Three-Dimensional Moderator Circulation Experimental Program for Validation of CFD Code MODTURC_CLAS

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Abstract

Detailed predictions of moderator flow patterns and the associated temperature distributions in the calandria of Ontario Power Generation Inc. (OPGI) reactors are performed for safety analysis of certain accident scenarios. The specialized computational fluid dynamics (CFD) code MODTURC_CLAS-IST V2.9 has been selected as the Canadian nuclear industry tool for performing these predictions. To close all gaps in the validation data base, a robust program of three-dimensional moderator circulation experiments is being conducted for OPGI at AECL's Chalk River Laboratories.

The program is divided into a separate-effect and component-testing stage, and a quarter-scale, calandria model, integral testing stage. The separate-effect and component experiments, performed in specially designed test sections and test loop configurations, include the round jet development test, moderator inlet diffuser characterization, tube bank pressure loss experiments, wall jet development studies and buoyant-jet experiments. The main Moderator Test Facility (MTF) will be used to conduct the integral quarter-scale calandria flow experiments. A series of such tests will be conducted, covering reactor conditions representative of 0 to 100% full power, with both 8 and 12 moderator inlet nozzle configurations. Transient tests are being devised that will provide data for the validation of the transient modeling capabilities of MODTURC_CLAS-IST V2.9.

The first series of separate-effect tests, involving pressure drop measurements for tube bundles accurately representing the CANDU calandria tube arrangement, has been completed and the results will be presented.

INTRODUCTION

The moderator system in a CANDU reactor is a low-pressure system that is separate from the primary heat transport system (Figure 1). The moderator-circulation system ensures that heat deposited in the moderator is removed so that a certain amount of subcooling is maintained during normal operation. Detailed predictions of the moderator-circulation patterns, and the associated temperature distribution in a CANDU reactor calandria is necessary for performing safety analysis of certain accident scenarios. These predictions are performed using the specialized computational fluid dynamics (CFD) code MODTURC_CLAS-IST V2.9.

The objective of the moderator circulation experimental program is to generate benchmark data to validate the CFD code MODTURC_CLAS_IST V2.9 for OPGI reactors. The facilities used to conduct the validation tests were designed to reproduce the important characteristics of moderator circulation and heat transfer in a CANDU reactor calandria under a range of operating conditions. The test program consists of: 1) separate-effect tests, and 2) integral tests.

The integral tests will be conducted in the Moderator Test Facility (MTF), that was constructed to study moderator circulation in CANDU reactors. The separate-effect tests will be conducted in specially designed loops and test sections that were incorporated into the MTF. This paper provides detailed descriptions of the test facilities and test program, and some preliminary results from the separate-effect tests.

SCALING OF THE TEST FACILITIES

In this section, the basis for deriving experimental conditions for a scaled facility is presented. If the fluid is to behave in a dynamically similar fashion in two different systems, the governing equations, boundary conditions, and geometry in both systems must be equivalent. The conventional procedure to derive the parameters that provide this similarity is to write the conservation equations and boundary conditions in non-dimensional form.

The heavy water moderator flow in a CANDU calandria under normal operating conditions is adequately described by the following equations for conservation of mass, momentum, and energy, respectively:

$$\nabla \cdot V = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + (V.\nabla)V = -\frac{1}{\rho_{ref}}\nabla P + \frac{\mu}{\rho_{ref}}\nabla^2 V + g\left(\frac{\rho - \rho_{ref}}{\rho_{ref}}\right) \tag{2}$$

$$\frac{\partial T}{\partial t} + (V.\nabla)T = \frac{k}{\rho_{ref} C_P}\nabla^2 T + \frac{q}{\rho_{ref} C_P} \tag{3}$$

where:

V	=	fluid velocity vector (m/s)
ρ	=	fluid density (kg/m^3)
ρ_{ref}	=	reference density (kg/m^3)
P	=	fluid pressure minus the static head at the reference density (Pa)
T	=	fluid temperature (^{o}C)
t	=	time (s)
g	=	gravity vector (m/s^2)
μ	=	fluid dynamic viscosity (kg/m/s)
k	=	thermal conductivity (W/m^{o}C)
C_P	=	specific heat (J/kg^{o}C)
q	=	local heat generation rate (W/m^3), a function of space and time.

The fluid is assumed to be incompressible and with constant properties, with the exception of the effect of density variations in driving the flow through buoyancy forces. Note that the equations are coupled via the last term in the momentum equation (equation (2)), representing the net buoyancy force on the fluid, due to the variation of fluid density with temperature.

By introducing the following system parameters:

U_i = inlet velocity magnitude (m/s)
ρ_{ref} = reference fluid density (evaluated at the reference temperature) (kg/m^3)
D = vessel diameter (m)
T_o = outlet fluid temperature (^{o}C)
ΔT = T_o - T_i (temperature difference between inlet and outlet) (^{o}C),

The following non-dimensional variables are defined:

V* = V/U_i
T* = $(T-T_{ref})/\Delta T$ (T_{ref} based on the outlet temperature)
P* = $P/(\rho_{ref} U_i^2)$
t* = tU_i/D
∇* = $D\nabla$

The final dimensionless equations are

$$\nabla^* \cdot V^* = 0 \tag{4}$$

$$\frac{\partial V^*}{\partial t^*} + (V^*.\nabla^*)V^* = -\nabla^* P^* + \frac{1}{\text{Re}}(\nabla^*)^2 V^* + \frac{gD}{U_i^2}\left(\frac{\rho - \rho_{ref}}{\rho_{ref}}\right) \tag{5}$$

$$\frac{\partial T^*}{\partial t^*} + (V^*.\nabla^*)T^* = \frac{1}{\text{Re}\,\text{Pr}}(\nabla^*)^2 T^* + q^* \tag{6}$$

where equations (4) to (6) correspond respectively to equations (1) to (3). Typically, in the analysis of buoyant flows, the density difference expressed in the last term of equation (5) is related to the temperature difference through the volumetric thermal expansion coefficient

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T} \approx -\left(\frac{\rho - \rho_{ref}}{\rho_{ref}(T - T_{ref})}\right) \tag{7}$$

This treatment is appropriate in the following analysis to derive conditions in the scaled test facility. Therefore, equation (5) may be approximated as

$$\frac{\partial V^*}{\partial t^*} + (\nabla^*.V^*)V^* = -\nabla^* P^* + \frac{1}{\text{Re}}(\nabla^*)^2 V^* - Ar\frac{g}{|g|}T^* \tag{8}$$

It can be seen that equations (4), (6), and (8) are completely determined by the following parameters:

Re (Reynolds number) = $\rho_{ref} U_i D/\mu$ (9)
= ratio of inertial to viscous forces in the fluid

Pr (Prandtl number) $= \mu C_P/k$ (10)
= ratio of momentum to thermal diffusivity

Ar (Archimedes number,) $= |g|\beta_{ref}\, \Delta T\, D/U_i^2$ (11)
= ratio of buoyancy to inertial forces

In addition to these dimensionless parameters, the solution is dependent upon the dimensionless heat source:

$$q^* = \frac{q(x,y,z,t)D}{\rho_{ref} C_P U_i \Delta T} \tag{12}$$

= local ratio of energy generation to energy transport by advection.

Analysis of Non-dimensional Groups Characterising the System

As summarised in the previous section, exact fluid dynamic similarity between the CANDU system and a scaled facility is ensured if the following conditions are met:

- geometrical similarity, including the similarity of the heat distribution q*,
- equivalent dimensionless boundary conditions (specified temperatures, velocity profiles at inlet and outlet), and
- equivalence of the following dimensionless quantities: Re, Re Pr, Ar, and q*.

The core-averaged heat generation q^*_{ave} is given by:

$$q^*_{ave} = \frac{\int_{core} q^* dV}{Core\ \ volume} \tag{13}$$

Note that if geometric similarity is maintained, an energy balance on the system ensures that q_{ave}* similarity is maintained.

Assuming geometric similarity is maintained and the working fluid chosen has similar fluid properties (thus providing similar Prandtl numbers), there are three independent variables that have to be determined for the test facility: 1) the vessel diameter (D), 2) the temperature difference between the inlet and outlet (ΔT), and 3) the inlet velocity (U_i). These three quantities may be determined by specifying the scale of the facility, and maintaining Ar and Re equivalence.

Consider the following relationships for Re and Ar equivalence in the two facilities (obtained from rearranging Equations (9) and (11))

$$\frac{U_{i,F}}{U_{i,C}} = \left(\frac{D_C}{D_F}\right)\left(\frac{\rho_C \mu_F}{\rho_F \mu_C}\right) \tag{14}$$

$$\frac{\Delta T_F}{\Delta T_C} = (\frac{U_{i,F}}{U_{i,C}})^2 (\frac{D_C}{D_F}) \frac{\boldsymbol{b}_C}{\boldsymbol{b}_F} \tag{15}$$

where the subscripts *C* and *F* refer to the calandria and test facility, respectively.

Assuming that the facility is to be reduced in scale, it can be seen from equation (14) that in order to maintain Reynolds number equivalence, the facility inlet velocity increases in direct proportion to the diameter decrease. In turn, from equation (15), the ratio of the temperature difference increases with the third power of the ratio of the diameters, a system requirement that becomes untenable for any significant reduction in scale.

The above analysis demonstrates that while it is theoretically possible to maintain equivalence of all dimensionless groups, it is not a practical requirement. The approach taken in scaling the MTF is to ensure equivalence of the most important parameters: the ratio of buoyancy to inertial forces (equation (11)), and the non-dimensional volumetric heat generation rate (equation (12)). In addition, ΔT and the facility scale were specified such that the required energy input is feasible, while the Reynolds number is sufficiently large to ensure that the flow throughout the facility is turbulent. The impact of not maintaining Reynolds number equivalence is that the relative contributions of momentum and energy diffusion in equations (6) and (8) are not the same. However, by ensuring turbulent flow throughout the vessel, the relative contributions of these diffusion processes to the overall balances is negligible.

TEST FACILITIES

Figure 2 shows a schematic of the test facilities that will be used to conduct the separate-effect and integral tests. The integral tests will be conducted in the Moderator Test Facility (MTF) while the separate-effect tests will be conducted in other test sections incorporated into the MTF. Following is a description of the test facilities in Figure 2.

Moderator Test Facility (MTF)

The MTF is the main test facility that will be used to conduct integral steady-state and transient tests. It is a ¼-scale, three-dimensional CANDU calandria model (Figure 3) capable of simulating moderator circulation under steady-state and transient conditions. The scale of the facility was selected using the scaling considerations from the previous section.

The MTF vessel has sufficient flexibility to allow simulation of the various inlet nozzle configurations used for different moderator circulation designs. Figure 4 shows the inlet nozzle and outlet port locations for the OPGI reactors. The fuel channels are simulated using electric heaters designed to provide axial and radial power profiles representative of CANDU reactor power profiles. Power to the heaters is provided by a 1.7 MW DC power supply.

An access tank on top of the vessel allows point temperature and velocity measurements inside the vessel. As shown in Figure 3, several transparent sections are incorporated into the vessel to facilitate flow visualization tests.

Separate-Effect Test Loops

The separate-effect test loops were incorporated into the MTF main loop to study specific phenomena relevant to moderator circulation, and to provide boundary condition data (e.g., inlet nozzle velocity profile). The separate-effect loops include the following:

Tube Bank Test Loop

The purpose of the tube bank test loop is to provide pressure loss data at conditions (geometry and Reynolds number) representing moderator flow over the calandria tubes. Three test sections having the same pitch-to-diameter ratio as that of the reactor pressure tubes are used: 1) flow at 90^o to the tubes, 2) flow at 60^o to the tubes, and 3) flow at 30^o to the tubes. Figure 5 shows a schematic of the tube bank test sections.

Single-Nozzle Test Loop

The single-nozzle test loop allows three-dimensional velocity distribution measurements of a jet issuing from a single nozzle immersed in water. It is used primarily to obtain velocity profiles at the exit of a scaled moderator inlet nozzle; these velocity profiles provide the inlet nozzle boundary condition for code simulations. It can also be used to study jet behavior in a confined enclosure. Figure 6 shows a schematic of the single-nozzle test section.

Jet Development Test Loop

The jet development test loop was designed to study the behavior of up to four jets issuing from ¼-scale CANDU moderator inlet nozzles. This test loop provides three-dimensional velocity measurements to study jet spreading along a curved surface, and the interaction between neighboring and opposing jets. Figure 7 shows a schematic of the jet development test section.

Buoyancy Test Loop

The buoyancy test loop was designed to study round-jet behavior in a non-isothermal environment. It has the capability of injecting two opposing jets at different temperatures and/or flowrates. Figure 8 shows a schematic of the buoyancy test section. The measurements from this test section include three-dimensional velocity and temperature distributions, and can be used to validate buoyancy models.

Instrumentation and Control

The above facilities are thoroughly instrumented to provide data suitable for code validation. The test conditions are tightly controlled (generally within the uncertainty of the instruments) using a PC-based data acquisition and control system (DAS). The instrumentation can be divided into loop and test-section instrumentation.

Loop Instrumentation and Control

The loop instrumentation consists of flowrate, temperature, and pressure measurements. The flowrate to individual inlet nozzles (e.g., integral tests and jet spreading tests) are automatically controlled by the DAS. The inlet temperature to any of the test sections can be controlled using the heat exchanger in Figure 2.

Test Section Instrumentation

The test section instruments consist of pressure cells, fixed thermocouples, movable thermocouples, and a three-component Laser Doppler Velocimetry (LDV) system. For the integral tests, the power applied to the heaters is also measured.

The pressure cells are used to measure pressure losses (e.g., tube banks tests). The fixed and movable thermocouples are used to measure temperature distribution (e.g., buoyancy tests and integral tests with heat addition). The LDV system is used to perform three-component velocity and turbulence measurements.

TEST PROGRAM

Separate-Effect Tests

Tube Bank Tests

The objective of the tube bank tests is to obtain tube-bank pressure loss coefficients in a tube-bank with a pitch-to-diameter ratio equal to that of CANDU moderator calandria tube array. The effect of moderator flow across the calandria tubes at different angles can be investigated using the test sections shown in Figure 5 (flows at 30, 60, and 90 degrees to the tubes). The test section with no tubes is used as reference. The results from these tests can be used to assess the pressure-loss model used in the code.

Round Jet

The round-jet tests are performed in the single nozzle test facility using a scaled replica of the nozzle used in a reference test performed by Hussein, George and Capp [1]. The nozzle was designed to ensure a top-hat velocity profile at the exit. The water circulation system was designed to supply an inlet flow rate corresponding to a Reynolds number of approximately 9.6×10^4 at a constant inlet temperature. Three-component velocity and turbulence measurements are taken at the nozzle exit, and downstream of the nozzle. The measurements may be compared to similar measurements reported in the literature, and to code predictions.

Inlet Nozzle Characterization

These tests are performed in the single-nozzle loop using a half-scale moderator inlet nozzle at a Reynolds number representative of in-reactor conditions. Three-component velocity and turbulence measurements are taken at the exit plane of the nozzle. The results will be used to establish the appropriate velocity boundary condition in the code simulations.

Jet Development on a Curved Surface

The wall-jet development tests will be performed in the jet-development test loop. The jet-development tests consist of four test configurations: 1) single developing wall jet, 2) two parallel developing wall jets, 3) two opposing developing wall jets, and 4) two pairs of opposing wall jets. For each configuration, three-component velocity and turbulence measurements at a large number of locations will be taken at several Reynolds numbers.

Buoyancy Tests

The buoyancy tests will be performed in the buoyancy-test loop using the same vessel used for the jet-development tests. The buoyancy-test loop injects hot and cold water from two opposing round nozzles. Temperature distribution (transient and steady-state) and three-component velocity and turbulence measurements (if steady-state is obtained) will be taken at test conditions with different Archimedes numbers (i.e., different ratios of buoyancy to inertia forces). The measurements may be used to validate predictions of the interaction of buoyancy and inertia forces without the presence of tubes in the flow field.

<u>Integral Tests</u>

The objective of the integral tests is to obtain validation data, based on combined phenomena under a wide range of operating conditions. The tests will cover moderator inlet-nozzle configurations representative of operating OPGI CANDU reactors (eight or twelve inlet nozzles). Steady-state and transient tests are planned. In the steady-state tests, three-component velocity and turbulence measurements and temperature-distribution measurements will be taken inside the vessel. In the transient tests, temperature-distribution measurements only will be taken.

Twelve-nozzle configuration

The twelve-inlet nozzle tests correspond to full-power conditions in the Darlington Nuclear Generation Stations. Two steady-state tests are planned for this configuration. In the first test, the total flow rate will be distributed equally among all inlet nozzles; in the second test, a flow imbalance will be imposed so that the flow distribution will correspond to a bank-to-bank difference of 55%-45% (*i.e.*, 55% of the total flow will be supplied to one bank of inlet nozzles only).

Eight-nozzle configuration

The eight inlet-nozzle tests correspond to zero power, full power and 50% full power conditions in Pickering B and Bruce B Nuclear Generation Stations. Five steady-state and two transient tests are planned for this configuration:

a) isothermal test with the total flow rate distributed equally among all inlet nozzles,

b) 50% full power conditions at Pickering B,

c) 100% full power conditions at Pickering B and 50% full power conditions at Bruce B,

d) 100% full power conditions at Bruce B,

e) a set of sensitivity tests to capture the transition between jet-dominated and buoyancy-dominated flow patterns,

f) a transient test which corresponds to a power rundown over a specified period while maintaining flow constant at the initial nominal value, and

g) a transient test which corresponds to a power rundown over a specified period in conjunction with flow rundown due to a pump trip.

TUBE BANK TEST RESULTS

The first series of the separate-effect tests to study tube-bank flow resistance were completed. The test conditions covered a Reynolds number range of approximately 5000 to 50 000, and three different flow angles to the tubes: 30, 60, and 90 degrees.

Each test consisted of 25 measurements spanning the Re range from approximately 5000 to 50 000. The following measurements were taken:

a) loop flowrate,
b) test section inlet and outlet temperatures,
c) test section pressure losses, and
d) other loop parameters used for online monitoring.

The results from the 90^o flow angle are shown in Figure 9 where the Reynolds number (Re) is defined as:

$$\mathrm{Re} = \frac{r\,\mathrm{V}\,\mathrm{d}}{m}$$

where r is the fluid density, V is the free-stream velocity, d is the tube diameter and μ is the fluid viscosity. The pressure loss coefficient is defined using:

$$\mathrm{DP} = \frac{1}{2}\, r\, \mathrm{V}^2\, \mathrm{Y}$$

where DP is the pressure drop per row of tubes, and Y is the pressure loss coefficient (PLC). The results are compared to three correlations from the literature [2,3], where it can be seen that good agreement is obtained at low and high Reynolds numbers. Over the low end of the Reynolds range the new data agrees with the results reported in [2], where an identical pitch-to-diameter ratio was used, but with a maximum Re of approximately 10000. Over the high end of the Reynolds number range covered (40 000 to 50 000), the new data agrees with one of the correlations proposed in [3].

The effect of flow angle is shown in Figure 10, where it can be seen that the PLC decreases with decreasing flow angle, as expected. The relative reduction in PLC was in good agreement with results presented in [3] (within $\pm$ 3%). The following correlations were obtained from the test results:

Flow at 90^o to tubes: $PLC_{90} = 9.52\ Re^{-0.258}$
Flow at 60^o to tubes: $PLC_{60} = 6.09\ Re^{-0.231}$
Flow at 30^o to tubes: $PLC_{30} = 2.33\ Re^{-0.218}$
($5000 < Re < 50\ 000$)

The consistency of the measurements was checked through repeat tests performed at similar flow conditions. Furthermore, the sum of the pressure losses measured by DP-cells #1 through 5 (see Figure 5) were compared to the total test section pressure drop, DP-cell #6. To ensure that the data used in correlation development did not include tube bank entrance or exit losses, only the DP-cell #4 measurements were used. Comparing the DP-cell #4 results to the other pressure drop measurement clearly shows that the tube bank section was free of entrance and exit effects.

SUMMARY AND CONCLUSIONS

An experimental program to provide three-dimensional moderator circulation data simulating OPGI CANDU reactor moderator circulation was presented. The experimental data will be used to validate the specialized computational fluid dynamics (CFD) code MODTURC_CLAS-IST V2.9.

The experiments are being conducted at AECL's Chalk River Laboratories and consist of separate-effect tests, and a quarter-scale calandria model integral tests. The separate-effect tests, performed in specially designed test sections and test loop configurations, include the round jet development test, moderator inlet diffuser characterization, tube bank pressure loss experiments, wall jet development studies and buoyant jet experiments. The main Moderator Test Facility (MTF) will be used to conduct the integral quarter-scale calandria flow experiments. A series of such tests will be conducted, covering reactor conditions representative of 0 to 100% full power, with both 8 and 12 moderator inlet nozzle configurations. Several transient tests are being devised that will provide data for the validation of the transient modeling capabilities of MODTURC_CLAS-IST V2.9.

Results from the first series of the separate-effect tests, involving pressure drop measurements for tube bundles accurately representing the CANDU calandria tube arrangement, were presented.

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2. G.I. Hadaller, R.A. Fortman, J. Szymanski, W.I. Midvidy, and D. Train "Frictional Pressure Drop for Staggered and In-Line Tube Banks with Large Pitch-to Diameter Ratio", Paper presented at the 1992 CNS Symposium, Kingston, 1992.

3. A. Zukauskas, R. Ulinskas, "Banks of Plain and Finned Tubes", Chapter 2.2.4, Fluid Mechanics and Heat transfer, Heat Exchanger Design Handbook, Hemisphere Publishing Corp., 1984.

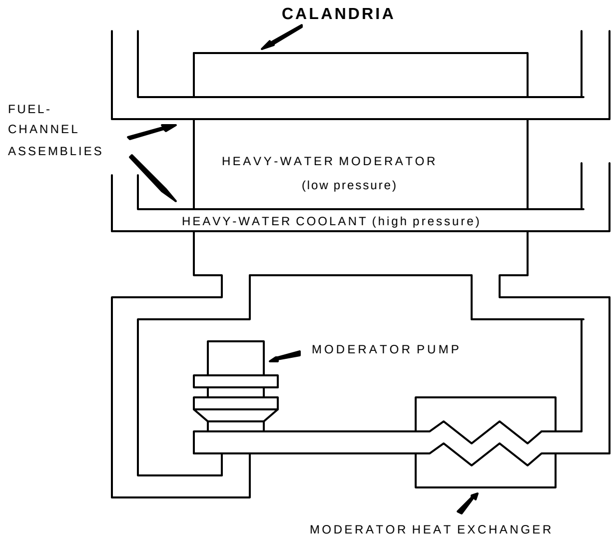

Figure 1: Moderator Circulation System

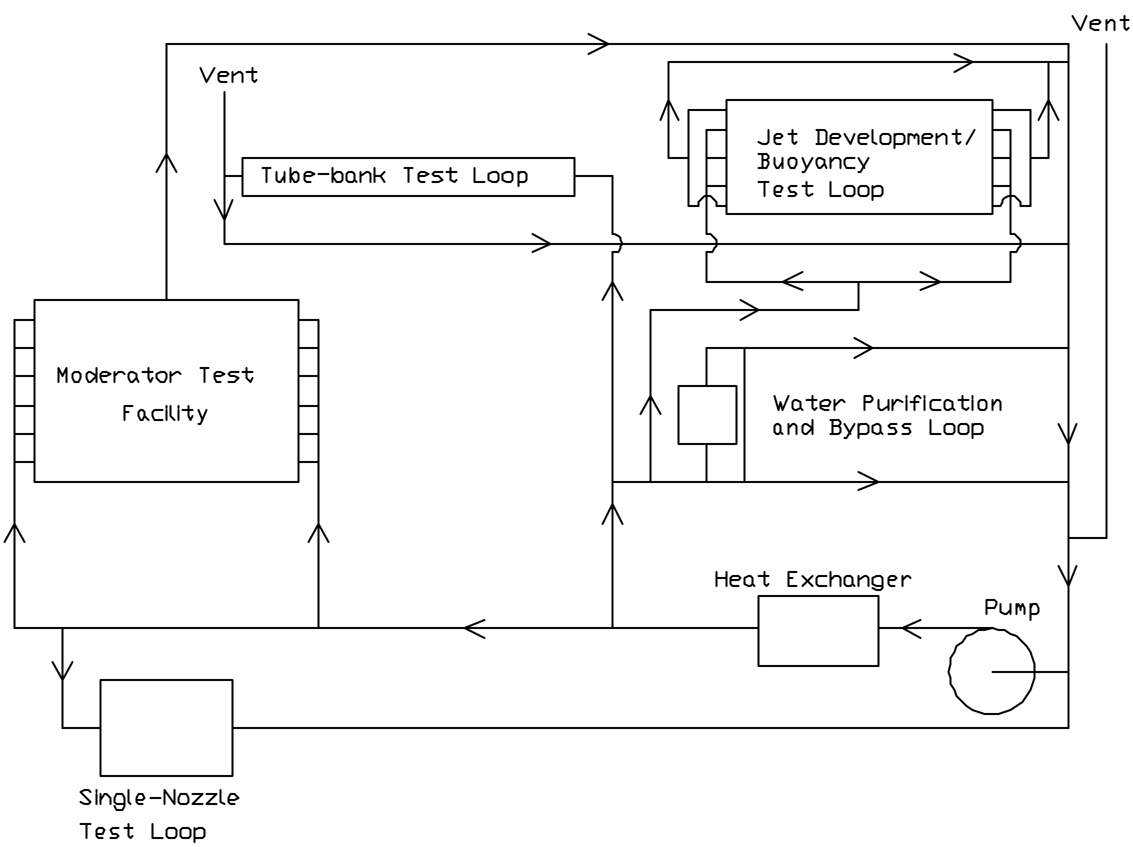

Figure 2: Schematic of the MTF and Separate-Effect Tests Loops

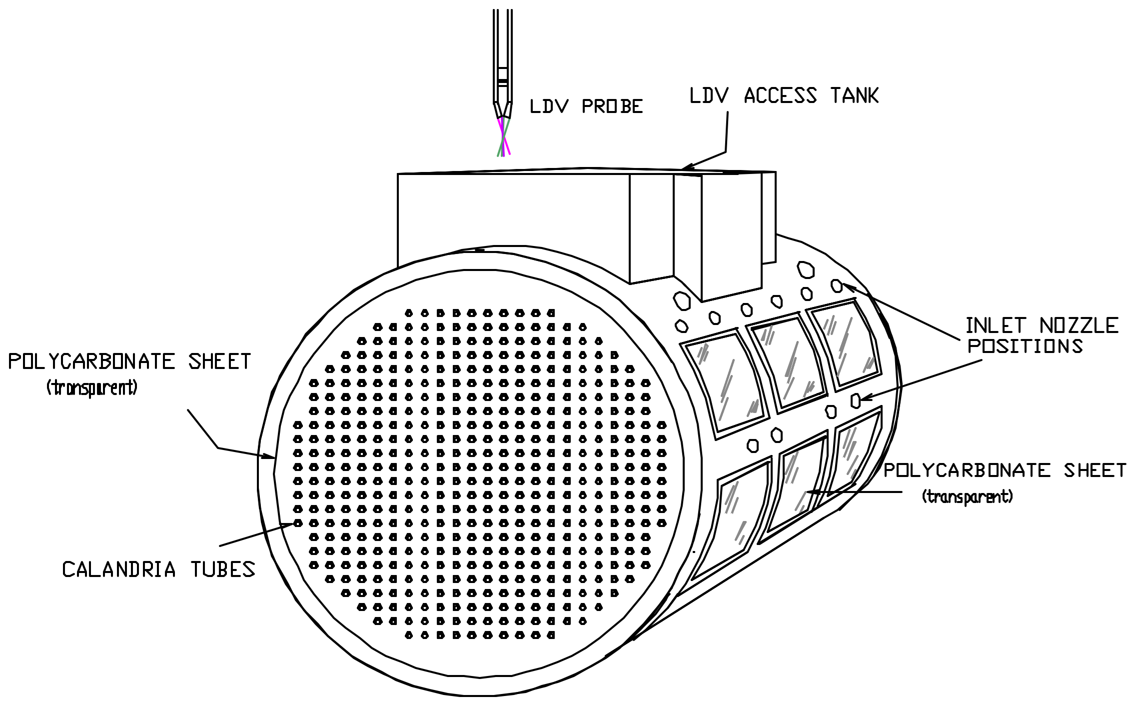

Figure 3: Moderator Test Facility

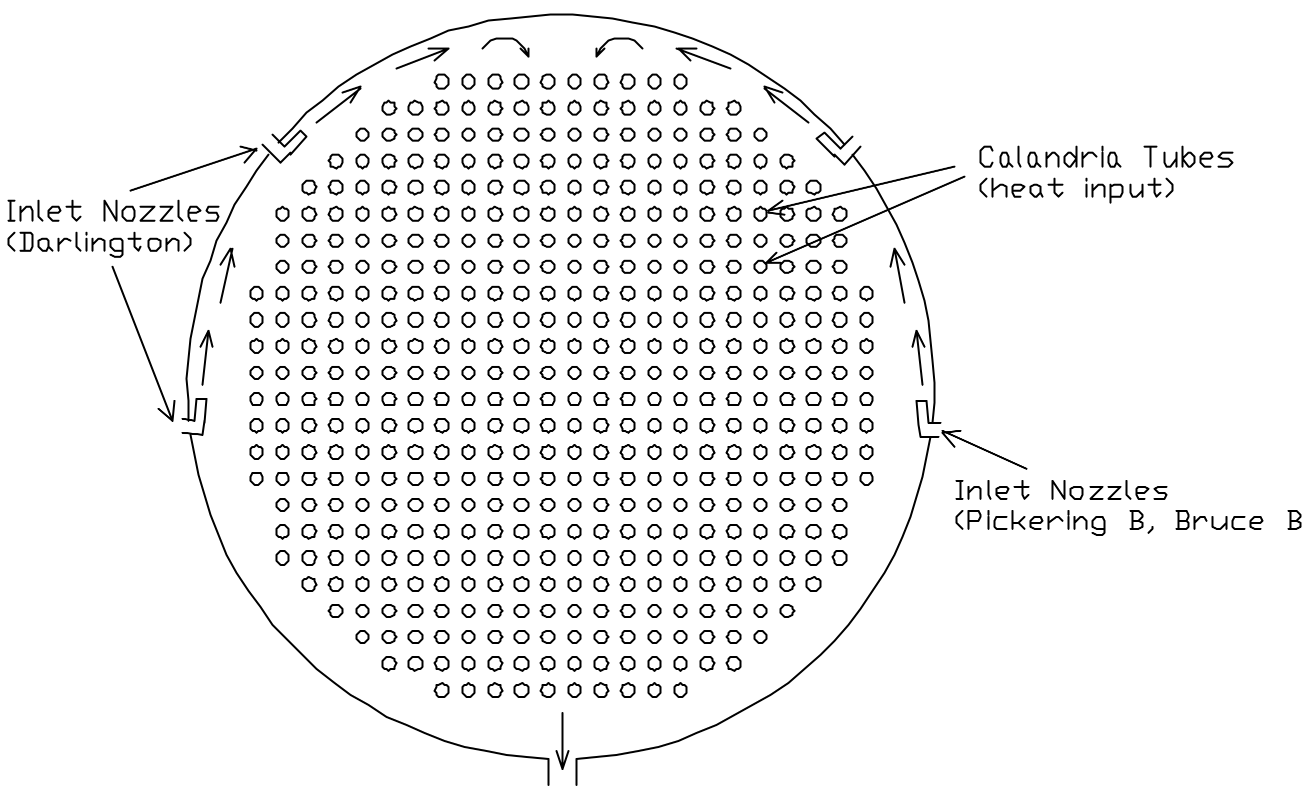

Figure 4: Moderator Circulation Patterns

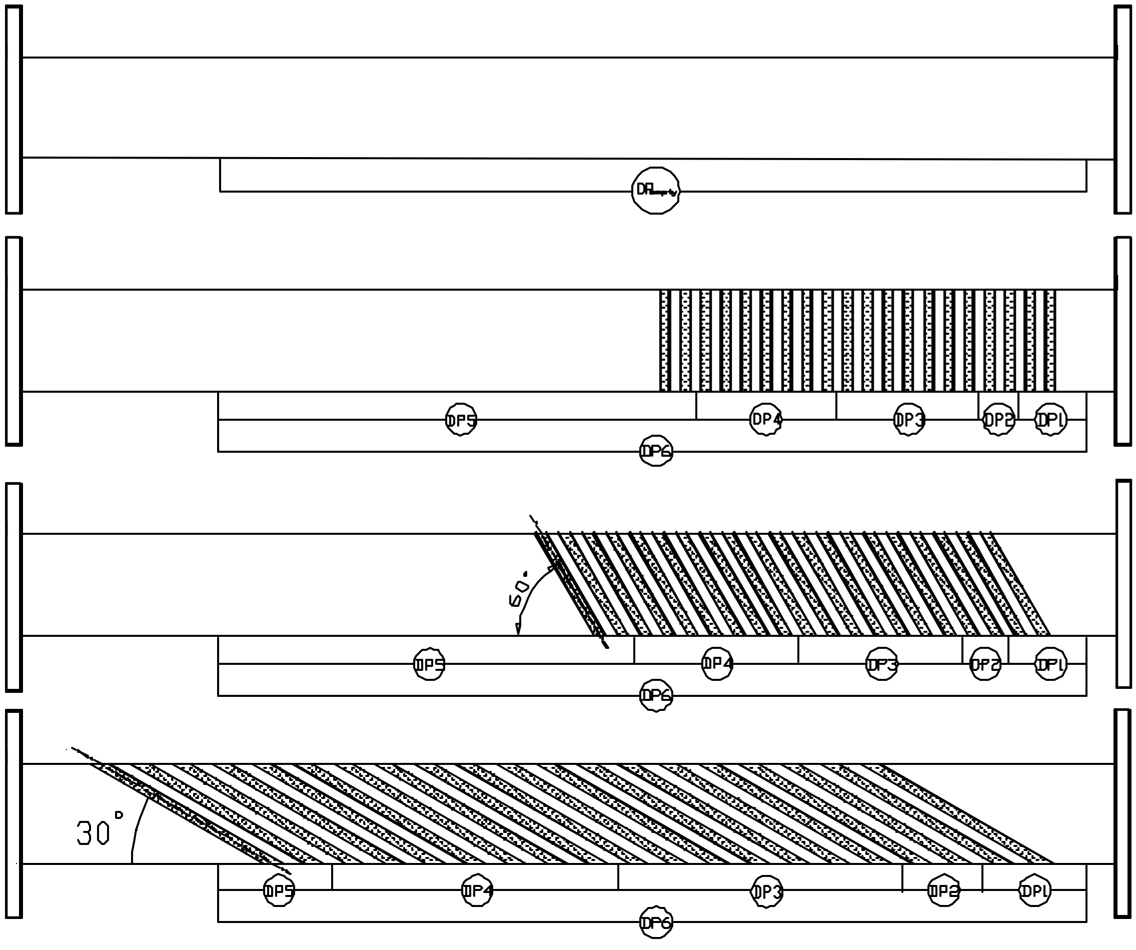

Figure 5: Tube Bank Test Sections

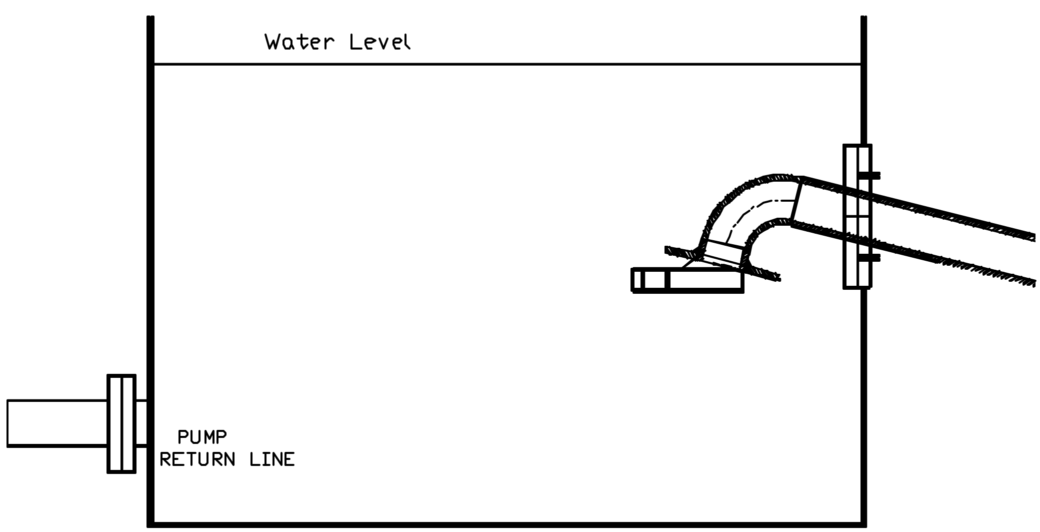

Figure 6: Single Nozzle Test Section

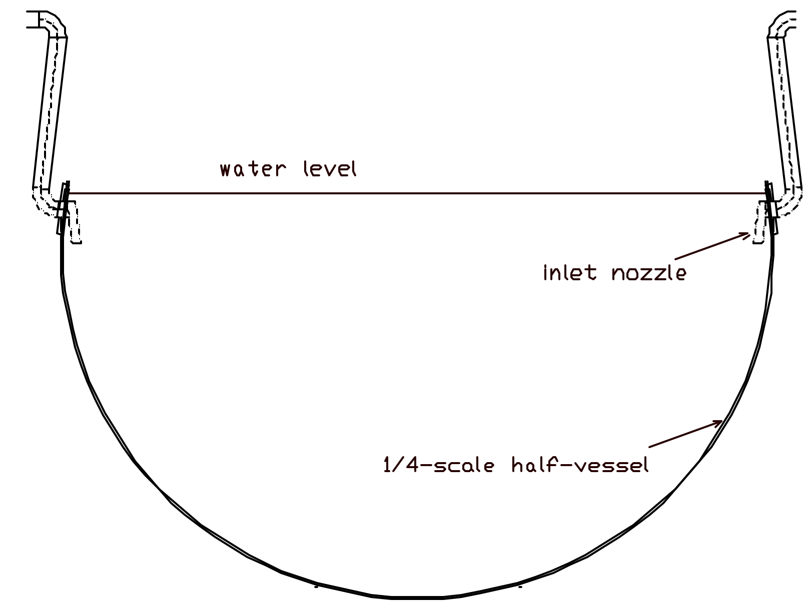

Figure 7: Jet Development Test Section

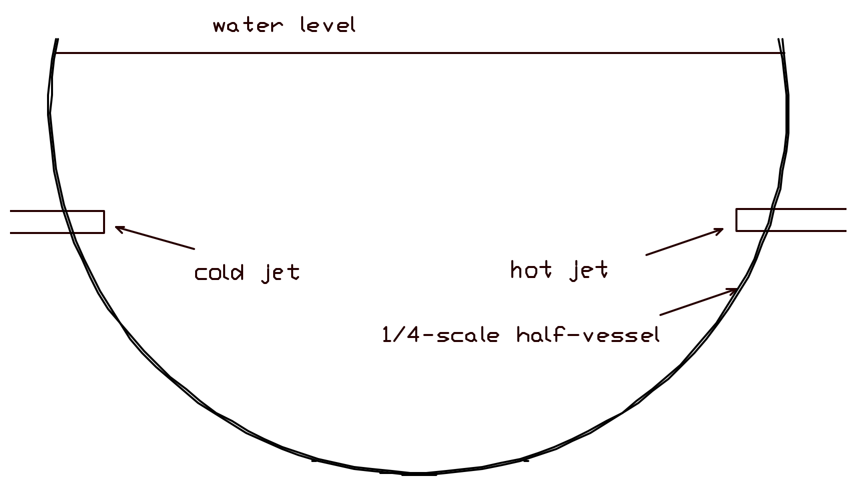

Figure 8: Buoyancy Test Section

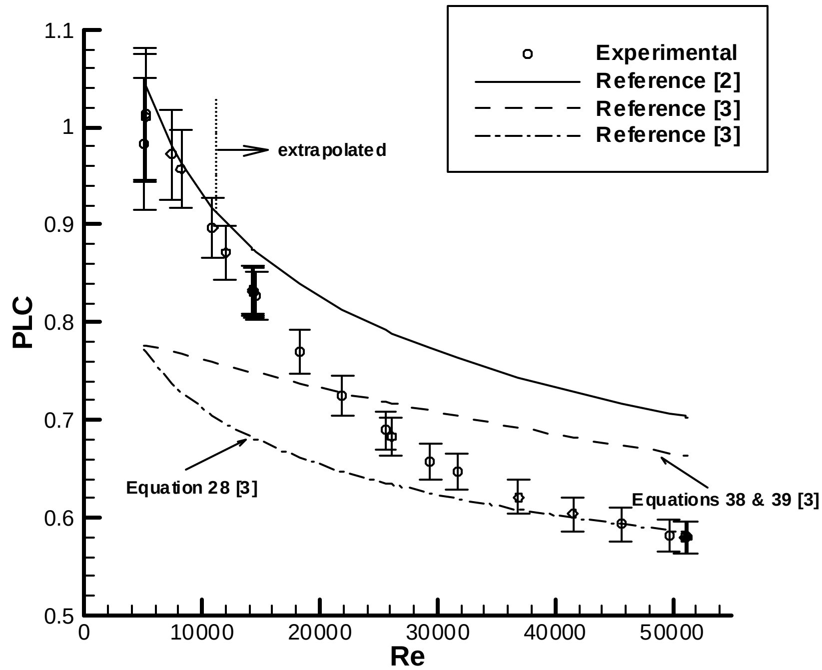

Figure 9: Tube Bank Pressure Drop Test Results

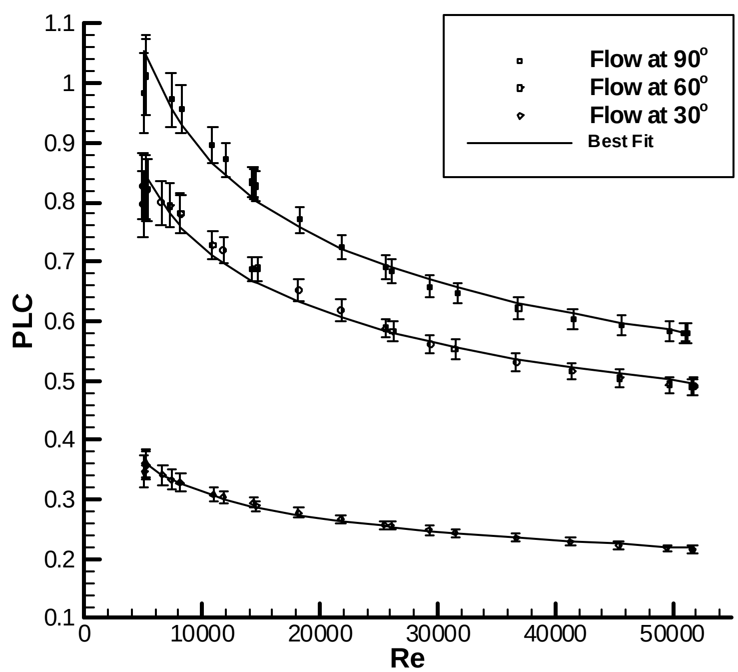

Figure 10: Effect of Flow Angle on Pressure Loss Coefficient (PLC)