Numerical analysis of fluid flow and heat transfer in 2D sinusoidal wavy channel

Arunanshu Chakravarty[1*]

[1]CTU in Prague, Faculty of Mechanical Engineering, Department of Process Engineering,Technická 4, 166 07 Prague 6, Czech Republic

Abstract

Wavy passages are one of the many devices being considered by manufacturers in the HVAC/R industry for a variety of heat exchanger applications. The numerical investigation of the flow field and heat transfer of air flowing in two dimensional sinusoidal wavy channel was conducted to compute the pressure drop characteristic and heat transfer. Simulations were performed for fully developed flow conditions at inlet sections of the channel of wavelength 0.04 m. The variation of pressure drop on flow velocity was studied and also the local Nusselt number and heat transfer were computed for the wavy channel geometry. The results of the wavy channel geometry were also compared with the heat transfer for the flow of air in two dimensional rectangular channels. It was found that the heat transfer by the usage of corrugated walls in an appropriate Reynolds number regime is enhanced as compared to the rectangular channel.

*Keywords:*wavy channel; heat transfer

1. Introduction

Potential heat transfer enhancement in heat exchanger devices has recently gained great popularity because of the importance of these devices in numerous engineering applications. There are several methods used to improve heat transfer enhancement in heat exchangers. One way to increase heat transfer rate is to use optimum wall geometry that gives minimum pressure loss [1]. Several methods are currently employed or are being investigated to increase the efficiency of the air-side heat transfer of heat exchangers. They are based on two main principles, the restarting of the thermal boundary layer and bulk fluid mixing [2]. Devices such as louvers and offset-strip fins restart the thermal boundary layer in the flow and may induce vortices to provide fluid mixing. This destroying and restarting of the boundary layer causes an increase in heat transfer by producing a thinner boundary layer. Vorticity in the flow can enhance heat transfer by destroying temperature gradients in the core flow – concentrating thermal gradients in the near-wall region. The primary disadvantage of most heat transfer enhancement devices is that they usually involve an obstruction to divert or disrupt the flow. Such a diversion can lead to pressure drop penalties that outweigh the benefits of heat transfer enhancement. Rather recently, researchers have revisited the use of wavy channels to improve the efficiency of a heat exchanger [2]. Figure 1 shows an example of this type of geometry. Unlike the methods discussed above, wavy channels do not directly obstruct the path of the core fluid in the device. Instead, they rely on shear-layer instabilities and flow impingement to exchange near-wall fluid with core fluid, increasing heat transfer. Such flow features might lead to improved heat transfer performance with a lower pressure drop penalty.

As shown in Figure 1, there are geometric parameters important to characterizing the wavy channel configuration..

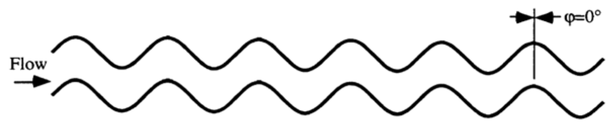

Figure 1. *Schematic of wavy passage configuration (ϕ = 0°) phase-shift.[3]*

A 0° phase shift geometry (ϕ=0°) indicates that the two walls of the channel are in-line with each other and there is a constant spacing between the channel walls. Goldstein and Sparrow were among the first to study heat and mass transfer performance of a corrugated channel in laminar, transitional, and turbulent flows within a triangular corrugated channel. They concluded that corrugated channels are an effective heat transfer device only at turbulent Reynolds numbers. They found heat transfer rates improved over a straight channel, but there was an even greater penalty in pumping power.

2. Objectives of this work

The objectives of this work were to perform computational flow visualization to better understand the flow behaviour in sinusoidal wavy passages with phase shift, ϕ = 0°. Also, to investigate the pressure drop characteristics on the flow behaviour in a range of Reynolds numbers and flow conditions typically encountered in HVAC/R applications in laminar flow regime. Finally to

*Corresponding author: Arunanshu.Chakravarty@fs.cvut.cz

explore the impact of flow behaviour on heat transfer performance in turbulent flow regime. The parametric study by varying the geometrical parameters like wavelength, phase shift, etc. were excluded from the present work. The main emphasis was laid in to study the computational fluid dynamics approach towards problem solving using numerical methods for an Industrial heat exchanger application.

Although the present work is based on purely numerical analysis approach, however, it is strongly suggested to perform experiments and validate the results obtained and not consider results of the presented CFD analysis as the only final results for the optimal design of sinusoidal wavy channels for heat transfer enhancement.

2. Model description

The problem setup consisted of modeling a 2D sinusoidal wavy geometry in the ANSYS Design Modeler software package (release 15.0) with phase shift of 0º.

2.1. Channel geometry

The 2D sketch was created using Design Modeler package of ANSYS 15.0. The sinusoidal wave was generated from the coordinate file for the sinusoidal wave. The phase shift ϕ was kept 0º which implies a constant cross-section between the upper and bottom channel walls. The geometry created in the Design modeler is shown in Figure 2.

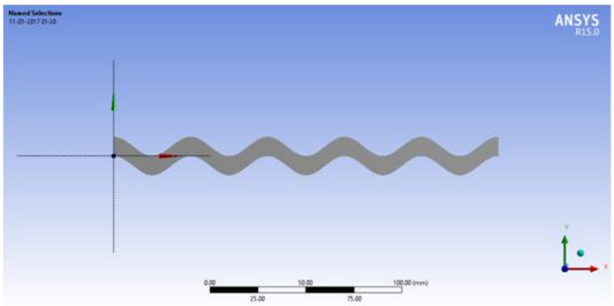

Figure 2. *Sinusoidal wavy passage with ϕ = 0º phase shift created in Design Modeler*

The geometrical parameters are tabulated in Table 1.

2.2. Spatial discretization

The flow region was discretized by structured meshing and quadrilateral mesh was generated in ANSYS meshing. To account for better capturing of flow physics near walls, the inflation layer was also applied. The meshed model was generated with 16153 nodes and 15672 elements.

Table 1. *Geometrical parameters of the wavy channel.*

Parameter	Value
Length of Channel (L)	0.2 [m]
Width of Channel (H)	0.01 [m]
Wavelength (λ)	0.04 [m]
Hydraulic diameter (Dh)	0.02 [m]
Phase Shift (ϕ)	0º

Figure 3 depicts the meshed model with detail view of inflation layers near the wall.

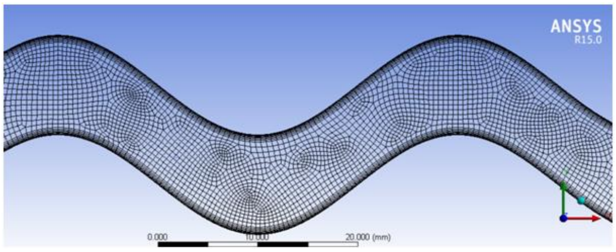

Figure 3. *Detailed view of meshed region showing the inflation layers near the walls of wavy passage with ϕ = 0º phase shift*

2.3. Governing equations

The Computational Fluid Dynamics approach for solving the governing equations of fluid flow and heat transfer was considered for this work. The upper and lower walls of the wavy channel were isothermally heated and kept at constant temperature of 400 K. The temperature of the inlet fluid was taken 300 K, less than that temperature of wavy walls. The flow was approximated as Newtonian, incompressible and two dimensional. The analysis was made for both Laminar and Turbulent flow regimes. To simplify the analysis, the effect of temperature on thermo-physical properties of fluid was neglected. Based on these assumptions, the continuity, momentum and energy equations for 2D are reduced to:

Continuity equation:

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

Momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \eta\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \eta\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Energy equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

2.4. Boundary conditions

Fully developed flow, and uniform temperature of the inflow of air were applied as boundary condition at the channel entrance. At the outflow boundary, the outlet pressure was set as an atmospheric. At upper and lower slip conditions and constant wall temperature were specified.

2.5. Numerical procedure

The governing equations of flow have been discretized by a finite volume method and pressure-velocity coupling system has been resolved by using the SIMPLE algorithm in ANSYS Fluent. The grids were non-uniform. Grids were finer near the boundaries while coarser at the core region. The convergence criterion, 10e-8 was chosen for all parameters in computational domain.

3. Result and discussion

For the determination of fluid flow regime, Reynolds number based on hydraulic diameter of the channel was calculated. The hydraulic diameter D_h was calculated as : For sinusoidal wavy channel, $D_h = 2 * h$, where h is the height of channel. For rectangular 2D channel, $D_h = 2ab/(a + b)$, where a is the width and b is the height of channel. The default width of 1 m for 2D geometry was taken for the calculation of hydraulic diameter and Reynolds number.

The simulations for calculating pressure drop were performed for the laminar flow regime. The inlet velocities were varied from 0.2 to 1.6 m/s in a step of 0.2 and the effect on corresponding Reynolds number on the pressure drop in the wavy channel is shown in Figure 4.

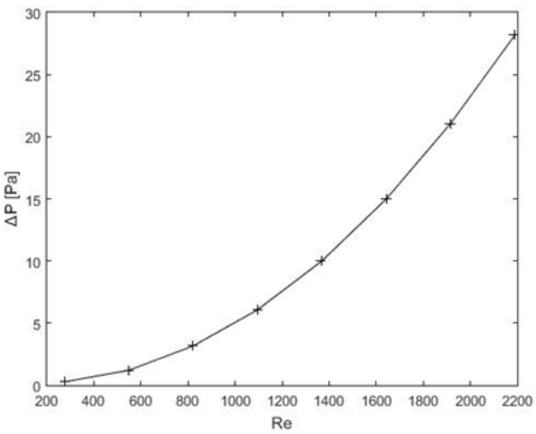

Figure 4. *Variation of pressure drop with Reynolds number in laminar regime.*

It can be inferred that the pressure drop increased as the flow velocity increased which is predictable according to the transport phenomenon theory. It can be concluded that during the design of wavy channels for the heat exchanger applications, increasing the velocity to enhance heat transfer always results in a penalty in terms of pressure drop and hence an increase in cost for pumping.

The static temperature contours for the laminar flow of air at 0.8 m/s in the wavy channel is shown in the Figure 5.

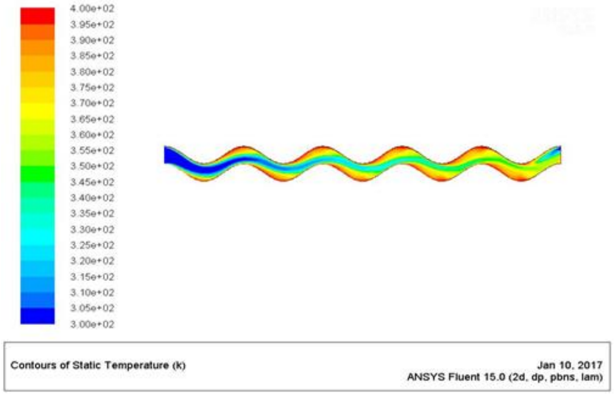

Figure 5. *Static temperature contour for the laminar flow of air at 0.8 m/s.*

From the contours of static temperature in the laminar flow regime, it can be seen that the core of the fluid remains less affected by the heat transfer as compared to the fluid near the walls.When a fluid flows in contact with a channel at low velocity it will do so in a way which does not produce any intermixing of the fluid: the boundary layer, the fluid in contact with the channel, will have its velocity reduced slightly by viscous drag and heat will flow through the fluid out of (or into) the channel wall by conduction and/or convection.

As the velocity of the fluid is increased it will eventually reach a level which will cause the fluid to form turbulence eddies where the boundary layer breaks away from the wall and mixes with the bulk of the fluid further from the tube wall. Hence, the flow regime of turbulent flow was also studied using realizable k-ε turbulence model.

The velocity vectors for the flow velocity of 4.5 m/s is shown in Figure 6.

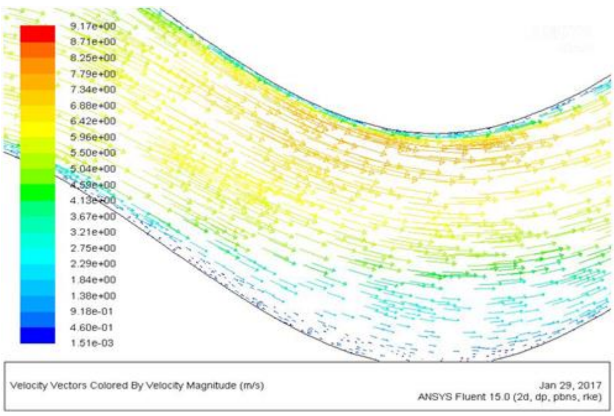

Figure 6. *Velocity vectors for the turbulent flow at 4.5 m/s.*

The contours of static temperature for the turbulent flow of air at flow velocity of 5 m/s is shown in Figure 7.

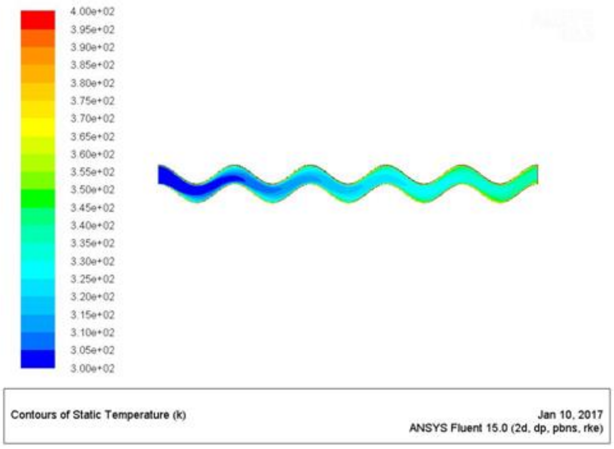

Figure 7. *Static temperature contour for the turbulent flow of air at 5 m/s.*

It can be observed from the static temperature contour of turbulent flow regime that the boundary layer narrows, hence the fluid core moves towards the walls. The dimensionless Nusselt number is defined as

$$Nu = \frac{hD_h}{\lambda_f} \tag{5}$$

where h is the heat transfer coefficient, λ_f is the thermal conductivity of fluid and D_h is the hydraulic diameter.

The Nusselt number for different values of Reynolds number in the turbulent regime was calculated to determine the enhancement in heat transfer at increasing velocities of flow in the wavy passage and Figure 8 depicts the variation of Nusselt number along the wavy passage for different ranges of Reynolds numbers.

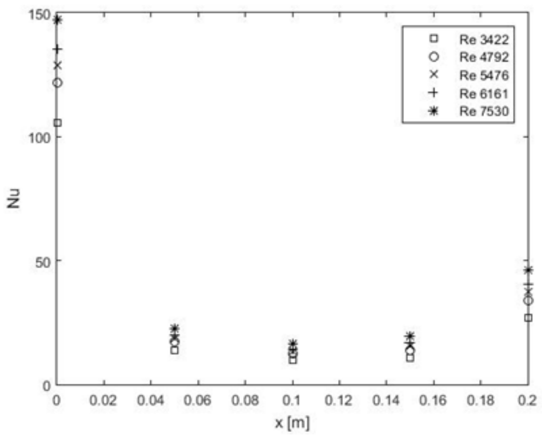

Figure 8. *Variation of local Nusselt number at various Reynolds numbers in turbulent regime for wavy channel*

The enhancement in heat transfer and Nusselt number attributed to the movement of temperature isotherms towards the walls and hence making narrower the boundary layer due to the turbulence effects. Comparison of wavy passage channel with the rectangular 2D channel was also performed to ascertain wavy passage as an effective solution for the heat transfer enhancement.The contours of static temperature for the turbulent flow of air at flow velocity of 5 m/s is shown in Figure 9.

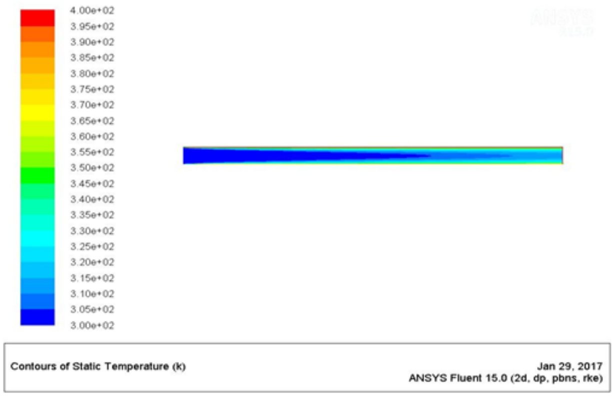

Figure 9.*Static temperature contour for the turbulent flow of air at 5 m/s in rectangular channel.*

The obtained variation of Nusselt number with Reynolds number for the two channels is shown in Figure 10.

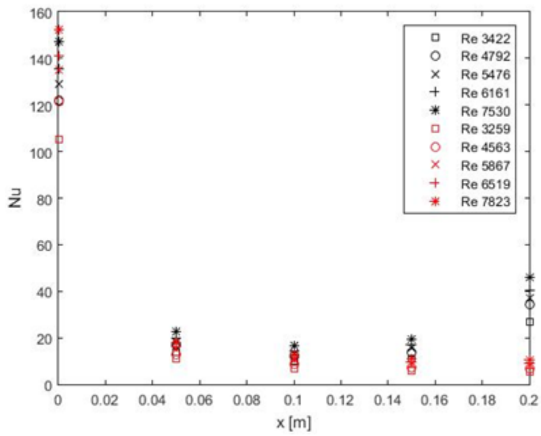

Figure 10. *Comparison of local Nusselt number for different Reynolds numbers in turbulent regime for wavy channel (in black) and rectangular channel (in red).*

It can be seen from the obtained values of Nusselt number in turbulent regime for the rectangular channel was less than the values obtained from the wavy passage geometry. So, it can be concluded that sinusoidal wavy passages are clearly an option for enhancing the heat transfer in channel geometries for the industrial heat exchanger applications.

4. Conclusion

Flow patterns and heat transfer characteristics in a sinusoidal wavy channel with phase shift, $\phi = 0^{o}$ was investigated by numerical solving of governing equations on a structured grid by the use of computational fluid dynamics. The pressure drop characteristics were evaluated for the laminar flow regime where the Reynolds number was calculated based on the hydraulic diameter of the channel. It was observed that the pressure drop increased as the flow velocity increased indicating a penalty in terms of increased pumping cost.

Further the heat transfer studies of wavy passage were conducted and simulations were compared with flow in 2D rectangular channel in turbulent flow regime. It was observed that the Nusselt numbers obtained in the turbulent regime for wavy channels were higher than those obtained in the rectangular channel which states wavy passage as an alternative device for heat transfer enhancement. The further scope lies in conducting parametric studies on the channel geometries and the experimental studies on sinusoidal wavy passage to validate the obtained results and for optimizing the design parameters for industrial heat exchanger applications.

Acknowledgement

The author would like to thank Ing. Jan Skočilas, Ph.D and Ing. Karel Petera, Ph.D for their sharing of knowledge in the areas related to numerical analysis of processes and computational fluid dynamics.

Symbols

λ	wavelength of channel (m)
D_h	hydraulic diameter of channel (m)
Re	Reynolds number (-)
Nu	local Nusselt number (-)
ϕ	phase shift (deg)
Pr	Prandtl number (-)
Δp	Pressure drop (Pa)
h	heat transfer coefficient (W m^{-2} K^{-1})
λ_f	thermal conductivity of fluid (W/(mK))
η	kinematic vicosity (m^2 s^{-1})

References

[1] Ozbolat, V et al. (2013). Flow characteristics and heat transfer enhancement in 2D corrugated channels Int. J. MAIMM, v.(7). pp. 2074-2078. Available from: http://waset.org/publications/17185/

[2] Russ, G and Beer, H.,(1997). Heat transfer and flow field in a pipe with sinusoidal wavy surface-I. Numerical investigation, Intl. J. Heat Mass Transfer, v40,(5),pp. 1061-1070.

[3] Rush T.A et al. (1997). An experimental study of flow and heat transfer in wavy passages, ACRC Project, University of Illinois, U.S.A.