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EUROPEAN DEVELOPMENTS IN SINGLE PHASE TURBULENCE FOR INNOVATIVE REACTORS

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Abstract

Thermal-hydraulics is recognized as a key scientific subject in the development of different innovative nuclear reactor systems. From the thermal-hydraulic point of view, different innovative reactors are mainly characterized by their coolants (gas, water, liquid metals and molten salt). They result in specific behavior of flow and heat transfer, which requires specific models and advanced analysis tools. However, many common thermal-hydraulic issues are identified among various innovative nuclear systems. In Europe, such cross-cutting thermal-hydraulics topics are the motivation for the THINS (Thermal-Hydraulics of Innovative Nuclear Systems) project which is sponsored by the European Commission from 2010 to 2014.
This paper describes the ongoing developments in an important part of this project devoted to single phase turbulence issues. To this respect, the two main issues have been identified:

- Non-unity Prandtl number turbulence.
  In case of liquid metals, molten salts or supercritical fluids, the commonly applied constant turbulent Prandtl number concept is not applicable and robust engineering turbulence models are needed. This paper will report on the progress achieved with respect to the development and validation of turbulence models available in commonly used engineering tools. The paper also reports about the supporting experiments and direct numerical simulations.
- Temperature fluctuations possibly leading to thermal fatigue in innovative reactors.
  The status is described of a fundamental experiment dealing with the mixing of different density gases in a rectangular channel, an experiment in a more complex geometry of a small mixing plenum using a supercritical fluid, and direct numerical simulations of conjugate heat transfer on temperature fluctuations in liquid metal.

Introduction

The civil utilization of nuclear energy for more than five decades shows significant advantages of nuclear power in the respect of carbondioxide emmisions, economic competitiveness and power supply security. Nowadays, nuclear power plays an important role in power generation and produces about 16% of the total electricity worldwide. The rapidly growing energy demand suggests an important role for nuclear power in the future energy supply, as for example denoted in the projections of OECD/IEA (2008) [1]. Therefore, nuclear energy is back on the agenda worldwide.

In Europe, the European Commission recently presented the Vision Report of the Sustainable Nuclear Energy Technology Platform for the role of nuclear fission energy to the European transition towards a low-carbon energy mix by 2050 (Euratom, 2007) [2].

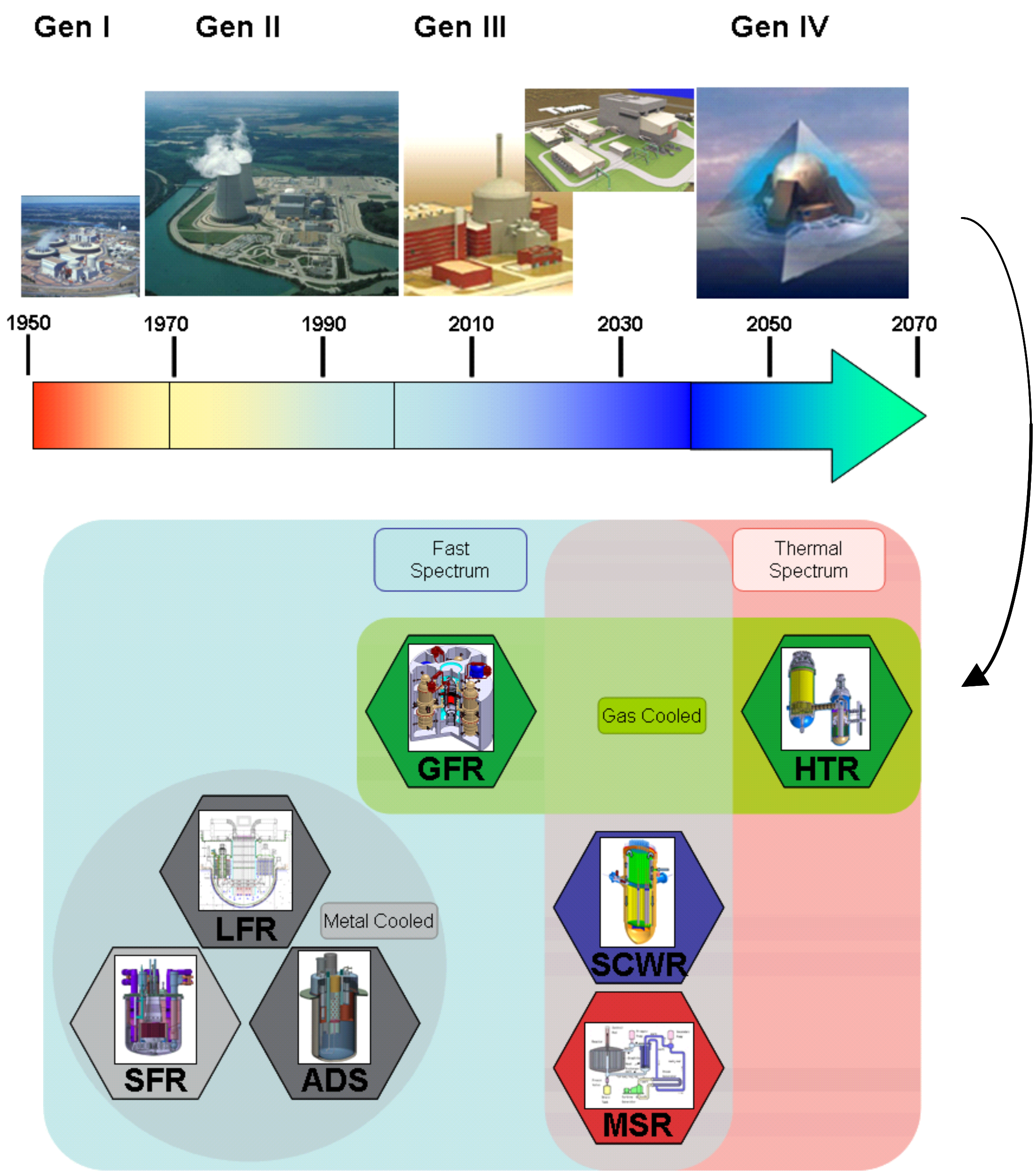

Figure 1 Four generations of nuclear reactors (top) and common characteristics of innovative nuclear systems (bottom)

The development of the nuclear power technology has undergone four generations as depicted in the upper part of figure 1. Compared to the second generation (Gen-II), the third generation (Gen-III) exhibits a higher safety level and improved efficiency. However, nuclear power plants (NPPs) of Gen-III show some shortages related to the requirements of a long-term nuclear power development, especially with respect to minimisation of uranium resources and long term radioactive waste.

Nowadays, management of nuclear waste becomes a key issue in the public acceptance of nuclear energy. Extensive studies in the last years, e.g. by PATEROS (2008) [3], Salvatores et al.(2009) [4], and Knebel et al. (2009) [5] showed that partitioning and transmutation may be a promising approach of the waste management.
For the long-term development of nuclear power, reactors of generation IV (Gen-IV) with enhanced economics, minimisation of resources and waste, and security features need to be developed. The Gen-IV International Forum (GIF), which was established in January 2000, recommended six innovative nuclear energy system concepts for meeting future energy challenges and proposed a technology roadmap for Gen-IV nuclear energy systems (USDOE, 2002) [6]. These six innovative nuclear energy systems are the high temperature reactor (HTR) (sometimes referred to as very high temperature reactor (VHTR)), the gas cooled fast reactor (GFR), the sodium cooled fast reactor (SFR), the lead-cooled fast reactor (LFR), the supercritical water cooled reactor (SCWR) and the molten salt reactor (MSR). In the THINS project, the Gen-IV nuclear systems and transmutation sub-critical systems, i.e. Accelerator Driven Systems (ADS), are considered as the innovative nuclear systems. Extensive descriptions of these reactor systems can be found in numerous references, like e.g. in GIF (2008) [7] and Abram & Ion (2008) [8].
Although the above mentioned reactor designs may seem very different, they also share common characteristics. The lower part of figure 1 shows the seven systems in a diagram which indicates the main similarities between the concepts. Firstly, the reactors are characterised by their operating spectrum. The MSR and the SCWR can be operated in both, thermal and fast spectrum, although in first instance operation in thermal spectrum is foreseen. Secondly, reactors are characterised by their coolant, which determines many common technology development challenges. The colour of the hexagons indicates the coolant use. The GFR and HTR share helium as a coolant. The SFR, LFR and ADS share a liquid metal as coolant. They may be referred to as Liquid Metal Cooled Reactors (LMFR). A special category of LMFR's are the reactors which employ a Heavy Liquid Metal (HLM) as coolant. These HLM cooled reactors, the LFR and the ADS, are depicted in dark grey colour.

Thermal-hydraulics is recognized as a key scientific subject in the development of the different innovative nuclear reactor systems. From the thermal-hydraulic point of view, the innovative reactors are mainly characterized by their different coolants (gas, water, liquid metals and molten salt). This results in different micro- and macroscopic behavior of flow and heat transfer and therefore requires specific models and advanced analysis tools. However, many common thermal-hydraulic issues are identified among various innovative nuclear systems, as outlined in Roelofs (2009) [9].

Figure 2 Institutes involved in the single phase turbulence work package of THINS

In Europe, such cross-cutting thermal-hydraulic topics are the subject of the 7th framework programme THINS (Thermal-Hydraulics of Innovative Nuclear Systems) project which runs from 2010 until 2014 and is described by Cheng et al., 2010 [10]. An important work package of this project is devoted to single phase turbulence issues. To this respect, two main subjects are identified and treated, i.e. non-unity Prandtl number turbulence and temperature fluctuations possibly leading to thermal fatigue in innovative nuclear systems. Figure 2 shows an overview of the institutes involved in this single phase turbulence work package.

This paper will describe the activities in the single phase turbulence work package of the THINS project. The issues identified for this work package were also identified for research programmes in Japan (Akimoto et al., 2009) [11] and Korea (Song et al., 2009) [12] respectively, and for (liquid metal cooled) fast reactors in Sienicki et al. (2003) [13], Li (2008) [14], and Todreas (2007) [15].

The project will take into account existing experimental data and will produce new experimental data where needed. As numerical simulations are becoming more and more integrated in the daily practise of the thermal-hydraulics researchers and designers, the overall objectives of the THINS project are the development and validation of new physical models, improvement and qualification of numerical engineering tools and their application to innovative nuclear systems. The objectives of the single phase turbulence work package are:

- To improve and develop turbulence models for non-unity Prandtl number flows (liquid metals and supercritical fluids).
- To implement improved models in engineering tools.
- To extend and further develop the existing LWR approaches for the application to innovative reactors to predict temperature fluctuations possibly leading to thermal fatigue

Section 1 describes the different computational fluid dynamics simulation techniques which are employed within the work package. Section 2 deals with non-unity Prandtl number turbulence and section 3 with thermal fatigue. Finally, section 4 provides a summary of this paper.

1. Computational Fluid Dynamics

For the coolants envisaged in innovative nuclear systems, usually experiments are very expensive and accurate measurements are complex or even impossible. Therefore, application of CFD for predictions of various flows characteristics becomes an attractive and complementary practice used in the design and evaluation process of innovative nuclear systems. As CFD is based on the principles of physics (i.e., mass, momentum and energy conservation laws), it is an appropriate numerical tool, which is able to capture all the flow and heat transport details (Ferziger & Peric, 2004) [16]. However, for certain simulation methods the computational costs are still too high for the current and probably future status of available computer power.

In short, CFD uses numerical methods to solve and analyze problems that involve fluid flows and heat transfer. Motion of these flows is commonly described by the Navier-Stokes equations that can be discretized and solved on computational meshes. An accurate solution of the Navier-Stokes equations involves capturing of all length scales that appear in the flow as described by Temam (2001) [17]. Hence, quite often flow simulations require introduction of a model to encounter scales that cannot be computationally resolved on the meshes, as for example in case of turbulence (Pope, 2000) [18]. The following modelling approaches are used:

- Reynolds Averaged Navier Stokes (RANS)
  These time-averaged equations give a steady-state solution of the Navier-Stokes equations with additional approximations (models) concerning turbulence. Many industrial problems are

solved using RANS approaches. Over time, many turbulence models suitable for RANS have been developed. Each of them has its own advantages and disadvantages (see e.g. Chen & Yaw, 1997) [19]. The well known models with a number of modifications are k-ε, k-ω, and non-linear turbulence models as well as Reynolds Stress Models.

- Unsteady RANS (URANS)
  In URANS simulations the RANS turbulence modelling approach is applied in which averaged equations are solved in time. Hence, URANS has the potential to resolve large scale flow oscillations in which the length scales of appearing macroscopic structures are much larger than the typical turbulence scales. A URANS approach demands more computational effort than RANS. On the contrary, application of URANS approach in comparison to DNS and LES (described hereafter) permits much coarser computational meshes for simulations, which consequently lead to much larger time stepping resulting in a significant reduction of the computational time (Hanjalic, 2005) [20].
- Large Eddy Simulation (LES) and hybrid approaches
  An implication of the widely applied Kolmogorov's scaling is that large structures that appear in a flow are often dependent on the geometry while the smaller scales are more universal. This aspect allows development of a modeling strategy in which the large flow-structures (eddies) are directly solved in a simulation while the small flow-structures are modelled by using a subgrid-scale model (SGS) (Sagaut, 2006) [21]. This approach is considered as more accurate than RANS and URANS modeling techniques. However, LES requires more computational effort than URANS, as LES implies that larger structures that appear in a flow need to be resolved, which is in particular costly in the near-wall regions, where the main flow structures are comparatively small. This difficulty has lead to development of hybrid models that attempt to combine the best aspects of RANS and LES methodologies in a single solution strategy. An example of a hybrid technique is the detached-eddy simulation (DES) approach (Spalart et al, 1997) [22].
- Direct Numerical Simulation (DNS)
  In the DNS approach, the Navier-Stokes equations are numerically solved without any turbulence model. This means that the whole range of spatial and temporal scales of the turbulence (from the smallest dissipative scales up to the main geometrical scales) must be resolved on the computational mesh. Therefore, DNS data may serve together with experimental data as reference for other computational approaches. However, due to the enormous amount of scales that need to be resolved and finite computational resources, one cannot expect to perform DNS for industrial problems. In fact, the use of DNS is restricted to low Reynolds number (Re) flows (flows with limited turbulence intensity) and simple geometries. In all cases where DNS cannot be applied, a model is required to simulate turbulence phenomenon. Usually for DNS, small computational domains are employed with additional simplifications as for example usage of periodicity assumptions in given flow directions.

2. Non-Unity Prandtl Number Turbulence

For modelling turbulent heat transfer, the current engineering tools apply statistical turbulence closures and adopt the concept of the turbulent Prandtl number based on the Reynolds analogy. Essentially, the turbulent Prandtl number concept is a structural coupling of velocity- and temperature fields, which may be considered as valid only for forced convective flows with Prandtl number of order of unity. In particular cases of liquid metal or supercritical flows, the turbulent Prandtl number concept is not applicable and robust engineering turbulence models are needed. The difficulties mentioned above in applying commercial CFD codes for computation of heat transfer involving liquid metals are well known see e.g. OECD/NEA (2007) [23], Grötzbach (2007) [24], Arien et al. (2004) [25], or Grötzbach (2003) [26] for a broad overview. The turbulence workpackage of the THINS project foresees in experiments and direct numerical simulations to support the development and validation of turbulence models for other computational approaches in commonly used engineering CFD tools.

Direct Numerical Simulation (DNS) data from UNIMORE and UCL serve together with experimental data from the DeLight facility at DUT as reference for computational approaches. UCL focuses on DNS for low Prandtl number flow in a rectangular channel at various Reynolds numbers and Prandtl numbers. In order to provide reference data at Reynolds numbers as high as possible, they intend to profit from the fact that when doing LES for momentum, at the same time because of the larger thermal boundary layer, DNS is performed for the thermal field. UNIMORE will perform DNS including separating flow conditions in a wavy wall channel and the natural convection between heated rods representative for a nuclear reactor core.

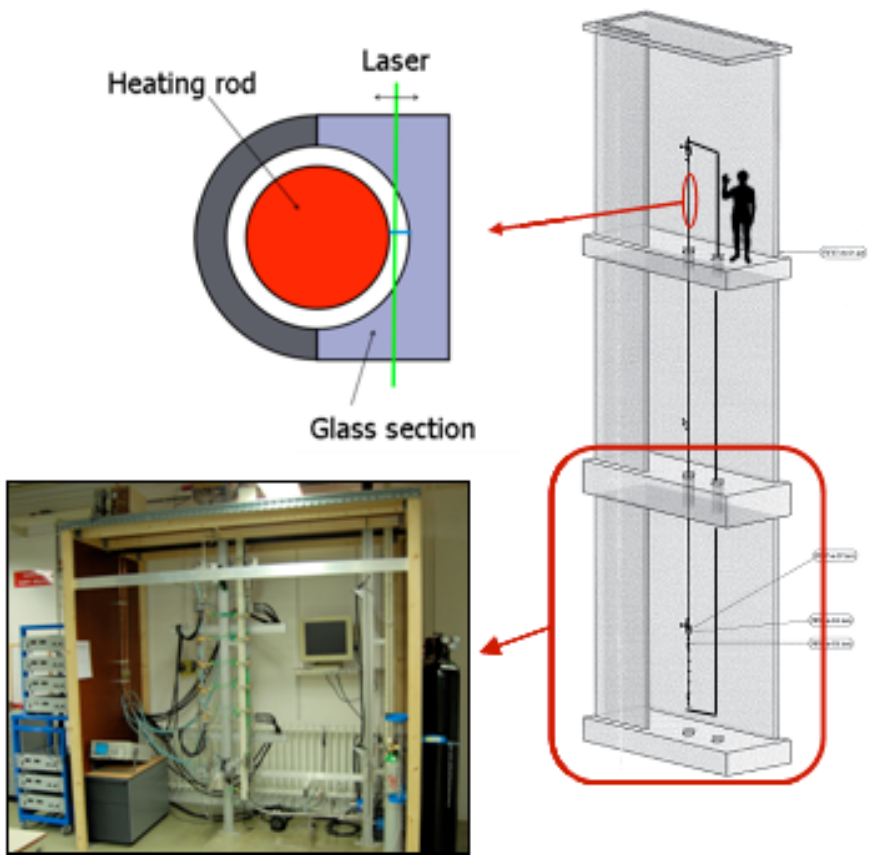

Figure 3 DeLight facility and the measurement section for high Prandtl number turbulence (DUT)

The DeLight facility of DUT is presented in figure 3. Within this facility, the turbulence measurement section is being constructed in a long vertical tube in which supercritical Freon R23 (Rohde et al., 2009) [27, 28] flows vertically upward. The test section will consist of an annular flow region around a central heated rod. Scoping CFD analyses have been performed by NRG in order to support the design and set-up of the experiment [29]. The aim of the experiment is to provide experimental data that can be used for high Prandtl number turbulence model development and validation. To this purpose, the experiments should allow local velocity measurements (2D-LDA) in the momentum boundary layer.

As the momentum boundary layer is expected to be very small near the (pseudo-)critical point, this will be a challenging task. In addition, the temperature will be measured at different positions with respect to the heated wall. For this purpose, fast thermocouples (~10 ms) will be used. Since the temperature boundary layer is even smaller than the momentum boundary layer (it was estimated from the supporting simulations that the thermal boundary layer is about 0.1 mm thick) due to the high Prandtl number of supercritical fluids near the (pseudo-)critical point, this will also be a challenging task.

In order to improve the turbulence energy transport models in engineering CFD tools for non-unity Prandtl number fluids, different routes are employed:

- CD-adapco has implemented in their widely spread STAR-CCM+ engineering code a carefully selected, existing advanced Reynolds Averaged Navier-Stokes (RANS) turbulence model based on the model described by Kenjeres and Hanjalic (2000) [30]. This model introduces two additional scales for the thermal field, the temperature variance and the temperature variance dissipation rate, which represent the counterpart to turbulence kinetic energy (k) and its dissipation rate (ε) in the velocity field. The additional scales allow to directly model the eddy diffusivity of heat, and therefore have the potential to accurately model heat transfer in non-unity Prandtl flows. The selected turbulence model has already been tested using dedicated academic codes. First verification of the implementation by CD-adapco and NRG has already shown promising results. Further verification will be performed by NRG using experimental data and DNS from literature and DNS data generated within the THINS project.
- ASCOMP is implementing a non-linear RANS turbulence model using an algebraic heat flux model similar to [30] in their CFD code TRANSAT. Obviously, this development will also profit from the DNS data generated within the project. The validation campaign will be carried out in cooperation between ASCOMP, UCL and TEES.
- To deal with supercritical fluids with Prandtl numbers larger than the order of unity requires development of new RANS turbulence models. In a cooperation between PSI and UNIPI supported by CD-adapco, a CFD modelling approach will be developed in STAR-CCM+. To this purpose, first basic understanding is needed of the turbulence production terms. This will be obtained from the experiments to be conducted in the DeLight facility, supplemented by DNS/LES simulations in the in-house PSI-Boil code of PSI. Furthermore, an extensive existing turbulence model assessment is being performed at UNIPI as e.g. reported in De Rosa et al. (2011) [31]. After that, a new model will be tested in first instance in the in-house code THEMAT, before implementing the model in STAR-CCM+.

  Furthermore, the existing modeling approach available in the open source CFD Code OpenFOAM will be improved by KTH. Improvements should be achieved either in computational time, or in meshing requirements or in accuracy. The basic idea is to improve the current wall functions such that they provide reasonable results for heat transfer at supercritical pressures and temperatures. To this purpose, it is proposed to implement the model from Craft et al. [32] in OpenFOAM. Validation will be performed by comparison to existing data and the data to be generated in the DeLight facility.

Development of LES modeling approaches for simulation of non-unity Prandtl number flows is also being carried out. Based on a two-point correlation method a novel SGS modeling approach for numerical simulations of turbulent flows with non-unity Prandtl numbers is developed by KIT and implemented in OpenFOAM. The new model should account for the effects of molecular fluid properties on the energy transfer. It will be derived considering both temperature and velocity fields and will make no use of the Reynolds analogy between the fields (Otic, 2009) [33]. The implemented model is validated by comparison to DNS data. Furthermore, a dynamic anisotropic SGS model for the heat flux is implemented by ASCOMP in their commercial TRANSAT code.

Preliminary simulations have shown that the implementation seems to be correct. Further verification and validation work will be performed in a next stage.

3. Thermal Fatigue in Innovative Nuclear Systems

Approaches developed for the assessment of thermal fluctuations which might possibly lead to thermal fatigue for current LWRs should be transferred and adapted to innovative reactors. To this purpose, a fundamental experiment dealing with the mixing of different density gases in a rectangular channel, an experiment in a more complex geometry of a small mixing plenum using supercritical fluids, and direct numerical simulations of conjugate heat transfer on temperature fluctuations in liquid metal will be performed to support the development and validation of approaches for innovative nuclear systems.

In order to deal with thermal fatigue issues in innovative nuclear systems, evaluation approaches used to predict temperature fluctuations in current LWRs, as e.g. described in Hannink et al. (2008) [34] and Dahlberg et al. (2007) [35], will have to be transferred and adapted to innovative reactors. To this purpose, mixing in a rectangular channel will allow a fundamental view on the mixing phenomena.

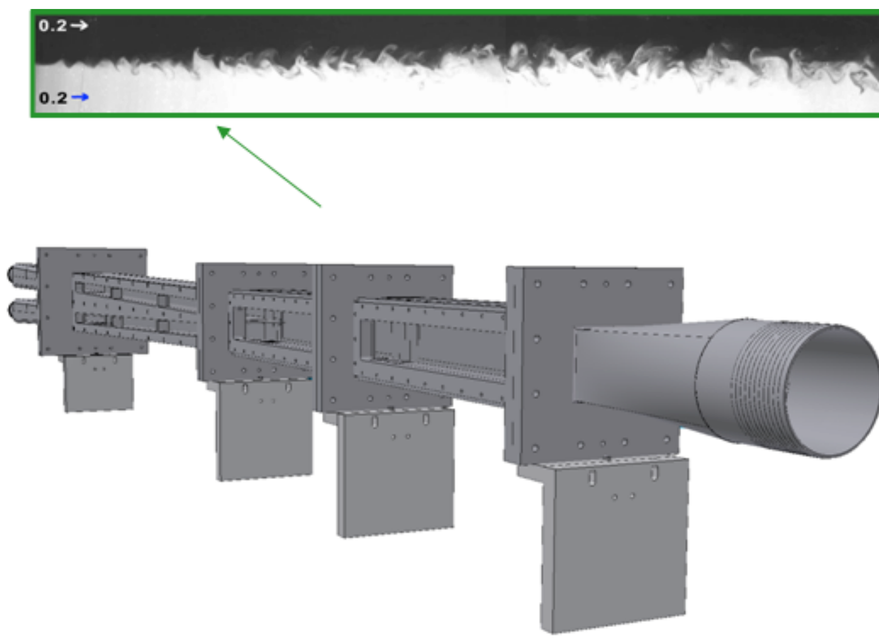

Figure 5 Outline of the HOMER test section at PSI.

The experiments to be conducted in the new facility at PSI, derived from the existing GEMIX (GEneral MIXing) facility, shown in figure 5 and described in more detail by Prasser et al. (2009) [36], will be directed towards gas-cooled systems, but the outcome will also provide important insights for other coolants. The new facility is called HOMER (HOrizontal Mixing Experiment in a Rectangular channel). Measurements will include local velocities using Particle Image Velocimetry (PIV) and local concentrations using Laser-induced Fluorescence (LIF). PSI, KIT and NRG will use the experimental data to develop and evaluate in parallel different modeling approaches using RANS and LES techniques.

Mixing in a core outlet plenum may lead to thermal fatigue damage. In order to develop a modeling approach available for this phenomenon, an experiment as sketched in figure 6 will be conducted in the DeLight facility at DUT which will capture the details of a mixing flow in a plenum. The application is using a supercritical fluid and will be representative for the European three pass core High Performance

Light Water Reactor (HPLWR) design (Schulenberg et al., 2006) [37], but the outcome will also provide important insights for other coolants. Scoping analyses and CFD modeling will be performed by NRG. The experimental data from the DeLight facility will be used for validation. The validated CFD tool should enable simulations to assess the transient mixing phenomena at full scale.

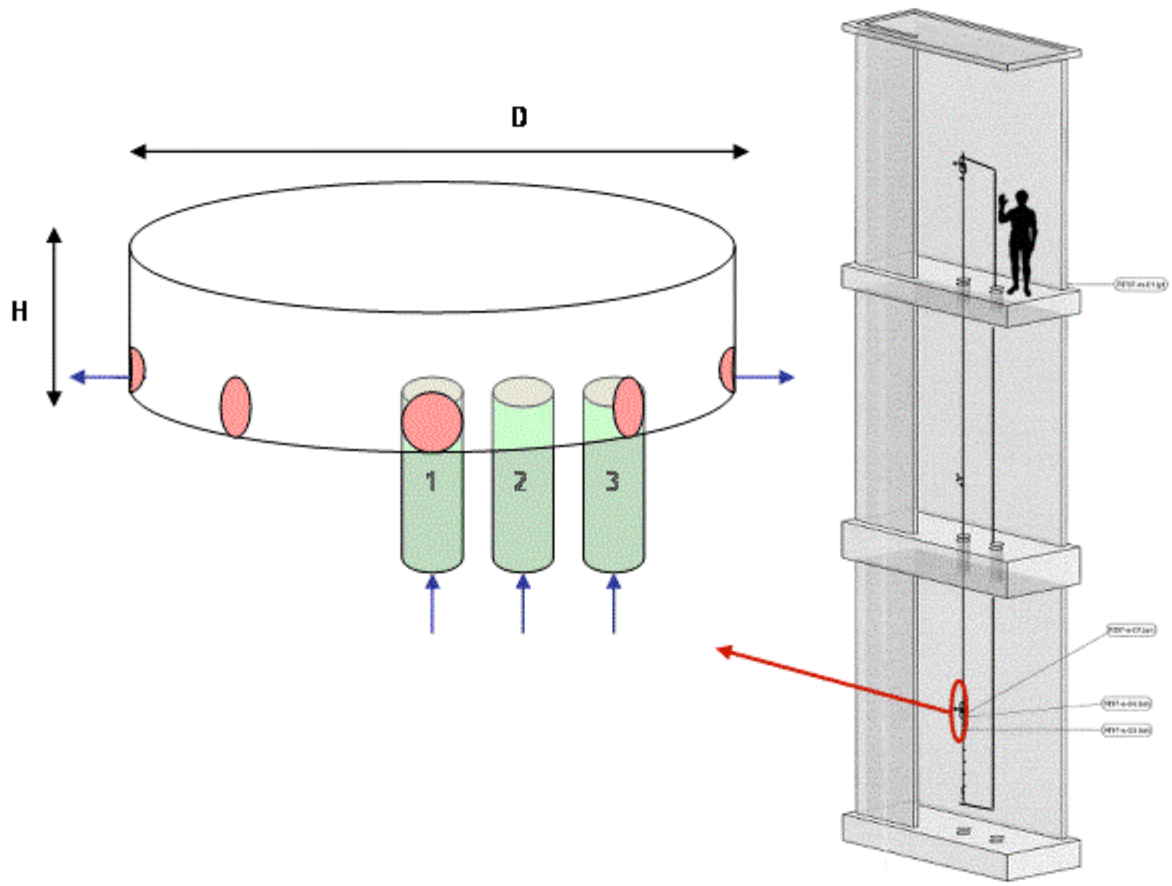

Figure 6 DeLight facility and the conceptual measurement section for mixing in a plenum (DUT)

The influence of conjugate heat transfer on temperature fluctuations in liquid metal is studied by JSI using DNS. In their simulations, they not only model the heat transport in the liquid, but also simulate the heat transport to and in the solid heated wall. Amongst others, they will focus on the heat transport between a sodium flow and a stainless steel wall. Their data will be used by IRSN to develop and validate an LES modeling approach with respect to modeling the influence of the heat transport in a solid wall on the temperature fluctuations in the fluid.

4. Summary

The European THINS project takes into account existing experimental data and produces new experimental data where needed. As numerical simulations are becoming more and more integrated in the daily practise of the thermal-hydraulics researchers and designers, the overall objectives of the THINS project are the development and validation of new physical models, improvement and qualification of numerical engineering tools and their application to innovative nuclear systems. This paper presents an important work package of the THINS project which deals with single phase turbulence. The objectives of this work package are:

- To improve and develop turbulence models for non-unity Prandtl number flows (liquid metal and supercritical flows).
- To implement improved and developed models in engineering tools.
- To extend and further develop the existing LWR approaches for the application to innovative reactors to predict temperature fluctuations possibly leading to thermal fatigue

With respect to single phase turbulence, two main issues have been identified and described, i.e. non-unity Prandtl number turbulence and thermal fatigue in innovative nuclear systems.

- Non-unity Prandtl number turbulence.
  For modelling turbulent heat transfer, the current engineering tools apply statistical turbulence closures and adopt the concept of the turbulent Prandtl number based on the Reynolds analogy. Essentially, the turbulent Prandtl number concept is a structural coupling of velocity- and temperature fields, which may be considered as valid only for forced convective flows with Prandtl number of order of unity. In particular cases of liquid metal or supercritical flows, the turbulent Prandtl number concept is not applicable and robust engineering turbulence models are needed. The project foresees in experiments and direct numerical simulations to support the development and validation of turbulence models for other computational approaches in commonly used engineering CFD tools. New RANS and LES models have been implemented in engineering codes and are currently being tested within the project. Furthermore, new experimental data and DNS results are underway to support this.
- Temperature fluctuations in innovative nuclear systems.
  Approaches developed for current LWRs should be transferred and adapted to innovative reactors. To this purpose, a fundamental experiment dealing with the mixing of different density gases in a rectangular channel, an experiment in a more complex geometry of a small mixing plenum using supercritical fluids, and direct numerical simulations of conjugate heat transfer on temperature fluctuations in liquid metal are underway to support the development and validation of approaches for innovative nuclear systems.

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6. References

[1] OECD/IEA, 2008. World Energy Outlook 2008: Presentation to the Press. London, UK.
[2] Euratom (European Commission, Directorate General for Research Euratom), 2007. The Sustainable Nuclear Energy Technology Platform, A Vision Report. European Commission, Brussels, Belgium.
[3] PATEROS, 2008. Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy. P&T Roadmap proposal for Advanced Fuel Cycles leading to a Sustainable Nuclear Energy. Deliverable D6.2, Syntheses Report.
[4] Salvatores M., Chabert C., Fazio C., Hill R., Peneliau Y., Slessarev I., Yang W.S., 2009. Fuel Cycle Analysis of TRU or MA Burner Fast Reactors with Variable Conversion Ratio using a New Algorithm at Equilibrium. Nuclear Engineering & Design vol. 239, p.p. 2160-2168.

[5] Knebel J. et al., 2009. Transmutation of High Level Nuclear Waste in an Accelerator Driven System: Towards a Demonstration Facility of Industrial Interest. FISA 2009, Prague, Czech Republic.

[6] GIF, 2002. A Technology Roadmap for Generation IV Nuclear Energy Systems. Generation IV International Forum, GIF-002-00.

[7] GIF, 2008. Introduction to Generation IV Nuclear Energy System and the International Forum. http://www.gen-4.org.

[8] Abram T., Ion S., 2008. Generation-IV Nuclear Power: A Review of the State of the Science. Energy Policy, vol 36, pp. 4323-4330.

[9] Roelofs F., 2009. Cross-cutting CFD Support to Innovative Reactor Design. ICAPP'09, Tokyo, Japan.

[10] Cheng X., Class A., Meloni P., Roelofs F., Tichelen K. van, Boudier P., Prasser M., 2010. European Activities on Cross-Cutting Thermal-Hydraulics of Innovative Nuclear Systems. NUTHOS-8, Shanghai, China.

[11] Akimoto H., Ohshima H., Kamide H., Nakagawa S., Ezato K., Takase K., Nakamura H., 2009. Thermal-hydraulic research in JAEA; Issues and Future Directions. NURETH13, Kanazawa, Japan.

[12] Song C.H., Kim K.K., Hahn D.H., Lee W.J., Bae Y.Y., Hong B.G., 2009. Thermal-Hydraulic R&Ds for Gen-III+ and Gen-IV Reactors at KAERI: Issues and Future Directions. NURETH13, Kanazawa, Japan.

[13] Sienicki J., Wade D., Tzanos C., 2003. Thermal Hydraulic Research and Development Needs for Lead Fast Reactors. IAEA Tecdoc 1520, Theoretical and Experimental Studies of Heavy Liquid Metal Thermal Hydraulics, Karlsruhe, Germany.

[14] Li N., 2008. Lead-alloy Coolant Technology and Materials - Technology Readiness Level Evaluation. Progress in Nuclear Energy, vol. 50, p.p. 140-151.

[15] Todreas N., 2007. Thermal Hydraulic Challenges in Fast Reactor Design. NURETH12, Pittsburgh, USA.

[16] Ferziger J.H., Peric M., 2004. Computational Methods for Fluid Dynamics. Springer-Verlag, 3rd ed.

[17] Temam R., 2001. Navier-Stokes Equations: Theory and Numerical Analysis. American Mathematical Society, AMS Bookstore, ISBN 0821827375, 9780821827376.

[18] Pope S.B., 2000. Turbulent Flows. Cornell University, New York (ISBN-13: 9780521598866 | ISBN-10: 0521598869)

[19] Chen C.J. & Jaw S.Y., 1997. Fundamentals of Turbulence Modelling. Taylor & Francis Group.

[20] Hanjalic K., 2005. Will RANS Survive LES? A View of Perspectives. J. Fluids Eng. Volume 127, Issue 5, 831

[21] Sagaut P., 2006. Large Eddy Simulation for Incompressible Flows - An Introduction. Scientific Computation. 3rd ed., ISBN: 978-3-540-26344-9.

[22] Spalart P.R., Jou W.-H., Stretlets M., Allmaras S. R., 1997. Comments on the Feasibility of LES for Wings and on the Hybrid RANS/LES Approach. Advances in DNS/LES. First AFOSR International Conference on DNS/LES.

[23] OECD/NEA, 2007. Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies. OECD NEA No. 6195, ISBN 978-92-64-99002-9

[24] Grötzbach G.,2007. Anisotropy and Buoyancy in Nuclear Turbulent Heat Transfer – Critical Assessment and Needs for Modelling. FZKA 7363, Karlsruhe, Germany.

[25] Arien B. Et al., 2004. Assessment of Computational Fluid Dynamic codes for Heavy Liquid Metals – ASCHLIM. EC-Con. FIKW-CT-2001-80121-Final Rep.

[26] Grötzbach G., 2003. Turbulence Modelling Issues in ADS Thermal and Hydraulic Analyses. IAEA Technical Meeting on Theoretical and Experimental Studies of Heavy Liquid Metal Thermal Hydraulics, Karlsruhe, Germany.

[27] Rohde, M., Marcel C.P., T'Joen C., Class A.G., Van der Hagen T. H. J. J., 2011. Downscaling a Supercritical Water Loop for Experimental Studies on System Stability. International Journal of Heat and Mass Transfer, vol. 54: p.p. 65-74.

[28] T'Joen, C; Rohde,M, 2011. Experimental study on natural circulation driven HPLWR, ISSCWR 5, Vancouver, Canada

[29] T'Joen, C; Rohde, M; Visser, DC; Lycklama a Nijeholt, JA; Roelofs, F; Van Der Hagen, THJJ, 2010. Preliminary natural circulation data of a scaled HPLWR experiment. IAEA Technical meeting on heat transfer, thermal-hydraulics and system design for supercritical pressure water cooled reactors, Pisa, Italy.

[30] Kenjeres S., Hanjalic K., 2000. Convective Rolls and Heat Transfer in Finite-length Rayleigh-Bernard Convection: A Two-dimensional Numerical Study. Physical Review E, Vol 62., N. 6.

[31] De Rosa M., Guetta G., Ambrosini W., Forgione N., He S., Jackson J.D., 2011. Lessons Learned from the Application of CFD Models in the Prediction of Heat Transfer to Fluids at Supercritical Pressure. ISSCWR-5, Vancouver, Canada.

[32] Craft T.J., Gerasimov A., Iacovides H., Launder B.E., 2002. Progress in Generalization of Wall-function Treatments. International Journal of Heat and Fluid Flow, vol. 23, p.p.148-16.

[33] Otic I., 2009. Numerical Modeling of Buoyant Turbulent Mixing at High Density Ratio. Trans. of the American Nucl. Soc., USA.

[34] Hannink M., Kuczaj A., Blom F., Church J., Komen E., 2008. A Coupled CFD-FEM Strategy to Predict Thermal Fatigue in Mixing Tees of Nuclear Reactors. Eurosafe, Paris, France.

[35] Dahlberg M., et al., 2007. Development of a European Procedure for Assessment of High Cycle Thermal Fatigue in Light Water Reactors: Final Report of the NESC-Thermal Fatigue Project. European Commission Institute for Energy, EUR 22763 EN, Petten, Netherlands.

[36] Prasser H.-M., Damsohn M., Fokken J., Frey S., 2009. Novel Fluid Dynamic Instrumentation for Mixing Studies Developed at ETH Zurich and PSI. NURETH13, Kanazawa, Japan.

[37] Schulenberg T., Starflinger J., Heinecke J., 2006. Three-pass Core Design Proposal for a High Performance Light Water Reactor. COE-INES-2, Yokohama, Japan.