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Results of 4-equation turbulence models in the prediction of heat transfer to supercritical pressure fluids

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HIGHLIGHTS

- A comparison of different available models for modelling the heat transfer is performed.
- Capabilities of four-equation models when dealing with supercritical fluids are assessed.
- The application of the Algebraic Heat Flux Model (AHFM) for modelling the turbulence heat flux is considered.

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ABSTRACT

The paper summarises the results obtained in the assessment of different turbulence models including low-Reynolds k–ε and k_θ–ε_θ equations, in the attempt to improve the prediction by RANS techniques of heat transfer to fluids at supercritical pressure. The work has been mainly developed in two phases. Firstly, 4-equation models available in literature were applied to a broad range of experimental data making use of the relationships suggested in their formulations for evaluating turbulent thermal diffusivity. These models were herein used with an Algebraic Heat Flux Model (AHFM), aiming at evaluating the turbulent heat flux; in the present work it was used only in the formulation of turbulence production due to buoyancy while the SGDH was used in the energy equation. In a second phase, the same models were applied repeatedly to a subset of the addressed experimental information with different calculation options, including constant values of the turbulent Prandtl number, mixing models for k–ε and k_θ–ε_θ equations in order to identify possible improvements. The results show that recourse to these models, which are more complex than common 2-equation ones, provides limited improvements in the comparison with experimental data.

1. Introduction

In recent years the study of the heat transfer phenomena appearing when using supercritical fluids has been greatly intensified at the University of Pisa, in particular analysing the capabilities of two-equation turbulence models based on the Reynolds Averaged Navier–Stokes equation technique (RANS) (Sharabi et al., 2007; May 2008; June 2008; Sharabi, 2008; Ambrosini, 2009; Sharabi and Ambrosini, 2009; Mucci et al., 2010; De Rosa et al., 2011; Badiali, 2011; Debrah et al., 2011; Ambrosini et al., 2013).

These models represent very interesting tools when studying "normal heat transfer", but they show limited capabilities when dealing with enhanced and deteriorated heat transfer, which are common phenomena when working with supercritical fluids. In particular, k–ε models usually are found to overestimate the heat transfer deterioration phenomenon, correctly predicting the general qualitative trend of wall temperature, but failing in predicting accurately the measured values. On the other hand the k–ω models are less sensitive to heat transfer deterioration and usually underestimate the wall temperature.

Some of the key features of the observed inaccuracies are summarised hereafter.

- In cases where deterioration is due to laminarization, the excessive estimated decrease in turbulent kinetic energy downstream the location where deterioration is predicted does not allow

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Nomenclature

a_{ij}	anisotropic stress tensor –
$C_{\varepsilon1}, C_{\varepsilon2}, C_{\varepsilon3}, C_\lambda, C_m$	model constants –
$C_t, C_{t1}, C_{t2}, C_{t3}, C'_{t1}$	constants of the turbulent heat flux models –
$f_{\varepsilon1}, f_{\varepsilon2}, f_d$,	Damping functions –
g	gravity m/s^2
G	mass flux kg/(m^2 s)
G_k	production of turbulence due to buoyancy m^2/s^3
ID	internal diameter m
k	turbulent kinetic energy m^2/s^2
P_k	production term of turbulence due to shearing m^2/s^3
Pr	Prandtl number –
Pr_t	turbulent Prandtl number –
Q''	heat flux kW/m^2
R	time scale ratio –
t	time s
$\overline{t'^2}$	temperature variance °C
T	temperature °C
T_{in}	inlet temperature °C
T_{pc}	pseudo-critical temperature °C
T_t	time scale of temperature field s
T_u	time scale of velocity field s
u, U	velocity m/s
x	axial position m
$y+$	dimensionless distance from the wall –
α_t	eddy diffusivity m^2/s
β	volume expansivity coefficient 1 K^{-1}
δ_{ij}	Kronecker delta –
ε	turbulent dissipation rate m^2/s^3
ε_t	dissipation rate of $\overline{t'^2}$ °C/s
ν	kinematic viscosity m^2/s
ν_t	eddy viscosity m^2/s
ρ	density kg/m^3
σ_ε	model constant –
ω	specific dissipation rate 1/s
AHFM	Algebraic Heat Flux Model
AKN	Abe Kondoh Nagano
GGDH	Generalised Gradient Diffusion Hypothesis
LS	Launder and Sharma
RANS	Reynolds Averaged Navier Stoles
SCWR	Supercritical Water-Cooled Reactor
SGDH	Simple Gradient Diffusion Hypothesis
YS	Yang-Shih

obtaining the heat transfer recovery often shown by the experimental data.

- The use of the Simple Gradient Hypothesis in the buoyancy production term of the turbulence kinetic energy equation, requiring the definition of a constant turbulent Prandtl number, is not suitable in the case of fluids which undergo strong changes in the thermodynamic properties as the supercritical fluids.

The present paper represents a further step along this research path, as it considers 4-equation turbulence models, which allow for adopting improved models for the turbulent heat flux and for a more accurate study of the turbulent thermal field. Four equations models are essentially modified k–ε models, as they use the typical equations for k and ε in order to solve the velocity field, but they also take into account two further equations for the solution of the thermal field: the temperature variance $\overline{t'^2}$ and its dissipation rate ε_t are usually the transported scalars in these balance equations. In this work, the following four-equation turbulence models were mainly considered: Abe et al. (1994, 1995) hereafter named in short AKN (1995), Hwang and Lin (1999), Deng et al. (2000) and Zhang et al. (2010) (Abe et al., 1994, 1995; Hwang and Lin, 1999; Deng et al., 2000; Zhang et al., 2010, 2012).

The advantage of using four equation models lies in the fact that they do not require a constant turbulent Prandtl number for the definition of the thermal eddy diffusivity. As an example, for the AKN (1995) model it is:

$$\alpha_t = C_\lambda \left[\frac{k^2}{\varepsilon}\left(\frac{2R}{C_m+R}\right) + 3k^{1/2}\left(\frac{\upsilon^3}{\varepsilon}\right)^{1/4}\frac{(2R)^{1/2}}{\mathrm{Pr}}f_d\right]\left[1-e^{-\frac{y^*}{14}}\right] \times \left[1-e^{-\frac{\mathrm{Pr}^{1/2}y^*}{14}}\right] \quad (1)$$

However, it must be remarked that the Zhang et al. (2010) model uses a constant turbulent Prandtl number for the definition of the eddy diffusivity; because of this feature, it seems to be less sensitive to the strong changes in thermodynamic properties that the fluid undergoes when crossing the pseudo-critical temperature. In addition, as pointed out in the papers by Zhang et al. (2010, 2012), one of the most important advantages of their model is the possibility of using advanced relationships for the definition of the turbulent heat flux such as the Algebraic Heat Flux Model (AHFM) reported below as proposed by Kenjereš et al. (2005):

$$\overline{u_j't'} = -C_t\tau\left[C_{t1}\overline{u_i'u_j'}\frac{\partial T}{\partial x_i} + (1-C_{t2})\overline{u_i't'}\frac{\partial U_j}{\partial x_i} + (1-C_{t3})\beta g_j\overline{t'^2}\right] + C'_{t1}a_{ij}\overline{u_i't'} \quad (2)$$

In the above Eq. (2), the anisotropic stress tensor, a_{ij}, is defined as:

$$a_{ij} = \frac{\overline{u_i'u_j'}}{k} - \frac{2}{3}\delta_{ij} \quad (3)$$

As it can be noted, two equation turbulence models cannot use these relationships as they require the knowledge of the local variance of temperature $\overline{t'^2}$. As suggested in the paper by Zhang et al. (2010), we adopted this model for the definition of the production term due to buoyancy G_k that appears in the equation of the turbulent kinetic energy:

$$G_k = \frac{g_i\overline{\rho'u_i'}}{\rho} = -\beta g_i\overline{u_i't'} \quad (4)$$

For what concerns the energy equation, the typical Simple Gradient assumption will be instead maintained. The production term due to buoyancy has a key role in experiments related to upward flow, where the heat transfer deterioration is often due to laminarization. As shown by Bae et al. (2005), in fact, when the axial velocity profile is flattened and the turbulent production due to shear stresses is decreased accordingly, the turbulent production due to buoyancy forces changes sign and becomes positive showing values higher than those due shear stresses. This effect has an influence on limiting the increase of the wall temperature following heat transfer deterioration.

A sufficiently broad range of operating conditions (Watts, 1980; Pis'menny, 2005; Pis'menny et al., 2005; Pioro and Duffey, 2007; Jackson, 2009; Kim and Kim, 2010) was considered in the performed analyses; cases concerning both heat transfer deterioration due to laminarization and the crossing of the pseudo-critical temperature threshold were analysed so that the obtained conclusions