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Status and perspective of turbulence heat transfer modelling for the industrial application of liquid metal flows

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HIGHLIGHTS

- Thermal-hydraulics is key safety factor for development of liquid metal cooled fast reactors.
- Commonly used Reynolds analogy is not applicable.
- Robust engineering models needed for modelling turbulent heat flux in all flow regimes.
- Promising routes are described.
- AHFM models seem to be most promising to be applied simultaneously in all flow regimes.

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ABSTRACT

Liquid metal cooled reactors are envisaged to play an important role in the future of nuclear energy production because of their possibility to use natural resources efficiently and to reduce the volume and lifetime of nuclear waste. Typically, sodium and lead(-alloys) are envisaged as coolants for such reactors. Obviously, in the development of these reactors, thermal-hydraulics is recognized as a key (safety) challenge. A fundamental issue to this respect is the modelling of turbulent heat flux over the complete range from natural, mixed and convection to forced convection regimes. Current engineering tools apply statistical turbulence closures and adopt the concept of the turbulent Prandtl number based on the Reynolds analogy. This analogy is valid mainly for forced convective flows with Prandtl number of order of unity. In the particular case of liquid metal, where the Prandtl number is less than 1, the turbulent Prandtl number concept is not applicable and robust engineering turbulence models are needed. Thus, a model is required which can deal with all flow regimes simultaneously in liquid metal flows. In the framework of the European project THINS (thermal-hydraulics for innovative nuclear systems), some promising routes for improvements have been identified and are currently under evaluation.

1. Introduction

The civil utilization of nuclear energy of more than five decades shows significant advantages of nuclear power in respect of environment protection, 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 the World Energy Outlook (2012). On a global scale, the accident at the Fukushima Daiichi nuclear power plant in Japan in March 2011 did have a minor effect on the future demand for nuclear power. Therefore, nuclear energy is on the agenda worldwide. Apart from the widely used light water reactors, a significant role is attributed to the deployment of fast reactors (IAEA, 2012). In most countries, the preferred option is the

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sodium cooled fast reactor with the lead cooled fast reactor and the gas cooled fast reactor as back-up systems from the systems selected by the Generation IV International Forum (GIF, 2002).

IAEA (2012) shows that over the years, more than 20 liquid metal cooled reactors have been operated around the world. Currently, a few liquid metal cooled reactors are operational. The BN-600 sodium cooled power reactor is successfully operated in Russia. Additionally, Russia, China and India operate the BOR-60, CEFR and the FBTR sodium cooled research reactors. Additionally, new liquid metal cooled reactors are under construction or are being planned. India is close to finishing the construction of the sodium cooled PFBR power reactor, whereas Russia is close to finishing construction of the sodium cooled BN-800 power reactor. For an elaborate overview of the status of fast reactor development the reader is referred to the technical report about the status of fast reactors made by the IAEA (2012).

Thermal-hydraulics is recognized as one of the key scientific subjects in the design and construction of liquid metal cooled reactors. To solve thermal-hydraulic issues, nuclear engineers apply analytical and empirical correlations, system thermal hydraulics (STH) codes, or subchannel codes. Additionally, computational fluid dynamics (CFD) techniques are becoming more and more integrated in the daily practice of the thermal-hydraulics researchers and designers.

The Prandtl number (Pr) of liquid metals is very low, i.e. of the order of 0.01–0.001 at operating conditions. Nuclear heat transfer applications with low-Prandtl number fluids are often in the transition range between conduction and convection dominated flow regimes. Most flows in reactors involve also anisotropic turbulent fluxes and strong buoyancy influences. Stieglitz and Schulenberg (2010) show that the possibilities for detailed measurement of local flow parameters in liquid metal cooled reactor components are challenging. From a fundamental research point of view the measuring capabilities to get data for more detailed physical modelling are limited. Therefore, numerical simulation and modelling of basic and prototypic flow configurations are more important for low Prandtl number fluids than usual for the analyses of the relevant physical phenomena and model development.

Grötzbach (2011) explains that turbulent heat transfer is an extremely complex phenomenon and has challenged turbulence modellers for various decades. The first challenge is related to its intrinsic coupling to the characteristics of turbulence which therefore requires, as a fundamental block, the ability to accurately model the momentum transport. Such a requirement is not trivial to fulfil for complex flows and has often hindered the ability to evaluate approaches for modelling the turbulent heat fluxes. Model developers have mostly assumed that turbulent heat transfer may be predicted from the knowledge of momentum transfer, in what is known as the Reynolds Analogy. This assumption has successfully been adopted for the last two decades in many industrial applications of CFD which are based on eddy diffusivity models (EDM). This success is justified because for fluids with a Prandtl number close to unity, this approach has provided reasonable predictions of global parameters such as Nusselt numbers and mean temperature distributions as shown by Baglietto (2011). For low Prandtl number fluids, the limitations of the eddy diffusivity approach have become evident, particularly for natural and mixed convection flows, as underlined for example by the Arien et al. (2004), OECD/NEA (2007), and by Grötzbach (2011) which provides a comprehensive review of the topic.

The limitations of the eddy diffusivity models are illustrated by Fig. 1. This figure shows the different heat transport behaviour of a liquid metal compared to a fluid like air. Direct numerical simulations (DNS) of a rectangular channel flow in which turbulence behaviour is calculated using the laws of physics instead of approximated by turbulence models clearly show a different behaviour of liquid metals. The typical high thermal conductivity of liquid metals leads to a large thermal boundary layer compared to the boundary layer which is typically of the same size as the momentum boundary layer for fluids like air and water.

Engineers have recognized this issue, and applied work-around approaches in the past, or dealt with the consequences of the limitations in the modelling. One of the work-around approaches is reported by Wolters et al. (2003). They report about the model validation for heat transfer to liquid mercury. It was concluded, that wall-functions could be used. However, using only the logarithmic thermal law-of-the-wall led to an overestimation of the wall temperatures even for a fine mesh. They report that this problem could be overcome by an implementation of a modified wall function. Komen et al. (2005) reveal that this modified wall function replaces the standard wall function for temperature by a wall function describing molecular conduction only as reported by Wolters (2002). Consequently, it was required to have the non-dimensional distance to the wall (y^+) smaller than about 60. On the other hand, the wall function for momentum requires that y^+ is larger than about 30. This leads to the strict requirement that the applied mesh should be refined near the walls such that the non-dimensional distance y^+ is located between 30 and 60. It is clear that this requirement poses many challenges to mesh creation. And moreover, different requirements are found for different low Prandtl number fluids.

Besides such work-around approaches, engineers and researchers have been attempting to close the modelling gap. It should be noted that a limited but growing number of momentum transfer models are available in most of the commercial codes and not a single turbulent heat transfer model, except for the turbulent Prandtl number concept applying the Reynolds analogy between the momentum and thermal field as described by Roelofs et al. (2013). Although, most code users are aware of this problem, they are restricted to the constant default value given in the code. Besides that, in most models the anisotropic eddy conductivity tensor is replaced by an isotropic scalar one. This means that each heat flux component is governed by the same unknown eddy conductivity. The simplest model among the first order models which apply isotropic eddy conductivities is a modified Prandtl mixing length approach in which a thermal length scale is introduced which depends on wall distance and molecular Prandtl number. However, from an academic point of view, second order models would improve largely the modelling capabilities with respect to such flows, with anisotropic turbulent heat transfer and counter-gradient heat fluxes as demonstrated by Grötzbach (2011). These models use transport equations for the turbulent heat fluxes. It was expected in the past that such second order models should be more universal than the first order models. However, introducing closure assumptions on this level remains a real challenge. Therefore, the expected level of universality seems not yet to be achieved. Algebraic heat flux models (AHFM) form a class of models between first and second order modelling as outlined by Grötzbach (2011). Many of such models have been developed and proposed over time, e.g. by Craft (1991), Hanjalic and Kenjeres (1995), Kenjeres et al. (1997, 2005), Kenjeres (1998), Kenjeres and Hanjalic (2000), Parneix et al. (2000), Hanjalic and Dol (2001), Gunarjo (2003), and Uapipatanakul et al. (2010). They are deduced by starting from the full second order transport equations for the heat fluxes.

In a typical liquid metal cooled fast reactor (LMFR), the liquid metal flow may cover all flow regimes, from natural via mixed to forced convection. Therefore, the ultimate goal of a new engineering model should be to provide reasonable results in all flow regimes. The purpose of the current paper is to describe the status and the future perspectives of the different state-of-the-art approaches taken to improve the modelling of heat transfer to