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Turbulence modelling for supercritical pressure heat transfer in upward tube flow

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HIGHLIGHTS

- Major assumptions of the turbulent models which may result in limitation of application in supercritical pressure heat transfer are discussed.
- Performance of three turbulence models in supercritical pressure heat transfer in upward flow is investigated by comparing with the DNS data.
- Comparing with the others, the EB-AFM appears promising as a candidate for further optimization.

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ABSTRACT

Performance of turbulence modelling for supercritical pressure heat transfer in a upward tube flow is investigated by modelling the case simulated by (Bae et al., 2005) with the direct numerical simulation (DNS). Three major assumptions, i.e. $(\partial\overline{p}/\partial x_i) \cong \overline{\rho} g_i$, $\rho' = -\beta\overline{\rho}t'$ and $\overline{\rho u_i'' h''} \cong C_p\overline{\rho u_i'' t''}$ are pointed out as the major limitation of existing turbulent models for their application in supercritical pressure heat transfer in an upward flow. For the sake of model evaluation three representative model combinations are selected, i.e. (i) the General Gradient Diffusion Hypothesis (GGDH) model (buoyancy production of turbulent kinetic energy) and the Simple Gradient Diffusion Hypothesis (SGDH) model (heat flux), (ii) the Algebraic Flux Model (AFM) (both buoyancy production of turbulent kinetic energy and heat flux), (iii) the Elliptic Blending-Algebraic Flux Model (EB-AFM) (both buoyancy production of turbulent kinetic energy and heat flux). In general, prediction of turbulent kinetic energy by the EB-AFM model agrees with the DNS data better than the other two. And the agreement is especially good in the near-wall region. Similar to the turbulence kinetic energy, prediction of the radial turbulent heat flux by the EB-AFM model is good in the near-wall region. Good performance of the EB-AFM model in the near-wall region implies that the model holds the correct asymptotic feature towards the wall. In the bulk performance of the EB-AFM model is unsatisfactory because of strong variation of fluid properties. The GGDH + SGDH and AFM model fail to predict the streamwise turbulent heat flux, while the EB-AFM model can qualitatively predict it. The direct simulation by Bae et al. showed that the heat transfer recovery in the downstream is due to negative $\partial(\rho u_x'' h'')/\partial x$. The investigated models do not predict such a phenomenon. Recovery of heat transfer is predicted by the EB-AFM model mainly due to more efficient heat transfer in the radial direction in the downstream. Contrary to the other models, the EB-AFM appears promising aspects as a candidate for further optimization.

1. Introduction

The Supercritical Water-Cooled Reactor (SCWR), designed to operate at supercritical pressure, has obtained much attention because of its high efficiency and reduced complexity (Oka and Koshizuka, 1993; Oka et al., 2010). Development of SCWR demands accurate prediction for heat transfer under the supercritical states. In supercritical pressure fluids flow behaviour and heat transfer near the pseudo-critical point is strongly affected by the strong variation of fluid property as shown in Fig. 1 (Cheng and Schulenburg, 2001; Pioro and Duffey, 2007; Pioro and Mokry, 2011).

Among numerous studies Computational Fluid Dynamic (CFD) modelling has been regarded as a possible solution to help understand heat transfer phenomenon in supercritical pressure fluids. However, a competent turbulence model is desired before the CFD calculation can be used to quantify heat and momentum transport by turbulence in supercritical pressure fluids. Challenge for turbulence modelling in heated supercritical pressure flows originates

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Nomenclature

a_{ij}	$(\overline{\rho u_i'' u_j''}/\bar{\rho}k) - 2/3\delta_{ij}$
C_p	Specific heat capacity at constant pressure, J/(kg K)
$C_{\varepsilon 1}, C'_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu, C_\eta, C_\tau, C_L$	k–ε–ζ–f model constants, listed in Table 1
C_t, C_ε	Coefficients in turbulent heat flux model, listed in Table 2
D	tube diameter, m
f	elliptic blending relaxation factor
g	gravity acceleration, m/s^2
G_b	bulk mass flux, kg/m^{2}s
G_k	buoyancy production rate of turbulence kinetic energy, kg/(m s^3)
h	specific enthalpy, J/kg
L	turbulence mechanical length scale, m
L_θ	turbulence thermal length scale, m
k	turbulence kinetic energy, m^2/s^2
P	System pressure, MPa
p	Relative pressure, Pa
P_k	mechanical production rate of turbulence kinetic energy, kg/(m s^3)
P_{tt}	production rate of temperature fluctuation invariance, K^2/s
Pr	molecular Prandtl number, $\mu C_p/\kappa$
Pr$_t$	turbulent Prandtl number, $\mu_t C_p/\kappa_t$
q_w	wall heat flux, J/m^2
r	radial coordinate, m
R	tube radius, m
Re	Reynolds number, $\rho UD/\mu$
S_{ij}	strain rate tensor, $1/2((\partial\tilde{U}_i/\partial x_j)+(\partial\tilde{U}_j/\partial x_i))$, S^{-1}
$\lvert S \rvert$	strain rate magnitude, $\sqrt{2S_{ij}S_{ji}}$, S^{-1}
T, t	temperature, K
t_{ji}	instantaneous viscous stress tensor, $\mu((\partial u_j/\partial x_i)+(\partial u_i)/\partial x_j)$, Pa
U	velocity, m/s
u	instantaneous velocity or axial instantaneous velocity, m/s
v	wall-normal instantaneous velocity, m/s
x	axial position, $x=0$ at the inlet, m
y	wall distance, m

Greek

α_θ	blending factor of Algebraic Flux Model
β	thermal expansion coefficient, K^{-1}
δ_{ij}	Kronecker delta
ε	dissipation rate of turbulence kinetic energy, m^2/s^3
ε_{tt}	dissipation rate of temperature fluctuation invariance, K^2/s
κ	thermal conductivity, W/(m K)
$\overline{\phi}$	Reynolds averaging of ϕ
$\langle\phi\rangle$	Reynolds averaging of ϕ
$\tilde{\phi}$	Favre averaging of ϕ
ϕ'	Reynolds-averaging fluctuation of ϕ
ϕ''	Favre-averaging fluctuation of ϕ
μ	dynamic viscosity, Pa s
μ_t	turbulent dynamic viscosity, Pa s
v	kinematic viscosity, m^2/s
R	thermal to mechanical time scale ratio
ρ	density
$\sigma_\varepsilon, \sigma_k, \sigma_\zeta$	turbulent Prandtl number in k–ε–ζ–f model, listed in Table 1
σ_θ	turbulent Prandtl number in turbulent heat flux model
τ	turbulence characteristic time scale
ζ	wall-normal portion of turbulence kinetic energy, $\overline{v^2}/k$
$\varsigma, \xi, \eta, \gamma$	Coefficients in turbulent heat flux model, listed in Table 2

Subscripts

in	inlet
b	bulk
pc	pseudo-critical
t	turbulent
w	wall
x	axial component
y	radial component

mainly from fluid property fluctuation. Mechanism of turbulence production and dissipation is also modified due to significant variation of fluid properties, especially density variation. From the aspect of turbulence production, density variation, i.e. buoyancy, can affect the flow through either external or structural effect. The external effect is a consequence of reduced Reynolds stresses in the buffer region, where turbulence production mainly occurs. Consequently, turbulence and heat transfer is impaired. The external effect is also commonly referred to as laminarization (Jackson and Hall, 1979). Most of Reynolds Averaged Stress (RAS) turbulence models can depict the external effect without further modification if we assume that these models can calculate the Reynolds stresses and velocity accurately. The structural effect accounts for production and dissipation of turbulence due to the correlation between density fluctuation and velocity fluctuation, i.e. the density fluctuation influences the flow structure.

Another apparent effect from variation of fluid properties is anisotropic behaviour of turbulent heat diffusivity even in very simple geometry like a round tube. In order to improve modelling of turbulent heat flux in a concise way (Bae et al., 2012) proposed a variable turbulent Prandtl number. Jaromin and Anglart (2013) showed that agreement between CFD prediction and experiment result can be achieved by tuning turbulent Prandtl number. Variable turbulent Prandtl number is an attractive solution due to its simplicity, but it can improve modelling to limited extent because it is mainly related to Simple Gradient Diffusion Hypothesis

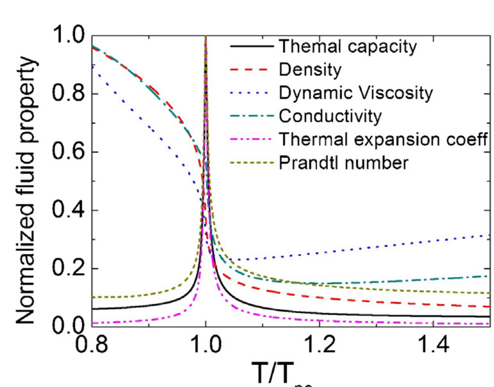

Fig. 1. Strong property variation near the pseudo-critical point.