International Journal of Heat and Mass Transfer 127 (2018) 1138–1146

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Use of AHFM for simulating heat transfer to supercritical fluids: Application to carbon dioxide data

A. Pucciarelli *, W. Ambrosini

Università di Pisa, Dipartimento di Ingegneria Civile e Industriale, Largo Lucio Lazzarino 2, 56126 Pisa, Italy

ARTICLE INFO

Article history:
Received 10 April 2018
Received in revised form 19 July 2018
Accepted 24 July 2018

Keywords:
Supercritical fluids
Heat transfer
Deterioration
CFD
AHFM

ABSTRACT

The present paper reports the results of analyses concerning heat transfer to supercritical pressure fluids, performed by adopting a $k-\varepsilon$ turbulence model modified in association with the AHFM model, here used for calculating both buoyancy effects and the turbulent heat flux. The promising capabilities of this approach were already highlighted in past studies and the present paper represents a further step in this line of research.

Experimental data concerning supercritical carbon dioxide flowing in tubes are here considered, with operating conditions involving both high and low mass flux values and spanning from relatively low inlet temperatures to values higher than the pseudocritical threshold. Some of the interesting features appearing in the experimental data are correctly reproduced by the model, which manages to predict reliable wall temperature trends, both qualitatively and quantitatively.

The performed analyses, though reporting successes in a sufficiently wide range of operating conditions, suggest that some parameters of the proposed model should be varied in accordance with the boundary conditions, e.g. considering the mass flux, in order to improve predictions in the most challenging situations.

1. Introduction

The present paper is part of a line of research started more than a decade ago with the aim of preparing the development of the Generation IV Supercritical Water-Cooled Reactor (SCWR). Together with design simplifications, this concept should also grant higher plant efficiencies, up to 45%, thus reducing both capital and operating costs in comparison to the presently available PWRs and BWRs [27]. In this frame, critical bottlenecks in the development of the SCWR are represented by the need for better performing materials and a better understanding of the thermal and fluid dynamic phenomena both involving deteriorated and improved heat transfer regimes.

Recent works concerned the implementation of the Algebraic Heat Flux Model (AHFM) in presently available turbulence models, as a useful tool for the prediction of buoyancy effects and for a better estimate of the turbulent heat flux; in particular, following the example of Zhang et al. [26], the AHFM was adopted for the prediction of both the production and the dissipation terms in the turbulent kinetic energy equation [17,3,18]. In later studies, [19,22,21], the AHFM model was also adopted as a basis for obtaining a better estimate of the turbulent Prandtl number with the aim of improving the predictive capabilities of the available turbulence models in the challenging conditions in which the wall temperature crosses the pseudo-critical threshold. One of the most relevant problems reported by k-ε turbulence models is in fact the prediction of strong wall temperature overestimates when the pseudo-critical temperature is exceeded by the fluid in the vicinity of the wall; the introduction of the AHFM allowed for obtaining more reliable predictions in a sufficiently wide range of operating conditions. In particular, many data sets, considering different fluids at supercritical pressure such as water, carbon dioxide and Refrigerant R23 were adopted for the first validations of the model, providing promising results; problems were instead encountered for operating conditions considering both high mass and high heat flux values often resulting in the prediction of unrealistically high wall temperature peaks.

A further step is here made dealing with the data by Kline [8], which report interesting thermal and fluid-dynamic behaviours and allow performing revealing sensitivity analyses. The model developed step-by-step in previous works [20,23]. Pucciarelli [21] was applied and updated in order to better cope with the presently considered experimental data, still maintaining good capabilities for the range of data addressed in past studies.

* Corresponding author.
E-mail address: andrea.pucciarelli@yahoo.it (A. Pucciarelli).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.125
0017-9310/

Nomenclature

Roman letters

C_t, C_{t1}, C_{t2}, C_{t3}, C_{t4}	constants of the AHFM model (–)
c_p	specific heat (J/kg K)
g	gravity (m/s^2)
G	mass flux (kg/m^2 s)
ID	inner diameter (m)
h	specific enthalpy (J/kg)
h^*	dimensionless specific enthalpy (–)
Pr_t	turbulent Prandtl number (–)
q''	heat flux (W/m^2)
t	time (s)
$\overline{t'^2}$	temperature variance (°C^2)
T	temperature (°C)
T_{in}	inlet temperature (°C)
T_{pc}	Pseudo-critical temperature (°C)
u	velocity (m/s)
v	radial velocity (m/s)
x	axial position (m)
y+	dimensionless distance from the wall (–)

Greek letters

β	isobaric thermal expansion coefficient (1/K)
ε	turbulent dissipation rate (m^2/s^3)
ε_t	dissipation rate of $\overline{t'^2}$ (K^2/s)
k	turbulent kinetic energy (m^2/s^2)
ν_t	eddy viscosity (m^2/s)

Subscripts

pc	pseudo-critical temperature
w	wall

Abbreviations

AHFM	Algebraic Heat Flux Model
SCWR	Supercritical Water-Cooled Reactor

In addition, the idea that at least an additional parameter of the model should be connected to the operating conditions is here suggested. The analyses proved that a single set of parameters is not sufficient for dealing with the considered breadth of operating conditions involved in practical applications to heat transfer to supercritical fluids; the use of parameters changing in accordance with the operating conditions or the definition of different sets of parameters depending on the imposed boundary conditions seems at the moment the most promising path. In this frame, a classification of the heat transfer phenomena that can be observed depending on the operating conditions is consequently required; different examples, such as the work by Kurganov et al. [10], are presently available in literature and should be considered as a reference for the development of turbulence models whose focus is to reproduce a specified range of heat transfer phenomena.

2. Adopted model

2.1. Aim of this new modelling step

In the present paper, it is tried to consolidate the results obtained in previous works [20,23], by adopting the Lien $k-\varepsilon$ turbulence model [12] in association with the Algebraic Heat Flux Model (AHFM). The latter is used for the purposes of calculating the buoyancy contributions in $k-\varepsilon$ equations and of achieving an improved estimate of the turbulent heat flux. In particular, a formulation based on the use of the turbulent Prandtl number is adopted in the energy equation, as it is the simplest way to implement this methodology in the adopted STAR-CCM+ commercial code [4]. The AHFM is used for a dynamic estimate of the turbulent Prandtl number, being updated at each iteration depending on the local conditions.

The model adopted in the present paper is the same used in a previous work [22]. However, the value of the empirical constants appearing in it (see e.g. Eq. (1)) are further discussed in front of a broader basis of data than considered in the past, including those from the experiments by Kline [8]. It is in fact necessary to clarify that the approximations introduced in the AHFM formulation lead to a number of constants whose value is uncertain and can be properly defined only by adapting them within reasonable ranges by the comparison with experiments. In previous work, data by Watts [24], Pis'menny et al. [15,16], Fewster [5] and Ornatsky and Glushchenko [14] were already considered, addressing both water and carbon dioxide. The very systematic data collected by Kline [8] presently offer a unique occasion for a further step in this regard.

2.2. Reminder of model structure

A brief overview of the adopted model is here reported; further details can be found in Pucciarelli and Ambrosini [22].

The following Eq. (1) defines the turbulent heat flux in the formulation of the AHFM proposed by Zhang et al. [26] in their work:

$$\overline{u_i't'} = -C_t\frac{\kappa}{\varepsilon}\left[C_{t1}\overline{u_i'u_j'}\frac{\partial T}{\partial x_j} + (1-\ C_{t2})\overline{u_j't'}\frac{\partial \bar{u}_i}{\partial x_j} + (1-\ C_{t3})\beta g_i\overline{t'^2}\right] \quad (1)$$

This expression, introduced by Launder [11] as a convenient approximation of the turbulence heat flux, was drawn for the sake of simplicity and effectiveness from the related transient transport equation and was later adopted and discussed by different Authors [6,26,23]. The particular form of Zhang et al. [26] is here adopted, because these Authors applied it to supercritical fluids, thus providing the main inspiration for our works in this field.

Since the temperature variance appears in Eq. (1), a set of two further equations for this quantity and its dissipation rate are required, thus increasing the computational cost of the simulation. Actually, in the model adopted here and in previous work by Pucciarelli et al. [19] and Pucciarelli and Ambrosini [22], only the scalar $\overline{t'^2}$ is modeled using a dedicated transport equation, while its dissipation rate, ε_t, is instead obtained through an algebraic relation, as proposed in previous works (e.g., [7,23]). In particular, the form of the transport equation for $\overline{t'^2}$ as proposed by Abe et al. [1] in their work is adopted, since it seems to be more directly linked to theoretical background than others.

The adopted relation for the definition of the turbulent Prandtl number is instead reported in Eq. (2), in which only the radial component of the turbulent heat flux appearing in Eq (1) is used. This simplification is introduced considering this component as the most relevant one for defining heat transfer characteristics in simple geometries, such as circular cross section tubes. An isotropic behaviour of the turbulence heat flux (i.e., the simple gradient assumption) is therefore assumed, as it is the most viable hypothesis for use in the STAR-CCM+ energy balance equation:

$$Pr_{tur} = -\frac{\nu_t}{\overline{u_r't'}}\cdot\frac{\partial T}{\partial r} \quad (2)$$