B102 波状管内の脈動流

Pulsatile Flow in a Wavy-Walled Tube

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ABSTRACT
The visualization of pulsatile flow in a wavy-walled tube for low flow rates is conducted by the aluminum dust method. We pay attention to the effect of Strouhal number on flow behaviors. It is found that, generally, the flow tends to remain stable in the accelerating phase and unstable in the decelerating phase. There exists a peak mass transfer enhancement at an intermediate Strouhal number, where inertia effects dominate the flow, while at low and high Strouhal numbers, the mass transfer enhancement is reduced, and the flows remain relatively stable.

Keywords: Flow visualization, Pulsatile flow, Wavy-walled tube, Mass transfer enhancement

1. Introduction
Heat and mass transfer enhancement under laminar flow conditions is of great importance in the fields of medical and biochemical engineering. Many investigators devote their efforts to the studies on pulsatile flow in the wavy-walled channels or wavy-walled tubes. Bellhouse et al. [1] pioneered the study of how large fluid oscillations can improve mass transfer in a furrowed channel and applied this scheme to a high efficiency membrane oxygenator. In order to explain the mechanism of such enhancement, Sobey [2,3] numerically analyzed oscillatory flow in a symmetric sinusoidal wavy-walled channel, and presented the flow diagram for wide ranges of Reynolds numbers and Strouhal numbers. He suggested that in the large Strouhal number region, viscosity effects dominate the flow. In the intermediate Strouhal number region, inertia effects dominate the flow. In the small Strouhal numbers region, the flow is virtually quasi-steady. The flow region dominated by inertia is more effective for mass transfer enhancement. Subsequently, Patera et al. [4] and Greiner [5] studied numerically and experimentally the resonant heat transfer enhancement in the grooved channel with a small cavity. They found that small fluid oscillations at the natural frequency of the hydrodynamic instability increases dramatically the amplitude of the instability, even for Reynolds number below the critical value at the onset of self-sustained oscillations, and enhances heat and mass transfer. They call this effect resonant transport enhancement. Otherwise, employing a wavy-walled channel, Nishimura et al. [6,7] considered the effects of some parameters on the pulsatile flow behavior, and pointed out that mass transfer enhancement depends on net flow, amplitude and frequency of fluid oscillation. They found that combination of flow separation and forced fluid oscillation can lead to a remarkable increment in heat and mass transfer rates even in the laminar flow regime. Recently, Nishimura et al. [8] also examined the influence of oscillatory frequency on mass transfer enhancement of the grooved channel with a small and large cavity for pulsatile flow. They showed that for the small cavities the optimum mass transfer enhancement occurs at an intermediate Strouhal number, which is corresponded well to the frequency of self-sustained oscillation of steady flow. However, for the large cavi- ty the mechanism of mass transfer enhancement cannot be explained only by the hydrodynamic resonance proposed by Patera et al.

Although there are some studies on pulsatile flow with different channels, the study for wavy-walled tubes has been scarcely reported. Lee et al. [9] investigated numerically chaotic mixing and mass transfer enhancement for pulsatile laminar flow. They proposed that at small oscillation fraction of the flow rate, the mass transfer enhancement increases as the Reynolds number increases. There exists an optimum Strouhal number, depending on the net flow Reynolds number, and is almost inversely proportional to the channel wavelength. The above background has motivated the present experimental investigation. We primarily reveal the effect of Strouhal number on the mass transfer enhancement of pulsatile flow by using the flow visualization technique.

2. Experimental apparatus and procedure
A schematic diagram of the experimental apparatus is shown in Fig. 1. The volumetric flow rate of pulsatile flow is expressed as follows:

\[ Q = Q_s + Q_0 \sin(2\pi t/T) \] (1)

where \( Q_s \) is the net flow, providing by the centrifugal pump. \( Q_0 \) is the peak flow of fluid oscillation, providing by the pulsatile pump, which is driven by a variable speed motor and the length of stroke and frequency of the piston allow to be changed. \( T \) is the period of oscillation. The following relation determines the peak flow rate of oscillatory flow:

\[ Q_0 = 2\pi \cdot f \cdot s \cdot (\pi D_p^2 / 4) \] (2)

where \( f \) is the frequency of oscillation \( 1/T \), \( s \) is the length of stroke of the piston and \( D_p \) is the diameter of the piston. The wavy-walled tube consisted of fourteen...
sections as shown in the figure. The diameters in the maximum and minimum circulation cross sections are 10 and 3mm, respectively. The wavelength is 14mm.

Three flow parameters characterize the pulsatile flow: the net flow Reynolds number

$$Re_p = \frac{\rho u D_{max}}{\mu}$$

the oscillatory fraction of the flow rate

$$P = \frac{Q_o}{Q_s}$$

and the Strouhal number

$$St = \frac{D_{max}}{2\pi f / u}$$

where u is the average velocity at the maximum cross section, defined as $u = 4Q_s/(\pi D_{max}^2)$.

Flow was visualized by means of aluminum dust method. Perfusion with a suspension of aluminum particles about 40 $\mu$m in diameter, enables us to observe the pathlines approximately corresponding to the streamlines in the whole flow field. The mass transfer rate is measured by the electrochemical method. The diffusional current $i_d$ is related to the Sherwood number as follows:

$$i_d = \frac{F C_b A D}{D}$$

where $F$ is the Faraday constant, $C_b$ is the concentration of the employed electrolyte. $A$ is the area of mass transfer surface and $D$ is the molecular diffusional coefficient. The temperature of electrolyte is kept 25°C (Schmidt number $Sc=1570$). The experiment is carried out at the fixed net Reynolds number $Re_p=151$, which is close to the critical value ($Re_c=160$) but still belongs to laminar flow regime according to the previous steady flow result[10]. Since the flow is quite complicated under the reversal flow condition ($P>1.0$), in the present study, two oscillatory fractions are adopted, that is, $P=0.4$ ($0.09<St<4.0$) and $P=1.0$ ($0.45<St<10.0$).

3. Results and discussion

3.1 Effects of Strouhal number on mass transfer enhancement

For pulsatile flow, the Sherwood numbers are normalized by their respective steady values, defining the mass transfer enhancement factor, $E = \frac{Sh_p}{Sh_s}$. Fig. 2 shows the relationships between the enhancement factor and the Strouhal number for two fixed oscillatory fractions. From the view of this figure we find that for the two oscillatory fractions the enhancement factors are small at the low and high Strouhal numbers. There is a peak mass transfer enhancement at the intermediate Strouhal number, that is, the optimum Strouhal number is $St=0.14$ for $P=0.4$ and $St=4.0$ for $P=1.0$, respectively. Obviously, the optimum values of Strouhal numbers for the above two cases are different, and they depend on the oscillatory fraction of flow rate. Otherwise, it is also shown that the peak enhancement factor for $P=1.0$ is larger than for $P=0.4$, indicating the more effective mass transfer enhancement at higher oscillatory fraction.

The above experimental results show that since the optimum Strouhal numbers for the two kinds of oscillatory fractions are quite different, we can deduce that the resonant mass transfer enhancement does not exist in the wavy-walled tube.

3.2 Effects of Strouhal number on pulsatile flow patterns

To bring out the details of mass transfer enhancement of pulsatile flow, the flow patterns were visualized with the aluminum dust method. The representative flow patterns at the two optimum Strouhal numbers for different oscillatory fraction are shown in Figs. 4 and 5. From the results of previous study[10] we have found that for the wavy-walled tube, the flow instability is triggered by the intermittent fluctuation generated in the shear layer between the mainstream and the separated vortex in the wave valley. Fig. 4 shows the flow patterns with 8 frames for $P=0.4$ and $St=0.14$, which were taken in the same time intervals in one cycle. The instantaneous flow rate defined by Eq. (1) is different for every moment, thus the instantaneous Reynolds number $Re_p$ based on it are also different from each other. From the view of these pictures we observe that there exist two kinds of flow state. One is the stable state, i.e., the pathlines in the
mainstream are aligned in the axial direction. The other is the unstable state, i.e., the pathlines are slightly disturbed in the radial direction in the shear layer region due to flow instability. In the present case, the unstable flow state appears at $t/T=0.125-0.625$, that primarily belongs to the decelerating phase. In the other words, in the accelerating phase, the flow tends to remain stable. The above results deduce that the instability generated from the shear layer in the decelerating phase leads to fluid mixing. The type summation of flow patterns for different Strouhal numbers is shown in Table 1. It is indicated that as the Strouhal number increases, the duration of unstable state shifts gradually from the accelerating phase to the decelerating phase, while the unstable flow interval become narrow. Eventually, under high Strouhal number($St\geq 2.66$), due to the effect of viscosity the flow instability is quite reduced and thus the pattern always shows stable state.

Fig. 5 shows the flow patterns for $P=1.0$ and $St=4.0$. It is seen that the unstable state exists at $t/T=0.375-0.875$, which is also primarily in the decelerating phase. The type summation of flow pattern for different Strouhal numbers is shown in Table 2. It shows that the time for the first onset of unstable flow is different with the Strouhal number increasing, and also shifts to the decelerating phase. However, the interval of unstable state has no significant change, and the unstable state is still kept at high Strouhal numbers($St\geq 6.67$), unlike the case of $P=0.4$.

The above results indicate that it is a common feature for pulsatile flow that the flow tends to unstable in the decelerating phase and stable in the accelerating phase. The instability generated from the shear layer in the decelerating phase contributes to the mass transfer enhancement. Moreover, the quantitative flow estimation of the optimum Strouhal numbers of mass transfer enhancement for the two oscillatory fractions is needed to be conducted in the future.

4. Conclusions

The experimental study of flow patterns and mass transfer enhancement in a wavy-walled tube for pulsatile flow has been conducted. The effect of Strouhal number is especially focused. The following conclusive remarks are drawn:

(1) The peak mass transfer enhancement exists at an intermediate Strouhal number. The optimum Strouhal number depends on the oscillatory fraction of flow rate.

(2) The flow state tends to stable in the accelerating phase and unstable in the decelerating phase. The instability generated from the shear layer in the decelerating phase leads to fluid mixing and contributes to the mass transfer enhancement.

References

Table 1 Types of pulsatile flow pattern at $P=0.4$

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Table 2 Types of pulsatile flow pattern at $P=1.0$

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Notice: + stable state; - unstable state