Experimental study of a natural circulation loop and RELAP5-3D analysis

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Abstract. Passive safety systems, which are being largely adopted in advanced nuclear reactors to enhance the safety of the plant, are often based on natural circulation for the decay heat removal and are characterized by the presence of non-condensable gases and pools with stagnant liquid at atmospheric pressure. At the Energy Department of Politecnico di Torino (Italy), the test facility PROPHET has been designed and operated with water in both single-phase and two-phase flow. It consists of a bayonet heat exchanger electrically heated at constant power, a condenser immersed in a pool containing a fixed initial mass of water and the connecting pipes. The effect of loop filling ratio and condenser shell-side level on the system behaviour are here studied. The experimental transients have been analysed in terms of phenomenological windows. Heat losses and the heat sink influence both the time behaviour and the final values of pressure and temperatures in the facility; the filling ratio determines the kind of natural circulation (single-phase or two-phase) and strongly affects the phenomena occurring during the experiments. The experimental results are also compared with the predictions of a RELAP5-3D model. Discrepancies between calculated and experimental values are estimated during the transients in order to evaluate the code prediction capabilities.

1. Introduction

Natural circulation, which is already used in many industrial fields, has recently become of particular interest in the nuclear sector [1] as regards passive systems for the decay heat removal in both normal and accidental conditions. This is the case of some Generation III+ reactors such as the Westinghouse AP1000, General Electric ESBWR, SPIC CAP1400, Generation IV reactors and Small Modular Reactors [2].

Worldwide there is a strong effort for the qualification and validation of system thermal-hydraulic codes for passive heat removal systems operating in natural circulation, since they have some particular features that should be carefully addressed, such as the presence of non-condensable gases in the coolant and large water pools that serve as intermediate heat sinks. Therefore, it is important to understand the limits of the computational tools available nowadays, with the aim to improve them to be used for the safety analysis of these innovative systems.

A test facility (PROPHET, PROtotype Passive HEat removal sysTem) has been built at Dipartimento Energia of Politecnico di Torino (Italy) [3, 4] to study heat transport in natural circulation and to assess the capabilities of system codes such as RELAP5-3D. PROPHET is a reduced-height reduced-pressure facility inspired to the second decay heat removal system (DHR2) of ALFRED reactor [5]. The facility is composed of a bayonet tube heat exchanger (heat source), a condensation pool (heat sink) and the connecting piping (hot and cold legs).

The present work analyses the effects of the condensation pool and the facility filling ratios on the thermal-hydraulic phenomena occurring during the heat-up transient of a natural circulation loop. The facility has also been modelled by RELAP5-3D and the code predictions are here compared with the experimental results.
2. PROPHET facility and experimental matrix
The PROPHET natural circulation experimental facility mainly consists of a bayonet tube heat exchanger, whose outer surface is electrically heated at a constant electric power, a condenser heat exchanger consisting of single pipe immersed in a condensation pool, connecting pipes and valves.

The test facility is shown in figure 1. The loop total inner volume is 3.2 dm$^3$. Its total height is 5.085 m, while the heated length in the bayonet is 1.06 m. The inner diameter and total volume of the pool shell side are 0.168 m and 0.0108 m$^3$ respectively. A more thorough description of the facility is reported in [6].

The PROPHET bayonet is heated by electric heating tapes wrapped around the outer tube, with a gross applied electric power of 1.75 kW. All pipes and the bayonet heat exchanger are made of stainless steel AISI 304. With respect to the previous experimental campaigns [4, 6] the safety valve and the pipes connecting the bayonet outlet to the condenser inlet have been insulated with a 3 cm thick rockwool layer.

Demineralised water flows downward through the bayonet downcomer, reaches the bayonet lower plenum and then flows upward in the annular region of the riser and hot leg and finally downward along the condenser and cold leg. The shell-side of the condenser is an annulus containing water initially at ambient temperature; the height of the water level is fixed at the beginning of each experimental test.

The system, initially at ambient pressure and temperature (measured by a thermocouple located 2 m aside of the facility), was operated in both single-phase and two-phase flow natural circulation, at a maximum pressure of 7 bar. The initial value of the total mass of water in the loop (filling ratio) and the initial water level in the condensing pool have been varied during the experimental campaign: their initial values are reported in Table 1, together with the corresponding initial mass of water (accuracy ±20 g) and volume of air in the loop.

![Figure 1. PROPHET facility: sizes in mm (left), measurement points (center) and photo (right).](image-url)
Table 1. Experimental test matrix.

| Filling ratio (%) | Condenser water level |
|------------------|-----------------------|
|                  | 0.45 m    | 0.40 m    | 0.35 m    |
| Water mass (kg)  |           |           |           |
| 80               | 2.569     | 2.567     | 2.596     |
| 85               | 2.719     | 2.733     | 2.73       |
| 90               | 2.879     | 2.899     | 2.871     |
| 93               | 2.98      | 2.98      | 2.98      |
| Air volume (m³)  |           |           |           |
| 0.631            | 0.633     | 0.631     |
| 0.481            | 0.467     | 0.470     |
| 0.321            | 0.301     | 0.329     |
| 0.22             | 0.22      |           |

The maximum filling of the facility corresponds to 93% of its total internal volume, since air remains trapped into the pipe connecting the loop to the safety valve and in the annular region of the bayonet located above the exit from the bayonet itself. The power source is turned on after 60 s from the beginning of the data acquisition and it is maintained constant at 100% for the rest of the transient duration. During this initial phase, the average value and the standard deviation of the acquired data are evaluated in order to estimate the experimental uncertainty of the initial conditions (standard deviations 0.01% for temperatures, 1% for differential pressures, 0.05% for absolute pressures). Forced circulation tests have been carried out in order to estimate the power actually received by the water flowing in the bayonet annulus; an average value of 1.225 kW was found [6]. No water is fed to the shell side of the condenser during the experimental test. Temperatures are measured by K-type thermocouples (accuracy ±1 °C) and absolute and differential pressure by Rosemount pressure transducers (accuracy ±0.004 bar and ±0.06 mbar respectively).

3. Experimental results and discussion
The analysis of the time behaviour of the measured thermal-hydraulic parameters showed the presence of three different Phenomenological Windows (PhW) characterized by specific phenomena:

- PhW1: Initial heat-up with negligible natural circulation; this phase begins when, at 60 s, the power is provided to the bayonet heat exchanger and ends when the temperature rise at the bayonet outlet is strongly reduced.
- PhW2: Natural circulation development; the end of this phase is conventionally fixed at the time when the temperature at the bayonet inlet starts to increase, i.e. when the fluid is completing its first tour along the loop.
- PhW3: Almost stabilised natural circulation.

During the first two PhWs, the test facility heat-up transient is strongly influenced by the thermal capacities of the solid structures, as shown by the different rate of increase of the temperatures in the different points of the test facility. Afterwards, even though temperatures and pressures are still increasing, their average rate of change is similar and it decreases with time. The thermal-hydraulic parameters may show oscillations, whose amplitude depends on the occurring phenomena, but their average value tends to become constant.

Figure 2 shows that the initial value of the pool water level has little effect on the system pressure (maximum difference 0.12 bar). Since the power provided to the bayonet heat exchanger is constant, an increase of the level induces an increase in the heat removed by the water pool and a decrease of the final pressure. Nevertheless, a negligible effect is shown in the first 6000 s of transient. The higher the pool water level is, the lower pressure and temperatures are. Differences between the final values of temperatures (figure 3) are anyway small (maximum difference 4°C), since the length of pipe where the heat transfer is increased is only 0.1 m, while the total length of the cold leg is approximately 3 m. It is worth underline that after 10000 s, the temperature change between outlet and inlet of the bayonet is approximately constant.
The parameter that most affects the thermal-hydraulic phenomena is the loop filling ratio. In particular, single-phase natural circulation occurs with loop fillings of 93%, 90% and 85%; in this latter case, two-phase flow occurs in some regions of the test facility during the natural circulation development phase (PhW2), but it is suppressed during the following phase. Fillings lower than 85% allow the development of two-phase natural circulation.

The phenomena occurring for loop fillings of 93%, 85% and 80% are separately analysed hereafter.

Figure 2. Pressure at the bayonet lower plenum (P1) with 85% of filling and different heights of the pool water level.

Figure 3. Temperatures at the bayonet inlet (T8) and outlet (T2), with 85% of filling and different heights of the pool water level.

3.1. Filling 93%, pool water level 40 cm
In this test the upper horizontal pipe is initially completely full of water and single-phase natural circulation occurs during the tests. The loop is progressively pressurised (figure 4), with rate of pressure increase that diminishes during the time as an effect of the increasing power exchanged in the heat sink (condenser and cold leg). The pressure curve shows different concavities and a flex at approximately 7500 s. Probably after this time, the power removed by the heat sink (both the pool and the non-insulated pipe of the cold leg) becomes greater than the power received by the water in the bayonet.

Figure 5 shows the time behaviour of the differential pressure DP1 in the bayonet downcomer; some small oscillations occur in the time interval 1800-2500 s, probably due to geometric discontinuities in the bayonet and transition from laminar to turbulent flow.

During the PhW1 (60-250 s) the water in the bayonet starts to heat up, as shown by the increasing temperatures in the bayonet lower plenum and at the bayonet outlet (figure 6), but natural circulation is still negligible, since no temperature changes are observed at the inlet and outlet of the condenser (figure 7). When the natural circulation flow rate increases, cold water reaches the lower plenum (decrease of T1) and, since the power received by the water in the bayonet annulus does not change significantly, a decrease of the temperature T2 at the bayonet outlet occurs.

During PhW2 (250-370 s) the development of natural circulation occurs; its end is conventionally fixed when the temperature at the bayonet inlet (T8) starts to increase; later on, it reaches the same value of the temperature in the bayonet lower plenum (T1).

During the first part of the PhW3 (stabilization of the natural circulation), up to approximately 1000 s into the transient, the heat received by the water pool is negligible, since its temperature (TP in figure 7) remains approximately constant.

The analysis of the temperatures time behaviours showed that the flow rate through the loop is very low during PhW1, it increases during PhW2 and is almost constant during PhW3. The flow rate depends on the difference of elevation between the thermal barycentre of hot and cold side and on pressure drops, which change along the transient and are characteristic of the loop geometry.
3.2. Filling 85%, pool water level 40 cm

The time behaviour of pressure during this test is reported in figure 8. The analysis of the temperatures time behaviours shows that the PhW1 lasts longer than in the previous test (60-750 s). The end of this phase is conventionally assumed at the time when the temperature $T_2$ stops its first fast increase. Even though, similarly to the test with 93% of loop filling, a single-phase natural circulation develops, some additional phenomena occurs; in fact, the initial presence of water-air interfaces in both the hot and cold leg 16 cm below the upper horizontal pipe, induces some U-tube oscillation in the time interval 300-1500 s, as witnessed by the oscillations of the pressure difference $D_P$ (figure 9) and of the temperatures at the bayonet inlet, bayonet lower plenum and bayonet outlet (respectively $T_8$, $T_1$ and $T_2$ in figure 10).

Both the end of PhW2 and the increase of the temperature in the pool are delayed with respect to the tests at 93% filling: PhW2 ends at approximately 1100 s and the increase of the pool temperature occurs at approximately 2000 s (figure 11).

The temperature at the bayonet outlet tends to approach the saturation value only at the end of the test.
3.3. Filling 80%, pool water level 40 cm

The relatively low loop filling of this test determines the development of two-phase flow natural circulation. Initially, similarly to the test with loop filling 85%, two liquid levels are present in the hot and cold legs, but they are located 41 cm below the upper horizontal pipe. U-tube oscillations occur in the time interval 300-1500 s, as it can be deduced by the oscillations of the temperatures at the bayonet inlet (T8), lower plenum (T1) and outlet (T2) that are shown in figure 12. Some effects can also be seen on the time behaviour of the absolute pressure in the bayonet lower plenum (figure 13). The differential pressure oscillations in the bayonet downcomer due to U-tube phenomena are partially hidden by two-phase natural circulation instabilities that characterize the phases with natural circulation (figure 14).

The PhW1 ends at approximately 650 s, at the end of the fast increase of the temperature T2, which afterwards shows oscillations around an average value that remains constant up to approximately 2000 s. Also, the temperature T1 in the bayonet lower plenum shows oscillations around a constant average value, but only up to 1500 s.

During the PhW 2 (650-1500 s) the water in the loop is subcooled, but boiling occurs locally inside the bayonet annulus.
In PhW3, after 1500 s, oscillations are observed in all the measured thermal-hydraulic parameters, even though the ones in the differential pressure DP1 and temperature T1 in the bayonet lower plenum are the most relevant ones. These oscillations are due to instabilities in two-phase natural circulation, which cause density oscillations and flow rate oscillations.

During the PhW3, the heat received by the pool up to approximately 2200 s is negligible, since its temperature remains constant (figure 15). Oscillations of the thermal-hydraulic parameters are still present; they are characterized by an approximately constant period, as typical of natural circulation in two-phase flow, and the average value of the parameters increases up to the end of the test, but with decreasing slope.

4. RELAP5-3D model.
The experimental tests have been simulated by the thermal-hydraulic system code RELAP5-3D (version 4.3.4) developed by INL for the simulation of thermal-hydraulic transients in nuclear reactors [8].
The slicing technique has been applied in the development of the nodalization (figure 16), which allows the reduction of possible fictitious flow oscillations when buoyancy forces have considerable importance. According to this technique [9], the volume sizes must be properly chosen in order to guarantee that the midpoint of the corresponding volumes in parallel vertical pipes are located at the same elevation.

A total number of 220 volumes, 235 junctions and 225 heat structures have been used to represent the natural circulation loop and the water pool (respectively System 1 and System 2 in figure 16).

The HEAT STRUCTURE HS02 represents the outer wall of the bayonet, while HS01 simulates the downcomer wall. Heat losses to the environment have also been simulated by imposing the ambient temperature and a heat transfer coefficient on heat structures, which accounts for both radiative and natural convective heat transfer. Its value, evaluated by taking into account the surface outer diameter [3], has been tabulated as a function of the wall temperature and provided as input to RELAP5-3D. Heat structures 7, 10, 11, 12, 13, 17 to 22 also simulates the 3 cm thick rockwool layer.

![Figure 16. RELAP5-3D loop nodalization.](image)
To better simulate the heat accumulated in the solid material in transient conditions, the flanges have been modelled by adding a local heat capacity. TIME DEPENDENT VOLUMES 252 and 330 are used to fix the ambient pressure as boundary condition.

Heat flux is imposed on the outer surface of HS02 after 60 s from the beginning of the simulation and it is kept constant.

To compare the predictions of the RELAP5-3D model with the experimental results, the discrepancy has been estimated in terms of relative error between calculated and experimental values.

Figure 17 reports a typical time behaviour of the relative error for some of the measured temperature and pressures during single-phase transients (filling 93%). The agreement between the code prediction and experimental results is good during the PhW3, where natural circulation is completely developed. Conversely, the agreement is poor during the bayonet heat-up phase (PhW1), when the flow rate in the loop is negligible or very low and the applied heat is accumulated in the heat structures and in the water filling the bayonet annulus. Figure 18 refers to a test with a relatively low filling ratio (80%) in which two-phase natural circulation occurs.

![Figure 17. Discrepancy between experimental results and prediction in test with 93% filling.](image1)

![Figure 18. Discrepancy between experimental results and prediction in test with 80% filling.](image2)

The agreement during PhW3 is good for the coolant temperatures, but it is fairly poor for the absolute pressure. The reason seems to be due to having nodalized the water pool by a PIPE component, which does not allow to simulate the positive effect of recirculation cells inside the pool and therefore underestimates the water pool efficiency.
5. Conclusions.
In the present experimental campaign, the power provided to the bayonet (1.75 kW), which influences the pressure transient, has been chosen to have pressures lower than 7 bar.

The experimental tests have allowed observing that the loop filling strongly influences the pressure transient and the natural circulation along the loop. With high loop filling, single-phase natural circulation is established. With lower fillings, water-air interfaces are initially present in both hot and cold legs and U-tube oscillation are observed before the complete development of natural circulation; during this phase the net flow rate is very low. For filling ratios lower than 85% two-phase natural circulation develops and U-tube oscillations are hidden by two-phase flow instability phenomena. The heat received by the water pool seems negligible up to 1000-2000 s, showing the pool heat sink is not “active”. Delays in the activation and development of the natural circulation are observed when the loop is not completely filled with water.

As far as the predictions by RELAP5-3D are concerned, in single-phase natural circulation the pressure drops and heat losses to the ambient and the water pool are well estimated and a good agreement is found for both pressures and temperatures in the final phase when the natural circulation is developed.

On the other hand, when natural circulation approaches the two-phase regime, the prediction of temperatures is fairly good whereas the prediction of the pressures shows disagreements.

The nodalization of the pool needs to be improved to better predict recirculation cells in the water pool, possibly using the multi-dimensional component available in RELAP5-3D.

Future research would be aimed to better study, both experimentally and numerically, the heat transfer in the water pool and the effect of local pressure drops along the loop.

6. References

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