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This is a Final draft version of a publication

published by American Nuclear Society

in Proceedings of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20)

DOI:

Please cite the publication as follows:

Telkkä, J., Riikonen, V., Räsänen, A., Kotro, E., Hyvärinen, J. (2023). Efficiency of Passive Open Loop Heat Removal Over Wide Range of Loop Flow Resistances – PASI Loop Tests in the EU-PASTELS Project. Proceedings of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20). 3285. pp. 1716-1726.

Efficiency of Passive Open Loop Heat Removal Over Wide Range of Loop Flow Resistances – PASI Loop Tests in the EU-PASTELS Project

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ABSTRACT

The PASI test facility, designed and constructed at LUT University, is a model of a containment cooling system using an open passive heat removal loop. The PASI facility consists of a pressure vessel simulating containment conditions and a circulation loop comprising an in-containment heat exchanger, riser and downcomer pipelines, a sparger, and a water pool as a heat sink / water reservoir.

The loop flow resistance research with the PASI facility has been carried out within the PASTELS (Passive Systems: Simulating the thermal hydraulics with experimental studies) project with funding by the EU Horizon 2020 program. The experiments within PASTELS have been done to quantify the sensitivity of the heat removal capability versus loop flow resistance and to map the loop operating conditions where instabilities or flow oscillations appear.

During each experiment, loop flow resistance was varied by a throttling valve, keeping the heating power to the containment constant. Experiments were done with different heating powers. It was observed that the system removed heat efficiently over a wide range of additional loop resistance. Loop flow rate was stable until saturation was approached. With close to saturation conditions in the loop, geysering-like flow oscillations set in. Heat removal capability remained consistently good despite the oscillations. Decreasing heating power decreased the oscillation frequency of the loop flow, and the oscillation amplitude stayed almost constant. After each increase in the flow resistance, void fraction in the riser increased and the system found at once a new quasi-steady state where heat was adequately transferred.

KEYWORDS
PASI facility, open passive heat removal loop, natural circulation, flow resistance, oscillation

1. INTRODUCTION

Naturally circulating heat removal loops are designed as passive safety systems in many light water reactor concepts for containment cooling and pressure reduction. Such circulation loops are designed to operate passively without an external power relying on relatively small gravitational pressure differences. Specific open passive containment cooling systems are included in the Russian AES-2006 (VVER-1200) type [1], the Chinese HPR1000 type [2], and the Korean iPower type [3] nuclear power plant designs.

Open passive containment cooling loops often operate at low atmospheric pressures and are sensitive to boiling oscillations due to a large water-steam density difference. Experiments in prototypical conditions enable to study and verify the safe operation performance of passive safety systems under postulated accident scenarios. To fulfill the experimental needs, the open passive containment cooling system test facility PASI was designed and constructed at LUT University, Lappeenranta, Finland. The first characterizing experiments of the facility were performed in 2018 and 2019 including natural circulation experiments [4]. The experimental work with the PASI facility has been continuing with a modified version of PASI within the Finnish national nuclear safety research programme SAFIR2022. The research activities have been proceeding within the PASTELS (Passive Systems: Simulating the thermal hydraulics with experimental studies) project with funding by the EU Horizon 2020 program. The experiments within the PASTELS project quantify the sensitivity of the heat removal capability versus loop flow resistance, pool water level, containment heat load, and map more thoroughly the loop operating conditions where instabilities or flow oscillations appear.

In the present paper, the effect of loop flow resistance on the behavior of an open loop passive heat removal system is presented. Within the PASTELS project, four experiments quantifying the sensitivity of the heat removal capability to the flow resistance were conducted in 2022. The experiments were performed with different heating powers. In each experiment, loop flow resistance was varied over large range.

2. PASI TEST FACILITY

The PASI facility is a one-loop model of an open passive containment cooling system. The applicable reference system for the PASI test facility is the passive containment heat removal system of the AES-2006 type pressurized water reactor. The design height scale of the PASI facility versus the reference system is 1:2. PASI (Figure 1) consists of a steam system, an open natural circulation system, and measurement and data acquisition systems.

The steam system includes a steam supply, a pressure vessel simulating the containment conditions, and a condensate draining system. Steam for the facility is produced with the PACTEL facility in another laboratory building and led to a buffer tank. The buffer tank is equipped with a small electrical heater to reduce the steam moisture or even superheat steam. The steam is injected from the buffer tank into the containment vessel rated for the pressure of 5 bar to simulate the containment environment. The steam in the containment vessel condenses on the surface of the heat exchange tubes and the vessel walls. The condensate is collected from the bottom of the containment vessel via a drain line to a small condensate tank and discharged to drainage.

The open natural circulation system contains a heat exchanger with a bundle of 15 heat exchange tubes, two collectors, a riser with a sparger, and a downcomer with open connections to a water pool forming a heat removal loop. The riser and downcomer contain nearly horizontal parts (inclination 4°). The diameters of the riser and downcomer are scaled down to maintain the relative gravitational and frictional pressure losses between the test facility and the reference system [5]. The main parts of the heat exchange tube bundle, the hot collector, and the riser inlet are inside the containment vessel. The heat exchange tubes penetrate the bottom of the containment vessel, and hence the cold collector is outside the vessel. The heat exchange tubes are arranged between the collectors into two rows in a triangular grid. The sparger consists of an inner pipe and a shroud with openings at the bottom and top (Figure 2). The main characteristics of the PASI facility are presented in Table I.

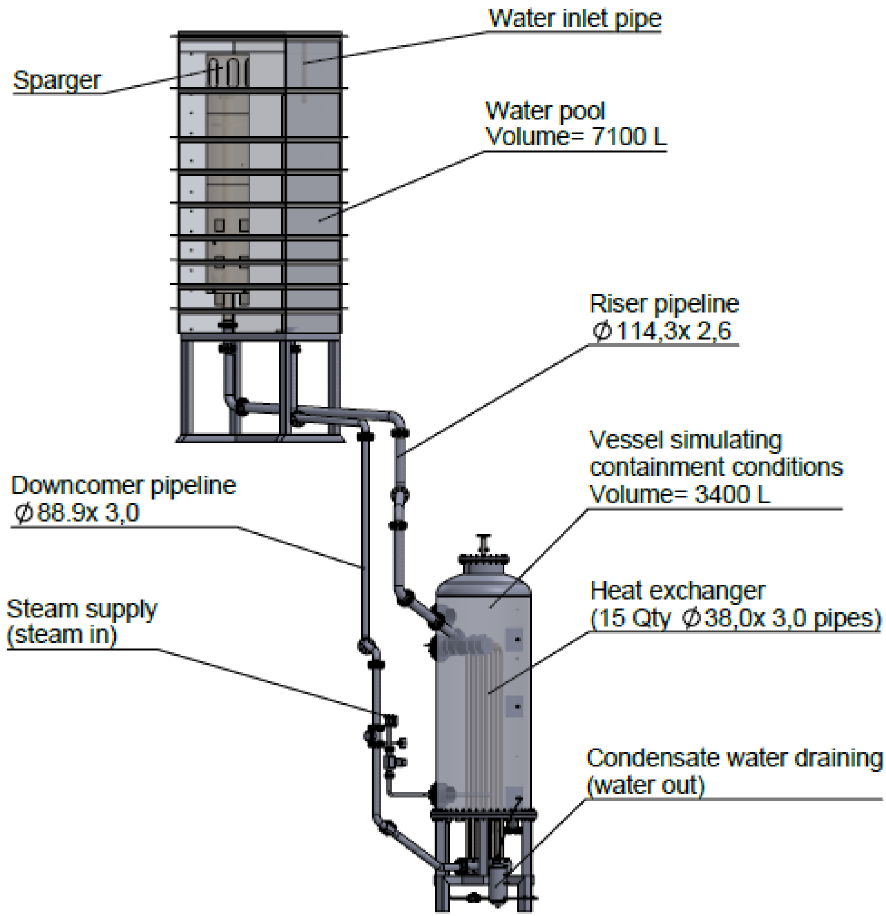

Figure 1. General view of the PASI test facility.

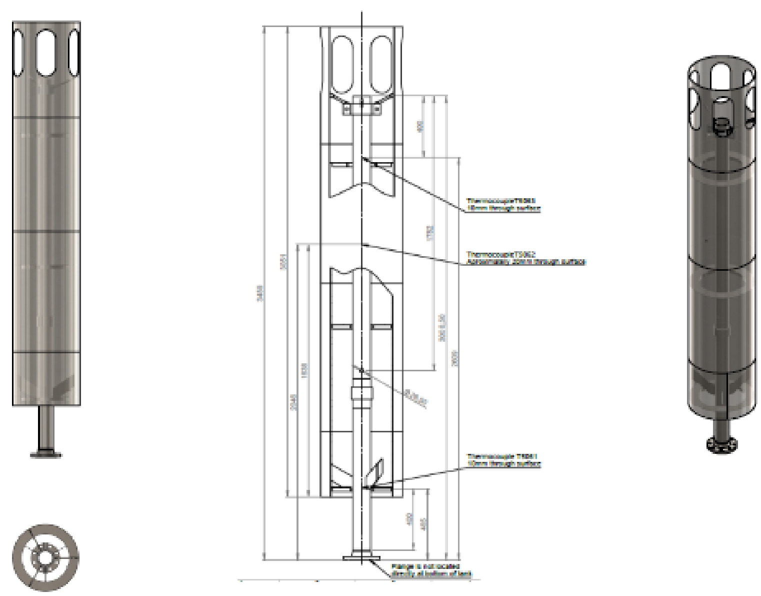

Figure 2. PASI sparger.

Table I. Main characteristics of the PASI test facility

Characteristic	PASI test facility
Reference system	PHRS-C /AES-2006
Height scale (riser & downcomer pipelines, heat exchanger)	1:2
Number of the heat removal loops	1
Number of the heat exchange tubes	15
Maximum pressure, containment vessel	0.5 MPa
Maximum temperature, containment vessel	443 K (170 °C)
Height of the loop	8.1 m
Height of the heat exchanger	2.8 m
Heat exchange tube outer diameter / wall thickness	38 / 3 mm
Riser pipeline outer diameter / wall thickness	114.3 / 2.6 mm
Downcomer pipeline outer diameter / wall thickness	88.9 / 3.0 mm
Main material of the components	Stainless steel
Insulation material / thickness	Mineral wool / 50 mm

The water pool acts as a water reservoir and heat sink for the natural circulation system. Initially the pool is filled with tap water. The pool water level can be maintained constant by a feedwater injection system. The feedwater is taken from the local tap water system and is cold but can be warmed if needed. A vertical overflow draining line drains excess water from the pool. The top of the overflow line is 3.026 m above the bottom of the pool, allowing to maintain the water level. The pool water can be drained from the bottom of the pool. The pool is not insulated as the other parts of the facility. The lid of the pool is not fully tight, and the conditions in the pool are under normal atmospheric pressure.

3. LOOP FLOW RESISTANCE EXPERIMENTS

The loop flow resistance experiments conducted within the PASTELS project characterized the system behavior with three different heating powers varying the flow resistance over wide range using a shutoff valve in the PASI downcomer line. Altogether four experiments (named PAS-01, PAS-02, PAS-03 and PAS-04) were performed. The fourth experiment was a repetition of the first experiment. The aim of the test was to repeat the first experiment as accurately as practically possible to get a verification of the functioning of the system.

Before the experiments, pressure losses of the shutoff valve were experimentally defined. With the results of this testing, the dimensionless pressure loss coefficient of the valve as a function of the valve position was calculated:

$$\Delta p = \xi \rho \frac{1}{2} w^2 \Rightarrow \xi = \frac{2\Delta p}{\rho \left(\frac{q_\mathrm{m}}{\rho A}\right)^2} \tag{1}$$

where Δp is the pressure loss, ρ is the density of the fluid, q_m is the loop mass flow, and A is the cross-sectional area of the pipeline. The results of the testing are presented in Table II and Figure 3. The results show that the flow resistance increases dramatically when the downcomer shutoff valve is closed by 90 %. The valve is a ball valve type, and the percentage values in Table II and Figure 3 do not correspond the blocked cross-sectional flow area of the pipeline. For example, with the valve 95 % closed, the loop flow path is practically fully blocked.

Table II. Results of the pressure loss testing of the downcomer shutoff valve

Valve position [% closed]	Differential pressure [Pa]	Dimensionless pressure loss coefficient
0	10	2
49	80	15
55	170	32
59	300	58
65	380	71
69	910	175
76	1500	279
79	4020	774
86	8900	1714
90	131800	33332
95	160000	110854

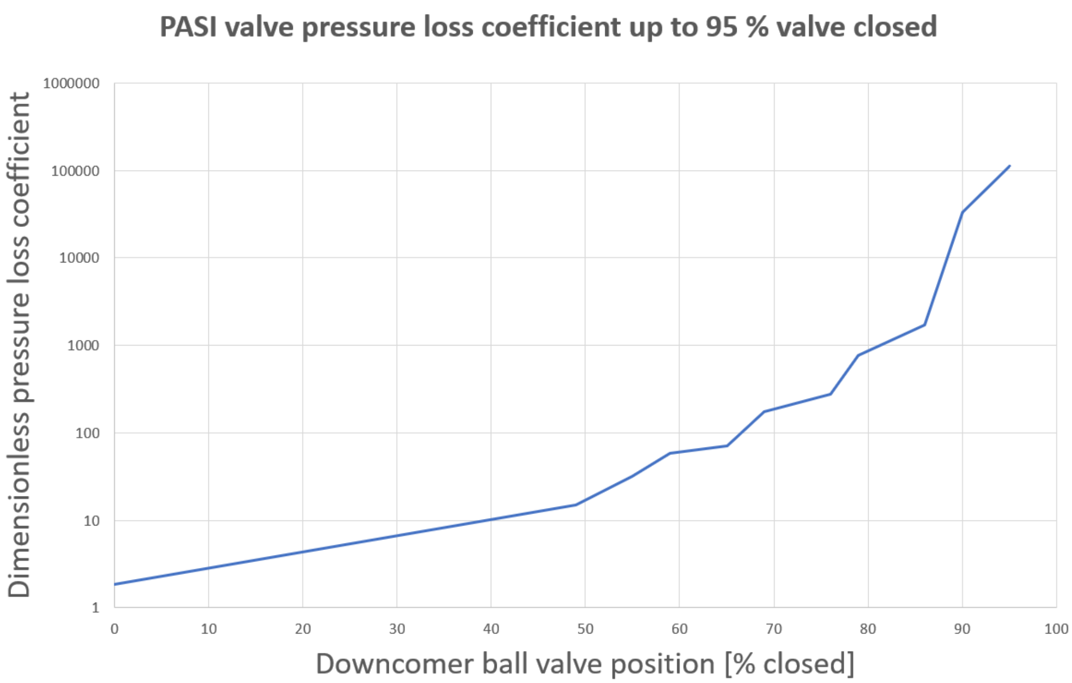

Figure 3. Dimensionless pressure loss coefficient of the downcomer line shutoff valve as a function of valve position.

The loop flow resistance experiments PAS-01 - PAS-04 were seen as “quasi-steady state” experiments since the cooling system evolved during the experiments and the water temperatures in the water pool changed. Nevertheless, the boundary conditions like steam mass flow at the inlet of the containment vessel were kept constant to keep the vessel inside pressure as constant as practically possible.

Each of the four experiments started from the atmospheric pressure and cold temperatures. The containment vessel was closed with normal laboratory air inside. The natural circulation loop of the facility and the water pool were filled with cold or room temperature water. The experiments began when the steam supply line valve was opened, and steam flowed into the lower part of the containment vessel. The existing air in the containment vessel was not removed. The facility was heated up with a continuous steam injection to the containment vessel corresponding approximately 200 kW heating power to reach more rapidly the high-temperature conditions in the water pool.

During this phase, the water in the tube bundle of the heat exchanger warmed up due to the transferred heat from the containment vessel to the loop side. The density difference between the downcomer and the tube bundle of the heat exchanger created a driving force, which caused the single-phase liquid natural circulation to begin. The warming loop water on the hot side of the loop flowed via the riser pipeline and the sparger into the water pool. After the start-up period of the experiments, the single-phase natural circulation mass flow rate in the loop reached a considerably stable, slightly increasing value. During this period, the system transferred heat efficiently with a power of approximately 150 kW. The rest of the heat (50 kW) warmed up the structures of the facility, was lost through the heat losses, and was extracted from the facility with the condensate.

After the heat-up of the facility, the heating power was reduced. The experiments were carried out in a similar way, but the heating power was varied. In the PAS-01 experiment, the heating power was 150 kW, which was the practical maximum value to keep the containment vessel pressure within the safety limits. In the PAS-02 and PAS-03 experiments, the heating power was 100 kW and 50 kW, respectively. The PAS-04 was a repetition of the PAS-01 experiment, hence, a heating power of 150 kW was used.

An oscillating two-phase natural circulation flow mode began when water at the outlet of the riser pipeline reached the saturation conditions. When the oscillation stabilized, the loop flow resistance was increased stepwise by changing the position of the downcomer shutoff valve. Figure 4 shows the downcomer line mass flow rate during the PAS-01 experiment. In Figure 4, the graph above shows the mass flow rate during the whole duration of the test including the heat-up phase, and the graph below shows the mass flow rate during the actual quasi-steady state steps 1-6 according to the downcomer shutoff valve positions. At the end of the experiments the downcomer valve was opened.

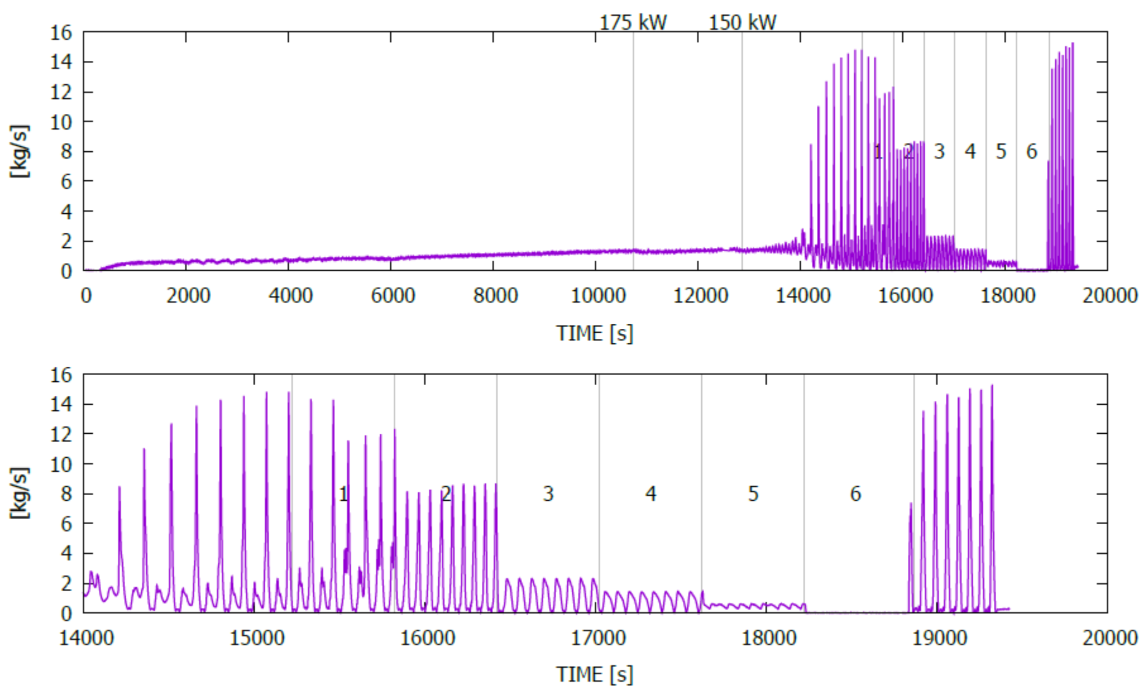

Figure 4. Downcomer mass flow rate during the PAS-01 experiment (error margin ±0.15 kg/s). Downcomer valve position: 1 – fully open, 2 – 50 % closed, 3 – 81 % closed, 4 – 86 % closed, 5 – 91 % closed, 6 - 95 % closed.

The two-phase natural circulation flow oscillated heavily. At the beginning, the flow mode was the coexistence of geysering and flashing. Geysering and flashing ([6], [7], [8]) are the two fundamental phenomena influencing on two-phase flow characteristics in an open natural circulation loop and both were observed in the PASI experiment with 150 kW heating power. In the other experiments, the geysering flow mode disappeared before the first step as the whole system was reaching saturation conditions. Before each higher peak there was a smaller increase in the flow rate. A local boiling process occurred in the top part of the heat exchanger. The bubbles entered and condensed quickly in the riser, making the natural circulation flow rate to fluctuate. When the water temperature at the riser reached the local saturation temperature, the flashing process occurred instantaneously starting from the top of the sparger. The flashing front moved downward along the riser rapidly, leading to the fast increase of mass flow rate due to a sharp increase of the driving force for the natural circulation. The increase of mass flow moved colder water from the downcomer to the heat exchanger and the riser. When the colder water from the downcomer filled the tube bundle of the heat exchanger, the density difference decreased, and the driving force of the flow almost disappeared. The flow rate decreased sharply and approached zero. As the boiling process started again in the tube bundle, a new cycle began. When the whole system was closer to the saturation conditions and no more condensing happened in the riser, the geysering flow peaks preceding the flashing peaks disappeared.

After each increase in the flow resistance, void fraction in the riser increased and the system found at once a new quasi-steady state. With the downcomer valve position of 95 % closed the downcomer flow stopped. The system still transferred heat efficiently evaporating water in the heat exchanger. The intensive flow oscillations returned at the end of the experiments when the downcomer valve was opened.

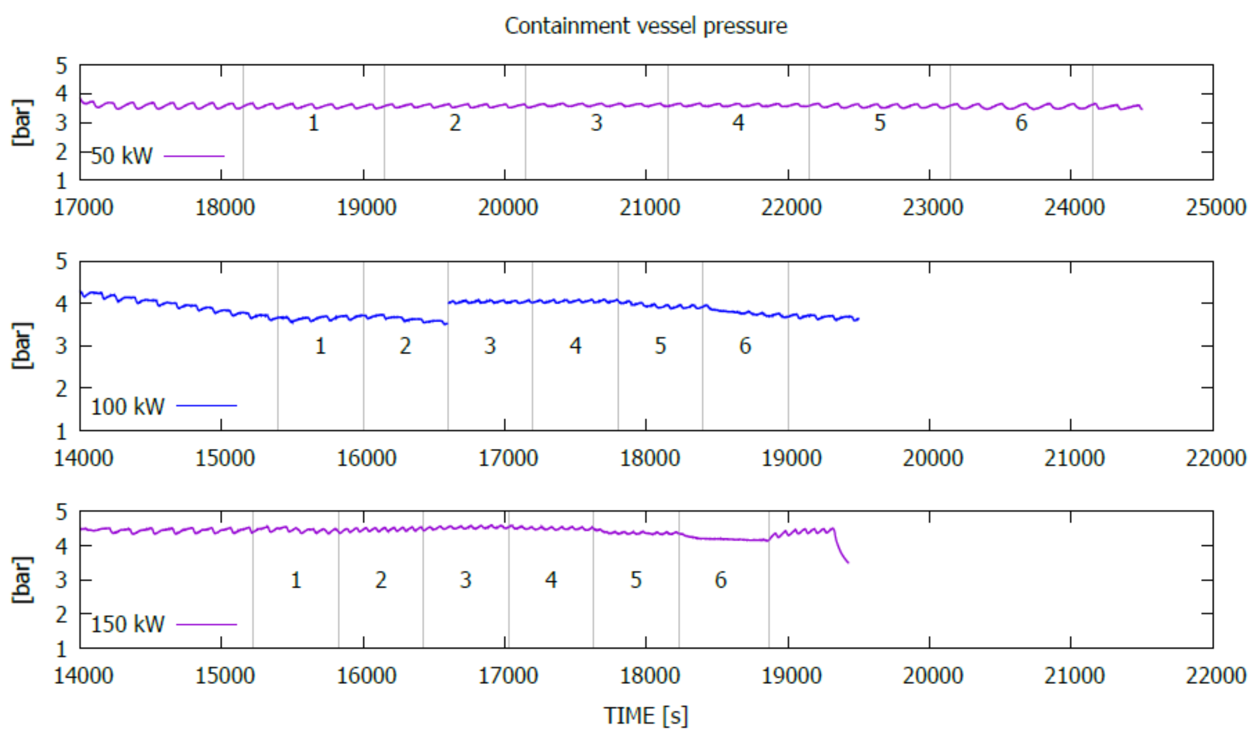

Figure 5. Pressure in the containment vessel (error margin ±0.03 bar). Downcomer valve position: 1 – fully open, 2 – 50 % closed, 3 – 81 % closed, 4 – 86 % closed, 5 – 91 % closed, 6 - 95 % closed. With 100 kW heating power there is a discontinuity between the second and third steps due to problems with the heating power adjustment.

The pressure in the containment vessel (Figure 5) stayed almost constant during each experiment. The pressure level increased with the used heating power. During the oscillation period, the pressure oscillated slightly. The maximum value of the pressure in the vessel stayed below the allowed maximum operational pressure. Hence, the heat removal loop was able to transfer heat efficiently from the containment vessel to the heat sink and to keep the pressure in the vessel within the safety limits showing that an oscillating flow is an efficient heat removal mechanism. With 100 kW heating power there is a discontinuity between the second and third steps due to problems with the heating power adjustment. That caused the containment vessel pressure to increase. After each increase in the flow resistance, the system found at once a new quasi-steady state where heat was adequately transferred. When the loop flow resistance was increased to 90 % or more, the heat transfer rate even increased decreasing the containment vessel pressure except in the experiment with 50 kW heating power.

The downcomer mass flow rates are shown in Figure 6 and the mass flow rate peak values and frequencies in Table III. In each experiment the peak frequency increased, and the amplitude decreased when the loop flow resistance was increased. With 50 kW heating power during the first quasi-steady state step, a new high flow peak occurred after approximately every 140 s (the frequency of the flow oscillations was approximately 0.007 Hz) and the amplitude was approximately 14.1 kg/s. When the downcomer valve was 91 % closed, the flow oscillation frequency was approximately 0.008 Hz and the amplitude approximately 0.6 kg/s. With 100 kW heating power the corresponding values were 140 s (0.007 Hz) and 14.1 kg/s during the first quasi-steady state step and 0.011 Hz and 0.6 kg/s when the downcomer valve was 91 % closed. In the experiment with 150 kW heating power in the beginning, a new high flow peak occurred after approximately every 130 s (0.008 Hz) and the amplitude of the peaks was approximately 15 kg/s. When the downcomer valve was 91 % closed, the flow oscillation frequency was approximately 0.014 Hz and the amplitude approximately 0.6 kg/s.

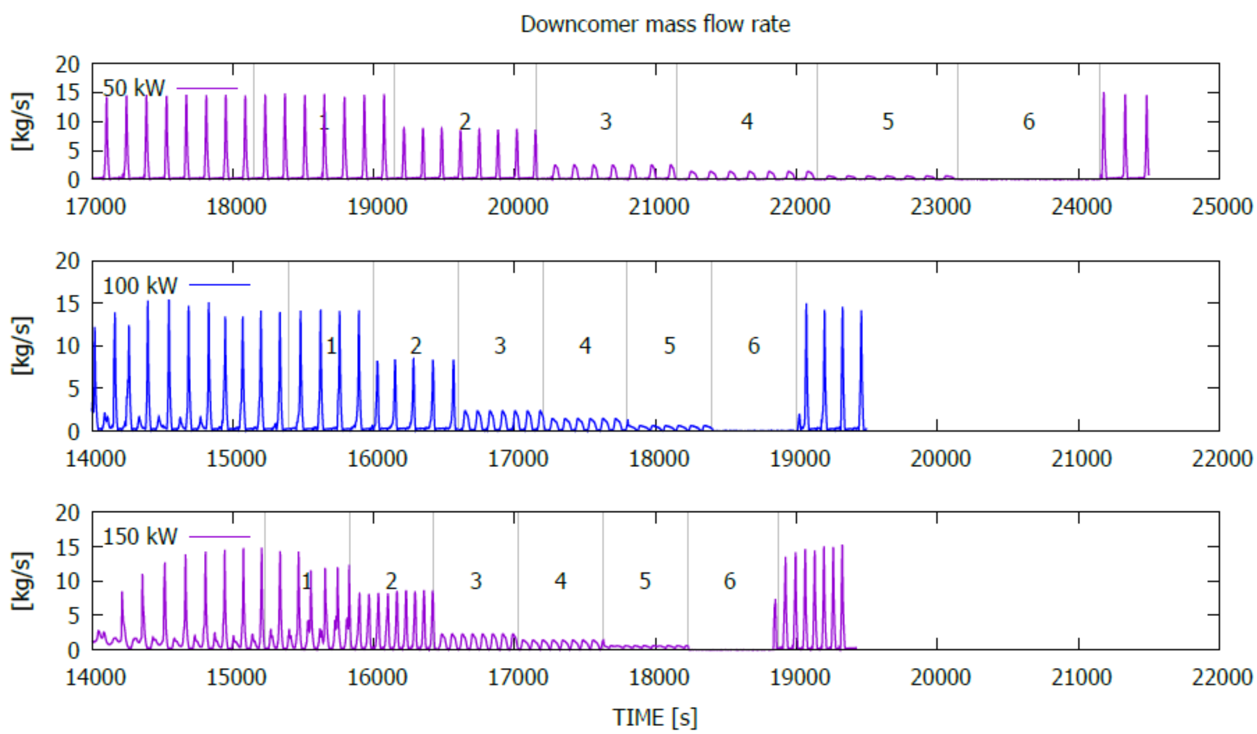

Figure 6. Downcomer mass flow rate (error margin ±0.15 kg/s). Downcomer valve position: 1 – fully open, 2 – 50 % closed, 3 – 81 % closed, 4 – 86 % closed, 5 – 91 % closed, 6 - 95 % closed.

Table III. Mass flow rate peak values and frequencies

Heating power [kW]	Mass flow rate peaks [kg/s]	Flow peak frequency [Hz]
50	14.1 – 0.6	0.007 – 0.008
100	14.1 – 0.6	0.007 – 0.011
150	15 – 0.6	0.008 – 0.014

The experiment results show that the peak frequency increases, and the amplitude decreases when the loop flow resistance increases. With the heating powers used in the experiments there is a loose connection between the heating power and the oscillation frequency of the loop flow and the oscillation amplitude. Increasing heating power increases them slightly. The loop flow resistance is more dominant.

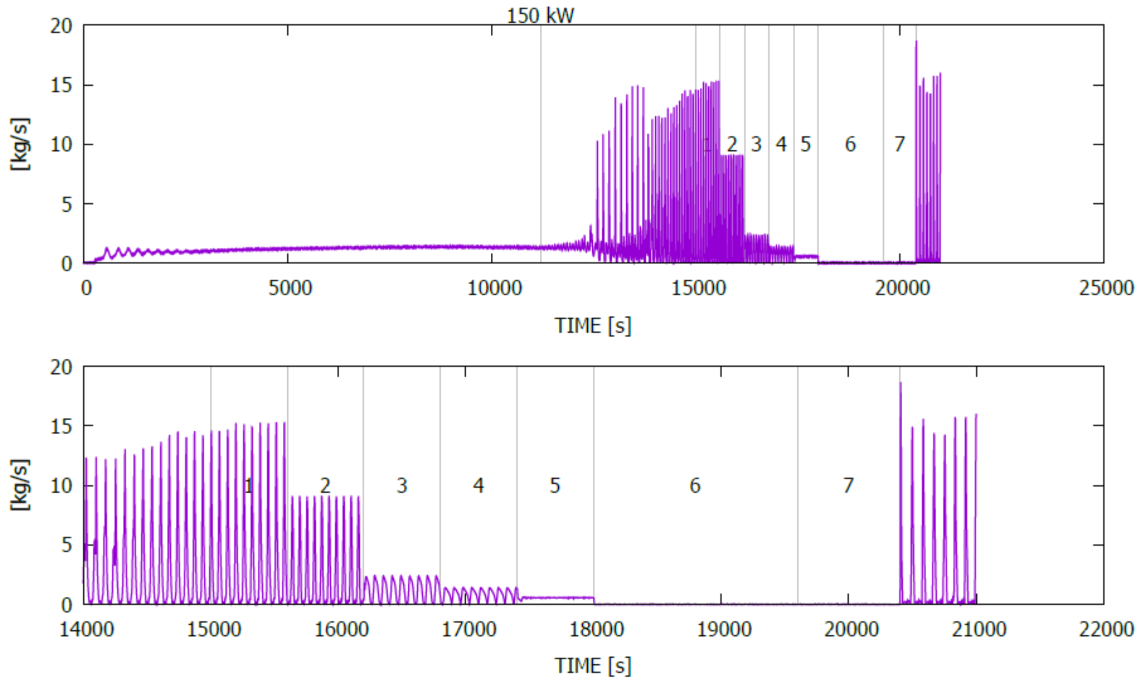

Figure 7. Downcomer mass flow rate during the PAS-04 experiment (error margin ±0.15 kg/s). Downcomer valve position: 1 – fully open, 2 – 50 % closed, 3 – 81 % closed, 4 – 86 % closed, 5 – 91 % closed, 6 - 95 % closed, 7 – fully closed.

In the repetition experiment with 150 kW heating power (PAS-04), a new high flow peak occurred after approximately every 64 seconds (0.016 Hz) and the amplitude was approximately 15 kg/s during the first quasi-steady state step with the valve fully open (Figure 7). The oscillation frequency was different from that of the first experiment (PAS-01) with the same heating power, where the frequency was 0.008 Hz. The frequency in the PAS-04 experiment was double compared with the first experiment. This is probably because in the repetition experiment, the system was let to stabilize longer before initiating the first step. There are not very big differences in the oscillation frequencies of the other quasi-steady state steps between the two experiments. Also, the oscillation amplitudes were pretty much the same in both experiments, except the steps 1 and 2, where the average amplitude was bigger in the repetition experiment. When the downcomer valve was 91 % closed, the water pool temperature profile was almost uniform in the repetition experiment and there were no more clear oscillations of the loop flow. There was also a slight difference in the oscillation wavelengths in the end of the experiments when the downcomer valve was re-opened. In that phase, interestingly there was a bigger wavelength in the repetition experiment.

4. CONCLUSIONS

The loop flow resistance experiments with the PASI facility within the PASTELS project were performed to quantify the sensitivity of the heat removal capability of a passive open loop heat removal system versus loop flow resistance and to map the loop operating conditions where instabilities or flow oscillations appear. Altogether four experiments were conducted varying the heating power and the loop mass flow resistance.

During each experiment, loop flow resistance was varied by a throttling valve, keeping the heating power to the containment vessel constant. Experiments were done with different heating powers. It was observed that the system removed heat efficiently over a wide range of additional loop flow resistance. The loop mass flow rate was stable until saturation was approached. With close to saturation conditions in the loop, geysering-like flow oscillations set in. Heat removal capability remained consistently good despite the flow oscillations.

The experiment results showed that there is a loose connection between the heating power and the oscillation frequency of the loop flow and the oscillation amplitude. Increasing heating power increases them slightly. The loop flow resistance is more dominant. The peak frequency increased, and the amplitude decreased when the loop flow resistance increased. After each increase in the flow resistance, void fraction in the riser increased and the system found at once a new quasi-steady state where heat was adequately transferred.

The results of the PASI experiments presented in this paper indicate that a passive open loop heat removal system can efficiently remove heat from the containment and maintain the containment pressure on a safe level regardless of strong loop flow oscillations or even very high loop flow resistances. Hence, it can be concluded that this kind of passive heat removal system seems not to be sensitive to changes in the loop friction.

ACKNOWLEDGMENTS

The experiments presented in this paper were performed at LUT University by the Nuclear Engineering research group with the PASI test facility. This work was performed under the PASTELS (Passive Systems: Simulating the thermal hydraulics with experimental studies) project with funding by the EU Horizon 2020 program.

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