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Study on the effects of system parameters on entropy generation behavior of supercritical water in a hexagon rod bundle

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ABSTRACT

In this study, a numerical simulation was performed to investigate the entropy generation behavior of the supercritical water flow in a hexagon rod bundle by using various system parameters, i.e., system pressure, heat flux, and mass flow rate. The Speziale–Sarkar–Gatski Reynolds stress model was verified using experimental data and then used to predict the flow and heat transfer of the supercritical water. The influence mechanism of the system parameters on the entropy generation behavior was discussed in detail. It was found that the system pressure has a minor effect on the entropy generation within the heat transfer enhancement region, while the effects of the mass flow rate and heat flux are significant. The entropy generation of the supercritical water in an inner sub-channel of the hexagon rod bundle decreases with the increasing mass flow rate and increases with the increasing heat flux. A non-dimensional entropy generation is defined to fully evaluate the comprehensive effects of the mass flow rate and heat flux. The results show that the increase in the mass flow rate has a greater effect on the reduction in non-dimensional entropy generation in the low–mass-flow-rate region rather than in the high–mass-flow-rate region. Based on the simulation results, the criteria of non-dimensional entropy generation of 0.4 is set up and the relationship between the mass flow rate and heat flux is determined to balance the minimum irreversibility loss and offer parameters value for practical application in the design strategy of a supercritical water-cooled reactor.

1. Introduction

Although research on the heat transfer of supercritical water (SCW) flows has been conducted for decades, this subject is still interesting because of the applications of SCW in nuclear engineering [1–4] and supercritical fluid oxidation and extraction [5,6]. As a generation IV nuclear technique, the SCW reactor (SCWR), which has a considerably higher thermal efficiency, has gained much attention from researchers [7,8]. Compared to the flow in a round pipe, the SCW flow in an SCWR is limited for a non-circular structure. Therefore, the circumferential heterogeneity of the heat transfer of the SCW makes the flow complicated and sets a higher requirement of engineering safety [9]. Researchers usually use the heat transfer coefficient (HTC) and the pressure drop to evaluate the flow and heat transfer performance of the SCW within the reactor core. However, the changes of HTC and pressure drop are related, which means that improvement in the HTC is often obtained at the high expense of pressure drop [1,2,10–13]. An entropy generation analysis [14], also known as the second law of thermodynamics, can be used to study the flow and heat transfer from the point view of energy analysis. It can comprehensively consider the heat transfer and flow resistance in the thermodynamic calculation for a process or system that involves a complex flow and a heat transfer phenomenon, e.g., the SCW flowing in the sub-channel of a reactor core.

In recent years, the entropy generation analysis has been widely used for the investigation and optimization of thermal processes. Eger et al. [15] proposed a new and canonical configuration for electric machines using the entropy generation analysis to find regions in which the heat transfer could be intensified in order to optimize the structure. The irreversibility loss distribution is confirmed to be a promising indicator for detecting the regions of great potential for improving the heat transfer. Saqr et al. [16] investigated the effect of the inlet swirl intensity and streamwise swirl decay on the heat transfer and local entropy generation in pipe flows. The computational fluid dynamics (CFD) results agreed well with the established laser Doppler velocimetry measurements, indicating that the swirl number radically affects the local entropy generation owing to the viscous dissipation in the inner core of the Rankine vortex structure. Furthermore, they extended the study based on the entropy generation minimization (EGM) principle

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Nomenclature

Be	Bejan number
g	gravity acceleration (m s^{-2})
G	mass flow rate (kg m^{-2} s^{-1})
H	enthalpy (J kg^{-1})
HTC	heat transfer coefficient (W m^{-2} K^{-1})
k	turbulent kinetic energy (m^2 s^{-2})
p	pressure (N m^{-2})
Pr_t	turbulent Prandtl number
q	heat flux (W m^{-2})
S_{gen}	entropy generation per unit volume (W m^{-3} K^{-1})
S_{genH}	entropy generation caused by heat transfer (W m^{-3} K^{-1})
S_{genF}	entropy generation caused by energy dissipation (W m^{-3} K^{-1})
S^*	non-dimensional entropy generation
T	temperature (K)
u, v, w	velocity components in the x, y and z directions (m s^{-1})
y^+	non-dimensional distance from the wall
z	flow direction (m)
β	constant in SST model
ε	dissipation rate of k (m^2 s^{-3})
ρ	density (kg/m^3)
μ	molecular viscosity (kg m^{-1} s^{-1})
μ_t	turbulent viscosity (kg m^{-1} s^{-1})

Subscript

b	bulk
ng	narrow gap
sc	sub-channel center
pc	pseudo-critical

[17]. The Nusselt number and entropy augmentation number were studied as functions of the wall-fluid temperature difference and swirl intensity, indicating that the EGM would be achieved only at a high wall-fluid temperature and swirl intensity. Zhang et al. [18] proposed the laminar flow field synergy equation based on the EGM method in free water jet impingement. The numerical simulation was verified using the experimental approach, thus ensuring that the local synergy angle could aid in the improvement of the heat transfer performance in jet impinging. The results show that the proportion of the total entropy generation rate mainly affects the stagnation zone rather than the wall jet zones.

As the SCW has a higher specific heat near the pseudo-critical temperature, it can absorb a large amount of heat without a significant temperature rise or phase change [13,14]. Owing to the special heat transfer characteristics of this fluid, the entropy generation behaves differently from that of sub-critical water Mohseni et al. [19] took into account the effect of the variation of the SCW properties on the entropy generation and found that lower entropy generation is always accompanied with a higher heat transfer rate. That is, the entropy generation behavior can reflect the heat transfer performance of SCW well. In Zhang's study [20], a numerical research on the entropy generation of SCW in a vertical tube with concentrated incident solar heat flux on one side was presented. The results show that the entropy generation decreases with the increasing mass flux and decreasing incident heat flux. In addition, a relationship between the incident heat flux and mass flux that can balance the minimum irreversibility losses and hydraulic resistance in the tube is determined.

Near the pseudo-critical point, the entropy generation reaches a minimum value as the heat transfer coefficient has a maximum value. However, owing to the non-circular flow cross-section in the SCWR, the entropy generation behaves differently in both the axial and lateral directions. Moreover, the system parameters can also remarkably affect the entropy generation behavior. Thus, further research should be conducted on the entropy generation behavior of SCW in a hexagon rod bundle while considering the effects of the system parameters.

In the nuclear industry, the changes in the system parameters can primarily influence the thermal efficiency and system security. However, the relevant researches are rarely mentioned in open literatures. In the present study, the system parameters, including the heat flux, mass flow rate, and system pressure, are taken into account. The contributions of two mechanisms of entropy generation, i.e., heat transfer and fluid friction, are also determined. Owing to the non-circular structure of the sub-channel, the circumferential heterogeneity is considered in the mechanism analysis. The commercial CFD software CFX is used as the working platform, and a great number of simulation cases under various system conditions are investigated in order to minimize the entropy generation and obtain a comparatively optimal strategy for the system-parameter configuration of the SCWR from a point view of energy analysis. This study extends the theoretical study of both the second law of thermodynamics and the SCW and might provide a valuable reference for the conceptual design of an SCWR.

2. Physical and mathematical modeling

2.1. Configuration

Fig. 1(a) shows the configuration of the inner sub-channel used in this study and the tight hexagon rod bundles consisting of seven fuel rods. Considering the rotational periodicity, as shown in Fig. 1(b), the shaded area is chosen as the sub-channel region for the numerical computation. It should be noted that there are two typical positions to be considered, i.e., the sub-channel center and narrow gap. These two positions exhibit two extremes of heat transfer and are represented by 30° and 0°, respectively. In this study, the angles at the positions along the cladding surface increase in the counter-clockwise direction.

The fuel-rod diameter is 8 mm, and the ratio of its pitch to its diameter is 1.125. The hydraulic diameter is 3.17 mm. The heat transform of the cladding surface is set as a uniform heat flux. The detailed information has been specified in previous studies [12,13].

2.2. Entropy generation analysis

Based on the second law of thermodynamics, the entropy is generated as long as a temperature difference exists. In the previous work by Bejan [14] and other extending researches, the entropy generation analysis was comprehensively developed. Generally, entropy generation may be an appropriate criterion for estimating the potential of improving the performance of the heat transfer. Within the fluid flows coupling the heat transfer, the entropy generation is the sum of that generated due to heat transfer (S_{genH}) and to fluid friction (S_{genF}), which has the same saying as energy dissipation [11]. Thus, the local entropy generation has the following basic form:

$$S_{gen} = S_{genH} + S_{genF} \tag{1}$$