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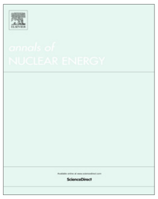

Capabilities of high y^+ wall approaches in predicting heat transfer to supercritical fluids in rod bundle geometries

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ABSTRACT

The present paper summarises the results of the simulation of heat transfer to supercritical water in rod-bundle geometries by a CFD code, using wall function models. Two different sets of experimental data were considered, concerning both relatively high and low mass flux conditions and inlet temperature spanning from low to near-critical values.

In past analyses, the unsuitability of low-Reynolds number turbulence models was observed in predicting heat transfer in rod bundles, when both high mass and heat flux values were imposed; in fact, large overestimations of wall temperatures were reported in such conditions. This motivated to try simpler models, such as the wall function approach, in order to investigate if, though expectedly not very accurate, they could at least reproduce the experimental data at an acceptable level.

As reported in the present paper, the selected models, which adopt a "high y^+" wall treatment (indicating wall functions in the STAR-CCM+ code), seem reasonably able at reproducing the general observed experimental trends. The present understanding of the phenomena and the available modelling techniques unfortunately do not allow obtaining better results when the wall or fluid temperature approach the pseudocritical value. However, the comparison with results obtained by low-Reynolds models shows that, at least when facing operating conditions similar to the ones considered in the present work, a downgrading of the adopted modelling techniques may be beneficial and allows obtaining reasonable results. Analyses were also performed considering conditions far from the pseudo-critical temperature, in which low-Reynolds models had provided good performance, reporting that the wall function approach seems effective also in these cases for obtaining first guess results.

1. Introduction

During the last years, several studies on heat transfer to supercritical fluids have been performed at the University of Pisa (Sharabi, 2008; Sharabi and Ambrosini, 2009; De Rosa, 2010; Badiali, 2011; Pucciarelli, 2013; Borroni, 2014; Pucciarelli et al., 2015, 2016; Pucciarelli and Ambrosini, 2017, 2018; Pucciarelli, 2017; Brogna, 2017) with the aim of contributing to the international effort (Schulenberg and Starflinger, 2012; Ruzickova et al., 2014; Rohde et al., 2016; Kiss et al., 2018) for the development of the Generation IV Supercritical Water Cooled Reactor (SCWR).

The first works mainly concerned studies on heat transfer in simple geometries, such as circular and annular ducts, with the main objective of understanding the most relevant involved phenomena and trying to implement new features in the currently available turbulence models. In particular, as highlighted by Jackson and Hall (1979a, 1979b) buoyancy effects may play a relevant role in defining the heat transfer characteristics, as both improved and deteriorated heat transfer may be induced. These phenomena often occur in the vicinity of the wall and, when performing numerical simulations, mesh refinements and "low-y^+" wall approaches (i.e., low Reynolds number models) are consequently often considered.

Together with these techniques, four-equation models were also adopted for the purpose of modelling the turbulent heat flux as a relevant contribution both for the definition of the buoyancy production term (Zhang, et al., 2012) and for a possibly more accurate estimations of the turbulent Prandtl number (Pucciarelli and Ambrosini, 2017). In particular, Pucciarelli and Ambrosini (2017) reported promising improvements by the use of algebraic heat flux models (AHFM) in the prediction of heat transfer to supercritical pressure fluids for different flow and boundary conditions. The

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introduction of AHFM as a valuable tool for the calculation of the turbulent heat flux contribution really improved the prediction of Low-Reynolds k-ε turbulence models, mitigating the too strong heat transfer deterioration phenomena that are usually predicted by these methods. Nevertheless, inaccuracies were observed to become larger as both heat and mass flux increased, approaching the conditions envisaged for the reactor core of the SCWRs (Schulenberg and Starflinger, 2012). At present the developed model is suitable for 2D geometries only, making it unsuitable for rod bundle analyses which require a 3D modelling. The capability of predicting heat transfer when dealing with high thermal load conditions is very important for the development of SCWRs, as large heat and mass fluxes are envisaged for the design conditions (Schulenberg and Starflinger, 2012): unfortunately, two-equation low-Re turbulence models seem not able at dealing with these challenging conditions.

In literature, only few studies concerning the numerical analysis of heat transfer to supercritical fluids flowing through rod bundles are presently available; nevertheless, some general suggestion on the present modelling capabilities may be drawn. Xiong et at. (2015) and Pucciarelli and Ambrosini, (2016) performed CFD calculations adopting as reference the experimental data by Zhao et al. (2013); several turbulence models were adopted and large wall temperature overestimations were in general observed when dealing with sufficiently high heat flux values. For cases dealing with lower thermal loads and far from the pseudo-critical temperature (see, e.g., Rohde et al., 2016), low-Reynolds number turbulence models reported instead good predicting capabilities in accordance with the experience gained from the analysis of heat transfer in pipe geometries.

In addition, the effect of the spacer grids on heat transfer phenomena was also observed, suggesting that they may both impair and improve the heat transfer conditions. Zhu et al. (2014) analysed the effect of two different spacer grid configurations on the fluid flow; in particular, improvements were observed in correspondence of the spacer grids, though heat transfer impairments occur in the downstream region, thus possibly posing problems relevant to reactor safety. Podila and Rao (2016) investigated instead the effect of wire wrapped spacers resulting in a general improvement of turbulence and heat transfer conditions.

The present paper addresses experimental data obtained for rod bundle geometries mostly in heavily thermally loaded conditions. Considering the unsatisfactory results obtained by low-Re turbulence models in such cases, the capabilities of simpler approaches, such as the ones adopting wall functions, are investigated in order to assess whether they can provide acceptable predictions. Though a wall function approach represents a downgraded model in comparison to the low-Re turbulence models, it provides limited values of wall temperatures, being rather insensitive to heat transfer deterioration, possibly improving the comparison with experimental data.

As a consequence, the present paper suggests that, since a sufficiently reliable turbulence model for challenging operating conditions is still missing, considering a wall function approach could be a good compromise for obtaining results which can mimic the experimental data at a lower computational cost. This paper obviously is not claiming that wall functions represent the best modelling technique, as its shortcomings are well known and observed in the available literature; as an example, they seem not to be able at predicting buoyancy induced phenomena. Our main aim is therefore highlighting the need for identifying models providing at least acceptable results while waiting that more successful techniques, as those assessed in 2D cylindrical geometries (e.g., AHFM) can be adapted also for the complex geometries involved in rod bundle analyses.

2. Considered experimental data sets and modelling assumptions

The experimental conditions investigated by Razumovskiy et al. (2016, 2017) were considered as the main source of data for the present work, owing to the inclusion in a presently running coordinate research project of IAEA of some of these data. The test section consists of a pressure tube containing three directly heated elements, positioned on the vertices of equilateral triangles: each rod consists of a thin steel pipe equipped with four helical ribs wound around it having a 400 mm pitch. In addition, seven thin fins (0.1 mm thick) are welded to the cylindrical surface at seven axial positions along the rods in order to mechanically support the system. The cross section of the described apparatus is reported in Fig. 1; its heated length is 485 mm.

The geometry considered in the performed calculations coincide with the real one except for two changes: the helical ribs were slightly reshaped (as shown in Fig. 2), in order to obtain a better nodalization by avoiding sharp angles, and the thin fins were simply disregarded, assuming that their contribution to the fluid flow is local and mostly negligible. Different nodalizations in terms of wall refinement were adopted to fit with the various considered modelling techniques; they include 1–10 boundary (or prism) layer nodes for the low-Re and high y^+ approaches respectively. A particular of the reshaped helical ribs for the numerical mesh with 10 boundary layers is reported in Fig. 2.

In order to enlarge the panorama of operating conditions for rod bundle cases, a second experimental set, also considered by Pucciarelli and Ambrosini (2016) for their numerical calculations with low Reynolds number models, was also addressed. Fig. 3 shows a sketch of the facility test section operated by JAEA, including a directly heated 7-rod bundle (as described in the benchmark problem description proposed by Rohde et al., 2016). Five spacer grids

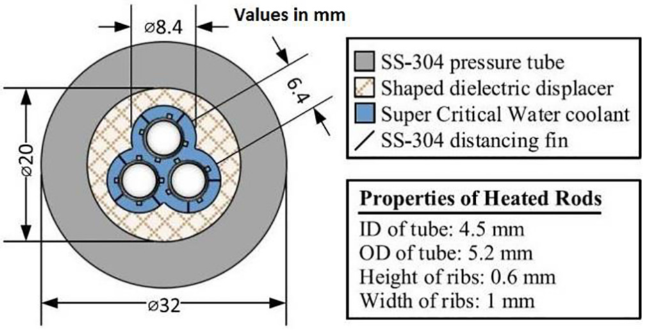

Fig. 1. Radial cross section of a 3-rod bundle (Razumovskiy et al., 2016).

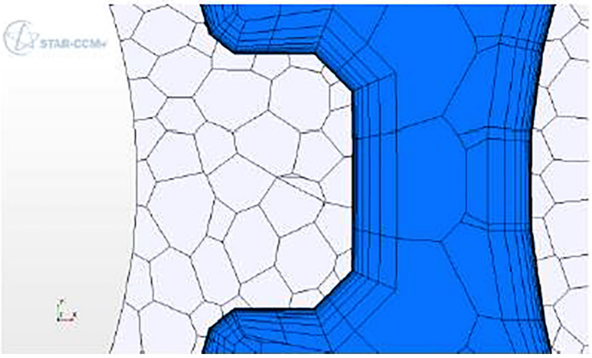

Fig. 2. Particular of the numerical mesh with 10 boundary layers.