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Review of the Safety Concern Related to CANDU Moderator Temperature Distribution and Status of KAERI Moderator Circulation Test (MCT) Experiments

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1. Introduction

Following a large break LOCA and before Emergency Coolant Injection (ECI) initiation, pressure tubes (PT) significantly heat up as a result of the initial power pulse and degraded coolant flow. Consequently, some pressure tubes balloon and come into contact with the calandria tubes (CT). Following the PT/CT contact, the pressure tubes cool as they transfer some of the absorbed heat to the moderator via conduction at contact locations. As long as sustained calandria tube dryout does not occur, the calandria tube surface temperature remains below the creep threshold temperature and no further deformation is expected. Consequently, a sufficient condition to ensure fuel channel integrity following a large LOCA, is the avoidance of sustained calandria tubes dryout. If the moderator available subcooling at the onset of a large LOCA is greater than the subcooling requirements, a sustained calandria tube dryout is avoided. The subcooling requirements are determined from a set of experiments known as fuel channel contact experiments [1]. The difference between available subcooling and required subcooling is called subcooling margins.

The moderator flow circulation patterns are complicated slow flows that significantly vary from buoyancy dominated to inertia dominated patterns. Accurate predictions of flow patterns are essential for accurate calculation of moderator temperature distributions and the related moderator subcooling[2].

2. Review of the Previous Researches

The flow inside the moderator tank of a CANDU-6 reactor during full power steady state operation has been suspected to be operating in the mixed convection regime where competition between the upward buoyancy driven flows and the downward inlet jet driven inertial flows, results in the formation of asymmetric localized recirculation zones wherein the hottest spot may occur as illustrated in the middle figure in Fig.1. As a result at some regions of the moderator tank where the buoyancy driven upward flow and the inertial momentum driven downward flows interface counter-currently, there exist some interface regions between these two flows like the middle one in Fig.1, and the local temperatures at these interface regions are known to oscillate with different amplitude at various fluctuation frequencies as shown in Fig.2.

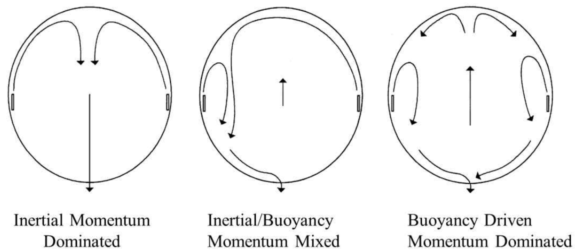


Fig. 1. Flow Pattern Transition Due to Competition between Inertial/Buoyancy Driven Momentum

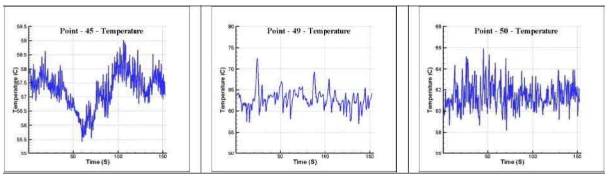


Fig.2. Examples of the local moderator temperature fluctuation at several interface regions between the inlet jets and buoyant hot flumes [3]

According to a numerical simulation of the moderator flow and temperature distribution at full power steady state carried out by previous researches showed that any small disturbances in the flow or temperature may initiate the system unstable and aggravate the asymmetric flow and temperature patterns [2]. This observation raised a safety concern as the local moderator temperature at some regions showed fluctuations with an amplitude that may jeopardize the safety margin, i.e. the difference between the available subcooling and the subcooling requirement.

The tests at the 3-D Moderator Test Facility (MTF) which was specifically designed to study moderator circulation at scaled conditions that are representative of CANDU reactors, reproduced the expected and observed moderator behavior in the reactor as well as the local temperature fluctuations arising from the delicate balance of forced and buoyancy induced flow [4]. Temperatures measured in the 3D MTF test exhibited high frequency oscillations in many locations especially in the upper half of the test vessel [9,10]. On the other hand, the reactor tests of Pickering B unit 7 exhibited large-scale low-frequency changes of temperatures. This difference in behavior is not clearly understood and explained yet. The temperature oscillations observed in reactor and in test measurements need to be characterized, and the apparent differences in their nature need to be explained.

Because of this safety concern 3 dimensional numerical simulations have been conducted by many research groups[3,5,6,7,8] for both for a CANDU-6 or large CANDU Moderator tank, and scaled-down test facilities of real CANDU reactors in operation. A. Sarchami and et al.[3] showed that the flow and temperature distributions inside the moderator tank are three dimensional and no symmetry plane can be identified. Competition between the upward moving buoyancy driven flows and the downward moving momentum driven flows, results in the formation of circulation zones. The moderator tank operates in the buoyancy driven mode and any small disturbances in the flow or temperature makes the system unstable and asymmetric. Different types of temperature fluctuations are noted inside the tank:
(i) large amplitude are at the boundaries
between the hot and cold
(ii) low amplitude are in the core of the tank
(iii) high frequency fluctuations are in the regions with high velocities and
(iv) low frequency fluctuations are in the regions with lower velocities.

Khartabil et al. [9] conducted three-dimensional moderator tests in MTF in the Chalk River Laboratories of Atomic Energy of Canada Limited (AECL). He [9,10] experimentally studied the moderator tank and measured its temperature in many locations during the operation using fixed thermocouples. This MTF is a 1/4 scaled CANDU moderator tank, with 480 heaters that simulate 480 fuel channels. It is specifically designed to study moderator circulation at scaled conditions that are representative of CANDU reactors.

3. Motivation of the MCT erection and experiments

Because of the importance of an accurate prediction of moderator temperature distributions and the related moderator subcooling as it relates to the safety margin of the moderator subcooling requirement against the sustained calandria tube dryout, it is important to have a computer code qualified for licensing application.

In order for a computer code to be qualified to predict the local subcooling of the moderator during major DBAs in CANDU-6 reactor for licensing application, it is necessary to have enough experimental data appropriate to validate the computer code. However as most of the experimental data relevant to moderator circulation and temperature of a CANDU-6 reactor are restricted from either publication or sharing through IAEA/OECD-NEA due to the proprietary nature, it was hard for Korean R&D institutes to acquire the experimental data necessary to validate the computer codes for moderator circulation and subcooling analyses of CANDU-6 plants. Thus it was decided to erect an experimental test facility from which the experimental data necessary to validate the computer codes for moderator circulation and subcooling analyses for licensing application as a part of the medium and long range nuclear R&D program.

To better understand the nature of the 3-D moderator circulation and temperature distribution and characterize the interactions between the major phenomena such as inertial momentum flow induced by the inlet jets, the buoyant upward flow generated by the volumetric heating from radiation, and to investigate the significance of the local temperature fluctuation to the safety margin of the calandria tube dryout that may cause the pressure tube failure under the large break LOCA without ECCS injection, a 1/4 scaled-down moderator tank of a CANDU-6 reactor, called Moderator Circulation Test (MCT), was erected at Korea Atomic Energy Research Institute (KAERI) and a series of experiments are being carried out or planned to generate the experimental data necessary to validate the computer codes that are used to analyze the accident analysis of CANDU-6 plants [10]. The scope of this paper is to review the basis of the safety concern related to this moderator subcooling and local temperatue fluctuation and describe the current status of MCT erection and some of the experiments carried so far including the separate effect experiment focusing on the wall jet interaction on a concave surface, i.e. the inner wall of the calandria tank, and local flow pattern measurement near the collision of two opposing inertial momentum flow developed from the inlet jets.

3.1 Counter-wall jet interaction on a concave surface

3.1.1 Wall jet development

Excessive local heating may occur around some calandria tubes at the central core region in a moderator tank. In some designs, an active control method is used, adopting an impinging jet, the so-called "fountain jet." The fountain jet is generated by counter interacting two wall jets that follow an inner periphery of the moderator tank and subsequently targets specific calandria tubes at a certain central core region as illustrated in Fig.3. Therefore, it is essential to understand detailed wall jet development along the inner periphery of the moderator tank.

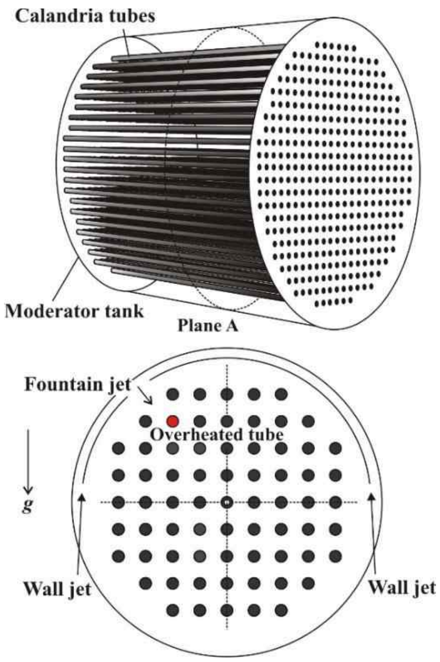


Figure 3. Schematics of a cooling scheme in a CANDU reactor for overheated caldaria tubes by the fountain jet.

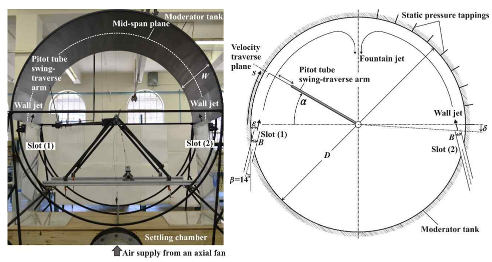
This study aims to characterize how the two-counter wall jets are developed and interact with each other to form the fountain jet, or the downward flow to be formed after collision of the two opposing jets as illustrated in the middle picture of Fig.1. It is expected that the CFD model for the jet development and formation of the fountain jet is correctly implemented and well validated against this experiment, the CFD prediction of the mixed flow pattern is expected to be improved appreciably. To this end, wall jet velocity profiles along the inner periphery of the moderator tank have been measured. Two separate cases; (a) a single wall jet development without the interaction with the counter wall jet and (b) two-wall jets forming the fountain jet, are considered at a fixed jet Reynolds number of Re_B = 15,000.

3.1.2. Experimental Details

Test setup and conditions

A test rig has been built to simulate and simplify a ¼ scale moderator tank model having a diameter (D) of 1.9 m. Active cooling jets are issued through two slots to form two-dimensional jets as illustrated in Fig. 2. In an actual configuration, the slots are directed downwards. However, to facilitate wall jet velocity measurements and flow visualization (not included in this report), the slot jets are discharged upwards as shown in Fig. 4. The azimuth angle of their exit is δ = 3.0° measured from the horizontal center axis. The slots have a certain angle and an off-set with respect to the tangent of the inner moderator wall e.g., β = 14.0° and ε = 1.6B as shown in Fig. 2(b).

A swing-traverse arm is installed at the center of the moderator tank and a Pitot tube with a diameter of 3.0 mm is mounted at its tip. This arrangement allows the axial velocity profiles to be measured at an arbitrary angle covering from α = 0º to α = 180º. The pressure taps of the Pitot tube are connected to a differential pressure transducer (DSA Scanivalve™). The measurement was carried out at the mid-span of the tank to ensure two-dimensional flow fields where the slot has a large aspect ratio (width-to-height ratio), L/B = 31.6. Detailed dimensions and test conditions are summarized in Table 1.



(a) (b)

Figure 4. Two-dimensional wall jet test setup; (a) a photograph of the test rig; (b) a schematic of test setup.

Table 1. Test rig dimensions and test conditions

Moderator tank	Diameter (D)	1.91 m
	Width (W)	1.23 m
Wall jet slot	Height (B)	0.019 m
	Length (L)	0.6 m
	L/B	31.6
	Slot inclination angle (β)	14.0° away from the tangent of the inner wall
	Slot off-set (ε) at the exit	0.034 m (or ε/B = 1.79)
	Jet Reynolds number, Re_B	12,000

The jet Reynolds number is defined as:

$$\mathrm{Re}_B = \frac{\rho w_e B}{\mu}$$

Wall jet develops as it moves downstream. Its development over a flat plate has been well-documented. However, there is a fundamental difference in the wall jet development between over a flat plate and over a concave surface. Due to the concavity, there is a pressure gradient along and normal to the inner wall of the moderator tank. Therefore, the wall jet structure is expected to differ from that over a flat plate. Firstly, the wall jet development of a single slot jet on the concave surface having a tank diameter-to-slot of *D/B* = 100 has been measured. Results are plotted in Fig. 5. The axial component of the slot jet measured at selected downstream positions e.g., α = 0°, 15°, 30°, 45° and 75° and traversed normal to the inner wall ($w(n/B)$) is normalized by the slot centreline velocity (w_e) at the slot exit. Here, *n* is the distance normal to the wall and *B* is the slot width. Although the slot is inclined away from the inner wall, the normal distance where the peak velocity (indicated by a filled circle) is located, moves closer to the inner wall until α = 30°. After which, it moves away from the wall gradually. The extent of momentum diffusion becomes substantial as the jet moves to downstream. However, until reaching the azimuth angle of α = 75°, the wall jet maintains its peak velocity more than a half of the initial peak velocity at the slot exit.

Secondly, the wall jet development of two-counter slot jets on the concave surface is compared in Fig. 5. It is surprising to notice that there is almost no visible difference of the velocity profiles although a slight deceleration is observable. At α = 90°, there exists stagnation due to the collision of the two slot jets. Therefore, an adverse pressure gradient is formed, which might affect upstream velocity profiles between α = 75° and α = 90°, which has not yet been considered. In this azimuth angle range, pneumatic velocity measurements using a pitot tube are limited due to strong flow turning towards the center of the moderator tank. Instead, the formation of the fountain jet can be visualized.

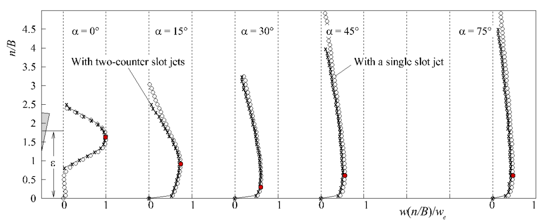


Figure 5. Wall jet axial velocity profiles at selected downstream locations; α = 0°, 15°, 30°, 45°, and 75°, comparing a single wall jet with two-counter wall jets forming a fountain jet.

Another interesting observation is that the wall jet axial velocity profile shows the same trend independent of the Reynolds number as shown in Fig.6. This means that the characteristic of the wall jet axial velocity profile may remain the same for the Reynolds number beyond 15000.

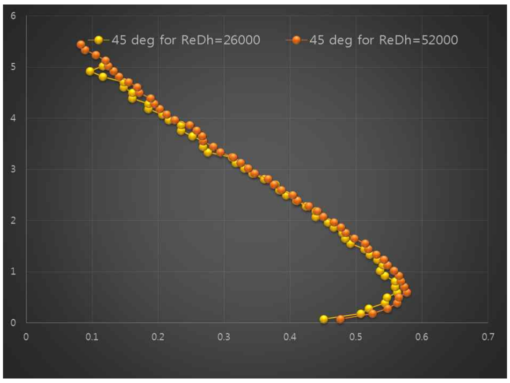
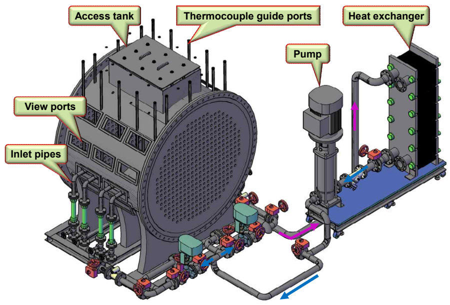


Figure 6. Independent trend of the wall jet axial velocity profile at the downstream location of α =45° for a single slot jet.

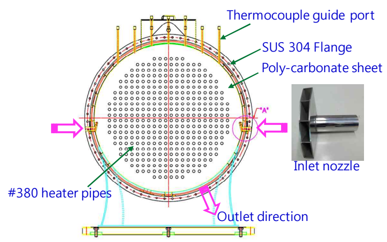
3.2 Velocity Measurement by PIV

An optical measurement system using the Particle Image Velocimetry (PIV) is installed. The velocity and temperature profiles in the test vessel are measured by the PIV and the thermocouple (TC) and/or Infrared (IR) temperature measuring systems, respectively. An access tank (950 mm × 650 mm) on top of the vessel allows the exposure of the laser beam as well as TC/IR measurements inside the vessel. The TC/IR rods are inserted in the 7 × 5 arrays of guide ports (Fig. 7(b)) penetrating the upper part of the tank wall and the access tank. The thermocouple measurements can be used for auxiliary temperature measurements as well as calibration of the Infrared Radiation (IR) temperature measurements. The loop instrumentation consists of flow rate, temperature, and pressure measurements. The multistage centrifugal pump is used to circulate water in the primary loop and a total flow rate is adjusted by the inverter control. The flow rate to each side of inlet nozzles is measured by a vortex flow meter and the flow split to each side is automatically controlled by 3-way valve. The flow rates to individual inlet nozzles can be monitored and adjusted by rotameters. The inlet and outlet temperatures are measured by T-type TCs. The inlet temperature is controlled by adjusting by-pass flow in the secondary side of the heat exchanger. For more detailed information of this MCT facility and projected experiments refer to the reference 12.

An example of the moderator velocity patterns of MCT measured by PIV is illustrated in Fig.8. The flow patterns clearly show the collision of the two opposing jets at the center region of the tank top ceiling for the heating of 100 kW and various inlet flow conditions.



(a) Overview of the primary water circuit of MCT



(b) Cross sectional view of the moderator tank

Fig. 7. Geometric configuration of the MCT test facility.

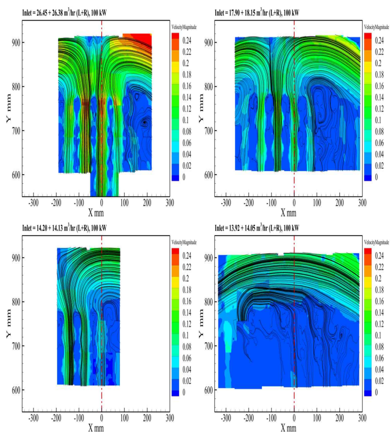


Fig. 8. Measured Flow Patterns at the Top Region where Two Jets Collide at Various Flow Rates and 100kW Heating

3. Summary and Conclusion

Following a large break LOCA and before Emergency Coolant Injection (ECI) initiation, pressure tubes (PT) significantly heat up as a result of the initial power pulse and degraded coolant flow. Consequently, some pressure tubes balloon and come into contact with the calandria tubes (CT). Following the PT/CT contact, the pressure tubes cool as they transfer some of the absorbed heat to the moderator via conduction at contact locations. As long as sustained calandria tube dryout does not occur, the calandria tube surface temperature remains below the creep threshold temperature and no further deformation is expected. Consequently, a sufficient condition to ensure fuel channel integrity following a large LOCA, is the avoidance of sustained calandria tubes dryout. If the moderator available subcooling at the onset of a large LOCA is greater than the subcooling requirements, a sustained calandria tube dryout is avoided.

The temperature oscillations observed in reactor and in test measurements such as MTF need to be characterized and quantified to show that it does not jeopardize the currently available safety margins.

Because of the importance of an accurate prediction of moderator temperature distributions and the related moderator subcooling, a 1/4 scaled-down moderator tank of a CANDU-6 reactor, called Moderator Circulation Test (MCT), was erected at KAERI and the current status of MCT experiment progress is described and further experiments are expected to be carried out to generate the experimental data necessary to validate the computer codes that will be used to analyze the accident analysis of operating CANDU-6 plants.

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