NUMERICAL PREDICTION OF TURBULENT CONVECTIVE HEAT TRANSFER WITH MOLTEN SALT IN CIRCULAR PIPE

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ABSTRACT

In order to understand the heat transfer characteristics of molten salt and assessment the well-known empirical convective heat transfer correlations. Heat transfer parameters (Nusselt number) calculated by four different RANS turbulence model are analyzed through comparison with present experimental data and the experimental data from the existing literature for turbulent convective. The k-ε model is extended, and the Realizable k-ε model with non-equilibrium wall functions model is proposed in this paper for assessing the thermal-hydraulic characteristics. On the other hand, good agreement was observed between the calculated data of molten salt and the existing well-known correlations. The predicted Nu number using Gnielinski's correlation and Sieter-Tate's correlation have been found to give the closest results to the experimental data.

KEYWORDS
Molten salt
Model
Heat transfer
Nusselt number

1. INTRODUCTION

TMSR[1]（Thorium-based-Molten Salt Reactor）is the fourth generation advanced reactors that represent the most cost effective and leading candidate technology for hydrogen production, electricity generation, chemical engineering and similar to other applications. Molten salt is recommended as a blanket material since it can work as both tritium breeder and neutron multiplier and a heat transfer fluid with advantage of atmospheric pressure, low corrosion, good chemical stability and favorable thermo-physical properties. As fuels and coolants salt, the heat transfer characteristics of molten salt have been considered one of the key design parameters when the molten salt is circulated in the TMSR. Therefore, it is necessary to study the molten salt characteristics and their thermal hydraulic performance in terms of heat transfer coefficients.

Most of the previous studies were concerned mainly with the heat transfer experimental works and analytic studies. These experiments essentially measured the physical properties of molten salts [2] and their heat transfer characteristics [3-8]. Several analytical studies [9-10] had also been carried out, Manidin et al.[10] used the Navier-Stokes and energy conservation equations to estimate thermal gradients in a molten salt. A.K. Srivastava et al.[11] study the heat transfer and pressure drop characteristics of FLiNaK salt flowing a circular pipe with the help of in-house developed CFD code, NAFA. Y.M. Ferng et al.[12] investigate the thermal-hydraulic characteristics of FLiNaK salt by a computation fluid dynamics. But these approaches to predict the heat transfer parameter is limited to the application of two turbulent model that is usually suitable for the conventional heat transfer mediums. Considering the molten salt special characteristics of high heat capacity and high Prandtl number, whether the existing turbulence models can be applied to calculate the heat transfer characteristics of molten salt is worth for assessment and validation.

In this paper, we make an evaluation of different two-equation models (Standard, RNG and Realizable k-ε, k-ω) in heat transfer simulation to investigate the thermal-hydraulic characteristics of molten salt and assessing the influence of the turbulent flow model on the solution. Finally, the k-ε model is extended through comparison with existing experimental data of Nusselt number and the validated model is proposed in this paper for assessing the thermal-hydraulic characteristics of molten salt. Through comparison between existing correlation and the predicted data by assessing CFD model of Nusselt (Nu) number, The predicted Nu number is also in close agreement with that determined using Gnielinski's correlation and Sieter-Tate's correlation, revealing that this correlation is more suitable for predicting the heat transfer characteristics of molten salt.

2. MODEL DESCRIPTIONS

A large molten salt circulating experimental loop has been built to investigate heat transfer characteristics of molten salt in Chinese Academy of Sciences Shanghai Institute of Applied Physics. The specially designed test section is a concentric tube in which a high temperature molten salt stream flowing inside the inner tube is cooled by a low temperature mineral oil stream flowing in the outer tube. The flow is countercurrent. The diameter of the outer tube is 39mm while the inner tube is 25mm. The concentric tube is 1200mm long and 2mm thick.

2.1 Geometric Parameters

As mentioned above, CFD modeling is constructed. The typical computational grid geometry of the entire inflow system is shown in Fig.1 (a) for the simulation and its corresponding mesh presentation on the 2-D cross section is presented in Fig.1 (b).

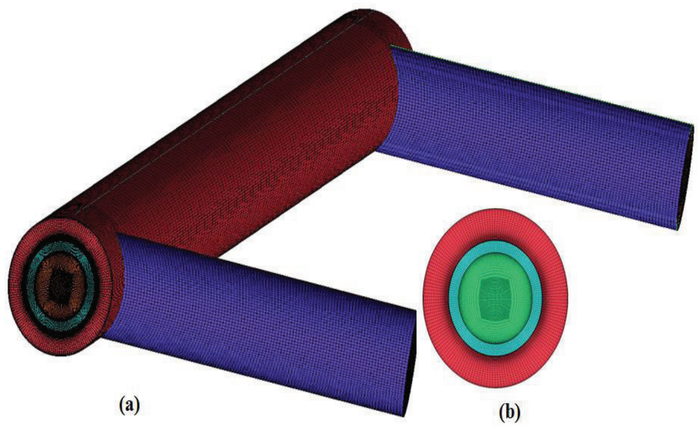

Figure 1. Schematics of simulation concentric tubes and its mesh distributions (a) In 3-D presentation; (b) on 2-D cross section.

2.2 Governing Equations

In order to assess the influence of the turbulent flow model on the solution, the following two equation model were considered and test: standard k-ε、RNG k-ε、Realizable k-ε、k-ω SST. For the first three of these models, three variants of wall treatment have been tested: the standard wall functions (SWF), the non-equilibrium Wall Functions (NEWF) and the enhanced wall treatment (EWT). After a thorough comparison of the results obtained with these models (see Section 3.2), the Realizable k-ε model with non-equilibrium Wall Functions was finally adopted. For the steady-state turbulent flow of an incompressible fluid the equations of continuity, momentum and energy [13]are:

$$\frac{\partial\left(\rho\cdot\bar{u}_i\right)}{\partial x_i}=0 \tag{1}$$

$$u_j\cdot\frac{\partial\left(\rho\cdot\bar{u}_j\right)}{\partial x_j}=-\frac{\partial p}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\left(\mu+\mu_t\right)\cdot\frac{\partial\bar{u}_j}{\partial x_j}\right) \tag{2}$$

$$C_p\cdot u_j\cdot\frac{\partial\left(\rho\cdot T\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(k+k_t\right)\cdot\frac{\partial T}{\partial x_j}\right) \tag{3}$$

The equations for the kinetic turbulent energy and the rate of dissipation of the turbulence kinetic energy corresponding to the Realizable k-ε model[14] are:

$$u_j\cdot\frac{\partial\left(\rho\cdot k\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\cdot\left(\left(\mu+\frac{\mu_t}{\delta_k}\right)\cdot\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\cdot\varepsilon-Y_m+S_k \tag{4}$$

$$u_j \cdot \frac{\partial(\rho\cdot\varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\cdot\left(\left(\mu+\frac{\mu_t}{\delta_\varepsilon}\right)\cdot\frac{\partial\varepsilon}{\partial x_j}\right) + \rho\cdot C_1\cdot S_\varepsilon + G_b - \rho\cdot C_2\cdot\frac{\varepsilon^2}{k+\sqrt{\nu\cdot\varepsilon}} \tag{5}$$

2.3 Numerical Method

The FLUENT code was used to solve the set of partial differential governing equations in order to determine the flow and heat transfer in concentric tubes heat interchanger. The governing equations are discretized in accordance with the finite volume method [15]. The SIMPLE algorithm was used for the treatment of velocity-pressure coupling and the face values of pressure terms have been evaluated using the PRESTO! Method. The second-order upwind scheme is used to treat the convection terms in the concentric tubes heat interchanger. As for viscous terms, second order central difference was assigned. As convergence criteria, excepting the residuals checking, variations of average pressure on outlet boundary and average temperature have been inspected to reach a stable condition.

2.4 Thermo-Physical Properties

Table I. Constants used to evaluate the thermo-physical properties of HTS salt

Working medium	Thermo-physical	a	b	c	d	e	f	g
HTS molten salt	Density（kg/m^3）	2.10608 E+03	-9.0683 0E-01	2.47000 E-04	0	0	0	0
	Specific heat（J/kgK）	1.55000 E+03	0	0	0	0	0	0
	Thermal conductivity（W/mK）	1.35634 E+00	-1.9940 0E-02	1.72000 E-04	-7.45000 E-07	1.71000 E-09	-2.00000 E-12	9.39000 E-16
	Viscosity（kg/ms）	2.63240 E-01	-4.1600 0E-03	2.82000 E-05	-1.02000 E-07	2.07000 E-10	-2.21000 E-13	9.70000 E-17
oil	Density（kg/m^3）	1.02151 E+03	-6.6486 0E-01	5.65000 E-05	-6.86000 E-07	0.00000 E+00	0.00000 E+00	0.00000 E+00
	Specific heat（J/kgK）	1.49436 E+03	4.06551 E+00	-2.84800 E-02	3.91661 E-04	-2.28412 E-06	5.99401 E-09	-5.77942 E-12
	Thermal conductivity（W/mK）	1.35634 E+00	-1.9940 0E-02	1.72000 E-04	-7.45000 E-07	1.71000 E-09	-2.00000 E-12	9.39000 E-16
	Viscosity（kg/ms）	8.90900 E-02	-2.5800 0E-03	3.13769 E-05	-1.97930 E-07	6.78653 E-10	-1.19829 E-12	8.52829 E-16

The working fluid is KNO_3-$NaNO_2$-$NaNO_3$（HTS）molten salt and oil for both the hot and cold passages.

The properties of molten salt, except for specific heat were considered to be temperature independent. The corresponding data was implemented in the numerical code as piecewise-linear functions of temperature. In addition, the physical properties of oil are strongly dependent on the temperature. These temperature-dependent physical properties (Φ) can also be approximated by the following polynomial.

$$\Phi = a + bT + cT^2 + dT^3 + eT^4 + fT^5 + gT^6 \tag{6}$$

The constants in the above equation for each property of molten salt and oil are listed in Table I. The pipe are Inconel600 stainless steel with the following constant thermo-physical properties. $\rho = 8400 kg / m^3$, $C_p = 500 J / (kgK)$ and $\lambda = 16.27 W / (mK)$

2.5 Boundary Conditions

To simulate the fully developed flow, periodic boundary conditions with respect to the main flow direction are imposed at the inlet and outlet of the domain. The application of periodic boundary conditions reduces the domain length resulting in a substantial reduction of the required computational power and time. The inlet of salt velocity and temperature respectively varies from 2m/s to 5m/s and from 473K to 575K, but the inlet of oil velocity and temperature for all simulation is set at 4.5m/s and 443K. The pressure is employed at the two outlets boundary condition and the operating pressure is 1atm.The backflow temperature was set equal to the average temperature of the two fluids at the inlets. At the inlets and outlets, as a boundary condition for the turbulence we chose the turbulence intensity and hydraulic diameter as the specification method.

3. RESULTS AND DISCUSSION

Previous most studies [11] usually used the standard k-ε model to predict the Nusselt number of molten salt. In this paper, To validate the capabilities of CFD-implemented RANS models applied to predict the heat transfer of molten salt, we make an evaluation of different RANS models (Standard, RNG and Realizable k-ε, k-ω) in circular pipe simulation using experimental data for heat transfer parameters as reference values to compare against the numerical results generated. Results of simulations are discussed below.

3.1 Turbulence Model Evaluation

In the turbulent regime (10000＜Re＜40000) five turbulence models were tested, the experimental and numerical Nusselt numbers results are shown in Fig.2. It can be clearly seen from this figure that Obtained results of Nusselt number in the concentric tubes with CFD simulation were compared with the experimental data from the existing literature for turbulent convective in circle pipe[16-18]. In Fig.2, the results obtained with the k-ε seem to fit better with the experimental data than the results obtained with the k-ω models tested. A possible justification for this may be based on the facts that additional diffusion terms in k-ω model can affect the estimation of heat transfer parameters, it means that k-ω model is not suitable to predict the convective heat transfer characteristics of the molten salt.

In other hand, it can be noticed that the realizable k-ε model results show a slightly better agreement with experimental results (Fig.2) in all k-ε models. A possible explanation for this fact is that the realizable k-ε model over-estimates the dissipation due to the changes introduced in the turbulent kinetic energy dissipation equation of the model. An over-estimated dissipation can be translated as an under-estimated mixing the flow model and as a consequence of that, heat transfer is also under-estimated in the model. Realizable k-ε model results reflect the behavior of a slowly strained flow. Which can be noticed in the reduction of k and the over-estimation of the turbulent viscosity (Fig.3).

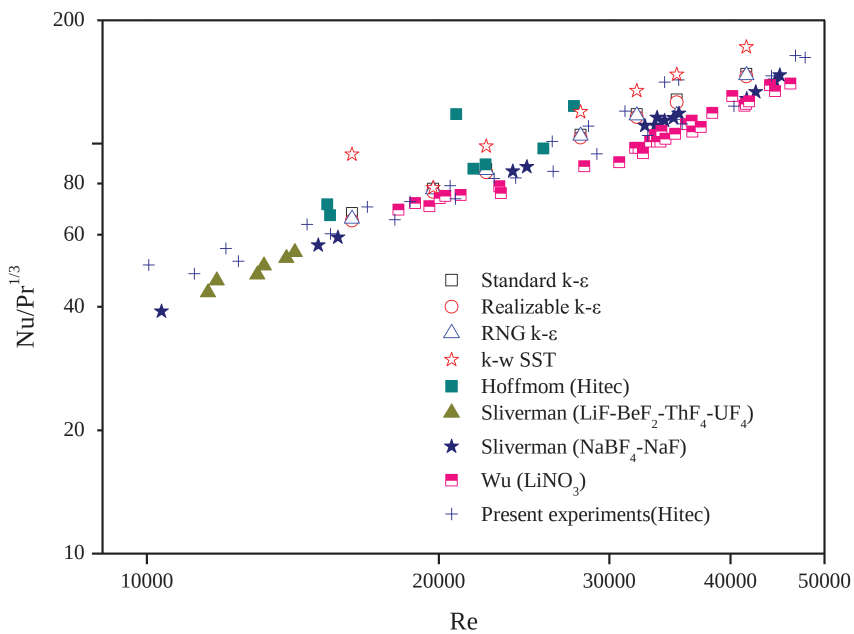

Figure 2. Comparison of Nu Number Between CFD and Experimental Measurements.

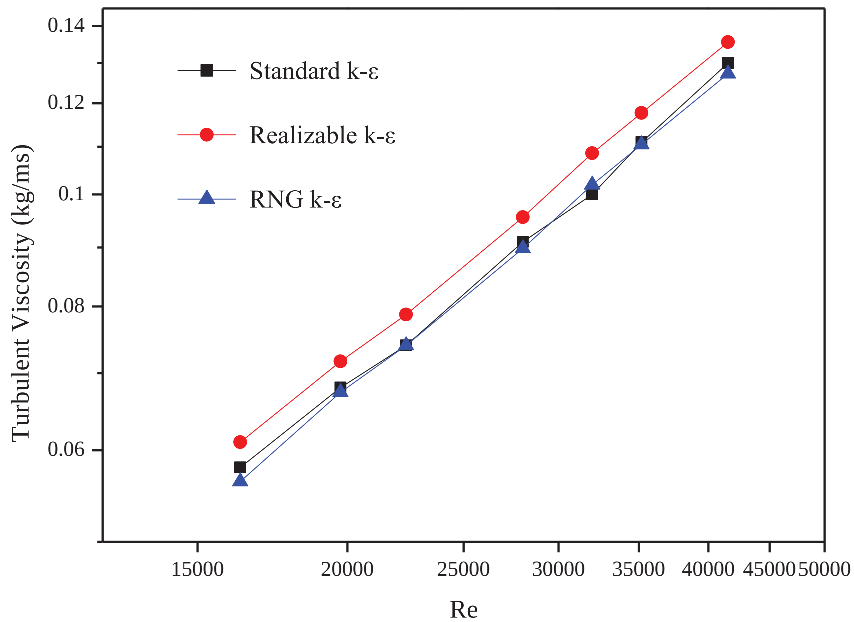

Fig.3. Comparison of Turbulent Viscosity Between CFD and Experimental Measurements.

3.2 Model Extend

Although the realizable k-ε model was found to give the better results with respect to the experimental data, there are still some difference between them. It is known that the k-ε models do not work in the near-wall region, Normally, for modeling near-wall flow with a k-ε model, it is necessary to use a wall function. Previous most studies usually used the default near-wall model (SWF). In this paper, according to the molten salt special characteristics of high temperature and high Prandtl number, the improved and extended model has been proposed to better predict the thermal-hydraulic characteristics of molten salt through comparison with present experimental data.

In the present study the following near-wall models were considered: SWF, NEWF and EWT. Fig.4 shows a comparison of Nu number predicted by different near-wall models predictions with the experimental data reported by Hoffmom[16], Silverman[17], and Wu[18]. It can be clearly seen from this figure that all near-wall models show a good correlation with the experiment data except the EWT, but the k-ε Realizable NEWT give results closer to the experimental data than k-ε Realizable Standard. The absolute values of the maximum and average relative errors with respect to the experimental data are 12.14% and 1.67% for the k-ε Realizable NEWT and 16.52% and 5.77% for the k-ε Realizable Standard. This fact can be the explanation that the NEWF may give improved results for the wall shear stress and heat transfer compared to other standard wall functions. On the other hand the EWT, which combines the best features of a law-of the wall and a two-layer zonal model. Appears suitable for low-Re flows or flows with complex near-wall phenomena.

This consistency with experimental measurements demonstrates that the present CFD methodology with Realizable k-ε turbulence model and the appropriate mesh distribution of NEWF model with the near-wall y^+ of 30-80 can be applied to investigate the thermal characteristics related to the molten salt in confidence. the near wall y^+ range is listed in Table Ⅱ. After a thorough comparison of the results obtained with these models, the Realizable k-ε model with non-equilibrium wall functions was finally adopted. Another point of computational advantage is that this model, which is not very sensitive to the inlet and outlet boundary conditions, also exhibits a more stable behavior and provides a relatively faster convergence.

Table Ⅱ. The near-wall y^+ for the present simulations

Re	16280	19739	22386	28009	32011	35194	41539
SWF	24～37	29～44	32～49	39～59	44～66	48～72	55～83
NEWF	25～36	29～45	32～48	39～59	44～66	47～72	55～84
EWT	1～4	1～4	1～5	1～3	1～3	1～4	1～5

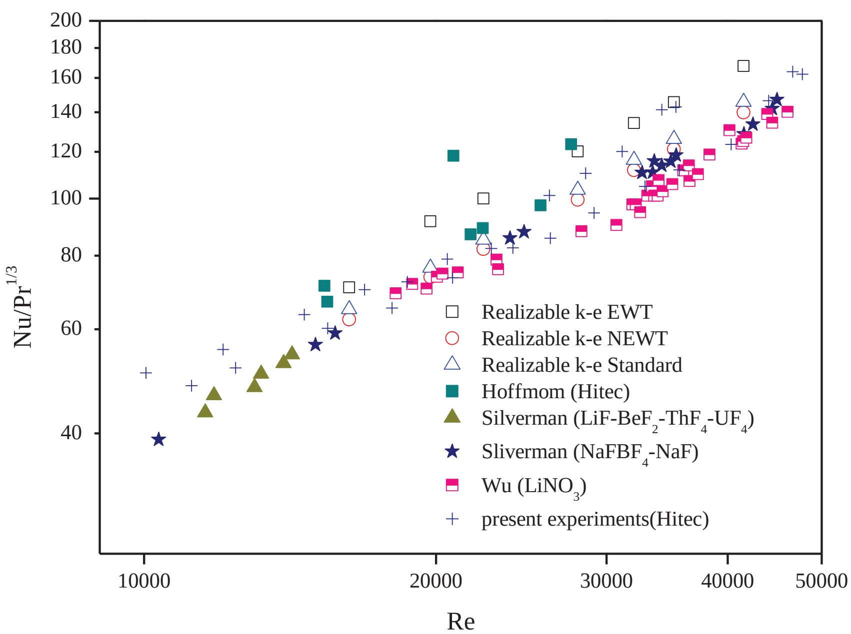

Figure 4. Comparison of Nu number between Extended Model and experimental data.

3.3 Prediction of Nusselt Number

In light of the previous comparisons (Figs. 2,4) and based on the above average errors, the k-ε Realizable

NEWT is considered as the most accurate turbulence model for the heat transfer in concentric tubes heat interchanger under study. This model has been used for all subsequent calculation in this study.

Regarding the CFD model verifications and expand, the values of Nusselt number predicted in the present study can also be compared with those calculated using the well-known correlations presented by Dittus-Boelter、Sieder-Tate、Hausen and Gnielinski. Hausen's correlation is valid for $2300<Re<10^6$ and $0.5<Pr<1000$, and the correlation has the form

$$Nu=0.037(Re^{0.75}-180)Pr^{0.42}[1+(D/L)^{2/3}](\mu_b \mu_w)^{0.14}$$

（2300<Re< 1000000，0.5<Pr<1000）;

Gnielinski's correlation is also suitable for the flow conditions corresponding to $2300<Re<10^6$ and $0.6<Pr<10^5$, and expressed as

$$Nu=0.012(Re^{0.87}-280)Pr^{0.4}[1+(D/L)^{2/3}](Pr_b/Pr_w)^{0.11}$$

（2300<Re< 1000000，0.6<Pr<100000）;

The comparisons results are presented in terms of the average heat transfer coefficient variation as a function of Reynolds number in Fig.5 and Fig. 6. It can be clearly demonstrated by this comparison that the present CFD prediction shows good quantitative and qualitative correspondence with experimental data and correlations. As clearly shown in Fig.5 and 6, the discrepancy is greater when these results are compared with Hausen's correlation and Dittus-Boelter's correlation calculations, but the CFD predicted results correspond well with those obtained by the Sieder-Tate's correlation and Gnielinski's correlation. The absolute values of the maximum and average relative errors between computed value and that obtained from correlations are, respectively 5.08 % and 2.2% for the Sieder-Tate and 6.95% and 3.62% for the Gnielinski. This agreement also reveals that these two correlations can be applied for calculating the Nu number of molten salt.

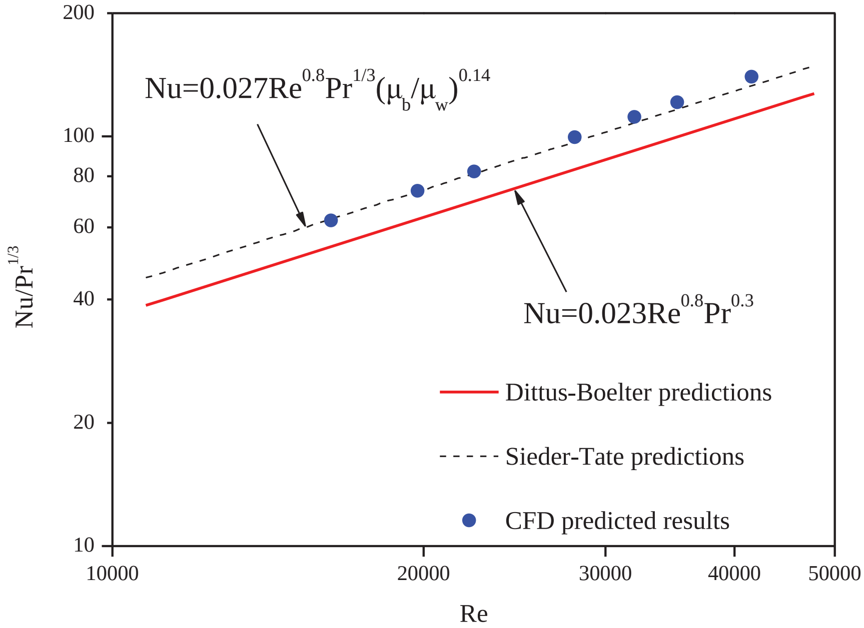

Figure 5. Comparison of Nu number between CFD、Experimental data and Hausen's correlation.

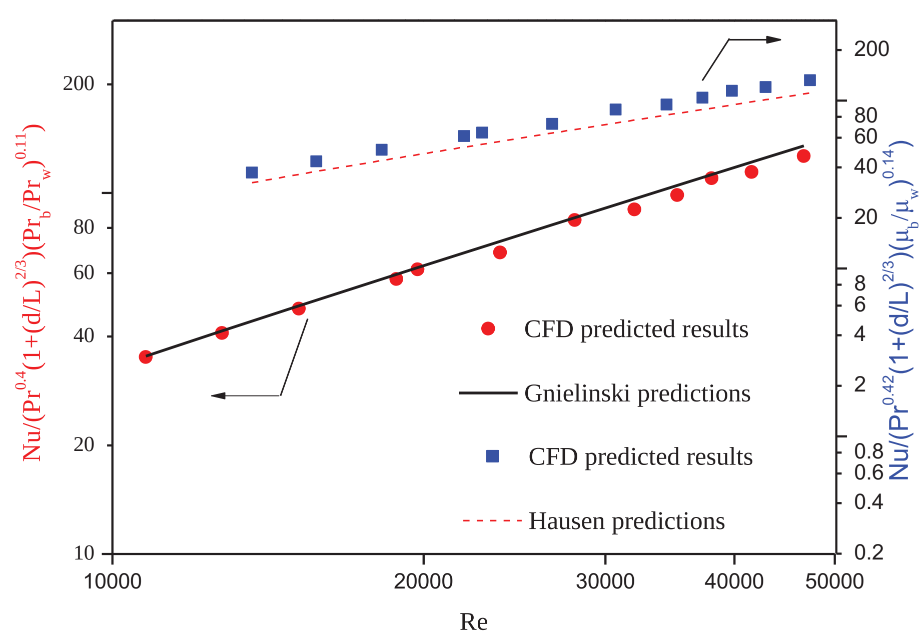

Figure 6. Comparision between the present data and Hausen' s correlation and Gnielinski' s correlation.

CONCLUSION

In order to understand the heat transfer characteristics of molten salt and assess the well-known empirical convective heat transfer correlations. This paper presented a comparison between experimental and numerical data for heat transfer in a concentric tubes to assess a computational fluid dynamics (CFD) model. Standard k-ε、RNG k-ε、Realizable k-ε、k-ω SST model were considered and test. It reveals that the first three two equation model have similar tendency for the heat transfer characteristics while the realizable k-ε model was found to give the better results with respect to the experimental data. But Realizable k-ε model predict heat molten salt special characteristics of high temperature and high Prandtl number with poor accuracy, it is not suitable to predict the the heat transfer characteristcs of molten salt directly. So k-e realizable model is modified and extended, finally combinations of the realizable k-ε model and non-equilibrium wall function were found to give the closest results with respect to the experimental data. This study also shows a comparison between the predicted CFD results by a improved model and the correlations for Nusscel number of molten salt. It can be concluded that existing classical convection heat transfer correlations are applicable for molten salt. Comparisons of the Nu number values show that Gnielinski's and Sieter-Tate's correlation is more suitable for calculating the heat transfer characteristics of molten salt than Hausen's and Dittus-Boelter's correlation.

ACKNOWLEDGMENTS

This work is performed with the support and under the auspices of the "Strategic Priority Research Program" of the Chinese Academy of sciences. And the authors gratefully acknowledge the support of TMSR Project.

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