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E-SCAPE: A scale facility for liquid-metal, pool-type reactor thermal hydraulic investigations

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HIGHLIGHTS

- The E-SCAPE facility is a thermal hydraulic scale model of the MYRRHA fast reactor.
- The focus is on mixing and stratification in liquid-metal pool-type reactors.
- Forced convection, natural convection and the transition are investigated.
- Extensive instrumentation allows validation of computational models.
- System thermal hydraulic and CFD models have been used for facility design.

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ABSTRACT

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible fast-spectrum research reactor under design at SCK·CEN. MYRRHA is a pool-type reactor with lead bismuth eutectic (LBE) as primary coolant.

The proper understanding of the thermal hydraulic phenomena occurring in the reactor pool is an important issue in the design and licensing of the MYRRHA system and liquid-metal cooled reactors by extension. Model experiments are necessary for understanding the physics, for validating experimental tools and to qualify the design for the licensing.

The E-SCAPE (European SCAled Pool Experiment) facility at SCK·CEN is a thermal hydraulic 1/6-scale model of the MYRRHA reactor, with an electrical core simulator, cooled by LBE. It provides experimental feedback to the designers on the forced and natural circulation flow patterns. Moreover, it enables to validate the computational methods for their use with LBE.

The paper will elaborate on the design of the E-SCAPE facility and its main parameters. Also the experimental matrix and the pre-test analysis using computational fluid dynamics (CFD) and system thermal hydraulics codes will be described.

1. Introduction

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), under design at SCK·CEN (De Bruyn et al., 2014), is a flexible fast-spectrum research reactor cooled by lead bismuth eutectic (LBE) in a pool configuration. Conceived as an accelerator driven system prototype, it is able to operate in sub-critical mode. Operating in critical mode, MYRRHA is identified as the European Technology Pilot Plant for the Lead Cooled Fast Reactor which is one of the Generation IV reactor concepts (ESNII, 2010).

The proper understanding of the thermal hydraulic phenomena occurring in the upper and lower plena of the reactor pool is an important issue in the design and licensing of the MYRRHA system and lead-cooled reactors by extension. A good knowledge of

Abbreviations: ACS, above core structure; CFD, computational fluid dynamics; E-SCAPE, European SCAled Pool Experiment; FC, forced convection; HX, heat exchanger; IPS, in-pile section; IVFHM, in-vessel fuel handling machine; LBE, lead bismuth eutectic; LFR, lead fast reactor; LOF, loss of flow; LOHS, loss of heat sink; MYRRHA, Multi-purpose hYbrid Research Reactor for High-tech Applications; NC, natural convection; PLC, Programmable Logic Controller; SD, silicon doping device; UDV, Ultrasonic Doppler Velocimetry.

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Nomenclature

$Eu = \frac{P}{\rho \cdot U^2}$	Euler number
$Fr = \frac{U^2}{g \cdot \Delta H}$	Froude number
$Pe = \frac{C \cdot \rho \cdot U \cdot d}{k}$	Péclet number
$Re = \frac{\rho \cdot U \cdot d}{\mu}$	Reynolds number
$Ri = \frac{g \cdot \beta \cdot \Delta H \cdot \Delta T}{U^2}$	Richardson number
$Ti = \frac{\Delta H}{U}$	time number, [s]
M	mass flow rate through core area A, [kg/s]
ΔP	pressure drop of the system, [Pa]
ρ	density, [kg/m^3]
U	average velocity at the core outlet, [m/s]
g	gravitational acceleration, [m/s^2]
ΔH	height difference between the thermal centers of the core and HXs, [m]
Q	heat source, [W]
A	core area, [m^2]
C	specific heat at constant pressure, [J/(kg K)]
ΔT	temperature difference between the core inlet and outlet, [°C]
d	hydraulic diameter of the core, [m]
k	thermal conductivity, [W/(m K)]
μ	viscosity, [Pa s]
β	thermal expansion coefficient, [1/°C]

Subscripts

r	ratio

convection patterns, flow mixing and stratification in operational and accidental conditions (e.g. partial or complete loss-of-flow, loss-of-heat-sink) etc. is indispensable. Model experiments are necessary for understanding the physics of the thermal hydraulic phenomena, to qualify the design for the licensing and for validating computational tools.

One of the key phenomena to be investigated is the decay heat removal after reactor shut-down by natural circulation. The use of passive systems to achieve safety functions is one of the guiding principles of the MYRRHA design, embedded in the MYRRHA safety approach. In order to adopt a natural circulation system, one must have an accurate prediction tool which enables to quantify natural-circulation flow. One option for prediction is a scale model experiment with a suitable thermal hydraulic similarity, which quantitatively relates it to the actual plant. The other one is a computational method, by which a set of equations describing an actual plant is numerically solved.

The E-SCAPE (European SCAled Pool Experiment) facility, built at SCK·CEN, plays an important role in both options. It is a thermal hydraulic model of the MYRRHA reactor with a uniform geometrical scale factor of 1/6 and an electrical core simulator of 100 kW as main power source, cooled by LBE. It provides experimental feedback to the designers on the forced and natural circulation flow patterns. Moreover, it enables to validate the computational methods for use with LBE.

In Section 2, the MYRRHA reference design is described. Section 3 introduces the facility E-SCAPE listing the different sub-systems. The main phenomena of investigation and the experiments that can be performed in E-SCAPE are defined in Section 4. The scaling approach is summarized in Section 5. Section 6 presents a detailed description of the main vessel, the external circuits and the auxiliary systems of E-SCAPE. The pre-test calculations performed with system thermal hydraulic and computational fluid dynamics (CFD)

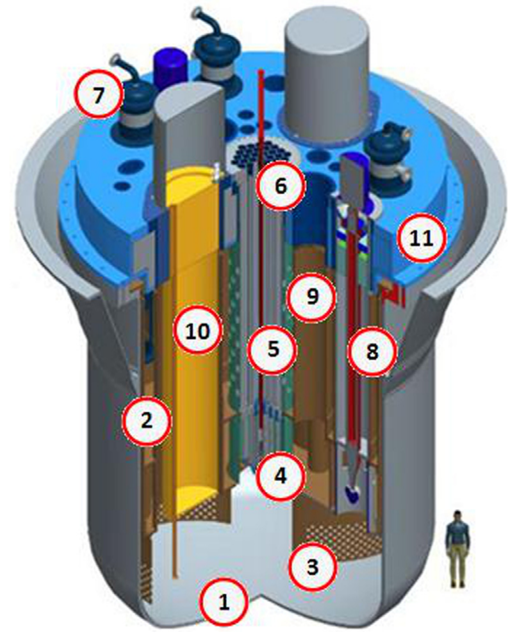

Fig. 1. MYRRHA reactor: main components.

codes are reported in Section 7. Conclusions are outlined in Section 8.

2. MYRRHA design reference

The design of the E-SCAPE facility is based on the MYRRHA design version 1.2 (Ait Abderrahim et al., 2011).

The model of the MYRRHA reactor is presented in Fig. 1. The reactor vessel ① has the task to contain the primary coolant and all the components of the nuclear reactor. The diaphragm ② is designed to separate the hot upper plenum from the cold lower plenum. The core ④ consists of fuel assemblies, control and safety rods, dummy and reflector assemblies and slots for experiments. It is inserted in the core barrel ⑤ , a perforated tube that allows the LBE coolant to reach the upper plenum and establish the first free surface. The above core structure or ACS ⑥ allows handling the control rods, the safety rods and the experiments. It also accommodates instrumentation and forces the fluid to go out from the lateral openings in the barrel. The LBE in the upper plenum enters the heat exchangers or HXs ⑦ , where water removes the heat by phase change. After leaving the heat exchangers, the coolant reaches the primary pumps ⑧ and is delivered to the lower plenum where it establishes the second free surface. In the upper plenum the silicon doping devices or SDs ⑨ allow the nuclear transmutation doping and the In-Vessel Fuel Handler Machines or IVFHMs ⑩ are responsible for the loading and unloading of the fuel assemblies and dummies in the core. The baffle ③ , a metal plate with a butterfly shape, limits the work area where inspection and recovery of lost fuel assemblies are performed to the range of the handler machines. All the penetrations are held in position and fixed by the cover ⑪ , which also provides radiation protection.

3. E-SCAPE layout and parameters

The E-SCAPE facility is a thermal hydraulic 1/6-scale model of the MYRRHA reactor. Fig. 2 shows its complete layout. Fig. 3 focusses on the main vessel. A replica of all main components (see Section 2 for numbering) is placed in the main vessel in order to maintain a geometric similarity. Unlike MYRRHA's full pool-type primary system configuration, E-SCAPE is equipped with external