Annals of Nuclear Energy 111 (2018) 340–346

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

On the effect of conjugate heat transfer on turbulence in supercritical fluids: Results from a LES application

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ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 11 September 2017
Accepted 13 September 2017
Available online 21 September 2017

ABSTRACT

The present paper reports the results obtained from Large Eddy Simulation (LES) analyses concerning the effect of conjugate heat transfer with walls when dealing with heat transfer to supercritical pressure fluids. A specific operating condition was investigated with and without walls showing a clearly understandable effect on turbulence of the actual characteristics of the wall, something further complicating turbulence modelling, already quite difficult in this field.

Unlike the experience of past studies, which considered conjugate heat transfer by LES or DNS when dealing with constant property fluids, and resulted in a limited influence on the observed phenomena, in the present work relevant effects are instead identified. In fact, in the case of supercritical pressure fluids, the strong changes in fluid properties close to the pseudo-critical threshold may provide a strong feedback on the velocity field and then on turbulence; in particular, the presence of a wall with realistic properties strongly damps the large temperature and fluid properties fluctuations obtained when imposing a constant heat flux.

Consequently, unlike fluids in standard conditions, heat transfer to supercritical fluids seems to be depending on the actual fluid-and-wall coupling, thus adding a further challenging aspect in this already complicated topic. Though further analyses are underway for confirming the observed behaviour, the presented findings related to a simple example open new scenarios in the development of heat transfer correlations and CFD models to be used for supercritical fluids. In fact, the available data, both experimental and by DNS, can no more be considered independent from the imposed boundary conditions at the wall and the effect of the wall properties should be seriously taken into account.

1. Introduction

Heat transfer to supercritical fluids is a relevant topic in several fields ranging from chemical plants to nuclear power engineering. Nowadays, no generally accepted method exists for predicting, with both sufficient accuracy and large applicability, the involved complicated phenomena occurring when dealing with heat transfer to supercritical fluids, in particular when heat transfer deterioration or enhancement occur. These conditions affecting heat transfer may be due to both buoyancy and property variation, which mainly occur when working in conditions close to the so called pseudo-critical temperature. In addition, a threshold behaviour for the onset of deterioration has been observed in the frame of past works both from the experimental (see e.g., Fewster, 1976) and the computational point of view (Pucciarelli and Ambrosini, 2017) making the prediction of the addressed phenomena even harder. In fact, ranges of boundary conditions exist in which even little changes in the imposed values may considerably affect the observed wall temperature trend.

In this context, several works have been performed in order to try mitigating the observed inaccuracies adopting different techniques, going from the development of heat transfer correlations (Pioro and Duffey, 2007; Mokry, 2011; Jackson, 2014) to computational fluid dynamics analyses adopting RANS (Palko and Anglart, 2008; He et al., 2008; Sharabi and Ambrosini, 2009), LES (Ničeno and Sharabi, 2013) and DNS (Bae et al., 2005; Wang and He, 2015) approaches. Concerning RANS analyses, the research performed at Pisa University has actively contributed to understanding the capabilities of the available turbulence models and to develop new techniques capable of performing better predictions (Sharabi, 2008; De Rosa, 2010; Badiali, 2011; Pucciarelli, 2013; Borroni, 2014) with the aim of paving the way for the development of the Generation IV Supercritical Water-Cooled Reactor (SCWR).

In this frame, the assessment of the Algebraic Heat Flux Model (AHFM) in the prediction of the turbulent heat flux, both in the production term of turbulence due to buoyancy and in the energy

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http://dx.doi.org/10.1016/j.anucene.2017.09.020
0306-4549/

equation as a valid alternative to the commonly adopted Simple Gradient Diffusion Hypothesis (SGDH) provided promising results (Pucciarelli et al., 2015, 2016; Pucciarelli and Ambrosini, 2017). In particular, this approach led these authors to consider more accurately the actual near-wall fluid conditions, since the phenomena occurring in this region considerably affect the observed behaviour.

In particular, both the actual wall and bulk temperature values, whenever higher than the pseudo-critical threshold, and the temperature fluctuations turned out to have a relevant role in defining the predicted heat transfer capabilities. With the aim to better understand the observed phenomena and to provide improved modelling and tuning of the developed RANS turbulence models, LES analyses have been performed and are here presented, focusing on the effect of the heating structures. In fact, resolved turbulence analyses (by both LES and DNS), which are not yet applicable to engineering analyses owing to the huge demand in computational resources, are used to contribute in refining the RANS turbulent models, which are applicable to real life plant equipment. In this regard, running resolved calculations with imposed heat flux at the wall or with conjugate heat transfer may provide different results when the fluid properties are considerably changing with temperature. This is due to the high level of temperature fluctuations observed at the wall with imposed heat flux, with respect to the much smaller oscillations obtained when the wall is taken into account, considering its actual heat capacity.

In the available literature, previous studies do exist on this topic (Sommer et al., 1994; Tiselj et al., 2001, 2013; Tiselj and Cizelj, 2012); nevertheless, fluids with constant properties were mainly investigated and the results reported only limited effects on the turbulent structures and even smaller consequences on the heat transfer capabilities. On the other hand, supercritical fluids report strong properties variations; large temperature fluctuations occurring in the near wall region at imposed heat flux may consequently imply, for instance, large density fluctuations, which affect both the velocity and the thermal fields. As a consequence, heat transfer deterioration may occur to be stronger or milder because of the changed turbulence conditions. On the basis of the results presented herein, it is shown that consideration of the heating walls when performing resolved calculations considerably contributes at reducing the observed temperature fluctuations at the wall, thus sensibly influencing the obtained results.

This result opens a new scenario in the development of suitable models for heat transfer to supercritical fluids, suggesting that the experimentally observed behaviour may be strongly influenced by the fluid-and-wall coupling, adding further degrees of freedom to the already complicated heat transfer phenomena concerning heat transfer to supercritical fluids. Though no comparison with experimental data is provided in this paper, owing to the simplicity of the addressed problem, consequent to the usual need to limit computational resources, the obtained results are clearly showing the effect of conjugate heat transfer, suggesting the need to include its effect in resolved calculations aiming to provide data for RANS model improvement.

2. Adopted model and imposed boundary conditions

The calculations reported in this work were performed adopting the commercial code STAR-CCM+ (CD-adapco, 2015) and were subsequently post-processed with MATLAB R2016a. The considered operating conditions concern water flowing in a plane channel at the supercritical pressure of 25 MPa, being a commonly envisaged operating pressure level for the future SCWR nuclear reactors. The inlet temperature was chosen to be close to the pseudo-critical threshold, in order to make likely to occur heat transfer deterioration phenomena. For the same reason, upward flow was selected since buoyancy induced heat transfer deterioration phenomena typically occur in these conditions. Table 1 reports the imposed boundary conditions for a channel being 7 cm long.

Two cases were addressed, the former considering conjugate heat transfer simulating the presence of a 1 mm thick steel wall and the latter neglecting it, in order to investigate the effect of the solid wall on the observed turbulence and heat transfer conditions. Conjugate heat transfer is obtained by solving the heat transfer equations of conduction in the wall and imposing the equality of the heat flux at the surface for conduction and convection in the fluid. The fluid properties were calculated adopting the NIST database (NIST, 2002); constant properties were instead considered for the heating wall. In particular, the default properties for stainless steel available in the adopted STAR-CCM+ code (CD-adapco, 2015) were adopted.

Fig. 1 shows the considered geometry for the case of conjugate heat transfer. This simple channel flow was selected as a suitable approximation of pipe flow; periodic boundary conditions were imposed on the lateral faces in order to simulate the presence of an infinitely broad flow, while a symmetry condition was instead imposed on the surface of the domain parallel to the heated one and far enough from it. Unlike similar applications for LES and DNS, the recirculating region often positioned just before the entrance of the heated section was disregarded; this was needed because of the selected low inlet Reynolds number (Re = 3868), which resulted in turbulence not to be sustained in the recirculating region: in fact, after a few cycles through the channel, the flow was again returning to laminar. As a consequence, a 1 cm long unheated entry length was imposed; the heated length is instead 6 cm long. Obviously, no conduction trough the wall is allowed in the unheated region for the case considering the steel wall, in order to obtain as far as possible similar conditions at the start of the heated length for the two addressed cases.

Turbulence conditions were assured adopting the Synthetic Turbulence Specification tool provided by the code, which allows generating turbulent property profiles while fixing some selected settings. In particular, suitable values for the turbulence intensity and turbulent length scale were imposed at the inlet section; an inlet radial profile for the mean axial velocity suitable for the selected Reynolds range was selected as well. In this regard, it must be mentioned that the focus of the paper is in comparing the results obtained with and without conjugate heat transfer at a same level of inlet turbulent conditions. The specific level of inlet turbulence is therefore just parametrical; several calculations can be performed by varying the turbulence levels and the boundary conditions at the inlet of the duct and assessing the effect of conjugate heat transfer on turbulent fields. For the present discussion, it is just needed to show that the obtained results are different with and without conjugate heat transfer in a specific representative case, showing that this effect cannot be neglected.

The adopted mesh for the fluid region consists in a $1400 \times 61 \times 40$ cells in the axial, normal to the wall and spanwise directions, respectively; the size of the cells is uniform in the axial and spanwise directions, while a progressive refinement is adopted in the direction orthogonal to the wall, in the vicinity of the wall itself. Additional $1400 \times 40 \times 40$ cells were instead included in the wall, with sizes similar to the ones of the fluid region.

By imposing these settings, suitable values in terms of wall units were obtained in the fluid; the related information is reported in Table 2.

Regarding the subgrid model, the WALE model (Nicoud and Ducros, 1999) was adopted, being available in the commercial code STAR-CCM+. A 0.001 s time step was adopted, considering that it