Nuclear Science and Techniques **21** (2010) 370–374

Simulation of quenching in horizontal geometry channel

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Abstract Two tests of refilling and reflooding in the horizontal geometry channel under different pressure conditions, respectively, are conducted to understand the thermal hydraulics behavior during a LOCA in the CANDU reactor. One case of refilling a hot horizontal tube test and four cases of reflooding a horizontal fuel channel test series (35% and 60% break size of reactor inlet header with single-end injection or both-end injection, respectively) have been simulated. The horizontal channel is simulated with the model splitting as parallel pipes with cross flow junction component. The simulation results have been compared with the tests in terms of wall temperature or heated-pin surface temperature. The results are reasonably acceptable and it shows that the code is applicable on horizontal channel quenching.

Key words Horizontal channel, Quenching, Parallel-pipe model.

1 Introduction

The core of CANada Deuterium Uranium (CANDU) power reactor consists of several hundred of horizontal fuel channels in a large cylindrical calandria vessel. Each fuel channel consists of an inner tube containing the fuel bundle and the primary coolant of pressurized heavy water, and an outer tube separated from the inner tube by an annulus of insulating gas.

As the best transient simulation code on light water reactors, the RELAP5 code has been used to analyze the CANDU thermal-hydraulics[1−3]. D. Dupleac *et al*.[4]. used a two-parallel-pipe model to study a single fuel channel in normal operation conditions, and compared the results with a single-pipe model, Ilie Prisecaru *et al*.[5] compared the LOCA transient results with the results of the CATHENA code. They found higher temperature of the upper elements and lower temperature of the lower elements, than the single-model and CATHENA code results.

A. Abdul-Razzak *et al*.[6] did the experiments of refilling a hot horizontal tube at atmosphere pressure, and studied hydraulics of the refilling process in horizontal channels, which differed from the commonly-used vertical systems because the gravity force caused flow stratification and different quenching behavior around tubes.

O. Sawamura *et al*.[7] conducted experiments of reflooding in a horizontal fuel channel with a facility consisting of a single channel, two headers, emergency core cooling systems (ECCS) and pipe lines, and measured transient temperature of the pins and header pressure during the reflooding process at different break sizes. The results differed in some way from the above experiments in the terms of the test conditions, such as the initial header pressure (3.526 MPa), channel power and so on.

In this paper, a parallel-pipe model is used to compare the results with Refs.[6,7] to verify the applicability of the RELAP5 on quenching in horizontal channels in two cases of low system pressures.

2 Quenching and models

A typical quench curve and the surface temperature are shown in Fig.1. The quench temperature is at the sudden drop, where the quench starts. The heat transfer mode is film boiling and transition boiling[6,7].

Supported by grant of Doctoral Fund of Ministry of Education of China (20090073110034)

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Received date: 2010-01-08

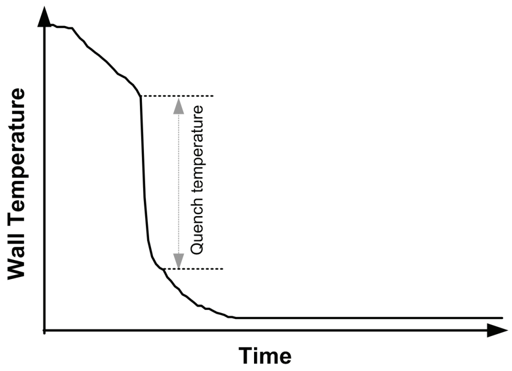

Fig.1 Typical quench curve and the surface temperature.

For the quench simulation, a two-dimensional heat conduction scheme with a fine-mesh-rezoning method was used to represent physics of the process. When the wall was heated to a temperature difference (ΔT=T_W−T_S, where T_W is the wall surface temperature, and T_S is the saturated temperature) of 75−600 K, the wall-to-fluid heat flux was computed as the maximum between the film boiling and transition boiling heat flux.

The transition boiling model used in RELAP5 can be described as follows[8]:

$$q_{th} = q_{CHF}A_f + q_g(1-A_f) \tag{1}$$

$$A_f = \exp\{-\lambda \min [15, (T_w-T_{SPT})^{1/2}]\} \tag{2}$$

$$\lambda = \alpha(\alpha_g)g(G) \tag{3}$$

$$\alpha(\alpha_g) = 0.075\alpha_g + 0.05/(1-\alpha_g^{40}) \tag{4}$$

$$g(G) = \max(2.4-G/10^5, 0.2G/10^5) \tag{5}$$

where, T_{SPT} is saturated temperature at total pressure (K), q_{th} is wall-to-fluid heat flux (w/m^2), q_{CHF} is boiling critical heat flux (w/m^2), q_g is heat flux to gas (w/m^2), T_S is saturated temperature (K), α_g is gas fraction, and G is mass flux (kg·m^{-2}·s^{-1}). The above model is modified from the Chen transition boiling model[9] by replacing q_{CHF} in Eq.(1) by q_f and using 15 K in Eq.(2).

$$q_{th} = q_fA_f + q_g(1-A_f) \tag{6}$$

$$A_f = \exp[-\lambda(T_w-T_{SPT})^{1/2}] \tag{7}$$

3 The facilities and tests

3.1 Refilling a hot horizontal tube[6]

The test facility for the refilling experiment is shown in Fig.2(a). The zircaloy test tube, in 3.0 m length, 25.0 cm I.D. and 2.0 mm wall thickness, was electrically heated to 490°C. Five measurement locations were in the axial direction, and the top and bottom of each location were measured. The thermocouples, as shown in Fig.2(b), were placed 0.127 mm away from the inner surface. The three tanks, one 1000 L and two 270 L, at 1.5 atm, supplied cooling waters with a flow flux 480 kg·m^{-2}·s^{-1}. Water could be heated to 60°C by the heaters inside the tanks.

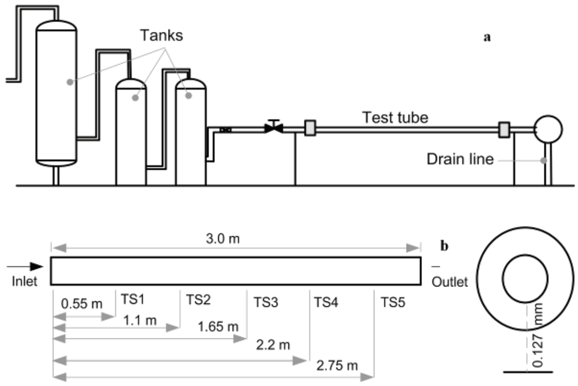

Fig.2 Schematic diagram of the test facility for refilling a hot horizontal tube (a) and the thermocouples locations (b).

3.2 Reflooding a horizontal fuel channel[7,10]

The facility for the reflooding test is shown in Fig.3 and the major parameters are: 5.94 m of heating section length, 37 heat pins, and 300 kW of channel power in chopped cosine of axial power distribution.

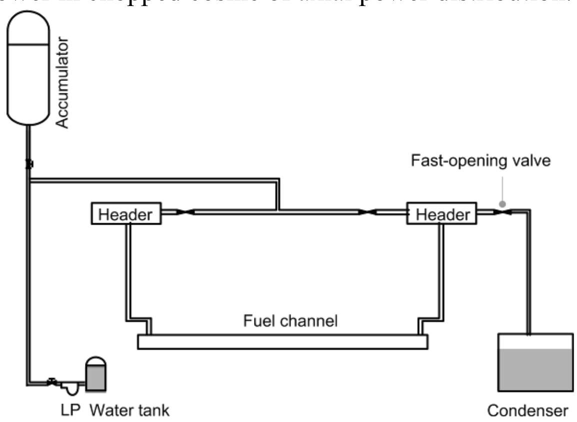

Fig.3 Schematic diagram of the test facility for reflooding a horizontal fuel channel.

Twelve fuel bundles in a fuel channel by an assembly of 37 were used to simulate the dimension and arrangement of the fuel elements as precisely as possible. The channel between two headers was designed for precise simulation of the reactor fuel channel. The elevated components and feeder configuration were designed for better simulation of the reactor fuel channel. The ECCS was composed of an accumulator injection system and a low pressure pump injection system. Four cases of the experiment series were designed as shown in Table 1.

Table 1 Parameters to reflood a horizontal fuel channel (300 kW) at 30°C of cooling water and 3.4 MPa of ECCS injection pressure.

Case No.	Initial sheath temperature / °C	Break size / %	Injection point
1	400	35	Single end
2	400	35	Dual ends
3	300	60	Single end
4	300	60	dual ends

The break size is simulated by a fast-opening valve and an orifice. The break size is in percentage, with 100% being the largest break, i.e. twice the cross-section of the reactor inlet header. The pins of the sixth fuel bundle in the channel were measured. The locations of measuring the pins are shown in Fig.4.

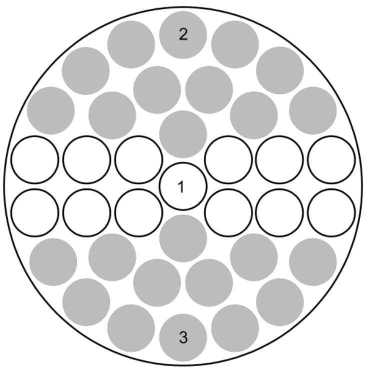

Fig.4 Locations of measuring the fuel bundle pins for the reflooding test.

The test channel between both headers was heated and pressurized by the steam of 3.526 MPa. After the pre-set conditions were reached, the steam supply and discharge were shut off and the pre-set power was supplied to the fuel assembly of simulation. The valve was actuated when the pre-set temperature reached at the hottest heater pin surface. The ECCS water was injected into the header automatically.

4 Simulation

4.1 System model

4.1.1 Refilling of a hot horizontal tube

The system model of refilling simulation is shown in Fig.5. The test tube is simulated with a two-parallel-pipe model, which is divided into two parallel pipes component (122,322) with cross flow junction (611). Volumes 421 and 521 are branch components to realize gravity effect during flow. The tank is marked with 395 as a time dependent volume, and the valve 262 controls flow rate. Volume 124 represents the drain line, and 817 simulates atmosphere environment.

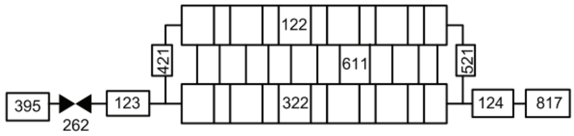

Fig.5 Code nodalization for the refilling test.

4.1.2 Reflooding a horizontal fuel channel

The system model of reflooding simulation is shown in Fig.6. It composes of the fuel channel, headers, ECCS, the break and other components. The single fuel channel is simulated with the three-parallel-pipe model, which is divided into three parallel pipes (122, 222 and 322) with the cross flow junction (611, 613). The components 421, 422, 521and 522 are branch components to realize the gravity effect in the horizontal flow. The branch flow area is equal to flow area of the top pipe. Volume 201 is the broken header, and Volume601 is the fast-opening valve.

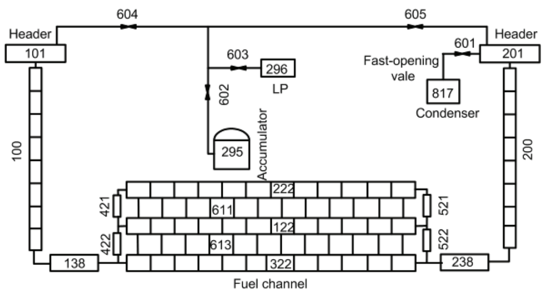

Fig. 6 System nodalization for the reflooding test.

4.2 Results

4.2.1 Refilling a hot horizontal tube

Fig.7 shows the channel surface temperatures. The wall temperature at the tube bottom dropped sharply to a low value after arrival of the refilling fronts, as the heat transfer mode was transition boiling. The sharp drop of wall temperature marks the initiation of quenching. The top side quenching process is similar to the bottom side, with a time delay though. This delay indicates the stratification effect in the channel flow. In the calculation results, the quenching process predicts clearly the measurement results in all spots. The wall temperature drops rapidly in the quenching, and the time delay is clear between quenchings at the top and bottom sides, while the peak temperature from which the quenching starts is somewhat higher than the measurement results.

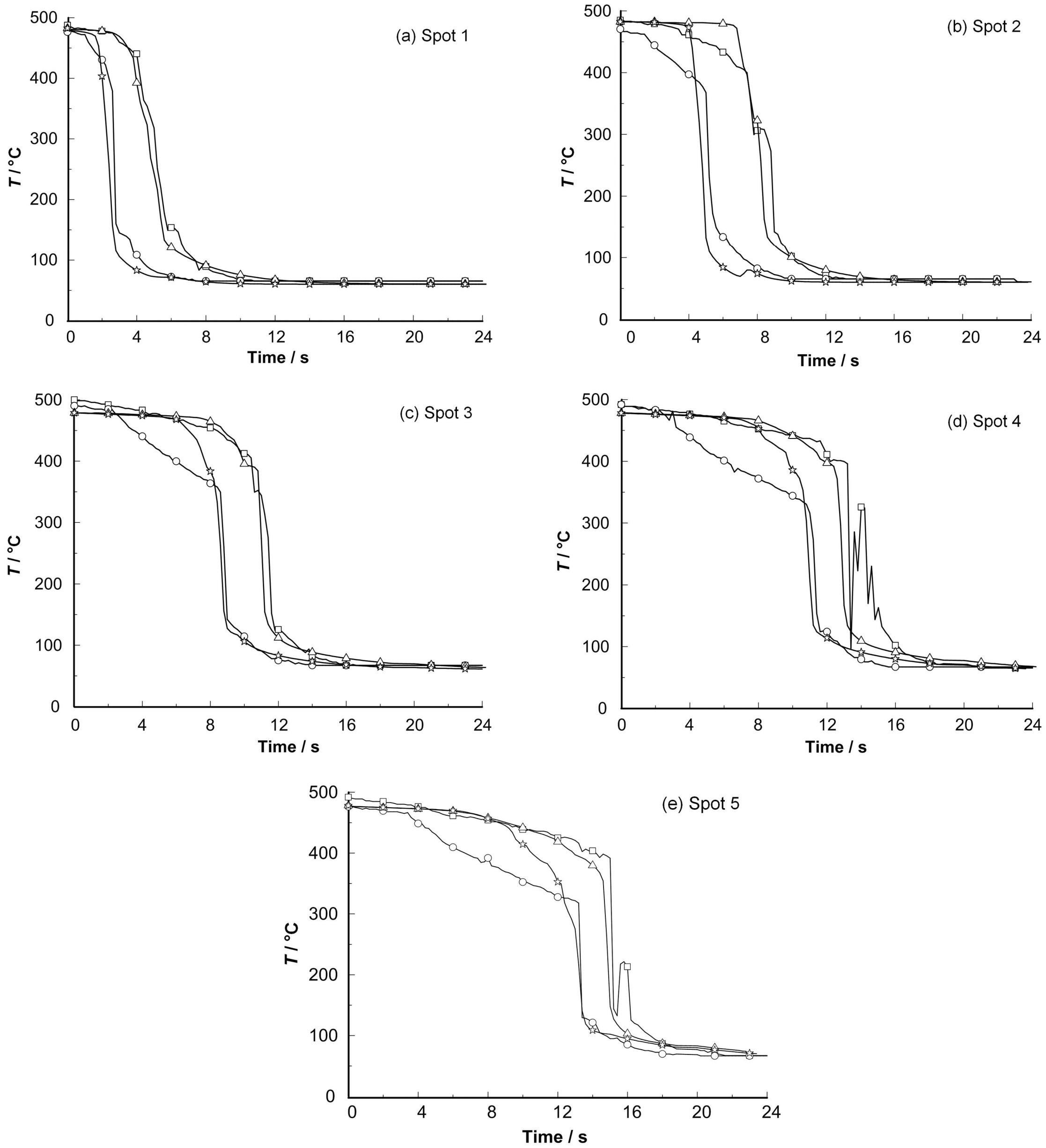

Fig.7 Transient wall temperature at different axial locations. □ (top) and ○ (bottom), measured; Δ (top) and ☆ (bottom), calculated.

4.2.2 Reflooding a horizontal fuel channel

Fig.8 shows the pin surface temperature transients of the reflooding test. After the break, the temperature rises soon to the peak temperature, where it goes down and drops suddenly. The quenching phenomenon proceeds rapidly along the channel. The surface temperature stays at the temperature approximate to the liquid saturation temperature for a while and then drops gradually. During the process, because of the gravity effect, the flow in the channel is stratified, and the temperature changes in the bundle elevation. From the RELAP5 results, the surface temperature transients can be predicted, and the quenching phenomenon occurs, too. Temperature difference between the upper and lower pins can be found in the two simulations because of the use of the parallel-pipe model. In the simulation, the surface temperature drops rapidly from the peak temperature, and the temperature difference in the later period after the quenching process is distinct to the ones in other periods.

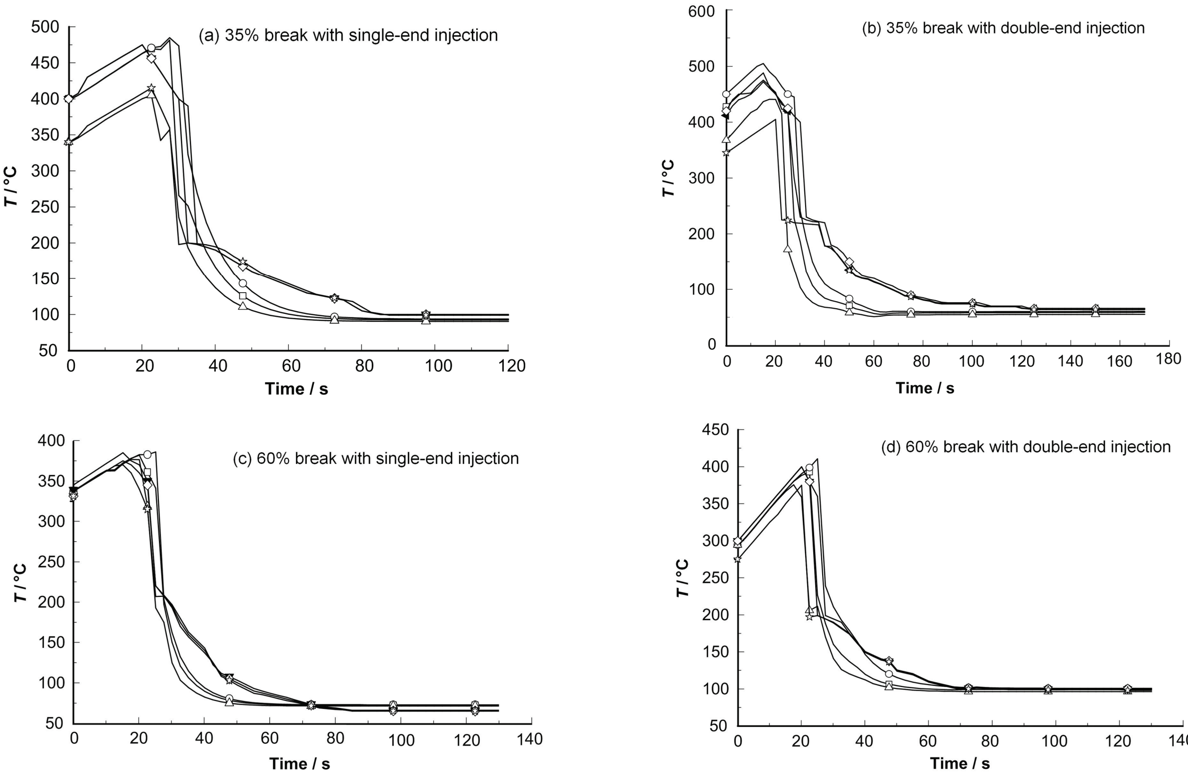

Fig.8 Temperature transients at heater pin surface in different conditions. □ (T_1), ○ (T_2) and Δ (T_3) calculated; ▼ (T_1), ◇ (T_2) and ☆ (T_3), measured.

5 Conclusions

In order to verify the applicability of the RELAP5 in the quenching process in a horizontal geometry channels, simulation of two experiments at different pressure conditions are delivered in this paper. Dividing one single pipe into parallel pipes with cross flow junction is used for the CANDU horizontal fuel channel. The results show the process is clearly predicted and quench phenomenon also occurs while there are some differences in the temperature in the period during the process. From the results, it is indicated that the applicability of the code is reasonably acceptable at relative low system pressures. Further studies shall be conducted to optimize the corresponding model for better applicability.

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