A Natural Circulation Cooling Concept for Advanced CANDU Reactors: Overview and Development Status

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Abstract

A flashing-driven passive moderator cooling system is being developed for Advanced CANDU[1]® reactors. This concept takes advantage of the separation between the moderator and coolant in CANDU reactors and enhances the role of the moderator as a passive heat sink. This paper summarizes the main results from experiments and analysis carried out in support of this concept and outlines planned activities required to provide the information needed to complete the development work.

1. INTRODUCTION

One of the unique features of CANDU reactors is the separation between the low-pressure moderator and the high-pressure coolant (Figure 1). This feature makes it possible to use the moderator as a backup heat sink for emergency heat removal. Current CANDU reactor designs use a pumped loop to remove heat deposited in the moderator during normal operation. A passive moderator cooling system has advantages in terms of cost reduction and improved reliability.

For the past several years, AECL has been studying methods of enhancing moderator effectiveness as a heat sink by designing and testing passive moderator heat rejection systems. The most promising of these designs is a passive, flashing-driven moderator cooling system. In this concept, the heavy-water moderator exits the reactor calandria at a temperature close to saturation (slightly subcooled) so that vapor is generated in a riser connecting the calandria to a heat exchanger (Figure 2). The two-phase flow in the riser results in a significant increase in driving force (over that from single-phase natural circulation), and makes it possible to reject the moderator heat load in a passive manner. This concept can be used to reject moderator heat under normal and emergency conditions using the same passive loop; this is desirable since it ensures the availability and functionality of the passive heat removal system. Operating the moderator close to saturation requires changes to the fuel channel design to remove restrictions associated with operating CANDU reactors that require the moderator to operate with a certain degree of subcooling [1][2]. The development of an advanced fuel channel design is a parallel activity that is part of the advanced CANDU development program at AECL [2].

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[1] CANDU is a registered trademark of AECL

[2] This is necessary to avoid film boiling on the calandria tube if the pressure tube balloons into contact with the calandria tube following a loss of coolant accident (LOCA) combined with loss of Class IV power.

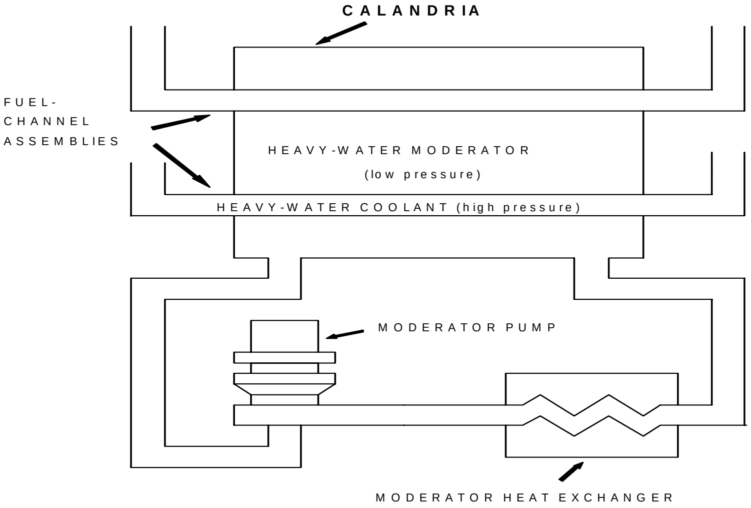


Figure 1 CANDU Calandria Schematic

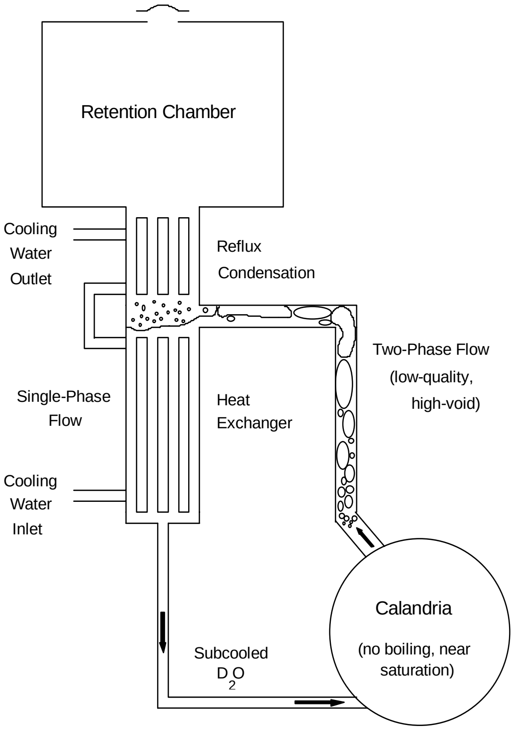


Figure 2 Flashing-driven PMCS Concept

2. PRELIMINARY SIMULATIONS AND TESTS

The initial studies consisted of steady-state simulations to examine the feasibility of rejecting the moderator heat load (~5% of reactor thermal power) using a natural circulation loop. The results showed that a single-phase loop was not practically feasible. A two-phase natural circulation system was necessary with the restriction that the moderator inside the calandria should remain in the liquid state. This restriction makes it necessary to design a loop where two-phase is generated by flashing in the riser. Further simulations showed that a loop with a reasonable height (~8.5m) would be able to remove moderator heat during normal operation. Furthermore, since the moderator heat during normal operation is comparable to decay heat following reactor shutdown, this loop could also be used for emergency hear removal if the emergency core cooling system fails.

The next step was to evaluate the stability of the system. This was done using the CATHENA [3, 4] thermal-hydraulics code, and a full-height scaled loop. The volume of the full-height test loop was scaled by factor of 60. The riser was constructed using glass piping to allow flow visualization. A schematic of the scaled loop is shown in Figure 3 [5].

Pre-test simulations of the scaled loop showed oscillatory behavior at low powers caused by periodic transition from single-phase to two-phase flow. This is expected since the increase in flow resulting from void generation in the riser leads to a decrease in the calandria outlet temperature below the saturation value at the riser outlet pressure. However, as the power was increased to the point where flashing was sustained (~25% of full power), the flow stabilized (Figure 4).

This behavior was verified experimentally, where the results showed good qualitative agreement with the CATHENA simulations (Figure 5). The flow remained stable as the power was increased to the simulated maximum heat load of ~1 MW [5].

The oscillations at low powers will be encountered during startup and are not expected to be problematic. However, it is desirable to eliminate or reduce the duration of these oscillations as the power increases to the stable region. A systematic investigation through separate-effects tests was carried out to provide a better understanding of the phenomena leading to the low power flow oscillations.

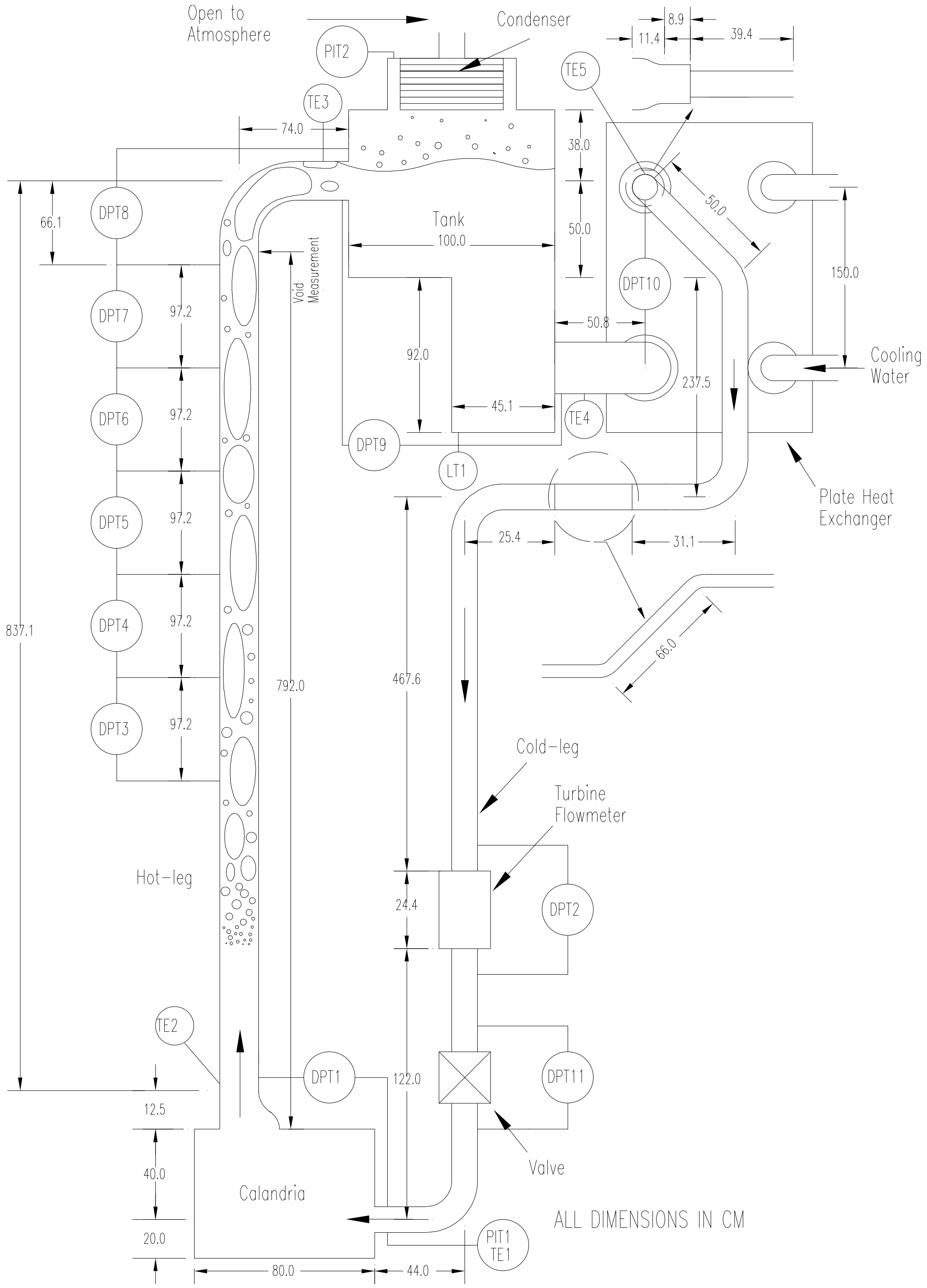


Figure 3 Schematic of Test Loop for Concept Verification Tests

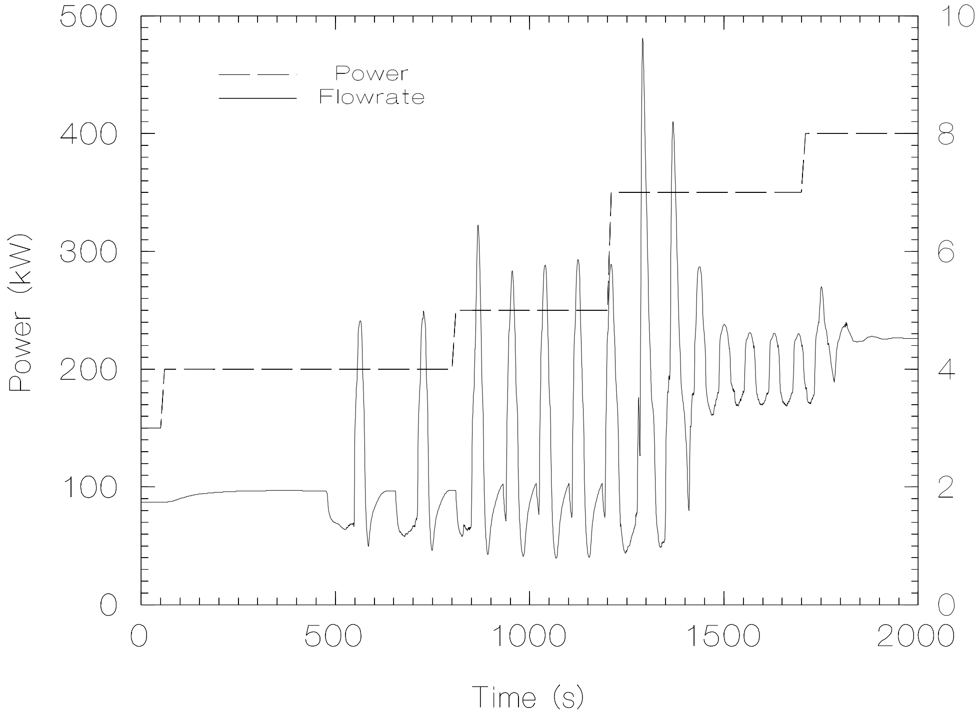


Figure 4 Pre-test CATHENA Simulations [5]

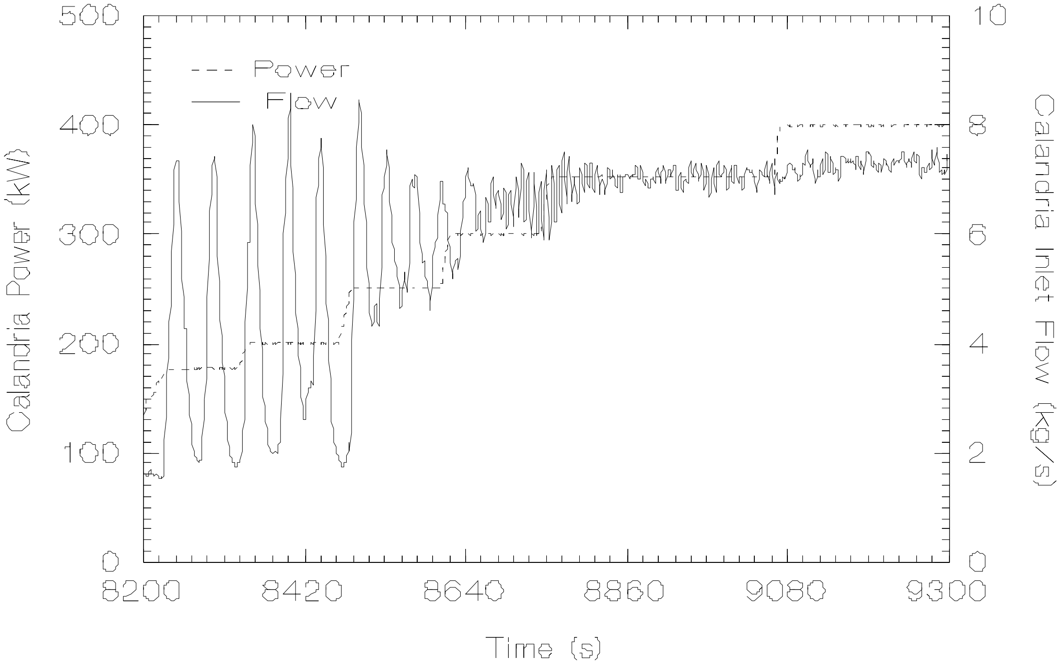


Figure 5 Sample Test Results [5]

3. SEPARATE-EFFECTS TESTS

The results obtained from the initial simulations and tests indicate that a stable behavior can be obtained if flashing can be sustained in the hot leg. Flashing can be sustained in the hot leg by ensuring that the calandria inlet temperature is close to saturation at the outlet riser pressure. Preliminary simulations showed that this was indeed the case. The loop was modified by removing the heat exchanger (that functioned as a subcooler) and retaining the elevated condenser and accumulator tank [6] (Figure 6).

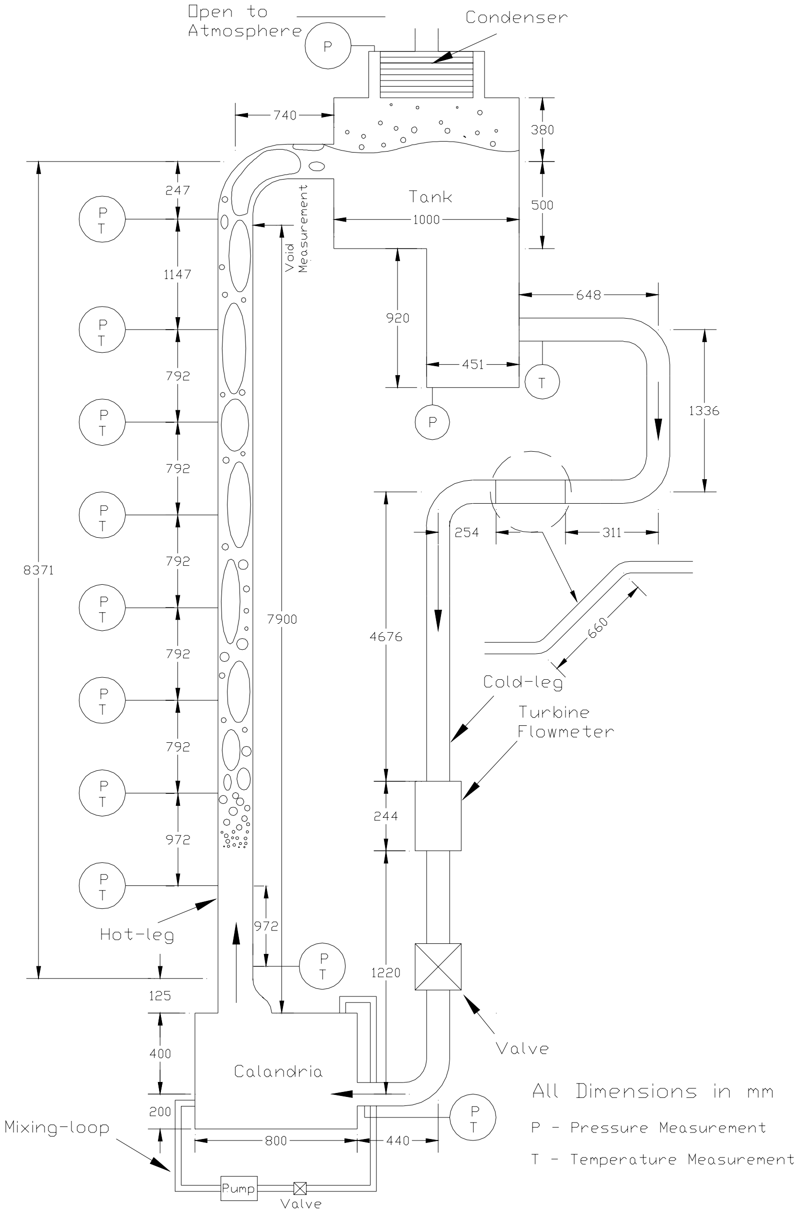


Figure 6 Schematic of Separate-Effects Test Loop [6]

Initial results from the separate effects tests showed that oscillations were still present at low powers (Figure 7). This was inconsistent with pre-test simulations that indicated stable behavior at all powers with a calandria inlet temperature close to saturation at the riser outlet pressure. Close examination of the results showed that two factors contributed to the low-power oscillations: 1) flow and temperature distribution inside the calandria, and 2) preferential void generation at the discontinuities between the glass riser pipe segments. The effects of these factors were eliminated by introducing a mixing loop (to reduce temperature fluctuations at the calandria outlet) and by introducing a rough surface (rough wire inserted in the center of the top glass pipe segment) in the riser [6] to provide a continuous surface for void formation. The experimental results following these modifications showed significant improvement in loop stability at all power levels (Figure 8).

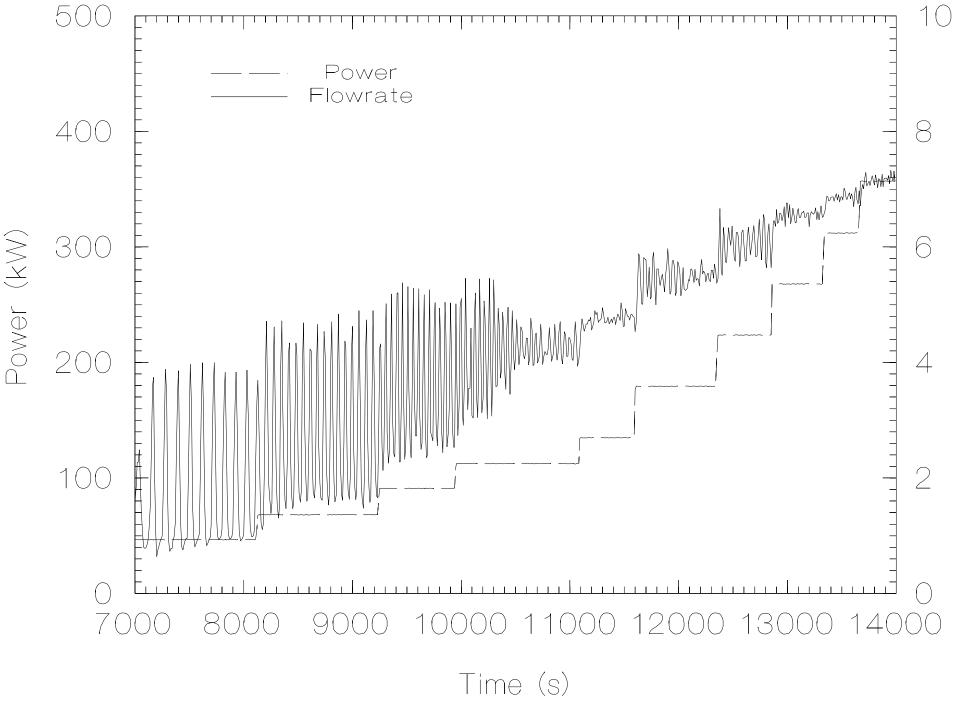


Figure 7 Separate-Effects Tests (mixing loop off)

Subsequent comparison between CATHENA and the experimental results showed that CATHENA predicted significantly higher flowrates (Figure 9). The reason is that CATHENA assumes thermodynamic equilibrium between the vapor and liquid phases where in reality a certain amount of superheat is required to initiate flashing. This results in a longer two-phase section in the riser and larger flowrates in CATHENA simulations. The experimental results showed that between 2-3^{o}C of superheat was required to initiate flashing. Another CATHENA simulation was carried out with an artificially increase pressure at the riser outlet in attempt to match the flashing locations with those observed in the experiment. The results are shown in Figure 10 where significant improvement can be seen. The remaining discrepancies can be attributed to uncertainties in the parameters used in the simulations, and to reduced void generation in the experiment away from the rough wire insert.

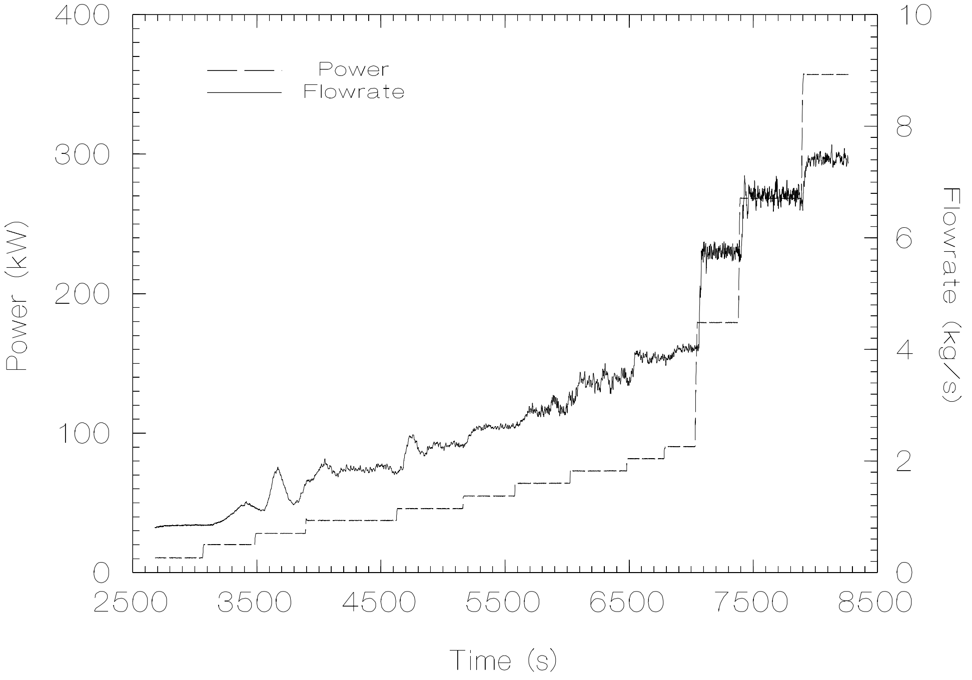


Figure 8 Separate-Effects Tests (mixing loop on)

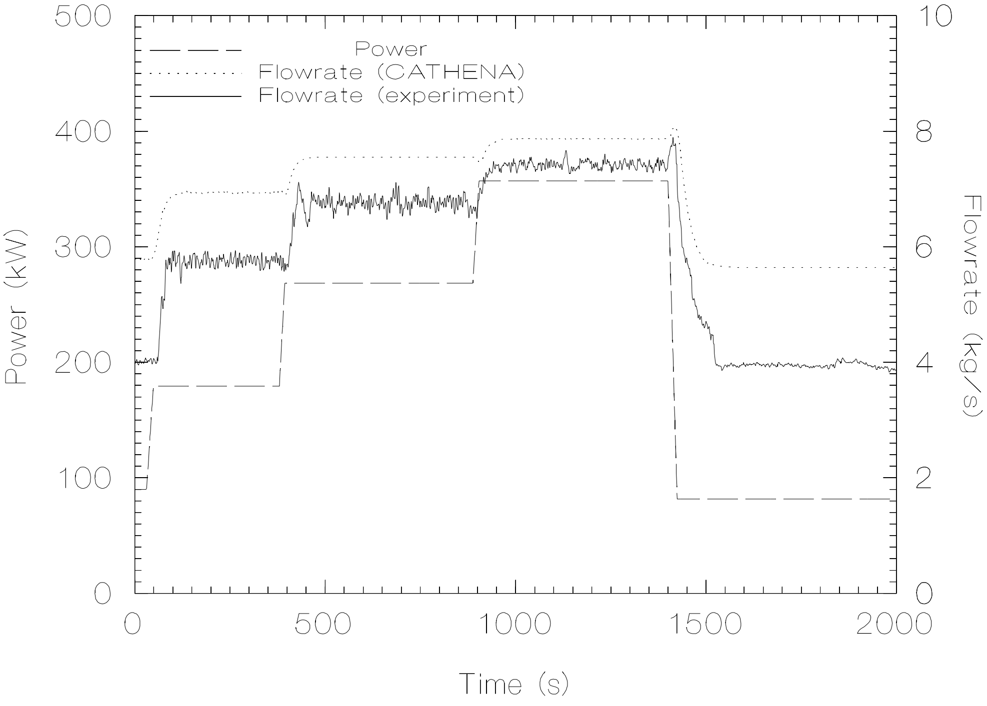


Figure 9 Comparison with CATHENA Using Experimental Condenser Pressure

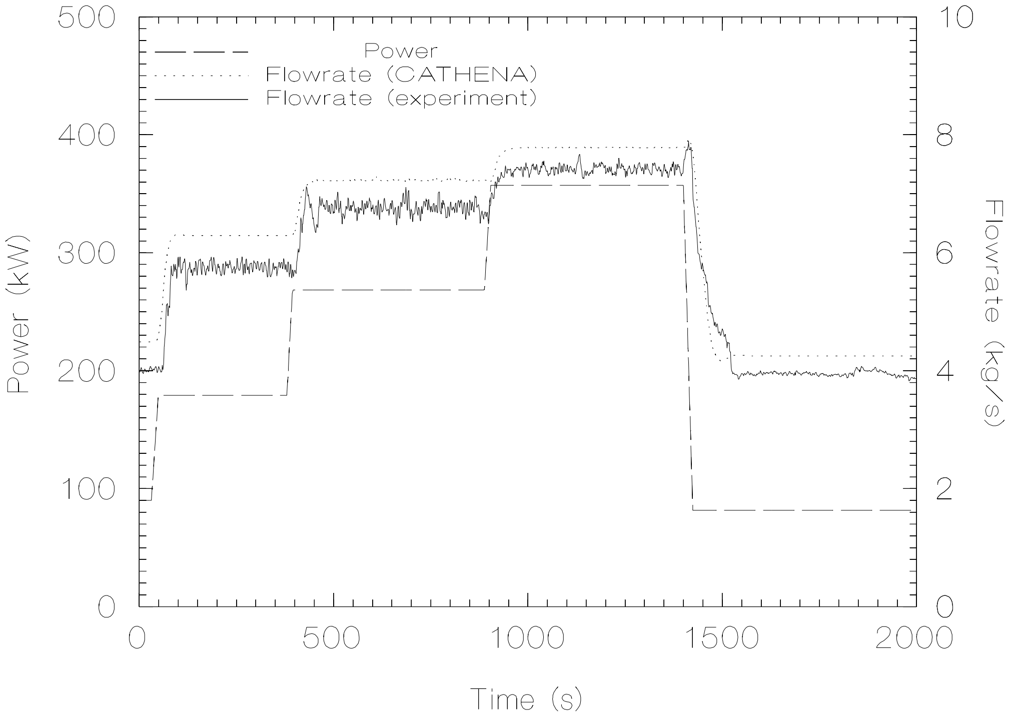


Figure 10 Comparison with CATHENA Using a Higher Condenser Pressure

Calandria Inlet and Outlet Configuration

The other separate-effects test studied the flow and temperature distributions inside the calandria. The objective was to investigate a suitable inlet/outlet configuration that would result in better mixing and in accumulation of higher temperature fluid close to the calandria outlet at all expected flowrates. An obvious choice is to locate the inlet at the bottom of the calandria vessel. However, another configuration that was used for certain CANDU designs was found to be superior [7]. This configuration is shown in Figure 11 where it can be seen that the inlet consists of a number of nozzles located in the upper portion of the calandria and pointing downwards. This configuration was tested in a ¼-scal calandria simulator [7] with detailed velocity and temperature distribution measurements using a range of flowrates expected at low and full power operation. A typical result is shown in Figures 12 and 13 where it can be seen that the flow and temperature distributions are consistent with the requirements of the passive loop. Transient tests were also conducted to simulate changing power levels (using temperature measurements only) and the same temperature distribution was maintained. This means that the flow configuration in Figure 11 can be used in the passive loop design to avoid any temperature variations at the calandria outlet that could be caused by three-dimensional effects within the calandria vessel.

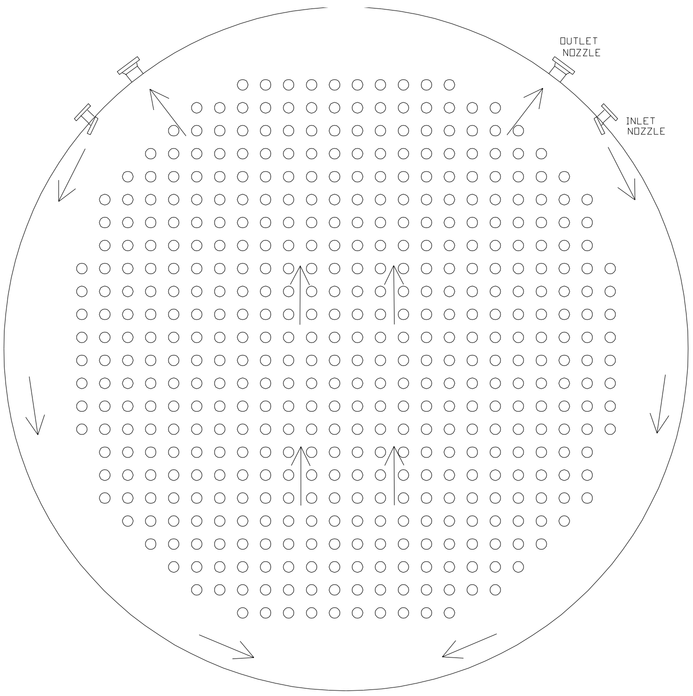


Figure 11 Moderator Flow Configuration Tested [7]

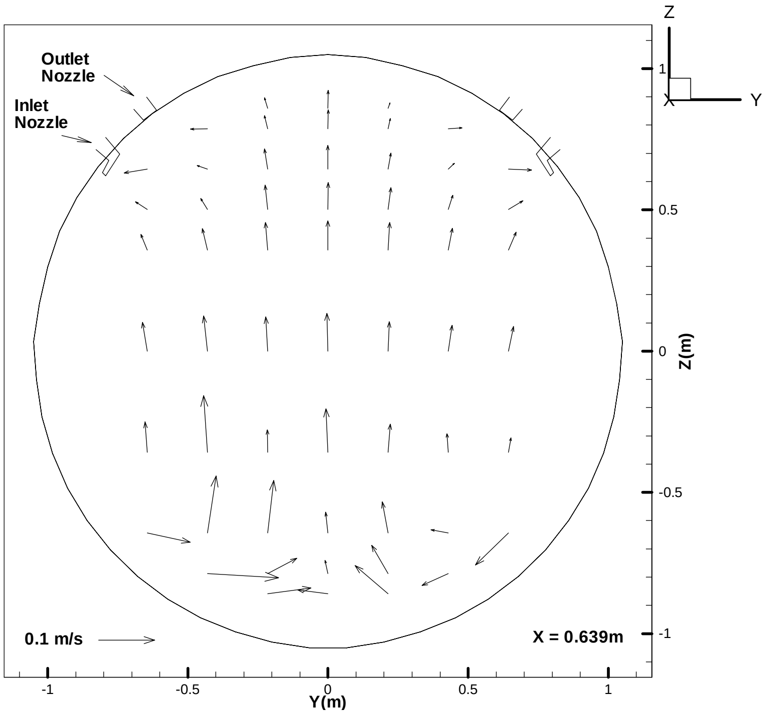


Figure 12 Measured Velocity Profile [7]

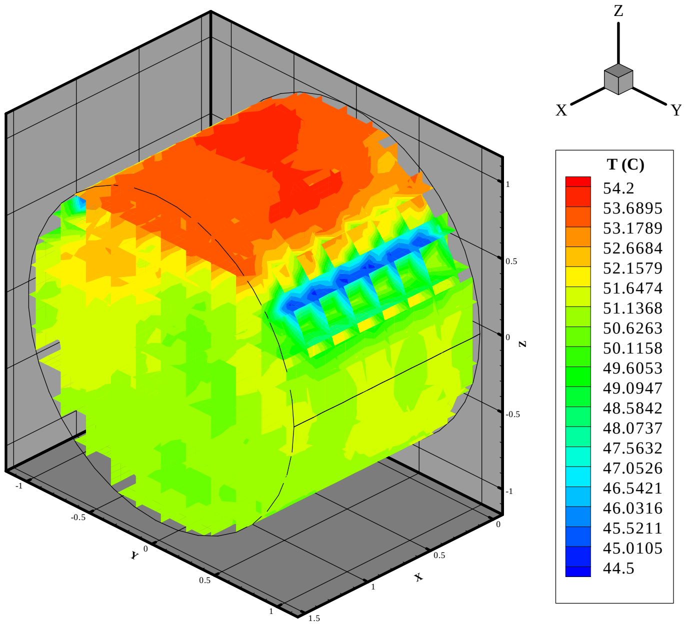


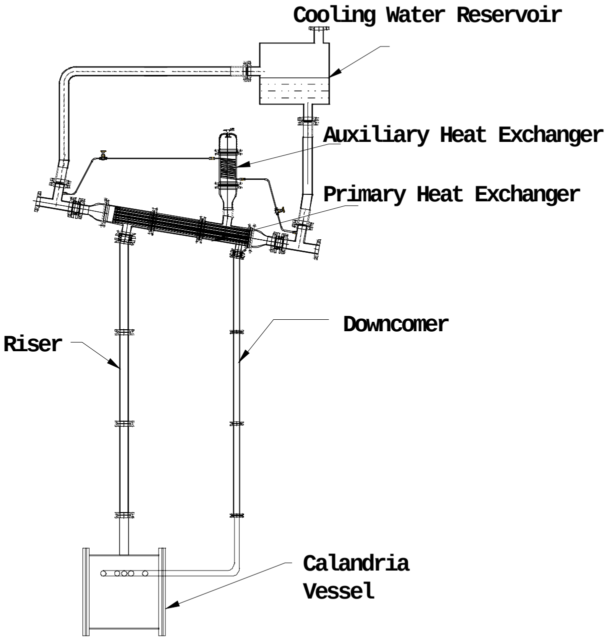
Figure 13 Measured Temperature Distribution [7]

4. MODIFEID LOOP

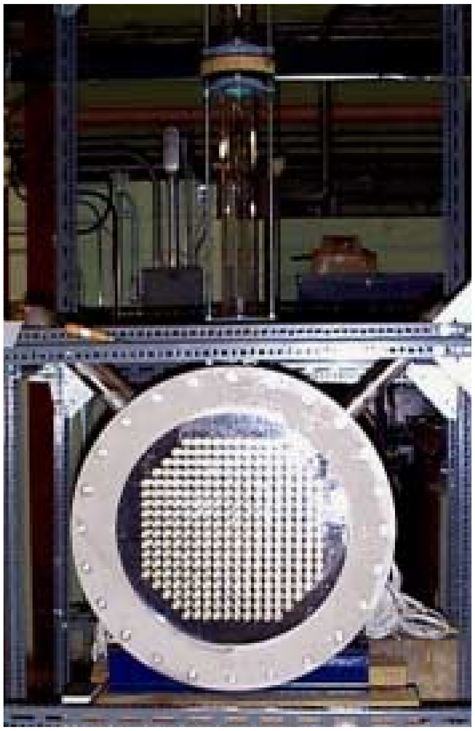
Results from the above tests were used to design and construct another loop with a different scale, and more representative calandria vessel geometry and flow configuration. The loop scale was chosen so that the calandria vessel linear dimensions were reduced by a factor of 10, and the loop height was smaller than the previous loop (Figure 14a). Construction of this loop was completed recently and is currently undergoing commissioning (Figure 14b). This loop will be used to provide more validation data and can be re-configured relatively easily to add more components (e.g., another passive loop above the heat exchanger to reject heat to an ultimate heat sink).

5. FUTURE PLANS

The larger (1/4-scale) calandria vessel that was used to study flow and temperature distributions will be used at a later stage to study the behavior of a larger flashing-driven loop. Results from the smaller scale loop will provide input to the design of the larger loop components. The two loops are expected to provide more validation data, including data on scaling effects that can be used to design the actual reactor loop.



(a)



(b)

Figure 14 Modified Loop

7. CONCLUSIONS

The separation between the high-pressure coolant and low-pressure moderator in CANDU reactors makes it possible to use the moderator as an additional heat sink to supplement the emergency core cooling system during some postulated accidents. A flashing-driven moderator cooling concept that can be used to remove moderator heat under normal conditions and decay heat under emergency conditions in advanced CANDU reactors is under development. In this concept, a sufficiently high moderator flowrate can be obtained due to the large density difference between the hot and cold-legs.

The research program so far has demonstrated the feasibility of employing a flashing-driven loop that can be used under normal and emergency conditions. Flow oscillations observed in earlier tests were found to occur at conditions where flashing cannot be sustained due a combination of low calandria inlet temperature and low power. These flow oscillations could be encountered during startup and are not expected to be problematic for this application. However, it is possible to avoid these oscillations by manipulating the calandria inlet temperature during startup so that flashing is sustained.

Another factor that could lead to flow oscillations is variations in the calandria outlet temperature that are caused by three-dimensional effects within the calandria vessel. Designing and testing a suitable calandria flow configuration resolved this issue.

A new loop was designed and built recently that incorporates lessons learnt from the early tests. This loop has sufficient flexibility to allow re-configuration and further testing. A larger loop is planned to provide supplementary data and to study scaling effects.

8. REFERENCES

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