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Research Paper

# Numerical analysis of heat transfer to water flowing in rifled tubes at supercritical pressures

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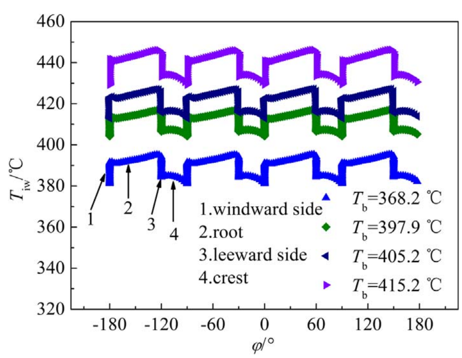
## HIGHLIGHTS

- Inner wall temperature varies periodically in circumferential direction.
- At the root the variation of heat flux is contrast to that of inner wall temperature.
- Heat transfer is enhanced due to fluid with large specific heat.
- The increase of thread height significantly improved heat transfer.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

Heat transfer to supercritical water flowing in vertical upward rifled tubes are studied. The shear stress transport turbulence model was applied to numerical analysis and was validated with experimental data. Results of numerical simulation showed that the present model could provide a satisfactory prediction with enough accuracy. According to the results, inner wall temperature varies periodically in circumferential direction. It peaks at the intersection of the root and the leeward side and reaches the minimum at the intersection of the crest and the windward side. The circumferential distribution of inner wall heat flux is similar to that of the inner wall temperature. However, at the root the variation of inner wall heat flux is contrast to that of inner wall temperature and the rotational flow caused by the screw thread may contribute to this result. Heat transfer enhancement occurs where the boundary layer is filled with fluid of large specific heat and the effect of kinetic energy is not dominant. The structural parameters of screw thread affect heat transfer in rifled tubes. The increase of thread height significantly improved the performance of heat transfer, but the effects of pitch, lead angle and thread form are negligible.

## 1. Introduction

Coal is the primary energy in China, but inferior coal occupies the majority of this important resource. Therefore, developing clean coal combustion technology to reduce pollution emission is the top priority. Supercritical circulating fluidized bed (CFB) is a promising combustion technology due to its excellent fuel adaptability and low emission of $SO_2$ and $NO_x$. However, traditional supercritical CFB boiler meets the problem of lacking evaporating surfaces. Then a new boiler with the so-called annular furnace is proposed in China. To keep the wall temperature within the permissible range, it is essential to evaluate the performance of supercritical heat transfer in this designed tube for the

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**Nomenclature**

| | |
|---|---|
| $d$ | diameter, m |
| $e$ | thread height, m |
| $g$ | gravitational acceleration, $m\,s^{-2}$ |
| $h$ | enthalpy, $kJ\,kg^{-1}$ |
| $k$ | turbulent kinetic energy, $m^2\,s^{-2}$ |
| $N$ | number of screw thread |
| $p$ | pressure, Pa |
| $P$ | pitch, m |
| $q$ | heat flux, $W\,m^{-2}$ |
| $T$ | temperature, °C |
| $u$ | velocity, $m\,s^{-1}$ |
| $w$ | thread width, m |
| $y$ | wall distance, m |
| $C_p$ | specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$ |

*Greek letters*

| | |
|---|---|
| $\lambda$ | thermal conductivity, $W\,m^{-1}\,K^{-1}$ |
| $\rho$ | density, $kg\,m^{-3}$ |
| $\varphi$ | circumferential angle, ° |

*Subscripts*

| | |
|---|---|
| ave | average |
| b | bulk |
| h | hydraulic |
| iw | inner wall |
| ow | outer wall |

*Abbreviations/Acronyms*

| | |
|---|---|
| CFB | circulating fluidized bed |
| HTC | heat transfer coefficient |
| HTD | heat transfer deterioration |
| SST | shear stress transport |

boiler.

Supercritical water experiences sharp thermo-physical property variations within a narrow range of temperature (less than 50 °C) and this region is known as the great specific heat region (GSHR). Swenson et al. [1] found that heat transfer was significantly enhanced in the GSHR and HTC achieved its maximum value which was much higher than that calculated with Dittus-Boelter's correlation. Similar experimental results were also obtained by Yamagata et al. [2], Yoshida and Mori [3] and Ackerman [4]. Ackerman [4] proposed the pseudo-boiling theory and believed that due to severe variation of density, heat transfer in the GSHR was analogous to what happened in boiling heat transfer at subcritical pressures. According to these studies, the enhancement can occur either in smooth tubes or in rifled tubes at supercritical pressures. Nishikawa et al. [5] indicated that heat transfer coefficient (HTC) for nucleate boiling in rifled tube was 3 ~ 5 times than that in smooth tube. Thus, better performance is achieved in rifled tube at subcritical pressures, but little study has been done to reveal whether it is also the case at supercritical pressures. Variations of thermo-physical properties can also result in heat transfer deterioration (HTD) at supercritical pressures. Jackson and Hall [6–8] found that HTD occurred in upward flow and disappeared in downward flow and proposed the two-layer theory to clarify the deterioration due to buoyancy effect. According to numerous studies [5,9–13], dry-out was delayed to a high vapor quality and departure from nucleate boiling (DNB) was suppressed in case rifled tube was used. Many researchers [4,14–16] also believed that HTD caused by buoyancy at supercritical pressures can be suppressed by rifled tube. However, limited work is performed to study how heat transfer is enhanced and the mechanism remains unclear.

As computer technology develops rapidly, numerical analysis has drawn much attention to study the microscopic mechanism of supercritical heat transfer in tubes. Limited to immature theory, early works used relatively simple models to predict heat transfer [17]. Then, various low Reynolds number $k$-$\varepsilon$ models were proposed and numerous studies have been performed using these models [18]. Menter introduced the shear stress transport (SST) model, which combined the $k$-$\varepsilon$ model and $k$-$\omega$ model such that the $k$-$\omega$ was used in the inner region of the boundary layer and switched to the $k$-$\varepsilon$ in the free shear flow. Over recent decades, the SST model was applied in many researches [14,15,19]. The results showed that the SST model showed good performance in reproducing HTD caused by either buoyancy or acceleration effect. But most of these numerical analysis focused on smooth tubes and more work should be done with rifled tubes to clarify how the screw thread alters the flow field and improves heat transfer.

The SST model is adopted in the present paper to numerically analyze the heat transfer of supercritical water in rifled tubes. Physical mechanisms of enhanced heat transfer are revealed with numerical results. Circumferential distributions of inner wall temperature and heat fluxes are obtained and the reasons lead to this result are discussed. Effects of structural parameters of the screw thread on heat transfer are also analyzed to find out the dominant factors.

## 2. Numerical models

### 2.1. Physical model

This paper studied a 2-m long rifled tube with a hydraulic diameter of 19.1 mm which is schematically shown in Fig. 1. The detailed structures of the screw thread, including thread height, thread width, pitch, lead angle etc., are shown in Fig. 2 and the specific values are listed in Table 1. We have done an experimental research on a rifled tube to gain its heat transfer performance in a macroscopic view. The inner wall temperature distributions along the tube with various flow conditions have been presented in the previous work. The rifled tube established in the numerical model is the same with that in the experimental study conducted by the authors. Therefore, the

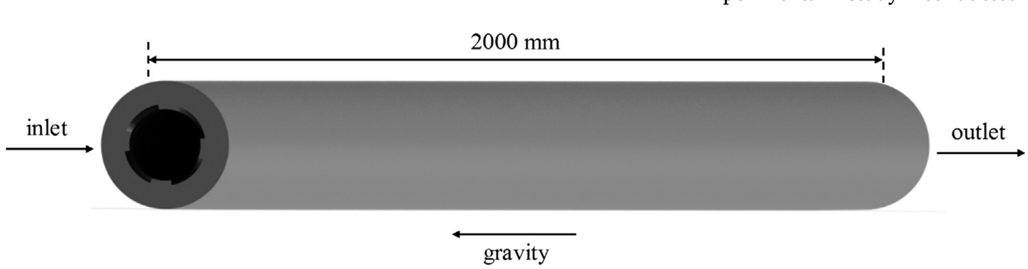


**Fig. 1.** Physical model of the rifled tube.