TRANSITION FROM FORCED TO NATURAL CIRCULATION ASSESSMENT IN CIRCE-THETIS EXPERIMENTAL FACILITY

Preliminary experimental results

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INTRODUCTION: in the framework of ENEA's research program focused on the development of Generation IV LFR (Lead-cooled Fast Reactor) technology, the CIRCE-THETIS experimental campaign holds a prominent position in the study of thermal-hydraulics of lead-cooled systems. The CIRCE facility, configured with the THETIS (Thermal-hydraulic HElical Tubes Innovative System) test section, enables the experimental reproduction of the thermal-hydraulic behavior of a lead-bismuth pool-type nuclear reactor core, with a thermal power output of up to 925 kW. The test section comprises the key components of the primary circuit of a pool-type LFR: the core, the heat exchanger, and the mechanical pump. CIRCE is also equipped with a secondary loop, operating with demineralized water, and a steam line. Additionally, the THETIS campaign includes the investigation of the RVACS (Reactor Vessel Auxiliary Cooling System), which is an air-forced vessel cooling system. During the pre-test phase, the thermal-hydraulic behavior of both the primary and secondary circuits was characterized, along with the assessment of the system's heat losses at various pool temperatures. The heat losses were identified as a thermal sink, which was necessary and sufficient to initiate natural circulation. Consequently, the transition from forced (FC) to natural circulation (NC) was studied following pump trips at different preset core power levels. Measurements were then conducted to determine the mass flow rate through the core, the peak core temperature, and the pressure losses along the primary flow path, with particular attention to those across the pump impeller.

1. CIRCE-THETIS FACILITY DESCRIPTION

The CIRCE experimental facility [1] has been designed to operate with liquid lead-bismuth eutectic alloy, to study thermal-hydraulic phenomena with integral effects that characterize the operation of liquid-metal-cooled nuclear reactors. The facility consists of three tanks, *FIG. 1*: the main tank (S100), the storage tank (S200), and the transfer tank (S300). These tanks are interconnected by a piping system equipped with both manually operated and remotely actuated valves, specifically designed to function with liquid metals. All surfaces in contact with the liquid metal, whether for flow or stationary conditions, are heated and thermally insulated. Additionally, these surfaces are instrumented with a sufficient number of thermocouples to monitor the temperature distribution within the fluid domain. Inside the tanks, an inert cover gas region is maintained, monitored via dedicated pressure transducers and thermocouples. To track fluid levels, the tanks are also equipped with level probes, which have been designed, manufactured, and certified at the ENEA Brasimone Research Center laboratories. Furthermore, the tanks are fitted with safety vent valves to manage potential overpressure conditions.

The main CIRCE tank is designed to accommodate various test sections, depending on the specific experiment to be conducted. CIRCE is also suitable for testing full-scale prototype components, such as pumps and heat exchangers. For heat exchanger testing, the facility includes a secondary loop designed to operate with water as the working fluid. This loop comprises a pump (the FW pump), an electric heater, a steam line, and a bypass for startup transients. The secondary system is engineered to operate at pressures up to 200 bar. It is fully instrumented with thermocouples, pressure transducers, and flow meters to measure the relevant thermo-hydraulic parameters along the entire fluid path. The main tank is also capable of housing a core simulator, which is an electrically heated core mock-up designed to deliver up to 925 kW of electrical power. The core simulator consists of a hexagonal-section assembly containing 37 rods, each with a diameter of approximately 1 cm and an active height of 1 m. The entire facility is fully remotely controllable, as it is equipped with an advanced control and data acquisition system. The THETIS test section (FIG. 2, FIG. 3)[3], consists of the prototypical helical coil steam generator (HCSG) [2], the main circulation pump (MCP), and the Fuel Pin Simulator (FPS). The FPS features an internal structure designed to isolate the electrical power supply cables from the lead-bismuth eutectic (LBE) using a dedicated dead volume. To establish the flow path and the separation between the two pools – the hot and cold pools, characteristic of a pool-type LFR design – the internals include the FPS collection vessel (fitting volume), the riser pipe connecting the hot pool (Separator) to the FPS, and the can wall of the MCP.

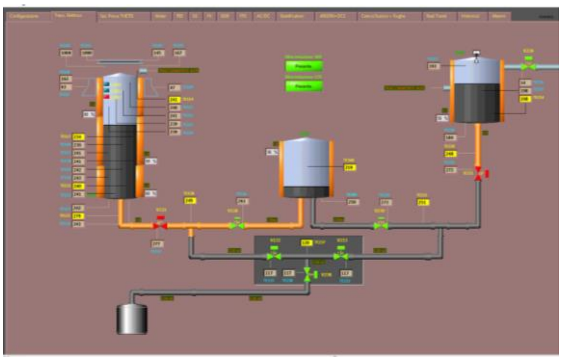

FIG. 1. CIRCE facility layout (SCADA view)

FIG. 2. CIRCE.THETIS Test Section

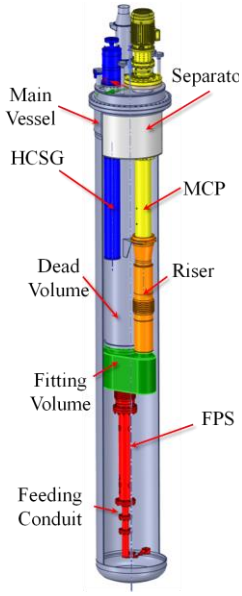

FIG. 3. CIRCE-THETIS Test Section schematic view

2. CIRCE-THETIS TEST MATRIX

The primary objective of the experimental campaign is to test and verify the effectiveness of the HCSG and the RVACS as decay heat removal (DHR) systems. Additionally, the campaign aims to characterize the thermal-hydraulic behavior of the prototypical pump. In TABLE 1, the key thermal-hydraulic parameters for the transients to be carried out in the CIRCE-THETIS facility are presented. Initially, the system is brought to steady-state conditions at full FPS power. The secondary circuit operates at 90 bars, with the water entering the HCSG slightly subcooled. Once steady state is established, **Test #1** is conducted: a simulation of a *Protected Loss of Flow* (PLOF). This involves tripping the MCP, followed by a reduction of the FPS' power, which decreases to approximately 7% of its nominal power (i.e., 31.5 kW) within about one minute. The Feed Water Pump (FWP) flow rate is then adjusted to balance the FPS power. In **Test #2**, the system starts from the steady-state at full power. After tripping the MCP and initiating the FPS power reduction, the FWP also tripped, and the RVACS blower started. Finally, **Test #3** reproduces the initial conditions of Test #1. Once steady-state is achieved, the decay heat removal (DHR) mode is switched from the HCSG to the RVACS, thereby simulating a *Loss of Heat Sink* (LOHS) scenario.

TABLE 1. CIRCE-THETIS TEST MATRIX

Test	FPS [kW]	MCP [kg/s]	HCSG [kg/s]	RVACS [m^3/s]
Steady State	450	35.2	0.23	-
#1	31.5	0.0	0.02	-
#2	31.5	0.0	-	1.2
#3	31.5	0.0	0.0	1.2

3. HEAT LOSSES QUANTIFICATION AND TRANSITION FROM FC TO NC ASSESSMENT

Before proceeding with the study of the system's behavior under natural circulation conditions, the overall thermal losses of the primary system were determined. To quantify the heat losses of the entire primary system, thermal balance calculations were performed. Following this, the FPS system was regulated to supply the power level derived from these calculations. This power input was then fine-tuned to achieve a steady-state temperature within the S100 pool. During this phase, the MCP operated at a regime sufficient to ensure the nominal flow rate through the FPS. Once a steady-state temperature field was established in the pool, a pump trip was initiated. The ensuing transient leading to the onset of NC was then observed. The system subsequently reached a new steady-state under NC conditions. As shown in FIG. 4, the system had reached steady-state conditions with the FPS operating at 50 kW, effectively balancing system's thermal losses and maintaining a primary pool temperature of 450°C. Immediately following the MCP trip, a temperature peak was recorded on the clad of the pin in the hot channel, reaching 537°C. Finally, the trend of the mass flow rate clearly indicates the onset of natural circulation, stabilizing at approximately 10 kg/s within about 8 minutes.

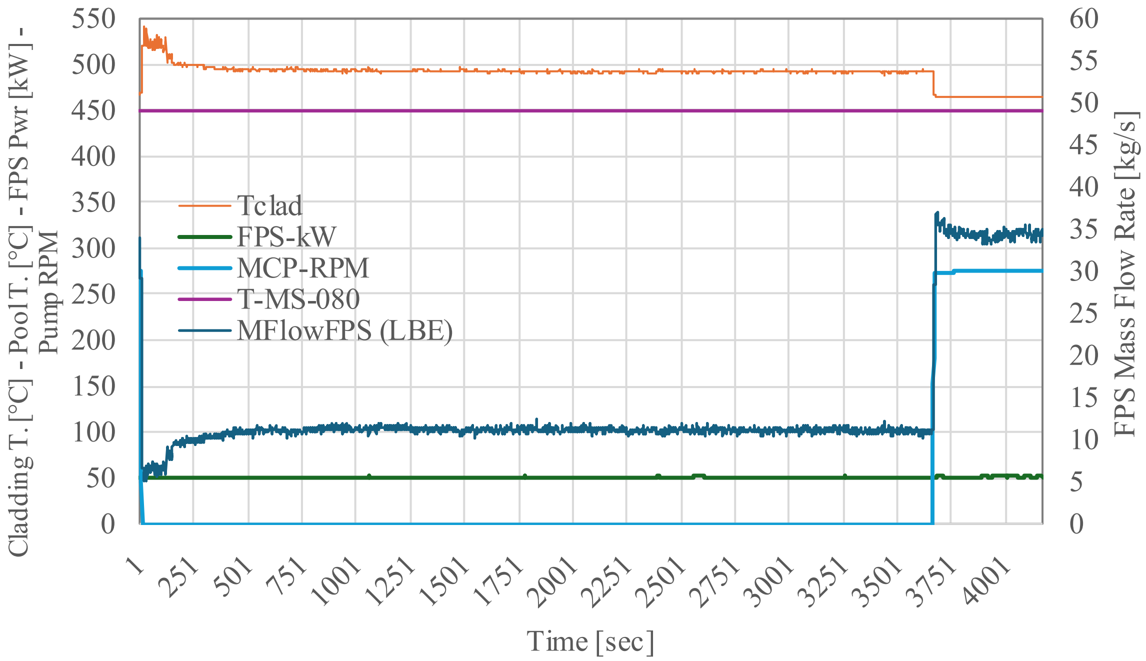

FIG. 4. Transition from FC to NC in CIRCE-THETIS: time trends of the key parameters

4. CONCLUSIONS

The system exhibited a strong tendency to establish natural circulation under all imposed core power conditions, relying solely on the thermal sink effect provided by the system's heat dispersion. The data acquisition and measurement system proved efficient and reliable in capturing all relevant phenomena, particularly the mass flow rate through the core under various natural circulation regimes, the peak temperature on the pin in the core's hot channel, the coolant pressure losses, the level differences between the hot and cold pools, and the temperature stratification within the pool.

REFERENCES

[1] TURRONI, P., et al. The CIRCE test facility. In: *ANS Winter Meeting, Reno*. 2001. p. 12-15.)

[2] TARANTINO, M., et al. Preliminary design of a helical coil steam generator mock-up for the CIRCE facility for the development of DEMO LiPb heat exchanger. *Fusion Engineering and Design*, 2021, 169: 112459.

[3] LORUSSO, Pierdomenico, et al. Design of a Novel Test Section for the Lead Fast Reactors Development: The CIRCE-THETIS Facility. In: *International Conference on Nuclear Engineering*. American Society of Mechanical Engineers, 2021. p. V002T07A032.