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PULSATING ENHANCED HEAT TRANSFER

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ПУЛЬСИРУЮЩИЙ УСИЛЕННЫЙ ТЕПЛООБМЕН

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Abstract. The paper mainly introduces the mechanism of turbulent fluid heat transfer enhancement and the factors affecting heat transfer. The physical parameters of pulsating fluid mainly include pulsation frequency and amplitude. The factors affecting heat transfer are the physical properties of the pulsating fluid and the installation of a pulsation generator. The position, the type of pulsation occurrence, the natural frequency of the heat exchange system, etc.; the methods for strengthening the pulsating heat transfer characteristics mainly include disturbing flow elements, changing the size of the flow channel structure, compound heat transfer enhancement, and setting the induction vibration device in the flow channel.

Аннотация. Представлен механизм усиления теплообмена турбулентной жидкости при различных факторах, влияющих на теплообмен. Физические параметры пульсирующей жидкости в основном включают частоту пульсации и амплитуду. Факторами, влияющими на теплообмен, являются физические свойства пульсирующей жидкости, а также режимы течения данной жидкости, задаваемые пульсатором потока и самой гидравлической системой. К этим параметрам следует отнести форму пульсации, собственную частоту гидравлической системы, частоту пульсаций скорости, давления и т.д. Среди способов усиления пульсирующего теплообмена, в основном, следует выделить возмущающие элементы потока, изменение размера структуры канала потока, усиление составного теплообмена и установку устройств для создания вибраций в канале теплообмена.

Keywords: pulsating fluid, enhance heat transfer, heat transfer characteristics.

Ключевые слова: пульсации жидкости, увеличение коэффициента теплопередачи, параметры теплообмена.

Introduction

Heat exchanger is the most common thermal equipment of various industry application [1], which Widely used in chemical, energy, machinery, transportation, refrigeration and aerospace, etc., which is an indispensable equipment for industrial process, improving the performance of heat exchanger can affect the recovery of energy consumption and low grade energy directly of various industry departments, and is an important aspect of low-carbon energy technology. Due to the wide scale of the heat exchanger, it is of great significance to improve the performance of heat exchanger, and has a profound industrial application background. In recent years, the pulsating heat transfer technique has been widely concerned, and a large number of researchers have further studied the pulsating reinforcement heat exchange. Therefore, the pulsating heat transfer technology is maturing. Pulsating heat transfer can be divided into passive reinforcement technology and active reinforcement technology. Passive technology means that there no need external forces to realize heat transfer reinforcement in the process of strengthening heat transfer; Active technology requires external forces to realize the reinforcement of heat transfer. Nowadays more scholars are doing more research on active reinforcement technology.

1. Pulsating heat transfer characteristics and their influencing factors

The flow of the pulsating heat transfer fluid under the pressure driven by the change of the sines and cosine function is called the oscillation flow, as shown in the form

$$\frac{\partial p}{\partial x} = A_0 + A_1 \cos(\omega t)$$

According to the formula, this is a periodic non-steady flow, the pulse of the fluid can also describe of amplitude of fluctuation on the average of the flow or the pressure. We can also divide the pulse flow into pulse flow and reciprocation according to the average velocity of the fluid is zero or not. The fluid pulsation can destroy the heat boundary layer, which can change the heat resistance and reach the purpose of strengthening the heat transfer.

The research history of pulsating heat transfer is relatively long, Richardson [2] studied the velocity of the flow and pulsation flow in the tube, the ‘ring effect’ is found, which marks the beginning of the study of pulsating heat transfer. According to the existing literature, which show that whether the pulsation can enhance the heat transfer or not, it has a lot to do with the flow of the flow medium. The fluid pulsation can strengthen the heat change in certain conditions because the fluid pulsation can destroy the heat layer and change the heat resistance, and the purpose of strengthening the heat change in turn. The pulsating convective heat transfer in the heat exchanger can be divided into two types: one is that the heat transfer surface generates vibration to achieve enhanced heat transfer, and the other is that the fluid itself pulsates to enhance heat transfer, and the heat transfer surface vibration is used to enhance heat transfer which damage to heat exchange equipment is therefore difficult to achieve in many engineering applications, so the use of fluid pulsation to enhance heat transfer is the main research direction.

Fluid pulsation enhanced heat transfer is mainly due to the pulsation of the fluid, which causes a large number of vortices to appear on the wall surface, which reduces the thickness of the viscous bottom layer close to the wall surface, increases the turbulence of the main fluid, increases the fluid mixing, and breaks the boundary layer, increase the effect of heat exchange surface, and then achieve the purpose of strengthening heat transfer, which divided into three parts during the enhance heat transfer: the first part is the formation of vortices, the second part is decomposition of vortices, and the last part is the diffusion of vortices, the formation of the vortices is the main part during process. The higher the density of vortex, the better the heat transfer effect. However, the

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generation of vortices is the result of the increase of radial velocity gradient along the wall surface, so a large radial velocity gradient can achieve the effect of enhancing heat transfer.

The parameters that affect the heat transfer characteristics of fluid pulsation can be roughly divided into the following three categories:

1. Pulsating parameters: including pulsating frequency, pulsating amplitude and pulsating type;
2. Geometric parameters: including pipe diameter, geometric structure of flow channel and channel surface condition, etc.;
3. Physical parameters: Reynolds number, average fluid velocity, location of pulsation source and flow state before pulsation, etc.

(1) Effect of Reynolds number on heat transfer by pulsation enhancement

The pulsating flow can promote the mixing of fluid molecules in the heat exchange. When the fluid flow state is in the laminar state or the transition state when the Reynolds number is low (for water Re<2400), the fluid can be better blended due to the pulsation. When the Reynolds number is high (for water Re>4000), the fluid flow state is already in a turbulent state, a large number of vortices have appeared in the fluid boundary layer at the wall surface, and because the fluid has a large flow inertia, the response to the external pulsation is relatively slow, therefore, there is no significant enhancement of heat transfer effect.

(2) The effect of pipe diameter on pulsating reinforced heat transfer

The heat transfer enhancement by pulsating flow is mainly due to the generation of vortices, and the process of heat transfer enhancement can divided into three parts: formation, decomposition and diffusion, The effect of pipe diameter is mainly reflected in the diffusion of vortex, The size of the pipe diameter directly leads to the distribution of the pipe section velocity, which affects the radial velocity gradient and its rate of change at the near wall. Therefore, the length of the vortex diffusion path mainly depends on the diameter of the pipe. The smaller the pipe diameter, the more conducive to the diffusion of vortices.

(3) The effect of pulsating type on pulsating reinforced heat exchange

Pulsation pattern refers to the variation form of flow velocity generated by pulsation, which is related to the mode of pulsation. During a period of pulsation, the flow velocity of the fluid can be divided into two stages of increase and decrease. The vortex is also generated during the increase of the flow velocity, so the good pulsation form should have a shorter increase period and a longer decay half period. The half cycle, the longer decay half cycle is to attenuate the fluid flow rate low enough to allow the fluid to achieve a large velocity amplitude during the increased half cycle and provide sufficient time for the vortex to decompose and diffuse, thus resembling sawtooth The pulsating form of the type having a slower flow rate drop and a steeper flow rate increase is more advantageous for enhanced heat transfer.

(4) The physical properties of the fluid affected Pulsating reinforcement heat exchange

The physical properties that affect fluid-enhanced heat transfer are primarily the viscosity of the fluid. Larger viscosity is conducive to the generation of vortices, and too high viscosity of the fluid will hinder the pulsation of the fluid flow rate, which will not enhance the heat transfer or weaken the pulsating heat transfer. The viscosity of the fluid results in a low Reynolds number, which means that fluids often occur in laminar flow conditions in conventional heat transfer equipment. The instability of the fluid at low Reynolds numbers is due to the non-viscous

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mechanism, but in high viscosity fluids this mechanism of initiation will be replaced by a viscous mechanism, when the Reynolds number is not high or low, The viscous and non-viscous mechanisms will interact [3–4].

The viscosity of the fluid leads to low Reynolds number, that is means the fluid is frequently in the laminar flow state in the conventional heat transfer equipment.

(5) Influence of pulsating source location on pulsating heat transfer enhancement

The position where the pulsation generator is installed has a certain influence on the pulsation-enhanced heat transfer. When the pulsation generator is installed in the front part of the heat exchanger, the pulsating flow generated by the pulsation generator will flow into the heat exchanger, increasing the disturbance, Lemlich and Armour [5] uses double tubes for experiments, steam and water for heat exchange. The pulsation generator is installed before the heat exchanger, the effect of the heat transfer is increased by 80%. When the pulsation generator is installed at the rear of the heat exchanger, the effect of the heat exchange is weakened. Before the pulsation generator is installed with the heat exchanger, the heat transfer coefficient of the heat exchanger will increase under certain conditions. When the pulsation generator is installed downstream of the heat exchange outlet, the heat exchange effect of the heat exchanger will be reduced. Darling [6] also found that the heat transfer coefficient increased by 90% when the pulsation generator was installed in the front of the heat exchanger, with a Re of 6000 and a pulsation speed of 160 cycles/mm.

2. Current state of the scientific problem

According to the existing literature, the pulsating flow will have three effects on the heat exchange system: one is that the pulsating flow will strengthen the heat transfer of the system; the other is that the pulsating flow will weaken the enhanced heat effect of the system; the third is that the pulsating flow will neither strengthen nor weaken the heat transfer of the system. Therefore, under what conditions, the pulsating flow can enhance the heat transfer of the fluid heat transfer, and further research is needed. Different experimental and simulation conditions will give different answers, there is no uniform understanding of heat transfer about the strengthen the pulsation. According to the current literature, different scholars give different answers on whether fluid pulsation can enhance heat transfer. Siegel [7] theoretically analyzed the pulse convection heat transfer problem under the isothermal boundary condition of the plate channel by replacing the velocity distribution with the average velocity of the section. Finally, it is concluded that the pulse flow has no significant effect on heat transfer. Chattopadhyay [8] numerical studies of flow and heat transfer in a circular tube under pulsating flow condition were carried out in the laminar regime, which studies focus on the frequency range of 1–20 Hz, with a Reynolds number of 200 and an amplitude of less than 1.0, Simulation results show that transient Nu follows the pulsation period in the initial length of about 2R, in the range of pulsation frequency and amplitude, pulsation has no effect on time-averaged heat transfer, although the Nu distribution varies in time in the near-entry region of the pipe. Hemida et al. [9] analyzed the heat transfer in laminar incompressible pulsating flow in a duct. Under linear boundary conditions, the effect of pulsation on the time average heat transfer coefficient tends to be negative, but remains relatively small; Under Non-linear boundary conditions, combined with pulsation may result in a noticeable enhancement of the time average Nusselt number. Yu et al. [10] theoretically studied pulsating laminar heat convection in a circular tube with constant heat flux. The results show that both the temperature profile and the Nusselt number fluctuate periodically about the solution for steady laminar convection, with the fluctuation amplitude depending on the dimensionless pulsation frequency, the amplitude, and the Prandtl number. It is also shown that the results indicated that pulsation has no effect on the time-averaged

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Nusselt numbers for pulsating convection heat transfer. Jackson and Purdy [11] and Genin et al. [12] observed no heat transfer enhancement with flow pulsation.

Kita et al. [13] studied the heat transfer for a sinusoidally pulsating laminar pipe flow under the case of constant wall temperature using the velocity profile obtain by Uchida and the constant fluid properties. The results indicated that pulsation has no effect on the time-averaged Nusselt numbers for pulsating convection heat transfer. Faghri et al. [14] carried out a theoretical analysis of the flow of a circular tube and low pulse frequency laminar flow. The results show that the velocity distribution is the same as the temperature distribution, and both can be considered as the superposition of the steady state value and the transient value. The expression of dimensionless temperature and Nu is given, the pulse flow in the fully developed region will increase Nu, and the degree of strengthening is related to the fluid parameters. Barnett et al. [15] theoretically analyzed the turbulent pulse flow of a circular tube channel and pointed out that when the pulse frequency is small, the heat transfer can be significantly enhanced. When the pulse frequency is high, the heat transfer enhancement effect is reduced. Kim et al. [16] used numerical analysis to study the heat transfer problem of the pulse flow entering the channel at the same temperature. The results show that pulse flow has obvious effect on heat transfer enhancement in the inlet section, but the difference between the time-averaged heat flow and the steady-state heat flow is very small in the fully developed section.

Richardson et al. [17] found that the pulsating flow field of a circular tube, a square tube and an elliptical tube may have a "ring effect". Under certain flow conditions, the maximum velocity on the channel section occurs near the tube wall instead of in the center of the tube. Guo et al. [18] theoretical analysis of three different pulsating frequencies (ω=1, 3, 6Hz) at high amplitude ($1<A_f$) and low amplitude ($0<A_f<1$) observed that heat transfer is reduced in a operating frequency 6 Hz when the pulsation amplitude is relatively small, but at higher amplitudes, the heat transfer increase with increasing frequency, so the frequency has a weak influence on heat transfer in the low frequency area ($0<\omega\leq0.5$). Jun et al. [19] studied the heat transfer characteristics of pulsating flow through experimental research, and concluded that with the increase of flow rate, the heat transfer increases gradually, and the strong pulsation leads to the enhancement of heat transfer. More recent studies on the heat transfer enhancement under pulsating flows can be found in Habib et al. [20–22] Habib et al. [20] experimentally investigated heat transfer characteristics to laminar pulsating pipe air flow under different conditions of Reynolds ($780<Re<1987$) number and pulsation frequency ($1<\omega<29.5$ Hz) and the tube wall of uniform heat flux condition was considered. The results showed the relative mean Nusselt number is strongly affected by pulsation frequency while it is slightly affected by Reynolds number. Habib et al. [21] experimentally investigated heat transfer characteristics to turbulent pulsating pipe air flow under a wide range of Reynolds ($8462<Re<48540$) number and pulsation frequency ($1<\omega<29.5$ Hz), the results showed that the relative mean Nusselt number is strongly affected by both pulsation frequency and Reynolds number. The frequency of turbulence (bursting frequency) also has an effect on heat transfer, the maximum enhancement of about 50% in mean Nusselt number was obtained at ω of 14.5, and the Reynolds number of 8462, where a resonance interaction between bursting frequency and pulsation frequency. Habib et al. [22] experimentally investigated heat transfer characteristics to both laminar and turbulent pulsating pipe air flow under different conditions of Reynolds number ($750<Re<12320$), pulsation frequency ($1<\omega<10$ Hz), pulsator location(upstream of the inlet of the test section tube) and the diameter(15–50 mm), the experiment results showed the closer the valve to the test section inlet, the better improvement in the heat transfer coefficient is achieved. Under the turbulent flow the maximum enhancement up to 50% at Reynolds number of 8000, but at the laminar flow at the same Reynolds number of 8000, a reduction in the relative mean Nusselt number up to 35%. Elshafei et al. [23] experimentally investigated the heat transfer of pulsating turbulent air in a pipe heated at uniform heat flux, the range of the Reynolds number from 104 to 4×104 and the pulsation frequency from 6.6 to 68 Hz, With installing the oscillator downstream of the tested tube exit, results showed that Nu is strongly affected by both pulsation frequency and Reynolds number. The variation is more pronounced in the entrance region than that in the downstream fully developed region. The relative mean Nu either increases or decreases, depending on the frequency range. As shown in these studies, Nusselt number could be affected by both pulsation frequency and Reynolds number. Both increase and reduction in the time-averaged Nusselt number with respect to that of the steady flow were observed depending on the range of frequency and Reynolds number. Hemida et al. [24]. Different types of thermal boundary conditions were considered including the thermally developed/developing regions. They concluded that when linear boundary conditions exist, the time average heat transfer coefficient tends to be constant or negative with very small differences, but when non-linear boundary conditions exist, pulsation or oscillation may result in a noticeable enhancement of the time-averaged Nusselt number.

3. The methods of pulsating flow in heat transfer enhancement

(1) Rib

The ribbed sheet not only increases the heat exchange area but also reduces the heat transfer resistance. Therefore, the simple addition of the ribs can also enhance the heat transfer. The ribbed sheet under pulsating flow conditions causes pulsating fluid to create vortex streets, thereby enhancing pulsating heat transfer. Different rib geometry and arrangement will produce different reinforcement effects. The addition of fins in the flow channel will result in an increase in the pressure drop at the inlet and outlet of the flow channel. When the inlet flow rate is too fast, the effect of enhanced heat transfer is more obvious. When the fluid flows through the fins, the vortex is generated due to the existence of the fins. The strength will also increase, and the thermal boundary layer will be destroyed, reaching the effect of strengthening heat, but the pressure loss will be greater. A new type of double triangular fin is installed in the flow channel. When the pulsating fluid flows through the double triangular fin, it will increase the disturbance of the pulsating fluid and accelerate the formation of the vortex street, thereby affecting the heat transfer characteristics of the pulsating fluid.

(2) Zoom tube

The heat transfer performance of the pulsating flow in the zoom tube is better than the steady flow of the fluid in the zoom tube, Compared with the steady state of the fluid flow in the scaled tube, the heat transfer enhancement is about 11.4%; the pulsating flow in the zoom tube enhances the heat transfer and also increases the resistance along the path. The analysis of the comprehensive evaluation index shows that the heat transfer performance of the zoom tube is significantly enhanced under the condition of pulsating flow. When the expansion ratio is $\gamma = 0.5\sim1$, the heat transfer coefficient increases with the expansion ratio. When the expansion ratio $\gamma = 1\sim2$, The heat transfer coefficient decreases with the increase of expansion ratio. When the expansion ratio $\gamma = 1$, the heat transfer enhancement effect of the scaling tube under the condition of fluid pulsation in the tube is better.The fluid pulsation in the tube significantly enhances the heat transfer performance of the zoom tube.

(3) Pulse flow induced vibration

The turbulent flow induced vibration boundary deformation movement and the near-wall pulsating flow by heat-liquid-solid bidirectional coupling which can effectively enhance the heat

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transfer of the near-wall shell fluid. The thermal fluid-solid bidirectional coupling effect and the enhanced heat transfer intensity increase as the pulsation frequency of the pulsating flow increases. The heat-fluid-solid bidirectional coupling enhances the heat transfer of the shell-side fluid by the increase in the temperature difference between the heat transfer driving force and the micro-convection induced by the internal eddy current generated by the near-wall shell-side fluid.

(4) Resonance mechanism

The pulsating frequency of fluid plays an important role in enhancing heat transfer under certain conditions. Under normal circumstances, the heat exchange system will have a fixed frequency during operation. When the natural frequency of the system and the frequency of the pulsation generator are the same or similar, the entire heat exchange system will resonate, which will increase the heat transfer efficiency of the heat exchange system, but also accompanied by the loss of equipment due to vibration.

Some studies [25–27] revealed that small fluid oscillation with the natural frequency of the hydrodynamic instability amplified the flow instability within a grooved channel, even at Reynolds numbers below the critical value for the onset of self-sustained oscillations, and thus enhanced heat transfer. The natural frequency was closely matched with the Tollmien–Schlichting wave for the grooved channel [26–27]. However, some previous experimental works showed that thermal resonance frequency did not always coincide with the natural frequency estimated by the hydrodynamic instability wave.

(5) Pulsating flow/electric field mixed heat transfer

Relevant literatures show that under certain conditions, when the pulsating flow acts alone, the heat transfer coefficient increases with the increase of the pulsation frequency and flow rate, but the increase is small, it shows that the effect of pulsating flow on heat transfer enhancement is not obvious; when the electric field acts alone, under the same flow conditions, the enhanced heat transfer coefficient increases with the increase of voltage, and the increase is larger, it indicates that the electric field can significantly enhance heat transfer. Under the same voltage value, the enhanced heat transfer coefficient gradually decreases with the increase of flow rate, indicating that the electric field is more sensitive to flow rate. When the pulsating flow/electric field is mixed, the enhanced heat transfer coefficient increases with the increase of the pulsation frequency and voltage, and decreases with the increase of the flow rate, indicating the pulsating flow interacts with the electric field, it can produce a positive composite strengthening effect. The mixed electric field has a greater influence on the heat transfer enhancement, and the mixing effect will be maximized under certain conditions.

Conclusions

In this paper, the pulse-enhanced heat transfer is discussed from five aspects. First, the fins are arranged in the flow channel. The presence of the fins will cause the pulsating fluid to generate a vortex with greater strength, and the second is to flow the pulsating fluid. In the improvement, when the expansion ratio of the zoom tube is optimal, the heat transfer of the pulsating fluid in the zoom tube is strong and the heat transfer of the stable fluid in the zoom tube is strong; and the third is to generate vibration by the components in the flow path when the pulsating fluid has its own characteristics, thereby improving the pulsation. The heat transfer characteristics of the fluid; the fourth is to use the natural frequency of the system to generate resonance with the fluid to generate the resonance frequency to improve the heat transfer effect of the heat exchanger. The fifth is to improve the heat transfer effect of the pulsating fluid through the composite enhanced heat transfer

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technology. At present, the research on pulsation-enhanced heat transfer has its own implementation. There are many ways to strengthen. For pulsation-enhanced heat transfer, we still have more work to do. Most of the current pulsating fluid media are air and water. We can Consider using other better fluid media for experimental research; the pulsation mode of the fluid is a sine wave or a sawtooth wave. We can also consider the pulsation mode of the composite waveform to study the heat transfer trapezoid of the pulsating fluid; Heat We can combine the best enhanced heat transfer methods to find a more economical and efficient combination. We still have a long way to go for enhanced heat transfer of pulsating fluids.

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