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Numerical Study on Heat Transfer Performance of Molten Salt Flowing in Inclined Non-uniform Heated Tube for Concentrating Solar Receiver#

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ABSTRACT

Heat transfer performance of molten salt (Hitec) flowing in various inclined tubes under uniform/non-uniform heat flux is numerically investigated. The effect of inclination angle (0°, 45°, 90°), inlet temperature (200 - 400 °C) and heat flux (50 - 350 kW/m^2) on turbulent heat transfer features of molten salt are discussed, and the differences on heat transfer performance and wall temperature distribution between uniform and non-uniform heating are compared. The results show that increasing inlet temperature can lead to low heat transfer ability, but the tube inclination angle and heat flux have almost no effect on heat transfer features. The lateral side non-uniform heat flux also has little effect on heat transfer performance compared with uniform heat flux, but can cause large temperature gap up to 300 °C around the tube. Comparisons of simulation results with existing Nu-correlations show that Qiu-equation have better prediction accuracy for all researching cases with errors of ±8%, especially for high Reynolds numbers. The present results can be helpful for the design and operation of concentrating solar receivers.

Keywords: Molten salt, Heat transfer performance, Inclined tube, Non-uniform heat flux, Concentrating Solar Receiver

NONMENCLATURE

D	inner diameter of tube (m)
h	specific enthalpy (kJ·kg^{-1}·K^{-1})
g	gravity (m·s^{-2})
k	turbulent kinetic energy (m^2·s^{-2})
L	length (m)
Nu	nondimensional Nusselt number (-)
P	pressure (Pa)
Pr	nondimensional Prandtl number (-)
q	heat flux (kW·m^{-2})
q'	local heat flux (kW·m^{-2})
q_{max}	the maximum heat flux at -90° (kW·m^{-2})
Re	nondimensional Reynolds number (-)
T	temperature (°C)
u	velocity (m·s^{-1})
y^+	the nondimensional wall distance (-)
z	axial distance from inlet (m)
Abbreviations	
CSP	Concentrating Solar Power
Symbols	
α	Inclination angle (°)
ε	turbulent dissipation rate (m^2·s^{-3})
θ	circumferential angle (°)
ρ	density (kg·m^{-3})
μ	dynamic viscosity of fluid (Pa·s)
ω	specific dissipation rate (m^2·s^{-3})

1. INTRODUCTION

With global warming and environment issues intensifying, the utilizations of renewable energy develop rapidly. Concentrating Solar Power (CSP) as a high-efficiency solar energy utilization technology, has been widely concerned in recent years [1]. Considering the randomness and intermittency of solar energy, molten salts are usually employed in CSP systems as an energy storage medium to receive solar irradiation and transfer heat to working fluids, due to its superior cost and thermostability [2]. Molten salt flowing in receivers is heated by non-uniform radiation of solar in one-side, which can induce non-uniform heat transfer features of molten salt and local hot spot burning in tube wall. So, research on flow and heat transfer characteristics of molten salts under non-uniform heat flux is greatly necessary for improving receiver performance and the safe operation of CSP systems.

As the fast development of CSP technology, Numerous studies have been carried out to reveal the flow and heat transfer performance of by using Solar salt [3-5], Hitec [6-8], FLiNaK [9,10] and several home-made salts [11,12]. For experiments, Liu et al. [13] obtained heat transfer dataset of $LiNO_3$ flowing in a horizontal tube, which was heated by oil, and good agreement was observed between the experimental data of molten salt and the existing well-known correlations. Wu et al. [11] researched convective heat transfer process of a new-made salt to water in a horizontal heat exchanger, and found that existing Sieder-Tate correlation [14] and Gnielinski correlation [15] show good agreement with the experimental data at Re 10000 ~ 21000. Kim et al. [12] experimentally studied the heat transfer features of a self-made five-component molten salt in a uniform heated vertical tube, and correlations for both transition and turbulent flow regions were proposed. Chen et al. [16,17] conducted series studies on heat transfer of molten salt heat exchanged with oil in horizontal circular tube, and existing heat transfer correlations for laminar, transition and turbulent region are respectively evaluated.

In view of the difficulty of experiments with non-uniform heat flux, numerical studies were generally conducted. Ferng et al. [10] studied thermal-hydraulic characteristics of FLiNaK salt flowing in uniform heated tube by CFD software. The effect of entrance length was discussed and the predictive ability of existing Gnielinski correlation was compared. Chen et al. [18] performed simulations of Hitec salt flowing in single-side (bottom, top and lateral) heated horizontal square tube. The results shown buoyancy have a great effect on heat transfer enhancement comparing with forces convective heat transfer, due to the secondary vortex at low Re region. Chang et al. [4] simulated the heat transfer performance of Solar salt in horizontal annular tubes, and the effects of annular diameter and eccentricity were discussed. Qiu et al. [19] recently in numerically studied heat transfer and flow friction performance of four salts (Hitec, Solar salt, NaF-NaBF4, and FLiNaK) with uniform/non-uniform heat flux in vertical tube, and found that the uniformity of heat flux had little effect on heat transfer and flow performance but lead to local overtemperature region. A new heat transfer correlation suitable for various salts was proposed to further improve the predictive accuracy of existing Sieder-Tate correlation. Ying et al. [20] further studied the convective heat transfer of molten salt-based nanofluid with Al_2O_3 nanoparticles in a non-uniform heated tube and the effects of particle concentration, fluid properties and heat flux profile on heat transfer performance were analyzed.

To sum up, most existing studies on heat transfer of molten salt are conducted in horizontal tubes under uniform heated condition or coupled convective heat exchanging with oil, especially for experimental research. Only Shen et al. [21] experimentally investigated the heat transfer characteristics of Hitec salt in a 16 mm inner-diameter horizontal tube with self-circumferential non-uniform heat flux at Re 10000 ~ 67000, and discovered that the overall heat transfer of molten salt flow in circular tube had little relation with nonuniform heat flux conditions but shown a large wall temperature difference in tube sections, which was similar with conclusions obtained by Qiu et al. [19] simulation. In addition, traditional tower-type CSP receiver tubes are usually assembled vertically, which accept non-uniform solar irradiation in one-side. Compared with vertical installation, receiver tubes adopting spiral inclined arrangement shows obvious advantages such as longer pipeline, more heat absorption and more uniform heating process. Secondary flow driven by buoyancy and centrifugal force in spiral inclined flow also has some enhancement effect on heat transfer of molten salt. However, the heat transfer process of molten salt in inclined tubes is still seldom discussed in past research, especially with non-uniform heat flux. The effect of operating parameters such as inlet temperature, heat flux and velocity on heat transfer remained poorly understood [17].

This paper focused on the heat transfer performance of Hitec salt flowing in inclined tubes under uniform/non-uniform heat flux. The effect of inclination angle, inlet temperature and heat flux on turbulent heat transfer features are investigated numerically. The differences on heat transfer performance and wall temperature distribution between uniform and non-uniform heating are compared. Finally, the suitability of existing heat transfer correlations for molten salt flowing in inclined tubes with non-uniform heat flux are examined.

2. NUMERICAL SIMULATION

2.1 Geometry model and boundary conditions

As presented in Fig.1, the simulating geometry employed in this study is a circular tube with 20 mm inner-diameter and 2 mm wall thickness. The heated length of the tube is 2.5 m and inclination angle is α, varing from horizontal (0^o) to vertical (90^o). The material of tube wall is SS316L. Hitec salt is selected as the heat transfer fluid, which is assumed as incompressible. The thermophysical properties of Hitec salt is acquired from ref.[19], and can be inserted into ANSYS Fluent simulator by User Defined Functions (UDF) compilation. Constant mass flux with preset temperature was adopted at the inlet, which keeping inlet Reynolds number (Re) from 10000 to 60000. The pressure outlet condition was set at the tube outlet. Uniform heat flux condition was exerted on the outer tube wall for general cases, while for non-uniform heating cases, cosine heat flux distribution ($q' = q_{max} \times \sin\theta$, where θ is circumferential angle) was only set at half- circumferential lateral side of the tube. The inner wall was set as no slip boundary. The interface between wall and fluid was set as fluid-solid coupling to consider the effects of both heat conduction and convection.

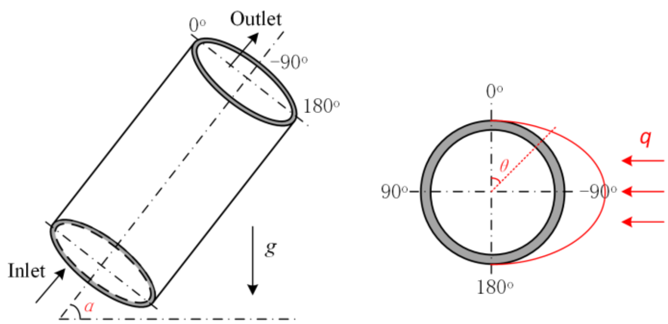

Fig.1 Geometry model of the simulation

2.2 Governing equations and solution procedure

For steady-state flow and heat transfer, the transport equations of mass, momentum, and energy can be described as follows:

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

$$\partial\left(\rho\bar{u}_i\bar{u}_j\right)/\partial x_j = -\partial P/\partial x_i + \partial\left(\bar{\tau}_{ij} - \overline{\rho u_i' u_j'}\right)/\partial x_j + \rho g_i \tag{2}$$

$$\partial\left(\rho\bar{u}_j h\right)/\partial x_j = \partial\left(\frac{\mu}{\mathrm{Pr}}\frac{\partial h}{\partial x_j}\right)\Big/\partial x_j - \partial\left(\overline{\rho u_j' h}\right)/\partial x_j \tag{3}$$

where ρ, μ and u are the density, viscosity and velocity, respectively.

The finite-volume method was employed to solve the governing equations and the SIMEPEC algorithm was used to treat the pressure and velocity coupling. The second order upwind scheme was applied to discretize the transport equations for a high accuracy. The under-relaxation factors were set as proper values during the simulation to keep the convergence of the iteration. During the simulations, variations of outlet temperature and several local wall temperatures were monitored until no changing. Meanwhile, the solution was considered as convergent when the residual is less than 10^{-6} for mass equation and less than 10^{-7} for other variables.

2.3 Mesh and verification

Both *k-ω* and *k-ε* type turbulent models have been recommended by previous researchers [10,22,23] for simulating molten salt turbulent flow and heat transfer issues. In the present paper, three turbulent models containing SST *k-ω*, RNG *k-ε* and Standard *k-ε* were selected and compared with the experimental data obtained by Lu et al. [6]. The detail turbulent expressions and constants can be referred in [24]. For SST *k-ω* model, the grid in boundary layer was refined enough to keep the nondimensional wall distance (y^+) of first node closing to 1.0, but for *k-ε* models with standard wall treatment method, the y^+ of the first node keeping within 30 - 60 was suitable for molten salt turbulent flow, due to the relative gentle variations of thermophysical properties of fluid salt. Fig.2 displays the comparisons between experimental data and simulating results of three models. It shows that Standard *k-ε* model have a better prediction accuracy for molten salt turbulent heat transfer simulation, and is adopted for further studies. The mesh was built and validated case by case to ensure the y^+ within 30 - 60. For present simulations with Re from 10000 to 60000 and inlet temperature from 200 to 400 °C, the total mesh cell number of all cases varies from 150000 to 800000.

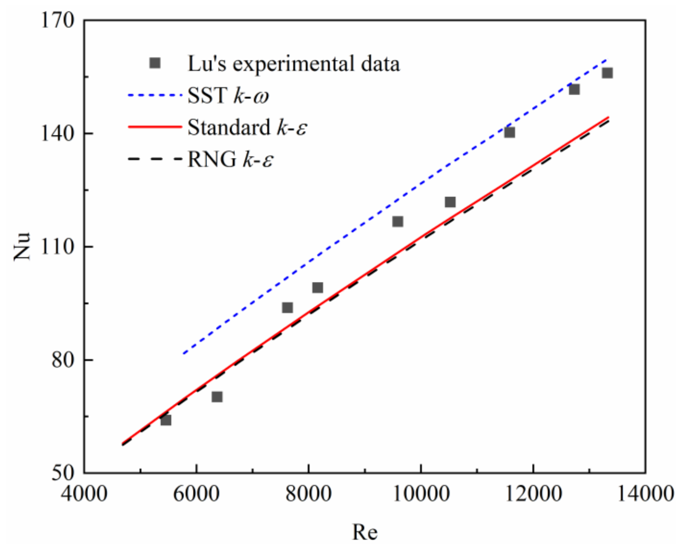

Fig.2 Comparisons between simulations and test data[6]

3. RESULTS AND DISCUSSION

3.1 Effects of inclination angle, inlet temperature and heat flux on heat transfer

Fig.3 displays the variations of Nu versus Re in different inclined tubes with two heat fluxes. It shows that heat transfer performance (Nu) is generally strengthen with the increase of Re from 10000 to 60000, and the Nu-Re variations keep a same trend with inclination angle increasing from 0° (horizontal tube) to 90° (vertical tube) at both uniform heat flux of 250 kW/m^2 and 350 kW/m^2, which indicate that turbulent heat transfer characteristics of molten salt is hardly affected by tube inclination angle and heat flux. The reason can be interpreted that, the effects of buoyancy and secondary flow disturbance on heat transfer in horizontal and inclined tubes are negligible against strong turbulent flow.

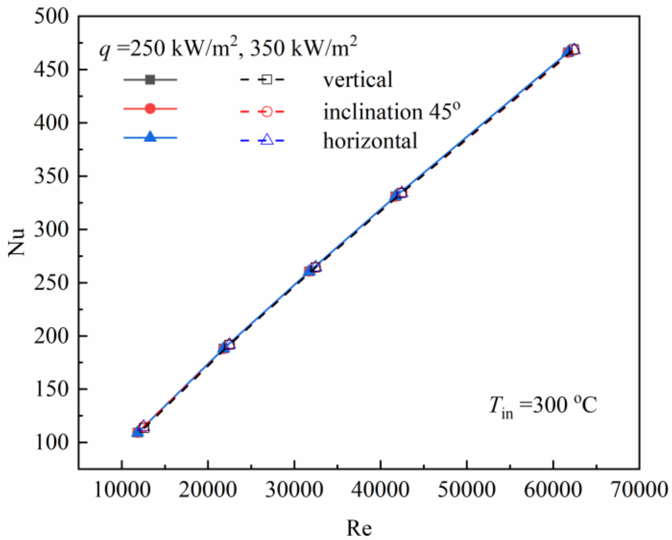

Fig.3 Effects of inclination angle with different q

Fig.4 displays Nu-Re variations of molten salt with different inlet temperatures in horizontal, inclined 45° and vertical tubes. It can be seen that, with the increase of inlet temperature from 200 °C to 400 °C, Nu of molten salt decreases in the whole Re range, and the declined extent of Nu is larger with higher Re, which means that the heat transfer performance of Hitec salt is weakened by increasing inlet temperature. This is mainly because higher inlet temperature introduces a lower thermal conductivity of salt and smaller temperature difference between fluid salt and tube wall, which diminishes the convective heat exchange. Fig. 4 also shows that the variations of Nu-Re in different inclined tubes is similar, meaning the effect of inlet temperature on heat transfer is independent of the inclination angles of receiver tube.

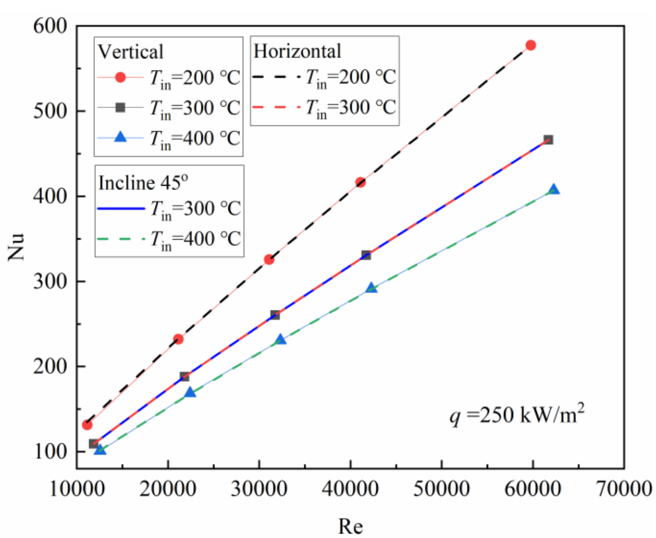

Fig.4 Effects of inlet temperature with different α

Fig.5 further shows the variations of Nu versus Re at different heat fluxes in vertical tube. It is seen that, the Nu-Re curves nearly have no change with heat flux increasing from 50 to 350 kW/m², which is consistent with the conclusion in Fig.3.

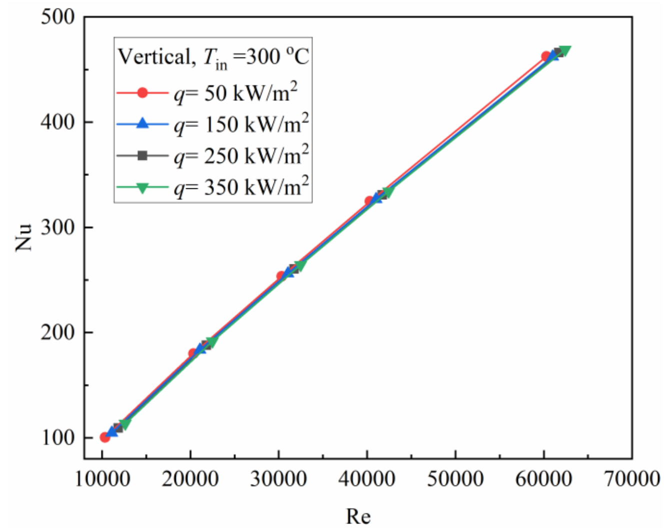

Fig.5 Effects of heat flux on Nu versus Re

3.2 Comparison between uniform and non-uniform heating cases

To find out the effect of heat flux uniformity on heat transfer of molten salt, non-uniform heat flux and equivalent uniform heat flux are exerted on outer surface of tube wall. As shown in Fig.6, non-uniform heat flux is set as a cosine distribution in one-side of the tube, while corresponding uniform heat flux is exerted on whole tube outer wall, keeping the total heat absorption equal in both two cases.

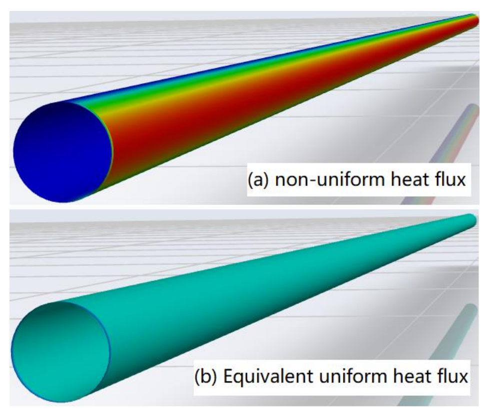

Fig.6 The diagram of uniform and non-uniform heat flux distributions with the same equivalent heat

Fig.7 given the comparison of Nu-Re curves between uniform and non-uniform heat flux cases. It indicates that little disparity exists among Nu-Re trends for different heat flux distributions and tube installations. The uniformity of heat flux has almost no effect on overall heat transfer performance for both vertical and inclined arrangement of solar receiver tubes. This conclusion is the same as that obtained by Qiu et al. [19]

in the variations of Nu versus Re with uniform/non-uniform heat flux by changing inlet temperature.

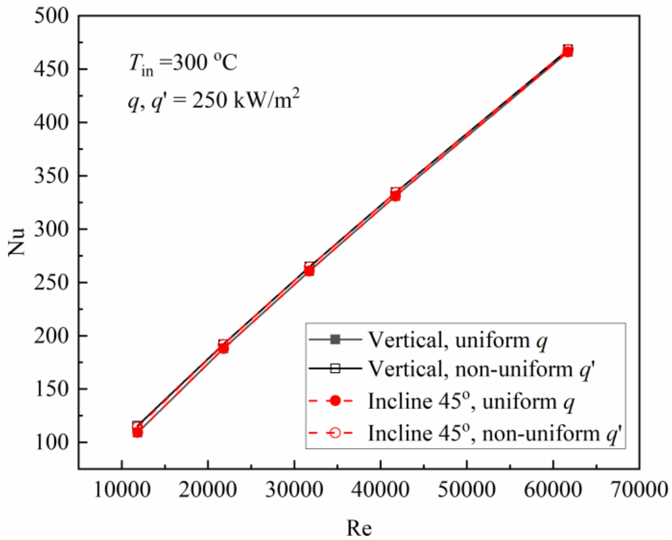

Fig.7 Comparisons of Nu-Re between uniform and non-uniform heat flux cases

The local circumferential distributions of inner tube wall temperature at z = 1.5 m section for corresponding cases in Fig.7 are depicted in Fig.8. It displays that large temperature difference appears in non-uniform heating tube compared with that in uniform heating cases. Local high temperature region formed and the maximum of wall temperature is about 900 °C and locates at the light side (θ = -90°). The temperature gap between receiving side and backlight side is up to near 300 °C, which can induce large thermal stress to threaten the safety operation of receivers, and must be monitored and mitigated as much as possible.

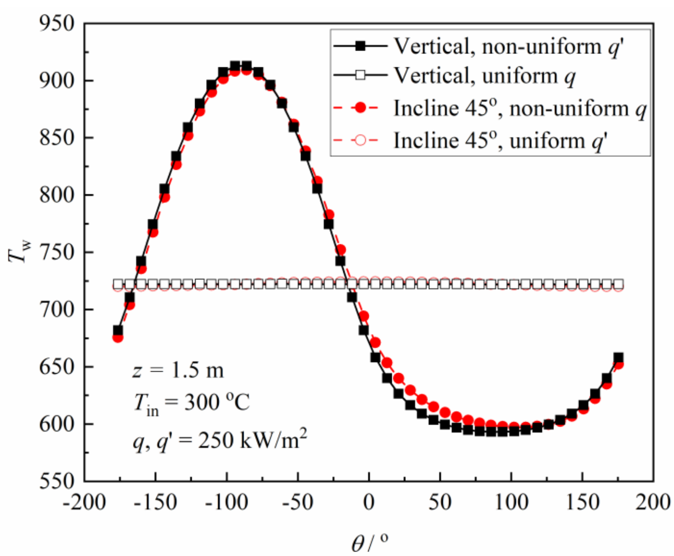

Fig.8 Comparisons of Circumferential T_w distribution between uniform and non-uniform heat flux cases

3.3 Prediction of existing heat transfer correlation

High-precision correlations for predicting heat transfer coefficients of molten salt are necessary for the design and optimization of receiver devices. Among numerous existing heat transfer correlations of molten salt, Qiu et al. [19] evaluated the accuracy of three existing popular correlations against heat transfer data of four molten salt covering Re from 10^4 - 11×10^4, then Gnielinski's correlation [15] and a new proposed correlation were recommended, shown in Eq. (4) and (5), respectively.

Gnielinski-correlation:

$$Nu = 0.012\left(\mathrm{Re}^{0.87} - 280\right)\mathrm{Pr}^{0.4}\cdot\left(\frac{\mathrm{Pr_f}}{\mathrm{Pr_w}}\right)^{0.11}\left[1+\left(\frac{D}{L}\right)^{2/3}\right] \quad (4)$$

where Re = 2300 - 10^6, Pr = 0.6 - 10^5.

Qiu- correlation：

$$Nu = 0.0154\cdot\mathrm{Re}^{0.853}\cdot\mathrm{Pr}^{0.35}\cdot\left(\frac{\mu_\mathrm{f}}{\mu_\mathrm{w}}\right)^{0.14} \quad (5)$$

where μ_f/μ_w = 1.01 - 1.30, Re = 10^4 - 10^5, Pr = 3.3 - 34.

The comparison of relative error between the prediction and original simulated results by two heat transfer correlations is displayed in Fig.9, which indicates that the Qiu-correlation shows a better prediction accuracy with relative errors falling into the range of ±8%, which against Gnielinski-correlation errors spanning from -5% to +13.5%. Then, the Qiu-correlation is recommended for heat transfer prediction of Hitec salt flowing in varying inclination tube with different heat flux supply.

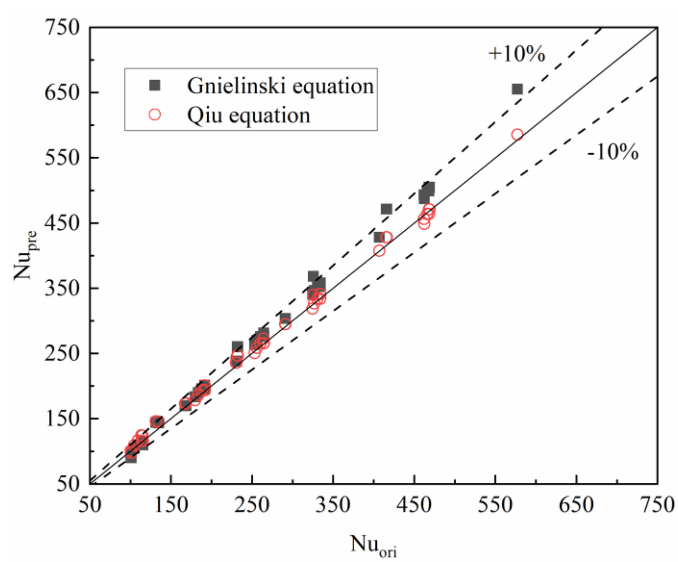

Fig.9 Comparison of Nu prediction errors between Gnielinski-correlation [15] *and Qiu-correlation* [19]

4. CONCLUSIONS

Turbulent heat transfer performance of molten salt (Hitec) flowing in various inclined tubes under uniform/non-uniform heat flux was numerically investigated. The parameter range contained inclination angle from 0^o to 90^o, inlet temperature from 200 to 400 ^oC and heat flux from 50 to 350 kW/m^2. The following conclusions can be drawn:

(1) Inclination angles and heat fluxes have almost no effect on turbulent heat transfer performance of Hitec salt in receiver tube, due to the negligible buoyancy and secondary flow effects.
(2) Increasing inlet temperature of molten salt can cause a lower heat transfer performance, due to lower thermal conductivity of salt and smaller temperature difference between fluid salt and tube wall.
(3) The uniformity of heat flux has almost no effect on overall heat transfer performance of salt, but lateral side non-uniform heat flux can cause local hot region with temperature gap up to 300 ^oC, which must be monitored and controlled to ensure safety operation of receivers in CSP systems.
(4) Qiu-correlation can be recommended for heat transfer prediction of Hitec salt flowing in varying inclination tube with different heat flux supply, during the design and development of solar receivers.

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