International Journal of Heat and Mass Transfer 108 (2017) 529–536

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Assessment of low-Reynolds number k-ε turbulence models against highly buoyant flows

Yoon-Yeong Bae *, Eung-Seon Kim, Minhwan Kim

Korea Atomic Energy Research Institute, 111 Daedeok-daero 989, Yuseong, Daejeon 34057, Republic of Korea

ARTICLE INFO

Article history:
Received 4 October 2016
Received in revised form 29 November 2016
Accepted 6 December 2016

Keywords:
Turbulent heat transfer
Low-Reynolds number turbulence model
Supercritical pressure
Strong buoyancy

ABSTRACT

Low-Reynolds-number k-ε turbulence models have been successfully used by numerous researchers in various applications. It has been found that the Myong-Kasagi model (MK) among them outperforms in simulations of thermal-fluid fields at supercritical pressures and near the corresponding pseudo-critical temperature. However, they are used as is without a clear understanding of the cause of the good performance. In this paper, several well-known low-Reynolds-number turbulence models, including MK, are critically reviewed against DNS data and RANS calculation results to find the reasons, if any exist, for the superiority of MK model.

The most outstanding factor identified may be the fact that MK introduced the Taylor microscale as the near-wall length scale and combined it with the integral length to result in a combined turbulence length scale, which is valid over the entire range of a turbulent boundary layer. The eddy viscosity formula with the incorporation of the turbulence length scale is naturally expected to provide a better representation of flows with strong buoyancy due to wall heating, especially in the near-wall region, where the buoyancy effect mainly occurs. As a result, MK-simulated highly buoyant flows showed excellent agreement with experimental data when applied with the property-dependent turbulent Prandtl number and shear-stress-dependent damping length. A comparison with DNS data of the turbulence data obtained from RANS calculations with MK also showed a good agreement.

1. Introduction

When a fluid flow undergoes a pressure higher than the critical pressure, physical properties vary significantly when passing the pseudo-critical temperature, which corresponds to the critical temperature at the critical pressure. For many applications, variation of the physical properties is below the tolerance limit of conventional turbulence models, which were originally derived from data obtained from experiments conducted with incompressible flows. The conventional turbulence models thus obtained have been found to perform fairly well in most of applications when the physical properties do not (or mildly) vary. However, the physical property variations encountered in the cases under supercritical pressure usually exceed the tolerable limit of the conventional turbulence model regardless of types used, and the calculation results significantly deviate from experimental findings.

Numerous researchers have attempted to simulate the flow-thermal behavior of fluids at supercritical pressures using conventional turbulence models by adding various models for buoyancy influence but without exception have failed to produce results that reasonably agree with the corresponding experimental data [1–3]. Low-*Re* k-ε models were extensively tested against the DNS data for supercritical CO_2 flows by He et al. [2], who demonstrated that the V2F model performed best. However, they also concluded that all low-*Re* k-ε models tested, including the V2F model, were not satisfactory in reproducing the turbulence properties of highly buoyant flows.

There have been attempts to employ the algebraic flux model (AFM), which is known to be effective in flows with strong buoyancy, in simulations of supercritical flows and thermal fields. The AFM employs four equations to determine the velocity and temperature fluctuations and their dissipations, and uses them in the evaluation of eddy viscosity. Zhang et al. [4] reported that good agreement with experimental data is achieved when employing the AFM. Similar work was also performed by Zhang et al. [5] using the AFM. Their work satisfactorily reproduced one particular case, but did not so another case, indicating that application of the AFM did not lead to a successful reproduction of strongly-buoyant flows. Feng [6] performed an extensive test of turbulence models using flows which ran through vertical tubes accompanied by heat transfer deterioration, concluding that all models tested overestimated wall temperatures and failed to address buoyancy effects properly.

* Corresponding author.
E-mail address: yybae@kaeri.re.kr (Y.-Y. Bae).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.039
0017-9310/

Nomenclature

C_μ	constant in the eddy viscosity
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	constants in the transport equation for ε
c_θ	constant defined in Eq. (4)
f_1, f_2	constants in the transport equation for ε
G_k	buoyancy production of turbulence
h	enthalpy
k	turbulent kinetic energy
p	pressure
P_k	shear production of turbulence
Pr_{t-v}	property-dependent turbulent Prandtl number
r	radial coordinate
R	tube radius
Re	Reynolds number
Re_t	turbulent Reynolds number, $k^2/(v\varepsilon)$
T	temperature
u, v	velocity in the x and r directions
u_τ	velocity in the x and r directions, $(\tau_w/\rho)^{1/2}$
x	axial coordinate
y	distance from the wall, $R-r$
y^+	non-dimensional distance from wall, yu_τ/v
$\bar{a}$	Reynolds average quantity (a: dummy)
$\tilde{a}$	Favre average quantity (a: dummy)

Greek symbols

β	volumetric expansion coefficient
ε	dissipation rate of the turbulent kinetic energy
μ, μ_t	molecular and turbulent viscosity
v, v_t	molecular and turbulent kinematic viscosity
ρ	density
σ_k, σ_ε	model constants for the turbulent diffusion of k, ε
τ	shear stress

Subscript

w	wall

The reason behind the general failure of the existing turbulence models in numerically calculating highly buoyant flows can be attributed to the ineffectiveness of the turbulence models employed, which without exception were based on experimental data obtained from incompressible flows and their interpretations. It is quite obvious that any models based on incompressible flows would be inadequate for an application to flows with strong buoyancy, where density change is so significant that they can be treated as compressible flows, if not exactly equivalent. There have been numerous attempts to adapt turbulence models to compressible flows while incorporating various modifications [7]; their direct application to supercritical flows, however, cannot be guaranteed, as the compressibility effect originates from pressure variations, while property variations in supercritical fluids come from temperature variations. Under these circumstances, a critical review of existing turbulence models is essential.

Bae [8] proposed a new formula for an extended turbulent Prandtl number, Pr_{t-v}, which depends on property variations as well as the properties of the flow and thermal field, proving its usefulness in simulations of highly buoyant flows by producing results in good agreement with experimental data. Bae et al. [9] developed a functional relationship between the damping length A^+ and the local shear stress and showed that the flow of a supercritical fluid accompanied by deteriorated heat transfer can successfully be simulated, with the reproduced results showing exceptional agreement with experimental data when the variable A^+ was incorporated with Pr_{t-v}. In their numerical simulations, Bae [8] and Bae et al. [9] employed the low-*Re* k-ε model proposed by Myong and Kasagi (MK) [10] as a baseline turbulence model without giving any rationale behind its selection.

The present paper describes why MK performs best among low-*Re* k-ε models in calculations of the flows and thermal fields of fluids at supercritical pressure by examining the turbulence properties and comparing them with experimental and DNS data [11]. Because the purpose here is not generally to assess low-*Re* k-ε models, the main focus will be directed toward a close examination of the performance of MK and a few selected models classified as belonging to the same group.

2. Low-*Re* turbulence models

The continuity, momentum and energy equations employed in this paper for a axisymmetric flow in a tube at a steady state are exactly the same as those described in [2,8]. x-direction is aligned with the vertical tube axis and r-direction with radial direction with the definition of the wall-normal distance $y = R - r$ at the wall. The gravitational force has components (-g, 0, 0). The continuity, momentum and energy equations are repeated for completeness.

$$\frac{\partial}{\partial x}(\bar{\rho}\tilde{u}) + \frac{1}{r}\frac{\partial}{\partial r}(r\bar{\rho}\tilde{v}) \tag{1}$$

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\bar{\rho}\tilde{u}^2) + \frac{\partial}{\partial r}(r\bar{\rho}\tilde{u}\tilde{v})\right] = -\frac{\partial p}{\partial x} + \bar{\rho}g + \frac{2}{r}\frac{\partial}{\partial x}\left[r\bar{\mu}_e\left(\frac{\partial \tilde{u}}{\partial x}\right)\right] + \frac{1}{r} \times \frac{\partial}{\partial r}\left[r\bar{\mu}_e\left(\frac{\partial \tilde{u}}{\partial r} + \frac{\partial \tilde{v}}{\partial x}\right)\right] \tag{2}$$

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\bar{\rho}\tilde{u}\tilde{v}) + \frac{\partial}{\partial r}(r\bar{\rho}\tilde{v}^2)\right] = -\frac{\partial p}{\partial r} + \frac{1}{r}\frac{\partial}{\partial x}\left[r\bar{\mu}_e\left(\frac{\partial \tilde{v}}{\partial x} + \frac{\partial \tilde{u}}{\partial r}\right)\right] + \frac{2}{r} \times \frac{\partial}{\partial r}\left[r\bar{\mu}_e\left(\frac{\partial \tilde{v}}{\partial r}\right)\right] - 2\frac{\bar{\mu}_e\tilde{v}}{r^2} \tag{3}$$

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\bar{\rho}\tilde{u}\tilde{h}) + \frac{\partial}{\partial r}(r\bar{\rho}\tilde{v}\tilde{h})\right] = \frac{1}{r}\left\{\frac{\partial}{\partial x}\left[r\left(\frac{\bar{\mu}}{\overline{Pr}} + \frac{\bar{\mu}_t}{Pr_t}\right)\frac{\partial \tilde{h}}{\partial x}\right] + \frac{\partial}{\partial r}\left[r\left(\frac{\bar{\mu}}{\overline{Pr}} + \frac{\bar{\mu}_t}{Pr_t}\right)\frac{\partial \tilde{h}}{\partial r}\right]\right\} \tag{4}$$

where the effective viscosity $\bar{\mu}_e$ is defined as the sum of dynamic viscosity and eddy viscosity, $\bar{\mu}_e = \bar{\mu} + \bar{\mu}_t$. The Boussinesq approximation was not enforced since the temperature varies so significantly that the temperature variation was considered too large to adopt the approximation. The energy solved in the energy equation was enthalpy (not total: the kinetic energy was negligible compared to the enthalpy, so there is virtually no difference between them). The mean dissipation was neglected since it was also considered negligible. The temperature was calculated from enthalpy and pressure.

The two equations for turbulent kinetic energy and its dissipation rate in axisymmetric coordinates are given below.

$$\frac{\partial}{\partial x}(\bar{\rho}\tilde{u}\tilde{k}) + \frac{1}{r}\frac{\partial}{\partial r}(r\bar{\rho}\tilde{v}\tilde{k}) = \frac{\partial}{\partial x}\left[\left(\bar{\mu} + \frac{\bar{\mu}_t}{\sigma_k}\right)\frac{\partial \tilde{k}}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\bar{\mu} + \frac{\bar{\mu}_t}{\sigma_k}\right)\frac{\partial \tilde{k}}{\partial r}\right] + \bar{\rho}P_k + \bar{\rho}G_k - \bar{\rho}(\tilde{\varepsilon} + D) \tag{5}$$