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Study on thermal and hydraulic characteristics of supercritical LNG in zigzag PCHE under sloshing conditions

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Abstract

Supercritical liquefied natural gas(LNG) in the printed circuit heat exchanger(PCHE) on the floating liquefied natural gas system(FLNG) will slosh due to wind and sea waves, which will affect its thermal and hydraulic characteristics. In this paper, the characteristics under different working parameters of zigzag channel PCHE are simulated and analyzed. Results show that compared to the static condition, the sloshing enhances the characteristics and has a greater effect on the flow uniformity along the flow direction. Furthermore, the sloshing amplitude and period are beneficial to the thermal and hydraulic characteristics, but excessive sloshing period and amplitude may cause stagnation or countercurrent in the flow process. Increasing the mass flux appropriately can prevent this from happening.

Keywords

Printed circuit heat exchanger(PCHE); Supercritical LNG; Zigzag channels; Sloshing condition; Thermal and hydraulic characteristics.

1. Introduction

Heat exchangers in the floating liquefied natural gas system(FLNG) should meet the requirements of miniaturization and high airtightness. These requirements can fit the narrow working spaces and harsh sea conditions [1,2]. The most common form of compact heat exchanger has the printed circuit heat exchanger(PCHE) developed by Heatric. This heat exchanger can conform to these requirements of FLNG [3-5]. For some previously published samples, the PCHE channel structure can boost the thermal and hydraulic characteristics. Moreover, the zigzag channel has better characteristics than another type, which are widely adopted in PCHE [6,7].

Supercritical fluid has the advantages of both gas and liquid, such as the density is like that of liquid, but the viscosity and diffusion coefficient is close to gas [8,9]. Therefore, supercritical LNG, as the working medium of PCHE, is designed to improve its thermal and hydraulic characteristics.

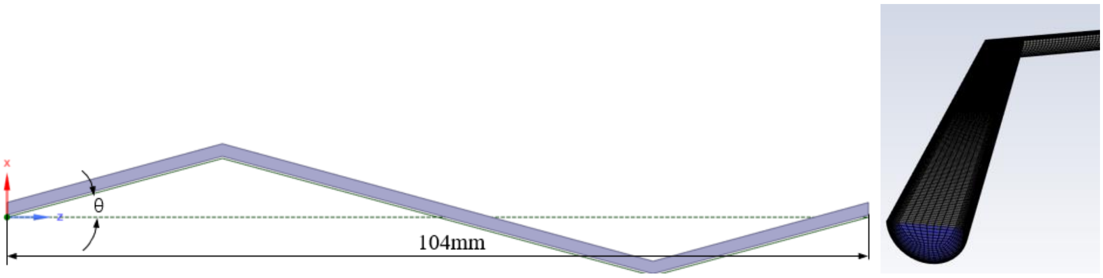
As is known, PCHE will slosh affected by wind and ocean waves, which affects the thermal and hydraulic characteristics accordingly. As a result, the sloshing condition should take into consideration. In previous studies, the working pressure and mass flux of supercritical LNG has a dominant reflection on the thermal and hydraulic characteristics [10]. Also, the thermal and hydraulic characteristics will change significantly when the parameters vary under sloshing conditions [11].

In this study, the numerical simulation approach could be conducted, and the zigzag channel PCHE is regarded as the research object. This paper first discussed the influence of pressure, mass flux, sloshing amplitudes, and sloshing periods on the thermal and hydraulic characteristics of supercritical LNG. Then, the effect between the sloshing and static conditions is compared. Additionally, the changes in thermal and hydraulic characteristics under different parameters are evaluated. They thereby can provide an informative optimization for heat exchanger performance in practical engineering.

2. Numerical Simulation

2.1. Model building and condition setting

As shown in Figure 1(a), the three-dimensional numerical model of the single periodic zigzag channel is carried out by ANSYS CFD software. Firstly, the period length is set as 104 mm, the model angle θ as 15°, and the diameter of the semicircle cross-section as 1.5 mm. In addition, the structuring grid cells have been divided, of which the distance between the first layer and the interface is set as 0.01 mm, the layers as 12, the growth factor as 1.2, and the grids as 1.7 million, shown in Figure 1 (b).



(a)schematic diagram of the zigzag channel (b) grid schematic

Figure 1: Schematic diagram of the channel

2.2. Critical condition and boundary condition setting

To put the LNG in a supercritical state, the temperature is controlled between 191K and 260K. A constant temperature about the boundary condition of the fluid wall is set as 260K, and the temperature of fluid intake as 191K. The mass-flow-inlet and pressure-outlet are applied to the fluid intake and fluid exit. Table 1 shows the working conditions under various operational circumstances.

Table 1:Different condition parameters

Parameter/ symbol	Example 1	Example 2	Example 3	Example 4
Work pressure/p_{in}	8~10	10	10	10
Mass Flow/G	207.2~407.2	207.2	207.2	207.2

Sloshing amplitude/A	0.032	0.032	0.016~0.064	0.032
Sloshing period/T	1	1	1	0.5~4

2.3. Sloshing condition setting

The sloshing direction of the channel is found as the z-axis and the cross-section of the channel as the x-y plane. Under sloshing circumstances, the formulas for sloshing displacement, velocity, acceleration, and period are as follows [12]:

$$x_z(t) = A\cos\omega t \tag{1}$$

$$v_z(t) = -\omega A \sin\omega t \tag{2}$$

$$a_z(t) = \frac{dv}{dt} = -\omega^2 A \cos\omega t \tag{3}$$

$$T = \frac{2\pi}{\omega} \tag{4}$$

These formulas are above adopted to realize sloshing conditions in ANSYS FLUENT, which are compiled into the user-defined function(UDF). The transient state is adopted for calculation, as well as the pressure and velocity are coupled through the SIMPLE algorithm. The residuals of the continuity, momentum, and energy equation are controlled below 10^{-5} and 10^{-7}, the time step as 0.001s, and the number of iterations per time step as 40 times. Calculation within a time step is used to judge the convergence of the transient state.

3. Results and discussion

3.1. Pressure and mass flow

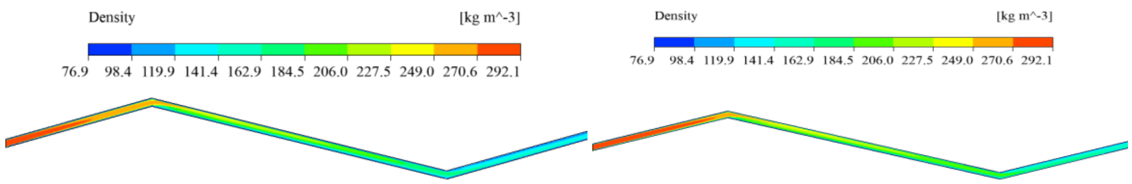
The influence of pressure and mass flux will contribute to corresponding changes in the thermal and hydraulic characteristics of supercritical LNG. Example 1 in Table 1 is simulated the heat transfer and flow of supercritical LNG in the channel. Figure 2 presents the density of the y-axis center cross-section in different inlet pressures at t=1s. As shown, the density gradually decreases along the flow direction and increases correspondingly at the same position as the working pressure elevates.

To analyze the influence of the supercritical LNG thermal and hydraulic characteristics under different working conditions, the time-averaged Nusselt number $\overline{Nu}$ and the time-averaged Darcy friction factor $\bar{f}$ are introduced. The formulas are as:

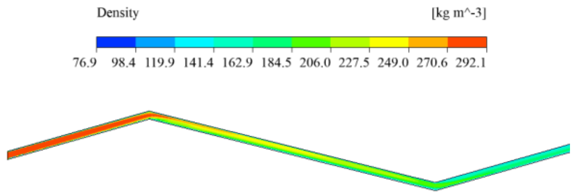
$$\overline{Nu} = \frac{1}{T}\int_0^T Nu(t)dt \tag{5}$$

$$\bar{f} = \frac{1}{T}\int_0^T f(t)dt \tag{6}$$

where $Nu(t)$ is the instantaneous Nusselt number, $f(t)$ is the instantaneous Darcy friction factor.



(a) 8Mpa (b) 9Mpa



(c) 10Mpa

Figure 2: Density cloud map of supercritical LNG under different pressures

As shown in Figure 3, $\overline{Nu}$ increases with the mass flux elevating or the pressure reducing. This can be explained that the Reynolds number being greater when the mass flux becomes larger or the pressure becomes smaller. A larger Reynolds number enables the turbulence to be stronger, the thermal characteristics are also strengthened. In the same way, $\bar{f}$ reduces with the elevation in mass flux or pressure. This is because the pressure drop increases with the mass flux or pressure elevating, and the flow uniformity deteriorates so that the hydraulic characteristics become weakened.

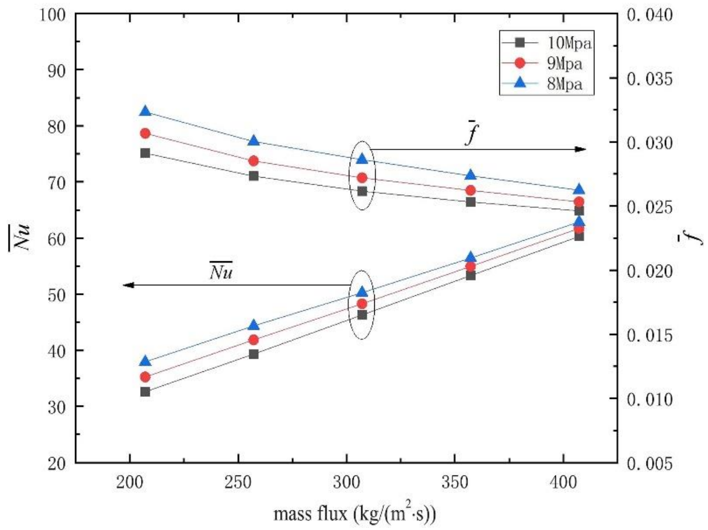


Figure 3: Thermal and hydraulic characteristics under different pressure and mass flux

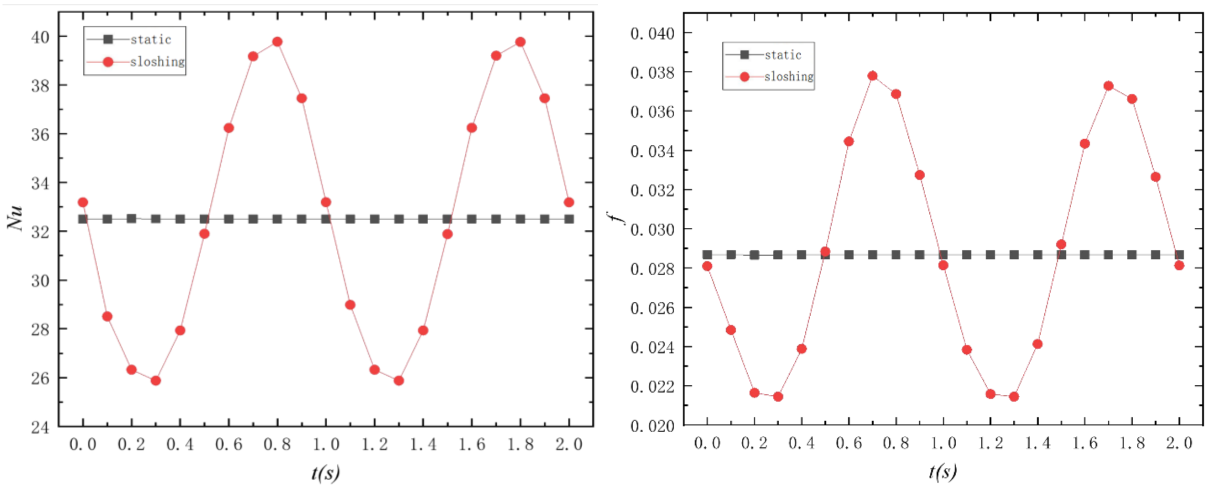
3.2. Analysis of thermal-hydraulic characteristics of sloshing and static conditions

In this section, the working condition is Example 2 revealed in Table 1. The thermal and hydraulic characteristics of supercritical LNG under static and sloshing conditions are identified in Figure 4. It can be seen from Figure 4(a) that the thermal characteristic of sloshing is the worst at 0.3s and the best at 0.8s. According to the calculated results, the $\overline{Nu}$ is 0.39% higher than the static, thus sloshing enhances the thermal characteristics. As shown in Figure 4(b), the hydraulic characteristics are the worst at 0.3s and the best at 0.7s. According to the calculated results, The $\bar{f}$ is 1.55% higher than the static, thus sloshing also enhances the hydraulic characteristics.

Figure 5 and Figure 6 illustrate the cross-sectional velocity cloud diagrams at the corners and the outlets of the channel in different sloshing times. It is found that the inertial force generated by the sloshing contributes to the turbulence at the corners, which makes the velocity become fluctuate, and changes the velocity extreme value area.

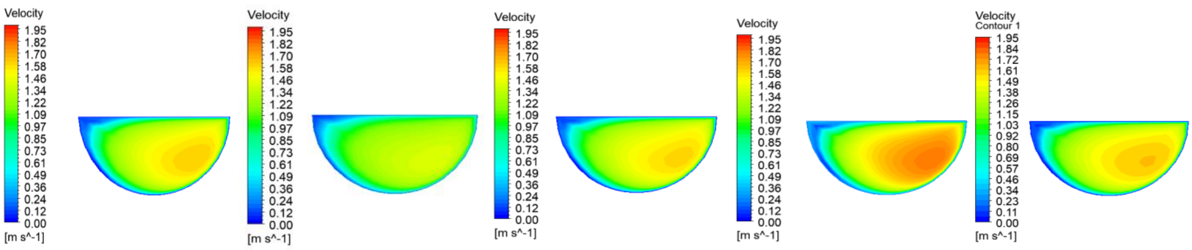
Figure 7(a) analyzes the velocity distribution of supercritical LNG at different channel positions, where the abscissa represents the channel position. Combined in Figure 5 and Figure 6, composite images of each frame are revealed. It can be shown that compared with static conditions, the best fluid distribution uniformity is at 0.25s. However, the fluid velocity and the turbulence are dropped because the inertial force is opposite to the flow direction. Therefore, the static thermal characteristics and the sloshing hydraulic characteristics are better during the 0 to 0.5s. In addition, the worst fluid distribution uniformity is at 0.75s. However, the fluid velocity and the turbulence are risen due to the inertial force is compatible with the flow direction. Therefore, the sloshing thermal characteristics and the static hydraulic characteristics are better during the 0.5 to 1s.

Figure 7(b) demonstrates the flow uniformity perpendicular to the flow direction (Y-axis), where Y/H=0 and Y/H=1 stand for the bottom and the top of the channel. The figure sketches that the flow uniformity in this direction changes little under the sloshing condition. In summary, we can conclude that sloshing has a greater impact on the flow uniformity in the flow direction, and has a small impact on that in the vertical direction.



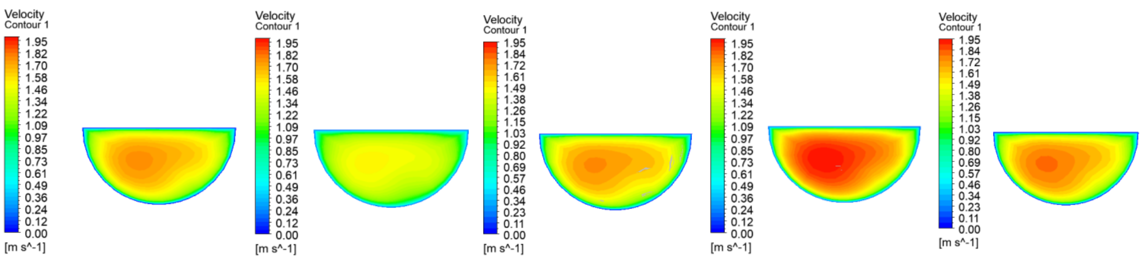
(a)thermal characteristics (b)hydraulic characteristics

Figure 4: Thermal and hydraulic characteristics under sloshing and static conditions



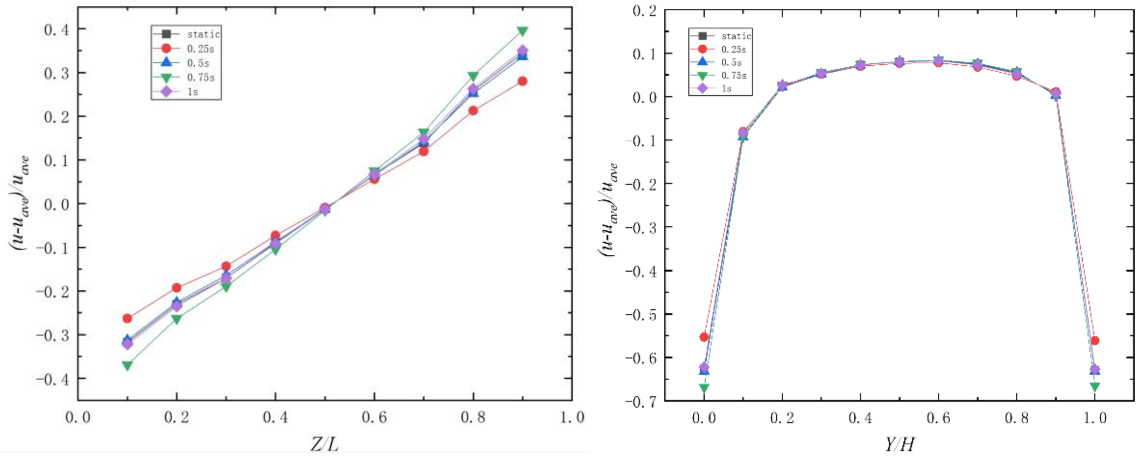
(a)t=0s (b)t=0.25s (c)t=0.5s (d) t=0.75s (e) t=1s

Figure 5: Cross-sectional velocity cloud diagram at the corner of the channel



(a)t=0s (b)t=0.25s (c)t=0.5s (d) t=0.75s (e) t=1s

Figure 6: Cross-sectional velocity cloud diagram at the exit of the channel



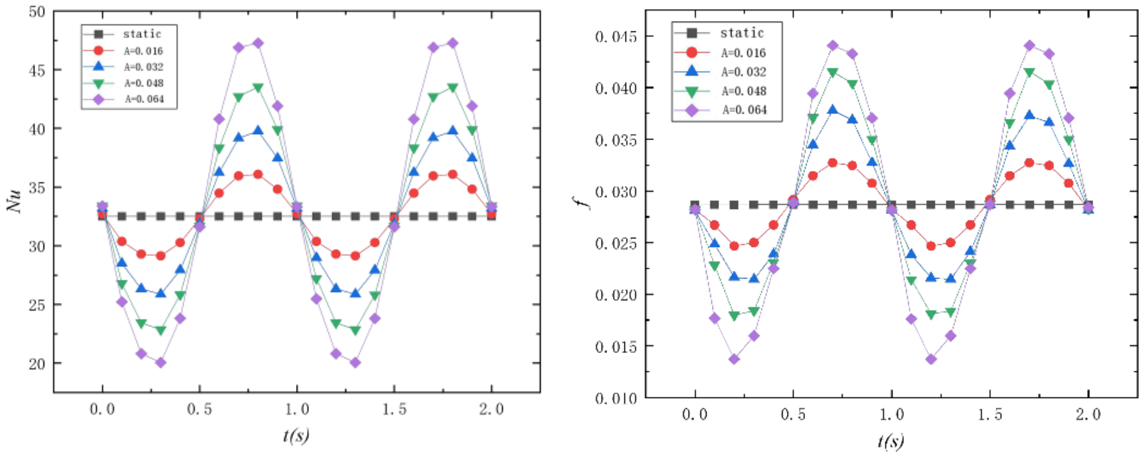
(a) Z-axis (b) Y-axis

Figure 7: Z-axis and Y-axis section velocity distribution

3.3. The influence of sloshing amplitude on thermal and hydraulic characteristics

Changes in sloshing amplitude will regulate the inertial force, turbulence, and flow uniformity, thereby improving its thermal and hydraulic characteristics. The working conditions of Example 3 in Table 1 are simulated. As shown in Figure 8(a), the sloshing amplitude increase makes the fluid velocity slower during the 0s to 0.5s, so the turbulence is dropped and the thermal characteristics are weakened. Therefore, the Nu at the same time decreases as the amplitude increases. On the contrary, the sloshing amplitude increase makes the fluid velocity faster, so the turbulence rises and the thermal characteristics are enhanced during the 0.5 to 1s. The results of the calculation found that the $\overline{Nu}$ for sloshing amplitudes of 0.016, 0.032, 0.048, and 0.064 increase by 0.12%, 0.39%, 1.04%, and 2.04%, respectively, compared with the static conditions. Hence, the thermal characteristics increase with the sloshing amplitude increase. The reason is that the additional acceleration increases with the increasing of sloshing amplitudes thereby rises the turbulence.

As shown in Figure 8(b), f at the same time decreases with the sloshing amplitude increasing from 0 to 0.5s. This is because the inertial force is opposite to the flow direction, which leads to the fluid velocity becoming slower, and the pressure drop is reduced. It means the fluid uniformity rises and the hydraulic characteristics are better. However, f at the same time increases as the amplitude increases from 0.5 to 1s. This is because the inertial force same as the flow direction, which leads to the fluid velocity becoming faster, and the pressure drop is enhanced so that the fluid uniformity drops and the hydraulic characteristics become worse. The results of the calculation discovered that the $\overline{Nu}$ for sloshing amplitudes of 0.016, 0.032, 0.048, and 0.064 increase by 0.39%, 1.55%, 2.37%, and 2.95%, respectively, compared with the static conditions. Therefore, the hydraulic characteristics weaken as the sloshing amplitude increasing. The reason is that the additional acceleration increases with the increasing of the sloshing amplitudes, which increases the pressure drop and results in poor hydraulic characteristics.

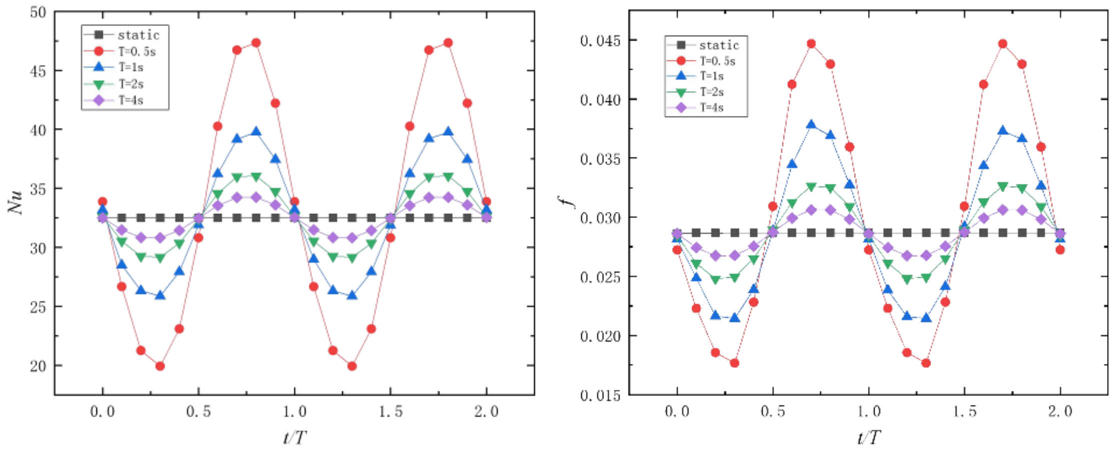


(a) thermal characteristics (b) hydraulic characteristics

Figure 8: Thermal and hydraulic characteristics under different sloshing amplitudes distribution

3.4. The influence of the sloshing period on thermal and hydraulic characteristics

The numerical simulation consists of the working conditions of Example 4 in Table 1. The influence of the sloshing period on thermal and hydraulic characteristics is displayed in Figure 9.



(a) thermal characteristics (b) hydraulic characteristics

Figure 9: Thermal and hydraulic characteristics under different sloshing periods distribution

Figure 9(a) illustrates the thermal characteristics under different sloshing periods, where the abscissa is the time and period ratio t/T. A conclusion can be drawn that when the sloshing period is larger, the thermal characteristics are closer to the static, thus the fluctuation range of Nu is reduced. Values of calculation about $\overline{Nu}$ in the sloshing amplitudes of 0.5s, 1s, 2s, and 4s increase by 2.24%, 0.39%, 0.18%, and 0.058%, respectively, compared with the static conditions. As a result, the thermal characteristics decrease as the sloshing period becomes larger. The reason is that the additional acceleration will decrease correspondingly as the sloshing period increasing, which can rise the turbulence.

Figure 9(b) shows the hydraulic characteristics under different sloshing periods. We can conclude that the larger period hydraulic characteristics are closer to the static. Compared with the static conditions, values of calculation about $\bar{f}$ in the sloshing amplitudes of 0.5s, 1s, 2s, and 4s increase by 6.1%, 1.12%, 0.27%, and 0.07%, respectively. As a result, the hydraulic characteristics decrease as the sloshing period becomes larger. The reason is that the additional acceleration increases as the sloshing periods increase, thereby increasing the additional pressure drop.

3.5. Influence assessment of thermal and hydraulic characteristics under sloshing conditions

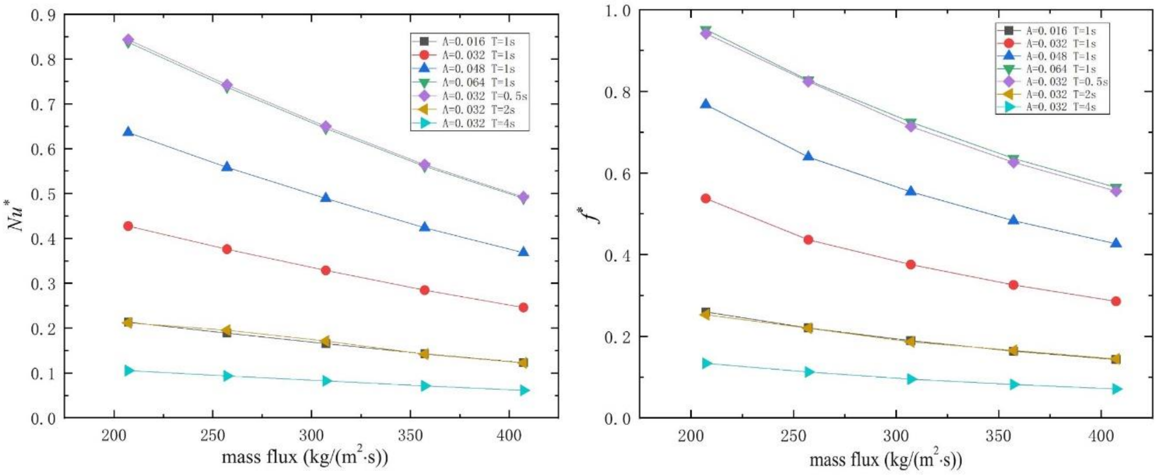
To assess the influence of diverse parameters on the thermal and hydraulic characteristics of zigzag PCHE, the relative amplitude of Nusselt number fluctuation Nu^* and the relative amplitude of Darcy friction factor fluctuation f^* are introduced[13]. The formulas are as:

$$Nu^* = \frac{Nu_{crest} - Nu_{trough}}{Nu_{static}} \tag{7}$$

$$f^* = \frac{f_{crest} - f_{trough}}{f_{static}} \tag{8}$$

where Nu_{crest}: the value of Nu crest point in a single period; f_{crest}: the value of f crest point in a single period; Nu_{trough}: the value of Nu trough point value in a single period; f_{trough}: the value of f crest point in a single period; Nu_{static}: Nu value under static conditions; f_{static}: f value under static conditions.

Figure 10 provides the effects of diverse parameters on thermal and hydraulic characteristics. It is found that the influence of thermal and hydraulic characteristics increases as the sloshing amplitude increases or the sloshing period extends while decreasing as the mass flux elevates. In addition, we can infer that the sloshing amplitude and period change by the same multiple at the same time, the values of Nu^* and f^* are not much different under the same mass flux.



(a) thermal characteristics (b) hydraulic characteristics

Figure 10: The influence of different sloshing parameters on thermal and hydraulic characteristics

As mentioned above, the sloshing period and sloshing amplitude are conducive to the thermal and hydraulic characteristics. However, sloshing will affect the stability of the operation. Too large a sloshing period and sloshing amplitude will cause stagnation or reverse during the flow process because of the inertial force, which will seriously damage the operation of the PCHE. Properly increasing the mass flux can prevent these phenomena from happening.

4. Conclusion

1) The thermal characteristics of supercritical LNG increase with the elevation of mass flux and decrease with pressure increases. The hydraulic characteristics increase with the reduction of mass flux or pressure. In addition, with the sloshing amplitude increasing, the thermal characteristics are enhanced, while the hydraulic characteristics are weakened. And with the sloshing period increases, the thermal characteristics are weakened, while the hydraulic characteristics are enhanced.

2) The thermal and hydraulic characteristics of supercritical LNG are enhanced under sloshing conditions. In addition, the sloshing has a greater impact on the flow uniformity in the flow direction but has a negligible effect in the vertical direction.

3) When the sloshing amplitude and sloshing period change exponentially, it has little effect on the thermal and hydraulic characteristics. Then, excessive sloshing period and amplitude may cause stagnation or reverse in the flow process. As a result, increasing mass flux appropriately will help reduce the influence of thermal and hydraulic characteristics, and prevent stagnation or reverse.

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