IOP Conf. Series: Journal of Physics: Conf. Series **796** (2017) 012046 doi:10.1088/1742-6596/796/1/012046

Preliminary numerical studies of an experimental facility for heat removal in natural circulation

C Bertani, M De Salve, M Caramello, N Falcone, A Bersano and B Panella

Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy

E-mail: marco.caramello@polito.it

Abstract. In recent years particular attention has been dedicated to passive safety systems for heat removal in nuclear power plants. Passive safety systems can achieve a high level of safety, as they carry out their mission relying solely on physical principles like natural circulation, without any need of operators or energy sources. To qualify these systems and components experimental activities are necessary to study and to understand the governing physical phenomena. The present paper shows the design of an experimental facility to be installed in the laboratories of the Energy Department of Politecnico di Torino. The facility is inspired by the decay heat removal system for ALFRED reactor and comprehends a heated bayonet tube and a heat sink for the heat removal (a heat exchanger inside a pool). The thermal power is in the order of 1 kW. A RELAP5-3D model of the facility has been developed and sensitivity analyses were performed to highlight the geometry of the heat exchanger, the final heat sink, and the mass of water inside the loop. The results of this phase serve to understand the physical limits of the facility, to demonstrate a preliminary feasibility and to optimize the geometry for the desired operating conditions.

1. Introduction

The safe operation of nuclear reactors has always been a topic of great interest both in the scientific and social environments. In the last few years existing power plants underwent through an extensive series of assessments and adaptations to integrate lessons learnt from recent accidents [1] while new reactor projects have been object of careful analyses to comply with the “safety by designs” principles [2]. In the framework of the systems for decay heat removal, a promising road to enhance the reactor safety is to use passive safety systems [3], especially in the light of the experience feedback given by generation III+ reactors. Such systems are designed to operate independently by relying solely on physical principles without the need of operators intervention. Passive safety systems have been tested and qualified for the operation in light-water reactors [4], but, as the components used may be different their application to liquid metal reactors has still to be confirmed. The Advanced Lead Fast Reactor European Demonstrator (ALFRED) [5] is a lead cooled fast reactor that makes use of bayonet heat exchangers to remove the heat from the primary system [6]. The heat exchanger geometry has some specific characteristics that may affect the natural circulation, such as the flow path and the regenerative heat transfer. It is therefore important to perform experiments for experience acquisition and code validation.

In the Energy Department of Politecnico di Torino many activities are carried out to study natural circulation in passive safety systems with bayonet heat exchangers. An experimental facility has been designed and is currently in the procurement and installation phase. The facility consists of a 1 meter heated bayonet tube and a heat exchanger inside a pool for final heat sink. The maximum power of the facility is in the order of 1 kW. In parallel to the experimental activity, a RELAP5-3D model of the facility has been developed to support the design by means of sensitivity studies and to perform pre-test calculations. The present paper describes the geometry and the phenomena to be studied in the experimental facility as well as the model and the preliminary sensitivity studies developed by means of the system code RELAP5-3D for design support. The results obtained suggest that the facility should be able to represent most of the relevant physical phenomena for the safety system and therefore may provide important informations for the development of these components.

2. Facility description

Figure 1 shows a drawing of the facility. Heat is generated on the bayonet heat exchanger at the bottom, where water enters from the downcomer pipe (see figure 2), reverses its direction and upflows in the annular region created between the coaxial pipes. At the outlet, the fluid exits transversely through a T-junction and crosses the vertical riser before reaching the heat sink. In this part, the fluid exchanges heat with water at ambient conditions housed in an annular pool around the pipe before entering again the bayonet from the top.

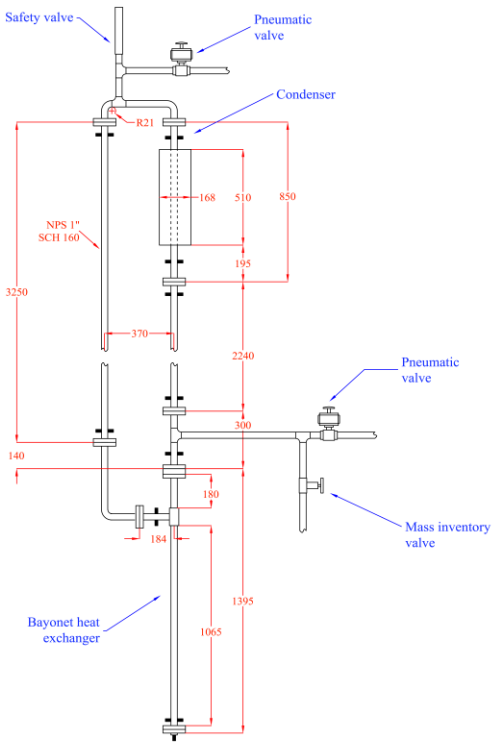

Figure 1. Drawing of the facility.

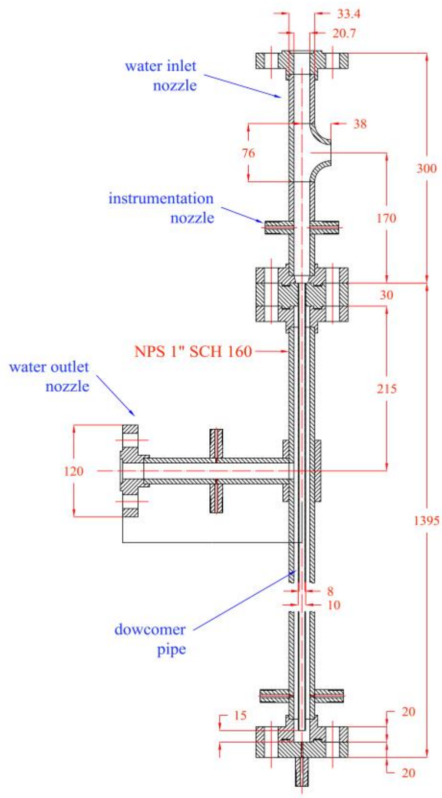

Figure 2. Drawing of the bayonet heat exchanger.

The overall motion of the fluid will be driven by buoyancy. The heat source increases the enthalpy of the fluid while the heat sink does the contrary, and the density difference drives the flow.

The facility is equipped with pressure transducers and thermocouples to monitor the condition of the fluid in several positions. Additional lines have been added to fill the facility with water, vent noncondensables and perform cold tests. These lines can be connected to an open circuit with a pump to characterize the pressure drops in forced circulation. A safety relief valve is set on the top of the

IOP Conf. Series: Journal of Physics: Conf. Series **796** (2017) 012046 doi:10.1088/1742-6596/796/1/012046

facility to prevent accidents deriving from overpressure transients. The different regions of the system are coupled by means of flanges for fast inspection and maintenance.

Heat is generated by means of electrical wires wrapped around the outermost tube of the bayonet heat exchanger. Considering the equipment available on the market and the surface area of the tube the power input should be of the order of 1.5 kW.

At this stage, the facility has been installed in the laboratory and cold tests are undergoing to characterize the hydraulic resistance of the loop.

3. RELAP5-3D Model

Validation of design, technical choices and sensitivity studies on the behavior of the facility have been supported by means of the commercial software RELAP5-3D©, that is a highly generic code for simulation of thermal-hydraulic problems in both nuclear and nonnuclear systems involving mixtures of vapor, liquid, noncondensable gases, and volatile solute [7]. Figure 3 shows a sketch of the Nodalization created for the study. The model comprises both the facility and the final heat sink.

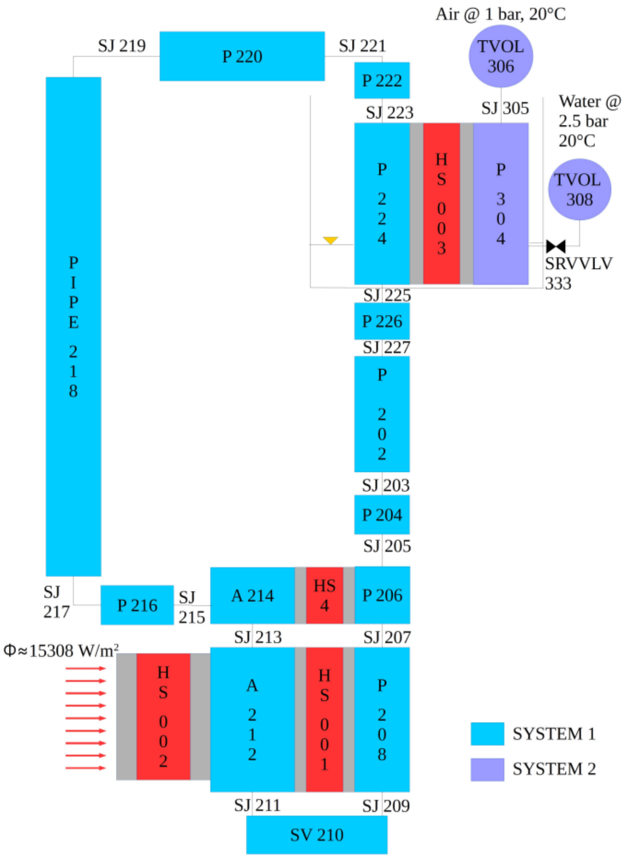

Figure 3. RELAP5-3D Noding.

The bayonet's downcomer is described by means of pipes 206 and 208. Single volume 210 models the volume of water in the inversion region. The bayonet's riser is modelled by means of annulus 212. Heat structures 1 and 2 models respectively (1) the regenerative heat transfer between the inner tube and the outer tube and (2) the outermost tube over which an imposed heat flux on the outside simulates the heating wires. Heat structure 4 models the heat transfer between the outlet of the bayonet and the uppermost region of the inner tube. The condenser is modelled by means of pipe 224 which transfers heat to the pool - modelled as pipe 304- through heat structure 3. Servo valve 333 provides water to the pool in order to keep the level to a user's defined set-point.

4. Results and discussion

This section presents the results obtained by means of the system code RELAP5-3D©. In the first part we have hypothesized an initial condition for the circuit and the water pool and have observed how the system reaches a steady state operation in natural circulation. In the second part, we modified the initial mass inventory in the circuit and the water level set point in the pool to understand how these two quantities affect the steady state operation. We have defined a custom void fraction expressing the volume fraction of steam at the initial pressure of 1 bar. It is the ones' complement of the volume occupied by the liquid phase. This parameter allows the filling level of the facility to be understood (when this value is 0, the loop is full of liquid water).

4.1. Startup procedure

The circuit is supposed to start in saturation condition at the pressure of 1 bar and the air in the facility is supposed to be completely vented out. The initial void fraction of the circuit is 50% (liquid water occupies an eight of more or less 2.7 meters while saturated steam is on the top). The timing of the events is as follows:

$t \in [0\text{-}50]$ s: power source is off and water pool is empty
$t \in (50\text{-}110]$ s: power source is turned on (ramp between 0 and 1.5 kW)
$t \in (110\text{-}170]$ s: power is kept constant and pool is empty
$t \in (170\text{-}230]$ s: water at 30 °C and 1 bar is injected in the final heat sink to form a level of 14 cm
$t \in (230\text{-}6000]$ s: power input and water level in the pool are kept constant.

The objective of the simulation is to understand if the system can reach a stable operating condition under natural circulation.

As the power input is turned on the pressure starts to increase and the water level in the loop decreases. Heat is removed by means of a pool boiling mechanism and the steam produced inside the bayonet reaches the top of the loop passing through the water level with a slug flow pattern. When the water is injected in the final heat sink natural circulation triggers and the flow rate stabilizes around a value of more or less 13 g/s. When the water in the pool reaches saturation and the power removed equalizes the power input the pressure stabilizes around 17.5 bar. The circuit then works in saturated conditions, apart from the downcomer channel below the final heat sink where water is below saturation of about 6 °C. The pressure reached by the circuit is such that the temperature difference between the loop and the pool can evacuate the power input with the natural circulation flow rate. Figures 4 to 8 show the behavior of some quantities during the transient.

When the water in the final heat sink starts to boil (around t=1100 s), a power jump in the heat removed from the final heat sink can be observed (figure 4), while pressure behavior in the loop experiences a sudden variation before stabilizing (figure 5).

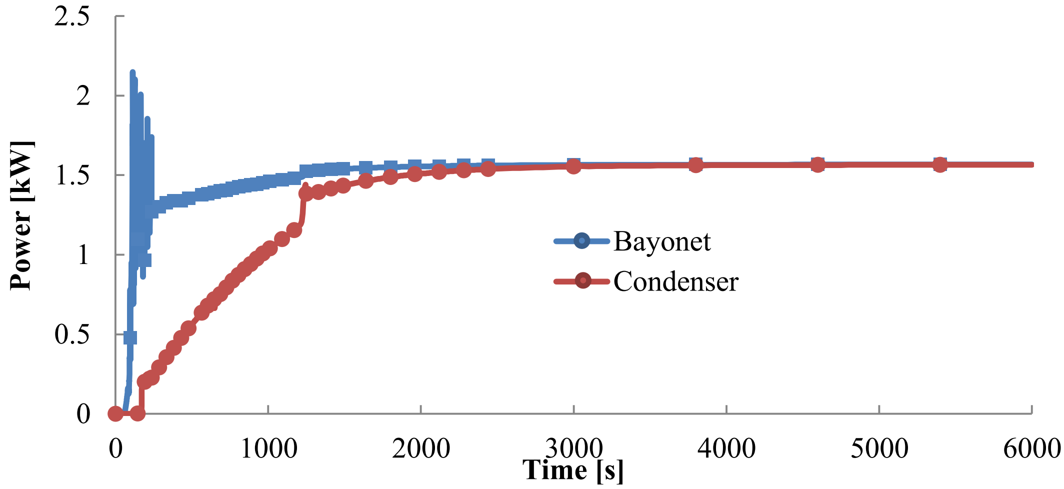

Figure 4. Power exchanged in the bayonet and the pool.

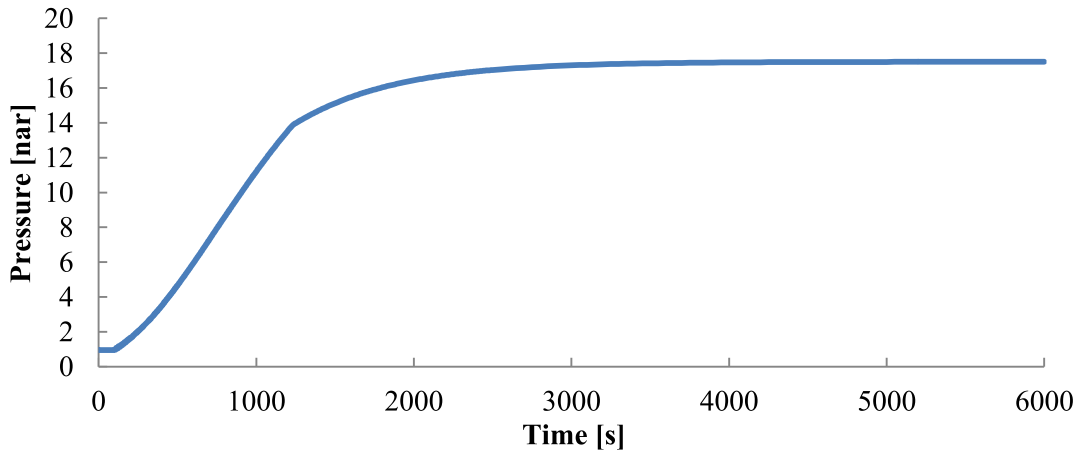

Figure 5. Pressure of the circuit.

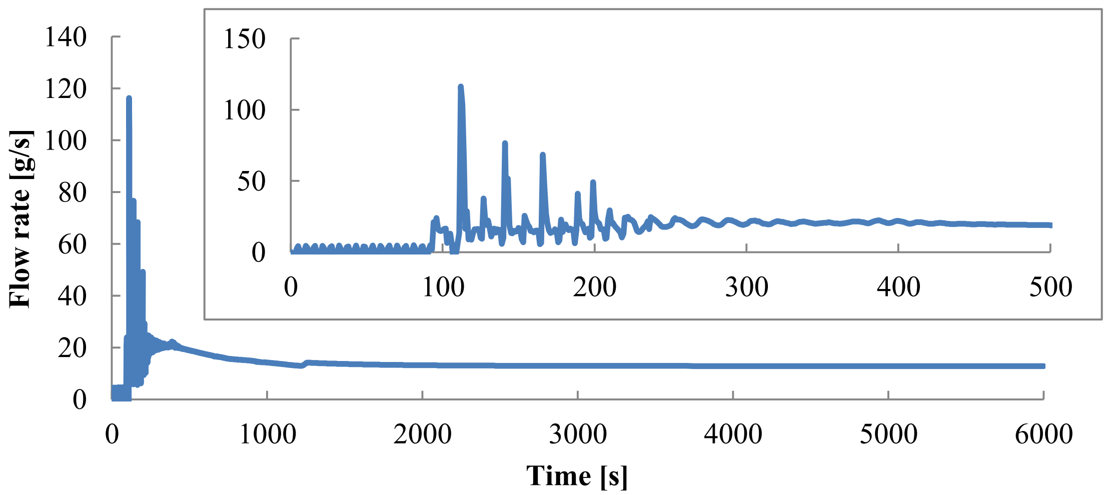

Figure 6. Flow rate at the outlet of the bayonet.

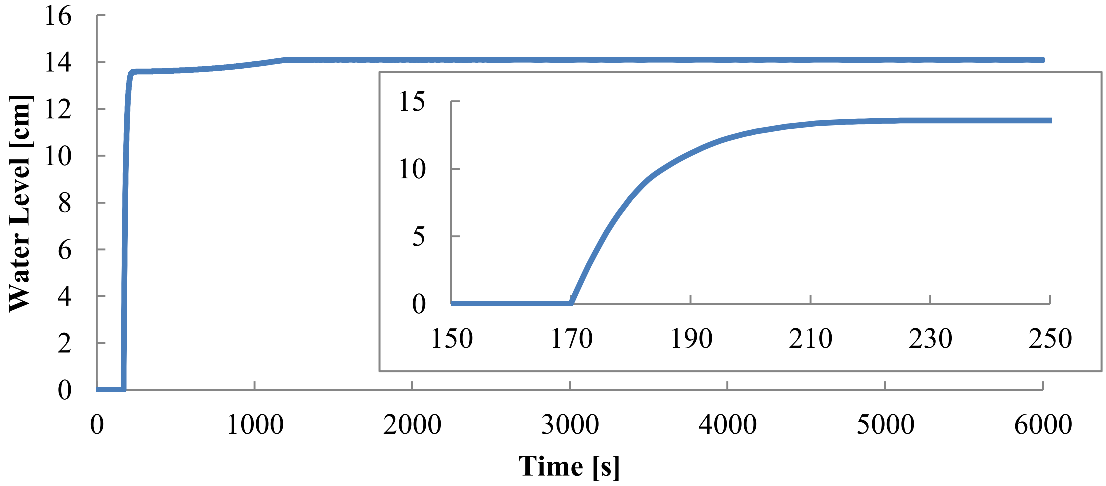

Figure 7. Water level in the final heat sink.

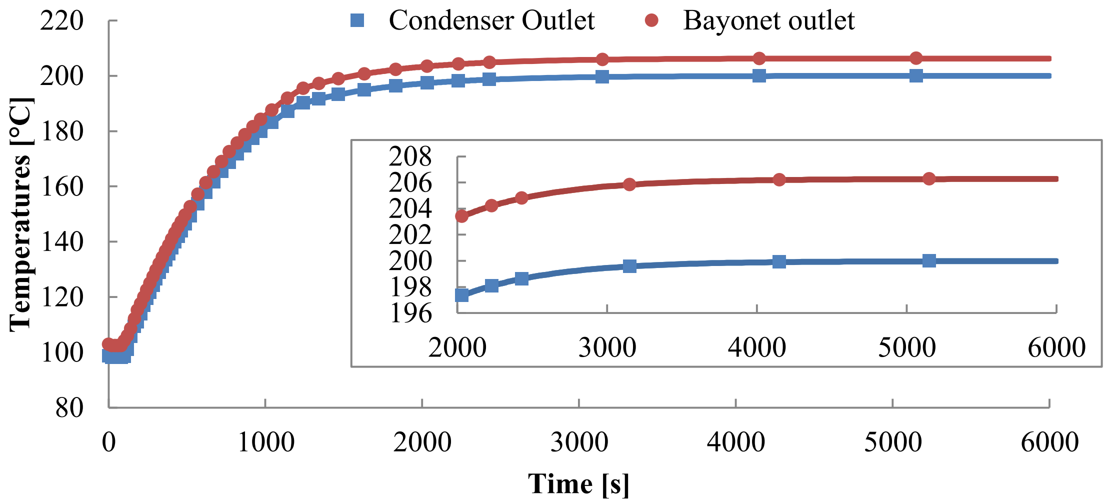

Figure 8. Temperatures in the loop (Bayonet outlet – Condenser outlet).

4.2. Sensitivity study on the initial mass and the water level in the loop

As far as the sensitivity study is concerned, we focused on both the water inventory inside the facility and the level inside the pool of the final heat sink, which defines its active length. The objective is to observe the expected operating pressure at which the system will operate, the temperature of the bayonet and the natural circulation flow rate. These quantities were important to understand both the piping dimension for integrity and the order of magnitude of the physical quantities for measurement.

Simulations were performed as follows. The model of the facility is initialized in saturated conditions with a mixture of liquid and steam. We therefore hypothesize to have completely vented all the noncondensables from the loop that contains a certain amount of water, or, alternatively, that the amount of noncondensables still in the facility do not affect the flow and the heat transfer. Starting from this point, heat is provided on the outermost diameter of the bayonet heat exchanger by means of an imposed heat flux boundary condition simulating the heating cables. By considering the available heating wires on the market we have assumed a power of 1.56 kW uniformly distributed on 97.5 cm of the bayonet. The water level inside the heat sink is kept constant by means of a control logic of the valve model. From this initial condition the system undergoes a transient until a steady state condition is reached. The system then works in a two-phase condition where water boils in the annular riser of the bayonet and condenses in the final heat sink. Steady state pressure, flow rate and temperatures will depend on the volume of the facility, on the mass of water stored and the active length of the final heat sink. The steady state condition has been analyzed to understand the possible operating conditions of the facility.

Cases are grouped according to the amount of water stored inside the loop.

Figure 9 shows the pressure reached in steady state condition by the facility depending on the initial void fraction and the active length of the heat sink. Maximum pressure reached by the system varies between 20 and 50 bar. A small heat sink or higher initial fillings of the facility go in the direction of a higher steady state pressure, because the available volume to expand is lower and a larger temperature difference between the loop and the environment is necessary to evacuate the heat (note that the fluid temperature in the region of the final heat sink is the saturation temperature at the working pressure).

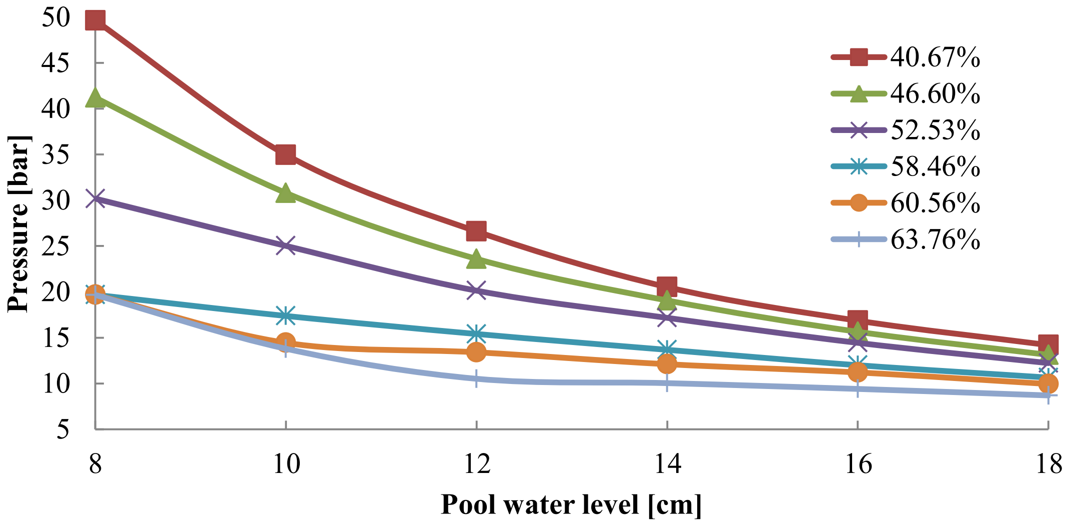

Figure 9. Steady state pressure as a function of the water level in the pool.

Figure 10 shows the flow rate circulating in the system. An increase of the final heat sink active length or the amount of water stored in the system increases the flow rate. The amount of natural circulation depends on the concomitant variation of the density difference between hot and cold legs, and the different height of thermal barycentres of the source and the sink. Also the void fraction of the fluid plays a role as it changes the friction in the loop. By varying the liquid level in the pool between 8 and 18 cm the maximum variation of the barycentres height difference is in the order of 3%, therefore its impact is limited. On the other hand, at a fixed amount of water in the loop, natural circulation increases as the length of the heat sink increases, because at decreasing pressure the density ratio between the liquid and the gas phase increases. By considering a fixed active length for the final heat sink, as the initial mass inventory increases the mass flow rate increases as well. This is due to the fact that despite the higher pressure the average void fraction in the two-phase pipes is larger. An important conclusion to this study is also that considering the low values of flow rates created by natural circulation careful attention shall be devoted to minimize the measurement uncertainty.

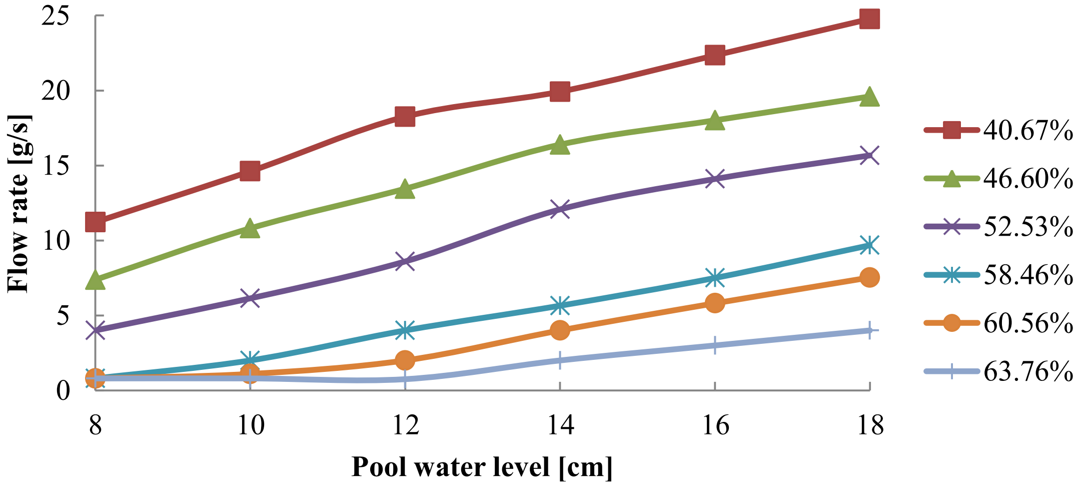

Figure 10. Natural circulation flow rate as a function of the water level in the pool.

Another figure of merit for the loop is represented by the maximum temperature in the heated pipe of the bayonet heat exchanger. The prediction can help to assess whether mechanical problems concerning the pipe can be expected in the region of interest. Figure 11 shows the maximum temperature for the inner wall of the outermost tube. As it is possible to see, the maximum temperatures are below 270 °C, therefore no mechanical problem is foreseen. In addition to that, as the heat transfer coefficient on the water side is considerably higher than the transmittance of the tube the temperature gradient on the pipe is almost constant in all the simulations considered, between 7 and 8 °C (the heat flux used in the simulations is constant).

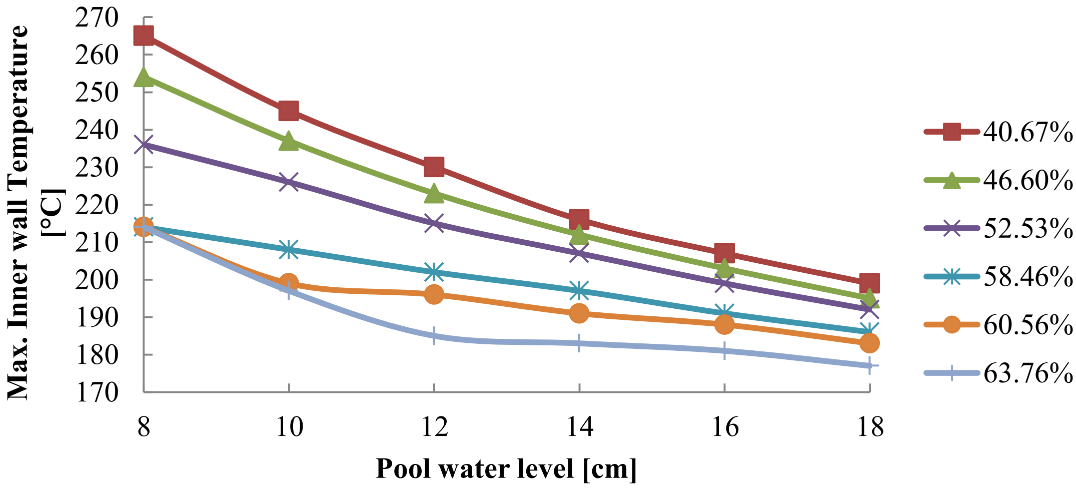

Figure 11. Maximum inner wall temperature as a function of the water level in the pool.

Figure 12 shows the water level in the cold leg. It is the transition front between the two-phase region and the single phase region, and decreases as the initial mass of water in the system decreases. Figure 13 shows the void fraction at the outlet of the bayonet heat exchanger. There is a very low dependence on the active length of the pool, while a large impact is provided by the initial mass of water in the system.

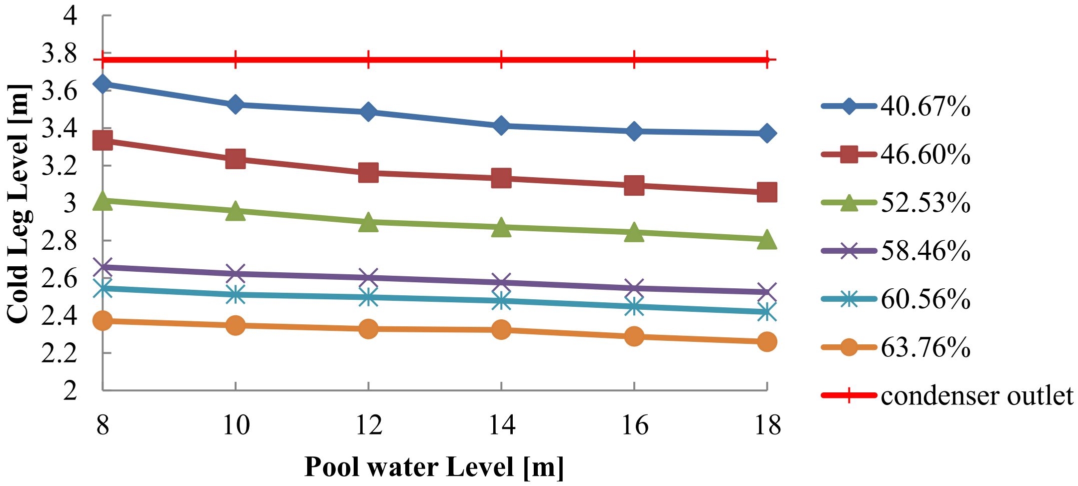

Figure 12. Transition front between two-phase region and single phase region.

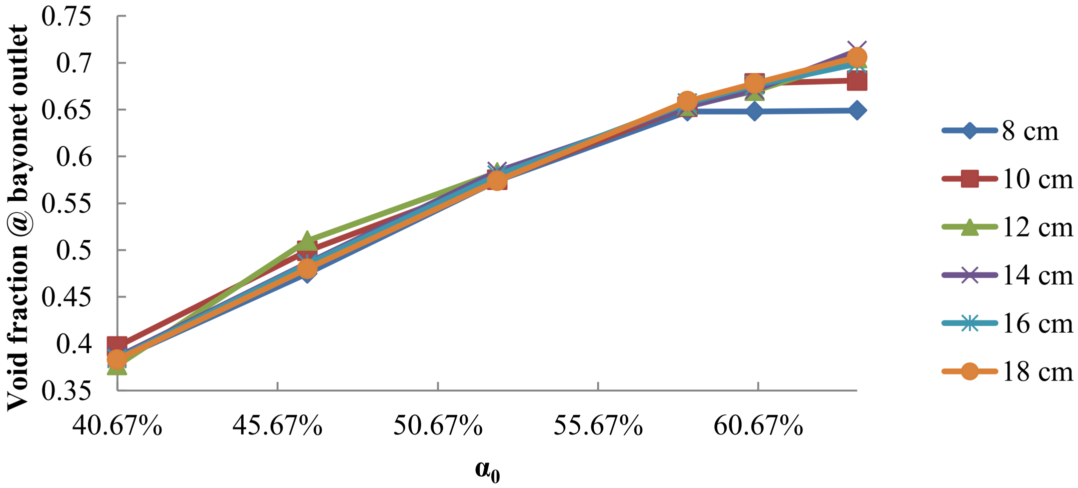

Figure 13. Void fraction.

As a last remark, the values of initial void fraction cover a range between 40% and 63%. We have observed high flow rate oscillations due to intermittent flow patterns outside this region. More detailed studies shall be carried out to understand the origin of instabilities, and a valuable help will be provided by the experimental results.

5. Conclusions and future work

In this paper a new experimental facility under construction at Energy Department of Politecnico di Torino to study the natural circulation in a safety system for innovative nuclear reactors has been presented. A Relap5-3D model developed to represent the operating conditions of the facility has been presented and used to study some steady state conditions for the loop under different hypotheses of water inventory and active length for the final heat sink. The model results have shown the possible application of the facility for a variety of different conditions and have highlighted the impact of the investigated parameters on the behavior of the loop. Operation compliance with maximum pressures and temperatures has been numerically validated. Preliminary simulations suggest to handle the measurement of the flow rate with particular care as it is low, and to foresee operating conditions characterized by unstable flow patterns for certain water inventories and heat sink values. Future work will be devoted to complete the facility, to perform the experimental activity (cold zero power test characterization, test matrix definition, hot maximum power tests) and to compare the results with the code prediction.

References

[1] International Atomic Energy Agency (IAEA) 2015 sti/pub/1710 Vienna
[2] US Department of Energy (DOE) 2008 DOE-STD-1189-2008 Washington
[3] International Atomic Energy Agency (IAEA) 2009 IAEA TECDOC-1624 Vienna
[4] U.S. National Regulatory Commission 2005 NUREG-1826 Washington
[5] Alemberti A, Frogheri M and Mansani L 2013 *International Conference on Fast Reactors and Related Fuel Cycles, Safe Technologies and Sustainable Scenarios* (Paris), France.
[6] Caramello M, Gregorini M, De Salve M, Bertani C, Alemberti A and Panella B 2015 *International Congress on Advances in Nuclear Power Plants (ICAPP)* (Nice) (American Nuclear Society) p 838–45
[7] RELAP5 2015 *RELAP5-3D 4.3.4 Code Manual Volume I: Code Structure, System Models and Solution Methods* Idaho National Laboratory