Characteristics of T-S wave in the grooved channels with different groove length for steady flow

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Abstract

Pressure drop and time-averaged and time-various local pressure in the grooved channels with six kinds of groove length are measured with the differential transducer and the pressure sensor respectively, and the flow structures are also visualized by the aluminum dust method. The local pressure signal shows that T-S wave appears in the first or second frequency, and the Strouhal number, based on the nature frequency of the T-S wave, is almost equivalent for the 1st or 2nd frequency in the same channel. Meanwhile, the Strouhal number for each channel decreases monotonously with the groove length. Furthermore it is found that an operation of pressure increasing will result in higher amplitude of the T-S wave, this behavior is very significant for the efficient heat exchanger in practical engineering.

Key Words: Grooved channel; T-S wave; 1st and 2nd frequency; Amplitude; Pressure increasing or decreasing

1. INTRODUCTION

Heat and mass transfer processes frequently limit the size, performance and efficiency of practical engineering devices, such as the plate heat exchanger, which is widely applied to the ocean thermal energy conversion (OTEC) system. Many investigators devote their effort to finding the effective channel shape and the technique to enhance the heat and mass transfer. As a fundamental element of plate heat exchanger, two-dimensional channels with various wall shapes are considered to realize this purpose.

The earlier study was carried out in the plane channel. Nishioka et al.[1] conducted an experimental investigation of the stability of plane Poiseuille flow. They confirmed that when the Reynolds number exceeds a critical value, the local velocity fluctuations display the sinusoidal wave forms. As further increasing the Reynolds number, the wave form deviates gradually from this regular shape to irregular one. The above flow behavior is numerically proved by Ghaddar et al.[2], they concluded that the flow instability in the plane channels displays the form of Tollmien-Schlichting wave, i.e. the T-S wave, and characterized by the wave number and frequency. Then, Stephanoff[3] observed the self-sustained shear-layer oscillation in a wavy channel. He found that when the mean velocity through the channel exceeds a critical value, this self-sustained shear-layer oscillation appears as one, or sometimes two, selectively amplified frequencies. With the similar channel, Wang et al.[4] numerically studied the convective heat transfer. Their result shows that the T-S wave will lead to the destabilization of the laminar thermal boundary layers, and as a result of the unsteadiness, there is increased mixing between the core and near-wall fluid, thereby resulting in enhanced heat transfer rate. Furthermore, the flow characteristics and the relationship between fluid mixing and flow instability also have been investigated systematically in the grooved channel by Nishimura et al.[5~7] and Greiner[8]. Both of their experimental and numerical results indicated that the existence of T-S wave exists in all of two-dimensional channels, and the nature of T-S wave has a closed relationship with the heat and mass transfer rate.

Although many studies described the behavior of T-S wave in the two-dimensional channels, the details about the effect of the operation conditions on the T-S wave is scarcely considered even though it is very significant for the heat transfer enhancement, it prompts us to carry out the present experimental study. In this study, the overall pressure drop and the local pressure will be measured in the series grooved channels with different groove length, and then the amplitude of T-S wave will be analyzed for the case of increasing or decreasing the channel pressure. Finally, combine with the flow visualization results, the characterristics of T-S wave in the grooved channels will be clarified.

2. EXPERIMENTAL SETUP

The schematic of the experimental apparatus is depicted in Fig. 1. The flow is provided by a centrifugal pump and the city water is used as the working fluid. The flow rate is adjusted by the control valve and measured with an electromagnetic flowmeter; Q represents the flow rate. The overall pressure drop of the test section is recorded by a differential transducer and five pressure sensors are used to measure the time-various pressure at eight different locations of the test section. The valve-1 and valve-2, located at the outlet of the test section and the downstream of the flowmeter respectively, are used to obtain the decreasing or increasing pressure operating condition. The aluminum dust method is used to realize the flow visualization and the flow patterns are recorded by a high vision digital video camera. The dimensions of the test section

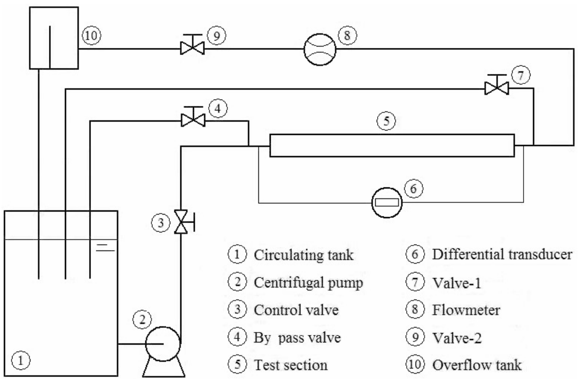


Fig. 1 Schematic diagram of the experimental system

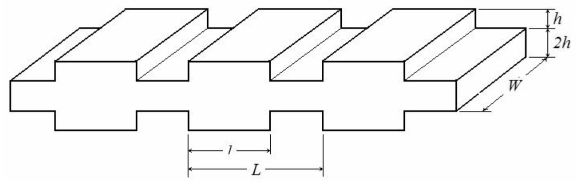


Fig. 2 Dimensions of the test section

are shown in Fig. 2. Total six kinds of grooved channels are examined in this study. Every grooved period length is L=20mm, W=200mm, h=2.5mm and the grooved lengths are l=4, 6, 8, 10, 12, 14mm, respectively. The local pressures are measured at eight different locations of the grooved channel, as shown in Fig. 3. The Reynolds number Re, Strouhal number St and friction factor f are calculated according to the following definitions:

$$\mathrm{Re} = \rho u h / \mu \tag{1}$$

$$St = f_T h / u \tag{2}$$

$$f = h\Delta P / (2L_P \rho u^2) \tag{3}$$

where, f_T is the frequency of T-S wave, ρ and μ are the density and viscosity of water, respectively. $u=(3/2)u_m$ is the characteristic flow velocity, here, $u_m=Q/(2Wh)$. ΔP is the overall pressure drop. L_P=1295mm, is the distance of the taps between the inlet and outlet. All the experiments are conducted at the room temperature.

3. RESULTS AND DISCUSSION

3.1 Effect of the groove length on the critical Reynolds number

The friction factor, obtained by the pressure drop, is one of the parameters reflecting fluid mechanical characteristics in channels. The relationships between the overall friction factor and the Reynolds number in the six kinds of grooved channels are shown in Fig. 4. It is seen that the lines of f-Re for all channels almost have the same slop in laminar flow regime, but their development becomes a little different when the Reynolds numbers Re exceed their critical value $\mathrm{Re_c}$, i.e., the $\mathrm{Re_c}$ will increase with the decreasing of the groove length, meanwhile, the friction factor increases gradually. Figure 5 shows the effect of the groove length on the $\mathrm{Re_c}$. For the series grooved channels used in this study, the $\mathrm{Re_c}$ approximately decreases in linear with the increment of the groove length. According to this result, the T-S wave only occurs in the upper area of the dashed line.

3.2 Local pressure in different channels

The local pressures in the eight different locations are measured for all the grooved channels. Figure 6 shows the representative result obtained at P3, P4 and

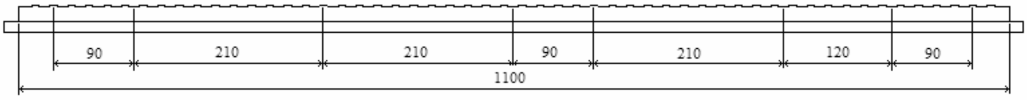


Fig. 3 Locations of the local pressure measurement

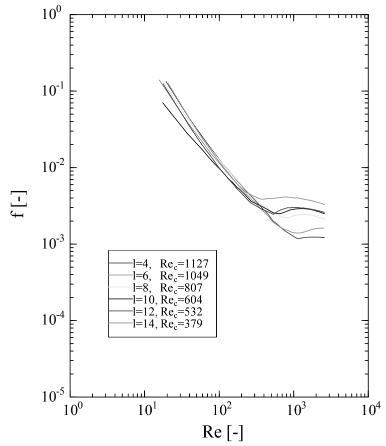


Fig. 4 *f vs.*Re in all channels

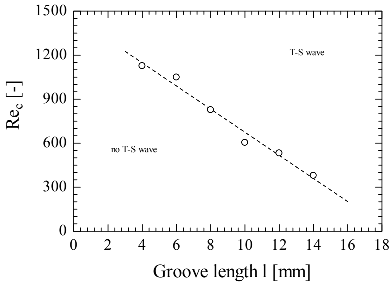


Fig. 5 Relationship between Re$_c$ and groove length

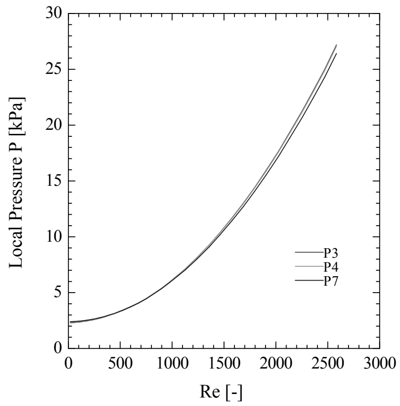


Fig. 6 P *vs* Re in the channel *l*=8 mm

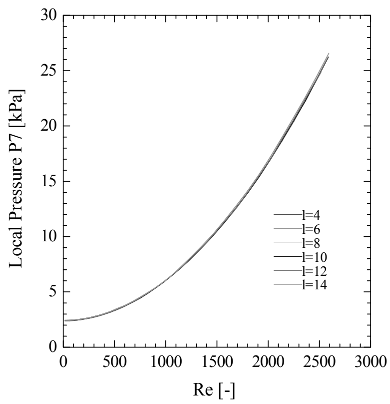


Fig. 7 P *vs* Re in all grooved channels

P7 from the channel with *l*=8mm. Obviously, the local pressure is nearly same when Re<1500, and the P7 decreases a little with further increasing the Re, means the pressure loss is increase contrast to the P3 and P4 and the power consumption must be considered fully when the flow speed is high enough. The comparison of local pressure for all channels at the same P7 is displayed in Fig. 7. All of the curves close each other, indicating that that all of the grooved channels have the same characteristics on the flow resistance.

3.3 Tim-variation of the local pressure

To check the relationship between the groove length and the nature frequency of the T-S wave, the time-variation local pressures are measured in different location for all channels. The T-S waves have been captured in three channels, that is *l*=8,10,12mm. In the other three channels, the T-S wave could not be recorded. The reason for this is considered to the limit of the maximum flow rate and the sensitivity of the pressure sensor. Figure 8~10 show the measurement results at P3 in the three kinds of grooved channels. It is found that the oscillations in the 1st and the 2nd

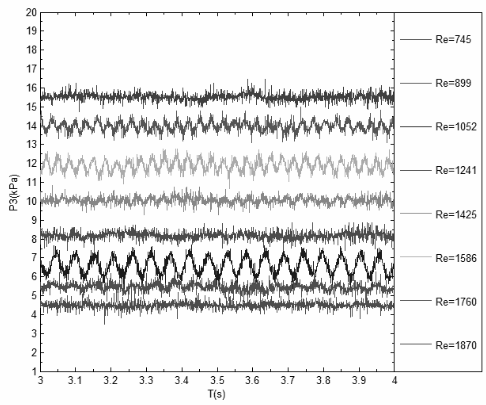


Fig. 8 T-S wave in the channel *l*=8 mm

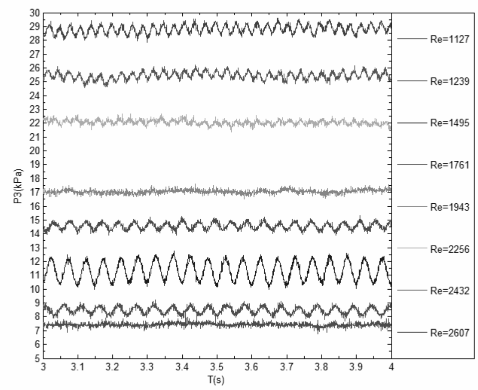


Fig. 9 T-S wave in the channel *l*=10 mm

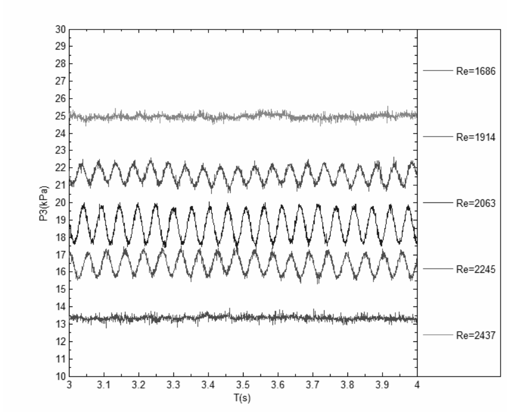


Fig.10 T-S wave in the channel l=12 mm

Table 1 Nature frequency of T-S wave in different channels

l (mm)	1st frequency			2nd frequency		
	Re	f_T(Hz)	St	Re	f_T(Hz)	St
8	1052	18.5	0.1099	1586	30	0.1182
				1760	31	0.1101
10	1239	18.8	0.09483	2432	33	0.08481
	1495	20	0.08361	2607	33.5	0.08031
12	1914	18.8	0.06139			
	2063	19.3	0.05847			
	2245	20	0.05568			

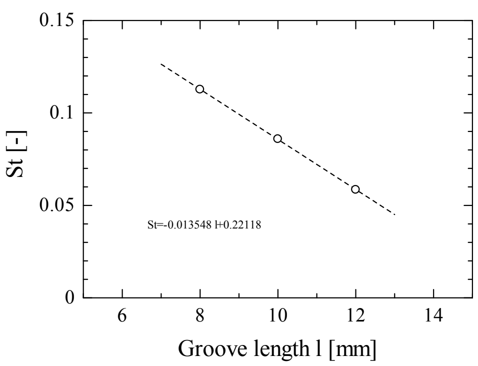


Fig. 11 Relationship between St and groove length

frequency appear in Fig.8 and 9, but only the 2nd frequency is found in Fig. 10. From these three figures, the frequency of the T-S wave in the 1st frequency and the 2nd frequency could be read easily. Based on the formula (1) and (2), the Strouhal numbers are calculated and shown in Table 1. From this table it is seen that for the same channel, whatever the 1st or the 2nd frequency, the value of the Strouhal numbers are very closed to each other, and the maximum error does not exceed 18%. This result agrees well with Stephanoff's study[3]. This fact is very important for the practical engineering; it means that once the 1st or the 2nd frequency is obtained, the nature frequency of the T-S wave at any Reynolds number could be calculated. Based on the averaged St for each used grooved channel in this study, a simple relationship could be concluded, that is, the Strouhal number decreases monotonously with the groove length, as shown in Fig.11. According to this conclusion, the St could be calculated conveniently for the channels with l=8 ~12mm.

3.4 Amplitude of T-S wave at in different locations

To have a insight to the amplitude of T-S wave in the channels, the T-S wave are captured at different locations for the three kinds of channels, and then all of the experimental data are processed with a program filter and the amplitude variation of the T-S wave with the flow rate are obtained as shown in Fig. 12~14. As described in the former, it is clear to see that the T-S wave in the 1st and the 2nd frequency exist in the channels with l=8 and 10, but only the 2nd frequency exists in the channel wit l=12. Moreover, the amplitude of T-S wave in the channel with l=10 is nearly two times higher than it in the other two channels, whatever for the 1st or the 2nd frequency. Another characteristic

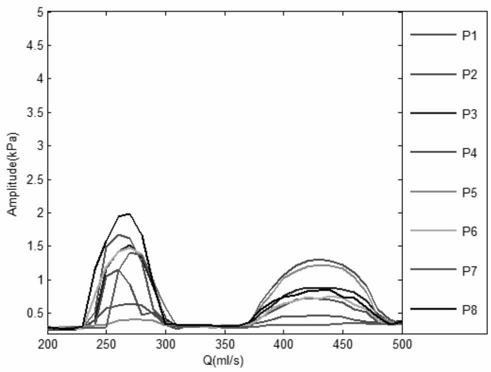


Fig. 12 Amplitude in the channel l=8 mm

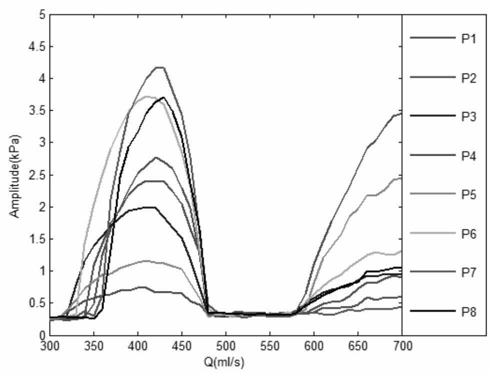


Fig. 13 Amplitude in the channel l=10 mm

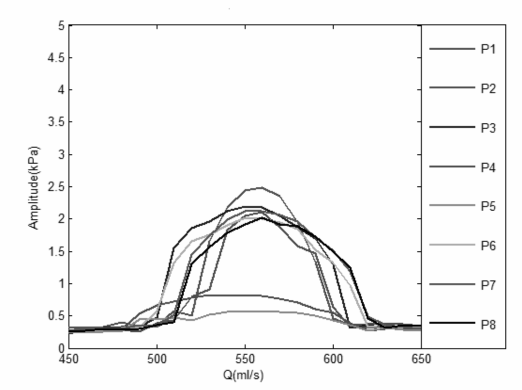


Fig. 14 Amplitude in the channel l=12 mm

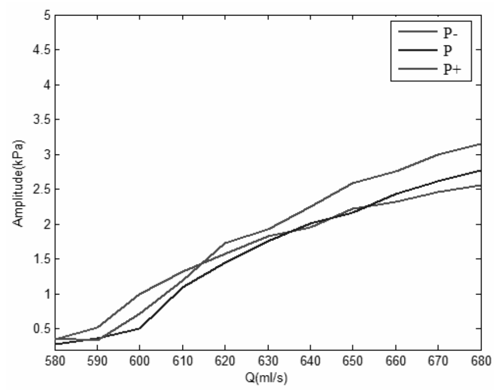


Fig. 16 Effects of pressure on amplitude in the channel l=10 mm at P4

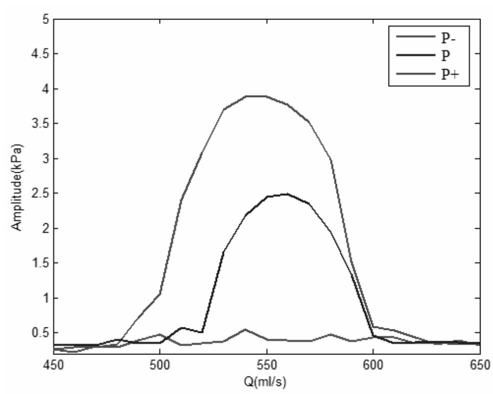


Fig. 17 Effects of pressure on amplitude in the channel l=12 mm at P2

of T-S wave, as shown in Fig. 12, could be found that the higher of the amplitude in the 1st frequency, the lower of it in the 2nd frequency, the same tendency is also seen in Fig. 13.

3.5 Effects of pressure increasing or decreasing on the amplitude of T-S wave

To understand the amplitude variation of the T-S wave, the effect of pressure on it is explored. The condition of pressure increasing or decreasing could be obtained by adjust the valve-2 or valve-1, and the variation of the pressure is controlled within $\Delta Q=\pm$ 50ml/s. Some experimental results are shown in Fig.15 ~17. For two locations in the same channel l=10, increasing pressure could make the amplitude of the T-S wave higher than no pressure change, and in the other side, decreasing pressure could make the amplitude of T-S wave lower than no pressure change, as shown in Fig. 15 and 16. For the other channel l=12, as shown in Fig. 17, the similar phenomenon is displayed. This result is very significant for the relative operation of the higher efficient heat exchanger in practical engineering. Generally, there has an optimum value of

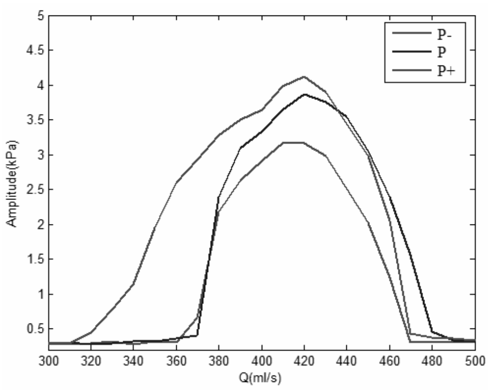


Fig. 15 Effects of pressure on amplitude in the channel l=10 mm at P7

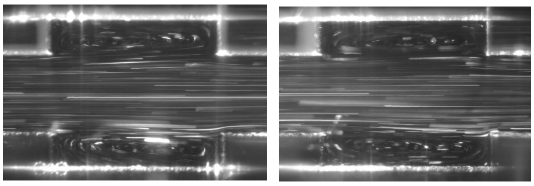
pressure increasing, in which, the maximum amplitude of T-S wave with minimum power consumption should be attained. It is an important work in the future.

3.6 Characteristics of the flow structure related to the T-S wave

It is known that the efficient heat and mass transfer must accompany the fluid mixing. To examine the relationship between the flow structure and the T-S wave, flow visualization is finished in the channel l=12mm, and some representative flow patterns are shown in Fig. 18. Obviously, in the laminar flow regime at Re=188, two stable large vortex form in the groove and the streamlines are arrayed in parallel. But after the flow enters transitional flow regime, the flow oscillation could be recognized at Re=532 and 600, although the weak oscillation could not be captured by the pressure sensor. It is seen that the fluid mixing occurs between the groove and the mainstream since the flow oscillation and hence destroys the vortex. As the flow enters turbulent flow regime at Re=1875, the flow oscillation in higher frequency appears and the flow mixing is further enhanced.

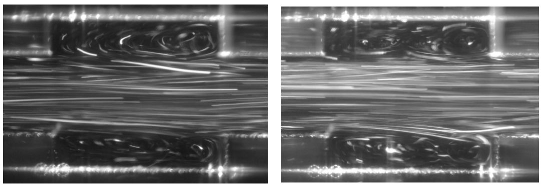
Laminar flow patterns

Re=188

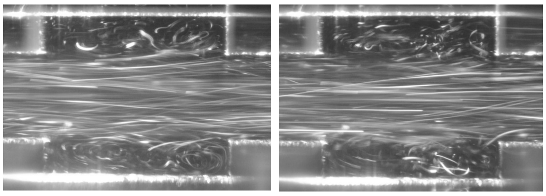


Transitional flow patterns

Re=532



Re=600



Turbulent flow patterns

Re=1875

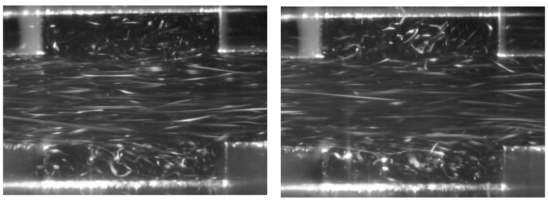


Fig. 18 Flow patterns in different flow regime in the channel l=12 mm

4. CONCLUSIONS

In the present study, the characteristics of T-S wave in the grooved channels with different groove length are explored experimentally. The most important results are concluded as follows:

(1) The T-S wave could be captured by analyzing the time-variation local pressure signal. The Strouhal number, based on the 1st or the 2nd frequency of the T-S wave, is almost equivalent for the same channel. Furthermore, the Strouhal number is found to decrease monotonously with the groove length. It means that once the 1st or the 2nd frequency is obtained, the nature frequency of the T-S wave at any Reynolds number could be calculated for the grooved channel with a constant period length.

(2) The operating condition of pressure increasing or decreasing strongly affects the amplitude of the T-S wave. Increasing the pressure of the channel will make the amplitude higher, and there must exist an optimum value of pressure increasing. This conclusion is very significant for the operation of the higher efficient heat exchanger. Confirming this optimum value is an important work in the future.

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