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Correction of low-Reynolds number turbulence model to hydrocarbon fuel at supercritical pressure

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ABSTRACT

At supercritical pressure, due to the drastic change of thermophysical property near the pseudo-critical temperature, the density fluctuation and density variation, along with buoyancy, play an important role in supercritical turbulence modelling. Based on the original LS (Launder–Sharma) low-Reynolds number turbulence model, the buoyancy modification, the density fluctuation modification, the density variation modification and the empirical coefficients modification are considered and the corresponding correction terms are derived and applied in the governing equations. Numerical simulation of heat transfer to hydrocarbon fuel flowing through the uniformly heated round pipe at supercritical pressure has been performed by the modified LS turbulence model incorporated into the in-house numerical code. Inlet temperature varied from 373 K to 473 K, with heat flux varying from 241 kW/m^2 to 470 kW/m^2. Inlet mass flux was 736 kg/(m^2·s) and operating pressure was 4 MPa. The flow directions included upflow and downflow. Compared with the original LS turbulence model, the modified LS turbulence model leads to the better agreement with the experimental results, with 41.16% improvement in computation accuracy in the current study. The consideration of density fluctuation and density variation effects makes the turbulence model more suitable for thermophysical property variation at supercritical pressure.

1. Introduction

Due to aerodynamic heating, serious thermal management problem has become a significant challenge in high-speed scramjet. Active regenerative cooling technology has been an effective way to solve this problem and hydrocarbon fuel is utilized as the coolant. At supercritical pressure, hydrocarbon fuel in tank is driven to enter into the cooling channel inside combustor chamber, then absorbs the heat from high temperature component by physical heat sink and chemical heat sink. During the heat absorbing process, the temperature of hydrocarbon fuel increases from subcritical temperature to supercritical temperature, turning into the supercritical fluid [1]. The thermophysical properties of supercritical fluids differ greatly from those under subcritical pressure, making an important impact on flow and heat transfer of fluid in supercritical equipment.

The flow and heat transfer of supercritical fluid [2,3] have been extensively studied since critical phenomena were firstly observed by Cagniard de la Tour in 1822 [4]. It has been generally observed by the temperature measurement technology that heat transfer enhancement or heat transfer deterioration may occur at supercritical pressure owing to the variable property effect, buoyancy effect and thermal-induced acceleration effect, depending on the heat flux to mass flux ratio at certain inlet temperature. Due to the extreme technical challenge for the flow field measurement at supercritical pressure, relatively few experimental studies have been carried out on the fluid mechanism of supercritical flows [5]. With the rapid developments of computer technology and numerical algorithm, the CFD (computational fluid dynamics) method is applied more and more in supercritical heat transfer, and is capable of simulating complex problem and getting detailed flow data. In engineering application, a commonly used CFD method to simulate supercritical turbulent flow is RANS (Reynolds-averaged Navier–Stokes) method in which turbulence model is the key for accurate simulation.

In early study, simple algebraic equation was used for modelling turbulence at supercritical pressure [6]. Shirakar [7] adopted this method to study the effect of swirl on heat transfer deterioration at supercritical pressure. Although only algebraic expression is used for the turbulence quantities, it could give good results for certain engineering applications and is seldom used for supercritical heat transfer now [8].

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Nowadays, two-equation turbulence models, especially various k–ε models, are widely used for supercritical heat transfer. Due to the abrupt change of thermophysical property near the heating wall, a high quality grid is needed and the low-Reynolds number (LRN) k–ε turbulence model may be more adaptive in supercritical turbulence modelling [9]. He et al. [10] numerically simulated supercritical carbon dioxide using the LS (Launder–Sharma) [11] and CH (Chien) [12] LRN models and found that the predicted wall temperature was significantly higher than experimental data in some cases. Such prediction deviation may be caused by that the conventional turbulence model is usually the semi-empirical and semi-theoretical model based on constant property assumption, however, at supercritical pressure, thermophysical properties vary drastically with temperature, especially in the vicinity of pseudo-critical temperature [13].

Due to the inherent limitation of RANS method, it could not give satisfactory prediction results for all of the turbulent flows and the existing model should be modified properly to fit supercritical turbulent flow. Mohseni and Bazargan [14] applied multiple correlation methods to the MK (Myong–Kasagi) [15] LRN model in predicting supercritical flow of water and carbon dioxide. They thought that the empirical coefficients in turbulence equations could not exactly satisfy the expression existing in variable property flow [16], leading to an inaccurate prediction for supercritical heat transfer. Zhang et al. [17] compared three kinds of turbulent heat flux model, including the simple gradient diffusion hypothesis (SSDH), the generalized gradient diffusion hypothesis (GGDH) and the algebraic flux model (AFM), in computing turbulent heat transfer of supercritical water and found that buoyancy model had significant effect on predicting wall temperature.

Regarding to turbulence modelling of supercritical hydrocarbon fuel, the relevant study is still in the developing stage [18,19]. Zhu et al. [20] assessed supercritical heat transfer of hydrocarbon fuel predicted by standard k–ω turbulence model against the experimental data of normal heat transfer and it could produce the variation trend of wall temperature along the tube but it over-predicted wall temperature in the second half of tube. They also found that the variation of computed pressure drop with temperature at adiabatic case agreed well with the corresponding measured result, revealing that compared with flow resistance, heat transfer was more sensitive to the turbulence model. Zhang et al. [21] conducted the modification of standard k–ε model in simulating supercritical RP-3 (Rocket Propellant 3) by correcting the coefficients $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ in ε equation at various working conditions, and the modified model had shown good predictions for pressure drop and averaged Nusselt number along the tube. However, the proposed turbulence model was mainly based on the experimental data about the global averaged value, without paying much attention on the local value affecting significantly heat transfer, especially near the heated wall where thermophysical properties vary drastically.

Compared with RANS study on supercritical heat transfer, DNS (direct numerical simulation) can give more detailed turbulence information to deeply understand thermal physics of the fluid at supercritical pressure [22]. Bae et al. [23] has done a lot of valuable works in supercritical DNS study of carbon dioxide in uniformly heated tube. It has been found that vigorous density fluctuation has significant effect on the transition from subcritical temperature to supercritical temperature. Hassan et al. [24] studied the effect of thermal boundary condition with permission of temperature variation on heat transfer of supercritical carbon dioxide by DNS and their work provided clear evidence that the thermal wall boundary condition had a large impact on Nusselt number and skin friction for fluids with large property variations. In addition, the turbulent flow of relatively low Reynolds number in simple configuration has been simulated by DNS method [5] to give detailed turbulent statistics data as the reference library for the comparison of RANS computations [25].

Table 1
Summary of turbulence models.

No.	Model	Code	Classification
1	Abid [31]	ABID	k–ε model
2	Abe–Kondoh–Nagano [32]	AKN	k–ε model
3	Lam–Bremhorst [33]	LB	k–ε model
4	Launder–Sharma [11]	LS	k–ε model
5	Yang–Shih [34]	YS	k–ε model
6	Shear stress transport [35]	SST	k–ω model
7	k–ε–υ^2–f [36]	V2F	Four-equation model

At current computer capacity level, since LES (large eddy simulation) is less computationally costly than DNS, it has access to simulate supercritical flow at relatively high Reynolds numbers as those used in real experiments [26]. Niceno and Sharabi [27] performed the LES simulation of supercritical water flowing in heated pipe to produce detailed information about the mean flow and turbulence explaining the occurrence of heat transfer deterioration.

It has not yet been developed to the stage where LES method can be widely used for the purpose of predicting flow and heat transfer of supercritical fluid in engineering application due to relatively large computational cost, not to mention DNS method. At present, in order to achieve accurate prediction of supercritical heat transfer in engineering application, it is becoming feasible to perform modification to the existing turbulent model in RANS method. As described above, the research on turbulence model under supercritical pressure is still in a start-up stage to date. There have been a few studies on turbulence modelling of supercritical water and carbon dioxide, and even fewer researches of hydrocarbon fuel [28,29] which need to be further explored for the design of active regenerative cooling technology. To satisfy engineering requirement of regenerative cooling system, main concern of this paper is devoted to the turbulence modelling of supercritical hydrocarbon fuel. Based on the conventional turbulence model and thermophysical property library of hydrocarbon fuel embedded to the in-house code, various correction ways to the governing equation responding to local flow condition under supercritical pressure have been analyzed and derived. Numerical simulation of supercritical hydrocarbon fuel flowing in the vertical heated tube using the modified code has been conducted in order to preliminary validate the correction ways against the experimental data. It is helpful to assist numerical simulation accuracy of hydrocarbon fuel at supercritical pressure.

2. Original model

It is necessary to select a turbulence model which performs better in predicting the flow and heat transfer to hydrocarbon fuel at supercritical pressure before applying multiple modification methods to the governing equations. In previous study [30], a variety of turbulence models was adopted to simulate heat transfer to hydrocarbon fuel flowing upward and downward through uniformly heated vertical pipe at supercritical pressure. Table 1 gives the summary of turbulence models used in the comparative study. Five LRN k–ε type turbulence models [11,31–34] and a k–ω type turbulence model [35] were selected. Recently, a four-equation model [36] has been found to predict better in supercritical heat transfer than some LRN models, so it is also selected in the comparative study.

A wide range of experimental conditions was computed and it has been found that most of turbulence models can reproduce the general trend of heat transfer to supercritical hydrocarbon fuel qualitatively, but from the quantitative point of view the performance of comparison with experimental data varied observably