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Numerical Simulation for Flow and Heat Transfer Characteristics of L-Type Chaotic Channel

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Abstract: In this paper, the author conducted numerical simulation on fluid flow and heat transfer of L-type chaotic channel with the use of periodic model, compared with common straight channel, analyzed and gained microscopic information flow field and temperature field distribution inside the channel, researched synergy of flow field and temperature field inside the channel with the use of synergy principle, and discussed influences of different Re figures on fluid heat transfer and flow inside the chaotic channel. Results show that L-type chaotic structure can generate chaotic convection under lower flow velocity, which increases disturbing degree of fluid inside the channel, so as to promote mixture and heat transfer of cold and hot fluid; synergy degree of velocity and temperature gradient on cross section of chaotic channel are better than that of straight channel, and average synergy angles for outlet cross sections of such two channels are respectively 66.3° and 88.0°; Nu number of L-type chaotic channel increases with the increase of Re. Particularly, increasing range is more obvious at low Reynolds number, but at the same time, friction coefficient inside the channel will increase.

Keywords: Chaotic convection, laminar flow, field synergy principle, numerical simulation.

1. INTRODUCTION

Worldwide energy crisis arisen in early 1970s has stimulated the development of various heat transfer augmentation technologies rapidly, generally favored by scientific and technological circles and industrial circles [1, 2]. Chaotic convection, as a kind of emerging technological mean of heat transfer augmentation, has been concerned by researchers at home and abroad gradually. Since Aref [3], American scholar, brought the concept of chaos into fluid mechanics field in 1983, chaotic convection has been used in heat transfer augmentation gradually.

Researches show that hydro flow-line generates swing and interface tension in special 2D or 3D channel for limitations of channel boundary and geometric structure, so as to gain diffusion property, similar to turbulent flowing, which is called as chaotic convection. This flow condition can enhance fluid mixture and promote energy exchange of middle cold fluid and hot fluid of heat transfer wall, so as to strengthen heat transfer on increasing pressure drop non-significantly. Kang [4] *et al.* have conducted numerical simulation computation towards fluid in winding 2D channel changing periodically by time and analyzed their mixed hardening actions. Lemenand [5] *et al.* have researched elbows which can produce chaotic convection, found that heat transfer of fluid in elbows had been strengthened obviously, and gained computational formula of *Nu* number of chaotic helix tube from numerical result of heat transfer with the use of genetic algorithm. Kong Songtao [6] *et al.* have measured such important parameters as flow dead zone and longitudinal and radial mixing degree of channel formed by a kind of new chaotic fin intuitively with the use of RTD method and verified heat transfer augmentation and scale inhibition of chaotic convection within the channel.

In this paper, L-type chaotic channel was regarded as the research object. At present, its chaotic characteristics [7] have been researched mainly, while heat-transfer characteristics of the channel have not been reported. Therefore, the author conducted numerical simulation on fluid flow and heat transfer inside L-type chaotic channel with the use of CFD software ANSYS 14.5, compared with common straight channel, gained microscopic information flow field and temperature field distribution inside channel, and researched synergy of flow field and temperature field inside channel with the use of synergy principle, so as to understand internal mechanisms of chaotic convection enhancement of heat transfer better.

2. PHYSICAL MODEL AND NUMERICAL METHOD

Geometric structure and size (unit in the figure is mm) of L-type chaotic channel is as shown in Fig. (**1**). Accordingly, straight channel is shown in Fig. (**2**). Thus it can be seen from the figure that flow cross sections of these two channels are rectangles (20 mm×10 mm). In accordance with calculation, equivalent diameter of these two structures is 13.333 mm [8].

Comparing the above two structures, the author adopted period model to conduct analog computation on them for their periodicity in flow direction of their structures. At computation, the author chose dispersed solver and laminar flow model and set fluid medium as constant water, inlet

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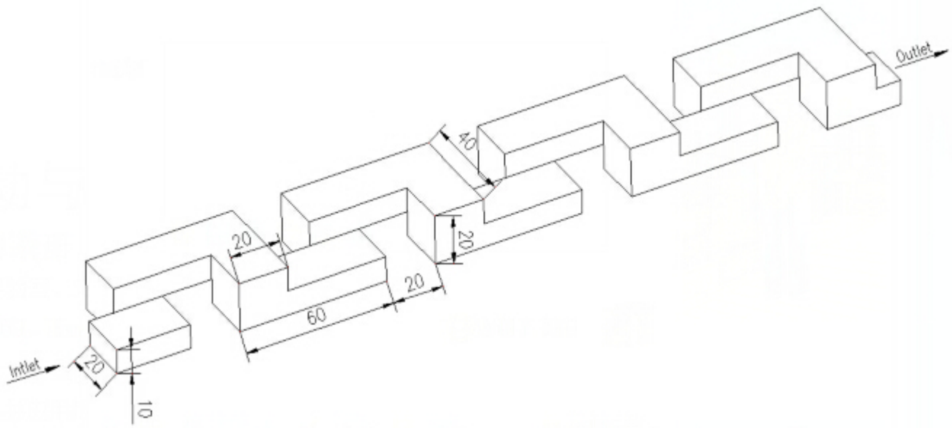

Fig. (1). Structure and size of chaotic channel.

temperature as 300 K, constant temperature of channel wall as 393 K, standard atmospheric pressure as the operating condition, standard zero-slip wall as the wall in boundary condition, and periodic boundary condition as inlet and exit wall of fluid. Coupled mode of pressure and velocity adopts SIMPLE algorithm, while momentum, and energy disperse mode adopts second order upwind. When residual error of continuity equation and momentum equation is less than 10-4 and residual error of energy equation is less than 10-7 in solution procedure, we regard it as calculation convergence. Assess gridding of two models during computation and conduct local encryption on gridding in flowing changes, so as to guarantee that computed results are independent solutions of gridding [9-11].

Fig. (2). Structure and size of straight channel.

3. SIMULATION RESULTS AND ANALYSES

Relevant L-type chaotic channel heat transfer experiment reports didn't show in computational process, the author verified them through comparing numerical simulation results of fluid in common straight channel and corresponding theoretical values. Based on basic knowledge of heat transfer theory [9], we know that theoretical value of flow resistance is fRe=62 when the fluid develops fully in the channel, while Nu=3.39 when the channel wall is heated uniformly.

Thus it can be seen from Table **1** that as for straight channel of different Reynolds numbers, relative error of Nu number and fRe value is small. When comparing calculated value of numerical simulation and theoretical value, the largest error is not more than 5%, so that correctness and reliability of numerical simulation method are verified.

3.1. Fluid Yard Analysis

As shown in Figs. (**3**, **4**), when Reynolds number Re=200, the two-fluid trace distribution diagrams show traces near the inlet section center of straight channel and L-type chaotic channel. It can be seen from figures that the two traces in straight channel move strictly in the rectilinear direction, namely the relative position of two traces whose inlet and exit section centers do not change. However, two traces in L-type chaotic channel swing and stretch continually to limits of channel's special geometric structure. Furthermore, their radial distance increases when compared with their initial position, which indicates that flow field in chaotic channel is relatively sensitive to initial conditions of fluid, and it is just one of the marked features of chaotic convection [10].

When *Re*=200, fluid velocity distributions in chaotic channel and straight channel are respectively shown in Figs. (**5**, **6**). As shown in Fig. (**5**), we can see that there is larger radial velocity component in the direction of main stream velocity for flow structure swings in the direction of main

Table 1. Comparison of numerical simulation value and theoretical value.

Re Number	Theoretical Value		Results of Numerical Simulation		Relative Error, %	
	Nu Number	*fRe* Value	*Nu* Number	*fRe* Value	*Nu* Number	*fRe* Value
50	3.39	62	3.542	62.105	4.484	0.169
100	3.39	62	3.524	62.142	3.953	0.229
200	3.39	62	3.512	62.501	3.599	0.808
300	3.39	62	3.448	62.259	1.711	0.418
400	3.39	62	3.493	62.386	3.038	0.623

stream fluid than when the fluid moves forward along the flow direction. As for the whole periodic channel, the maximum velocity transits from bottom right to top left of flow field and go back to bottom right finally. Velocity size distribution of fluid in the whole channel is different with different geometric position, so that some features of turbulent flow are shown. Therefore, chaotic convection belongs to laminar flow in nature. However, as for straight channel, fluid is laminar flow. High flow-rate fluid particle and low flow-rate fluid particle are entirely different, mutually uncorrelated; obviously, it is a typical laminar flow.

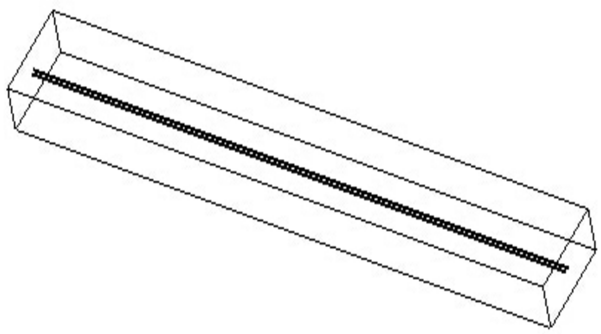

Fig. (3). Two special traces in straight channel.

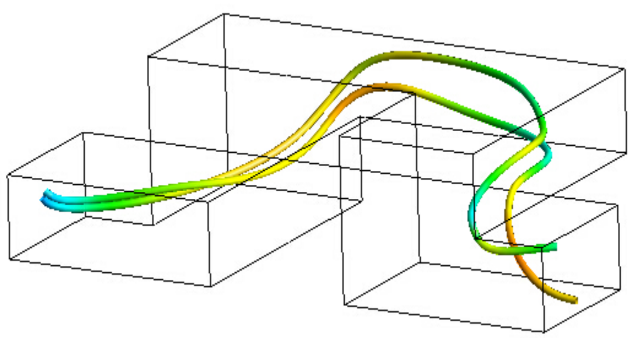

Fig. (4). Two special traces in chaotic channel.

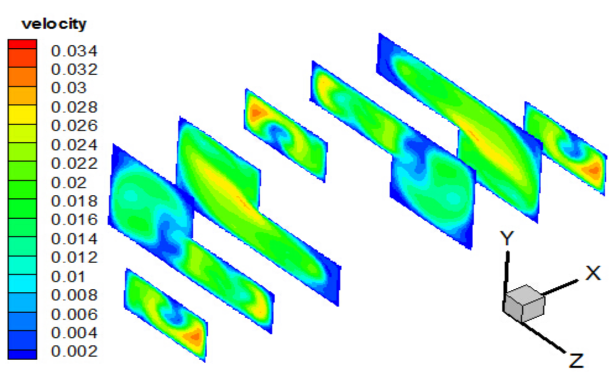

Fig. (5). Velocity distribution diagram of chaotic channel.

3.2. Analyses on Fluid Temperature Field

Temperature distributions for all cross sections of two channels when *Re*=200 are shown in Figs. (**7**, **8**). As for straight channel, temperature distribution of each cross section is almost the same, high in near wall while low in center. With small diffusivity between cold and hot fluid,

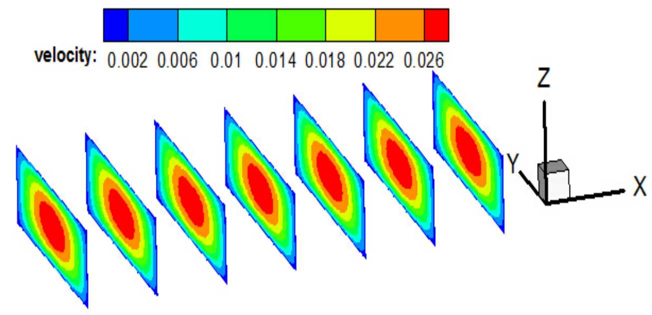

Fig. (6). Synergy angle distribution diagram of straight channel.

main heat-transfer mode of fluid in straight channel is mainly heat conduction. However, temperature distributions of all cross sections of L-type chaotic channel are different and even fluid temperature in cross sections and center exceeds fluid temperature in near walls. In general, temperature distribution of all cross sections of chaotic channel is more uniform than that in straight channel, and there are not any laws. Chaotic convection generated in chaotic channel increases velocity gradient near the wall, which can make fluid flow from high-temperature area to low-temperature area, and promotes mixture of cold and hot fluid, namely heat can be transferred through convection. However, straight channel transfers heat through heat conduction, so that advantages of heat transfer augmentation are self-evident. In order to show strengthening effects more visually, we can compute average temperature in two channels. Through computation, when *Re*=200, average temperature in chaotic channel is 343.1 K, while that in straight channel is 309.2 K. Thus it can be seen that average temperature in chaotic channel is obviously higher than that in straight channel.

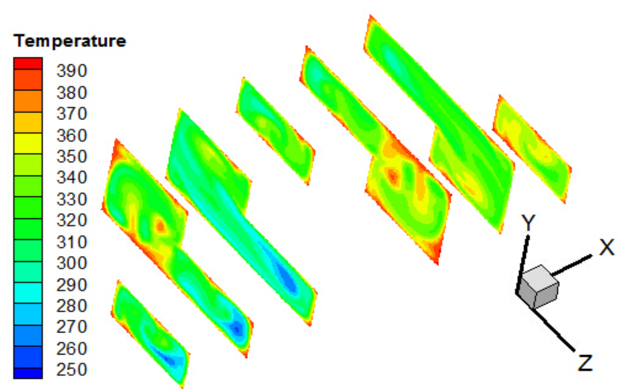

Fig. (7). Temperature distribution diagram of chaotic channel.

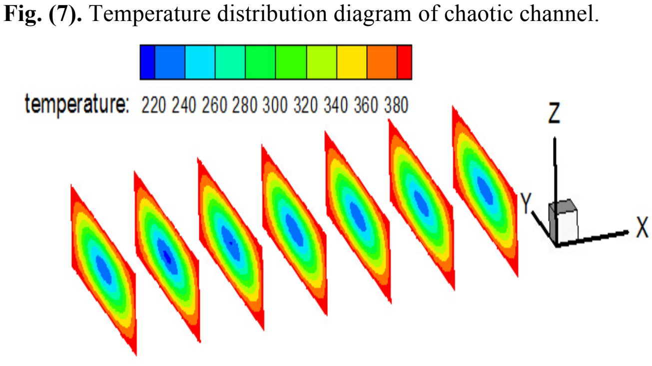

Fig. (8). Temperature distribution diagram of straight diagram.

3.3. Analyses of Synergy of Flow Field and Temperature Field

When *Re*=200, synergy angle isoline distribution diagrams for outlet cross section of chaotic channel and straight channel, are shown in Figs. (**9**, **10**). The exit face of chaotic period channel is the middle position for straight section of the whole channel. In accordance with field synergy theory, features of heat convection lie on not only flow velocity, temperature difference of fluid and solid wall, and thermo-physical properties of fluid, but also included the angle of velocity vector and temperature gradient, namely size of synergy angle. The smaller the included angle is, the better synergy of velocity vector and heat flow vector are, which is more in favor of heat transfer. Through comparing the above two diagrams, we can see intuitively that synergy angles of more than half of cross sections are equal to or greater than 86° (the closer to 90°, the worse to synergy effect), which indicates that synergy of velocity vector and temperature gradient of the cross section is worse. However, field synergy angle isoline of chaotic channel is uniform. The synergy angle of the cross section's top left corner and right wall is about 40°, which indicates that synergy effect of velocity vector and temperature gradient is very good. Field synergy angle in some places in the center is close or equal to 90°, which indicates that their synergic effect is poor, but field synergy angle in most places is much less than 90°. Therefore, as for the whole cross section, synergy of velocity and temperature gradient is better than that of straight channel, namely field synergy angle in outlet cross section of chaotic channel is less than that of straight channel. Through computation, average field synergy angle in outlet cross section of chaotic channel is 66.3°, while that in straight channel is 88.0°.

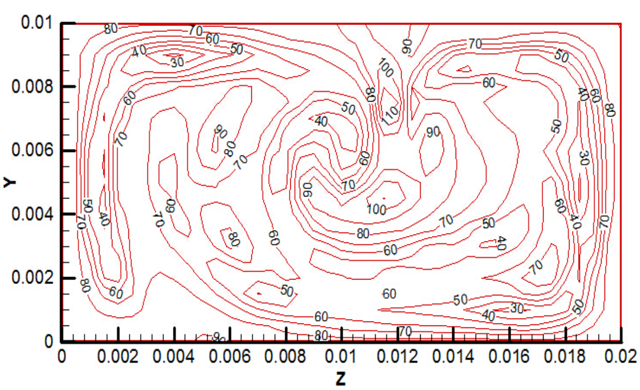

Fig. (9). Synergy angle distribution diagram of chaotic channel.

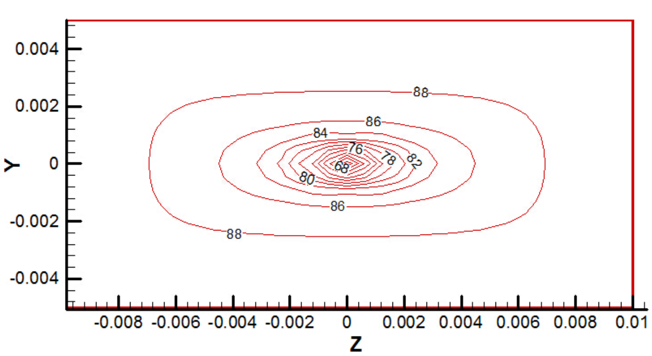

Fig. (10). Synergy angle distribution diagram of straight channel.

3.4. Influences of Reynolds Number on Heat Transfer and Fluid

In this paper, the author conducted analog computation on two channel structures whose Reynolds number is 50, 100, 200, 300, and 400 respectively; *Nu* number and Poiseuille number (namely *fRe* value) of two channels are shown in Fig. (**11**). Obviously, we can see from the figure that Nusselt number *Nu* in L-type chaotic channel is not a constant, but it increases with the increase of Reynolds number, so that some features are shown in heat transfer. However, it also can be seen from the figure that *Nu* number doesn't increase linearly with the increase of *Re* number, but it increases slowly with the increase of *Re* number. Through computation, growth rate of *Nu* number decreases from 117.76% to 16.13% when *Re* number increases from 50 to 400, which indicates that the smaller the *Re* number in chaotic channel structure is, the more obvious the enhancement of heat transfer is. Furthermore, it can be seen from figures that *Po* number in chaotic channel is obviously larger than that in straight channel and it increases with the increase of *Re* number, which indicates that friction coefficient in channel increases when chaotic channel structure conducts enhancement of heat transfer, so that larger pressure drop is generated. Therefore, it is necessary to optimize their structure, so as to gain ideal enhancement results of heat transfer with smaller pressure drop.

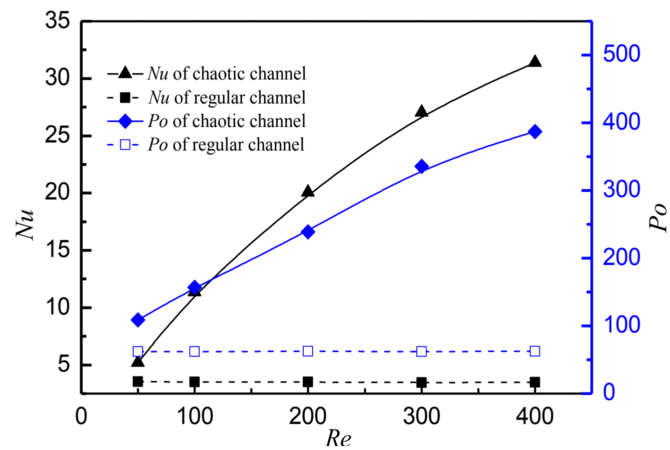

Fig. (11). The relationship between Nu number and Po & Re number in two kinds of channels.

CONCLUSION

In this paper, the author conducted 3D numerical simulation of fluid flow and heat transfer on L-type chaotic channel with the use of periodic model, compared with common straight channel, and the following results are gained:

1) L-type chaotic channel can produce chaotic convection which is relatively sensitive to initial conditions under low flow velocity, so that disturbing degree of fluid in channel increases, temperature of cross section distributes more uniformly, and mixture and heat transfer are strengthened;

2) Nu number of L-type chaotic channel is not a constant, like common laminar flow, but increases with the increase of Re number. Particularly, it

increases obviously at low Reynolds number. However, friction coefficient in channel will increase at the same time.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest

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