Numerically and Experimentally Study on Flow Structure in Grooved Channels for Pulsatile Flow

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Abstract

In this paper, the characteristics of different flow structures and their relationship with heat transfer performance are analyzed in two-dimensional rectangular channel with different slot lengths under pulsating flow field. Aiming at the fully developed region of the groove flow path, the aluminum dust method was used to realize the flow visualization. A fixed-time photography system built by photoelectric sensors was used to obtain the image of fluid flow structure at eight moments in a cycle, and the numerical simulation results are used to verify the fluid flow structure. It is found that different slot lengths of grooves, different oscillatory fractions and different Strouhal numbers will affect the flow structure of the fluid in the grooves. The occurrence time of strong unstable flow in the groove moves forward with the increase of *St* number, and the duration of unstable flow also extends with the increase of *St* number, which also indicates the improvement of heat transfer performance.

Keywords: Grooved channel, Oscillatory fraction, Aluminum dust method, Flow structure, Numerical simulation

1. Introduction

The structure of the basic unit of plate heat exchanger will affect the flow structure of the internal fluid and thus affect the heat transfer efficiency of the heat exchanger. As the basic unit of plate heat exchanger, the flow structure of fluid in grooved channels with four different slot lengths under pulsating flow field is studied, the numerical simulation results are verified with the experimental results and the general rule of fluid flow structure in grooved channels under fluctuating flow field is put forward. Many scholars have studied the heat and mass transfer performance of channels with different shapes. (Yanxia Yang et al., 2019) conducted numerical simulation on the herring-shaped channel and found that vortexes and heat transfer dead zone exist on the wall surface of the channel, and increasing the inlet velocity could significantly improve the heat transfer efficiency. (Adachi and Uehara, 2001a) tested channels of different shapes and found that heat transfer performance of expansion channel was better than that of contraction channel under the state of oscillating flow. (Weiwei Yang et al., 2004) explored the effect of pulsating flow in grooved channels on the enhancement of mass transfer. The results showed that the numbers of Re, A, and St numbers all had a great influence on mass transfer. In this paper, the flow structure characteristics under pulsating flow field are studied based on the flow visualization experiment.

2. Numerical simulation and experiment

2.1 Numerical simulation method

The object of numerical simulation in this paper is the rectangular groove channel with slot length of 10 mm. Since the thickness of the model can be ignored compared with the width, the two-dimensional model is used to simplify the calculation. (Adachi and Uehara, 2001b) the results show that the instantaneous velocity field in the groove is periodically

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repeats when the flow enters the full development stage. And at the position about the ninth groove from the entrance, the flow reaches the stage of full development. This study is also aimed at the fully developed flow, so the simulation in this paper will use 15 periodic groove modules to model. In order to reduce the influence of fluid reflux on the simulation results, a 200 mm long tailpipe is added to the back end of the model. The model diagram is shown in Fig. 2.1.

Fig.2.1 Model diagram of groove channel

ICEM software is used for structural mesh division of the model. It is assumed that the inlet fluid temperature is 8℃ and the wall temperature is 28℃, and the working medium in the calculation area is incompressible Newtonian fluid, whose density, viscosity and other parameters are constant. The inlet of the channel fluid was set to the velocity inlet boundary, and the pulsating flow velocity inlet equation was written with UDF, and the velocity direction was perpendicular to the inlet cross section. The outlet is set as a pressure outlet, and the fluid pressure is 1 standard atmosphere.

The governing equations used in the numerical calculation are as follows:

Mass conservation equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

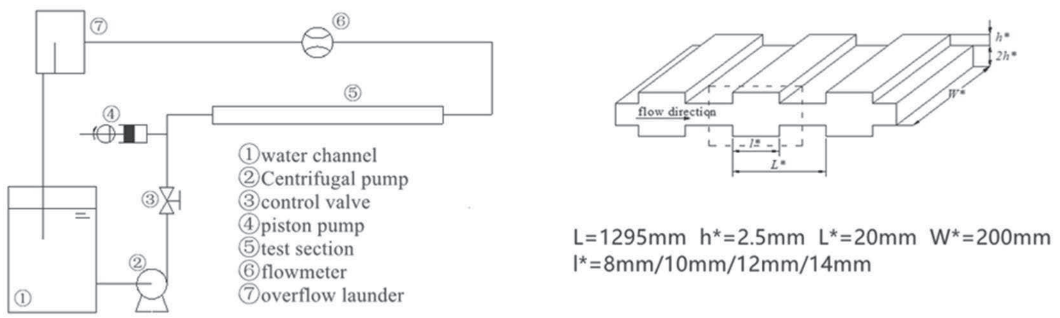
Momentum conservation equation:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\rho g_x-\frac{\partial \rho}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\rho g_y-\frac{\partial \rho}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y} \tag{2}$$

2.2 Experimental settings

The experimental device diagram is shown in Fig. 2.2 (a) below. The whole device is composed of seven parts: water tank, centrifugal pump, control valve, piston pump, test section, flowmeter and overflow tank. The experimental medium was tap water, and the whole experiment was carried out at standard room temperature. The experiment started with a water pump which pumped water from a tank into a pipe, and the flow of tap water was controlled by a control valve. The piston pump is connected to the frequency controller and the stepping motor. Different frequency pulses can be output by setting the parameters of the frequency controller. The frequency controller makes the stepping motor run at a constant angular velocity set by us, and the stepping motor drives the reciprocating motion of the piston pump, so that the working medium superimposes a forced vibration flow in the direction of motion, forming the pulsating flow field we want. After entering the test section, the pulsating flow flows through the flowmeter into the overflow tank and then back to the tank. The overflow trough exists to eliminate the influence of gravity on the experiment.



(a) Experimental device (b) Groove channel

Fig.2.2 Experimental device and groove channel

In this experiment, aluminum precipitation method was used to realize flow visualization. The aluminum precipitation method is to add 40um aluminum powder into the working medium, and use the reflection of aluminum powder on the light to observe the fluid morphology to realize the visualization of fluid flow. Flow visualization requires a photographic device with a light sensor to capture fluid flow images. The light source is injected into the test section from the slit, and the flow pattern of the fluid at this time can be clearly presented by using the reflection of aluminum powder on the light. There is a large disk on the transmission shaft, and eight isolines are carved on the disk. The transmission cycle of the shaft is a pulsation period, and each isoline corresponds to a moment. When the reflective paper is rotated to a certain position, the photosensor of the camera senses light, and the current fluid flow pattern can be photographed. By changing the position of reflective paper, the fluid flow patterns at eight moments in a pulsation cycle can be recorded in turn(T refers to a pulsating period). Flow visualization system is shown in Fig. 2.3.

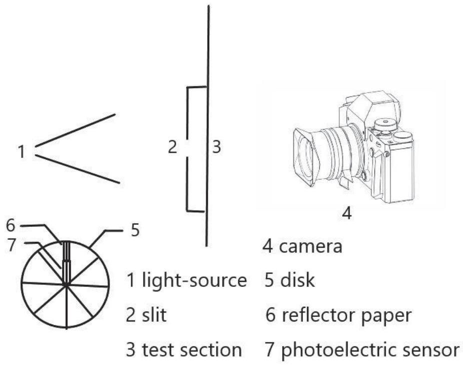


Fig.2.3 Flow visualization system

The test parameters given in the experiment are the detailed dimensions of the groove flow path as Fig.2.1(b), piston pump diameter D_p, volume flow of working medium Q_s, oscillatory fraction *P* and stroke *S*. The sectional velocity at the entrance of the groove channel is *Us=Qs/2wh*, the characteristic velocity of groove flow path is *Um=3Us/2*. The parameters required for the experiment are defined as follows:

$$\mathrm{P} = \frac{Q_0}{Q_S} \tag{3}$$

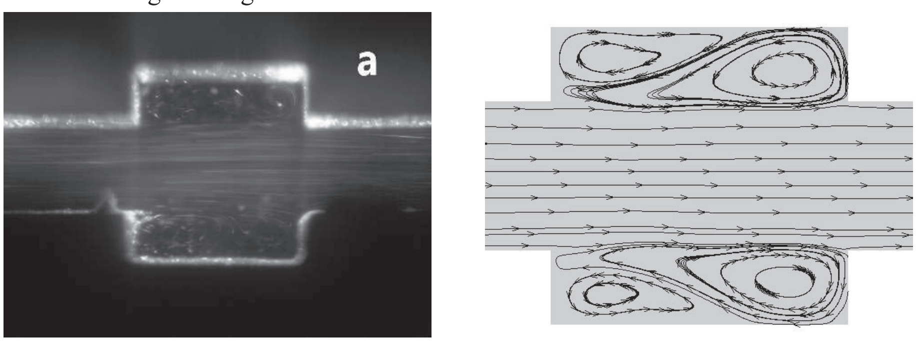
$$Q_0 = 2\pi f s(\frac{\pi D_p^2}{4}) \tag{4}$$

$$S_t = \frac{fh}{U_m} \tag{5}$$

3. Results and discussions

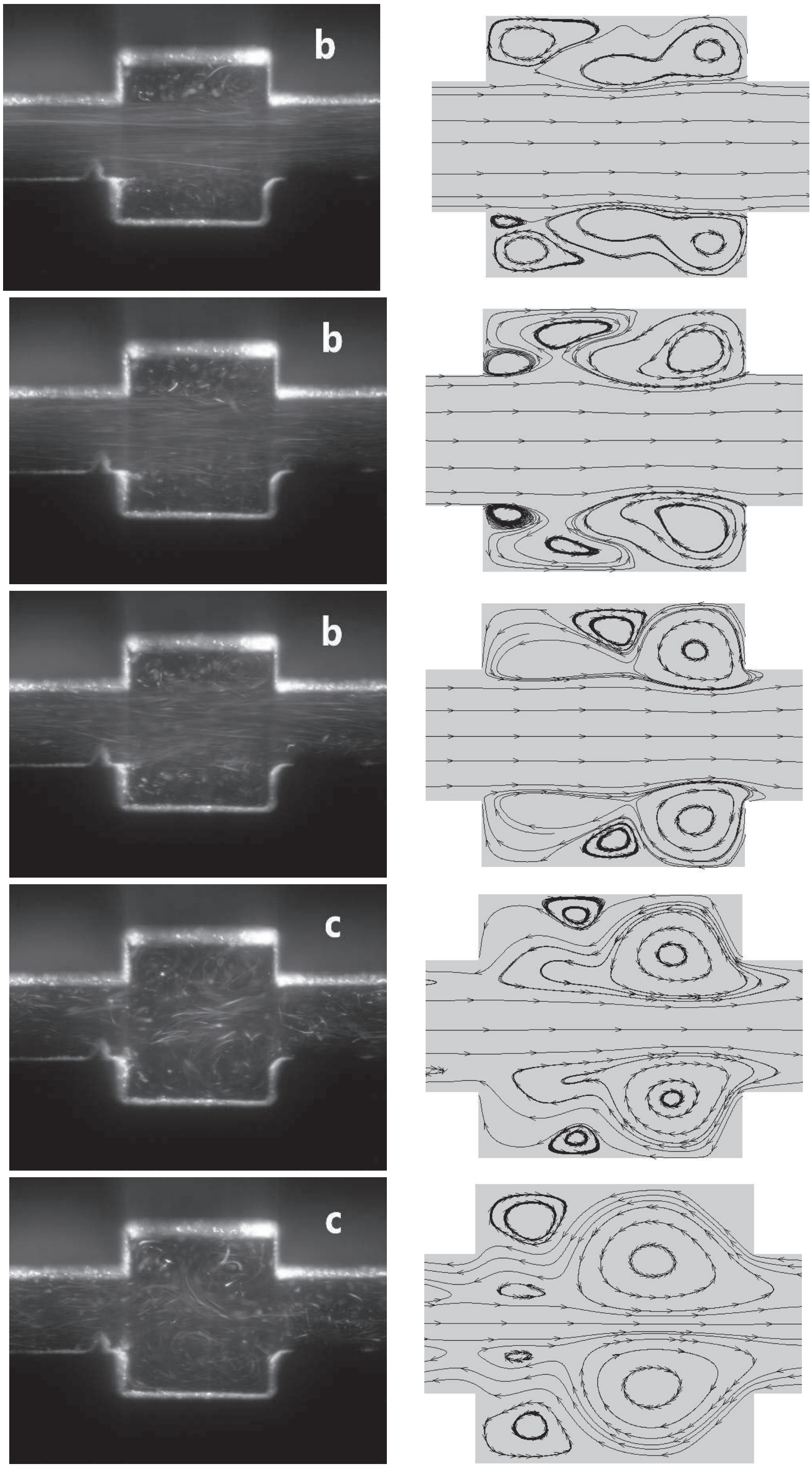
3.1 Numerical simulation results

When *P* =1, *Re*=570, *St*=0.006754749, the fluid flow diagram of the fully developed region at eight moments is compared with the experimental images as Fig.3.1:



t/T=0.000

Fig.3.1 Comparison of fluid morphology and numerical simulation results



t/T=0.125

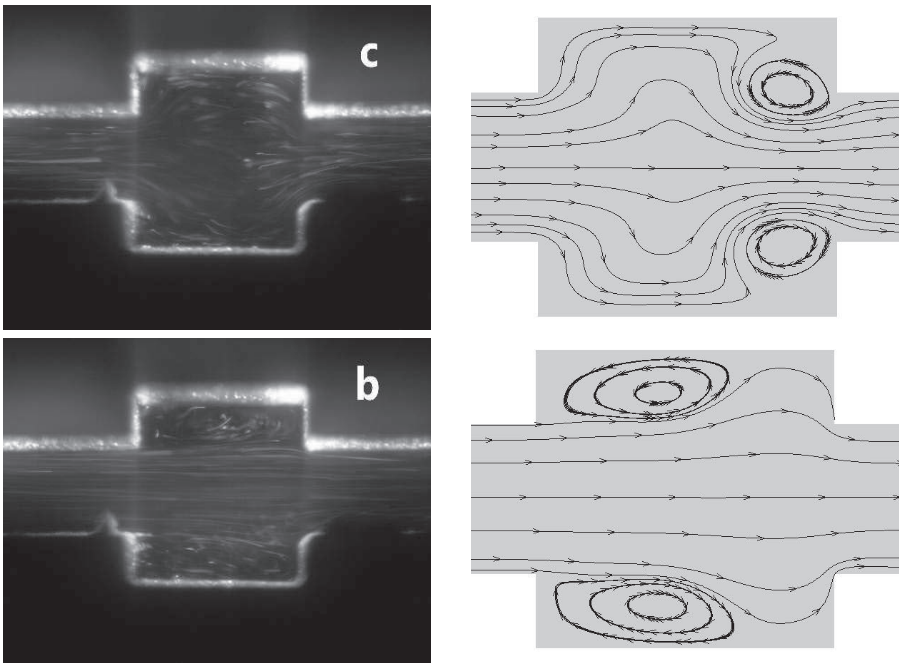
t/T=0.250

t/T=0.375

t/T=0.500

t/T=0.625

Fig.3.1 Continue



t/T=0.750

t/T=0.875

Fig.3.1 Continue

It can be seen that the vortex structure in the groove in the numerical simulation results is in good agreement with the flow visualization results at different times in a period of pulsating flow, indicating that the numerical method used in this study is reasonable and correct with sufficient accuracy, and can be applied to the numerical simulation of different structural flow paths in the future.

3.2 Experimental results and discussions

From the pictures taken by the camera, we can classify the flow of the fluid in the channel as stable, weakly unstable and strong unstable. In the subsequent induction, "a" represents stable flow, "b" represents weak unstable flow, and "c" represents strong unstable flow. When the flow in the channel is reverse, add a hyphen (-) before the symbol, for example, “-a”. When the instantaneous Reynolds number is zero, the fluid is at rest, and the aluminum powder appears as dots rather than lines in the fluid, using the bold alphabet example "**a**".

Trace lines in the main flow area of the steady flow are parallel, stable vortices exist in the groove area, and working medium in the main flow area and groove area is not mixed. The reason for the formation of stable flow is that the Reynolds number at this time is less than the critical value, which makes the random pulsation disappear quickly in the forward transmission process. Therefore, the fluid in the mainstream zone is a stable laminar flow state, and this flow pattern generally appears in the accelerating region. The trace lines in the mainstream area of weak unstable flow are clear but not parallel. The mainstream area and the groove area can be distinguished, but the working medium has obvious mixing phenomenon. The reason for the formation of weak unstable flow is that at this time, the mainstream area is still in a state of acceleration, and new vortices are generated near the mainstream area. However, the old vortices formed by the acceleration of the last cycle still exist. The slower old vortices rotate oppositely to the faster new vortices, so the old vortex is offset by the new vortex. The main flow area and the groove area of the strong unstable flow cannot be distinguished, and the working fluids are all doped together. The reason for the strong unstable flow is that the main flow area slows down, and the vortex absorbs the flow in the main flow area and the groove area to grow and expand.

In this experiment, the flow visualization method was used to obtain the images of fluid flow patterns at eight moments in a pulsating cycle through a photographic device with a light sensor. The influence of strong unstable flow on heat transfer was studied by testing the grooves of different sizes with different Oscillatory fractions. By observing the table, the conclusions are as follows:

(1) Under the same slot length and the same oscillatory fraction, with the increase of St number, the occurrence time of weak unstable flow is continuously postponed, and the occurrence time of strong unstable flow is more and more advanced, and the duration of strong unstable flow is also more and more strong.

(2) Under the same oscillatory fraction and the same St number, the occurrence time of strong unstable flow is advanced with the increase of slot length, and the duration time of strong unstable flow is increased with the increase of slot length.

(3) When the oscillatory fraction *P*=1.414, the instantaneous Reynolds number is 0 at *t*=0.625s and *t* =0.875s, which is 1/8 period earlier than that at *P*=1.

According to the existing research results (Mu, 2016, Nishimura et al., 2004), strong unstable flow structure increases the mixing of the mainstream and the wall fluid, which can effectively enhance the heat transfer effect.

Table 3.1 Flow structure of grooves with different sizes under different oscillatory fractions and different *St* numbers when *Re*=300

P	Slot length	S_t	t							
			0.000	0.125	0.250	0.375	0.500	0.625	0.750	0.875
0.5	8	0.00067547	a	a	a	a	a	a	a	a
		0.00135095	a	a	a	a	a	a	a	a
		0.00225158	a	a	a	a	a	a	a	a
		0.00337737	a	a	a	a	a	a	a	a
	12	0.00067547	a	a	a	a	a	a	a	a
		0.00135095	a	a	b	b	a	a	a	a
		0.00225158	a		a	b	b	a	a	a
		0.00337737	a	a	a	a	b	b	b	a
	14	0.00067547	a	b	b	b	a	a	a	a
		0.00135095	a	b	b	b	b	a	a	a
		0.00225158	a	b	b	b	b	b	b	a
		0.00337737	a	a	b	b	b	b	b	b
1	8	0.00135095	a	a	a	a	a	a	**c**	-b
		0.00270190	a	a	a	b	b	c	**c**	-b
		0.00675475	a	a	a	a	b	c	c	-c
	12	0.00135095	a	a	b	b	b	b	**c**	-c
		0.00270190	a	a	b	b	b	c	**c**	-c
		0.00675475	a	a	a	b	c	c	c	-c
	14	0.00135095	a	b	b	b	b	b	**c**	-c
		0.00270190	a	b	b	b	b	c	**c**	-c
		0.00675475	a	a	b	b	c	c	**c**	-c
1.414	8	0.00191053	a	a	a	a	b	c	-a	c
		0.00382106	a	a	a	a	b	c	-a	c
		0.00955266	a	a	a	a	c	c	-c	c
	12	0.00191053	a	a	b	b	b	**c**	-b	c
		0.00382106	a	a	b	b	c	c	-c	c
		0.00955266	a	a	b	b	c		-c	c
	14	0.00191053	a	b	b	b	b	**c**	-a	c
		0.00382106	a	b	b	b	c	c	-c	c
		0.00955266	a	b	b	c	c	c	-c	c

Table 3.2 Flow structure of 10-10 groove when *P*=1, *Re*=570

S_t	t							
	0.000	0.125	0.250	0.375	0.500	0.625	0.750	0.875
0.00108076	a	b	b	b	b	b	**c**	-b
0.00112579	a	b	b	b	b	b	**c**	-b
0.00117474	a	b	b	b	b	b	**c**	-b
0.00122814	a	b	b	b	b	b	**c**	-b
0.00128662	a	b	b	b	b	c	**c**	-b
0.00135095	a	b	b	b	b	c	**c**	-b
0.00142205	a	b	b	b	b	c	c	-b
0.00150106	a	b	b	b	b	c	c	-b
0.00158935	a	b	b	b	b	c	c	-b
0.00168869	a	b	b	b	b	c	c	-b
0.00180127	a	b	b	b	b	c	c	-b
0.00192993	a	b	b	b	b	c	c	-b
0.00207838	a	b	b	b	b	c	c	-b
0.00225158	a	b	b	b	b	c	c	-b
0.00245627	a	b	b	b	b	c	c	-b
0.00270190	a	b	b	b	b	c	c	-b
0.00300211	a	b	b	b	b	c	c	-b
0.00337737	a	b	b	b	c	c	c	-b
0.00385986	a	b	b	b	c	c	c	-b
0.00450317	a	b	b	b	c	c	c	-b
0.00540380	a	b	b	b	c	c	c	-b
0.00675475	a	b	b	b	c	c	c	-b

4. Conclusions

In this paper, the experimental and numerical simulation methods are combined to explore the fluid flow structure in the fully developed region in a pulsating period of the groove channel. The following main conclusions can be drawn:

(1) The images obtained by numerical simulation are in good agreement with the experimental fluid flow structure images, indicating that the numerical simulation method used in this study is reasonable and can be applied to the numerical simulation research of different structural flows in the future.

(2) The experimental results show that the fluid flow structure in the groove is related to the groove length, *St* number and oscillatory fraction. With the slot length, the pulsation ratio and *St* number increase. The more fully the fluid is mixed in the mainstream area and the groove area, the more conducive to heat transfer.

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