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European activities on crosscutting thermal-hydraulic phenomena for innovative nuclear systems

X. Cheng[a,*], A. Batta[a], G. Bandini[b], F. Roelofs[c], K. Van Tichelen[d], A. Gerschenfeld[e], M. Prasser[f], A. Papukchiev[g], U. Hampel[h], W.M. Ma[i]

[a] Karlsruhe Institute of Technology (KIT), Germany
[b] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy
[c] Nuclear Research and Consultancy Group (NRG), The Netherlands
[d] Studiecentrum voor Kernenergie – Centre d'étude de l'Energie Nucléaire (SCK·CEN), Belgium
[e] Commissariat à l'Energie Atomique (CEA), France
[f] Paul Scherrer Institute (PSI), Switzerland
[g] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Germany
[h] Helmholtz-Zentrum Dresden-Rossendorf e.V. (HZDR), Germany
[i] Kungliga Tekniska Högskolan (KTH), Sweden

HIGHLIGHTS

- This paper serves as a guidance of the special issue.
- The technical tasks and methodologies applied to achieve the objectives have been described.
- Main results achieved so far are summarized.

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ABSTRACT

Thermal-hydraulics is recognized as a key scientific subject in the development of innovative reactor systems. In Europe, a consortium is established consisting of 24 institutions of universities, research centers and nuclear industries with the main objectives to identify and to perform research activities on important crosscutting thermal-hydraulic issues encountered in various innovative nuclear systems. For this purpose the large-scale integrated research project THINS (Thermal-Hydraulics of Innovative Nuclear Systems) is launched in the 7th Framework Programme FP7 of European Union. The main topics considered in the THINS project are (a) advanced reactor core thermal-hydraulics, (b) single phase mixed convection, (c) single phase turbulence, (d) multiphase flow, and (e) numerical code coupling and qualification. The main objectives of the project are:

- Generation of a data base for the development and validation of new models and codes describing the selected crosscutting thermal-hydraulic phenomena.
- Development of new physical models and modeling approaches for more accurate description of the crosscutting thermal-hydraulic phenomena.
- Improvement of the numerical engineering tools for the design analysis of the innovative nuclear systems.

This paper describes the technical tasks and methodologies applied to achieve the objectives. Main results achieved so far are summarized. This paper serves also as a guidance of this special issue.

Abbreviations: ADS, accelerator-driven subcritical nuclear systems; CFD, computational fluid dynamics; DHR, decay heat removal; DNS, direct numerical simulation; GFR, gas-cooled fast reactor; GIF, Gen-IV International Forum; HLM, heavy liquid metal; HTR, high temperature reactor; LBE, lead bismuth eutectic; LDA, laser Doppler anemometry; LES, large eddy simulation; LFR, lead-cooled fast reactor; LMR, liquid metal reactors; MRI, matching refractive index; MSR, molten salt reactor; PTV, particle tracking velocimetry; RANS, Reynolds-averaged Navier–Stokes equations; SC, supercritical; SCWR, supercritical water cooled reactor; SFR, sodium-cooled fast reactor; THINS, thermal-hydraulics of innovative nuclear systems; VHTR, very high temperature reactor.

* Corresponding author.
E-mail address: xu.cheng@kit.edu (X. Cheng).

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1. Introduction

For the long-term development of nuclear power, reactors of generation IV (Gen-IV) with enhanced safety, economics, sustainability and non-proliferation features need to be developed. The Gen-IV International Forum (GIF) recommended six innovative nuclear energy system for meeting future energy challenges and proposed a technology roadmap for Gen-IV nuclear energy systems (USDOE, 2002). These six innovative nuclear energy systems are very high temperature reactor (VHTR), gas-cooled fast reactor (GFR), sodium-cooled fast reactor (SFR), lead-cooled fast reactor (LFR), supercritical water cooled reactor (SCWR) and molten salt reactor (MSR).

One aspect of sustainability is the reduction of nuclear waste. Nowadays, management of nuclear waste becomes a key issue in the public acceptance of nuclear energy. Extensive studies in the last years showed that partitioning and transmutation is a promising approach of the waste management. Transmutation using accelerator-driven subcritical nuclear systems (ADS) has attracted strong attention worldwide due to its claimed favorable safety features and its high incineration rate of nuclear waste (IAEA, 2003).

Thermal-hydraulics is recognized as a key scientific subject in the development of the different innovative reactor systems. From the thermal-hydraulic point of view, different innovative reactors are mainly characterized by coolants, flow channel structures formed by different fuel lattice arrangements and primary circuit lay-out (pool vs. loop). They result in different micro- and macroscopic behavior of flow and heat transfer and require specific models and advanced analysis tools. On the other hand, many common thermal-hydraulic issues are identified among various innovative nuclear systems (THIRS, 2008).

In 2010, the EU project THINS (Thermal-Hydraulics of Innovative Nuclear Systems) was launched (www.ifrt.kit.edu/thins/), which focuses on several crosscutting issues and synergizes infrastructure for the thermal-hydraulic research of the innovative nuclear systems in Europe. The overall objectives of the THINS project are the development and validation of new physical models and qualification of numerical analysis tools. Specific objectives are:

- Establishment of a ***data base*** for the development and validation of new physical models and numerical codes for a more accurate description of the selected crosscutting thermal-hydraulic phenomena. Generic experiments are performed in the THINS project to produce a comprehensive data base for the validation purpose. In addition, direct numerical simulation (DNS) will be performed to provide numerical data base, which is of crucial importance for the development of turbulence models. With this project, a data base will be established for the fundamental thermal-hydraulic issues occurring in the innovative nuclear systems.
- Establishment of an ***experimental platform*** for the thermal-hydraulic research of the innovative nuclear systems. In the past, also in the frame of the previous European projects, experimental facilities, specifically for the thermal-hydraulics of innovative nuclear systems, have been built and operated at various institutions (http://vella.brasimone.enea.it/na.htm). The THINS project will make the optimum utilization of the available European experimental facilities and expertise, combine the resources available and establish a European experimental platform.
- Establishment of a ***numerical platform*** for the design analysis of the innovative nuclear systems. Numerical codes for nuclear thermal-hydraulics cover various classes of spatial scales, i.e. system analysis based mainly on lumped parameter approach, sub-channel analysis specifically for fuel assembly and reactor core and CFD codes for detailed local flow behavior. With the THINS project, more reliable and validated codes will be proposed based on advanced physical models and numerical methodology. Coupling of the code solutions at various scales and the qualification of the coupled calculations extend the applicability and ensure the reliability of the numerical platform.

The THINS project has a duration of five years and will terminate in January 2015. In January 2014 the International Workshop on Thermal-Hydraulics of Innovative Nuclear systems, THINS-2014, took place at the University of Modena, Italy (http://www.thins2014.unimore.it) with the aim to review the project progress, to disseminate the main achievements of the project among the international nuclear community and to foster the exchange of the newest scientific and technical results between researchers and experts. In this paper, the main objectives, technical tasks, scientific methodology and some main results are presented, in order to give an introductory overview of the THINS project and provide guidance to this special journal issue.

2. Technical tasks

The THINS project is structured with the following six work packages (WPs):

- WP1: Advanced reactor core thermal-hydraulics.
- WP2: Single phase mixed convection.
- WP3: Single phase turbulence.
- WP4: Multi-phase flow.
- WP5: Code coupling and qualification.
- WP6: Education and training.

The first five WPs are devoted to the individual crosscutting issues. Experiments are foreseen to provide experimental evidence and fundamental test data base. New physical models are developed and further employed to improve codes. The last WP is devoted to the education and training of young nuclear engineers and researchers.

2.1. Advanced reactor core thermal-hydraulics

Design of innovative reactor cores requires detailed analysis of the thermal-hydraulics within the fuel assemblies with high resolution inside individual sub-channels. The goal of this work package is to provide validated and verified simulation tools of the coolant flow within the reactor core components for typical states encountered in liquid metal cooled fuel assembly.

The THINS project considers different numerical approaches applicable to the design analysis of innovative reactor cores. The first approach is based on sub-channel analysis codes. Efforts are made to introduce advanced numerical methods, e.g. coarse grid simulation, and to improve the physical models suitable for specific conditions of innovative reactor cores. The purpose of the second approach is to develop CFD simulation tools with more advanced models than the current state-of-the-art RANS modeling and improved accuracy. The complex nature of heat transfer in pebble bed requires the development of new algorithm techniques to describe the core, as well as robust methods capable to treat convective–conductive–radiative heat transfer with fluid flow across complex structure of pebble bed. In the THINS project a method is proposed based on macroscopic modeling of flow phenomena in pebble bed reactors. The macroscopic properties are obtained by LES simulation technique applied to a geometry consisting of spheres in an array with irregular structure.

Two experiments are considered in this WP to provide test data for the validation purpose, as shown in Figs. 1 and 2. Test data in fuel assemblies with liquid metal for mixed and natural convection