Three-Dimensional Analyses of Fluid Flow and Heat Transfer for Moderator Integrity Assessment in PHWR

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ABSTRACT

A CANDU reactor has the unique features and the intrinsic safety related characteristics that distinguish it from other water-cooled thermal reactors. If there is the loss of coolant accident (LOCA) and a coincident failure of the emergency coolant injection (ECI) system, the heavy water moderator is continuously cooled, providing a heat sink for decay heat produced in the fuel. Therefore, it is one of major concerns to estimate the local subcooling of moderator inside the calandria vessel under postulated accident in CANDU safety analyses. The Canadian Nuclear Safety Commission (CNSC), a regulatory body in Canada, categorized the integrity of moderator as a generic safety issue and recommended that a series of experimental works be performed to verify the safety evaluation codes for individual simulated condition of nuclear power plant, comparing with the results of three-dimensional experimental data.

In this study, three-dimensional analyses of fluid flow and heat transfer have been performed to assess thermal-hydraulic characteristics for moderator simulation conducted by SPEL (Sheridan Park Experimental Laboratory) experimental facility. The parametric study has also carried out to investigate the effect of major parameters such as flowrate, temperature, and heat load generated from the heaters on the temperature and flow distribution inside the moderator. Three flow patterns have been identified in the moderator with flowrate, heat generation, or both. As the transition of fluid flow is progressed, it is found that the dimensionless numbers (Ar) and the ratio of buoyancy to inertia forces are constant.

1. INTRODUCTION

As for other water-cooled reactors, loss-of-coolant accidents (LOCA) in CANDU reactors can be the precursors to fuel damage, which can result in radiological consequences. However, a CANDU reactor has the unique features and the intrinsic safety related characteristics that distinguish it from other water-cooled thermal reactors. One of the safety futures is that the heavy water moderator is continuously cooled, providing a heat sink for decay heat produced in the fuel if there is a LOCA and a coincident failure of the emergency coolant injection (ECI) system. Under such dual failure conditions, the hot pressure tube (PT) would deform into contact with the calandria tube (CT), providing an effective heat transfer path from the fuel to the moderator.

Under conditions of high pressure tube temperature and high coolant pressure following

LOCA accidents, the PT could strain (i.e., balloon) to contact its surrounding CT (PT/CT contact). Following contact between the hot PT and the relatively cold CT, there is a spike in heat flux to the moderator surrounding the CT, which leads to sustained CT dryout. The prevention of CT dryout following PT/CT contact depends on available local moderator subcooling. Higher moderator temperatures (lower subcooling) would decrease the margin of the CTs to dryout in the event of PT/CT contact. As for LOCAs with coincident loss of the ECI, fuel channel integrity depends on the capability of the moderator providing the ultimate heat sink. Although a couple of computer codes such as 2DMOTH, PHOENICS, etc. were used to predict moderator temperature for these accidents, they were not adequately validated due to the uncertainty of temperature prediction. The CNSC requested to perform three-dimensional moderator test facility experiments with an aim to validate safety analysis tools.

In this study, an objective is to establish a sound theoretical basis for the models and then verifying them systematically against experiments under potential upset conditions. A three-dimensional CFD code, FLUENT, is used to simulate the moderator circulation inside the calandria-like cylindrical tank. To evaluate the uncertainties, a lot of sensitivity studies are performed for various parameters. Comparing with experiments and previous simulated results, the fluid flow and temperature distribution are evaluated under the similar fluid flow situations.

2. SPEL EXPERIMENT

SPEL experimental apparatus, which is built for the understanding of the moderator circulation inside the calandria of a CANDU reactor, is not a scaled model of a real CANDU reactor, but has salient features of a typical CANDU reactor. These features can be summarized as follows:

- matrix of horizontal tubes parallel to the cylindrical axis,
- heating of the fluid in the center region of Calandria-like tank by volumetric heat generation without boiling and thereby induced Buoyant flow, and
- re-circulating flow induced by the inlet jets in the cylindrical tank.

Thus, the fluid flow inside the cylindrical tank is expected to be the result of the interaction of momentum forces generated by the inlet jets with buoyancy forces by volumetric heat generation.

Figure 1 shows the experimental setup of SPEL small-scale moderator facility. In the central region of the cylindrical tank, 52 tubes working as electrodes make a tube matrix. Around the tube matrix, there are free spaces for moderator fluid representing reflector region. Two inlet nozzles are located upward at both left and right sides of the tank. One outlet is at the bottom of the tank. Table 1 is the summary of dimensions and characteristics of the SPEL experimental apparatus. Volumetric heat generation was achieved by electrolytic resistance heating. The working fluid was a solution of water and sodium chloride. The copper tubes forming a tube matrix in the vessel acted as the electrodes. High amperage, low voltage alternating current was passed via the tubes through the working fluid generating heat.

3. MODELLING DETAILS AND ASSUMPTIONS

To simulate the SPEL experiments, all dimensions are as close to the experimental apparatus as shown Fig. 2. The working fluid is water at 0.1MPa. The properties are set uniform and constant, independent of temperature and pressure.

For the thermal hydraulic analysis of CANDU moderator, the general purpose CFD code, FLUENT-5.5, is used to solve coincidently continuity equation, momentum equations and energy equation. The flow is assumed to be steady, incompressible and single-phase. The buoyancy effects are accounted for by the Boussinesq approximation. SIMPLEC algorithm is used, which is recommended for the flow with strong Buoyancy effect. The standard k-ε turbulence model associated with logarithmic wall treatment is used to model turbulence generation and dissipation within the vessel. Buoyancy forces are modeled using the Boussinesq approximation in which density is assumed to be a linear function of temperature. A comparison is made between previous CFD analyses based on 2DMOTH, PHOENICS, and the current analysis for the SPEL experiment. Moreover, the present moderator analysis model predicts the moderator temperature reasonably, i.e., the maximum temperature inside calandria-like tank is 40.3°C, which is somewhat lower than the SPEL experimental result of 41°C.

Figure 3 is the comparison of experimental and computed temperature along a vertical centerline. Figures 3-a and 3-b show that the temperature profiles predicted by both this study and PHOENICS is well agreed with those of the SPEL experiments. The temperature profiles decreases slightly from upper region. In the meanwhile, the temperature profile predicted by 2DMOTH is underestimated at the bottom region of the Calandria compared with that of the SPEL experiment. In Figures 3-c and 3-d, they show the predicted temperature profiles near inlet of moderator. They are shown that the temperature profile decrease sharply due to the momentum of moderator inlet flow at the regions on the flow passage of moderator. However, the temperature profile increases due to the heat generation in the Calandria and it decreases at the bottom region due to the forced convection. Both the SPEL experiment and the predicted temperature are similar results and the maximum temperature deviation between those is about 2.5□.

4. RESULTS AND COMPARISON

According to the computational results with CFD code for SPEL geometry, it is found that three flow patterns, e.g., momentum dominated flow, mixed type flow and buoyancy dominated flow, respectively, are observed in the Calandria as shown in Fig. 4. It is also noticed that the onset conditions of these flow patterns mainly depend on the heat load and inlet velocity.

Figures 5-7 show the effects of major input parameters, e.g., the inlet velocity and the temperature of moderator and the heat load generated from heaters on the temperature and velocity distribution inside Calandria. From the effect of inlet velocity of moderator shown in Fig. 5, as the inlet velocity is increased, which causes the momentum to be increased both of the maximum and the outlet temperatures are decreased. It is also noticed that the ranges of inlet velocity where the mixed type flow is observed, broaden as the heat load of heaters is increased.

In Figure 6, it is shown the effect of inlet moderator temperature. It is found that the maximum and the discharge temperatures are changed linearly with the changes of the inlet moderator temperature. It is also noticed that the inlet moderator temperature does not have a big effect on the temperature distribution inside Calandria.

When the heat load is increased, the maximum and the discharge temperatures are increased regardless of the flow patterns inside Calandria, as shown in Fig. 7 in the condition of momentum dominated flow.

Figure 8 shows the flow pattern map of moderator inside Calandria resulted from the parametric studies. It is noticed that when Ar, the ratio of buoyancy force to inertia force, is about 0.5, the flow transition from buoyancy dominated flow to mixed type flow, vice versa, while the flow transition from mixed type flow to momentum dominated flow, vice versa, in the condition of 0.08 in Ar. In other words, as the transition of fluid flow is progressed, it is found that the dimensionless numbers, Ar are constant. Therefore, it is recommended that the studies on operating condition of heavy water reactor with both buoyancy force and inertia force, following the calculation with real geometry of Calandria and the preparation of the flow pattern map should be carried out in future.

5. CONCLUSION

Three-dimensional analyses of fluid flow and heat transfer have been performed to assess thermal-hydraulic characteristics for moderator simulation conducted by SPEL experimental facility. The parametric study has also carried out to investigate the effect of major parameters such as inlet velocity, temperature, and heat load generated from the heaters on the temperature and flow distribution inside the moderator. The main conclusions are as follows;

- Three flow patterns have been observed in the Calandria with flowrate, heat generation, or both, that is, momentum dominated flow, mixed type flow and buoyancy dominated flow
- The major input parameters affecting the flow patterns inside Calandria are the inlet velocity and heat load. However, the inlet moderator temperature does not have big effect on the flow pattern.
- As the transition of fluid flow is progressed, it is found that the dimensionless numbers (Ar) and the ratio of buoyancy to inertia forces are constant.

REFERENCE

[1] K. H. Bang, J. Y. Lee, S. O. Yu, M. W. Kim, and H. J. Kim, “A Three-Dimensional Analyses of Fluid Flow and Heat Transfer for Moderator Integrity Assessment in PHWR,” Proceedings of the KNS Spring Meeting, May, Gwangju, 2002.

[2] C. Yoon, B. W. Rhee and B. J. Min, “Validation of a CFD Analysis Model for Predicting CANDU-6 Moderator Temperature Against SPEL Experiments,” Proceedings of ICONE10, April 14-18, Virginia, USA, 2002.

[3] D. Koroyannakis, R. D. Hepworth and G. Hendrie, “An Experimental Study of Combined Natural and Forced Convection Flow in a Cylindrical Tank,” TDVI-382, AECL, 1983.

Table 1. Summary of the Experimental Apparatus

	ID, [m]	OD, [m]	L, [m]	Number	Comment
Test Vessel	0.74	0.775	0.254	1	
Heater Tubes		0.038	0.254	52	0.075m square pitch

Table 2. Comparison of Experimental and Computed Temperatures

	SPEL experiments	FLUENT-5.5	2DMOTH
Inlet Temperature	30.0°C	30.0°C	30°C
Outlet Temperature	34.3 ~ 34.5°C (±0.2°C)	34.1°C	34.9°C
Maximum Temperature	41°C	40.3°C	40.4°C
$\Delta T = T_{outlet} - T_{inlet}$	5.7°C (±2.0°C)	4.1°C	4.9°C

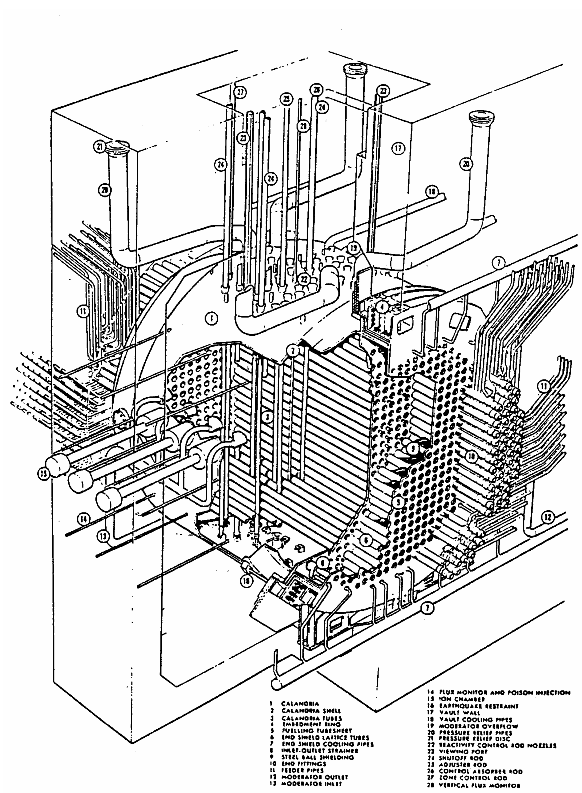
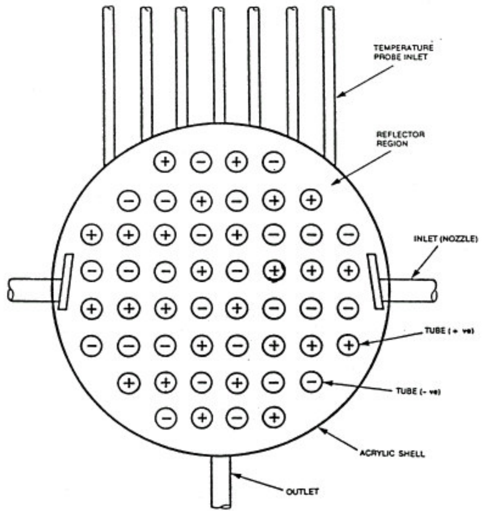
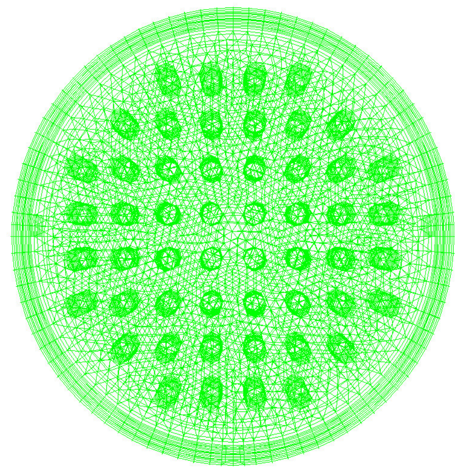


Figure 1. CANDU-6 nuclear reactor.



(a) SPEL experimental facility



(b) mesh for calculation

Figure 2. Schematic diagram of SPEL and calculation domain.

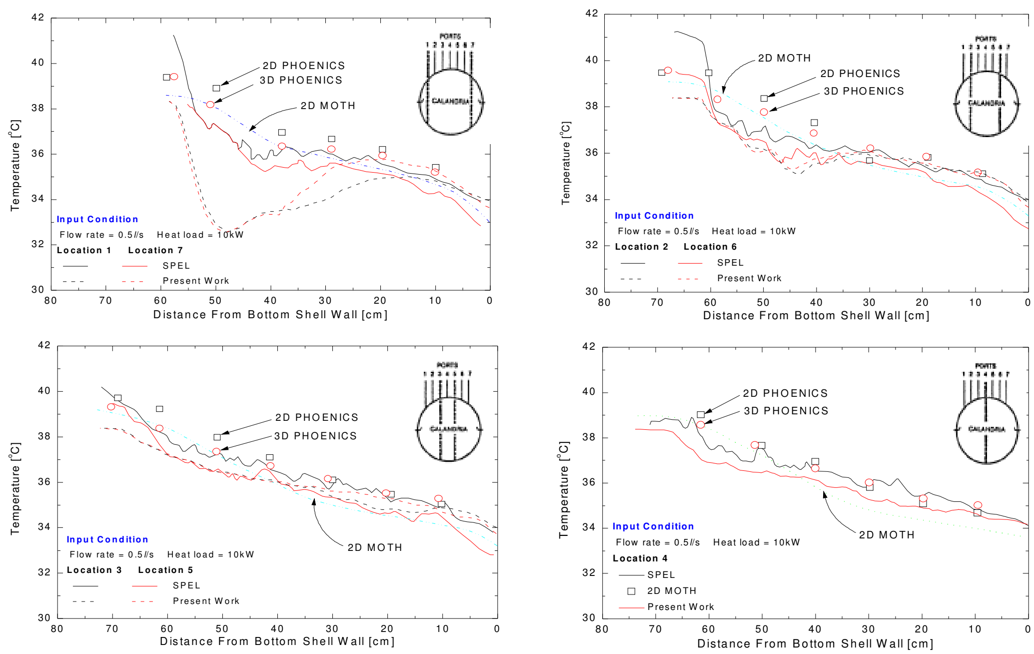
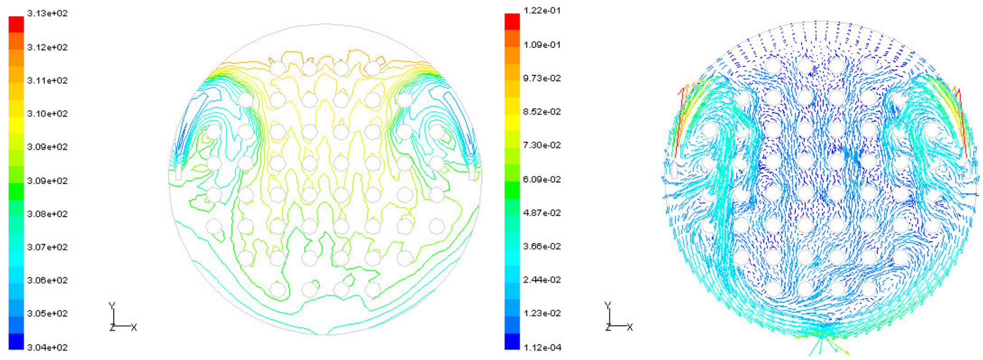
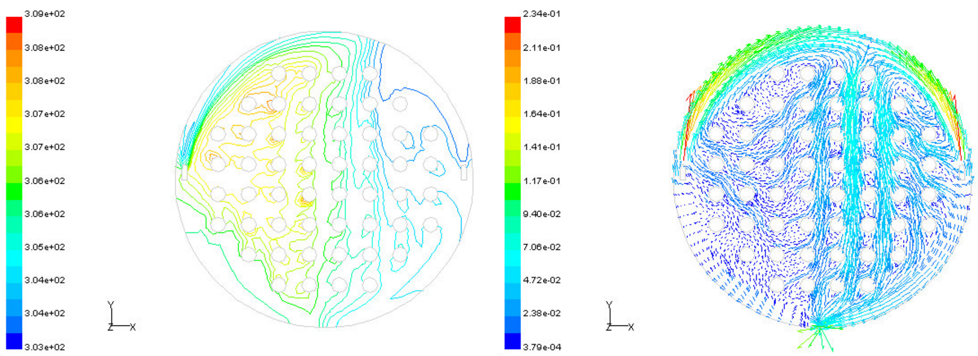


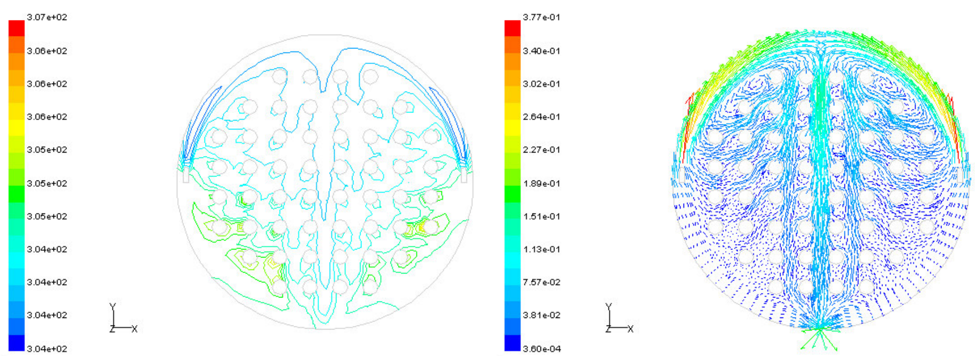
Figure 3. Comparison of experimental and computed temperatures along a vertical centerline.



(a) buoyancy dominated flow (V_{in}=0.13m/ s, T_{in}=30□, Heat Load=10kW)



(b) mixed type flow (V_{in}=0.25m/ s, T_{in}=30□, Heat Load=10kW)



(c) momentum dominated flow (V_{in}=0.40m/ s, T_{in}=30□, Heat Load=10kW)

Figure 4. Typical flow pattern of moderator inside Calandria.

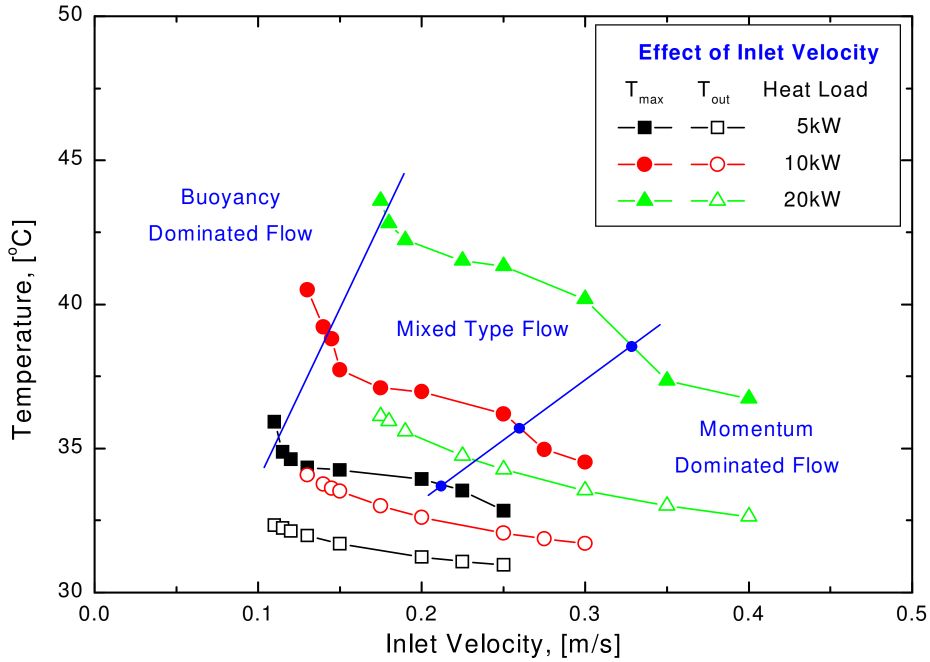


Figure 5. Effect of inlet velocity of moderator.

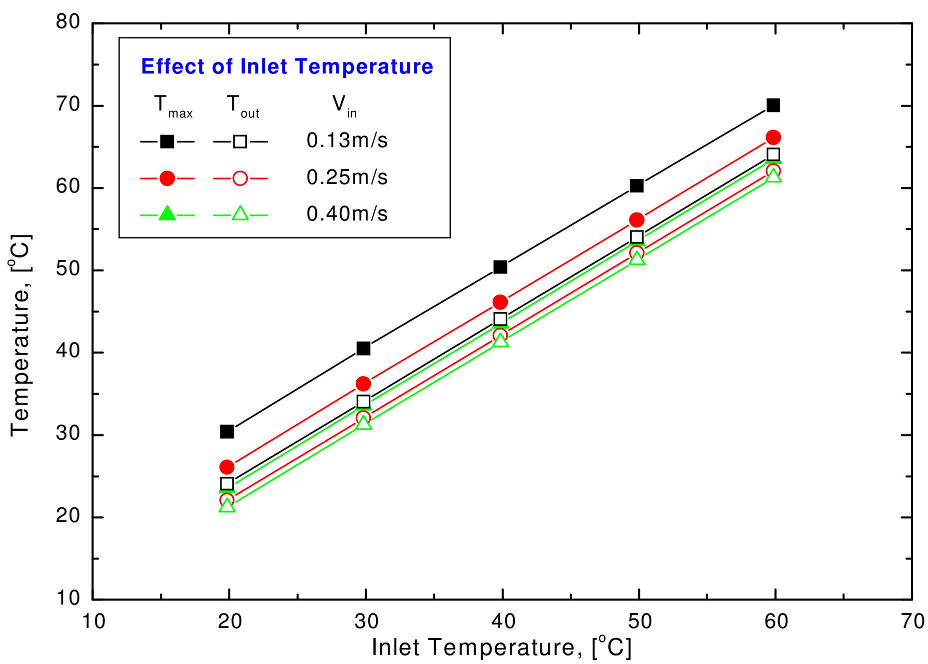


Figure 6. Effect of inlet temperature of moderator.

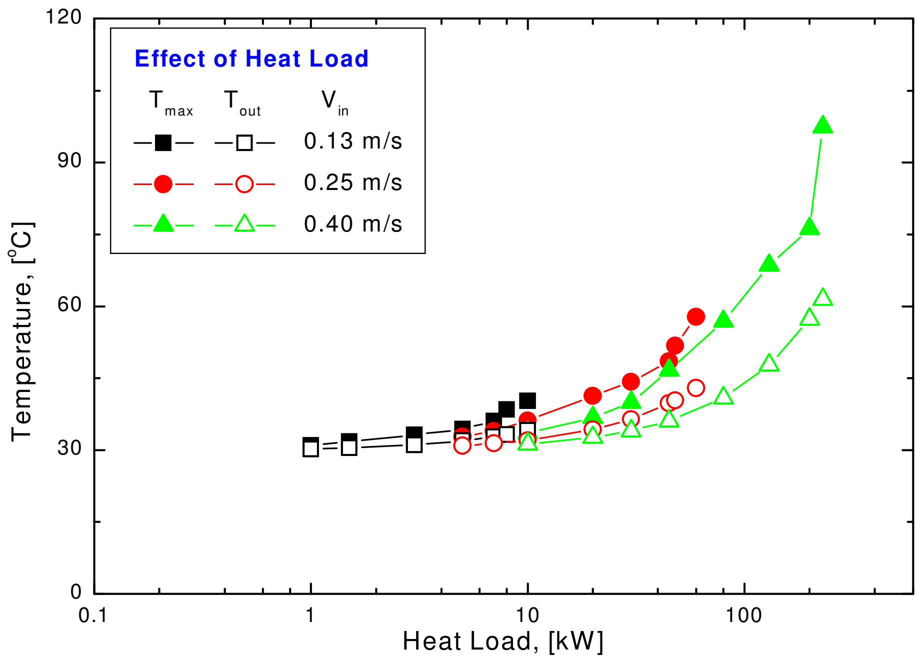


Figure 7. Effect of heat load of heaters.

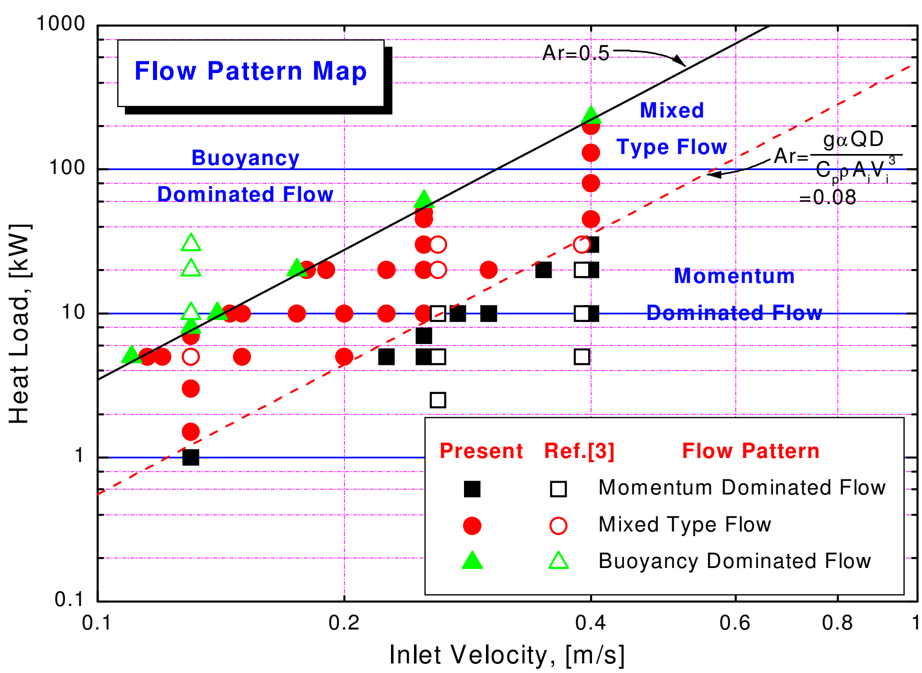


Figure 8. Flow pattern map of moderator inside Calandria.