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THE BOUNDARY LAYER CHARACTERISTICS OF DIFFERENT TURBULENCE MODELS IN PREDICTING SUPERCRITICAL HEAT TRANSFER BEHAVIOURS

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Abstract

The heat transfer behavior of supercritical water has large difference with that of subcritical water due to its unusual fluid property variation in the pseudocritical region. Computational Fluid Dynamics techniques are playing more and more important roles in investigating the hidden mechanisms of that, however, whether the extension of subcritical turbulence models to supercritical conditions has not yet been fully resolved, especially in heat transfer deterioration situation. The boundary layer is the main region responsible for the heat and momentum transport between the wall and the bulk fluid part, so it is very important for the turbulence models to describe the boundary layer characteristics. In this paper, the two main wall treatment methods- the wall function method and the low Reynolds number model are discussed based on the property variation wall function. It is found that the different turbulent models predict different boundary layer characteristics which lead to the big divergence in predicting the wall temperature. This work is a preliminary step towards the improvement of turbulence models under supercritical conditions.

1. Introduction

The heat transfer characteristics of supercritical water have attracted plenty of attention as it could be considered as potential coolant and moderator in advanced power conversion system. Igor[1] gave a very comprehensive review of state of the art of ongoing progress including nearly all aspects of the supercritical water in the power engineering applications. Many experiments have been done since last 50's, such as Bishop[2], Swenson[3], Yamagata[4] and so on. Besides this, in company with the progress of numerical techniques, lots of work is devoted to the numerical simulation of supercritical water. The turbulence models embedded in commercial software are all developed with respect to subcritical water. The suitability of extending them to supercritical conditions have become of interest of many researchers. Koshizuka[5] et al. performed numerical simulation with low Reynolds number k-□model in comparison with Yamagata's experiments. Wen and Gu examined kinds of turbulence models in predicting heat transfer deterioration phenomena caused by buoyancy[6] and acceleration[7] effect. S He et al[8] made an assessment of the turbulence models with the direct numerical simulation results. The performances of turbulence models are discussed.

The boundary layer is the main region responsible for the momentum and energy transport. Near the boundary layer, the inertial force and viscous force acts together to bring about the strong turbulence intensity including nonlinear and instable structures. The velocity gradient promotes the turbulence generation. The viscous damping effect transfer the energy of large eddies to small eddies, till down to the Kolmogorov scale. The wall boundary layer is just the place where the two forces fight and make balance. According to long term of experimental observation and numerical analysis, the wall boundary layer could be divided into three parts: the inner viscous sub layer, the fully turbulence layer and the buffer layer between them. The supercritical water is characterized by its large variation of fluid property near the pseudocritical point. The boundary layer characteristics under supercritical conditions are still not clear.

In this paper, kinds of turbulence models are compared in predicting the boundary layer profile. The mesh sensitive test is first performed to make clear the various demand for different wall treatment methods. Then the new function law is proposed up to account for the fluid property variation of supercritical water. At last, both the wall function method and low Reynolds method are analyzed in predicting the near wall heat and momentum characteristics. This paper aims to provide a new perspective to evaluate the performances of turbulence model.

2. Numerical modelling and mesh sensitive test

2.1 The turbulence model and wall treatment methods

The commercial software Fluent is used as the simulation tool in this paper. Kinds of turbulence models are incorporated in this software[9]. Generally, there are two catalogues of wall treatment methods: the low Reynolds number method and the wall-function method. The low Reynolds number method solves the turbulent transport equations across the whole boundary layer, from the log layer zone to the wall. The turbulent fluctuation is limited and impaired by the presence of the wall. Low Reynolds number correction should be accounted for to model the damping effects. This method has high demand on the mesh refinement in the boundary layer. The wall function method makes a bridge between the wall and the log layer region, thus obviating the trouble of numerical issues. This method is applicable to the high Reynolds number flow and complex geometry. The wall function method has wide applications in engineering problems because of its simplicity. But it is also limited in complex flows with strong swirl vortex and boundary layer separation for the standard wall function method. Thus some improved versions of wall function methods are proposed up, such as the non-equilibrium model, enhanced wall function and so on. The non-equilibrium method could account for the situation when the pressure gradient exits in the boundary layer. Besides, the two layer wall function methods are used to calculate the turbulent kinetic energy at the first grid point near the wall. The enhanced wall function also divides the boundary layer into two parts: the viscous influence area and the fully turbulent region. The difference is the one equation transport model is used in the viscous influence area. Fluent software supports all these wall treatment methods.

2.2 The numerical setup

The supercritical experiments done by Ornatskiy[10] in 1972 are used as the comparison reference. The experiments are typical heat transfer deterioration cases in high mass flow. It is generally believed that the heat transfer deterioration is hard to predict for normal turbulence models. One group of the experimental parameters is listed here: G=1500kg/m^2s, q=1810kW/m^2, P=25.5MPa, Tin=388K. The experiments were done in circular pipe.

2.3 The mesh sensitive test

Various wall treatment methods have different requirements on the mesh parameters. For example, the standard wall function requires the first grid point to lie in the log layer region. However, the low Reynolds number model forces the first grid point to lie in the viscous layer. In order to check this, the mesh sensitive tests are performed to four kinds of representative wall treatment methods: the low Reynolds number kind model-SST (Shear Stress Transport model) and three kinds of wall function methods (The standard wall function method, the Enhanced Wall Treatment and Non-equilibrium Wall Function). For the wall function method, the RNG turbulence model is used. For simplicity, the RNG method plus standard wall function is abbreviated as RNG, the RNG plus the Enhanced Wall Treatment abbreviated as RNGEWT and the RNG plus Non-equilibrium Wall Function abbreviated as RNGNEW. Four kinds of meshes are generated to complete the mesh sensitive tests. Their main differences are the locations of the first grid point. Since the value of y^+ is dependant on the calculation results and turbulence model selection, the rough range calculated by SST model is presented here.

Table 1 Mesh parameter matrix

Name	dy(mm)	y^+
mesh	3.00E-07	~0.1
mesh1	3.00E-06	0.7~1.5
mesh2	3.00E-05	11~22
mesh3	1.00E-04	38~100

Fig. 1 presents the mesh sensitive test results for the four wall treatment methods. Here the number in the name corresponds to the mesh parameters in Table 1, e.g., the RNGEWT1 means the RNGEWT model with mesh1. Based on the value of y+ for each mesh, the location of the first grid point could be roughly determined. The y+ for “mesh” and “mesh1” are all below or around one which means the first grid point resides in the viscous layer, so the low Reynolds number model is suitable. The y+ for “mesh2” is between 10 and 20, so part of the first grid points are in the buffer layer; while for “mesh3”, most the first grid points lie the log layer zone. The calculation results for each turbulence model are tightly dependant on the mesh parameters. The “standard” wall function and “NEW” wall function belong to the wall function treatment methods. The matched mesh parameters are “mesh2” or “mesh3”. If the “mesh” or “mesh1” parameters are used, the wall temperature will be under estimated. The “EWT” treatment method uses the one equation Wolfstein model in the viscous layer. It could be considered as low Reynolds number kind. The matching mesh is “mesh” and “mesh1”. If the large scale “mesh3” is used, the wall function method will be automatically turned on whose calculation results are close to the one predicted by standard wall function or "NEW" wall function.

Each kind of turbulence model has its matching mesh type. The wall function method requires the first grid point to be in the log layer, while in the viscous layer, the prediction wall temperature would be lower and it is hard to get a mesh independent result through decreasing the mesh size. The low Reynolds number type model needs the first grid point in the viscous layer and the mesh insensitive results can be obtained through decreasing the mesh size.

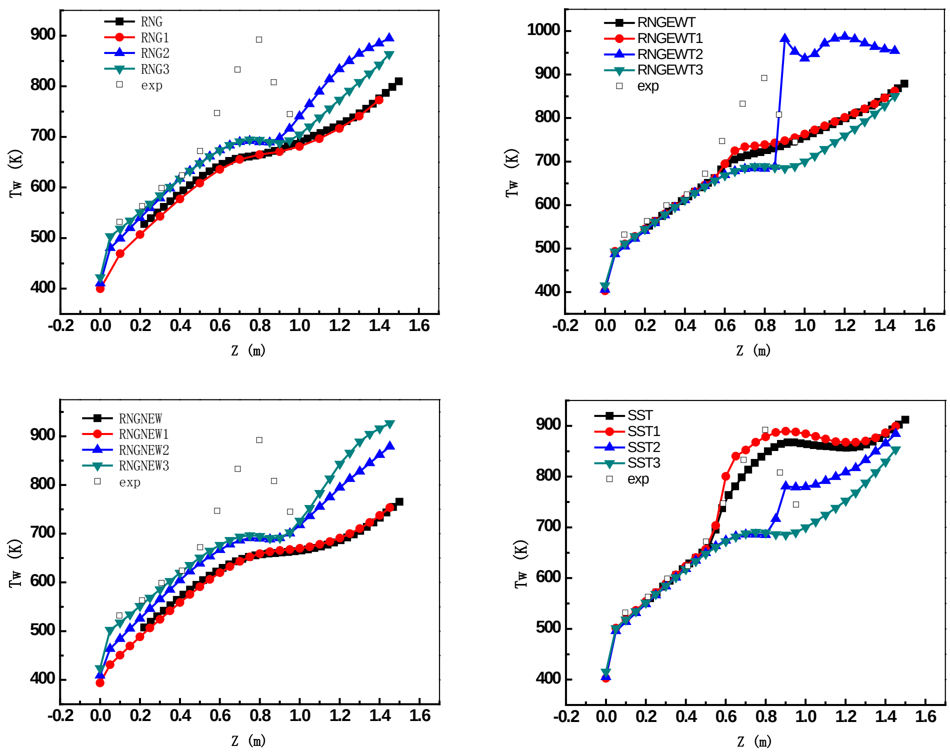


Fig. 1 The mesh sensitive test for various turbulence models

Fig. 2 (a) shows the calculation results for these wall treatment methods with the "mesh". The wall temperature predicted by standard wall function and "NEW" wall function is lower than the experimental data, also lower than the SST model and "EWT" model. If the "mesh3" is used for the standard wall function and "NEW" wall function, the calculation results become closer to the SST model in predicting the front and back region of the wall temperature peak. Each kind of turbulence model should adopt its matching mesh parameters to get a reasonable result.

Among these four methods, the SST turbulence model shows closer agreement with the experimental data which could capture the peak point of the wall temperature profile. However, it predicts weaker heat transfer recovery region than the experimental data.

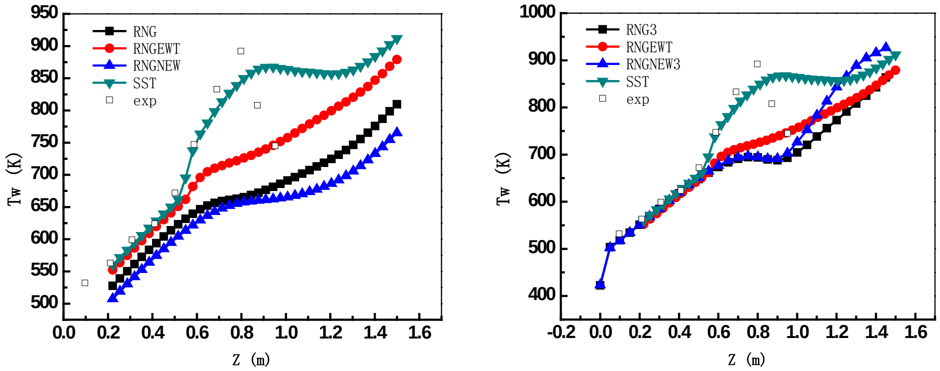


Fig. 2 The comparison results of various turbulence models

3. Results and discussions

3.1 The new definition of wall function quantity

The traditional wall function theory is developed under the weak property variation assumption. However, under supercritical conditions, the big temperature difference along the wall normal direction could lead to large fluid property variation near the pseudocritical point. The traditional wall function has to be corrected to account for such situation.

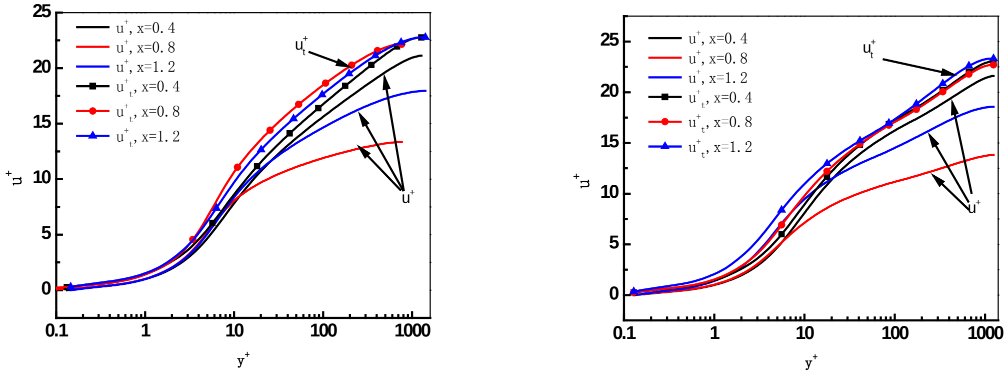
Van Direst[11] proposed such kind of dimensionless velocity to reflect the influence of fluid property variation on the law of the wall.

$$u_t^+ = \begin{cases} \int_0^u \frac{\mu}{\mu_w} \frac{du}{u_\tau} & u < u_c \\ \int_{u_0}^u \left(\frac{\rho}{\rho_w} \right)^{1/2} \frac{du}{u_\tau} & u > u_c \end{cases} \tag{1}$$

Here u_c stands for the velocity at the interface of the viscous layer and turbulent layer; u is fluid velocity; ρ is fluid density; μ is dynamic viscosity; u_τ is the friction velocity. Generally, the dimensionless velocity in the turbulent layer is used to represent the whole boundary layer without causing much deviation. In contrast the traditional dimensionless velocity is defined below:

$$u^+ = \frac{u}{u_\tau} \tag{2}$$

Fig. 3 presents the velocity profiles described by both the traditional dimensionless velocity and the Van Direst velocity at different locations. Large scatter of distribution appear for the traditional velocity, while compact distribution for the Van Direst velocity. The Van Direst velocity accounts for the fluid property variation along the wall normal direction, thus keeping the basic form of wall function satisfied. Based on this new definition of velocity, it could be observed that the boundary layer under supercritical conditions could also be divided into three regions, just as the traditional one. Both the SST model and EWT model could resolve the boundary layer, although their predicted wall temperature differs much.



(a)SST (b)EWT

Fig. 3 the velocity profiles at different locations

In a similar way, the thermal law of the wall could also be improved to account for the fluid property variation based on the boundary layer equation. The dimensionless temperature is defined below:

$$T^* = \begin{cases} \int_{t_w}^{t} -\dfrac{\rho c_p u_\tau}{q} dt & t < t_c \\ \int_{t_w}^{t} -\dfrac{\rho c_p u_\tau}{q} \left(\dfrac{\rho_w}{\rho}\right)^{1/2} dt & t > t_c \end{cases} \tag{3}$$

Here t_c stands for the fluid temperature at the interface between the viscous region and turbulence region; c_p is the specific heat capacity; q is the wall heat flux. Generally, the dimensionless temperature defined in the turbulent layer is used to represent the whole boundary layer without causing much deviation.

In contrast, the traditional dimensionless temperature is defined below:

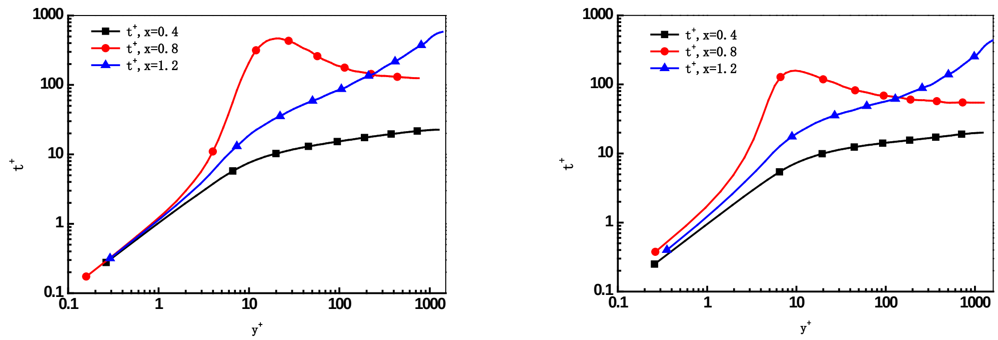
$$T^* = \frac{(T_w - T_p)\rho c_p u_\tau}{q} \tag{4}$$

Sometimes the wall friction velocity could be substituted by the local turbulent kinetic energy:

$$T^* = \frac{(T_w - T_p)\rho c_p k_p^{1/2}}{q} \tag{5}$$

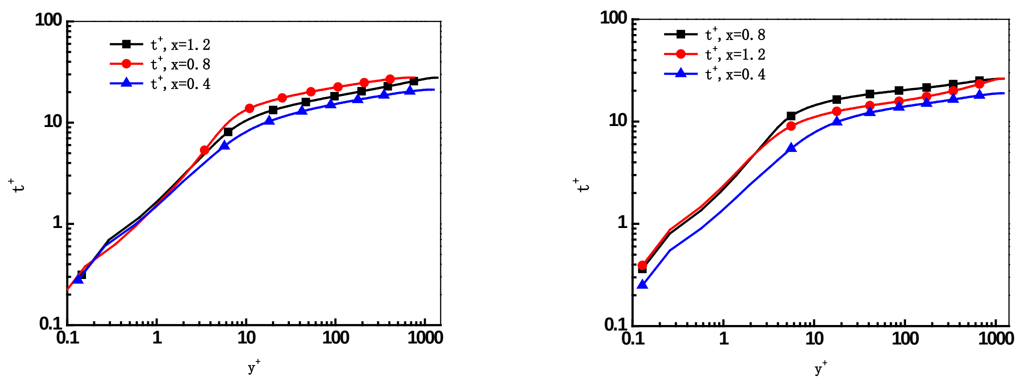
In comparison with the traditional dimensionless temperature, the modified one considers the integrated effect of the fluid density and heat capacity along the wall normal direction. Fig. 4

shows the temperature profile presented by the traditional dimensionless temperature at different locations. The fluid temperature is different at different locations, causing the divergence of fluid properties and changing the relationship between the dimensionless temperature and the dimensionless distance. That's the reason of big scatter of temperature profiles at different locations. However, if the modified dimensionless temperature is used, the differences at various locations could be largely reduced (See Fig. 5). So the modified temperature could also be used to describe the thermal law of the wall under supercritical conditions.



(a)SST (b)EWT

Fig. 4 The traditional temperature profile



(a)SST (b)EWT

Fig. 5 The modified temperature profile

3.2 The boundary characteristics of wall function methods

Based on the new definitions of velocity and temperature, the boundary layer characteristics calculated by wall function methods could be analyzed. Fig. 1 shows that various turbulence models differ much in predicting the peak wall temperature. SST model could reflect the basic trend of the peak; however, other models underestimate the value seriously. In order to obtain detailed information about the performances of each turbulence model, a plane is cut at the axial position of Z=0.8m near the peak wall temperature. The fluid temperature versus the wall distance is shown in Fig. 6. The first grid point for the RNG3 and RNGNEW3 is located in log layer region. There is a big jump between the first grid point and the second one. Both the SST turbulence model and the EWT model could resolve the whole boundary layer. So the calculated temperature can transit smoothly from the wall to the bulk fluid region. At the place where y+ is larger than 10, both models predict very close fluid temperature which also agree with the wall function method. At the place where y+ is between 1 and 10, the temperature predicted by SST model rises from 650K to 820K; at the same time, the temperature predicted by RNGEWT rises from 650K to 720K. At the place where y+ is below than 1, both SST and RNGEWT models predict similar tendency of temperature variation. The place with y+ between 1 and 10 is roughly the buffer region, placed between the viscous and turbulent layer. The buffer layer plays the role of connecting the two layers on both sides. In viscous layer, the molecular viscous force dominates the basic mechanism, and in turbulent layer, the turbulent fluctuation rises to the leading actor. However, in buffer layer, both forces are important and the conflict of them makes it difficult for the turbulence models to predict the phenomena here.

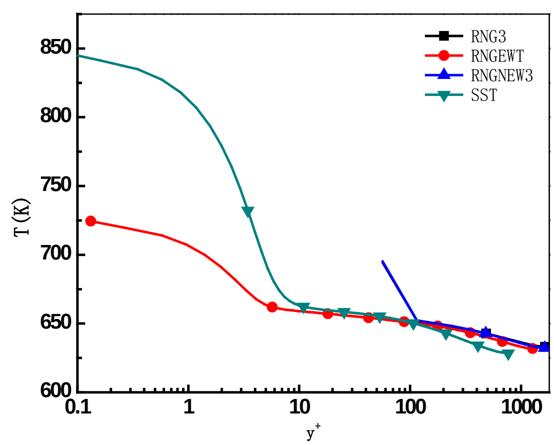
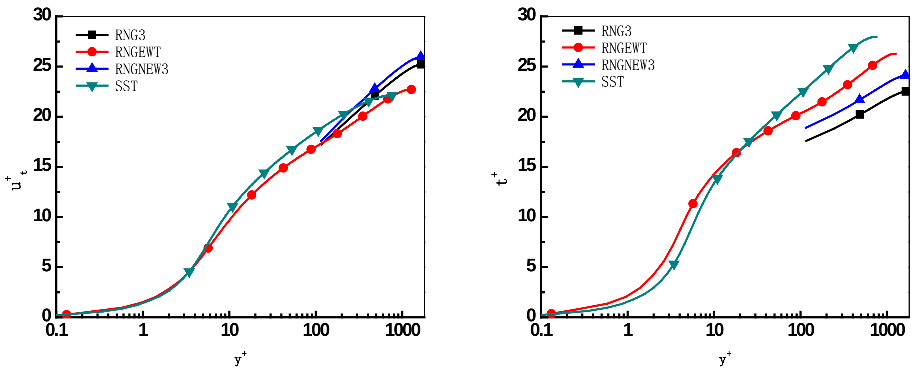


Fig. 6 The comparisons of temperature profiles by different turbulence models

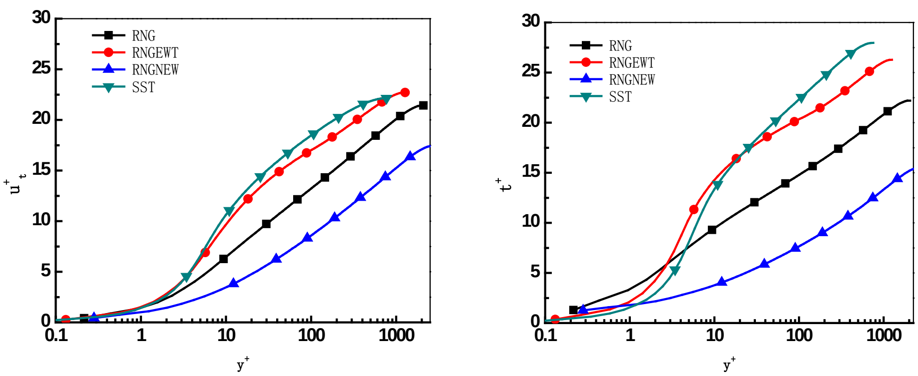
The boundary layer characteristics could be further explained based on the new definitions of dimensionless velocity and temperature. Fig. 7 presents both the velocity and temperature profiles for the four models with the new definitions. Both the SST and RNGEWT model predicts similar velocity profile including the viscous layer, buffer layer and turbulent layer. The RNG3 and RNGNEW3 use the mesh with the first grid located in the log layer. This is in accordance with their suitable range. Although the velocity profiles are close, the temperature profiles show more obvious discrepancies. The deviation origins from the place of y+ about 1 and starts to get amplified across the buffer layer to the turbulent layer. Such deviation may seem small in contrast with the calculated magnitude of temperature difference. The buffer layer, especially in the thermal law of the wall is important in numerical simulation of the heat transfer characteristics of supercritical water.

The RNG and RNGNEW could only take effects on the mesh with the first grid point in the log layer. The reasons behind this could be clarified through similar method. Fig. 8 shows the velocity and temperature profiles for these four models. The difference in contrast with Fig. 7 is that RNG and RNGNEW use the mesh with the first grid point located in the viscous layer. From the figure, both the RNG and RNGNEW methods directly extend the trend of velocity and temperature in log layer to the wall without resolving the buffer layer and the viscous layer. It should be of notice to make sure the location of the first grid point in using the wall function method. Besides, since the wall function method can't solve the whole boundary layer and the traditional thermal law of the wall may not persist under the strong property variation condition, it should be careful to use it in the engineering design.



(a) Velocity profile (b) temperature profile

Fig. 7 The comparisons of velocity and temperature profiles for different turbulent models



(a) Velocity profile (b) temperature profile

Fig. 8 The comparisons of velocity and temperature profiles for different turbulent models

3.3 The boundary characteristics of low Reynolds number methods

The low Reynolds number model can solve the turbulent transport equations through the whole boundary layer in consideration with the wall damping effect in approaching to the wall. It has better theory background. However, the wall damping correction depends on empirical experiences and differs from model to model. Fluent supports kinds of low Reynolds number model, such as Abid, Lam-Bremhors (LB), Launder-Sharm (LS), Yang-Shi (YS), Abe-Kondoh-Nagano (AKN), Chang- Hsieh-Chen (CHC) and so on. SST model is also a kind of low Reynolds number type model. In order to compare all these kinds of turbulent models, their predicted results of wall temperature are presented in Fig. 9. For comparison and completeness, the RSM and RNG model which incorporates the wall function method are also displayed here. Obvious discrepancies could be observed from model to model. Some low Reynolds number models, such as Abid, YS, predict big wall temperature oscillation in the peak temperature region. The result calculated by CHC model is far out of the physical range and is not shown here. The prediction results of LB and AKN are relatively better. LS model predicts the wall temperature far lower than the experimental data, which shows a tendency of wall function method. The Reynolds stress model (RSM) shows advantage in strong anisotropic flow fields, however its wall treatment method still adopts the wall function method. Its behavior is similar with k-ε type model RNG in circular pipe with supercritical water. The SST turbulence model shows better performances in predicting the wall temperature in comparison with experimental data. Besides, the SST turbulence model is more robust and stable than other low Reynolds number k-ε model, which is very important in practical applications.

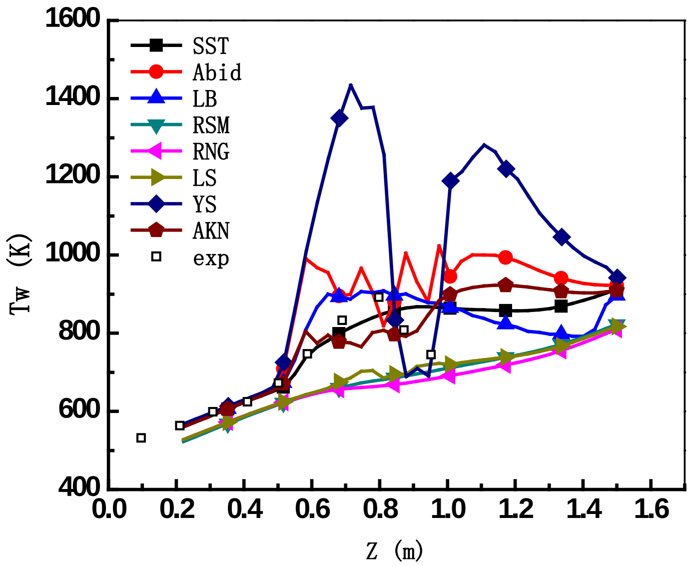


Fig. 9 The comparisons of wall temperature for various turbulent models

In order to see the details of each turbulent model, a plane is cut at the axial place of 0.8m near the wall temperature peak. Fig. 10 shows the temperature variation along the wall normal direction at the cross section for various turbulent models. At the place with y+ larger than 10, nearly all turbulence models predict similar wall temperature profile. The place with y+ between 1 and 10 is the region where big discrepancy origins for various turbulence models. Some turbulence models predict very sharp temperature increase, such as LB, AKN and SST; some predict very flat temperature variation, such as LS, RNG and RSM. At the place with y+<1, the temperature variation becomes small again. The buffer layer region with y+ between 1 and 10 is the place which is hard to predict for various turbulent models.

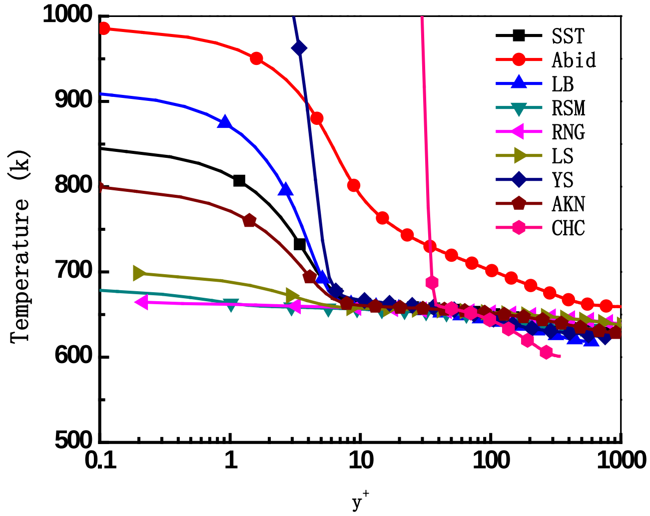
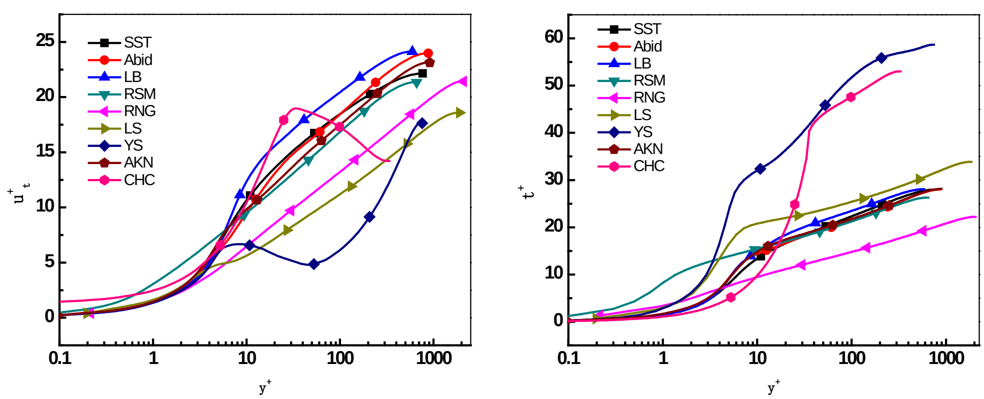


Fig. 10 The comparisons of temperature profiles for various turbulent models

The new definitions of dimensionless velocity and temperature are used to observe the details of each turbulence model. Fig. 11 presents the velocity and temperature profiles at the same location versus the dimensionless wall distance. Although the temperature discrepancy is very big, the difference of the momentum law of the wall predicted by each turbulence model is not that big, except the one with obvious deviation. The boundary layer could be described by most low Reynolds number turbulent model including viscous, buffer and turbulent layer. The thermal law of the wall has more diversity; still the difference seems relatively small in comparison with the actual wall temperature. However, such little difference could lead to big deviation in capturing the peak wall temperature.



(a) Velocity profile (b) temperature profile

Fig. 11 The comparisons of velocity and temperature profiles for different turbulent models

4. Conclusions

The boundary layer characteristics of supercritical water have been studied in this paper with respect to various turbulence models and wall treatment methods. New dimensionless velocity and temperature are defined to help clarify the basic mechanism. The main conclusions are listed below:

1) There are two kinds of wall treatment methods in turbulence modeling, the wall function method and the low Reynolds number method. Each kind of method has its matching mesh parameters. The wall function method requires the first grid to be in the log layer, while the low Reynolds number method requires the first grid in the viscous layer

2) The boundary layer characteristics under supercritical water conditions have to account for the fluid property variation near the pseudocritical point. New dimensionless velocity and temperature have to be defined to consider this. With the new definitions, the momentum and thermal law of the wall could be reconstructed.

3) The comparisons of various turbulence models with experimental data have been done. It is found that different turbulence models have very big performances. The wall function method and the low Reynolds number model are discussed based on the property variation wall function. Different turbulent models predict different boundary layer characteristics which lead to the big divergence in predicting the wall temperature. The buffer layer is the region responsible for the difference and could be considered as a direction for future improvement.

5. Acknowledgement

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Nomenclature

Letters:

c_p	Heat capacity (kJ kg^{-1} K^{-1})
k	Turbulent kinetic energy (m^2s^{-2})
G	Mass flux (kg m^{-2} s^{-1})
P	Pressure (MPa)
q	Wall heat flux (kW m^{-2})
Tw	Wall temperature (K)
T	Temperature (K)
T*	Dimensionless temperature
u^+	Dimensionless velocity
u	Velocity (m $s\text{-}^{1}$)
u_τ	Friction velocity (m s^{-1})
u_c	Velocity at the interface (m s^{-1})
y+	Dimensionless wall distance
Z	Axial location (m)

Greek letters:

ε	Turbulent dissipation rate (s^{-1})
μ	Dynamics viscosity (kg m^{-1} s^{-1})
ρ	Density (kg m^{-3})

Subcripts

w	Wall
b	Bulk

Abbreviations

RNG	Renormalized Group model
EWT	Enhanced Wall Treatment
NEW	Non-equilibrium Wall Function
SST	Shear Stress Transport model