Mass-Transfer Enhancement in a Wavy-Walled Tube by Imposed Fluid Oscillation

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The present experimental study deals with mass-transfer enhancement and fluid dynamic behavior in a wavy-walled tube for pulsatile flow. Three flow parameters are considered here: the net flow Reynolds number, the oscillatory fraction of the flow rate, and the Strouhal number. Among them, we especially focused on the effect of Strouhal number on mass-transfer enhancement under the condition of no reverse flow. Time-averaged transport enhancement by means of imposed fluid oscillation is found to vary with the net flow Reynolds number and with the oscillatory fraction of the flow rate. The most effective mass-transfer enhancement is registered when the net flow falls on just before the transitional flow regime for steady flow. Furthermore, there is an optimum Strouhal number, corresponding to the maximum transport enhancement, that depends on the oscillatory fraction of the flow rate. The results of time variation for flow behavior show that stable and unstable flow states exist during one oscillation cycle. The duration of the unstable flow state, corresponding to the optimum Strouhal number, is found to be the longest, and it leads to a remarkable fluid exchange between the mainstream and the recirculation zone, thus contributing to the mass transfer enhancement. These results indicate that the transport enhancement mechanism for the wavy-walled tube is quite different from the resonant transport enhancement observed in the two-dimensional (2-D) wavy-walled channel.
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Introduction

Heat- and mass-transfer processes exist everywhere in engineering. Their enhancement under laminar flow conditions is of a great importance in the fields of medical engineering and biochemical engineering. For example, when blood oxygenators and bioreactors process very viscous liquids containing shear-sensitive materials, it is necessary to use laminar flow, rather than rely on turbulence, to obtain efficient mixing and excellent heat- and mass-transfer characteristics. Recently, a significant research effort has been devoted to find techniques and conditions for heat- and mass-transfer enhancement under laminar flow conditions. Several investigators have found that the combination of flow separation and forced fluid oscillation leads to a remarkable increment in heat- and mass-transfer rates (Bellhouse et al., 1994; Millward et al., 1996; Nishimura, 1997).

Bellhouse et al. (1973) developed a high-efficiency membrane oxygenator that combines large oscillations with a much smaller mean flow through a wavy-walled channel to achieve high mass transfer rates. To explain the mechanism of such enhancement Sobey (1980, 1983) numerically analyzed oscillatory flows without net flow in a sinusoidal wavy-walled channel under laminar flow conditions. He suggested that an oscillatory flow induces a vortex formation–ejection cycle, which is believed to be responsible for enhanced mixing and

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mass transfer. A flow diagram for wide ranges of Reynolds numbers and Strouhal numbers based on the maximum oscillatory flow was proposed. That is, 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 number region, the flow is virtually quasi-steady. The numerical results showed that the flow region dominated by inertia is effective for mass transfer enhancement. Nishimura et al. (1995, 1996) systematically studied flow and mass-transfer characteristics in the symmetric and asymmetric sinusoidal wavy-walled channels over wide ranges of flow parameters for pulsatile flows. They showed that mass-transfer enhancement depends on three parameters: net flow Reynolds number, oscillatory fraction of the flow rate, and Strouhal number based on the net flow. The enhancement factor increases with the increase of these three parameters in their experimental range, and the asymmetric channel has a larger enhancement factor than does the symmetric channel. Moreover, some investigators also carried out the studies for other geometric channels.

Ghaddar et al. (1986a) numerically investigated the relationship between flow instability and heat-transfer enhancement in grooved channels. They first discussed the instability of steady flow in grooved channels with different geometric parameters. Their simulations indicated that when the Reynolds number exceeds a critical value, the flow instability results in a self-sustained oscillation with a certain frequency, attributed to the Tollmien–Schlichting waves, similar to the plane channel case. Furthermore they found that the occurrence of Tollmien–Schlichting waves is a common feature for 2-D channels, although the frequency is different, depending on the geometric parameter. Applying the numerical results to the study of heat-transfer enhancement, Ghaddar et al. (1986b) pointed out that the oscillatory flow imposed at the Tollmien–Schlichting frequency leads to a resonant excitation and associated transport enhancement, which they called "resonant enhancement." A characteristic of resonant enhancement was also presented; that is, when the oscillatory fraction of the flow rate varies between 0 and 1.0, this optimum frequency has no remarkable shift. Otherwise, they concluded that the transport enhancement has a close connection with the flow separation. For example, no resonant enhancement occurs for pulsatile flow in the plane channel because no velocity perpendicular to the main stream is generated, although the Tollmien–Schlichting waves exist. To identify the above numerical results, Greiner (1991) carried out the experimental study in the grooved channel with a small cavity. He confirmed that small fluid oscillations at the Tollmien–Schlichting frequency increase dramatically the amplitude of the instability, even for Reynolds numbers below the critical value at the onset of self-sustained oscillations, and thus enhance heat transfer. Furthermore, Nishimura et al. (2000a) examined the influence of oscillatory frequency on mass-transfer enhancement in grooved channels with different cavities. They pointed out that for a small cavity the optimum mass-transfer enhancement occurs at an intermediate Strouhal number, which corresponds well to the resonant enhancement theory. However, for a large cavity, the nonresonant mass-transfer enhancement is also observed at the other Strouhal numbers. Therefore, they inferred that there is another explanation for mass-transfer enhancement mechanism besides the hydrodynamic resonance (Nishimura et al., 2000b). This is an important contribution to the mechanism of heat- and mass-transfer enhancement for this research field.

As the extension of studies on flow in the 2-D channels, the pulsatile flow in the axisymmetric tubes has been studied but not sufficiently. Mackley and Stonestreet (1995) studied experimentally the effect of fluid oscillation within a baffled tube. They showed that the addition of baffles to a smooth tube results in a significant improvement in fluid mixing and heat transfer. Changing the amplitude has a stronger effect on the heat transfer than changing the oscillation frequency. For a large amplitude of oscillation, the overall power dissipation follows the quasi-steady theory. For small-amplitude oscillation the power dissipation is larger than that predicted by the quasi-steady model, indicating that the device is operating in a non-quasi-steady regime. However, the effect of Strouhal number has not been discussed in detail. Subsequently, Lee et al. (1999) investigated numerically chaotic mixing and mass-transfer enhancement for pulsatile laminar flow. They indicated that, at a small oscillation fraction of the flow rate, the mass-transfer enhancement increases as the net flow Reynolds number increases. There is an optimum Strouhal number, depending on the net flow Reynolds number, almost inversely proportional to the tube wavelength. Based on the concept of hydrodynamic resonance in grooved channels (Ghaddar et al. 1986b), they explained the mass-transfer enhancement in the wavy-walled tube.

Most recently, Nishimura et al. (2003) completed an experimental study on steady flow in a wavy-walled tube and described the nature of flow transition in detail. Using wall shear stress measurement and flow visualization technique, they found that the flow instability is quite different between the wavy-walled channel and the wavy-walled tube. That is, when flow enters the transitional flow regime, there are no Tollmien–Schlichting waves in the wavy-walled tube. Instead, the turbulent motion appears intermittently in the laminar flow. Considering the difference of flow instability, it seems that the theory of resonant enhancement is not adapted to the pulsatile flow in the wavy-walled tube, and this inference contradicts the numerical result proposed by Lee et al. (1999), which motivates the present experimental investigation.

The present study deals with mass transfer enhancement in a wavy-walled tube under pulsatile flow conditions. The effects of net flow, oscillatory fraction of the flow rate and Strouhal number of oscillation on mass transfer enhancement are examined. Among them, there is particular focus on the influence of Strouhal number.

Experimental Apparatus and Procedure

The experimental apparatus is shown in Figure 1. The volumetric flow rate of pulsatile flow is expressed as

$$Q_i = Q_S + Q_O \sin(2\pi t/T) \quad (1)$$

where Q_S is the net flow rate, Q_O is the peak flow rate of fluid oscillation, and T is the period of oscillation.

A centrifugal pump provides the net flow, and the flow rate is determined with a rotameter. A pulsatile pump, driven by a variable speed motor through a Scotch–Yoke mechanism that allows the length of stroke and frequency of the piston to be

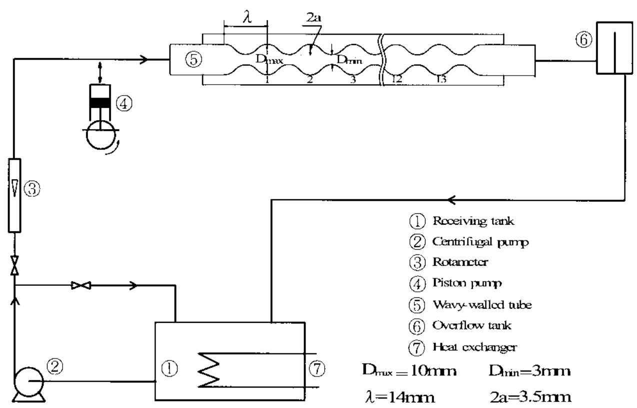


Figure 1. Flow system and details of wavy-walled tube.

changed, generates the imposed oscillatory flow. The following relation determines the peak flow rate

$$Q_O = 2fs(D_P^2/4) \tag{2}$$

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. To obtain a wide Strouhal number range, two kinds of piston diameters, 10 and 15 mm, are used in the present study.

The wavy-walled tube consists of 14 wave modules. Figure 1 shows the dimensions of the tube. Each module is 14 mm long (λ) and 3.5 mm deep ($2a$). The diameters at the maximum and minimum circular cross sections are 10 and 3 mm, respectively. The geometric dimensions are the same as those of the wavy-walled channel previously used by Nishimura and Kojima (1995). Three flow parameters characterize pulsatile flow.

(1) The net flow Reynolds (Re) number

$$\mathrm{Re}_I = \rho u_{II} D_{max}/\mu \tag{3}$$

(2) The oscillatory fraction of the flow rate

$$P = Q_O/Q_S \tag{4}$$

(3) The Strouhal (St) number

$$\mathrm{St} = D_{max}(2f/u_s) \tag{5}$$

where u_s is the average velocity at the maximum circular cross section, defined as $u_s = 4Q_S/(\pi D_{max}^2)$. Experiments were carried out in the following ranges of flow parameters: $40 < \mathrm{Re}_s < 300$, $0 < P < 9$, and $0.08 < \mathrm{St} < 15$.

In the present experimental study, the pulsatile flow patterns are visualized by the aluminum dust method. Perfusion with a suspension of aluminum particles, about 40 μm in diameter, enable us to observe the path lines approximately corresponding to streamlines within the whole flow field. A sheet light produced by a 250-W slide projector is used to illuminate the vertical cross section of the tube. Photographs are taken using a motor-driven camera to obtain the sequential pulsatile flow patterns. A video camera is also used to record the flow patterns.

The mass-transfer rate is measured by the electrochemical method, which can be applied to unsteady flows (Mizushina, 1971). The electrochemical reaction used is the cathodic reduction of ferricyanide ions to ferrocyanide ions at the cathode. The reverse reaction takes place at the anode. The measurement systems are shown in Figure 2. The nickel module at the 9th wave section is used for the cathode, and the other two nickel modules at the 6th and 12th wave sections are used for the anode. Furthermore, to keep enough area ratio of the anode to the cathode, the nickel pipes are attached to both ends of the wavy-walled tube and they are also used for a subsidiary anode. Thus the diffusional controlled condition is maintained in this experimental range. The diffusion current i_d is related to the Sherwood number as follows

$$\mathrm{Sh} = i_d D_{max}/(F C_b A D) \tag{6}$$

where D_{max} is the diameter in the maximum circular cross section of the tube, F is the Faraday constant, C_b is the concentration of ferricyanide ion, A is the area of mass-transfer surface for the cathode, and D is the molecular diffusivity of ferricyanide ion.

The electrolyte contains 0.01 N potassium ferri/ferrocyanide and 1.0 N sodium hydroxide, and its temperature is kept at 25°C. The Schmidt number is 1570. Under the analogy between heat and mass transfer, this system is equivalent to a high Prandtl number heat transfer.

Results and Discussion

Steady flow experiment (P = 0.0)

Flow characteristics for steady flow in a wavy-walled tube have already been described in the previous study (Nishimura et al., 2003). To compare with pulsatile flow, the mass-transfer rate for one wavelength, which is measured in the 9th wave section, is presented in Figure 3 as $\mathrm{Sh}_S/\mathrm{Sc}^{1/3}$ vs. Re_s Three regions are clearly distinguishable for the variation of the Sherwood number with the Reynolds number, and the critical Reynolds number for the flow transition covers $\mathrm{Re}_t = 160$–200. The Sherwood number increases with a slope of 1/3 in the laminar flow regime and 3/5 in the turbulent flow regime,

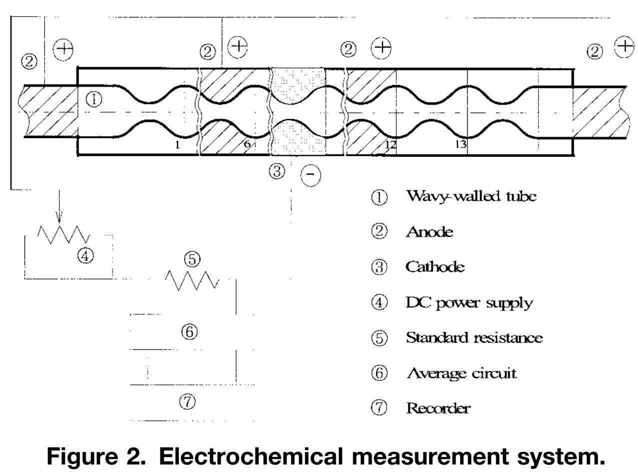


Figure 2. Electrochemical measurement system.

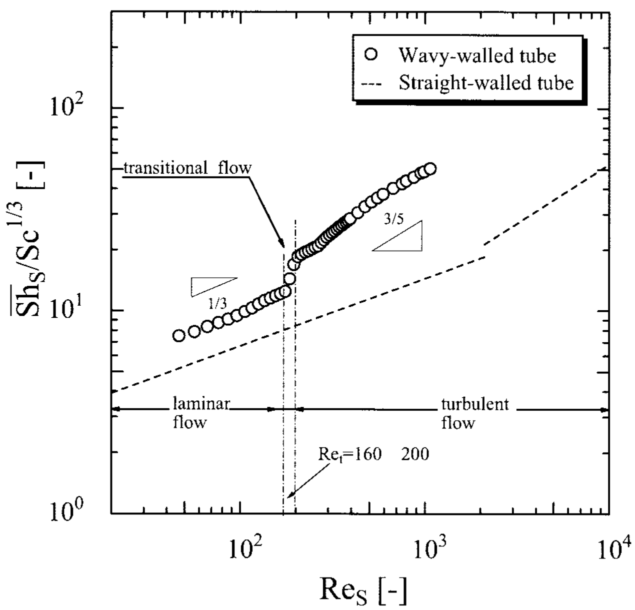


Figure 3. Sh vs. Re_s for steady flow.

respectively. A sudden change of Sherwood number is observed in the transitional flow regime attributed to the flow instability (that is, the presence of intermittent turbulent motion in the laminar flow), which is quite different from the Tollmien–Schlichting instability (Nishimura et al., 2003). In comparison with the result obtained for the straight-walled tube with the maximum diameter D_{max}, shown by the dotted line, the Sherwood number for the wavy-walled tube is larger, particularly in the turbulent flow regime.

Pulsatile flow experiment (P > 0.0)

Mass-transfer Enhancement. For pulsatile flow, the mass-transfer rate has a periodic variation in time, attributed to the imposed oscillatory flow. Here, the time-averaged results of mass transfer for one wavelength are first described. The Sherwood numbers for pulsatile flow are normalized by their respective steady values, defining the mass-transfer enhancement factor, $E = Sh_P/Sh_S$. The mass transfer can be enhanced when E is >1.0. Figure 4 shows the relationship between the enhancement factor and the oscillatory fraction of the flow rate at different net flow Reynolds numbers. The dotted lines, defined by the same gradient, are drawn in each figure. These lines represent referential ones, with no particular physical meaning.

At $Re_s = 47$, as shown in Figure 4a, the net flow belongs to laminar flow. It is seen that the enhancement factor increases in a nonlinear manner with the oscillatory fraction. In the range of $P < 1.0$, the enhancement factor has almost no change and is close to 1.0 (that is, no enhancement). However, for $P > 1.0$, the enhancement factor increases suddenly. At $Re_s = 151$, as shown in Figure 4b, the net flow approaches the transitional flow regime but still belongs to the laminar flow. As P increases, the enhancement factor increases in a linear manner on the dotted line. At $Re_s = 203$, as shown in Figure 4c, the net flow belongs to turbulent flow. The enhancement factor again becomes smaller than the one for $Re_s = 151$, although the enhancement factor increases gradually with the oscillatory fraction. From observation of these figures, the effect of net flow Reynolds number is clearly seen. That is, when the net flow is in the laminar flow regime, the mass-transfer enhancement factor increases as the net flow Reynolds number increases. With further increase of net flow Reynolds number, especially in the turbulent flow regime, the enhancement factor is reduced because of the increment in the mass-transfer rate in this flow regime for steady flow, as shown in Figure 3. Therefore, the most effective mass-transfer enhancement takes place at a net flow Reynolds number just below the transitional flow. This trend was also observed for the grooved channels (Nishimura et al., 2000a).

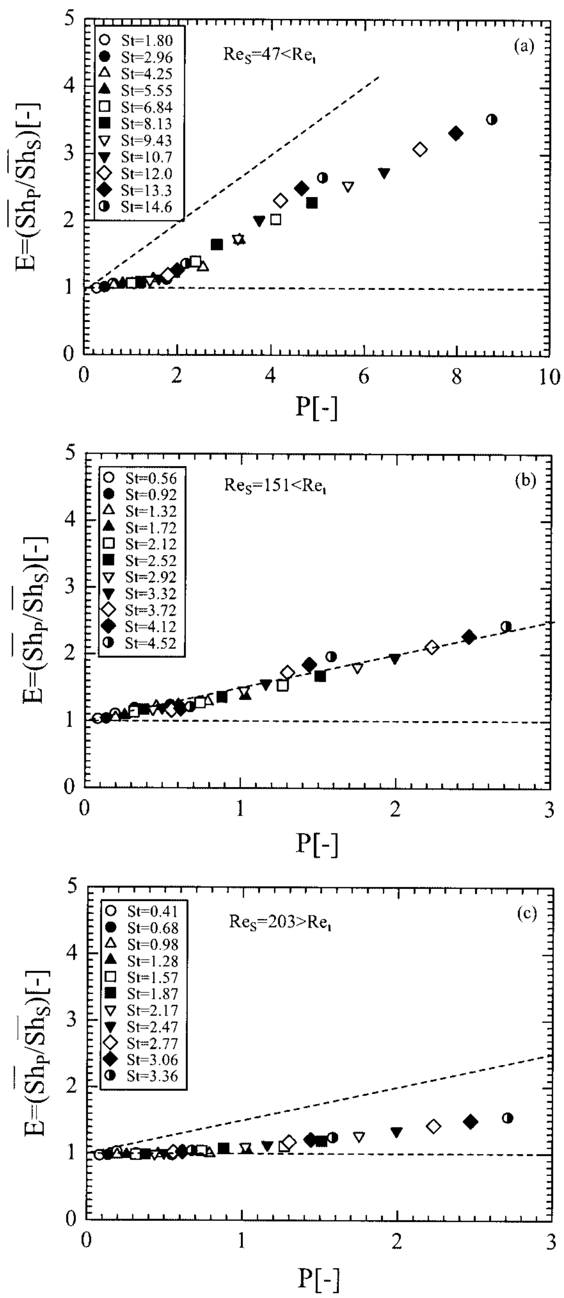


Figure 4. *E* vs. *P* at different Reynolds numbers.

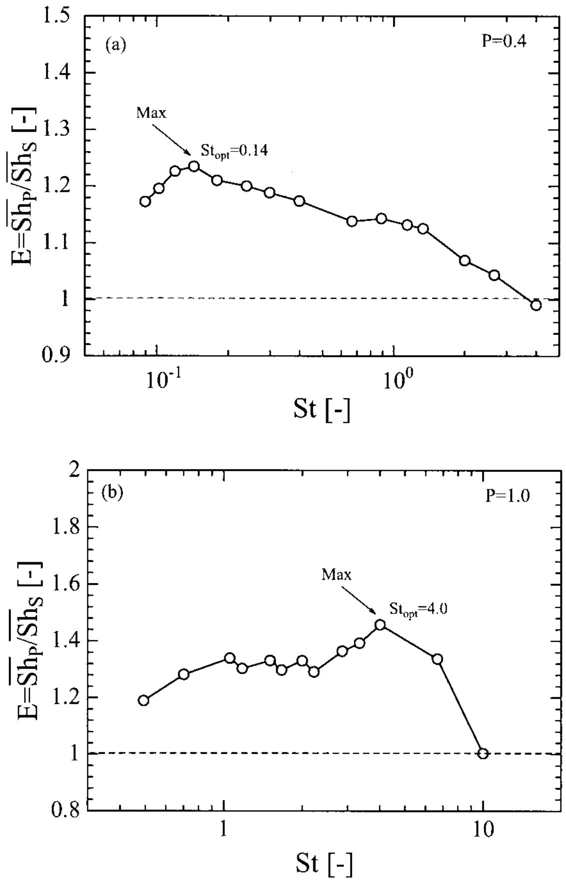


Figure 5. *E* vs. St at Re_s = 151.

From the above description, the effect of net flow Reynolds number is clear, although the effect of Strouhal number is unclear because the lower and higher Strouhal numbers are not included. We examine the enhancement factor in a wide Strouhal number range for a fixed net flow Reynolds number (that is, Re_s = 151). It is known that for $P > 1.0$ the effect of reverse flow on mass-transfer enhancement of pulsatile flow occurs. In the present study, the oscillatory fraction is limited in the range of $P > 1.0$. Figure 5 shows the relationship between the enhancement factor and the Strouhal number under the conditions of $P = 0.4$ and 1.0 at $Re_s = 151$.

For $P = 0.4$, as shown in Figure 5a, the enhancement factor increases as the Strouhal number increases. At St = 0.14, the enhancement factor reaches a peak value. Over this Strouhal number, the enhancement factor decreases with increasing the Strouhal number. At a higher Strouhal number St = 4.0, the enhancement factor is slightly less than 1.0, indicating no mass-transfer enhancement. For $P = 1.0$, as shown in Figure 5b, a similar trend is also displayed. However, the optimum Strouhal number for a peak enhancement factor is much higher than that of $P = 0.4$.

The relationship between the optimum Strouhal number and the oscillatory fraction is shown in Figure 6. As the oscillatory fraction increases, the optimum Strouhal number has a substantial increment. The previous studies of grooved channels (Ghaddar et al., 1986b; Kunitsugu and Nishimura, 1999) pointed out that the optimum frequency of flow oscillation in the case of resonant enhancement, attributed to the Tollmien–Schlichting waves, hardly changes as the oscillatory fraction increases. To confirm resonant transport enhancement for other geometric channels, we have additionally performed numerical simulation in a wavy-walled channel. The channel geometry is the same as that used in the previous experiment (Nishimura and Kojima, 1995). The flow is assumed to be 2-D and all of the test wave sections constitute the domain under analysis. At the inlet section, the uniform velocity is used, and at the outlet section, the velocity is adjusted to satisfy the mass balance for the computational domain. We use the software Fluent (Version 4.5) and the number of control volume is 15125. The numerical pulsatile flow pattern at each moment during one oscillation cycle agreed with the corresponding flow visualization photographs (Nishimura and Kojima, 1995). The relationship between the optimum Strouhal number and the oscillatory fraction is also shown in Figure 6, which demonstrates that there is a resonant enhancement in the wavy-walled channel

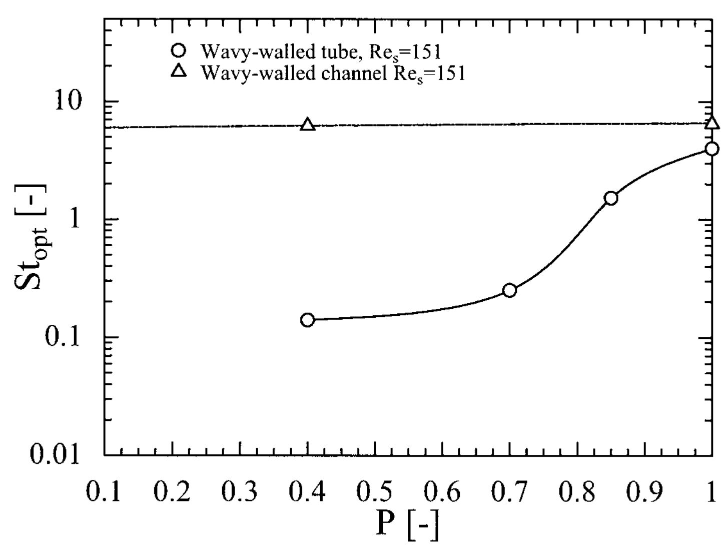


Figure 6. St_{opt} vs. *P*.

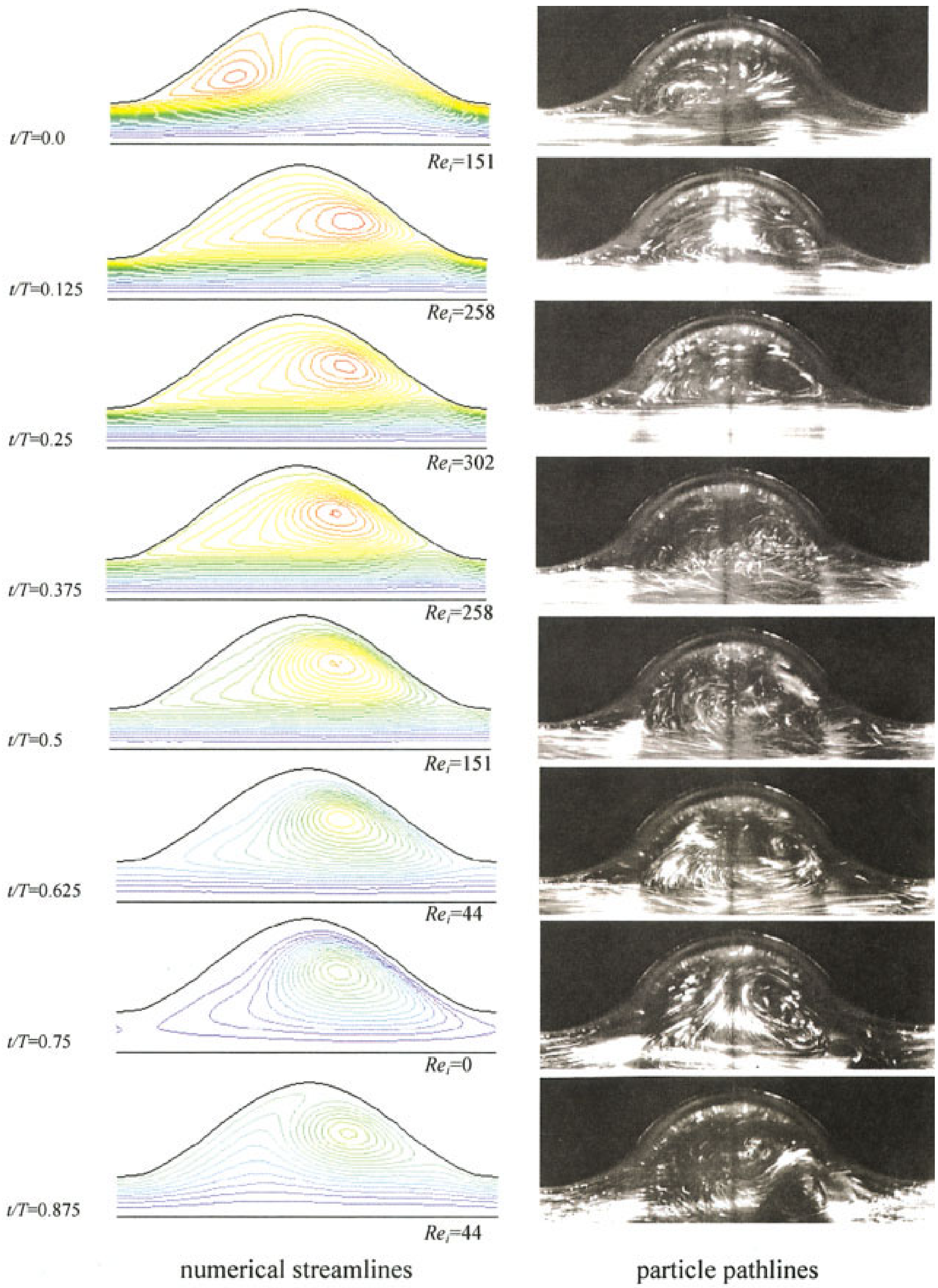


Figure 7. Numerical and experimental flow patterns for Re_s = 151, P = 1.0, and St = 4.0.

and the optimum Strouhal number is almost identical to that for self-sustained oscillation attributed to the Tollmien–Schlichting waves. Thus, it is found that the resonant mass transfer enhancement does not exist for the wavy-walled tube, in contrast to the wavy-walled channel.

Fluid Flow in One Oscillation Cycle. Because the mechanism of mass transfer enhancement in the wavy-walled tube cannot be explained by the resonant enhancement, a numerical analysis for pulsatile flow has been conducted to obtain the flow behavior. The flow is assumed to be axisymmetric, and the numerical procedure is the same as that for the wavy-walled channel mentioned above.

Several simulations have been carried out under the present experimental conditions, Re_s = 151, P = 1.0, for different Strouhal numbers. Figure 7 shows the numerical and experimental flow patterns for St_{opt} = 4.0 as a representative case. The numerical streamlines are in good agreement with the experimental particle pathlines during t/T = 0.0–0.25, but they are in disagreement during t/T = 0.375–0.875. The particle pathlines are highly disturbed in the latter period. This partial

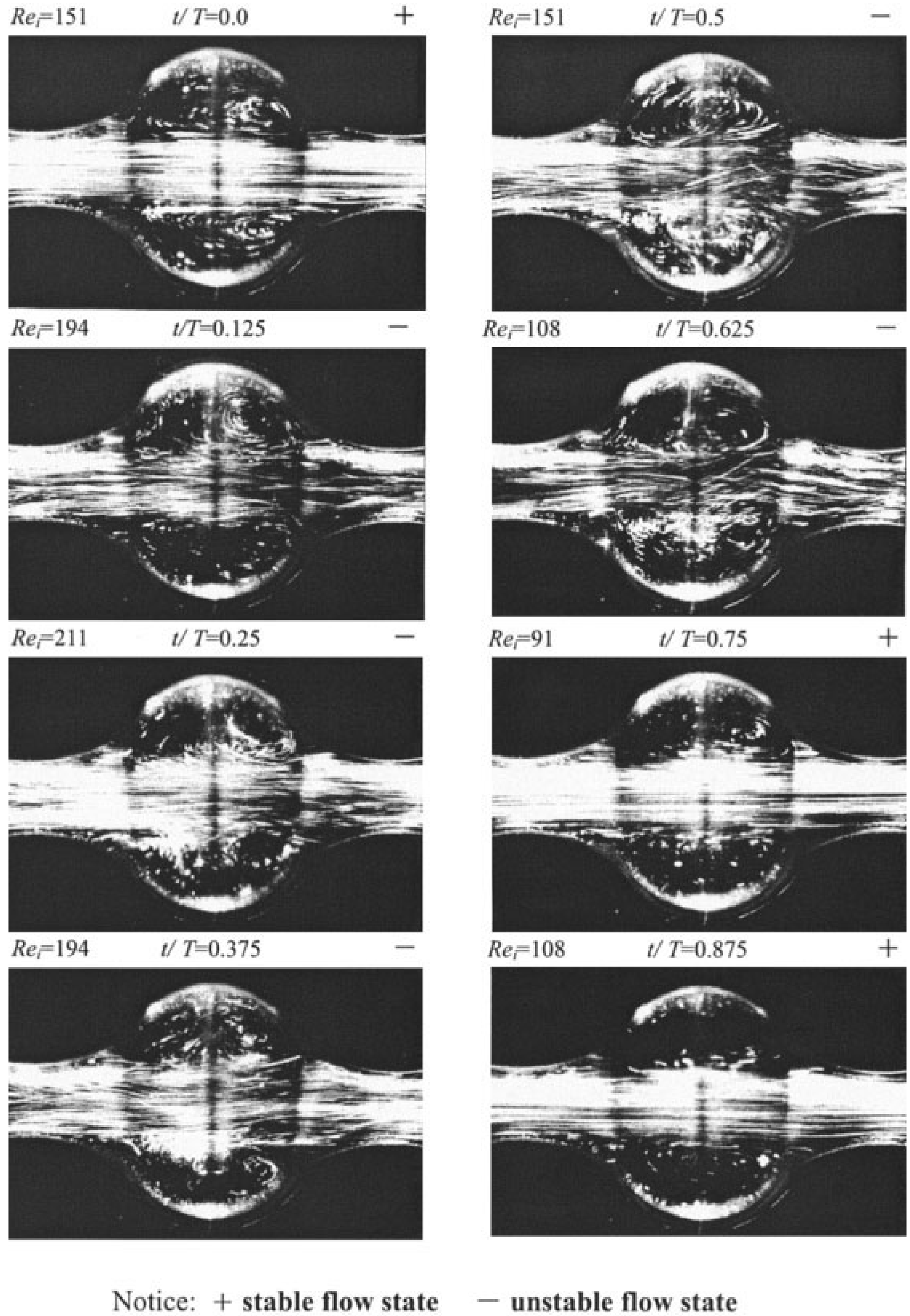


Figure 8. Flow patterns at P = 0.4 and St = 0.14.

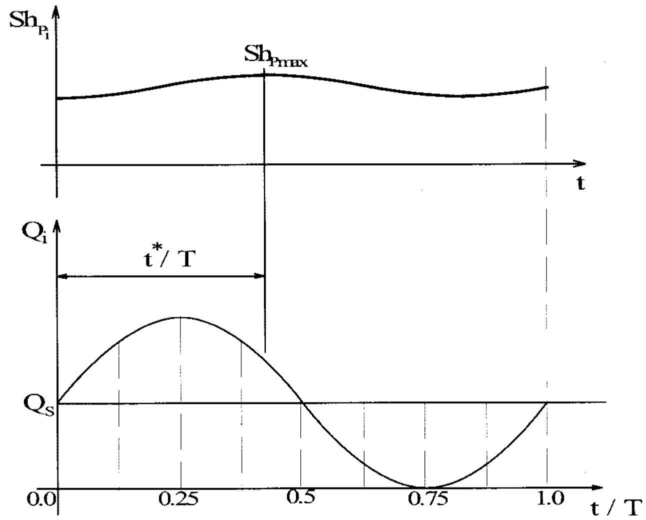
discrepancy may be explained by the intermittent flow instability that appears at $\mathrm{Re}_s = 151$, where the flow is close to the transitional regime for steady flow. Of course, at low Reynolds numbers, the agreement between the numerical and experimental results is satisfactory during one oscillation cycle. The present simulations cannot predict the flow behavior at high Reynolds numbers. So, we examine experimentally the Strouhal number effect on the flow behavior, using the aluminum dust method.

Figure 8 shows the pulsatile flow patterns in the 9th wave section during one oscillation cycle for $\mathrm{Re}_s = 151$, $P = 0.4$, and $\mathrm{St}_{opt} = 0.14$. At $t/T = 0.0$, the pathlines in the mainstream are aligned in the axial direction, displaying the stable state with flow separation, whereas at $t/T = 0.25$ of maximum flow rate the pathlines are disturbed in the radial direction, exhibiting the unstable state. In particular, the separated shear layer between the mainstream and the recirculation vortex experiences rigorous fluctuation. After that the flow rate is decelerated (t/T = 0.375–0.625), and the trend becomes stronger. However, the flow again reaches a stable state at $t/T = 0.75$ of minimum flow rate, which is kept up to $t/T = 1.0$. These flow patterns are observed in each wave section except in the entrance part of the wavy-walled tube. A similar result has been obtained for the pulsatile flow in a straight-walled tube (Ohmi

Table 1. Stable and Unstable States of Flow Patterns during One Oscillation Cycle at P = 0.4

		t/T							
Re_s	St	0.0	0.125	0.25	0.375	0.5	0.625	0.75	0.875
151	0.09	+	−	−	−	−	+	+	+
	0.10	+	−	−	−	−	+	+	+
	0.14	+	−	−	−	−	−	+	+
	0.24	+	−	−	−	−	+	+	+
	0.30	+	+	−	−	−	+	+	+
	0.40	+	+	−	−	−	+	+	+
	0.67	+	+	−	−	−	+	+	+
	0.80	+	+	−	−	−	+	+	+
	0.89	+	+	−	−	−	+	+	+
	1.14	+	+	+	−	−	−	+	+
	1.33	+	+	+	−	−	−	+	+
	1.60	+	+	+	−	−	−	+	+
	2.00	+	+	+	+	−	−	−	+
	2.66	+	+	+	+	+	+	+	+
	4.00	+	+	+	+	+	+	+	+

*Note: +, stable flow state; −, unstable flow state.
†St_{opt} = 0.14.



Re_s=151, P=1.0, St=1.67, t^*/T=0.424

Figure 9. Time variation of Sherwood number.

et al., 1981; Steller and Hussain, 1986). This state has been termed "turbulescent" by some researchers. However, the nature of this instability is still under question even for straight-walled pipes (Brereton and Mankbadi, 1995). In the wavy-walled tube, the Kelvin–Helmholtz instability is likely to appear in the separated shear layer, which promotes the unstable state. To confirm this instability, we need quantitative estimation such as velocity measurements and direct numerical simulations, although this topic is beyond the scope of this article because mass-transfer enhancement has great interest for us.

Based on a number of flow visualization results, the flow patterns are concluded for different Strouhal numbers for P = 0.4, as shown in Table 1. As the Strouhal number increases, the onset of the unstable state gradually shifts from the acceleration phase to the deceleration phase and the duration of unstable state is reduced. After the Strouhal number becomes >2.66, the flow pattern maintains a stable state all the time because, at high Strouhal numbers, the flow is dominated by viscosity effects. It should be noticed that the duration of unstable state at the optimum Strouhal number St_{opt} = 0.14 is the longest in contrast to that at the other Strouhal numbers, indicating that the unstable state leads to a remarkable fluid exchange between the mainstream and the recirculation zone. The classification of flow patterns under the condition P = 1.0 for different Strouhal numbers is also shown in Table 2. It is seen that the flow patterns have a similar feature to the case of P = 0.4 (that is, the duration of unstable state at the optimum Strouhal number St_{opt} = 4.0 is also the longest). However, several unstable asymmetric flow patterns appear, which indicates more effective fluid exchange. Furthermore, the unstable states are kept at higher Strouhal numbers until St = 10.0, unlike the case of P = 0.4, although duration of the unstable state becomes smaller.

Table 2. Stable and Unstable States of Flow Patterns during One Oscillation Cycle at P = 1.0

		t/T							
Re_s	St	0.0	0.125	0.25	0.375	0.5	0.625	0.75	0.875
151	0.45	+	−	−	−	−	+	+	+
	0.74	+	+	−	−	−	−	+	+
	0.99	+	+	−	−	−	−	+	+
	1.27	+	+	−	−	−	−	+	+
	1.67	+	+	+	−	−	−[a]	−[a]	+
	2.00	+	+	+	−	−	−[a]	−[a]	+
	2.22	+	+	+	−	−	−[a]	−[a]	+
	2.86	+	+	+	−	−	−[a]	−[a]	+
	3.34	+	+	+	−	−	−[a]	−[a]	−[a]
	4.00	+	+	+	−	−	−[a]	−[a]	−[a]
	5.00	+	+	+	+	−	−[a]	−[a]	−[a]
	6.67	+	+	+	+	+	−	−[a]	−[a]
	10.0	+	+	+	+	+	−	−[a]	−[a]

*Note: −[a], untable and asymmetric state.
†St_{opt} = 4.0.

To reveal the relationship between the mass transfer and unstable flow state, the time variation signals of Sherwood number for different oscillatory fractions were obtained by using an oscilloscope. The time in which the maximum mass-transfer rate appears during one oscillation cycle is measured for different oscillatory fractions and Strouhal numbers. Figure 9 shows a typical result at Re_s = 151, P = 1.0, and St = 1.67. It is found that the maximum mass-transfer rate during one oscillation cycle takes place in the deceleration phase. In this case, the time is t^*/T = 0.424 in the deceleration phase. Table 3 shows the flow states at the optimum Strouhal numbers for different oscillatory fractions of the flow rate. The time of maximum mass-transfer rate almost locates in the middle of each unstable duration; that is, t^*/T = 0.31, 0.32, 0.42, and 0.75 for P = 0.4, 0.7, 0.85, and 1.0, respectively. It is concluded that

Table 3. Stable and Unstable States of Flow Pattern during One Oscillation Cycle at the Optimum Strouhal Number for Different Oscillatory Fractions

		t/T								
P	St_{opt}	0.0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	t^*/T
0.4	0.14	+	−	−	−	−	−	+	+	0.31
0.7	0.25	+	−	−	−	−	−	+	+	0.32
0.85	1.52	+	+	−	−	−	−[a]	−	+	0.42
1.0	4.00	+	+	+	−	−	−[a]	−[a]	−[a]	0.75

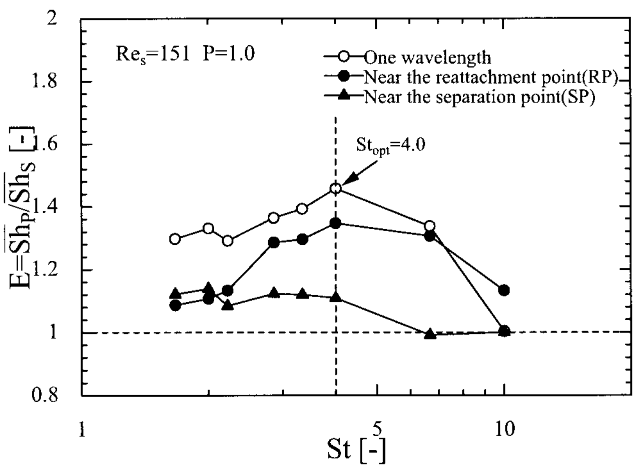


Figure 10. Local mass-transfer enhancement.

the unstable flow state in the deceleration phase contributes to the mass-transfer enhancement.

Finally, to examine the local mass-transfer effect, two point electrodes are inserted near the separation point and reattachment point in the recirculation vortex, and the time-averaged enhancement result is obtained at $Re_s = 151$ and $P = 1.0$, as shown in Figure 10. The local mass-transfer enhancement has a similar effect of Strouhal number compared with that for one wavelength. In particular, the enhancement factor near the reattachment point is higher than that near the separation point, meaning that more effective transport enhancement can be expected at the reattachment point.

Conclusions

The experimental study on fluid flow and mass-transfer enhancement was performed in a wavy-walled tube for pulsatile flow. The effect of Strouhal number constituted a particular focus of the investigation. Conclusive remarks have been drawn as follows:

(1) The effect of mass-transfer enhancement strongly depends on the net flow Reynolds number. In the present experiment, the most effective enhancement occurs at a net flow Reynolds number just before the flow transition observed for steady flow.

(2) The maximum mass-transfer enhancement exists at an intermediate Strouhal number for a fixed oscillatory fraction of the flow rate. The corresponding optimum Strouhal number strongly depends on the oscillatory fraction of the flow rate. The resonant transport enhancement, attributed to the Tollmien–Schlichting waves, does not exist in the wavy-walled tube, in contrast to the wavy-walled channel.

(3) The flow state tends to be stable in the accelerating phase and unstable in the decelerating phase. The unstable flow, which results from the shear layer between the mainstream and the recirculation vortex, leads to a remarkable fluid mixing and contributes to the mass-transfer enhancement. Furthermore, locally, a higher transport enhancement is obtained near the reattachment point. The mechanism of this flow instability during one oscillation cycle is the subject of future work.

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