A FLASHING DRIVEN MODERATOR COOLING SYSTEM FOR CANDU REACTORS: EXPERIMENTAL AND COMPUTATIONAL RESULTS

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Abstract

A flashing-driven passive moderator cooling system is being developed at AECL for CANDU reactors. Preliminary simulations and experiments showed that the concept was feasible at normal operating power. However, flow instabilities were observed at low powers under conditions of variable and constant calandria inlet temperatures. This finding contradicted code predictions that suggested the loop should be stable at all powers if the calandria inlet temperature was constant. This paper discusses a series of separate-effects tests that were used to identify the sources of low-power instabilities in the experiments, and it explores methods to avoid them. It concludes that low-power instabilities can be avoided, thereby eliminating the discrepancy between the experimental and code results. Two factors were found to be important for loop stability: (1) oscillations in the calandria outlet temperature, and (2) flashing superheat requirements, and the presence of nucleation sites. By addressing these factors, we could make the loop operate in a stable manner over the whole power range and we could obtain good agreement between the experimental and code results.

1. INTRODUCTION

CANDU® moderator heat-rejection systems normally use pumps to circulate the hot heavy water to heat exchangers where the heat is rejected to pumped service water (Fig. 1). However, heavy-water circulation by natural convection has advantages, and a system to reject heat passively using a flashing-driven natural-circulation loop is being developed at AECL.

The main feature of the flashing-driven concept (Fig. 2) is that vapour is generated by flashing. Preliminary simulations using the CATHENA [1] code have shown that a flashing-driven natural-circulation loop can be used to remove normal moderator heat without any flow instabilities [2]. This concept was verified experimentally using a scaled flashing-driven loop [3]. However, while stable operation was obtained at normal operating power, flow instabilities were observed at low powers (<25% full power).

Separate-effects tests were subsequently conducted to investigate the cause of low-power instabilities. The tests were conducted with a constant cold-leg temperature so that instabilities related to the hot-leg (flashing) part of the loop could be isolated. Two factors were found to be important for loop stability: (1) oscillations in the calandria outlet temperature, and (2) flashing superheat requirements and the presence of nucleation sites.

If the liquid in the calandria is not sufficiently mixed, temperature oscillations can occur at the calandria outlet, and the flow will oscillate because the elevation of the onset of flashing changes with temperature. Temperature oscillations were observed at low powers (<25% full power). The calandria outlet temperature in an actual CANDU reactor can be stabilized with a suitable inlet-outlet configuration. The effect of stabilizing the calandria outlet temperature was investigated by mixing the calandria water in the separate-effects tests. The result was that low-power oscillations were practically eliminated. Residual oscillations remained, but they were finally traced to the lack of sufficient nucleation sites along the glass riser.

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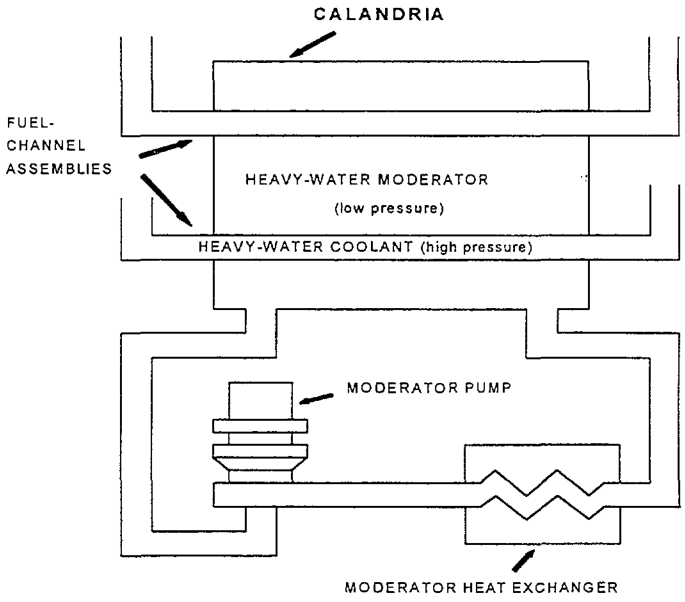

FIG. 1. CANDU calandria schematic.

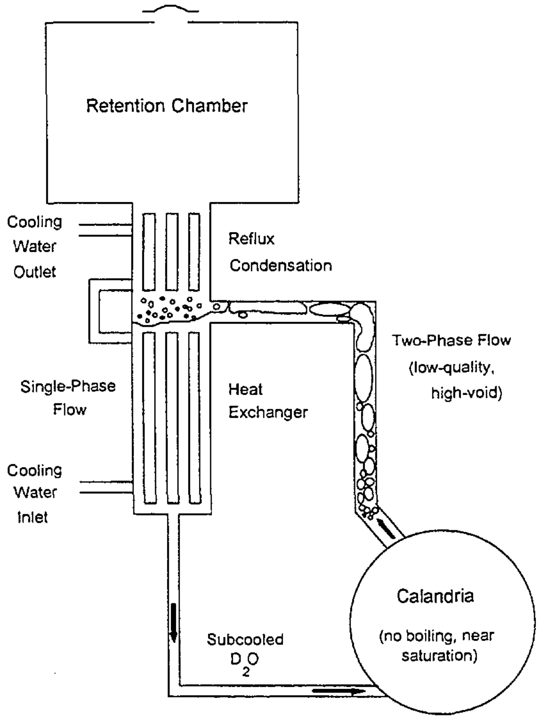

FIG. 2. Flashing-driven concept.

The riser in the experiment was made of glass pipe segments to facilitate flow visualization. Discontinuities existed at the points where the glass pipes were connected. This set-up caused void generation to be non-uniform along the riser because more superheat was required to initiate flashing at the smooth glass surface (which did not have sufficient nucleation sites) than at the points where the glass pipes were connected. This phenomenon caused minor oscillations at low powers, where flashing started in the upper pipe segment. At higher powers, the oscillations disappeared because void, which acted as further nucleation sites, filled most of the riser. This effect was investigated by introducing an artificial roughness through the insertion of a rough wire in the middle of the top glass riser section. Tests conducted at low powers clearly showed the formation of void on the wire surface but not on the smooth glass surface. This uniform void generation stabilized the flow at powers where unstable operation was observed previously, without the wire insert. In an actual steel riser, void formation should be uniform along the pipe, thereby stabilizing the flow.

Another factor that affects code prediction is the amount of superheat required to initiate flashing. If thermal equilibrium is assumed, the code will predict a longer two-phase region than when a finite amount of superheat is required for flashing. This hypothesis was investigated by artificially lowering the flashing point in the code simulations so that the amount of superheat was equal to that observed in the experiments.

The results (experimental and code predictions) indicated stable loop operation with calandria mixing and improved nucleation. By accounting for these effects, as well as for the amount of superheat required to initiate flashing, good agreement was obtained between the experiments and code simulations.

2. PRE-TEST CATHENA SIMULATIONS

The observed loop behaviour in earlier tests (flow stabilization with increased power) [3] was consistent with the pre-test CATHENA simulations. However, the agreement was only qualitative because of uncertainties in the loop parameters used in pre-test CATHENA simulations. Post-test analyses with more accurate loop parameters did not improve the agreement between the experiments and code simulations.

Closer examination of the experimental results showed that the temperature oscillations were inconsistent with the assumption of a completely mixed calandria. A major assumption in the preceding CATHENA simulations was that the calandria could be modeled as a mixed-volume component. In reality, the flow distribution within the calandria is three-dimensional, and is strongly dependent on the inlet-outlet geometry. Moreover, CATHENA simulations showed that the loop was always stable with a constant calandria inlet temperature.

The preceding results prompted the following modifications to the test loop, which is described in Reference 3:

(1) Keep the calandria inlet temperature constant throughout the test.

(2) Reduce the three-dimensional effects of the flow distribution in the calandria to approximate mixed conditions.

3. EXPERIMENTAL SET-UP AND PROCEDURE FOR SEPARATE-EFFECTS TESTS

Scaling of the original test loop [3] was done by keeping the height similar to that of the reactor loop, and by reducing the volume of all pipe components by a factor of 60. The calandria was scaled by a factor of 600 (undersized by a factor of 10).

A schematic of the modified test loop is shown in Fig. 3; it consists of a calandria (with a mixing loop), an 8.5-m-long glass riser (1.0-m-long glass pipe segments with an inner diameter of 10 cm), a condenser and tank, and a steel downcomer. The tests described in

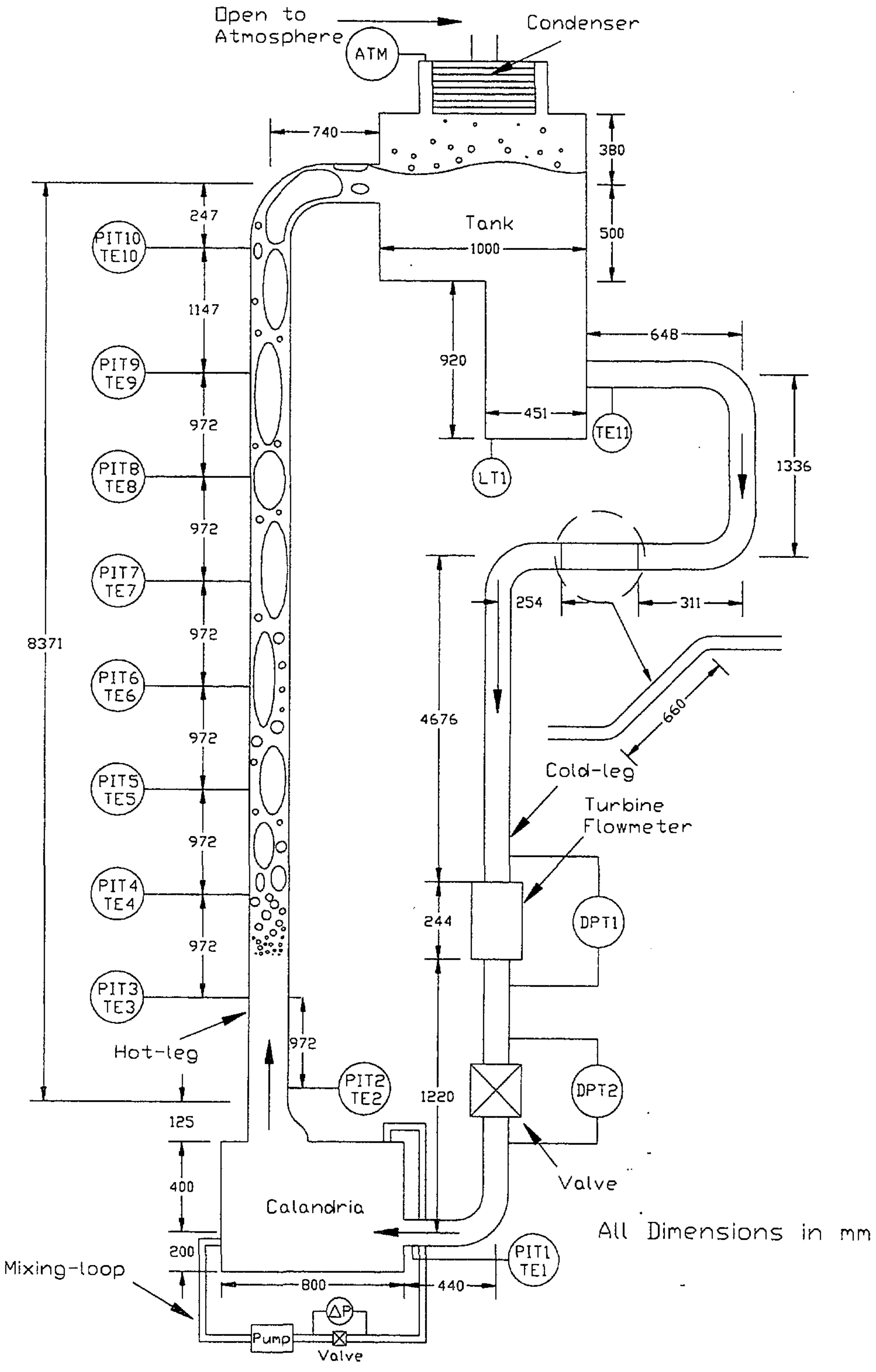

FIG. 3. Schematic of test loop for separate-effects tests.

Reference 3 used the same loop but with a subcooler at the condenser outlet to bring the calandria inlet temperature to normal operating values (below 100 °C).

For the separate-effects tests, one requirement was to keep the calandria inlet temperature constant, to isolate any possible effects of varying inlet temperature on loop stability. The easiest way to achieve this was to keep the cold-leg at the condenser saturation temperature (~100 °C). The water volume in the tank below the condenser helped absorb variations in the condensate temperature and ensured that the cold-leg temperature remained constant. The reduction of three-dimensional effects in the calandria was achieved by adding a mixing-loop to the calandria (see Fig. 3).

The measurements consisted of total calandria power, flowrate into the calandria, and temperatures and pressures at various locations (see Fig. 3). The flowrate was measured using a turbine flowmeter. Temperatures were taken using Type K thermocouples, and pressures were measured using Rosemount pressure cells.

A PC-based data-acquisition system was used to scan data at three rates: (1) one scan/10 s (slow), (2) one scan/s (medium), and (3) five scans/s (fast). The experiments were also recorded on video tape, to aid in data analysis.

Before each test, the water in the loop was first heated and degassed for about 3 hours. At the end of the degassing period, the water temperature in the whole loop corresponded to saturation at the condenser pressure (≅ 100 °C). The experimental constraint was that the calandria outlet temperature was not to exceed the saturation temperature at the calandria pressure (approximately 117 °C).

4. EXPERIMENTAL RESULTS

4.1. Mixing-loop turned off

This test was first done to provide a reference point for runs with a mixed calandria. The results are shown in Fig. 4, where it can be seen that the flow is unstable up to 112 kW (approximately 25% simulated full power). These oscillations are accompanied by oscillations in the outlet temperature, which cause the flashing point to oscillate. This oscillation, in turn, results in oscillations in the driving head, which result in flow oscillations.

4.2. Tests with calandria mixing

The mixing loop was operated to better simulate a mixed calandria. The results are shown in Fig. 5, where it can be seen that the large-amplitude oscillations associated with the large calandria outlet temperature oscillations have disappeared.

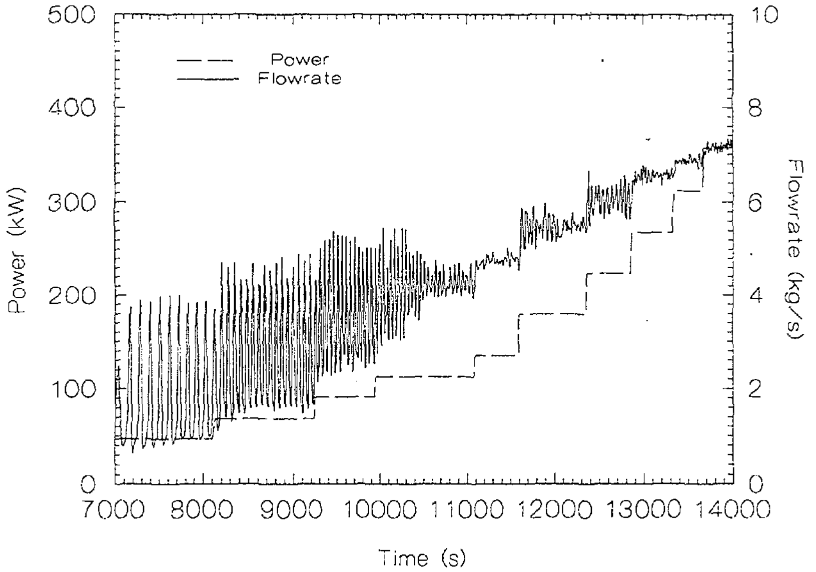

FIG. 4. Results without calandria mixing.

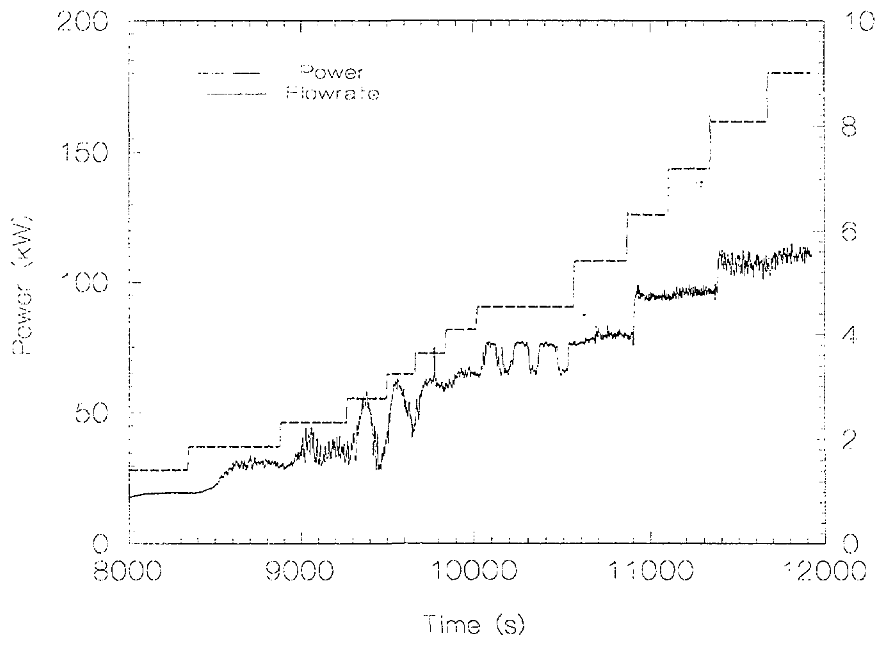

FIG. 5. Results with calandria mixing.

Fig. 5, however, shows that there are still some minor oscillations at some power levels below 108 kW. Visual observations in the top part of the glass riser showed the presence of slug flow when two-phase conditions existed in the riser. Closer examination of the two-phase region showed that discontinuities in the glass riser (at the flanges connecting the 1-m-long glass segments) acted as preferential locations for void generation. This finding is not surprising because the glass surface is very smooth, which means a larger superheat is required for void generation at the continuous glass surface than at the discontinuity between any two glass pipes. This discontinuity in the glass surface caused non-uniform void generation along the pipe (in the direction of decreasing pressure) and resulted in slug flow and minor flow oscillations at low powers.

The above observations were limited to the top 1 m of the glass pipe at low powers. At higher powers, no effect of preferred nucleation sites on stability was observed. The reason is that as the flashing point moves closer to the calandria (at higher powers), the resulting void act as further nucleation sites. This makes the flashing more uniform in the rest of the pipe, and the effect of non-uniform void generation close to the location where flashing begins is swamped by the larger two-phase length where flashing is uniform.

While the oscillations shown in Fig. 5 were minor and occurred at low powers, another test was conducted, to examine the effect of superheat and nucleation sites on flashing and flow stability.

4.3. Effect of superheat and nucleation sites

This phenomenon was investigated experimentally by inserting a rough wire in the middle of the top glass section (~ 1-m long), where the effect of preferred nucleation sites caused slug flow. Tests with the wire insert clearly showed the formation of void on the wire surface, but not on the smooth glass surface. This uniform void generation eliminated slug flow and the associated flow oscillations at low powers. The results are shown in Figure 6, where it can be seen that the flow is stable at all powers (what appear to be flow oscillations at powers less than 50 kW are flow transients associated with the power increases). A comparison of Figures 5 and 6 at powers less than 100 kW clearly shows the effect of the wire insert on flow stability.

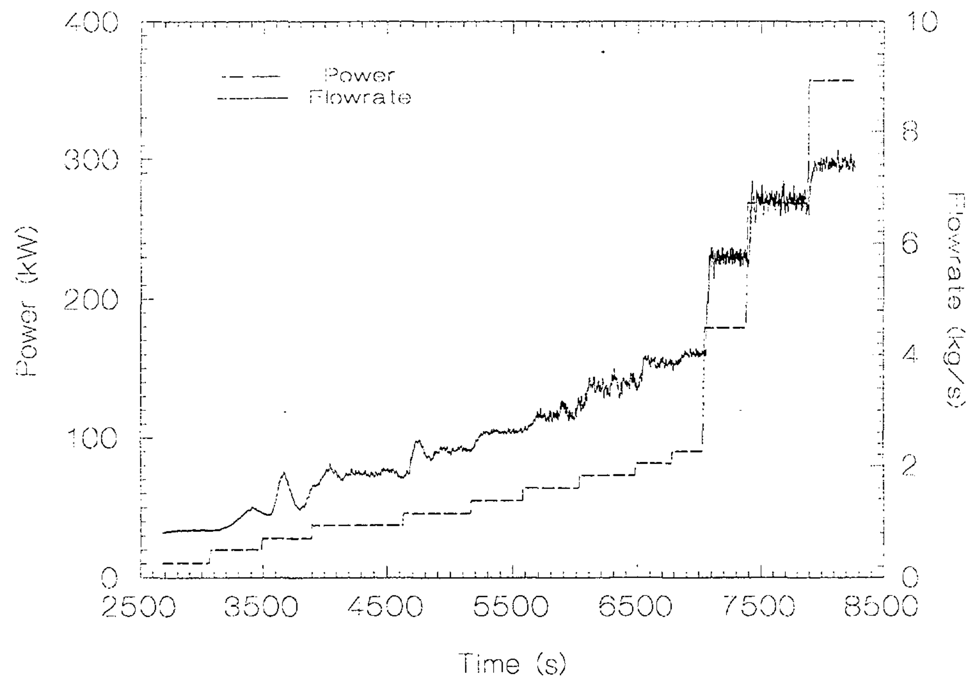

FIG. 6. Effect of increased nucleation sites.

The cause of the observed low-power flow oscillations, with the calandria inlet temperature equal to the condenser saturation temperature, was finally traced to insufficient calandria mixing and to the lack of uniform nucleation sites along the smooth glass pipe surface. Accounting for these effects gave experimental results that are in agreement with CATHENA predictions, in that the flow is always stable for the configuration shown in Figure 3.

5. POST-TEST CATHENA SIMULATIONS

Results from the wire-insert experiment (with calandria mixing) were used for comparison with CATHENA. Two cases were simulated: (1) gradual power change, and (2) fast power change.

5.1 Gradual power change (low-power)

These simulations correspond to the test results in Figure 6 where power was increased gradually from 10 kW to 90 kW (~3% to 25% of full power). The experimental results and CATHENA predictions are compared in Figure 7, where it can be seen that CATHENA significantly overpredicted the flowrate. The discrepancy is much greater than the uncertainties in the experimental measurements.

A closer examination of the experimental results showed that relatively high superheat (~2.4 °C) was required to initiate flashing. This conclusion is consistent with studies of critical two-phase flow [4], which are described in Reference 5; these studies reported that flashing occurred at temperatures higher than the saturation temperature by 2 to 3 °C. CATHENA, on the other hand, predicted a much smaller superheat (a fraction of a degree). This discrepancy caused CATHENA to predict more void in the glass riser which, in turn, caused the flowrate to be overpredicted.

The importance of superheat was investigated by imposing a higher pressure at the condenser and fixing the calandria inlet temperature at 100 °C, to artificially raise the flashing point. A value of 111 kPa was chosen because the saturation temperature at that pressure (102.4 °C) equaled the experimental calandria outlet temperature at 10 kW, where single-phase flow was observed. The CATHENA predictions are shown in Figure 8, where it can be seen that the difference between predicted and measured flow is significantly reduced. Although the imposed pressure did not cause the flashing point to match that of the experiments at all powers, the results showed that the difference between the predicted and measured flowrates in Figure 7 was primarily caused by a large superheat requirement that resulted in delayed flashing.

Despite the improved agreement between CATHENA and the experiments, Figure 8 still shows higher predicted flow at all powers, which cannot be explained by experimental uncertainties alone. The discrepancy can be explained again by the superheat required to initiate flashing, which affects the rate of void increase in the low-quality region just above the onset-of-flashing point. Because these experiments were conducted with a wire insert to provide more nucleation sites, it is not surprising that visual observations clearly showed the presence of void around the wire. However, no void was present in a relatively large portion of the pipe cross-section. This absence of void caused the void fraction, and therefore the driving force, to be less in the experiment than it would be in the ideal case of complete thermal equilibrium.

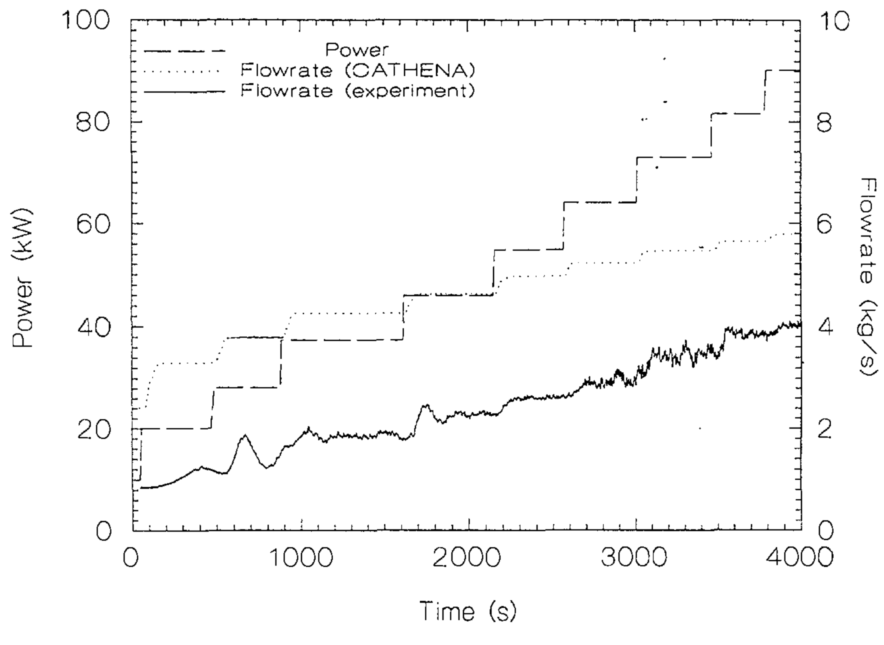

FIG. 7. Low-power comparison with CATHENA using experimental condenser pressure.

Figure 8 also shows some oscillations at very low powers. Both the experimental and CATHENA results suggest that the flow would converge if given sufficient time. No attempt was made to refine the comparison at these powers because the flashing was concentrated in a very small region in the top of the glass riser, which did not include the wire insert.

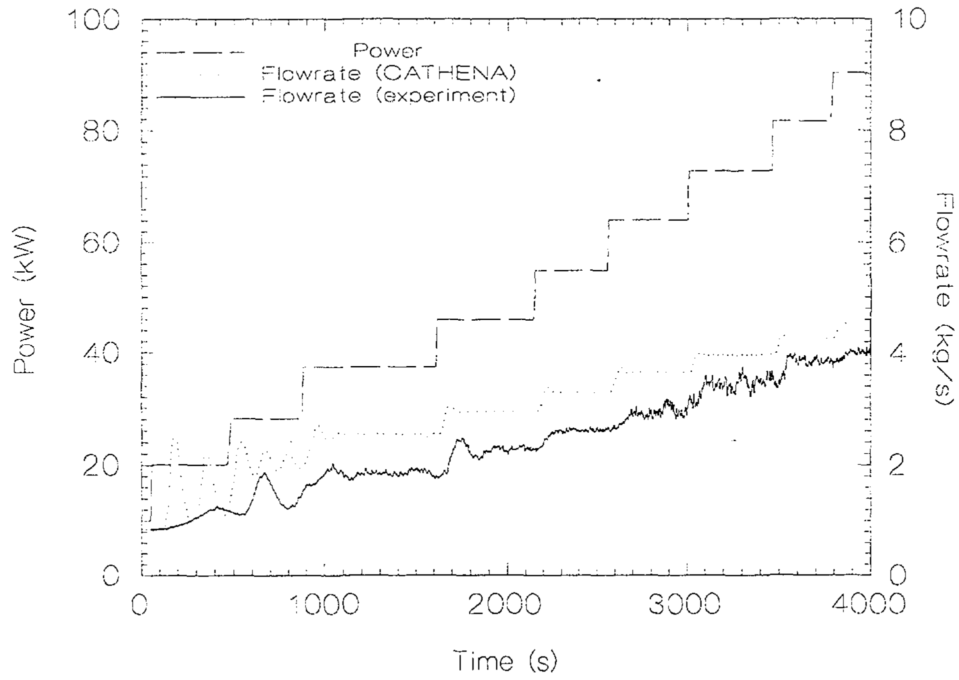

FIG. 8. Low-power comparison with CATHENA using a condenser pressure of 111 kPa.

5.2. Fast power change (high-power)

The test consisted of a fast, three-step power increase from 90 kW to 357 kW, and then a fast power decrease to 82 kW. The results (with atmospheric condenser pressure) are shown in Figure 9, where it can be seen that CATHENA again overpredicts the flow. However, the agreement is better at higher powers, where the two-phase region occupies most of the glass riser.

This better agreement at high powers occurs because the generated void act as nucleation sites that further promote vapour generation. At the point where flashing begins, there is a small amount of void, and thermal non-equilibrium effects cause less void to be generated than when there is complete thermal equilibrium. As the two-phase mixture travels along the glass riser, thermal non-equilibrium effects begin to diminish as more void is generated, creating more nucleation sites. If the two-phase length is long enough (i.e., at high powers), then the void generation in most of the two-phase region will be close to the ideal case of thermal equilibrium between the two phases. This consideration explains the better agreement between CATHENA and the experimental values at the high powers in Figure 11 (>300 kW).

The effect of increasing the condenser pressure to artificially suppress flashing was again simulated for the fast power increases. The results are shown in Figure 10, where it can be seen that the agreement improves, especially at lower powers.

In all cases, CATHENA predicts the loop behaviour well, and discrepancies related to non-equilibrium effects are beyond the capabilities of CATHENA at the present time.

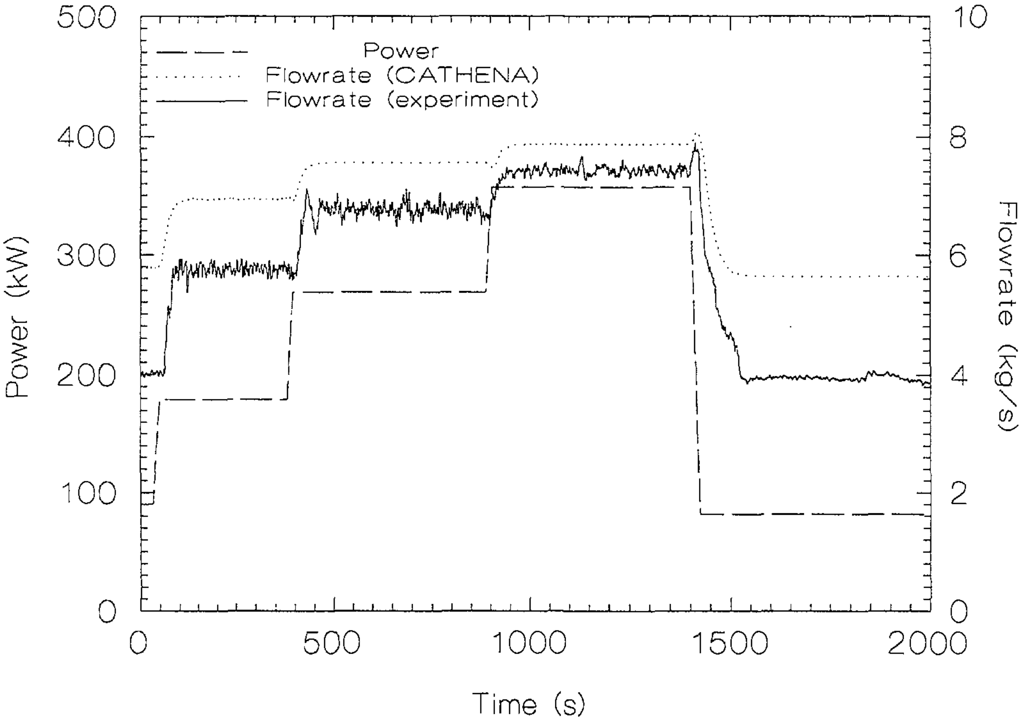

FIG. 9. High-power comparison with CATHENA using experimental condenser pressure.

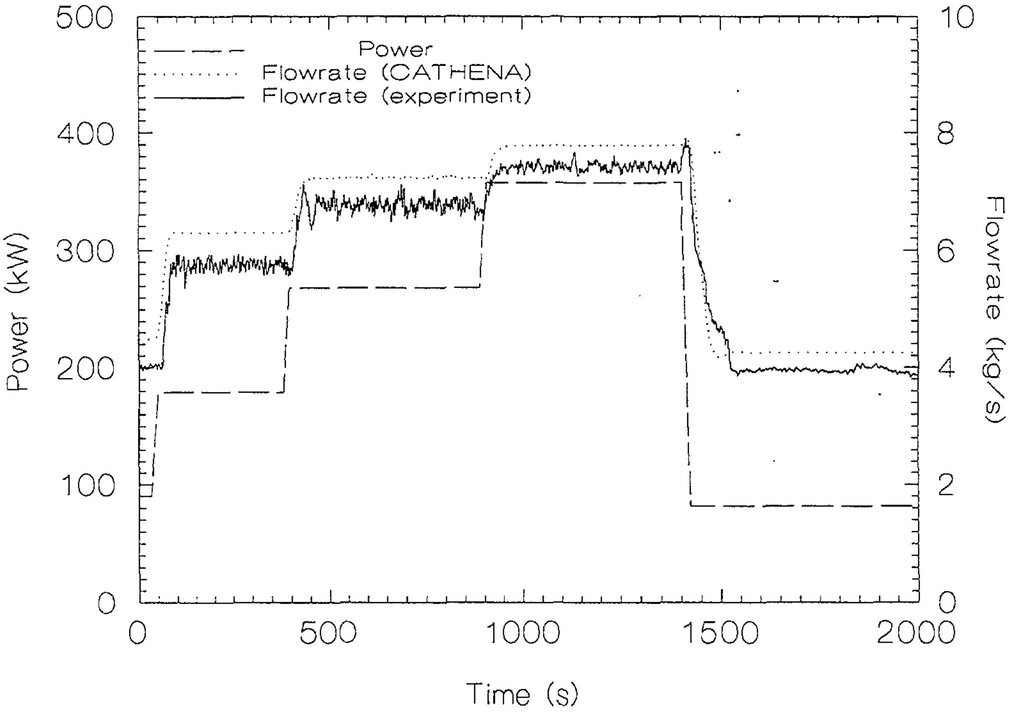

FIG. 10. High-power comparison with CATHENA using a condenser pressure of 111 kPa.

6. DISCUSSION AND CONCLUSIONS

The initial experiments proved that the concept of a flashing-driven natural-circulation loop was feasible. CATHENA pre-test simulations were successful in predicting the loop behaviour and were instrumental in guiding the experimental program.

Post-experiment attempts to refine CATHENA simulations led to a series of special-effects tests to help understand the flashing phenomenon. The special-effects tests demonstrated that two factors were important for flow stability: (1) flow patterns and temperature distribution within the calandria, and (2) flashing superheat requirements and the presence of nucleation sites.

If the temperature distribution within the calandria is within a range where temperature oscillations occur at the calandria outlet, the flow will oscillate because the elevation of the onset of flashing changes with temperature. This problem was dealt with in the test loop by mixing the calandria water, which significantly improved loop stability. The flow and temperature distribution within an actual calandria should be investigated further using a properly sized calandria, and with a suitable inlet-outlet configuration.

The experiments were conducted with the calandria inlet temperature equal to the condenser saturation temperature (~100 °C). The results (experimental and CATHENA predictions) indicated stable loop operation with calandria mixing and improved nucleation (wire-insert experiments). By accounting for these effects, we obtained good agreement between the experiments and code simulations.

The case of a variable calandria inlet temperature resulted in flow oscillations at low powers [3]. The results of the separate-effects tests suggest that insufficient mixing in the calandria and non-uniform flashing must have contributed to this instability. However, CATHENA simulations showed that another reason for these oscillations was variations in the outlet temperature that resulted directly from variations in the inlet temperature. This effect was significant in those tests because the calandria was undersized by a factor of 10 [3]. With a properly sized calandria, temperature variations in the cold-leg should by dampened, and the loop behaviour should be similar to that obtained with a constant calandria inlet temperature. This hypothesis was verified using CATHENA, and further tests are planned with a larger calandria.

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