

Numerical Simulation of Heat Transfer in Primary Surface with Corrugations Recuperators

Liu Xuedong, Liu Hanpeng, and Zhou Ling

Abstract—Study fluid flow and heat transfer characteristics of microchannel in a primary Cross-corrugated(CC) surface recuperators with corrugations and without corrugations, using CFD method. The pitch-over-height ratios P/H of Cross-corrugated (CC) surface is from 1.5 to 4.0, included angles $\beta=75^\circ$. The study was performed using CFD software FLUENT to create unit model and simulate fluid temperature, velocity, heat transfer coefficient and other parameters. The results from these simulations were compared to experimental data. It is concluded that, when the Reynolds number is constant, if increase P/H , j/f will decrease, also the decreasing trend will become weak. Under the condition of $P/H=2.2$, if increase the inlet velocity j/f will decrease; in addition, the heat transfer performance in surface with corrugation will increase 10% compared to that without corrugation. The study results can provide the basis to optimize the design, select the type of heat transfer surface, the scale structure, and heat-transfer surface arrangement for recuperators.

Keywords—Cross-corrugated surface, Primary surface, Numerical simulation, Heat transfer.

I. INTRODUCTION

MICRO-TURBIN, which has developed rapidly in the distributed generation field, is a new kind of generator. recuperators as the main part of the Micro-turbines, adopting the efficient compact heat exchanger skill is one key factor for the success of regenerator [1]. Besides, mini-gas turbine is the core of the emerging energy island supply system as well. Energy island uses efficient gas turbine as its power. Only its generating electric power efficiency has risen to 30% for the usage of regenerator, which nearly reaches the efficiency of one big electrified wire fence. What's more, it uses heat, electricity and cold to produce energy, the total efficiency can above 80%. Thus, regenerator is crucial for energy island as well [2].

Further requirements on recuperators, of which compact size is already identified above, are the following:

- 1) High thermal effectiveness and low pressure losses. These affect the gas turbine cycle efficiency.
- 2) High reliability and durability give low maintenance cost and long operational life time.
- 3) Minimum weight and volume. The weight is directly proportional to material cost and a small volume of the unit

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makes the gas turbine packages easier to handle. So good for mass manufactured at low costs [3].

Enhancement of the heat transfer process is the core technology for developing new heat exchange equipment and improving the efficiency of heat transfer [4]. In order to enlarge heat transfer area, compact heat exchanger through welding a plate-fin on the conducting board. Plate-fin, as second conducting surface, its power is far below the conducting board through its conducting surface is 10 times of the later [5].

The presented results of the design calculations about compact recuperators are focused on cross-corrugated recuperators core. The fluid flow is complicated in cross-corrugated core. So the flow and conducting capacity is only analyzed by experiment and numerical simulation at present [6].

II. NUMERICAL SIMULATION

A. Physical Model

The need of compact heat transfer equipment, contributed to development of the study about a variety of different structure corrugated duct flow and heat transfer. Corrugated passage characteristics of the fluid flow largely depend on the flow in the region of separation and reattachment vortex current. The intensity of the heat transfer and the size of the heat transfer area depend on the continuous destruction and rebuilding of the boundary layer [7], so that the fluid produces rotation, the unstable vortex induced by shear layer as well as the formation of the hydraulic diameter smaller channel, etc. Pressure loss on a wall depends largely on the mainstream in the direction of the gradient wall rather than vertical gradient of secondary flow, a lower pressure loss cause a larger heat exchanger result in paying more attention to use vortex motion to enhanced heat exchanger. In this paper, intensification of heat exchange in Cross-corrugated passage (Fig. 1.) is to use two different fluids in the vicinity of composition cross-flow section, the interaction between two beams of fluid cause vortex, and the motion of vortex becoming unstable free shear layer to strengthen the fluid disturbance and admixture.

Fig. 2 shows recuperators surfaces with or without corrugation. The great differences from previous design are as following: first is to forge and press smaller corrugations in channel wall of cross-sectional shape with sine-wave, in order to increase the heat transfer area, and to enhance heat transfer effects; second is that two kinds medium flow in every passage made up by every two adjacent passages do not in the same

direction, they always maintain a certain angle β , so that one fluid flow in upside of one plant while another fluid flow in downside of another plant, they bounded by channel center plane. Hence, that will cause every two flow to interfere with each other, and then increase convective heat transfer coefficient in passages. The shape of heat transfer surface is corrugation, which included a certain angle with flow direction. The section shape of tilt direction's normal direction is Sine curve, the cycle is P , amplitude is $2H$. Selecting the two pieces of plate with four contact points on that part as a model element [3], every unitary cell can be indentified as sketched in Fig.2. It has two inlets (W , D) and two outlets (E , U) and its geometry is completely specified by the parameters p (pitch), H (external height), S (wall thickness) and β (corrugation angle), all indicated in the figure.

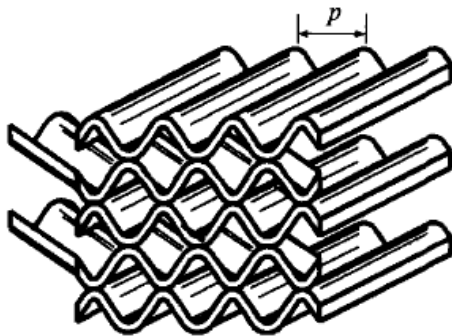
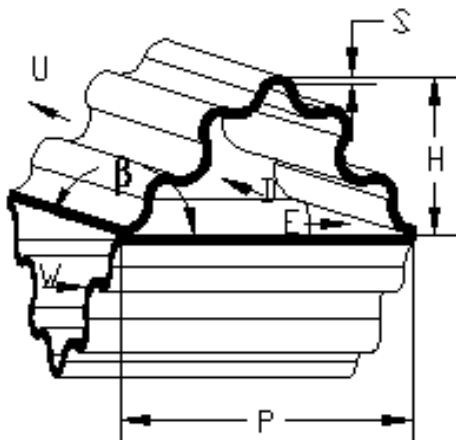
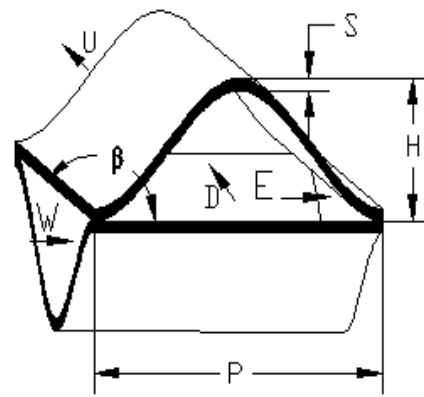


Fig.1 Cross corrugated (CC) surface



(a)



(b)

Fig. 2 Unitary cell of surface, (a) surface with corrugations; (b) surface without corrugations

B. Calculation Model

The Reynolds numbers of cold and hot gas are both under 1000, and the passages are straight, so along with flow direction, turbulence is not the main form of the two-fluid flow, hence the flow model for all models are in the laminar model and the fluid was treated as Newtonian [8]. Fluid temperature will change during the whole process when fluid reverse flow and heat transfer in recuperators [9]. In order to get close to the real flow and heat transfer conditions, the results from this study must be regarded with the differences of gas density, thermal conductivity, dynamic viscosity and specific heat capacity at constant pressure with the temperature change.

The naming of the heat transfer surface as following: $CCP/H-\beta$. For example, $CC2.0-75^\circ$ means in the CC surface, P/H is 2.0, included angle between corrugation is 75° . E. U Triainen, B. Sunden and Nie Song did some research on different included angle effect on the heat transfer, based on their research results could get conclusion: when included angle between corrugation β is 75° or 60° the heat transfer performance is better [3]-[5]. This paper focused on a variety of heat exchange surface hydraulic diameter D_h , in general are equal, on the surface the pitch-over-height ratios P/H is 1.5 to 4.0, included angle between corrugation β is 75° with surface corrugations and surface without corrugations in CFD numerical simulation. The specific dimensions are provided in table 1.

TABLE I
THE SIZE AND ARRANGEMENT OF CC SURFACE CALCULATION CELL

P/H	1.5	2.2	3.1	4.0
P (mm)	1.95	2.36	2.86	3.48
H (mm)	2.32	1.07	0.93	0.87
D_h (mm)	1.54	1.54	1.54	1.54

C. Governing Equation

For fully developed steady flow state three dimensional mass conservation, under the conditions of ignoring the force of volume, governing equations can be written as [5]:

Continuity equation:

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial u_i}{\partial x_j} \right) \quad (2)$$

Energy equation:

$$\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\mu}{pr} \frac{\partial T}{\partial x_j} \right) \quad (3)$$

As a result of the recuperators applied to micro-turbine, the recuperators on pressure loss requirement is small, its main heat flow requirements of resistance is very low so that need run at a relatively low Reynolds number [10], therefore, CFD numerical simulation is intended primarily for Re in a lower level of the laminar range (Re in the range 200 to 1000)

D. Boundary Conditions And Calculation Method

A primary surface heat exchangers made up of cross-corrugated plants which are semi-orthogonal arrangement. The geometric structure of fluid channel is cyclical variation. For the crossed-corrugated design, every unitary cell can be indentified as sketched in Fig. 3. It has two inlets (E, U) and two outlets (W, D). A complex flow and temperature field is established to inlets. All outlets are treated as fully developed flow, that is to say, after fluid flow out of inlets, the drag coefficient and the average Nusselt number of passage surface will keep constant. Both bottom and upper surfaces of passage are all with no-slip boundary condition, and with constant temperature, the down inlets and outlets with the same condition of velocity and pressure. For this paper in recuperators simulation, inputting two fluid mass flow rates of inlet, temperature and outlet pressure boundary conditions. Between the cold air and hot flue gas is the stainless steel part, which is coupled fluid-solid heat transfer boundary, so the software does iterative calculation automatically. Considering the cycle of average pressure gradient is unknown, a cycle calculated fields couldn't meet the need to alternative calculate the cyclical conditions of inlet and outlet. Thus, the calculation in this paper choose a slightly larger than a cycle range to analyze the full developed flow and heat transfer laws. Flow field and temperature field using split algorithm, convection discrete using index format, the coupling of pressure and velocity using standard SIMPLE methods, to increase the precision of calculations on the momentum equations and energy equation with second-order upwind discrete.

III. COMPARING NUMERICAL SIMULATION RESULTS TO EXPERIMENTAL DATES

The main factors affecting the heat transfer and flow

characteristics of the CC heat exchanger surface are plate thickness of the CC ducts, the pitch-over-height ratios P/H and the corrugation β [11]. Using commercial software CFD preprocessor Gambit to build the three-dimensional model and divide the unstructured grid mesh. The division of the grid is a non-uniform: the grid mesh near the inlets and outlets is more intensive than that in the middle part, so that to solve the high temperature and velocity gradient near the wall effectively [12], [13].

Fig. 3, Fig. 4, Fig. 5, and Fig. 6, show the velocity vectors and velocity contours of the CC2.2-75° cell sections surface with or without corrugations, respectively. As shown in the Fig. 3, that the flow of the fluid can be decomposed into two components: one part, as shown in the bottom half of Fig. 3, the main flow moving forward along the channel surface. The other, as shown in upper part of Fig. 3, the secondary flow surrounded along the channel surface. At the same time the wall ripples also strengthen this kind of flow. This flow may be considered between the upper and lower two fluid mixed-to-peer interaction. Two kinds of fluids mixed together can be considered as a spiral flow of move forward (up and down two shares). Fig. 7 and Fig. 8 respectively show the of the CC2.2-75° cell sections surface with and without corrugations. From the temperature cloud, the heat transfer performance of cell sections surface with corrugations more strengthen than that without corrugations. What's more the secondary flow enhanced heat transfer: the spiral secondary flow can take the lower temperature at the center of the fluid to the near wall, and the generation of boundary layer will be turbulent as well. Therefore, the intensive of secondary flow (such as increasing P/H) could achieve the purpose of strengthening heat transfer [14].

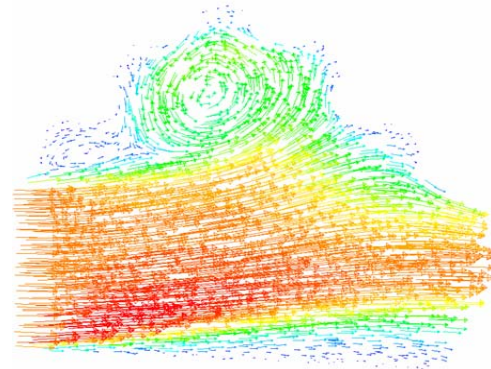


Fig. 3 Velocity vectors cell sections surface with corrugations

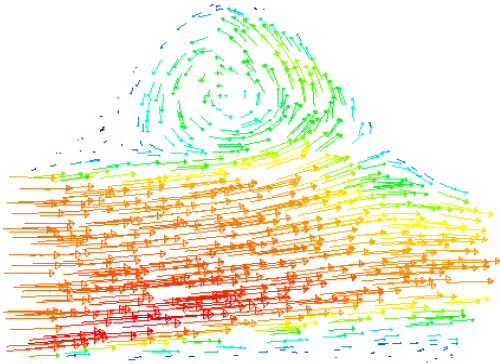


Fig. 4 Velocity vectors cell sections surface without corrugations

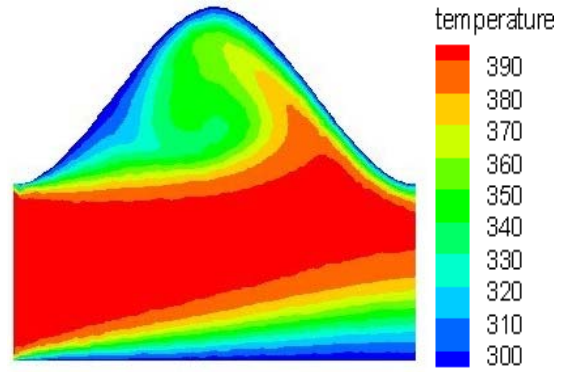


Fig. 8 Temperature contour of cell sections surface without corrugations

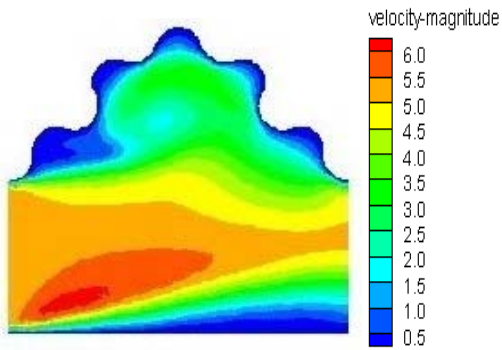


Fig. 5 Velocity contour of cell sections surface with corrugations

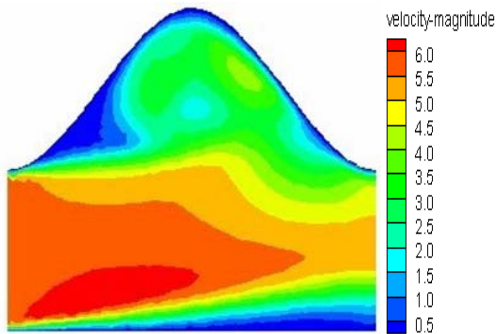


Fig. 6 Velocity contour of cell sections surface without corrugations

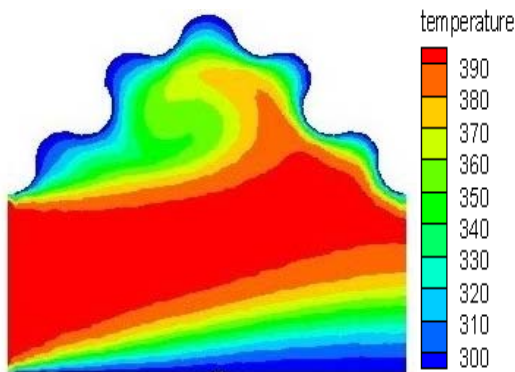
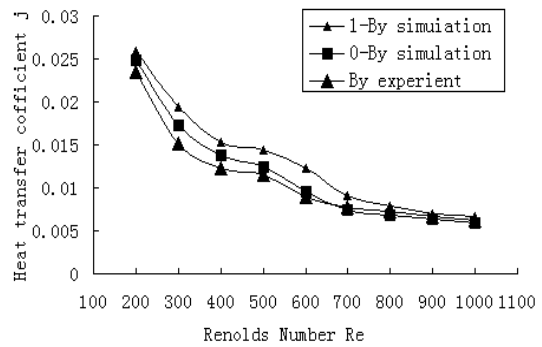


Fig. 7 Temperature contour of cell sections surface with corrugations

From experimental results [3] and numerical simulation results prove that: the results from simulation were compared to published data, with corrugations and without corrugations both using CC2.2-75° model, the difference results of the Fanning friction factor f between simulation and experimental within 9% more or less, the Heat Transfer factor j within 11% more or less as well, also, the average Nusselt number of passage surface within 8% more or less. At the same time, for heat transfer performance, the surface with corrugations of the recuperators is better than that without corrugations, while the former's resistance is greater than that of the latter, the problem can be solved by increasing the power of compressor. Above on what has been mentioned, it well describes the reliability of numerical simulation.



1- with corrugations; 0- without corrugations
Fig. 9 Comparison of f in numerical simulation with experimental results

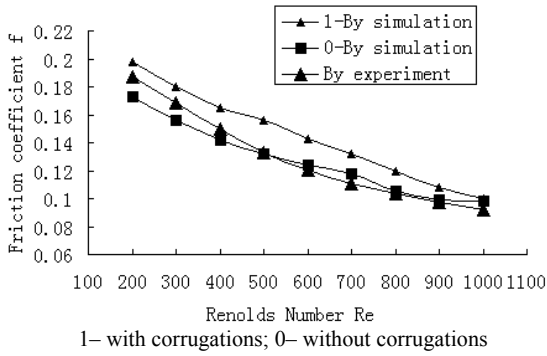


Fig. 10 Comparison of j in numerical simulation with experimental results

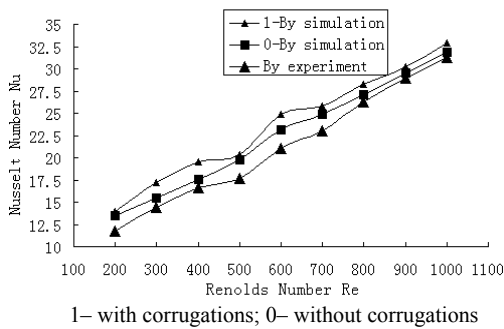


Fig. 11 Comparison of Nu in numerical simulation with experimental results

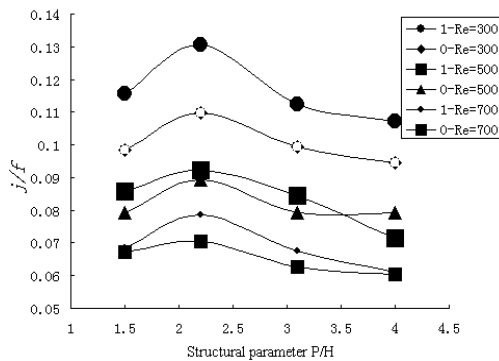


Fig. 12 j/f with the changes in structural parameter P/H

Using the ratio of the Heat Transfer factor j and the Fanning friction factor f (j/f) as a measure standard of a heat exchanger performance. Fig. 12 shows a plot of the change in j/f versus the Reynolds number in the condition of the included angle between corrugation $\beta=75^\circ$ with or without corrugation. From the numerical simulation results, it is clear to find that the performance of the recuperators surface with corrugations increased 5% to 20% to that without corrugations. What's more, the j/f tends to increase with increasing pitch-over-height

ratios (P/H) at first, and then with increasing P/H , j/f decrease, also the trend became weak, which could be attributed to the changing P/H . Within a certain extent, the friction area between up and down movement of the two flow increase with changing P/H with hydraulic diameter and β constant, thus strengthen the secondary flow and the effect of heat transfer. While over the range, increasing P/H lead to reducing secondary flow, thereby hindering the effect of heat transfer, then hindered the heat transfer effect.

IV. CONCLUSION

The secondary flow could be predicted through numerical simulation. The secondary spiral flow is able to bring the lower temperature of center fluid to a place where close to the wall to disturb boundary layer, so that to enhance heat transfer.

Numerical simulation of Fanning Friction factor f and Heat Transfer factor j with different flow velocities and different structural parameters using CFD. Clearly, j/f tends to decrease with increasing pitch-over-height ratios (P/H) and the trend became weak with Re constant, j/f decrease with increasing inlets velocity with same structural parameters. The results indicated that the recuperators performance which surface with corrugations is far better then that without corrugations.

Comparison the simulation results about Fanning friction factor and heat transfer factor j of a primary Cross-corrugated (CC) surface recuperators passage with experimental results, the data were basically the same, that means the calculation of numerical model and simulation method in this paper is feasible and accurate, which provided the basis to optimize the surface structure type of recuperators.

ACKNOWLEDGMENT

The first author is appreciative to the Program for Postgraduates Research Innovation in Universities of Jiangsu Province for the financial support.

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