Effect of the Turbulent Prandtl Number on a Simulation of the Heat Transfer from the Supercritical Water in a Vertical Upward Tube Flow

Seong Hoon Kim, Young In Kim, Yoon Yeong Bae, and Bong Hyun Cho
Korea Atomic Energy Research Institute, 150, Deokjin-dong, Yuseong-gu, Daejeon, Korea
arnoldk@kaeri.re.kr

1. Introduction

In a previous research [i], a series of simulations was performed to test various 2-equation turbulence models for the estimation of the vertical upward flow of water in a heat tube at a supercritical pressure. We found that the RNG k-ε model with the enhanced wall treatment performed best for the wall temperature estimation among the tested turbulence models when the experiment by Yamagata et al. was simulated.

We also found that the standard k-ε and RNG k-ε model provided similar estimations when they were used with the wall function as a wall boundary condition. It can be deduced that the difference of the two models under the logarithmic layer may result in a different estimation of the wall temperature when the enhanced wall treatment is used, and the difference of the two models above the layer has little effect on the estimation.

Variation of the strain rate and temperature in the viscous sublayer is relatively higher than the other regions. Variation of the water properties is also high in this region. Flow acceleration, buoyancy, and property variations that are caused by a temperature change can affect the turbulent structure. Among these many factors, this research focuses on the turbulent Prandtl number (Pr_t).

2. Methods and Results

2.1 Computational Method

Computations are performed with the commercial computational fluid dynamics code, FLUENT [ii]. Variation of the water properties at a supercritical pressure is considered by user defined functions. The selected 2-equation turbulence models are: SST k-ω (SST), Wilcox's original k-ω (KW), Abe-Kondoh-Nagano k-ε model (AKN), and the standard k-ε model with the enhanced wall treatment (SKE). The turbulent Prandtl number is selected as follows: the constant values of 0.85 and 0.72 respectively. Kays and Crawford turbulent Prandtl number model is also tested.

The wall heat flux is 930 kW/m^2. The tube is 2 m long and has a diameter of 7.5 mm. The computational domain is axisymmetric. The axial and radial direction grid sizes are small enough to achieve a grid independency. The nondimensional height of the first grid off the wall is around 1 to meet the requirements of the Low-Reynolds number turbulence models.

2.2 Turbulent Prandtl Number

The turbulent Prandtl number was set to be 0.85 as a default of FLUENT in the previous research. However, the RNG k-ε model in the code adopts a different approach for Pr_t. In the RNG k-ε model, the effective thermal conductivity varies with the ratio of the molecular viscosity to the effective viscosity. The value of Pr_t in the RNG k-ε model formulation is about 0.72 in the fully turbulent region. To check the effect of the turbulent Prandtl number on the wall temperature estimation, the constant value of 0.72 is tested.

There have been many researches on the turbulent Prandtl number formulations [iii,iv]. Kays and Crawford [v] suggested a turbulent Prandtl number model, which is given by:

$$Pr_t = \frac{1}{\dfrac{1}{2\,Pr_{t\infty}} + \dfrac{C Pe_t}{\sqrt{Pr_{t\infty}}} - (C\,Pe_t)^2\left[1-\exp\left(-\dfrac{1}{C\,Pe_t\sqrt{Pr_{t\infty}}}\right)\right]} \tag{1}$$

where

$$Pe_t = Pr\frac{\nu}{\nu_t} \tag{2}$$

$Pr_{t\infty}$ is the turbulent Prandtl number far away from the wall and C=0.3. Their suggestion for $Pr_{t\infty}$ is 0.85.

2.3 Result

Figure 1 shows the comparison of the estimated wall temperature. The experimental data and the RNG k-ε model with the enhanced wall treatment are also presented for a comparison.

As Pr_t decreases from 0.85 to 0.72, all the tested models show a dramatic drop of the estimated wall temperature. The difference between the estimation of the SKE and RNG models becomes small as Pr_t decreases. The AKN model estimates a 60°C lower wall temperature at 2000 kJ/kg of the bulk temperature. Peak temperatures that are shown by the AKN and KW models with $Pr_t=0.85$ disappear when $Pr_t=0.72$.

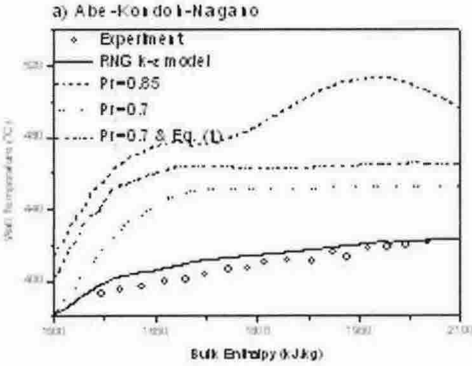
When Pr_t has a lower value, the effective conductivity becomes higher for a given eddy viscosity, which is calculated from the turbulence model. As a result, the energy transfer from the wall to the fluid is enhanced and the wall temperature is reduced.

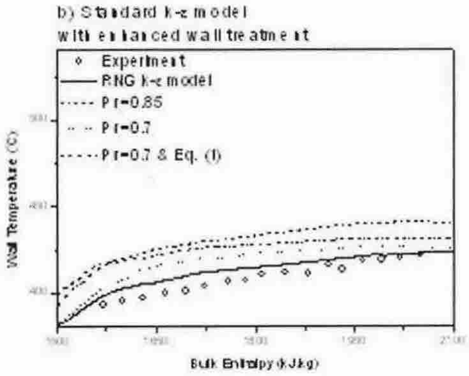
To examine the effect of the Pr_t variation throughout the boundary layer, we conducted simulations with Eq. (1) and $Pr_{t\infty}=0.72$. As is shown in Figure 1, the wall temperature is estimated as higher than the result of the constant value of $Pr_t=0.72$ for all the tested turbulence models. According to Eq. (1), Pr_t approaches to 2 $Pr_{t\infty}$ at the wall. Because of a small diffusion near the wall, the estimated wall temperature is increased.

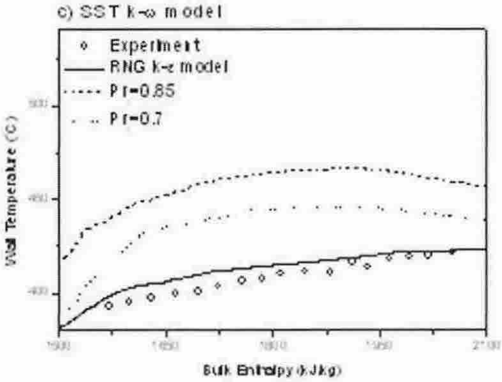
The constant value and the functional form of Pr_t give different estimations of the wall temperature. It means that Pr_t may be one of the keys for making an accurate simulation for the temperature fields at a supercritical pressure.

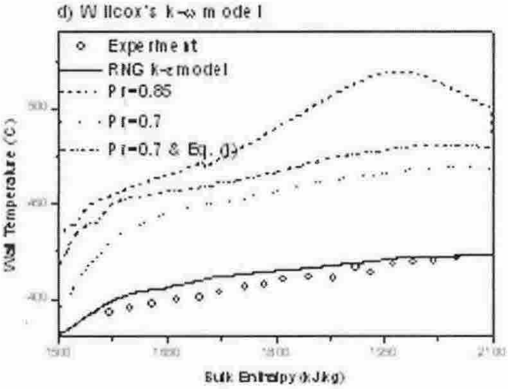
3. Conclusion

1) The turbulent Prandtl number of 0.72 gives a more accurate estimation than the simulation with 0.85 for the wall temperature.
2) The turbulent Prandtl number model by Kays and Crawford with $Pr_{t\infty}$=0.72 predicts a higher wall temperature than the constant value simulations with Pr_t=0.72 for all the tested turbulence models.
3) This research shows that the turbulent Prandtl number is an important factor for the numerical simulation for flows at a supercritical pressure. A more complex turbulent Prandtl number model or turbulent thermal diffusivity transport model is required.


a) Abe-Kondoh-Nagano


b) Standard k-ε model with enhanced wall treatment


c) SST k-ω model


d) Wilcox's k-ω model

REFERENCES

---

[i] S. H. Kim, Y. I. Kim, Y. Y. Bae, and B. H. Cho, Numerical Simulation of the Vertical Upward Flow of Water in a Heated Tube at Supercritical Pressure, Proceedings of ICAPP '04, June 13-17, 2004, Pittsburgh, PA USA.
[ii] FLUENT User's Guide, 2001.
[iii] W. M. Kays, Turbulent Prandtl Number – Where are We?, J. Heat Transfer, Vol. **116**, pp. 284, 1994.
[iv] B. Weigand, J. R. Ferguson, and M. E. Crawford, An Extended Kays and Crawford Turbulent Prandtl Number Model, Int. J. Heat Mass Transfer, Vol. **40**, pp. 4191, 1997.
v[v] W. M. Kays and M. E. Crawford, Convective Heat and Mass Transfer, 3rd ed., McGraw-Hill, New York, 1993.