical LBLOCA to core recovery, typical results from a worst analysis yielded an initial cladding temperature in the hot assembly of 871 °C.
- Coolant temperature was selected to maintain a constant subcooling to facilitate the determination of parametric effects.
- Coolant was injected directly into the test section from the lower plenum for the forced flooding rate tests.
- Upper plenum pressure at the end of blowdown was approximately 0.14 MPa for an ice condenser plant, and about 0.28 MPa for a dry containment plant. The upper plenum pressure was extended for 0.42 MPa for parametric effect.

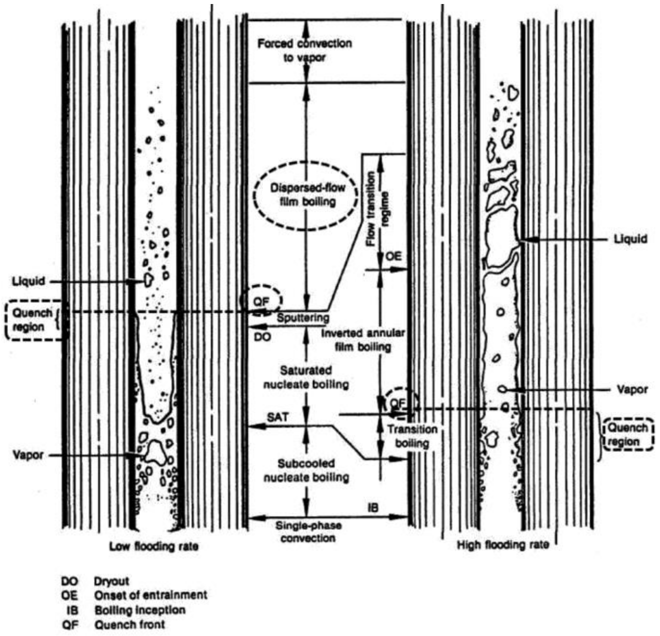


Fig. 2. Heat transfer and hydraulic flow regimes in reflooding phase [1]

The Fig.3 showed the axial power profile for FLECHT-SEASET tests. The power step size is 183mm for the elevation between 610 mm and 3048 mm. The profile was based on a center peaked cosine shape. The test section, carryover vessel, and exhaust line components were pressurized to the desired system pressure. The coolant in the accumulator was pressurized to 2.76 MPa. Water then was injected into the lower plenum until it reaches the beginning of the heated length of the bundle heater rods. Coolant was circulated and drained to ensure that the water in the lower plenum and injection line was at the specified temperature before the run.

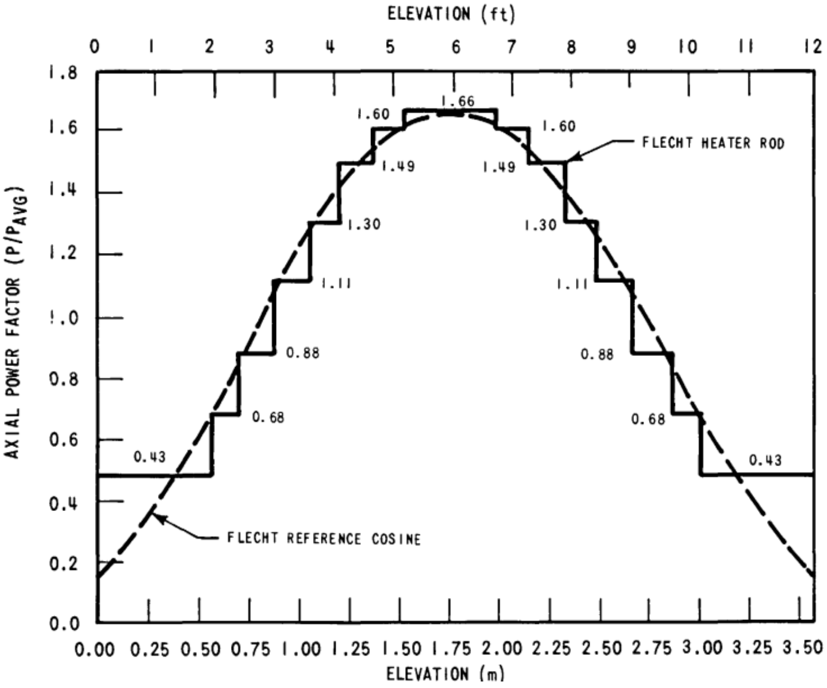


Fig. 3. Cosine axial power profile [3]

Table I. FLECHT-SEASET's experimental data selected for verification of RELAP5/MOD3.3 (patch 4)

Test No.	Upper Plenum pressure (MPa)	Reflood flow velocity (mm/sec)	Coolant temperature (^{o}C)
31805	0.28	21	51
31504	0.28	24.6	51
31701	0.28	155	53

Table I presented some main FLECHT-SEASET tests for reflooding in our study.

Test 31504 was designed with reflood rate of 2.46 cm/s at 0.28 MPa. Inlet liquid temperature was 324 K (50 °C). The test 31504 have had very similar initial and boundary conditions to those of Test 31805 but the flooding rate was slightly higher than test 31805, but much lower than test 31701 (15.5 cm/s). By using big different of boundary condition of these tests, the reflooding model in RELAP5 were verified.

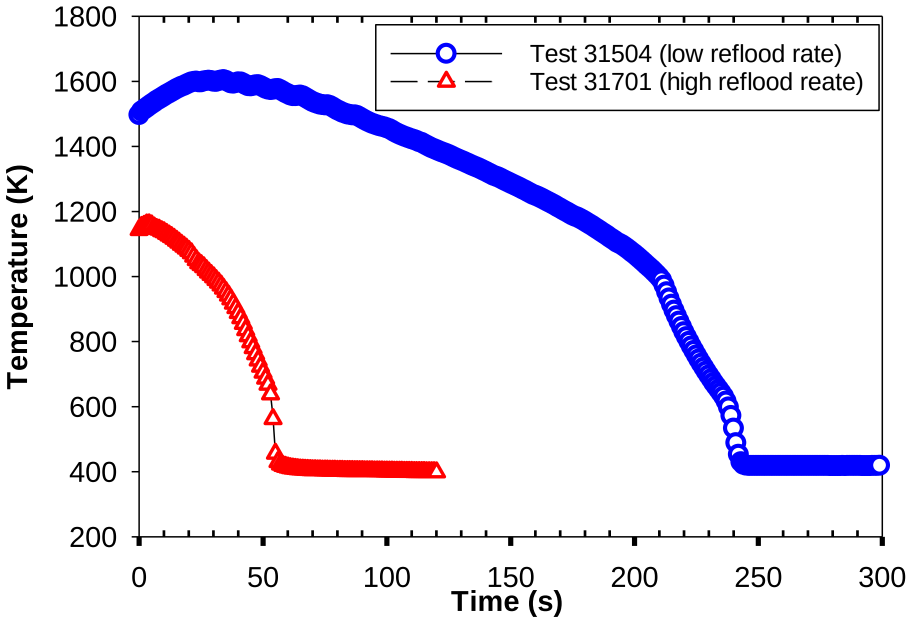


Fig. 4. The experimental data of rewetting phenomena between high and low reflooding rate

The fig. 4 showed the typical rewetting phenomena in the rod bundle between low and high reflooding rate. It was clear that if the heater was cooled with higher rate, the rewetting rod or quenching time may have occurred earlier in case of test 31701.

C. Modelling the FLECTH-SEASET by RELAP5/MOD3.3

The main feature of the RELAP5/MOD3.3 input deck for the assessment of FLECHT-SEASET tests:

- The lower plenum was modeled as a time-dependent volume for the source of water injection (water temperature at test value).

- The injection of subcooled water was modeled as a time-dependent junction with a constant liquid velocity specified for each test.

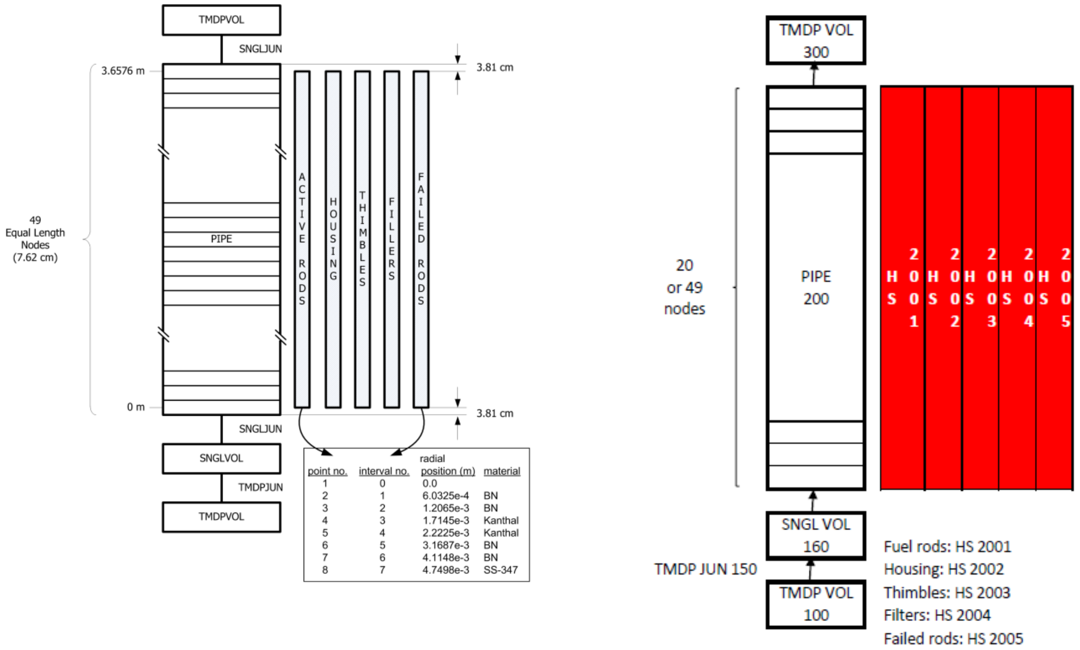
- The upper plenum was modeled as a time-dependent volume with a constant pressure at the specified temperature.

- The 336 cm heated test section was nodalized into 49 equally spaced nodes, each 0.0762 m long.

- The heater rods were represented by a heat structure geometry of 49 heat structure and bundle option were applied.

- The grid spacer enhancement factors based on the FLECHT-SEASET grid spacer were applied to all heat structure.

Fig. 5 showed the nodalization diagrams of the heated test section using 49 volumes. Only the components required to model the thermal-hydraulic behavior of the forced reflood test were simulated in the input model.



point no.	interval no.	radial position (m)	material
1	0	0.0	
2	1	6.0325e-4	BN
3	2	1.2065e-3	BN
4	3	1.7145e-3	Kanthal
5	4	2.2225e-3	Kanthal
6	5	3.1687e-3	BN
7	6	4.1148e-3	BN
8	7	4.7498e-3	SS-347

Fig. 5. The modelling of FLECHT-SEASET and nodalization of RELAP5/MOD3.3 [3]

III. SIMULATION RESULTS

The time-step investigation was carried out using FLECHT-SEASET TEST 31504. The rod surface temperature at the 2.006 m elevation with different time-step sized were shown in the Fig. 6. The results showed that in the early reflood period, when the heat transfer mode was essentially dispersed film boiling, there were no significant variations in rod surface temperature with respect to time step size. In the rapid cooling and quenching period, small temperature variation was seen.

By conducting the calculation using RELAP5/MOD3.3, Fig. 6 showed that time step has less effect on calculation. However, the results of cladding temperature show that the calculation of RELAP5/MOD3.3 was under-estimated comparing with experimental data (Fig. 7). However, the quenching time (wall wettability) was well predicted at the elevation of 2.006 m.

The Fig. 7 showed the RELAP5/MOD3.3 calculated the surface temperature at specified elevation (2.006 m) and the comparison with the measured temperature. The calculated rod surface temperature during the temperature rise portion of the test compared well with the measured data. One of the most important data which was the quenching time or rewetting time was well predicted. However, the simulated rod surface temperature was lower than calculation model even the trend of temperature transient over the time was well predicted. The simulated result from our study shown that the code was not well predicting the rod surface temperature. Therefore, the further study for the reflooding model in RELAP5/MOD3.3 need to be investigated.

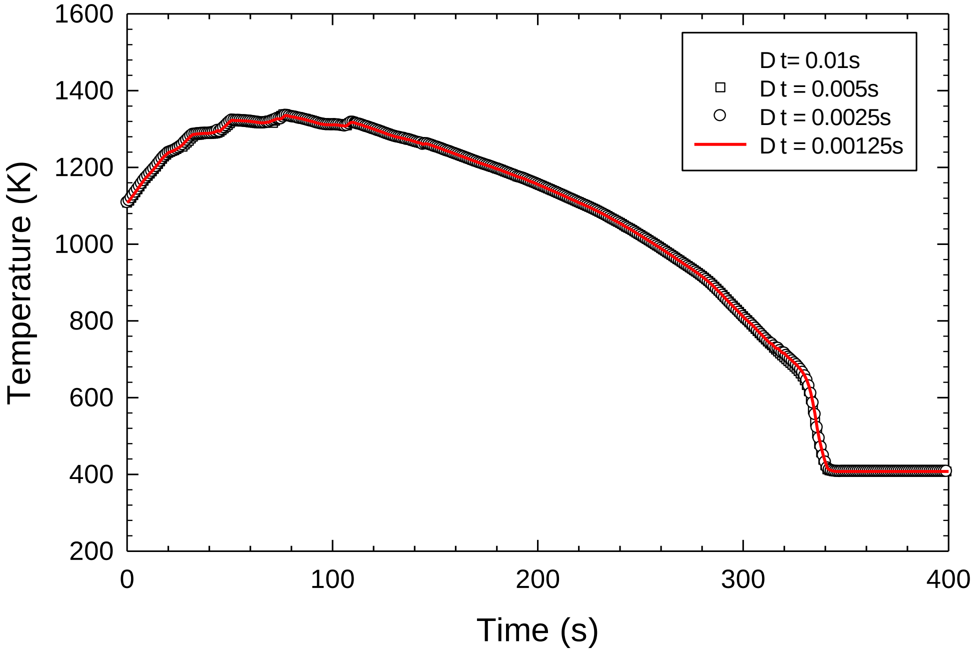


Fig. 6. Time-step size investigation for the rod surface temperature for Test 31504 at 2.006 m

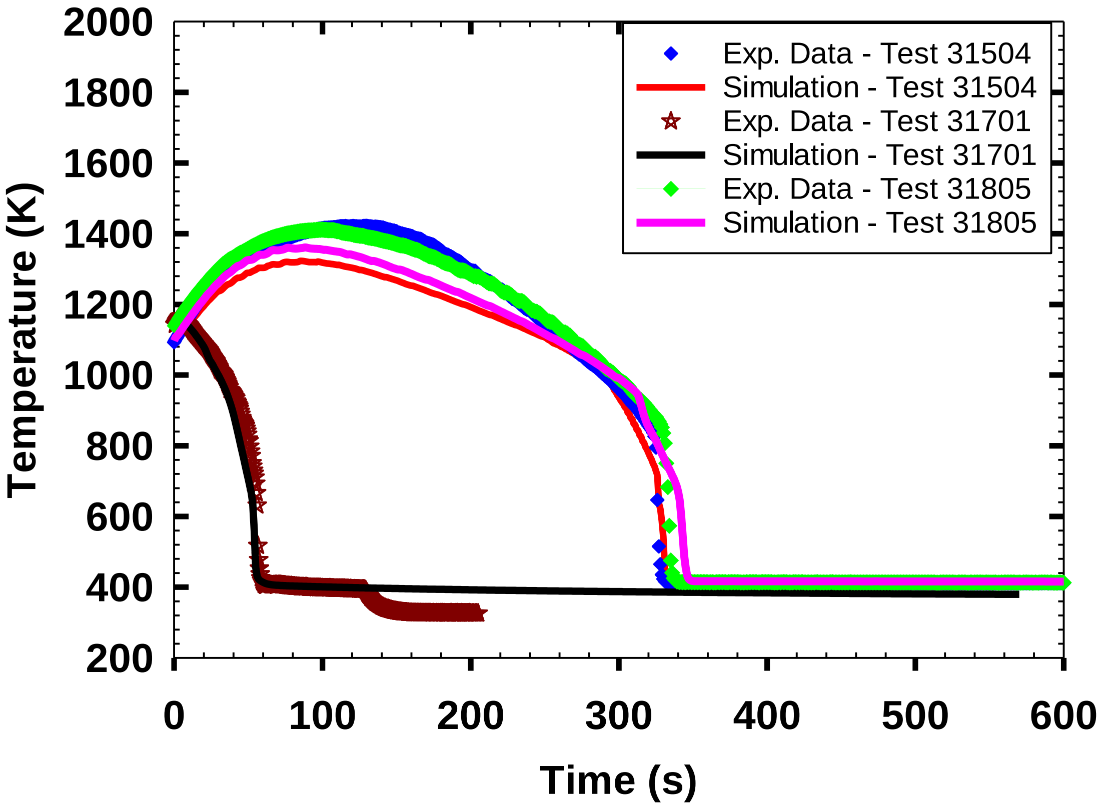
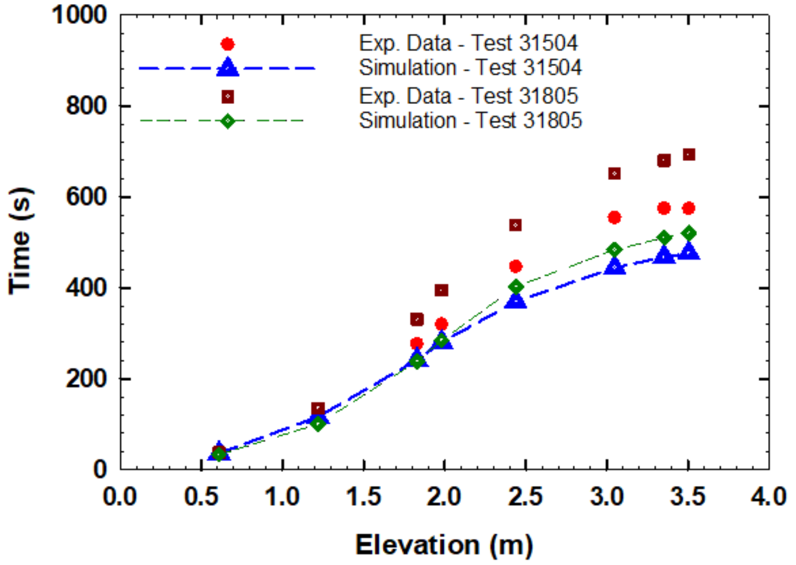
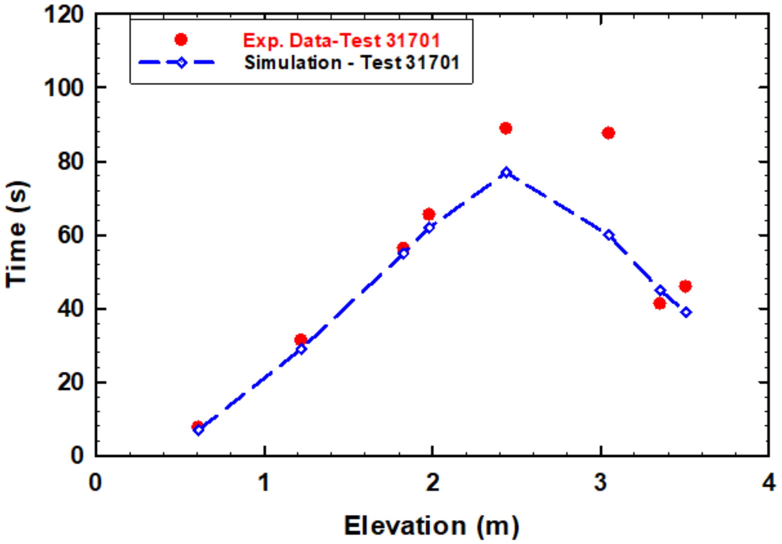


Fig. 7. Comparison between simulation and experimental data of the rod surface temperature: Test 31504 and Test 31805 and 31701



(a)



(b)

Fig. 8. Comparison of quenching time along the rod between:
(a) low reflooding rate and (b) high reflooding rate

The quenching time as a function of elevation in the test assembly was shown in Fig. 8. In the high reflooding rate, the quenching time shown good agreement from the lower and upper region of the rod. However, at low reflooding rate the quenching time was well predicted by RELAP5 and lower part of the rod. In high elevation, the complicated thermal-hydraulic phenomena existed by interaction of heat transfer from rod to gas, liquid and droplet. In current version of RELAP5/MOD3.3 (patch 4), the heat transfer coefficient in the Dispersed Flow Film Boiling (DFFB) region was divided into heat transfer from wall to gas and from wall to liquid in which a Dittus-Boelter model for the pipe multiplied by the void fraction [7,8]. Therefore, the effect of droplet entrainment, interfacial drag and its models for three phases (liquid, gas and droplet) need to be considered for modification [6].

The calculated water mass accumulation was generally less than measured (Fig. 9). Most of the mass accumulation reached the high-power mid-plane region of the test bundle, the water accumulation became a balance of injected water entering compared to entrained and evaporated water leaving. In that case that captured the time of power termination and the water accumulation suddenly increased in both the measurements and calculation. The water quickly accumulated in the test section as evaporation and entrainment. The RELAP5 has similarly simulated this behavior.

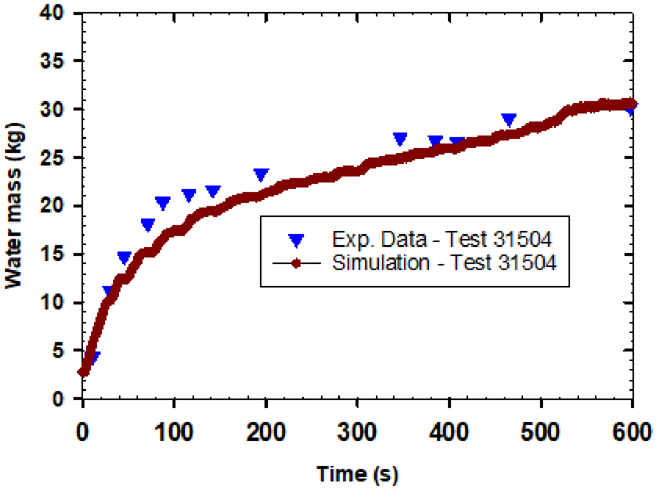


Fig. 9. Comparison of the water mass inventory for Test 31504

IV. CONCLUSIONS

A model for prediction the reflooding phenomena during the loss of coolant accident of light water reactor was performed using the RELAP5/MOD3.3 (patch 4). The simulation by using RELAP5 was investigated by comparison with experimental data for the specific tests with low and high reflooding rate using FLETCH-SEASET tests. The lower one intended to be investigated in which the low rate for injection of water to the hot channel may cause the more dangerous situation for fuel cladding. Therefore, two tests (31504, 31805) consisted low reflood rate were intensively investigated and the high reflooding rate was 31701 tests.

As a result, in both cases, the RELAP5/MOD3.3 has calculated the rod surface temperature in good agreement for the complete transient. However, the quenching time at high elevation (above 2.006 m) had under-estimation. Therefore, in order to fully verify the reflood model implemented in the RELAP5 code, in the future work, the detail reflooding model in which the effect of droplet entrainment, interfacial drag and its models for three phases (liquid, gas and droplet) need to be investigated. Other method could be conducted by applying the uncertainty method. By doing this work, the full assess of FLETCH-SEASET's experimental data would be crucial.

ACKNOWLEDGEMENT

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