Flow and Heat Transfer in Curve Channel with Cosinoidal Wave Wall Structure

L Y Zhang¹, Z Lu², X Yang¹, L C Wei²,³, X Z Meng¹ and L W Jin*¹

¹ School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Shaanxi, 710049, China.
² School of Energy and Power Engineering, Xi’an Jiaotong University, Shaanxi, 710049, China.
³ Shenzhen Envicool Technology Co., Ltd., Shenzhen, 518129, China.
E-mail: lwjin@xjtu.edu.cn

Abstract. Heat transfer rate in curve channel decreases with channel curvature since the secondary flow turns weak with the decrease of centrifugal force. In this paper, the periodical wave wall structure is introduced into curve channel for improving heat transfer rate in the curve channel with small curvature. The channel radius is not constant anymore but varies periodically based on a cosinoidal function. Three-dimensional numerical investigation was carried out to explore the flow and heat transfer characteristics in the curve-wave channel, and the effects of wave frequency and average curvature on the heat transfer performance were analysed. The results show that the heat transfer rate in curve channel can be improve up to 95.50% due to the periodical wave wall structure, while the friction factor increases by 53.94%. The effect of periodical wave wall structure on heat transfer is dependent on the overall curvature of curve-wave channel and stronger for larger-curvature curve-wave channel. The performance factors of all the curve-wave channels are almost above 1, indicating that this structure can be used as an economic passive heat transfer enhancement method.

1. Introduction

Curve channel has received much attention due to its high heat transfer performance and has been employed in the design of heat exchangers [1-2]. It is important to note that heat transfer rate may decrease with channel curvature since the effect of centrifugal force gets weak [3]. The decrease of channel curvature is inevitable in some practical applications due to the increased radius [4-5]. Therefore, it is imperative to enhance further the heat transfer performance in the curve channel with small curvature. According to the latest development on the curve channel, two popular methods are used to improve heat transfer in the curve channel. One is to use nanofluids as working fluids [2]. However, deposition of nanoparticles may deteriorate heat transfer due to the increased thermal resistance on the wall surface. Another is to modify the geometry of curve channel, for example, the heat transfer surface can be corrugated [6]. The surface modification is usually applied in the helical channel and the relevant study on the spiral channel with increasing radius along flow direction is rather scarce.

In order to improve the heat transfer rate in the small-curvature curve channel, the periodical wave wall structure was introduced into the curve channel to strengthen the secondary flow and break thermal boundary layer periodically. The flow and heat transfer characteristics in the curve-wave channel were...
numerically studied. The effects of wave frequency and average curvature on flow and heat transfer in the curve-wave channel were analysed to provide useful reference for the design of heat exchangers with such geometric structure.

2. Model description

Figure 1 shows the schematic diagram of a curve-wave channel. It can be noted that the most obvious difference between curve-wave channel and curve channel is that wall curvature of curve-wave channel varies periodically along the main flow direction. The radius of curve-wave channel varies periodically based on cosine function and the geometry of curve-wave channel can be governed by the following equation.

$$ r = A \cos(n \cdot \theta) + R_0 $$

where, $r$ is the actual radius of the central line of curve-wave channel at different position along the main flow direction; $A$ is the wave amplitude; $n$ controls the frequency of wave; $\theta$ indicates the different position along flow direction, and varies from 0 to $\pi$ in the present study; $R_0$ is the average radius of curve-wave channel.

It is important to note that there are many geometric parameters affecting the flow and heat transfer in a curve-wave channel. In this paper, only the effects of wave frequency and average curvature are discussed. The wave amplitude of channel wall for the simulated curve-wave channels is fixed at 1.2 mm. The effects of wave frequency on flow and heat transfer were studied at a given average channel radius $R_0 = 160$ mm, while the effects of average channel radius (100 mm, 120 mm, 140 mm, 160 mm, 180 mm and 200 mm) were explored at a constant wave frequency $15/\pi$. The wave frequency of the curve-wave channel wall includes $9/\pi$, $12/\pi$, $15/\pi$, $18/\pi$ and $21/\pi$, which means there are 9, 12, 15, 18 and 21 wave units for a half circular channel. The channel cross-section normal to the main flow direction is rectangular and its size is consistent for all the curve and curve-wave channels. The channel width and height are 3 mm and 6 mm, respectively; the thickness of the base and cover plate is 6 mm while the thickness of the channel wall is 1.5 mm.

3. Numerical simulation

3.1. Modeling of curve and curve-wave flow

The flow in the curve and curve-wave channels were assumed to be laminar, steady and incompressible, and the effects of gravity were neglected in the present study. The numerical simulations including the meshing of calculation zone were completed through the commercial CFD software ANSYS 15.0. Water was selected as the heat transfer fluid while aluminum as the channel material, their thermal properties were assumed to be constant and given in Table 1.
Table 1. Thermal properties of the coolant and channel material.

| Material  | Density $\text{kg m}^{-3}$ | Specific heat capacity $\text{J kg}^{-1}$ | Thermal conductivity $\text{W m}^{-1} \text{K}^{-1}$ | Viscosity $\text{kg m}^{-1} \text{s}^{-1}$ |
|-----------|--------------------------|------------------------------------------|--------------------------|-----------------|
| Water     | 998.2                    | 4182                                     | 0.6                      | 0.001003        |
| Aluminium | 2719.0                   | 871                                      | 202.4                    | -               |

3.2. Boundary conditions
Uniform velocity and atmosphere pressure boundary conditions were applied at the channel inlet and outlet, respectively, and the velocity was determined to realize the different Reynolds number. The inlet temperature of the working fluid was set as 300 K. Only the bottom and top walls were heated with constant heat flux 26000 W m$^{-2}$, and the heat transfer between channel and surrounding environment was neglected.

3.3. Numerical scheme
The calculation zones were discretized with structured mesh. The SIMPLE algorithm was applied to solve the pressure-velocity coupling equation while Standard algorithm was employed to discretize the pressure items, the second order upwind scheme was used for the momentum and energy equation. In order to avoid the return flow at channel outlet and achieve solution convergence easily, the exit part of fluid zone was extended four times over the hydraulic diameter of channel.

4. Results and discussion
4.1. Validation of numerical scheme
The numerical scheme employed in the present study was validated first through solving flow and heat transfer problem in a curve channel. The details of the channel geometry and simulation process can be found in the references [7, 8]. The comparison of the results shown in Figs. 2 and 3 indicates that the maximum differences between the present numerical results and the results from the references are 9.91% and 3.44% respectively, indicating a good agreement between the current study and the published literature.

![Figure 2. Pressure drop versus $Re$.](image)

![Figure 3. $Nu$ along flow direction.](image)

4.2. The effects of wave frequency
In this part, the effects of wave frequency on flow and heat transfer in the curve-wave channel are discussed. The different wave frequencies can be realized by changing the value of $n$ in Equation (1). The variations of average $Nu$ and $f$ with both wave frequency and $Re$ are shown in Figs. 4 and 5, respectively.

It is seen that the effect of wave wall structure is significant for large $Re$, and heat transfer rate in the curve channel increases by 2.94-95.50% after introducing wave wall structure. Higher heat transfer rate
can be obtained by increasing the wave frequency of the channel wall, and meanwhile, the fanning friction factor increases by 3.26-53.94%.

4.3. The effects of average curvature
The curvature of a curve channel may change along flow direction in practical application, therefore, it is also necessary to study the effect of average curvature on heat transfer in curve-wave channel. For simplifying the problem, the wave amplitude and wave frequency are fixed at 1.2 mm and 15/π, respectively. The variations of average $Nu$ and $f$ with average channel radius are given in Figs. 6 and 7, respectively.

It is not difficult to find that the overall channel radius still has significant influence on heat transfer in curve-wave channel. The heat transfer rate decreases with the increase of average channel radius, which demonstrates that the wave amplitude or wave frequency of curve-wave channel should be adjusted to maintain a high heat transfer rate when its average curvature decreases. The fanning friction factor also decreases with the average channel curvature, since the channel tends to be flat for a given wave frequency and wave amplitude.

4.4. The comprehensive performance factor
Taking energy-saving into consideration, the performance factor $(Nu / Nu_0) / (f / f_0)$ is employed to evaluate the effectiveness of this passive heat transfer enhancement technique. $Nu_0$ and $f_0$ are the overall Nusselt number and friction factor for the curve channel with the same radius as the average radius $R_0$ of the curve-wave channels.
It is seen from Figs. 8 and 9 that the performance factors of curve-wave channels with different wave frequencies and average curvatures are almost above 1. This indicates that the heat transfer enhancement due to the wave wall structure dominates the overall performance taking into consideration of pressure loss. In addition, the performance factors gradually increase with \( Re \) for all the channels except for \( R_0 = 100 \) mm. The higher performance factor can be achieved through increasing the wave frequency when \( Re \) is lower than 450. However, it is noted that the performance factor of the channel with 21 wave units is lower than that with 18 wave units when \( Re \) is larger than 450. This suggests the heat transfer enhancement is less than the increase of pressure loss while increasing wave units from 18 to 21. In the process of designing heat exchanger with such geometric structures, the wave frequency of channel wall should be determined carefully with consideration of the overall channel curvature to achieve a high heat transfer rate and a relatively low pressure drop simultaneously.

**Figure 8.** The variation of performance factor with \( Re \) for the curve-wave channels with different wave frequency.

**Figure 9.** The variation of performance factor with \( Re \) for the curve-wave channels with different average curvature radius.

5. Conclusion

Numerical investigation was carried out to explore flow and heat transfer in curve-wave channel. The effects of wave frequency and average curvature on the heat transfer rate and pressure drop in curve-wave channel were discussed. Heat transfer rate can be improved significantly after introducing periodical wave wall structure into curve channel. The heat transfer rate can be improved significantly after introducing periodical wave wall structure into curve channel. The heat transfer in curve-wave channel can be further enhanced by increasing the wave frequency. The effect of periodical wave on heat transfer is also dependent on the overall curvature of curve-wave channels and stronger for larger-curvature curve-wave channel. The analysis of performance factor indicates that the heat transfer enhancement attributed by the wave wall structure dominates the overall performance taking into consideration of pressure penalty.

Acknowledgements

The authors are grateful for the support by the Scientific and Technological Innovation Project in Shaanxi Province (2015KTCQ01-99), the Key Scientific Research Innovation Team Project of Shaanxi Province (2016KCT-16).

6. References

[1] Naphon P and Wongwises S 2006 Renewable Sustainable Energy Rev. 10(5) 463-90.
[2] Huminic G and Huminic A 2016 Renewable Sustainable Energy Rev. 58 1327-47.
[3] Cheng K C and Akiyama M 1970 Int. J. Heat Mass Transfer. 13(3) 471-90.
[4] Alaç Z and Altun Ö 2014 Int. J. Therm. Sci. 77 96-107.
[5] Naphon P 2016 Int. J. Heat Mass Transfer. 93 293-300.
[6] Zachár A 2010 *Int. J. Heat Mass Transfer*. **53**(19-20) 3928-39.
[7] Chu J C, Teng J T, Xu T T, Huang S, Jin S, Yu X F, Dang T, Zhang C P and Greif R 2012 *Exp. Therm. Fluid Sci*. **38** 171-83.
[8] Guo J, Xu M and Cheng L 2011 *Int. J. Therm. Sci*. **50**(5) 760-68.