Journal of Physics: Conference Series

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To cite this article: S D'Amico *et al* 2017 *J. Phys.: Conf. Ser.* **923** 012007

35th UIT Heat Transfer Conference (UIT2017) IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **923** (2017) 012007 doi:10.1088/1742-6596/923/1/012007

Analysis of a full-scale integral test in PERSEO facility by using TRACE code

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Abstract. Over the last decades a lot of experimental researches have been done to increase the reliability of passive decay heat removal systems implementing in-pool immersed heat exchanger. In this framework, a domestic research program on innovative safety systems was carried out leading the design and the development of the PERSEO facility at the SIET laboratories. The configuration of the system consists of an heat exchanger contained in a small pool which is connected both at the bottom and at the top to a large water reservoir pool.

Within the frame of a national research program funded by the Italian minister of economic development, the DEIM department of the University of Palermo in cooperation with ENEA has developed a computational model of the PERSEO facility in order to simulate its behaviour during an integrated test. The analysis here presented has been performed by using the best-estimate TRACE code and - in order to highlight the capabilities and limits of the TRACE model in reproducing qualitatively and quantitatively the experimental trends - the main results have been compared with the experimental data. The comparison shows that the model is able to predict the overall behaviour of the plant during the meaningful phases of the transient analysed. Nevertheless, some improvements in the modelling of certain components in which take place complex three-dimensional phenomena are suggested in order to reduce some discrepancies observed between code results and test measurements.

1. Introduction

In the framework of the research program devoted to improve the reliability of residual heat removal systems characterized by in-pool heat exchangers as heat sink and requiring the actuation of a triggering valve to start their operation, ENEA and CEA have developed an innovative device called *thermal valve* [1]. The thermal valve, which was conceived for advanced light water nuclear reactors, rely on gravity injection and natural circulation and consists of a diving bell surrounding an in-pool heat exchanger with a pilot valve located on the top. During an accidental scenario, the pilot valve is opened allowing the steam to condensate in the pool through an effective natural circulation which assures a passive removal of the decay heat. Because of some operating and construction problems, mainly due to the need of a pilot valve with a large flow area, ENEA and SIET have proposed a new configuration, the so-called PERSEO (In-Pool Energy Removal System for Emergency Operation), which consists of two pools and an heat exchanger. In stand-by conditions the pool containing the heat exchanger is empty while the pool representing the water reservoir is full of cold water. The pools are connected to each other at the bottom and the top to allow the natural circulation and to guarantee a long term energy removal during the accidental scenarios. A triggering valve, which determines the device operation is installed on the pool bottom connecting pipe (liquid line). The valve opening causes the flooding of the heat exchanger allowing the heat transfer from the primary side to the pool side. An injector is installed at the exit of the steam duct located at the top of the pools (steam line) in order to improve the pool water mixing and to avoid thermal stratification phenomena. The system has been tested at the SIET laboratories in Piacenza by modifying the existing PANTHERS IC-PCC facility (Performance Analysis and Testing of Heat Removal System Isolation Condenser - Passive Containment Condenser), which was utilized in the past for testing a full scale module of SBWR in-pool heat exchanger. Two types of tests were performed on PERSEO test facility: *integral tests*, aimed at verifying the behaviour and performance of the device following a request of operation and *stability tests*, finalised to study some critical problems occurring in case of sudden condensation at the steam-water interface or in case of triggering valve re-opening. The experimental tests have allowed a complete evaluation of the efficiency and reliability of the PERSEO innovative decay heat removal system and they have confirmed its effectiveness [2], [3], [4].

The analysis reported in the paper have been performed by using the best-estimate TRACE code with the purpose of evaluating the prediction capability of the computational model, developed by the DEIM thermal-hydraulic research unit, in analysing an integral test devoted mainly to investigate the flow regime variation and the trend of power as a function of the water level in the pools.

The main results have been compared with the experimental data in order to highlight the capabilities and limits of the TRACE model in reproducing qualitatively and quantitatively the experimental trends. The comparison shows that the model is able to predict the overall behaviour of the plant during the transient, but some improvements in modelling specific components in which take place complex three-dimensional phenomena have been suggested, in order to reduce the discrepancies observed between code results and test measurements.

2. PERSEO facility description

The PERSEO facility, whose scheme is shown in Fig. 1, was built at the SIET laboratories by modifying the existing PANTHERS IC-PCC facility that was utilised for testing a full scale module of the GE-SBWR in-pool heat exchanger [2].

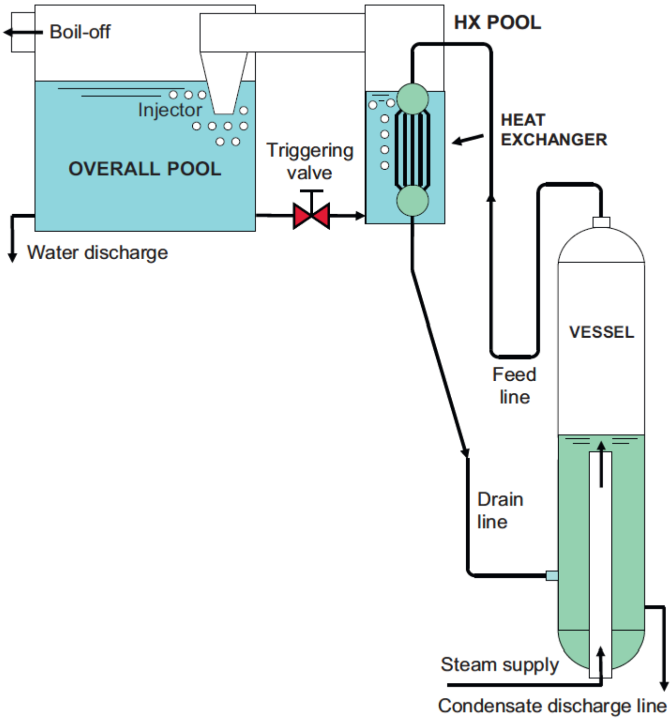

Figure 1. PERSEO facility layout [5].

The PERSEO design was an evolution of the thermal valve concept and they differ mainly for the location of the triggering valve which is installed liquid side in PERSEO, namely on the line connecting two pools at the bottom. The main features of the PERSEO design are reported in Table 1.

Table 1. PERSEO facility design features [2].

Quantity	**Value**
Power	20 [MW]
Vessel pressure	10 [MPa]
Vessel temperature	310 [°C]
Heat exchanger pressure	8.62 [MPa]
Heat exchanger temperature	302 [°C]
Super-heated steam flowrate	12 [kg/s]
De-superheating water flow rate	3 [kg/s]
Pool side pressure	0.15 [MPa]
HX Pool temperature	300 [°C]
Overall Pool temperature	130 [°C]
Pool side water flowrate	25 [kg/s]

As already said, the triggering valve is closed during normal operation and the pool containing the heat exchanger (HX pool) is empty, while the other pool (Overall pool) is full of cold water. During emergency conditions the valve is opened which leads to the heat exchanger (HX) flooding and the consequent heat transfer from the primary side to the pool side. The pools are connected at the top by means of a pipe ending with an injector which promotes the steam circulation and the homogenization of water temperature inside the Overall pool. The primary side of the facility is maintained at the saturation conditions by supplying the steam coming from the nearby power station: the pressure is kept constant by controlling the steam supply and discharge valves.

Before starting the experiment, the primary side reaches the saturation conditions specified for the test and the proper water level. At the same time the feed line, the heat exchanger and the drain line are being filled of saturated steam. The HX pool is full of air or steam according to the test matrix, while the Overall pool is full of cold water at the nominal level.

Once reached the initial test conditions, the triggering valve is opened and the HX pool is flooded by cold water. Steam condensation at the primary side of heat exchanger occurs soon after the HX pool flooding and the heat is transferred from the primary side to the pool side. Steam produced in the HX pool is driven to the Overall pool through the steam duct. The only connection between the pool side and the environment occurs throughout the Boil-off pipe located at the top of the Overall pool.

In such kind of system, the heat transfer rate decreases according to the water reserve.

3. TRACE code brief description

Best-estimate thermal-hydraulic system codes are complex tools developed to simulate both normal and transient conditions in nuclear installations (power plants, research reactors, spent fuel pools and experimental facilities). Among them, the TRACE (TRAC/RELAP Advanced Computational Engine) developed by the USNRC is an advanced, two-fluid, thermal-hydraulic computer code designed for use in realistic studies of light water reactors. It consolidates the capabilities of four codes (TRAC-P, TRAC-B, RELAP 5 and RAMONA) into one. In fact, system thermal-hydraulic analysis addresses the simulation of complex thermal-hydraulics phenomena by a best estimate approach in order to get an evaluation of the plant behaviour which will be as realistic as possible. The TRACE code is capable of analysing of LOCAs, operational transients, accident scenarios and phenomena in nuclear power plants and related experimental facilities. TRACE uses different types of components which could be further subdivided into various numbers of physical volumes (or cells), to model each physical piece of equipment comprised in the reactor system. Over each finite volume cells, the fluid, conduction and kinetics equations are averaged. The hydraulic components in TRACE include BREAKs, CHANs

(BWR fuel channels), VESSELs, PIPEs, FILLs, PRIZERs (pressurizers), HEATRs (feed-water heaters), PLENUMs, PUMPs, SEPDs (separators), TEEs, TURBs (turbines), JETs (jet pumps) and VALVEs and so on. Models supplied in TRACE include multidimensional two-phase flow, such as critical flow model, offtake model and counter current flow model, non-equilibrium thermo-dynamics, re-flood, level tracking and generalized heat transfer. In addition, it contains not only a point kinetics model but also the capability to be coupled with external 3D neutronic codes-and the possibility to be managed through the graphical user interface SNAP [6], [7].

4. TRACE model

The PERSEO TRACE nodalization has been made by using TRACE V5.840 patch 4 and it models in detail the experimental facility [8]. The total number of thermal-hydraulic components presented in TRACE model are 113, being 33 PIPEs, 5 VESSELs, 9 VALVEs, 7 BREAKs, 1 FILLs, 3 TEEs, 2 PUMPs and 53 HEAT STRUCTUREs. In addition, 34 TRIPs, 89 CONTROL BLOCKs and 104 SIGNAL VARIABLEs complete the model. In particular, where the 1D approach is not sufficient (i.e. secondary flows are not negligible) as in the pressure vessel, in the Overall pool and in the HX pool, the 3D component “VESSEL” has been used.

4.1. Principal physical models adopted

In order to better simulate the behavior of the various systems during an integral test, several physical models made available by the code have been used [9].

The “level tracking” model have been adopted in all vertical components to localize, as well as possible, the liquid-gas interfaces. Models of counter-current flow limitation have been used at the cell junctions where this event was expected during flooding and reflux condensation phases. The “offtake” model has been applied at the side junctions of ducts where a horizontal stratified two-phase flow could have occurred to predict the correct offtake flow quality that would have come out from the main tube. At cell edges that simulate the break and the ADS orifices the “critical flow” model has been used.

4.2. Primary side model description

The primary circuit has been reproduced from the vessel to the heat exchanger, while the steam supply has been provided by means of a proper control volume. The pressure vessel and its riser, Fig. 2, have been described using the VESSEL component: its nodalization consists of 21 axial levels, 2 radial rings and 8 azimuthal sectors. The azimuthal nodalization has been chosen in order to better simulate the circumferential position of the nozzles and with the purpose of reproducing as best as possible the pressure drops. The feed-line and the by-pass line have been modelled by means of 9 PIPEs and 2 TEEs, while the drain line has been described by using 2 PIPEs and 2 VALVEs. The heat exchanger has been nodalized by means of 2 cartesian VESSELs and 15 PIPEs: the component VESSEL has been used to simulate the two header and their nodalization consists of 2 axial levels, 17 X-sections and only 1 Y-sectors; each PIPE simulates 8 tubes of the tube bundle. Fig. 3 shows the nodalization of the heat exchanger. The pressure and level controls systems have been also modelled by using 4 VALVEs, 1 TEE and the needed SIGNAL VARIABLEs and CONTROL BLOCKs.

4.3. Pool side model description

The Overall pool nodalization has been done through the application of a cartesian VESSEL that is divided in 14 axial levels, 2 X-sections and 2 Y-sectors and by using a PIPE for the upper part; The boil-off has been simulated by means of another PIPE component. The discharge line has been simulated by means of a PUMP and a BREAK allowing to simulate a constant flow rate leaving the water reservoir. The HX pool has been described by using another cartesian VESSEL: its nodalization is characterized by 73 axial levels, 1 X-section and 1 Y-sectors. The Steam-duct and the cone-shaped injector have been simulated by using a PIPE, while the vacuum breaker has been simulated through a BREAK and a VALVE component. Fig. 4 shows the nodalization of the pool side.

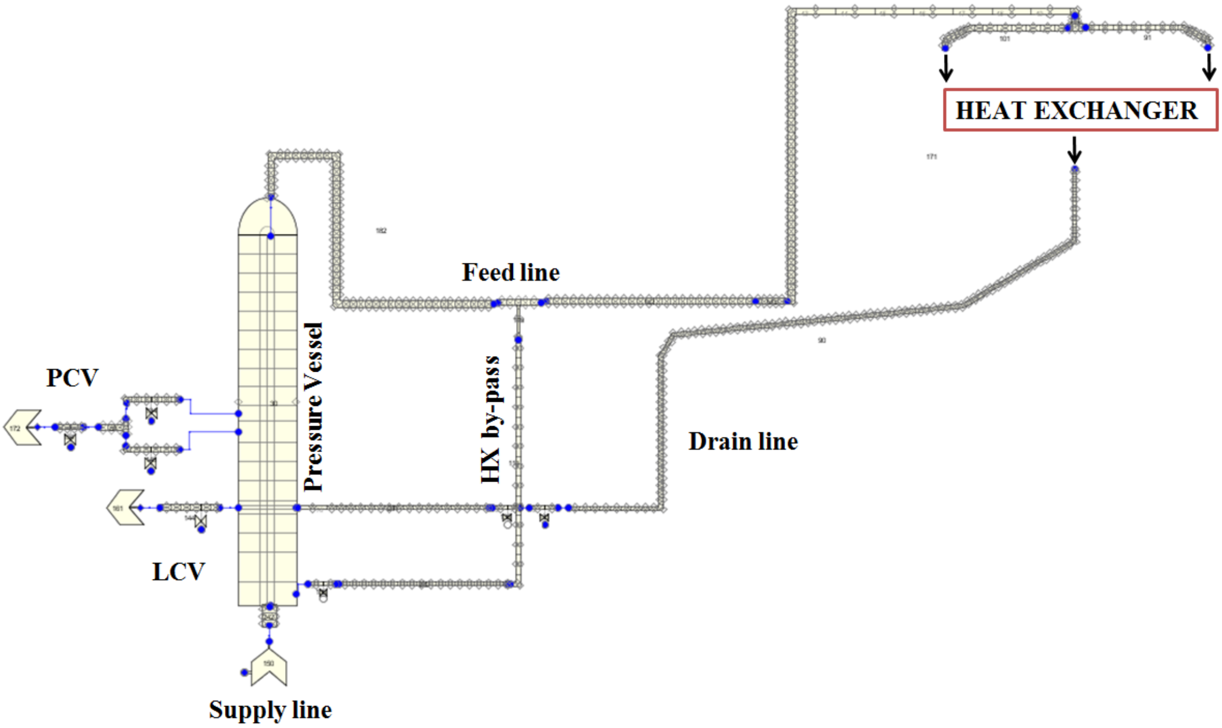

Figure 2. Primary side nodalization .

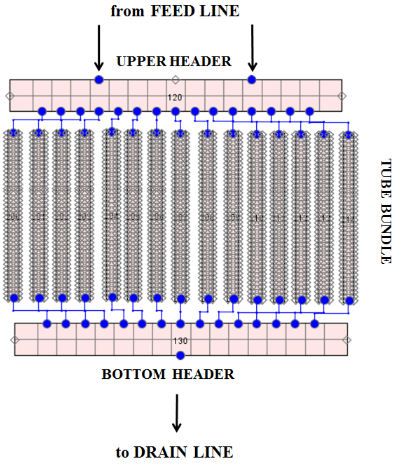

Figure 3. HX nodalization.

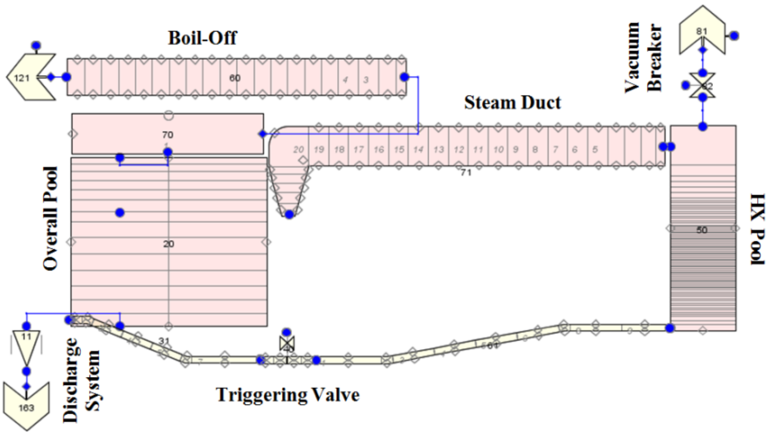

Figure 4. Pool side nodalization.

5. PERSEO facility test program objectives

The PERSEO facility test program was aimed at verifying the new system operation, steadiness and performance. The performance concerned the heat transfer start-up after the triggering valve opening, its steadiness with the two pools full of water and the exchanged heat trend according to the water level in the pools. The PERSEO facility set-up was conducted performing a series of shake down tests suitable to verify the correct plant operation and to characterise the main parameters of the facility such as the water pouring-off from the Overall pool to the HX pool.

The PERSEO experimental tests can be distinguished in: *integral* and *stability* tests; both of them suitable for the system concept demonstration. The integral tests were aimed at demonstrating the behaviour and performance of the system following an accidental scenarios during all its main phases.

The stability tests were aimed at studying some critical problems happening in case of sudden condensation at the steam-water interface or in case of a re-opening of the triggering valve.
The main conditions and a short description of the integral and stability tests has been reported in Table 2, together with a short description of tests [2].

Table 2. PERSEO facility test matrix [2].

Test	Test conditions	Description
6	Primary side pressure: 7 [MPa]	Integral test interrupted at the beginning of the pool level decreasing
7	Primary side pressure: 7 [MPa]	Stability and integral test: partial and subsequent HX Pool filling with reaching of boiling conditions and level decreasing
8	Primary side pressure: 7 [MPa]	Stability test: partial HX Pool filling with reaching of boiling conditions
9	Primary side pressure: 4 [MPa]	Integral test

The tests confirmed the effectiveness of the PERSEO innovative system: the heat transfer from the primary side to the pool side is soon actuated after the triggering valve opening and it is stable, decreasing as the HX pool level [2], [3]. The steam generated in the HX pool accelerated into the Overall pool by means of the injector promotes the water circulation and avoids the thermal stratification in the Overall poll. Instabilities due to the sudden steam condensation, pointed out after an early interruption of the heat transfer and during the HX pool re-flooding were dumped very soon by using the vacuum breaker installed at the HX pool top or on the Steam-duct according to the test [4], [5].

6. PERSEO test data analysis

The test 6 has been selected by the authors in order to carry out the comparison between the experimental data and the TRACE numerical results. In fact, the test has been considered the most representative from the performance and stability point of view and for thermal-hydraulic system code assessment.

6.1. Experimental test description

The experimental test analysed is an integral test with the primary side pressure of 7 MPa; the main steps have been reported in the following:

- pressurization of the primary circuit to the pressure of 7 MPa,
- opening of the triggering valve,
- reaching of saturation conditions in HX pool and Overall pool,
- level decrease in the pools until the injector outlet uncovering,
- level decrease accelerated by water discharge from the Overall pool,
- triggering valve closure and HX pool boil-off,
- depressurization of the primary circuit.

The aim of the test was devoted to investigate the items below:

- the system actuation and reaching of the thermal regime in both the pools,
- the effectiveness of the injector in mixing the Overall Pool water,
- the power variation after the Overall Pool level decreasing below the injector outlet,
- the trend of power as a function of the water level in the pools, decreasing for the loss of mass through the boil-off.

The test starts at time 1100 s by opening the triggering valve which determines the HX water level increasing through the cold water flowrate between the two pools; once reached the bottom header of the heat exchanger, the heat begins to be exchanged from the primary to the pool side. The primary circuit pressure decrease rapidly due to the heat removal and it is manually increased. After about 250 s, the pressure average value returns to 7 MPa until 4967 s when the primary circuit is quickly depressurized and the test concluded due to a break on a vessel discharge line. The HX pool level begins to increase at time 1114 s and reaches the maximum value at 1550 s.

After the Overall pool level decreasing for the HX pool fill-up, its average level remains quite constant until about 4400 s when the valve of the discharge line is opened. Regarding the removed heat from the primary circuit, it is possible to observe an increase according the HX pool level trend up to stabilise at about 17.7 MW when in the HX pool are reached the boiling conditions. Before the water injection, the temperature of the air contained in the HX pool is around 240 °C due to the HX radiation, then the temperature decreases for the incoming of cold water. The steam, produced in the HX pool and accelerated into the Overall pool by means of the injector, promotes the water circulation and mixing avoiding the thermal stratification in the Overall pool. Unfortunately, for problems on the pressure vessel control system, a fast discharge of hot water from the vessel is operated and causes a break of the line towards the condenser leading the end of the test [2].

6.2. Comparison between experimental data and numerical results

The PERSEO test analysis here presented has been performed by the thermal-hydraulic research groups of the DEIM department of the University of Palermo. In order to improve the prediction capability of the PERSEO TRACE model, several nodalizations of the experimental plant have been studied; they have been used to perform simulations of different tests comparing the results with the experimental ones [8]. Unfortunately, a pressure boundary condition at the HX pool top has been maintained active for 150 s during the start-up to avoid large instabilities calculated by the code; these instabilities are generated by the simple models adopted to treat non-condensable gases. A great importance has been given to the proper simulation of the connection between the injector outlet and the Overall pool, which affects the water circulation and mixing. The simulation of the test by using TRACE code has been performed up to the phase in which the discharge of the water from the Overall pool takes place since the main phenomena have been investigated. The TRACE numerical results show a good agreement with experimental data. The calculated primary pressure well reproduces the facility behaviour during the main phases of the test though some mismatch is present in timing and value when the pressure is manually increased operating through the supply valve, Fig. 5. The Overall pool level predicted by TRACE code is quite similar to experimental data in trend and values, as well as the calculated HX pool level, Fig. 6. The Fig. 7 reports the steam flow rate supplied to the heat exchanger and the condensate flowrate discharged in the pressure vessel (the condensate flowrate experimental measure is not valid before time 1000 s). As can be seen, the flow rates predicted by the code are in good agreement with the experimental data even though the oscillations due likely to the pressure control system operation.

An important limit of the model must be underlined, that is the difficulty of the code of reproducing the experimental exchanged power without using a proper fouling material in the HEAT STRUCTUREs of the heat exchanger, Fig. 8. This difficulty depends on the heat transfer regime selection logic for the pre-CHF (Critical Heat Flux) and condensation regimes [9] which means an overrate of the control volumes involved in the subcooled nucleate boiling regime (pool side): the overestimation strongly depends on the discretization used to simulate the facility components.

The steam produced in the HX pool is driven and accelerated into the Overall pool through the injector which promotes water mixing in the pool reducing the thermal stratification that is quite well predicted by the code, Fig. 9.

Fig. 10 shows the HX top pressure: it can be observed a quite good agreement in curve trends, but a general overestimation of the calculated variable for 1000 s after the transient starting.

Anyway the overall behaviour of plant is well predicted by TRACE code providing a confirmation of the model capability to simulate the thermal hydraulic phenomena that occur in this advanced safety system.

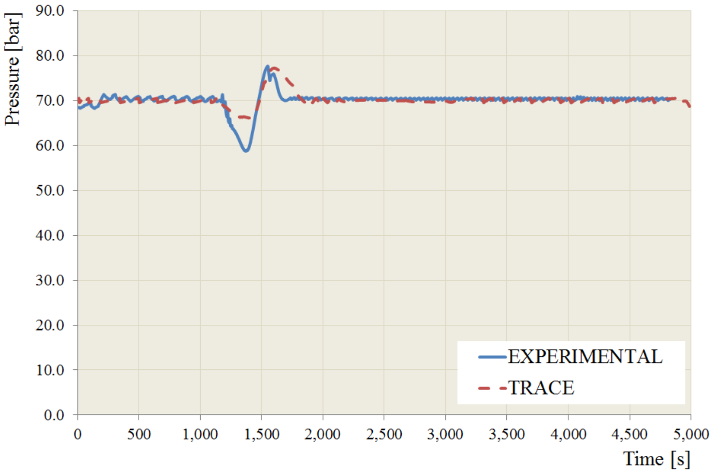

Figure 5. Primary side pressure.

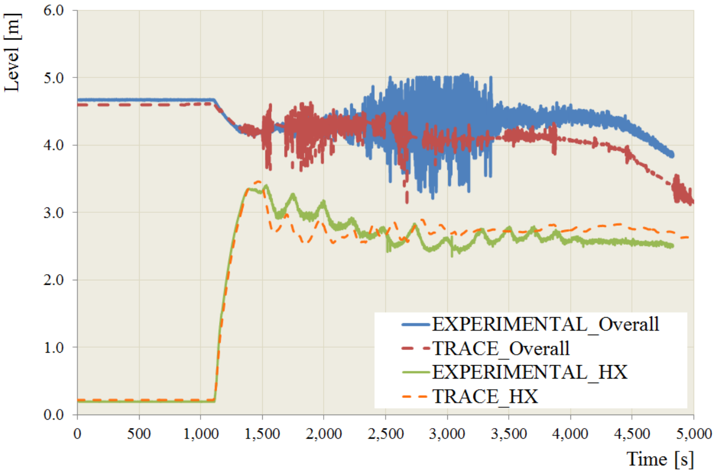

Figure 6. Overall and HX pools water level.

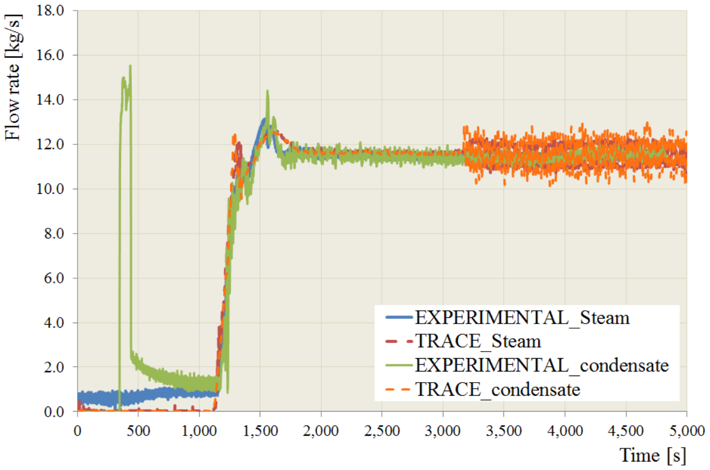

Figure 7. Steam and condensate flowrate.

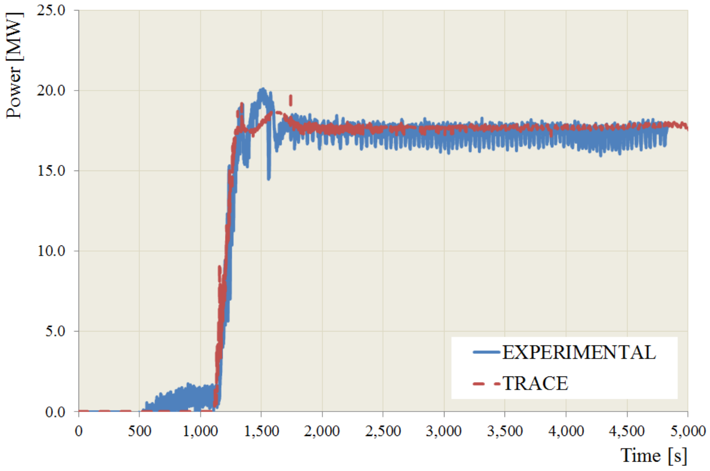

Figure 8. HX exchanged power.

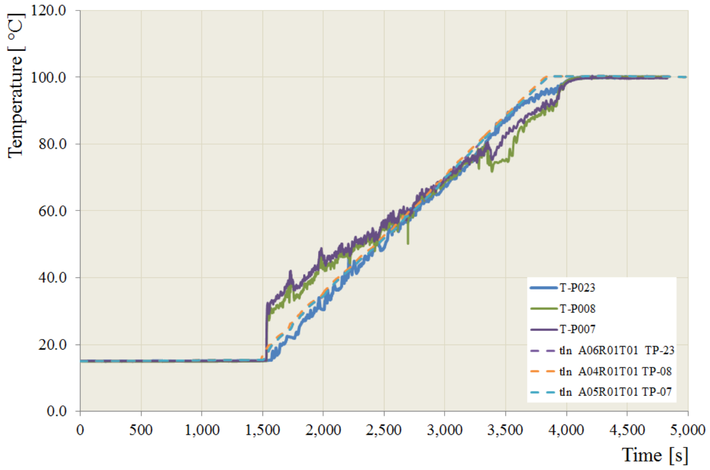

Figure 9. Overall pool temperature.

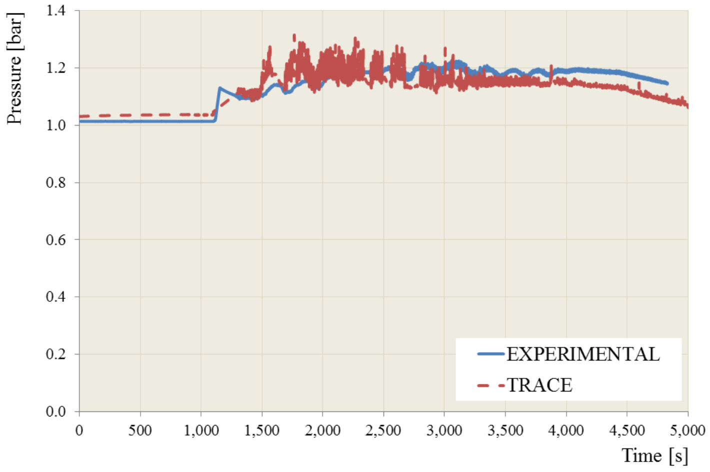

Figure 10. HX Top pressure.

7. Conclusions

The present work concerns a comparison between experimental and numerical results obtained for the integral test 6 of the test matrix prepared for the PERSEO facility. The numerical analysis here presented has been performed by using TRACE thermal-hydraulic code with the purpose of evaluating its prediction capability. The main results show that the TRACE model well predict the overall behaviour of the plant during the transient, even if some limits of the code were identified in simulating particular phenomena and quantities. As already highlighted, the code limit to reproduce the experimental exchanged power depends on the heat transfer regime selection logic for the pre-CHF and condensation regimes. Moreover, others discrepancies observed between code results and test measurements can be attributed to complex three-dimensional phenomena suggesting improvements in the modelling of some components. As recommended in [4] a wider comparison with other best estimate codes is necessary in order to set-up a definitive model suitable to simulate such innovative decay heat removal system. The activity has been funded by Italian Minister of Economic Development.

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