VALIDATION TEST PLAN OF A CANDU-6 MODERATOR TANK SCALED-DOWN TEST FACILITY

Bo W. Rhee[1], Hyoung T. Kim[1], Michael D. Atkins[2], Tongbeum Kim[2]
[1]: Severe Accident and PHWR Safety Research Division, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, South Korea
[2]: School of Mechanical, Industrial & Aeronautical Engineering, University of the Witwatersrand, Johannesburg, South Africa
Corresponding Address
bwrhee@kaeri.re.kr

ABSTRACT

The computational fluid dynamics (CFD) codes play an important role in the accident analysis of CANDU-6 plants. However, a rigorous experimental validation of such codes is not an easy task but essentially required. To this end, the construction of a scaled-down moderator tank of a CANDU-6 reactor has been implemented. The parameters to consider for the validation are flow circulation and local temperature distribution inside the moderator during steady operation and major accident conditions. The key features to consider include the inlet jet development, buoyancy force, and viscous friction against the flow across the calandria tube array. In this paper, a ¼ scaled-down test facility and instrumentation are described. Details of thermo-fluidic measurements using particle image velocimetry (PIV) are described and infrared (IR) thermography are addressed. Some progresses, including further issues and challenges, on the CFD modeling of the shear jet development at the periphery of the moderator circulation tank, the collision of the shear jets and their interaction with the upward buoyant flumes generated by local calandria tubes are presented. Furthermore, a method to validate the scaling of the CANDU-6 test facilities based on CFD analysis and similarity analysis is proposed.

KEYWORDS
Validation test plan, CANDU-6, Moderator circulation, Scaling analysis, Scaled-down test facility, CFD analysis

1. INTRODUCTION

The CANDU reactor has a square array of horizontal fuel channels surrounded by heavy water moderator contained in a horizontal, cylindrical tank, called a calandria. Each fuel channel consists of two concentric tubes, a pressure tube (PT) inside a calandria tube (CT), with a gap that is filled with CO_2 insulating gas. During normal operation, the moderator absorbs about 5% of the total reactor power as a result of absorbing neutron kinetic energy and gamma radiation generated by the fuel and in-core structures (such as guide tubes and calandria tubes). The moderator is pumped out of the outlet ports of calandria and cooled through heat exchanges, and then returned to the calandria via a set of inlet nozzles. However, following a large Loss Of Coolant Accident (LOCA) without Emergency Core Injection (ECI), the PT heats up significantly as a result of the initial power pulse and degraded coolant flow. Consequently, some PTs balloon and come into contact with the CTs. Following this PT/CT contact, the PTs are cooled as they transfer some of the absorbed heat to the moderator via conduction at contact locations. As long as a sustained CT dryout does not occur, the CT surface temperature remains below the creep threshold temperature and no further deformation is expected. Consequently, a sufficient condition to ensure the fuel channel integrity following a large LOCA, is the avoidance of a sustained CT dryout. If the moderator available subcooling at the onset of a large LOCA is greater than the subcooling requirements [1], a sustained CT dryout is avoided. The subcooling requirements are determined from a set of experiments known as the fuel channel contact boiling experiments [2]. The difference between available subcooling and required subcooling is called subcooling margins. The local temperature of the moderator is a key parameter in determining the available subcooling. To predict the local temperature in the calandria, numerous experimental and numerical researches have been carried out.

In order for a computer code to be qualified to predict the local subcooling of the moderator during major Design Bases Accidents(DBAs) in CANDU-6 reactor for licensing application, it is necessary to have enough experimental data to validate the computer code. As most of the experimental data relevant to moderator circulation and temperature of a CANDU-6 reactor are restricted for either publication or sharing through IAEA/OECD-NEA due to the proprietary nature, it is essential to develop own experimental database for the moderator circulation and subcooling analyses of CANDU-6 plant. To this end, an experimental test facility, a scaled-down moderator tank of a CANDU-6 reactor, also called the Moderator Circulation Test (MCT) facility has been designed and built at Korea Atomic Energy Research Institute (KAERI) [3].

2. MODERATOR CIRCULATION TEST (MCT) FACILITY

Moderator Circulation Test (MCT) facility is the large-scale facility designed to reproduce the important characteristics of moderator circulation in a CANDU-6 calandria under a wide range of operating conditions. It is reduced in a 1/4 scale and a moderator test vessel is built to the specifications of the CANDU-6 reactor design, where a working fluid is sub-cooled water at atmospheric pressure.

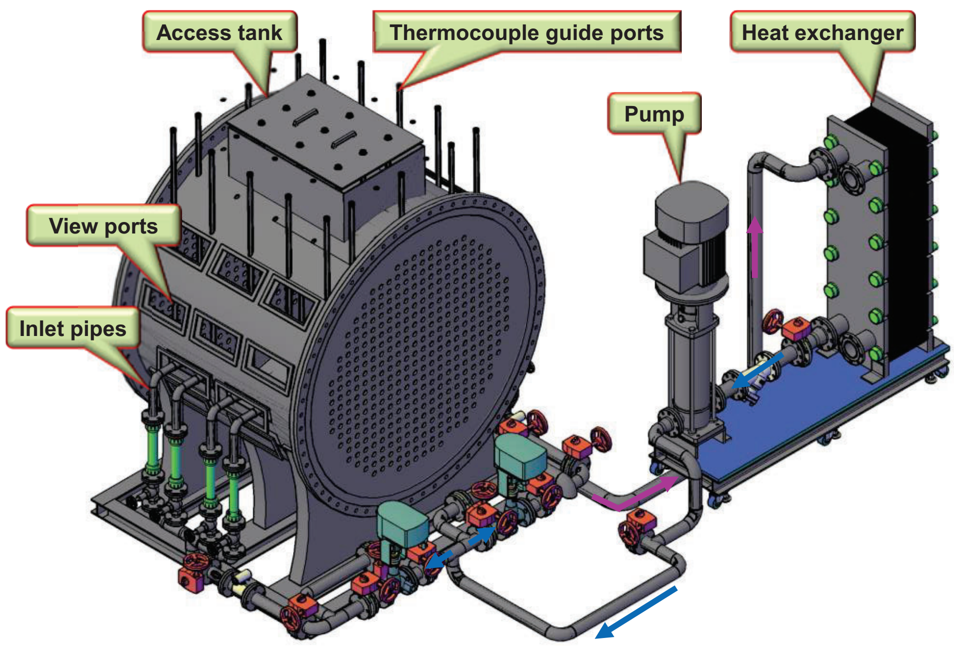
The MCT consists of the primary and secondary water circuits, same as the CANDU-6 moderator system. The primary circuit, shown in Fig. 1(a), includes a moderator tank, a circulating pump, a heat exchanger, and intermediate pipe lines. The cold water is pumped to the tank through eight separate nozzles, four nozzles at each side, and the heated water exits through two outlet pipes at the bottom of the tank. In the heat exchanger, the (primary) hot water from the tank is cooled by the secondary side water circulating through an external cooling tower. Then, the cooled water comes back to the inlet nozzles via a circulating pump.

The inner diameter and axial length of test vessel are 1900 mm and 1500 mm, respectively. The test vessel is equipped with 380 acrylic pipes (for non-heating test) or electric heaters simulating the horizontal fuel channels (for heating test) (see Fig. 1(b)). The electric heaters are designed to provide axial and radial power profiles representative of CANDU-6 power profiles. An axial power profile is a symmetric cosine profile with a peak-to-average ratio of 1.4. A radial power profile is created by arranging the heaters in two concentric power zones, with an individual heat power ratio of 1.4 between the inner and the outer zones.

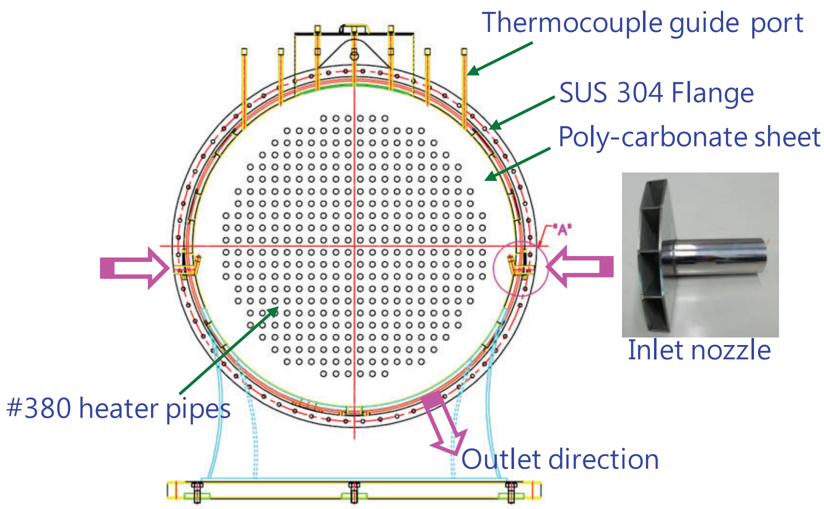
Tank walls with 5 mm in thickness and other support structures are made of SUS 304 stainless steel. Several transparent sections are incorporated into the vessel to facilitate flow visualization. The front and backward side of viewing windows are made of poly-carbonate sheet with 15 mm in thickness, which is sealed between two opposing stainless steel flanges (each 35 mm and 25 mm in thickness) with a silicone O-ring. Eight view ports are installed to each side of the tank wall.

The velocity and temperature profiles in the test vessel are measured by the Particle Image Velocimetry (PIV) and the Laser Induced Fluorescence (LIF) measurement systems, respectively. An access tank (950 mm × 650 mm) on top of the vessel allows the exposure of the laser beam as well as thermocouple measurements inside the vessel.

The loop instrumentation consists of flow rate, temperature, and pressure measurements. The multi-stage 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 thermocouples. The inlet temperature is controlled by adjusting by-pass flow in the secondary side of the heat exchanger. Pressure tap can be used to measure the pressure drop between the inlet and outlet of the pump.



(a) Overview of the primary water circuit of MCT



(b) Cross sectional view of the moderator tank

Fig. 1 Geometric configuration of the MCT test facility.

3. KEY THERMO-FLUIDIC FEATURES AND TEST PLANS

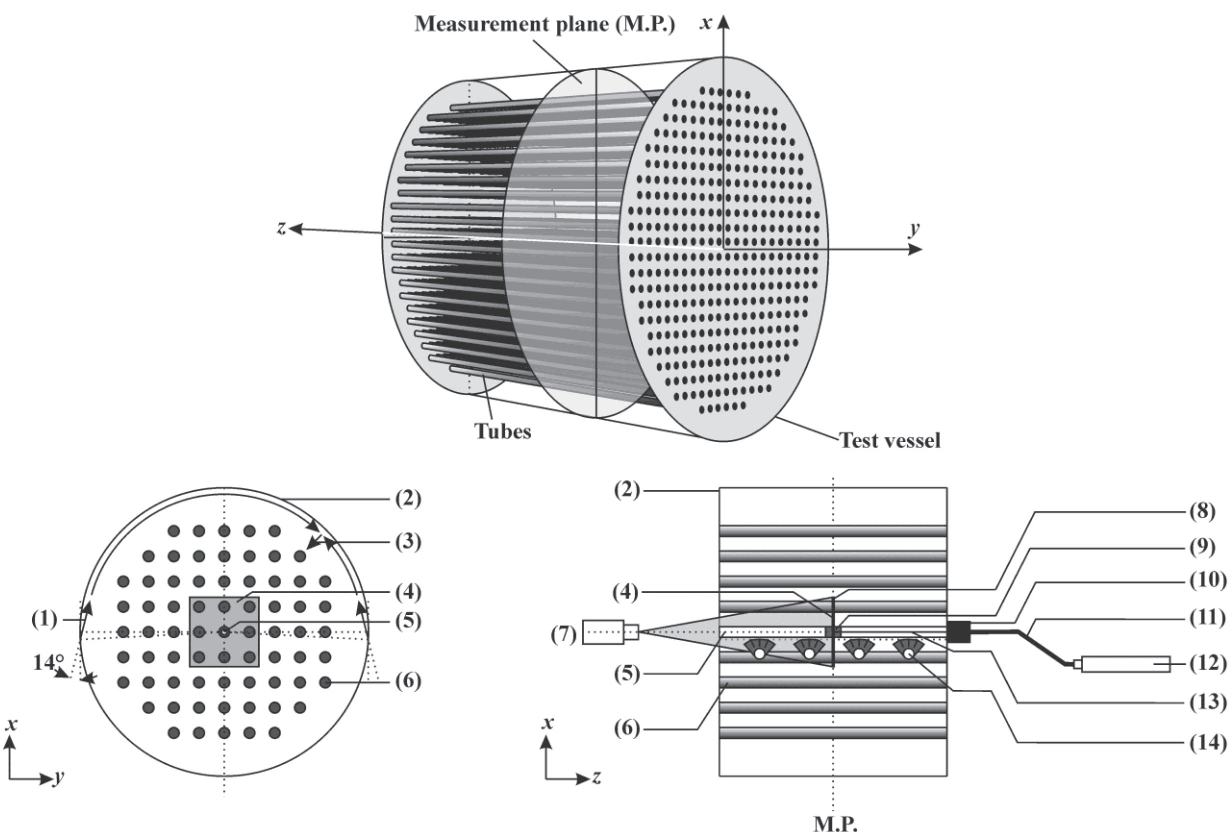
The parameters of interests in this facility which is a scaled-down mock-up of the CANDU-6 moderator tank are the moderator flow circulation and temperature inside the moderator tank during a steady state condition and major accident conditions. The major phenomena involved include the inlet flow induced shear jet development, upward buoyant flow generated from the heating by the horizontally square-arrayed tubes, and the viscous pressure drop against the flow across the calandria tube array. As these three phenomena compete one another inside the moderator tank depending on the various operating conditions, the flow condition may vary from buoyancy dominated stratified flow, mixed flow and inertial dominated forced flow. From the many preceding works, it was found that a quasi-steady state mixed flow condition where the flow and temperature distribution travel a range of cyclic pattern during the steady state condition of CANDU-6, and at any condition of this cyclic quasi-steady pattern may start an accident like Large-Break LOCA. In the course of the large break LOCA without ECC injection the integrity of the fuel channels may be jeopardized due to the possibility of a sustained film boiling outside the calandria tube should the contact of overheated fuel channel and calandria tube occur, and as the local subcooling adjacent to the fuel channel is the criterion for sustained film boiling, an accurate prediction of the moderator temperature inside the tank during accident is utmost important to the reactor safety.

3.1. Projected Internal Illumination PIV Test

The Moderator Circulation Test (MCT) facility is a horizontally orientated test vessel, with multiple rods that are located parallel to the vessel's longitudinal axis. The measurement of the flow field within the multiple tube bundle configuration of the MCT shown in Fig. 2 will be undertaken using the Particle Image Velocimetry (PIV) experimental method. The experimental investigation of the cross-flow field that is induced by both natural and forced convection driving systems will be investigated within the measurement plane in Fig. 2. However, the intermediate flow-field between the tubes is difficult to access optically and hence the conventional implementation of the PIV method has a significant limitation that stems from having an externally generated light sheet, in addition to having the optically opaque tubes that are typically in the optical path of the light sheet. Consequently, shadow regions develop, which often fall within the PIV measurement region and prevent the tracer particles that are introduced into the flow field of the MCT from being illuminated. Without adequate illumination, the location of these particles cannot be recorded and hence no measurements of the velocity field in the shadow regions are possible, i.e., shadows prevent the measurement of the intermediate flow-field between the rods (cylinders).

This study will implement an alternative "internal illumination" PIV method that aims to overcome the limitations of the conventional external PIV illumination methods. The details of internal illumination are shown in Figs. 2. The benefit of this proposed internal illumination method is that the shadow region can be eliminated, thus facilitate the measurement of the intermediate flow field directly between the rows of tubes in the MCT using the PIV technique. The internal PIV illumination method has been successfully demonstrated by Atkins and Kim (2015). This new illumination method also makes planar laser flow visualization possible either by laser light scattering or by laser induced fluorescence (LIF).

Internal illumination requires that optical elements are placed inside of a certain tube of the MCT vessel, the location of this tube in principle is arbitrary. The optical elements generate a thin laser disk of light around the tube in question, where there is 360 degree laser light coverage, allowing the flow field adjacent to this cylinder to be illuminated simultaneously. This type of illumination is primarily achieved by (1) inserting a transparent glass tube section at some location (e.g., mid-span) along the span of the given tube and (2) special laser light sheet forming optics are then placed inside this transparent glass tube section. A laser source then emits a pulsed circular laser beam, which is directed along the axis the tube in question. This laser beam is then transformed into the so-called "laser disk of light" or "laser light disk" by the laser optics which consisted of a 90 degree cone mirror. Consequently, laser light radiates outwards through the transparent walls of this glass section.



Item	Description	Item	Description
(1)	Cooling jet	(8)	Laser light disk (360 degree illumination)
(2)	Test vessel	(9)	Laser light disk forming optics (custom made)
(3)	Collided jet	(10)	Adaptor (custom made)
(4)	PIV measurement area (location arbitrary)	(11)	Articulated laser light guide
(5)	Internally illuminated cylinder (heated)	(12)	Dual cavity Nd: YAG laser light source
(6)	Heated tubes	(13)	Laser beam (circular)
(7)	CCD camera	(14)	Inlet nozzles

Fig. 2 Schematic of the MCT vessel, showing the horizontal tubes and an arbitrary measurement plane and the experimental internal illumination PIV setup with the PIV measurement area.

3.2 Shear Jet Flow Development and Collision Test

To obtain the experimental data to validate the CFD code and associated models, one needs to establish a test plan and test matrices. As the development of the shear jet flow induced by the inlet flow through the inlet nozzles, collision of two opposing shear jets at the top region of the tank occurs as depicted in Fig. 3. The resulting downward recirculation after the jet collision flow plays an important role in determining the overall flow pattern inside the moderator tank. The pressure distribution along the jet direction and resulting flow patterns will be measured using direct measurement and visualization techniques. The experimental data for various test conditions will be analyzed to understand the physics of the phenomena and will be used to develop a model for CFD codes.

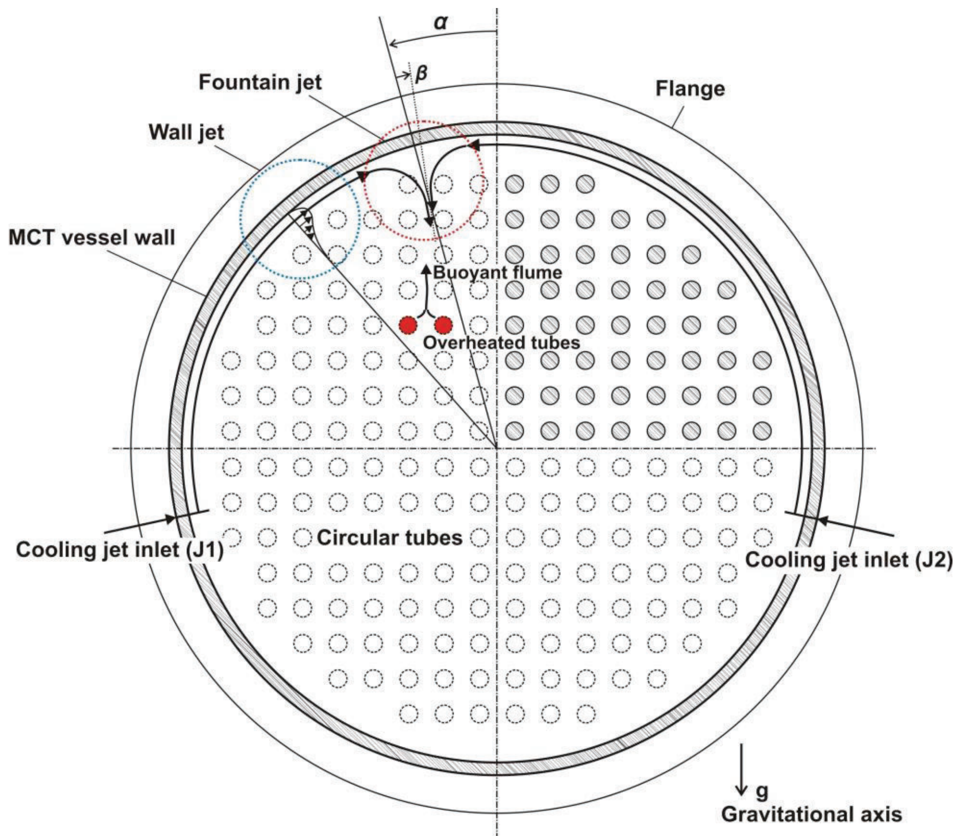
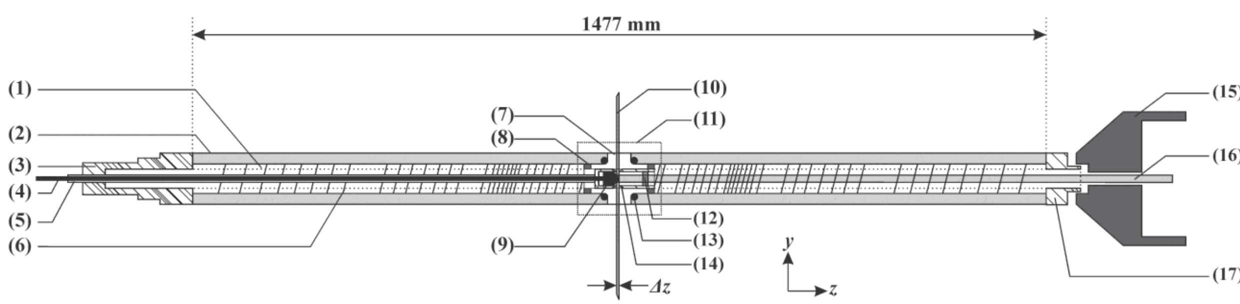


Fig. 3 Schematic diagram of a moderator tank of a CANDU-6 depicting the inlet jet collision and resulting recirculating fountain flow.

3.3 Buoyant Flow and Overall Flow and Temperature Measurement Test

The development of the upward buoyant flows generated in the central tube bank region of the moderator tank is also one of the important phenomena. The directional pressure drop across the tube bank region at various yaw angles may be another factor affecting the overall flow pattern inside the tank. Also the development of the shear jet flow induced by the inlet flow through the inlet nozzles, collision of two opposing shear jets at the top region of the tank occur as depicted in Fig. 3. The resulting downward recirculating after the jet collision flow play important role in determining the overall flow pattern inside the moderator tank. As in practice, three of these phenomena occur simultaneously, the flow patterns inside the moderator tank will be measured by PIV technique and the temperature field will be measured by the various thermocouples located at various positions inside the tank.

For the measurement of the interaction between the buoyant flow and the shear jet, internal illumination will be implemented where the illuminated cylinder is also heated. This configuration is shown in detail in Fig. 4. A requirement for the internal illumination is that (1) the illuminating cylinder is hollow to allow for the transmission of the laser beam along the central axis of the tube (2) The laser optical device necessary to form the thin light sheet is located at some position along the span of the cylinder (i.e., mid-span). To meet these requirements the insulating MgO rod that is used as part of the SUS sheath pipe heating system; needs to be hollow with a large enough diameter to allow (1) the transmission of the laser beam to the light disk forming optics and (2) the removal of the optical elements that are placed inside of the illuminating cylinder. Secondly, both the outer SUS sheath pipe and the MgO insulating rod needs to be split into two parts. These two pieces would then be joined by the transparent optical glass section with a sealed and bonded interface as depicted in Fig. 4. The outside diameter of the transparent optical glass section must match the outside diameter of the SUS sheath pipe. The transparent optical glass section provides a window to allow for the transmission of the laser light into the adjacent flow field.



Detail of the heated illuminated cylinder

Item	Description	Item	Description
(1)	Hollow MgO rod (OD~ 28 mm, ID~12 mm)	(10)	Laser light disk (360 degree illumination)
(2)	Sheath pipe SUS 304 stainless (OD 33 mm, thickness 1.5 mm)	(11)	Laser light disk forming optics (custom made)
(3)	Bracket A (hollow)	(12)	Optical elements (optional)
(4)	Control rod (mirror)	(13)	Seal
(5)	Control rod (optical shroud)	(14)	Optical shroud (custom made)
(6)	Heating wire (variable pitch)	(15)	Adaptor (custom made)
(7)	Transparent optical glass section (custom made)	(16)	Laser beam (circular)
(8)	Glass heating ring	(17)	Bracket B (hollow)

(9)	Cone mirror		

Fig. 4 Detailed schematic of the heated illuminating tube.

The heated cylinder without any modification has a cosine power distribution in the axial direction due to the variable pitch of the heating wire that is wound around the insulating MgO rod. Heating rings may also be attached to either end of the transparent optical glass section, to heat the glass and limit the discontinuity in the power distribution.

The thermocouple or IR sensor rods are inserted in the 7 × 5 arrays of guide ports (Fig. 1(b)) penetrating the upper part of the tank wall and the access tank. For the local fluid temperature measurement, either the thermocouple or Infrared (IR) thermometry measurements will be used.

4. SIMILARITY CONDITIONS

If the same working fluid is used for both the prototype and the scaled-down facilities, Prandtl number (PrPr) can be considered nearly uniform inside the tank. The Reynolds number (Re) and Archimedes number (Ar) depend on ΔT, U_i, and D. Therefore, if any combination of these for Re and Ar and the dimensionless volumetric heat source, q^*, are kept the same for both facilities, the hydrodynamic similarity inside the moderator tank may be maintained. However, in practice, it is not possible as the tank dimension of the scaled-down tank becomes larger than that of the prototype tank. In particular, maintaining the similarity in the Reynolds number is not practical because of the need for a reduced tank size.

The CFD codes solve the Reynolds-Averaged form of the conservation equations in which the instantaneous velocity, pressure and temperature are expressed as the sum of mean and fluctuating components:

$$V = \bar{V} + V'$$

$$P = \bar{P} + P'$$

$$T = \bar{T} + T'$$

The fluctuating components result in turbulent stresses in the momentum equation and turbulent heat fluxes in the energy equation. The most practical for engineering applications to model these effects is the use of additional parameters in the form of eddy viscosity for momentum and eddy thermal diffusivity for energy. The assumption being that the behavior of turbulent stresses and turbulent heat fluxes is analogous to stresses due to fluid viscous effects in the presence of velocity gradients and to heat fluxes resulting from thermal conduction (or thermal diffusion) along temperature gradients. These parameters are in turn based on the two-equation k-epsilon model of turbulence.

The turbulent viscosity, μ_t, is thus calculated from the turbulent kinetic energy, k, and energy dissipation rate, ε:

$$\mu_t = C_\mu \rho_r \frac{k^2}{\varepsilon} = 0.09 \rho_r \frac{k^2}{\varepsilon} \tag{3.1}$$

While the turbulent thermal conductivity, k_t, is assumed proportional to the turbulent viscosity via the turbulent Prandtl number, σ_t, which is generally of order 1:

$$k_t = \frac{C_p \mu_t}{\sigma_t} \quad (3.2)$$

Applying these definitions and simplifications to the mass, momentum and energy equations, results in the following equations for mass, momentum and energy conservation:

$$\nabla \cdot \bar{V} = 0 \quad (3.3)$$

$$\frac{\partial \bar{V}}{\partial t} + (\bar{V} \cdot \nabla)\bar{V} = -\frac{1}{\rho_r}\nabla \bar{P} + \frac{\mu}{\rho_r}\left(1 + \frac{\mu_t}{\mu}\right)\nabla^2 \bar{V} - g\beta(\bar{T} - T_r) \quad (3.4)$$

$$\frac{\partial \bar{T}}{\partial t} + (\bar{V} \cdot \nabla)\bar{T} = \frac{k}{\rho_r C_p}\left[1 + \left(\frac{Pr}{\sigma_t}\right)\left(\frac{\mu_t}{\mu}\right)\right]\nabla^2 \bar{T} + \frac{q}{\rho_r C_p} \quad (3.5)$$

According to Khartabil[4], the dimensionless variables may be defined as:

$V^* = V/U_i$, $T^* = (T - T_{sat})/\Delta T$, $P^* = P/\left(\rho_{ref} U_i^2\right)$

$t^* = tU_i/D$, $\nabla^* = D\nabla$, $Re = \rho_{ref} U_i D/\mu$

$Pr = \mu C_\rho/k$, $Ar = g\beta_{ref}(T - T_i)D / U_i^2$

$$q^* = \frac{q(x,y,z,t) \quad D}{\rho_{ref} C_p U_i \Delta T}, \Delta T = (T_o - T_i) \quad (3.6)$$

Using these definitions to replace all dimensional variables in the governing equations (3.3-3.5), yields:

$$\nabla^* \cdot \bar{V}^* = 0 \quad (3.7)$$

$$\frac{\partial \bar{V}^*}{\partial t} + (\bar{V}^* \cdot \nabla^*)\bar{V}^* = -\nabla^* \bar{P}^* + \frac{1}{Re}\left(1 + \frac{\mu_t}{\mu}\right)\nabla^{*2}\bar{V}^* - Ar\frac{g}{|g|}\bar{T}^* \quad (3.8)$$

$$\frac{\partial \bar{T}^*}{\partial t} + (\bar{V}^* \cdot \nabla^*)\bar{T}^* = \frac{1}{PrRe}\left[1 + \left(\frac{Pr}{\sigma_t}\right)\left(\frac{\mu_t}{\mu}\right)\right]\nabla^{*2}\bar{T}^* + q^* \quad (3.9)$$

Hence, for complete similarity between prototype and model we must have:

$$\frac{Ar_p}{Ar_m} = \frac{q_p^*}{q_m^*} = \frac{\left[\frac{1}{Re}\left(1+\frac{\mu_t}{\mu}\right)\right]_p}{\left[\frac{1}{Re}\left(1+\frac{\mu_t}{\mu}\right)\right]_m} = \frac{\left[\frac{1}{PrRe}\left(1+\frac{Pr\mu_t}{\sigma_t\,\mu}\right)\right]_p}{\left[\frac{1}{PrRe}\left(1+\frac{Pr\mu_t}{\sigma_t\,\mu}\right)\right]_m} = 1 \quad (3.10)$$

Where p and m represent the prototype CANDU-6 and the ¼ scaled-down test facility.
Therefore, if these conditions are satisfied for both the prototype CANDU-6 and MCT, one can argue that the similarity is achieved. However in reality it is difficult to prove the last two equalities as they require CFD results over the whole solution domain. Thus our approach to justify the design of the scaled-down facility is first to decide the geometric scale, thermal power scale and flow scale based on the first two equalities, i.e., Ar and volumetric heat source ratios. Second, to perform CFD analyses for CANDU-6 full power condition and the scaled-down facilities for the operating conditions determined from the first step. And then examine if the temperature and flow patterns of MCT are similar to those of CANDU-6 and the last two similarities are satisfied based on the CFD analyses results.

5. CFD ANALYSIS OF CANDU-6 MODERATOR AND MCT

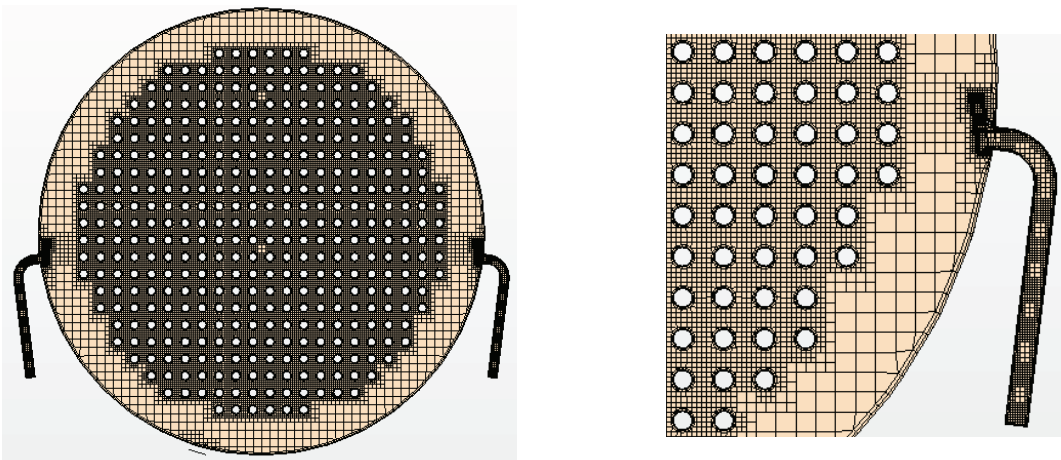
Two sets of the CFD simulations for the CANDU-6 full power steady state and scaled-down moderator tanks with two different powers have been performed to examine how flow and temperature fields in both reactors are comparable.

5.1 CFD modeling

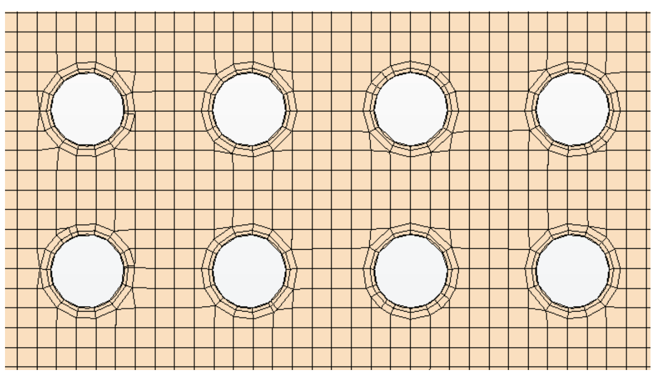
A commercial CFD code, STAR-CCM+ has been used for the normal operating conditions.

5.1.1 Mesh generation

Based on the engineering judgement of the authors on the CFD simulation experience of CANDU-6 moderator circulation problems, the following mesh grid are selected to analyze these cases:



(a) Frontal Mesh Grid (Mesh number: 4,050,000)



(b) Mesh Grid Adjacent to the Fuel Channels

Fig. 5 Mesh configuration for CANDU-6 and the scaled-down model.

5.1.2 Boundary conditions

Flow boundary condition is applied to 8 inlet surfaces and outlet boundary condition to 2 outlet surfaces. The moderator enters the calandria with the average velocity of 2.05 m/s and 0.46 m/s, 0.72 m/s at nozzle exit respectively, through each inlet nozzle for the CANDU-6 and scaled-down models with thermal power of 0.5 MW and 1.566 MW, respectively. An axial power profile is a symmetric cosine profile with a peak-to-average ratio of 1.4. Actual radial power profile approximated by a quadratic polynomial (as shown in Fig. 6).

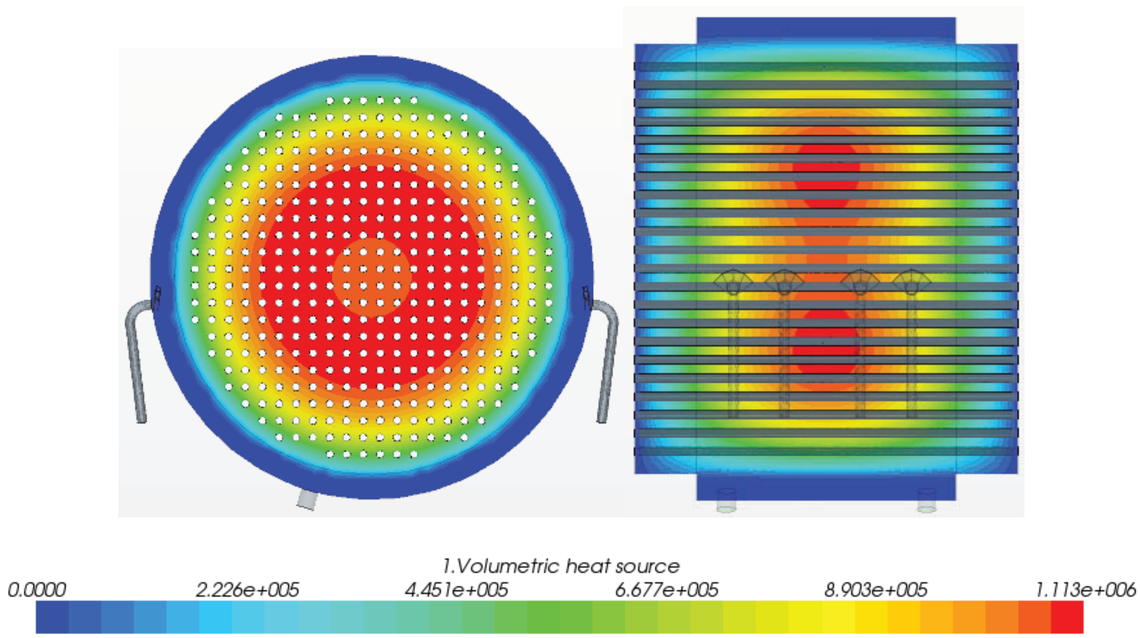
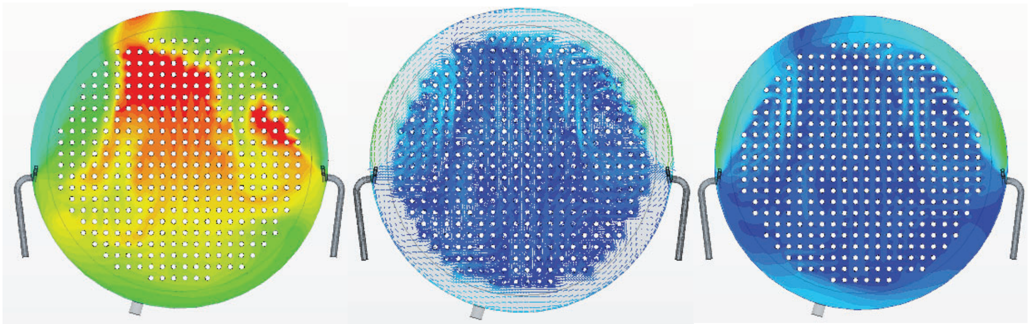


Fig. 6 Volumetric Heat Distribution in the radial and axial direction for CANDU-6 (W/m^3)

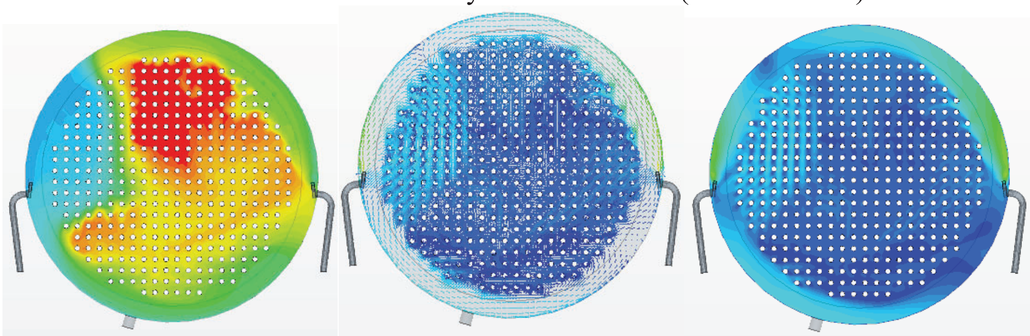
5.1.3 Calculation results

The results of the CFD analysis show that the flow and temperature pattern of the scaled-down facility is similar to those of CANDU-6, except that the hot spot at the ceiling between 11 and 12 o'clock direction of CANDU-6 at Fig.7(a) does not appear at the scaled-down case at Fig.8(a). The point of two opposing inlet jets collision at the ceiling is well matched at the 11 o'clock direction in both cases, and the overall velocity scalar contours of both cases also look similar. In the authors' opinion, there seems to be a reasonable similarity in the moderator flow circulation and the temperature distribution exists between CANDU-6 and MCT based on this result.



(a) Temp. Distribution (b) Velocity Vector Profile (c) Velocity Scalar Contour

Fig. 7 Temperature and Flow Distribution at the Axially Middle Plane for CANDU-6 Moderator Circulation at a Full Power Steady State Condition (STAR-CCM+).



(a) Temp. Distribution (b) Velocity Vector Profile (c) Velocity Scalar Contour

Fig. 8 Temperature and Flow Distribution at the Axially Middle Plane for a 1/4 Scaled-down MCT at a Steady State Condition with 0.5 MW (STAR-CCM+).

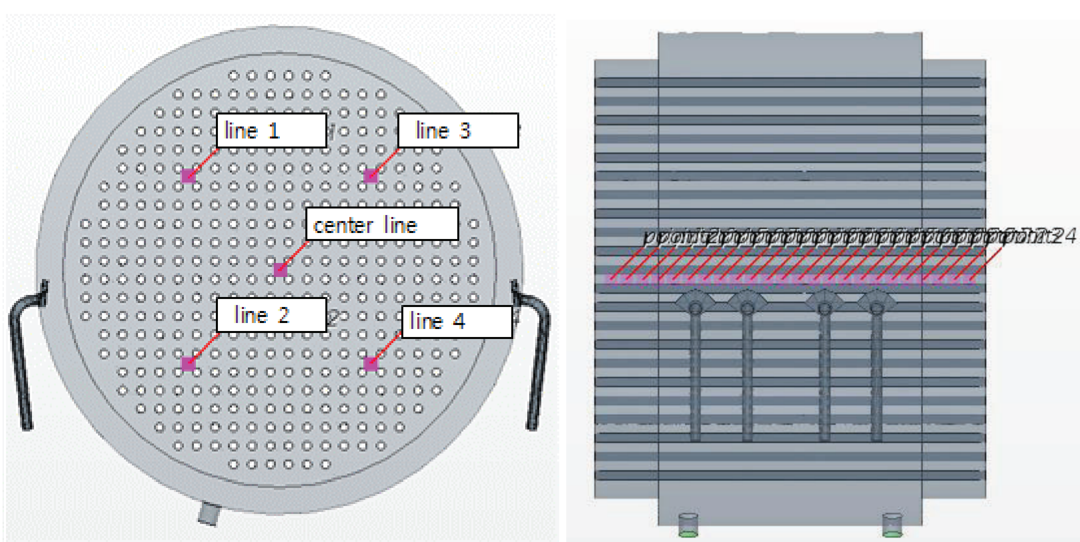


Fig. 9. Locations where the similarity condition of eq(3.10) for CANDU-6 and MCT will be compared

6. CONCLUSIONS

The objective of building a scaled-down moderator tank of a CANDU-6 reactor is to generate the experimental data necessary to validate the computer codes which are used to analyze the accident analysis of CANDU-6 plants. To this end a scaled-down facility of the moderator tank of a CANDU-6 reactor, the Moderator Circulation Test (MCT) facility, was designed and erected at KAERI. A test plan to obtain the experimental data that are necessary to validate the CFD codes to simulate the 3-D moderator circulation and temperature fields inside the moderator tank of CANDU-6 reactor is described. On the other hand the authors are still striving to find the conditions for the scaled-down test facility, MCT, to meet the hydrodynamic similarity, and proposed one. As a way to confirm if the similarity condition can be satisfied in the proposed test condition of MCT, a series of CFD analyses of the CANDU-6 moderator and MCT steady state operating conditions are performed and compared. As the results of the CFD analyses showed that the flow and temperature pattern of the scaled-down facility is similar to those of CANDU-6, and the criteria of hydrodynamic similarity proposed is planned to confirmed based on the CFD results. Due to the complex geometry of the CANDU-6 moderator tank, numerous experimental limitations for quantifying the inlet jet development, buoyancy force, and viscous friction against the flow across the calandria tube array have been encountered. To overcome these limitations, several new experimental methods have been devised and proposed to generate the experimental data to validate the CFD codes and their models which are critical to capture the key phenomena important to reactor safety.

ACKNOWLEDGMENTS

This work has been financially supported by the National Research Foundation of Korea (NRF). The grant number is 2012M2A8A4025964.

REFERENCES

1. H.Z. Fan, R. Aboud, P. Neal and T. Nitheanandan, "Enhancement of the Moderator Subcooling Margin using Glass-peened Calandria Tubes in CANDU Reactors," *Proc. 30th Annual Conf. Canadian Nuclear Society*, Calgary, Canada, May 31-June 3, 2009.
2. G.E. Gillespie, "An Experimental Investigation of Heat Transfer from a Reactor Fuel Channel: To Surrounding Water," *Proc. 2nd Annual Conf. Canadian Nuclear Society*, Ottawa, Canada, 1981.
3. Hyoung Tae Kim and Bo Wook Rhee, "Scaled-Down Moderator Circulation Test Facility at Korea Atomic Energy Research Institute," Science and Technology of Nuclear Installations, Article ID 760870, Hindawi Publishing Corporation, 2015.
4. H.F. Khartabil and et. al., Three-Dimensional Moderator Circulation Experimental Program for Validation of CFD Code MODTURC_CLAS,21th CNS Nuclear Simulation Symposium, 2000.
5. L.N. Carlucci, V.Agranat, G.M. Waddington, H.F. Khartabil and J. Zhang, "Validation of the MODTURC_CLAS Moderator Circulation Code for CANDU 9 Steady-State and Transient Conditions," 21st CNS Nuclear Simulation Symposium, Ottawa, September 24-26, 2000.
6. Bo W. Rhee, H.T. Kim, "Derivation of the Scaling Criteria for a Small Scale CANDU Moderator Test Facility," Transactions of the KNS Spring Meeting, Jeju, Korea, May 17-18,2012.
7. B.W. Rhee, H.T. Kim, S.K. Park, J.E. Cha, H-L Choi "A Scaling Analysis of a CANDU-6 moderator tank scaled-down test facility," Proceedings of the 21th International Conference on Nuclear Engineering, ICONE21, July 29-August 2, 2013, Chengdu, China
8. M.D. Atkins, T. Kim, "Isotropic-planar illumination for PIV experiments," *Experiments in Fluids* 56(3) (2015):63.