

The Influence of Oscillatory Fractions on Mass Transfer of Non-Newtonian Fluid in Wavy-Walled Tubes for Pulsatile Flow

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Abstract. The shape of pipeline structure, fluid medium and flow state have important influence on the heat transfer and mass effect of fluid. In this paper, we investigated the mass transfer behavior of Non-Newtonian fluid CMC solution with 700ppm concentration in five different-sized axisymmetric wave-walled tubes for pulsatile flow. It is revealed that the effect of mass transfer is enhanced with the increase of oscillatory fractions P based on the PIV measurements. Besides, mass transfer rate was measured by the electrochemical method in the larger oscillatory points rate range. It is observed that mass transfer rate increases with the increase in P and reached the maximum mass transfer rate at the most optimal oscillatory fractions P_{opt} . After reaching the optimal oscillatory fractions P_{opt} , the mass transfer rate decreases with increasing P .

1. Instruction

The flow of fluid and heat and mass transfer in various flow paths become an important part in the study of fluid mechanics. It is very important to clarify the mechanism of flow characteristics and transfer process for the development and designment of various heat transfer equipment. Changing flow field can enhance the heat transfer effect. Currently, there is less research on the oscillatory fractions of the pulsating flow in the wave-walled tube.

Nishimura et al. studied the characteristics of fluid flow and mass transfer in sinusoidal wavy-walled tube. Their results show that the rapid fluid mixing produced by eddy motion can achieve better quality transfer enhancement in the basin with inertial influence. The results of the study of the flow field of the unopposed flow in the wall tube showed that the most effective mass transfer intensification occurred before the net flow was about to enter the transitional flow. The optimal number of frequencies with flow rate is non-linear. They point out that because there is no self-excited oscillatory fractions in the three dimensional tube, resonance enhancement cannot be used to explain the strengthening mechanism. However, the results of the study that accompanied the pulsating flow of the reverse flow were not given. In this paper, the effect of oscillatory fractions on mass transfer is studied. It provides some reference for the development of high efficiency and low consumption heat transfer device.

2. Experimental Setup and Methods

The experimental equipment of this study mainly consists of three parts: PIV equipment shown in figure 1, mass transfer rate measurement system illustrated in figure 2 and pulsatile flow system



plotted in figure 3 and 4. Here, PIV technology is applied to the experimental system of pulsatile flow field, which enables us to illustrate the complex flow characteristics. The working fluid with tracer particles is extracted from the storage tank by centrifugal pump, and its net flow is controlled by the rotor flow meter. Before entering the wave wall tube, the pulsation pump superimposes the sine vibration of the working fluid. Pulse laser to produce light irradiation on the wave wall tube central axis, vertical plane of the high-speed digital camera to catch the image data of the tested area, at the same time through collecting transmission to the computer's memory. The synchronous controller is used to control the optical fiber sensor, digital camera, and image acquisition board, so that they can work in a strictly synchronous signal and ensure the coordination of all parts.

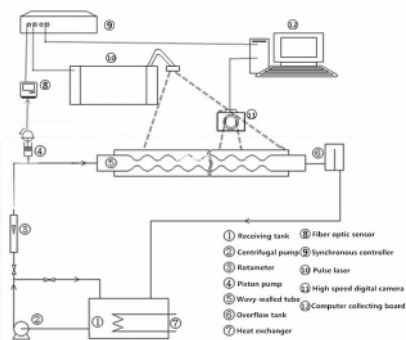


Figure 1. Experimental setup.

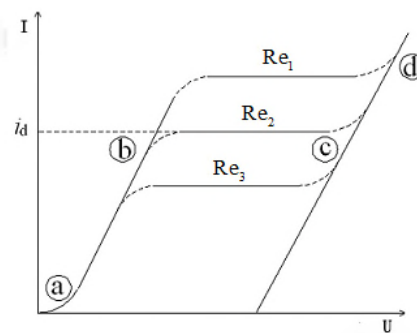


Figure 2. Limiting current i_d vs. Voltage u .

Electrochemical technology is one kind of limiting current technology based on the electrochemical reaction, namely in solid electrodes on the surface to maintain a voltage causes the electrochemical reaction rate as large as possible, reaching the electrochemical polarization. Polarization current relatively become stable at this time, and its size is determined by the mass transfer rate as is shown in the figure 2.

The measurement system of mass transfer rate is shown in figure 3. Nickel cathode module was set in the ninth wave band, the anode was set at 6 and 12 wavelength, respectively. At the same time, in order to ensure that the ratio of anode and cathode surface area is large enough, choosing entrance section and export section of nickel pipe as auxiliary anode. In this experiment, the electrolyte with special preparation was used as the working fluid. The number of Schmidt of this solution was 1570, which meets the diffusion control conditions.

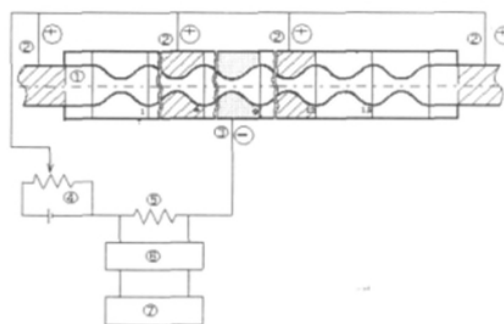


Figure 3. Mass transfer rate measurement system.

3. Definition and Choice of Parameters

3.1. Definition of Parameters

Quantity of pulsation flow is steady flow combine to oscillatory flow, and it can be defined as

following:

$$Q_i = Q_s + Q_o \sin(2\pi t / T) \quad (1)$$

where Q_i is the oscillatory flow, Q_s is steady flow, and Q_o is peak of oscillatory flow. Here, Q_o is defined as:

$$Q_o = 2\pi f s (\pi D_p^2 / 4) \quad (2)$$

Here, f is the frequency of oscillation, s is the useful length of the piston, and D_p is the diameter of the piston.

The Reynolds number for steady flow:

$$Re_s = u_s D_{\max} / \nu \quad (3)$$

The oscillatory fraction of the flow rate:

$$P = Q_o / Q_s \quad (4)$$

As a non-dimensional expression of oscillatory frequency, the Strouhal number is defined:

$$St = D_{\max} (2\pi f / u_s) \quad (5)$$

To express the waviness degree of the wavy-walled tubes, the wave factor F_w is defined as:

$$F_w = \frac{D_{\max}}{D_{\min}} \times \frac{2a}{\lambda} \quad (6)$$

3.2. Selection of Parameters

Figure 4 shows the pattern of wavy-walled tube used in this study, and it is clear to see that the tube is axial symmetry. The sizes of them are listed in table 1.

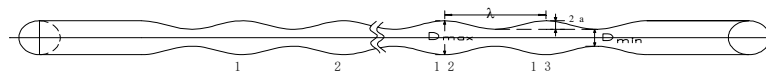


Figure 4. Dimensions of wavy-walled tube.

Table 1. Size of five wavy-walled tubes.

F_w	0.83	0.69	0.58	0.36	0.15
$D_{\max}(\text{mm})$	10	10	10	10	10
$D_{\min}(\text{mm})$	3	3	3	5	7
$2a(\text{mm})$	3.5	3.5	3.5	2.5	1.5
$\lambda(\text{mm})$	14	17	20	14	14

3.3. Selection of Vibration Fraction

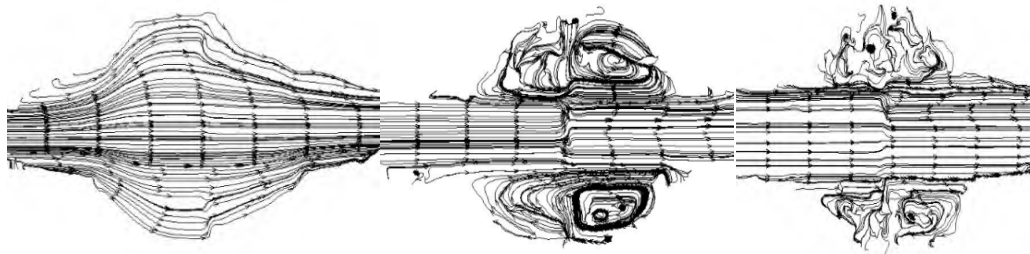
Since PIV can only study flow characteristics in qualitative research, the study scope of vibration fraction P is limited, and $P=1/\sqrt{2}$, $P=1$, and $P=\sqrt{2}$ are selected under PIV experiment. The electrochemical mass transfer experiment was selected as $P=1/\sqrt{2}$, 1, $\sqrt{2}$, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 and 6.

4. Results and Discussion

4.1. PIV Experimental Results

Pulsating flow field separately on the five sets of wave wall tube PIV image velocimetry experimental study, the PIV technology was applied to the pulsating flow field of tube flow field, the wave wall

tube in the period of a vibrating flow visualization pictures, software Tecplot processing image data to obtain the flow chart, further analysis concludes two kinds of stable flow structure and an unstable flow structure as is shown in figure 5.

**Figure 5(a). “I”****Figure 5(b). “II”****Figure 5(c). “III”.**

Integrated the three kinds of flow pattern, flow by clear layers to form vortex, finally the flow and vortex damage, through the comparisons of mixed flow can be found that three kinds of flow pattern corresponding to the mass transfer effect must be “I < II < III” relationship.

As is shown in table 2, the experiment obtained the flow structure corresponding to each of the eight equal parts of each vibration cycle of each of the three vibration points, and the number of the second flow form was denoted by n .

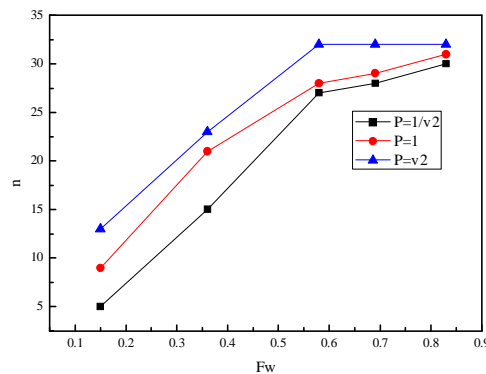
Table 2. The influence of F_w and p on flow structure.

$F_w=0.83/0.69/0.58 \quad n=32$								
St	(t/T)							
	0	0.125	0.25	0.375	0.5	0.625	0.75	0.875
0.59	II	II	II	II	II	II	II	II
1.0	II	II	II	II	II	II	II	II
1.82	II	II	II	II	II	II	II	II
3.33	II	II	II	II	II	II	II	II
$F_w=0.36 \quad n=23$								
0.59	I	I	I	II	II	II	II	II
1.0	I	II	II	II	II	II	I	II
1.82	I	I	II	II	II	II	II	II
3.33	II	I	I	II	II	II	II	II
$F_w=0.15 \quad n=13$								
0.59	I	I	I	I	II	II	II	II
1.0	I	I	I	II	II	II	II	II
1.82	I	I	I	I	I	II	II	I
3.33	I	I	I	I	I	II	II	I

To sum up, the second type of flow number of each oscillatory fraction is shown in table 3.

Table 3. The number of the second flow type of each oscillatory fraction.

F_w	$P=1/\sqrt{2}$	$P=1$	$P=\sqrt{2}$
0.15	5	9	13
0.36	15	21	23
0.58	27	28	32
0.69	28	29	32
0.83	30	31	32

**Figure 6.** The number of the second flow type of each vibration fraction.

It can be seen from figure 6 that the number of the second type of flow in each vibration is increased with the increase of F_w , indicating that the mixing degree of flow increases with the increase of F_w ; In addition, in the same pipeline, n increases with the increase of the oscillatory fraction, indicating that the mixing of the fluid increases with the increasing of the oscillatory fraction. It can be concluded that the mass transfer effect of fluid is related to the oscillatory fraction, and the mass transfer effect is enhanced with the increase of P in the test range of the PIV.

4.2. Electrochemical Mass Transfer Experiment

To measure the average current of each oscillatory fraction, the strengthening coefficient $E=I_0/I_s$ is compared with the limiting current I_0 under the steady flow field. The mass transfer coefficient of different vibration fraction P is shown in the table below.

Table 4. The mass transfer coefficient of different oscillatory fraction p .

P	$1/\sqrt{2}$	1	$\sqrt{2}$	2	2.5	3	3.5	4	4.5	5	5.5	6
U	3.65	4.5	5.42	6.5	7.19	7	7	7.3	6.7	5.9	6.16	6
E	1.04	1.28	1.54	1.85	2.05	2	2	2.08	1.91	1.68	1.76	1.04

Figure 7 shows that mass transfer effect is related to the rate of oscillatory fraction in the pulsating flow field. In the range of oscillatory fraction of electrochemical mass transfer experiment, the mass transfer coefficient increases with the increase of the vibration fraction, reaching the maximum when P is equal to 3. Then it decreases with the increase of the vibration fraction.

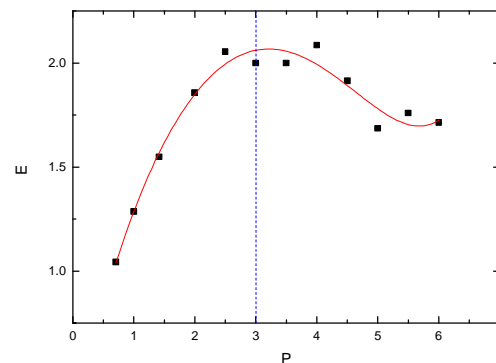


Figure 7. E VS. P.

5. Conclusions

1) The mass transfer effect of the fluid is related to the vibration fraction in the pulsating flow field, and the mass transfer effect is enhanced with the increase of P in the scope of the PIV test.

2) In the pulsating flow field, mass transfer effect is related to the rate of oscillatory fraction. In the range of vibration fraction of electrochemical mass transfer experiment. The mass transfer coefficient increases with the increase of the vibration fraction, reaching the maximum when P is equal to 3. Then it decreases with the increase of the vibration fraction. Therefore, it makes sense to increase the value of the vibration fraction in the range of $P \leq 3$.

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