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Temperature-driven Switching and Deflection of Bistable Flow Crossing Side-by-side Tubes

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ABSTRACT

In this work, we conducted 2-D numerical simulation to explore the characteristics and mechanism of temperature-driven switching and deflection of bistable flow crossing side-by-side tubes. The results show that the temperature gradient has a notable effect on the deflection of flow through the gap between two tubes with the side-by-side arrangement when the ratio of pitch to dimeter is 1.5. The gap flow deflects to the tube side with a higher temperature. With the increase of temperature gradient between the two tubes, the deflection angle is larger and the deflection state can be kept stably for a longer time. The analysis on drag and lift demonstrates that the switching and deflection of bistable flow driven by temperature results from the effect of temperature gradient on the separation of flow boundary layer. This research provides another control mechanism of bistable flow, and enriches the theory research and the application on thermal control techniques.

Keywords: Bistable flow, Temperature-driven, Switch, Side-by-side tubes, Numerical simulation

1. INTRODUCTION

The bistability in flow is a phenomenon that the fluid can flow along one side and can be provoked to the other side and keep stable state, which occurs when the fluid flowing across tubes arranged in a characteristic pitch or through a slit. This flow behavior is highly lighted not only in academic researches but also in applications as the fluid amplifier, the fluid oscillator and the logic circuit[1]. This study adopts numerical simulation to study the bistable slit jet deflection under different temperature gradients in detail. This study plays an important role in further understanding the deflection mechanism and control technology of bistable slit jet and provides a theoretical basis for the design of temperature driven bistable slit jet flow control devices.

2. MODEL AND METHODS

In this paper, finite volume method, zonal structured grid and two-dimensional Laminar model are used to investigate the flow around parallel cylinders at low Reynolds number. The governing equations describing the computational domain are as follows [2]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial xj}\right) \qquad (2)$$

Energy equation：

$$\frac{\partial (\rho T)}{\partial t} = div(\frac{\lambda}{c_p} gradT) - div(vUT) + S_T \quad (3)$$

State equation：

$$\rho = \rho(P, T) \qquad (4)$$

Here, ρ is density, μ is viscosity, C_p is specific heat capacity, P is pressure, T is temperature, λ is fluid's thermal coefficient, S_T is the heat source in the fluid and the part of the fluid mechanical energy converted into heat energy due to viscous action.

2.1 Boundary conditions

Figure 1 shows the flow domain with the arrangement of side-by-side tubes. The cylinder diameter *D*=10mm, and the pitch of two tubes *m* is as the same value as that in the experiment. The river length is from -100mm to 300mm, width is from -100mm to 100mm. The left boundary is the velocity inlet, and the inlet velocity is 0.01m/s. The right boundary is set as free flow and remains default., The surface temperature of the unheated cylinder is set at 21ºC, which is the same as the flow field temperature. Meanwhile, with water as the medium, the formula is as follows:

$$\mu = 2.2556 \times 10^{-11} T^4 - 3.0985 \times 10^{-8} T^3 + 1.6032 \times 10^{-5} T^2 - 0.0037081T + 0.32432$$

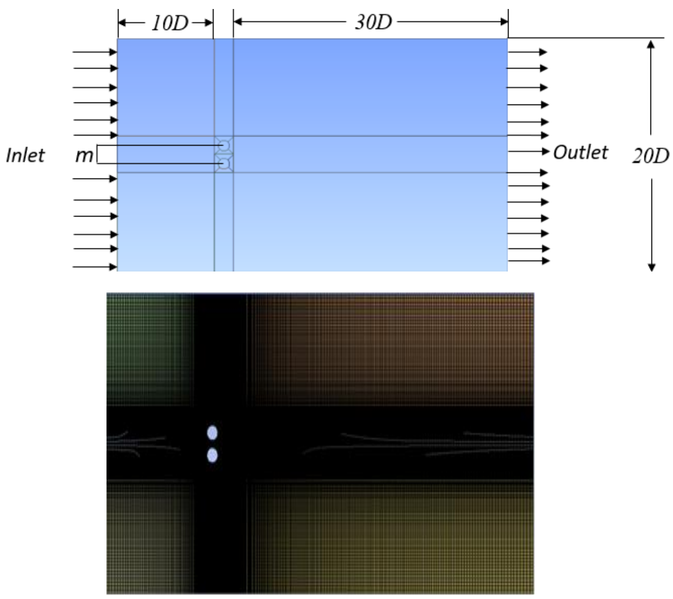

Fig.1 Parallel cylinders and the physical models

2.2 Grid independence and validation

The mesh quality has a very important effect on the calculation result and calculation speed. In order to accurately describe the flow characteristics of the whole flow field, this paper uses Mechanical to encrypt the zonal structured grid around the cylinder and the main area of the flow field. The encrypted grid and local grid of the cylinder wall are shown in Figure 2. According to the theory of boundary layer[3], the first-layer grid of cylindrical wall needs to meet y+≈1, and the formula is as follows:

$$y^+ = 0.172 \frac{\Delta y}{d} Re^{0.9}$$

Δy is the distance from first layer point to the wall of the tube, and the *d* is the tube diameter, *Re* is Reynolds number.

3. RESULTS AND DISCUSSION

The experiments select temperature gradient as Lin's research [4] to study the flow pattern and characteristic parameters of the bistable slit jet under heating and non-heating conditions, and describe the deflection and switch mechanism.

When the surface temperatures of the two cylinders are same and the temperature of the flow field is equal, the duration is very short. In order to verify the influence of temperature on the deflecting direction and stability time of bistable slit jet flow, keeping the cylinder spacing *r*=1.5, *Re*=100. First keeping the second cylinder at the same temperature as the flow field, raising cylinder 1's temperature 20°C, then setting cylinder 1 at the same temperature as the flow field, raising cylinder 2 temperature 20°C and observing the effect of temperature gradient direction change on slit jet deflection characteristics Then, keeping the surface temperature of cylinder 2 equal to the flow field temperature, and heating cylinder 1 to 61°C and 81°C to form a temperature difference of 40°C and 60°C, and observing the influence of temperature on slit jet deflection as showing in Fig.2-5.

At the same time, the velocity of the monitoring point *A* in the Y direction is measured to reflect the jet deflection characteristics showing in Fig.6. According to the velocity vector diagram of the upper and lower cylinders heating separately, it can be seen that the slit jet has the characteristic of deflecting towards the heating side, which means different temperature gradient direction at the same time can change the slot jet flow deflection direction, which shows that the temperature gradient can have the effect of control slot jet deflection and verifies the experiment results.

After measuring the model for 200s, it is found that when the upper cylinder is heated, the deflection time of clearance flow upward is longer than that when the upper cylinder is heated, and the deflection Angle tends to the positive direction of *Y*-axis. When the lower cylinder is heated, the opposite result is obtained, that is, the gap flow is deflected downward for a longer time. With the increase of temperature difference, the larger the deflection angle formed by the jet at the exit, the longer the deflection time to one side, as shown in Table.1. According to equation (4) and S. Kumar's experiment, changing the temperature doesn't change the related properties of vortices, but fundamentally changes the boundary layer around the cylinder and the viscosity of the fluid.[5] When the surface of a cylinder begins to heat up, the temperature gradient around it increases and the thermal boundary layer begins to thin, thus reducing the diffusion of vorticity in the boundary layer. Producing peace flow boundary layer in the diffusion of vorticity, the imbalance may change the location of the shear layer separation point, so that when the heating cylinder pressure to reduce, the deflection of clearance flow condition and on the other side of the clearance flow has not attached side because of its relative vorticity increases, leading to the increase of the shear layer of entrainment rate and the change of the pressure, when the change is up to its limit, The clearance flow begins to move towards the unattached side, forming the bistable change of clearance flow.

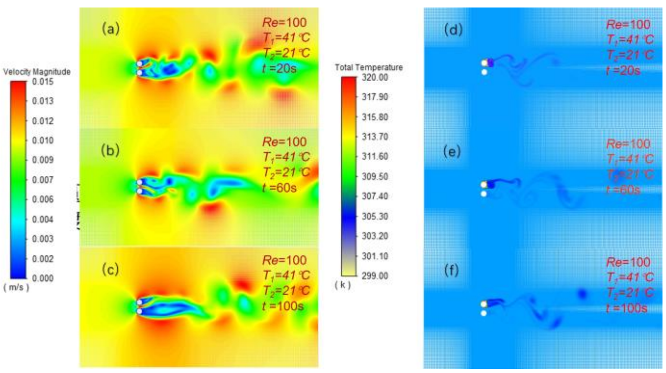

Fig.2 The development of slit jet flow field and temperature field with time when tube 1 is 20℃ higher than tube 2 :(a) Velocity diagram at t=20s; (b) Velocity diagram when t=60s; (c) Velocity diagram when t=100s; (d) Temperature cloud at t=20s; (e) Temperature cloud at t=60s; (f) Temperature cloud at t=100s

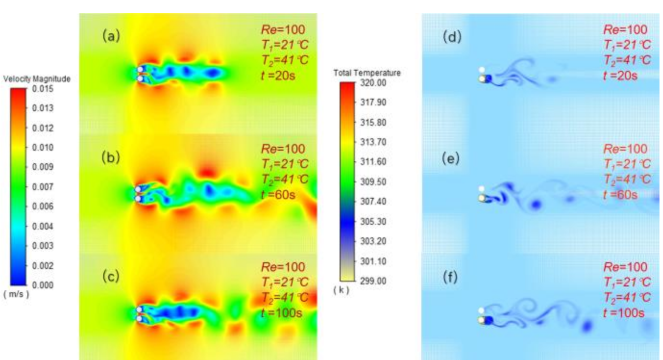

Fig.3 The development of slit jet flow field and temperature field with time when tube 1 temperature is lower than tube 2 20℃ :(a) Velocity diagram at t=20s; (b) Velocity diagram at t=60s; (c) Velocity diagram at t=100s; (d) Temperature cloud at t=20s; (e) Temperature cloud at t=60s; (f) Temperature cloud at t=100s

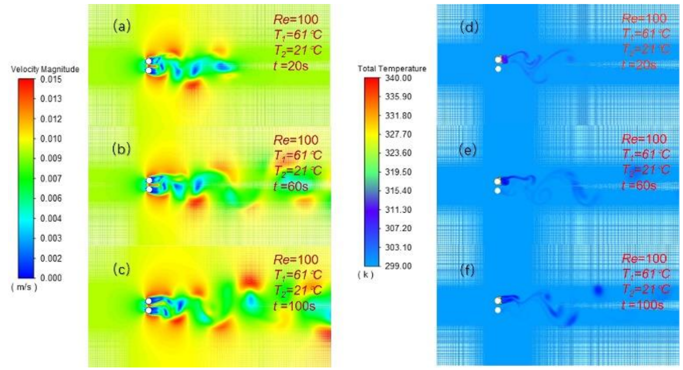

Fig.4 The development of slit jet flow field and temperature field with time when tube 1 is 40℃ higher than tube 2 :(a) Velocity diagram at t=20s; (b) Velocity diagram at t=60s; (c) Velocity diagram at t=100s; (d) Temperature cloud at T =20s; (e) Temperature cloud at t=60s; (f) Temperature cloud at t=100s

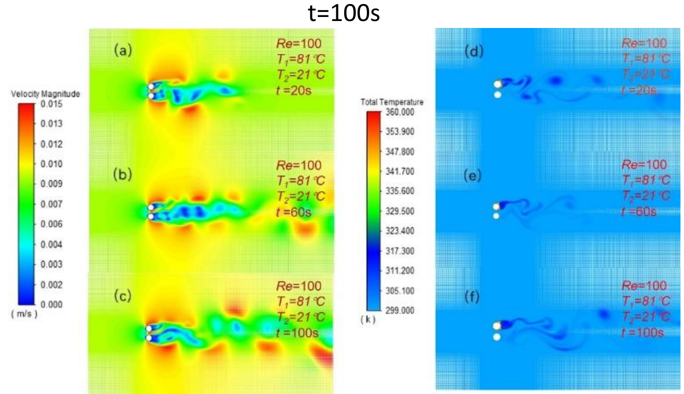

Fig.5 The development of slit jet flow field and temperature field with time when tube 1 is higher than tube 2 at 60℃ :(a) Velocity diagram at t=20s; (b) Velocity diagram at t=60s; (c) Velocity diagram at t=100s; (d) Temperature cloud at t =20s; (e) Temperature cloud at t=60s; (f) Temperature cloud at t=100s

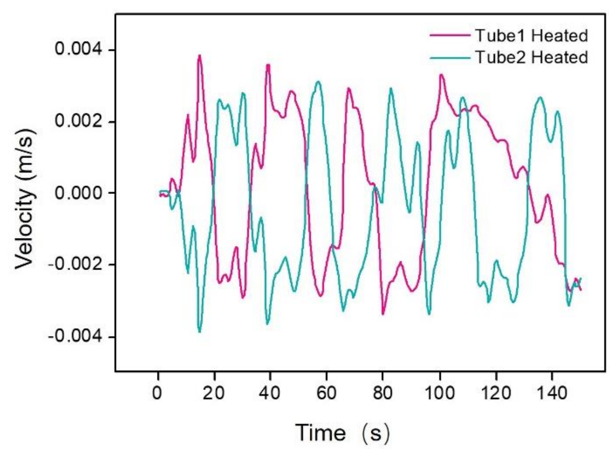

Fig.6 The velocity curves of the monitoring point A in the Y

direction under the heating condition of tube 1 and tube 2 respectively

	Upward deflection time(s)	downward deflection time(s)	deflection angle(°)
upper cylinder heated	152.3	47.7	1.45
no cylinder heated	97.3	102.7	-0.12
lower cylinder heated	125.5	74.5	-0.65

Table.1 The deflection of clearance flow when the upper and lower cylinders are heated separately and without heating

4. CONCLUSIONS

This study uses the Fluent for parallel flow around circular tube formation of the bistable slit jet, analyzes the effect of temperature gradient on the bistable jet deflection characteristics and enriches the experimental results. The conclusions are as follows:

Temperature gradient can control the deflection of bistable slit jet. The temperature gradient in different directions can change the deflection of the jet flow to the side with higher temperature. The larger the temperature difference, the longer the time keeping the jet deflected to one side. The reasons for this phenomenon lie not in the wake of the vortex shedding frequency, but the fluid viscosity is influenced by reduced heating viscosity, the thermal boundary layer begins to thin, and the fluid separation time lags, which reduces the diffusion of vorticity in the boundary layer, and produces peace flow boundary layer of vorticity diffusion, the imbalance may changes the location of the shear layer separation point, After heating the cylinder, the pressure begins to decrease and the slit jet deflects. On the other side, on the unattached side of clearance flow, the relative increase of vorticity leads to the increase of shear laminar entrainment rate. When the change reaches the limit, the slit jet begins to move to the unattached side, thus forming the bistable change of clearance flow. The authenticity of the prediction of vorticity change can also be obtained by the temperature cloud image. This study plays an important role in further understanding the influence of temperature on bistable slit jet flow, and lays a theoretical foundation for microfluidic research and design and thermal control device research.

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