Proceedings of the Korean Nuclear Society Spring Meeting
Pohang, Korea, May 1999

RELAP5 Simulation of the Small Inlet Header Break Test B8604 Conducted in the RD-14 Test Facility

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Abstract

A small inlet header break experiment in the RD-14 test facility was simulated with RELAP5/MOD3 code. The RELAP5 has been developed for best-estimate transient simulation of pressurized water reactors and associated systems, but it has not been assessed for a CANDU reactor. Therefore, this study has been initiated with an aim to identify the code applicability in CANDU reactors. The RELAP5 results were compared with experimental data and those of CATHENA performed by AECL. The RELAP5 analyses demonstrate the code's capability to predict, with sufficient accuracy, the main phenomena occurring in the transient, both qualitative and quantitative view. However, some discrepancies in the depressurization of the primary heat transport system after the break and the consequent time delay of the major phenomena were observed.

I. Introduction

A small inlet header break test (B8604) [1] conducted in the RD-14 test facility [2,3] was simulated with RELAP5/MOD3 code. The RELAP5 code has been developed for best-estimate transient simulation of pressurized water reactors (PWRs) and associated systems, but it has not been assessed for CANDU reactors. Therefore this study has been initiated with an aim to identify the code capability in the CANDU reactors. A previous work performed by S. Lee et. al.[4] shows that the RELAP5 could be applicable to assess the transients and accidents in the CANDU reactors. However it is indicated that there are some works to be resolved, such as modeling of headers and multi channel simulation for the reactor core, etc.

The calculation results were compared with the experimental data and those of the CATHENA[5] performed by AECL. CATHENA code was developed by Atomic Energy of Canada Limited (AECL) primarily for the analysis of postulated loss of coolant accident events in CANDU Reactors. CATHENA uses a full two-fluid representation of two-phase flow in piping networks.

II. RD-14 Test Facility

The RD-14 test facility is a full-scale pressurized-water loop. The RD-14 is not a "scale" model of any particular CANDU reactor. Rather, it possesses many geometric features of a CANDU reactor heat transport system, and is capable of operating at conditions similar to those expected to occur in a reactor under normal operation and some postulated accident conditions. The facility is designed to produce the same fluid mass flux, transit time, pressure and enthalpy distributions in the primary system as those in a typical CANDU reactor under forced circulation conditions. The most important parameters of RD-14 are compared with those of a typical CANDU reactor in Table 1.

A detailed description of the RD-14 facility is given in References 2 and 3. The RD-14 heat generation system consists of two full-scale (6m long), full-power (maximum of 5.5MW) horizontal channels, representing reactor fuel channels. Each channel contains 37 electrically heated fuel element simulators, which have uniform heat flux distribution and almost the same heat capacity as reactor fuel. End-fitting simulators are provided to connect each channel with the rest of the primary system.

III. Test Procedure and CATHENA Results

1. Test Procedure

Test B8604 [1] was a blowdown test with ECI (Emergency Coolant Injection) available to all four headers. Primary pump storage was initiated at the same time as the power was tripped. After the pumps were stopped, ECI water was initiated at headers 3 and 4. Although some heater temperatures as high as 400 °C were recorded between 150 and 200 s, they were soon quenched, and adequate cooling was maintained for the remainder of the injection period.

The primary circuit pressure dropped rapidly after initiation of the break at 10 s, reaching 8.9 MPa at the outlet headers by 30 s and starting both the heated section power and pump speed reduction ramps. By 50 s the primary pressure reached 5.5 MPa initiating high pressure ECI to headers 1 and 3. Void briefly formed at the outlet of both heated section due to the falling pressure but collapsed later as the power was reduced and ECI began. By 80 s ECI flow to header 1 stopped and all ECI flow was directed to header 3. At 140 s the primary pumps stopped and the sections as a result of the reduced primary flow temporarily raised the primary pressure stopping the flow of ECI. During this time upper FES elements in both heated sections became uncovered (stratified flow in channel) and began to heatup. Void generated in the channels eventually reached the outlet feeders and a small positive thermosiphoning flow was established. As void was pushed out of the heated sections (quenching hot upper FES elements) and condensed in the steam generators, the primary pressure fell, which allowed ECI at headers 3 and 4 to resume. A period of stable thermosiphoning persisted until about 880 s when ECI stopped due to depletion water in the high pressure tank. Shortly after this time thermosiphoning stopped, the heated section upper FES become uncovered and began to heatup. The experiment was finally terminated at 1160 s by a high temperature trip (sheath temperature above 600 °C) in heated section 2.

2. Test Condition

Primary System : Outlet Header Pressure - 10 Mpa
Input Power - 5.0 Mw per heated section
Flowrate - 27 L/s
Secondary System : Steam Drum Pressure - 4.5 Mpa
Feed Water Temperature - 187 °C
ECI : Accumulator Tank Pressure at 5.5 Mpa
Break : 7.0 mm diameter, located at inlet header 4

3. CATHENA Analysis Results

CATHENA simulation showed good agreement with the experimental observations until the primary flows stopped at about 140 s after primary pump rundown. During this the primary pressure and therefore the onset of ECI was accurately estimated. Generally, ECI flows were correctly directed to headers 1 and 3 although some small flows were incorrectly predicted to occur at headers 2 and 4 for brief periods of time. After 140 s CATHENA simulation predicted that a thermosiphoning flow established in the negative direction, not the positive direction as observed in the experiment. This error in flow direction caused significant differences in some of the plotted parameters. ECI flow distribution after the primary pumps stopped was also not well predicted. The primary pressure was well predicted until depletion of the ECI tank occurred. After that time, there is evidence that the ECI system was not isolated from the primary loop and nitrogen gas was injected into the primary loop. The event was not modelled and resulted in significantly differences between predicted and experimental pressure.

IV. RELAP5/MOD3 Simulation

1. Nodalization

The Nodalization used to simulate the RD-14 test facility contains 204 volumes, 206 junctions for the single channel analysis and 260 volumes, 278 junctions for the multiple channel analysis. System model for RELAP5 calculation is shown in Fig. 1, which is basically same as CATHENA model to eliminate the effect of nodalization. The system model composes of primary heat transport system including heaters and pumps, secondary system, ECI system, accumulator, and break model, etc.

At the time test B8604 was conducted, the sprial-arm separators had not been installed in the steam generators. Instead of recirculating via the external downcomer, the secondary side operated in a “kettle-like” fashion. The secondary side circuit upstream of the steam generators and the secondary side control system were not modelled as idealized in CATHENA. However the steam separators to represent the recirculation within the steam generators was modelled.

2. Base Calculation

1) Pressures

Fig. 2 shows the header 3 pressure history. When the break was opened, there was a sharp pressure decrease until void generation “flashing” began. Pressure decreases more slowly most probably because of void generation in the piping between the heated section outlets and steam generator inlets. The heated section power ramp and the primary pump speed ramp reduced void generation and caused the primary pressure to fall again. RELAP5 simulated a lower rate of pressure decrease than in the experiment between 30 s and 100 s and it may be considered that the lower depressurization rate is due to an underestimate of the boiler heat transfer coefficient or lower break flowrate. The decrease in pressures of the headers resulted in the delay of ECI to the system. However RELAP5 captured the overall transient behavior in general.

A sharp rise in pressure occurred as the primary pressure loop because liquid filled (void collapsed) and primary pressure rose to match the ECI tank pressure at 100 s (80 s in the test). The loop was pressurized by the generation of void in the heated sections since the time of this pressure rise occurred coincident with zero primary flow and with the appearance of void at the heated section outlets at 170 s (130 s in the test). As the primary pump stopped, a thermosiphoning flow was established which caused the pressure to drop and allow ECI into the primary loop. A period of stable pressure remained to the end of the transient.

2) Fluid Flow

The loop volumetric flow at the outlet of test section is shown in the Fig. 3 and Fig. 4 The agreement is generally good except the delays of the sequences due to lower pressure decrease as indicated above. The data indicate that a temporary high volumetric flow occurred at test section 1 outlet at about 140 s, coincident with the formation of a steam bubble at that location. REALP5 predicts this behavior at 220 s.

Figures 5 to 8 show the ECI flows into the four headers. The initial surge of flows between 50 s and 100 s was injected at headers 1 and 3 only, since the continued operation of the pumps during that period kept the pressure in the other two headers above the ECI system pressure. RELAP5 captured this division of flow and reproduced the timing and overall magnitude of the flow during this time well.

Following a period of in which all ECI flows were stopped, injection was resumed to headers 1, 3, and 4 at time ranging from 160 s (header 3) to 200 s (header 1). The resumption of flow of these three headers are reproduced by RELAP5. However, RELAP5 predicted a flow into header 2, which did not occur in the test.

3) Fluid Temperatures

The fluid temperatures at the inlet and outlet of the two test are well predicted throughout the transient.

4) Void Fractions

The void fractions at the inlets and outlets of the test sections are well predicted for the outlets of the heated sections, however predictions at the inlets of the heated sections are poor.

5) Sheath Temperatures

Most of the sheath temperature in both heated sections indicated dryout occurring at some time during the period from 100 s to 300 s. Comparisons are shown in Figures 9 to 12 at the inlet and outlet end of the heated sections. It can be seen that the occurrence of dryout and the resulting temperature excursions are predicted. After 300 s, the code predicts that all sheath temperatures remain close to the coolant temperature. It should be noted that the RELAP5 calculates one-dimensional temperature gradient. This means that it cannot predict the peripheral temperature distribution, resulted from the flow stratification, of an FES with the current RELAP5 model as is to be expected [4]. Therefore, temperatures calculated by the present RELAP5 analysis should be considered as an averaged one. This is a limitation of the RELAP5 in simulating the CANDU reactor. In spite of its limitation, agreement between the RELAP5 and experiment is reasonably good.

3. Sensitivity Studies

1) Break Flow Discharge Coefficients

Increases in the discharge coefficients of single phase, two-phase and mixtures from 1.0 up to 1.5 did not change the pressure decrease in the headers.

2) Break Modeling

A single volume upstream of the break valve and environment were modeled and the results predicted better in the depressurization rate in the headers, however too much cooling in the primary loop was observed and the overall results are not better in general.

V. Conclusion

RELAP5/MOD3 simulations of the small inlet header break in the RD-14 facility has been performed, with an aim to identify the RELAP5 applicability in a CANDU system in comparison, with the experimental results and with the CATHENA simulation. The RELAP5/MOD3 results agreed well with the experimental results. The general conclusions from the present work are as follows:

1. The RELAP5/MOD3 predicted reasonably well thermal-hydraulic behaviors in the small inlet header break tests. However, some discrepancies were observed in the depressurization after the break and consequent time delay of the major phenomena. It may be considered due to an underestimate of the boiler heat transfer coefficient or lower break flowrate.

2. The RELAP5 calculates one-dimensional temperature gradient, therefore, it cannot predict the peripheral temperature distribution, resulted from the flow stratification, of an FES with the current RELAP5 model. Temperatures calculated by the present RELAP5 analysis should be considered as an averaged one. Regardless of its limitation, agreement between the RELAP5 and experiment is reasonably good.

3. Issues identified from the present analyses will examined through the sensitivity study and in particular the model development of the multi-channel analysis will also be performed in the near future.

References

1. J.P. Malloy and G. Sabourin, “CATHENA MOD-3.3g Simulation of RD-14 Experiment B8604,” THB-CD-021, AECL, Sept. 1990.
2. J.P. Malloy, CATHENA idealization- Documentation of the RD-14 Test facility, RC-54-1, AECL, 1988.

3. B.N. Hanna and T.E. MacDonald, CATHENA Idealization Documentation of the RD-14 Test Facility, Secondary Side Charcterization Tests, RC-54-2, AECL, 1988.
4. S. Lee, et.al, “RELAP5 Code Assessment in a CANDU Reactor,” NURETH-8, Kyoto, Japan, October 1997.
5. Hanna, N.N., "CATHENA MOD-3.2n, Theoretical Manual", THB-CD-002, AECL-WL, 1989.

Table I Comparison of Characteristics of RD-14 and CANDU reactor

Parameters	RD-14	Typical Reactor
Operating Pressure (MPa)	10	10
Loop Volume (L)	951.4	57000.
Loop Piping I.D. (m)	.074	Varies
Heated Sections:	37-rod bundles	37-element bundle
Length (m)	6	12 x 0.5
Rod diameter (m)	.0131	.0131
Flow tube diameter (m)	.1034	.1034
Power (kw/channel)	5500.	5410.
Pumps:	single stage	same as RD-14
Impeller diameter (m)	.381	.813
Rated flow (kg/s)	24.	24. (max/channel)
Rated head (m)	224.	215.
Specific speed	565	2000
Steam Generators:	recirculating U-tube	recirculating U-tube
Number of tubes	44	37/channel
Tube diameter I.D. (m)	.01363	.01475
Secondary heat-transfer area (m2)	41	32.9/channel
Heated Section-to-Boiler Top Elevation Difference (m)	21.9	21.9

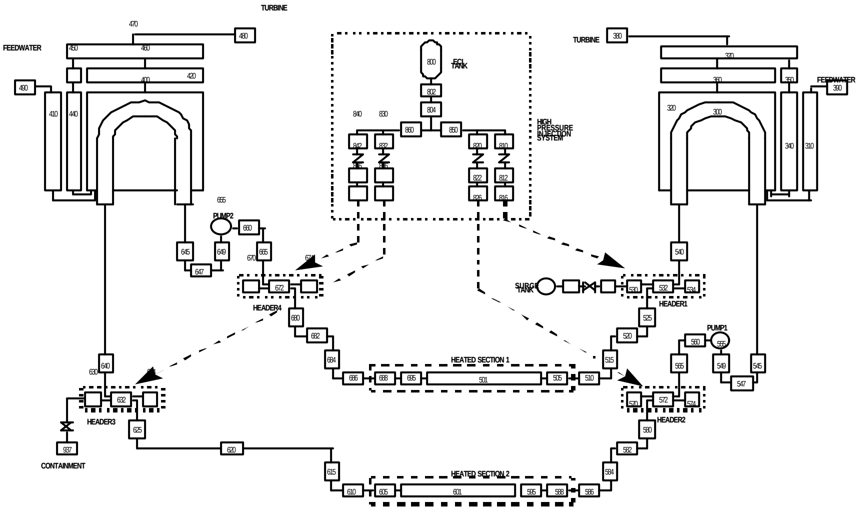

Fig. 1 Nodalization of RD-14 for RELAP 5 Analysis

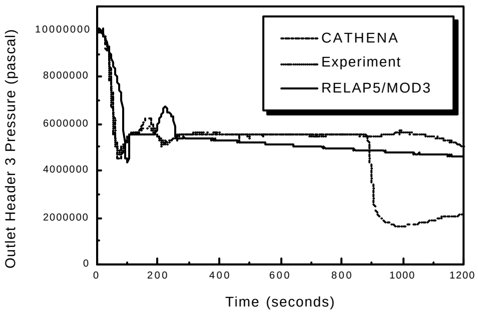

Figure 2 Pressure Profile at Outlet Header 3

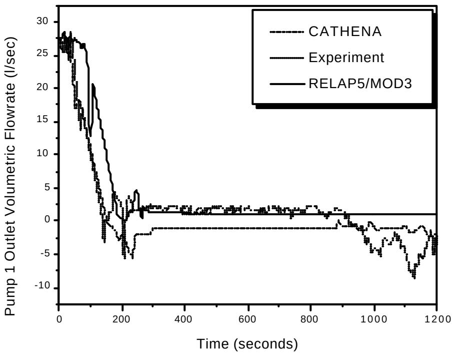

Figure 3 Volumetric Flowrate at Outlet of Test Section

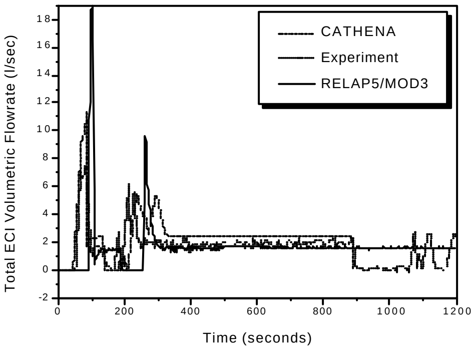

Figure 4 Total ECI Volumetric Flowrate

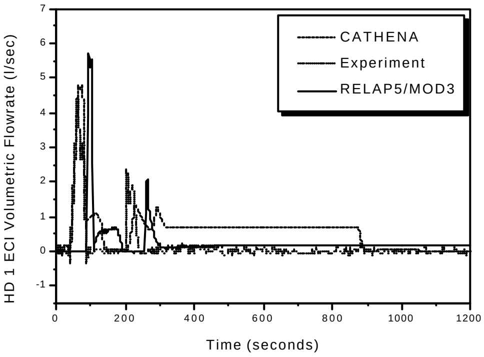

Figure 5 ECI Flowrate into Header 1

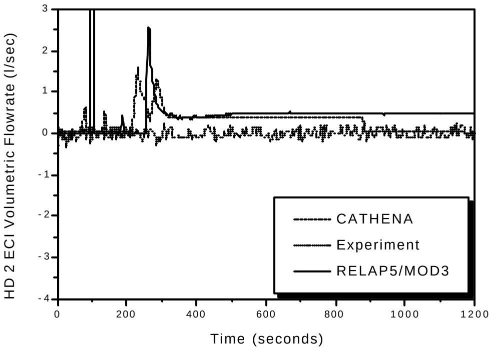

Figure 6 ECI Flowrate into Header 2

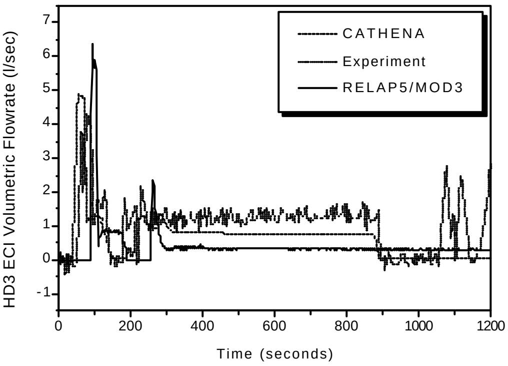

Figure 7 ECI Flowrate into Header 3

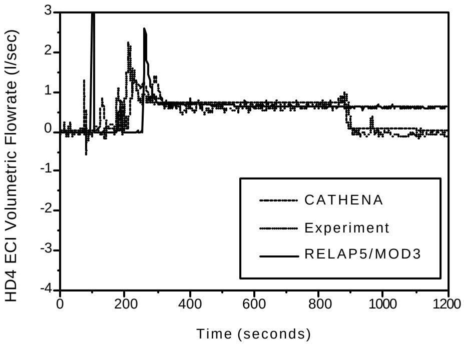

Figure 8 ECI Flowrate into Header 4

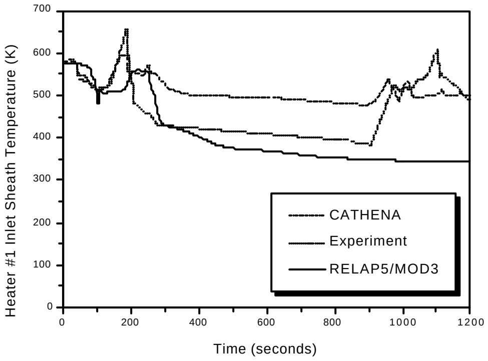

Figure 9 Temperature Profiles at Inlet Sheath of Header 1

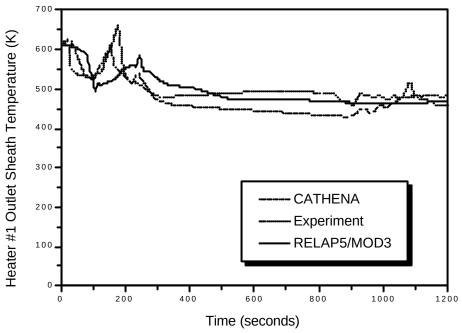

Figure 10 Temperature Profiles at Outlet Sheath of Header 1

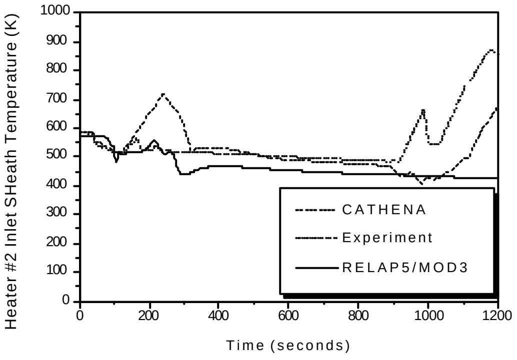

Figure 11 Temperature Profiles at Inlet Sheath of Header 2

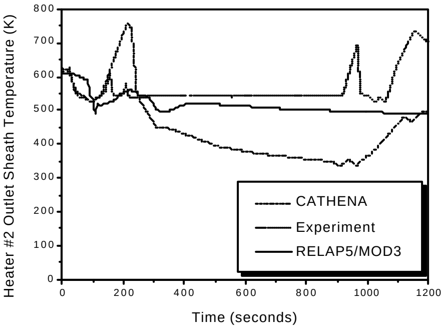

Figure 12 Temperature Profiles at Outlet Sheath of Header 2