International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2016): 79.57 | Impact Factor (2015): 6.391

Thermal and Fluid Flow Analysis of an Corrugated and Wavy Channels: "A Comprehensive Review"

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Abstract: ***This paper focuses to extensive review on the fluid flow and heat transfer over a corrugated, smooth and wavy channel. Corrugated and wavy channel have been used in many environmental and industrial applications such as heat exchanger, combustion chamber, heating and cooling system, chemical process, etc. The main purpose for adopting corrugated, wavy surface instead of using smooth channel is due to enhance the mass and heat transfer phenomenon, related with large pressure discrepancy. Essentially, the fully developed flow over a corrugated, wavy surface, in any laminar or turbulent flow, is greatly advanced and complex than the flow over a smooth surface. Several researches have been carried out experimentally, numerically and computationally to explore the flow characteristics over corrugated and wavy surfaces for various engineering applications which has been stated in this paper.***

Keywords: Corrugated, heat transfer, Mass transfer, Reynolds Number

1. Introduction

In a flow channel sudden compression or expansion is very significant design in various practical applications for cooling or heating systems. Countless heat transfer industrial applications through facing sudden compression or expansion of channel have been comprised in energy systems equipment, turbine blades cooling, chemical processes, combustion chambers, electronic cooling systems, environmental control systems and high performance heat exchangers. Mainly, the pressure drop and heat transfer improvement in the re-attaching flow area and within the reverse flow area was significant. For instance, the low pressure drop and the high heat transfer augmentation attained near the wall channel region while the low rate of heat transfer achieves at the corner where the sudden change take places starts in flow region.

2. Mathematical Modeling

For the fluid flow through pipe, duct and channel the conventional governing equations are the **Navier–Stokes equations** can be written in the most useful form for the development of the finite volume method:

$$\rho\frac{Du}{Dt} = -\frac{\partial p}{\partial x} + div(\mu\, grad u) + S_{Mx} \quad (1)$$

$$\rho\frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + div(\mu\, grad v) + S_{My} \quad (2)$$

$$\rho\frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + div(\mu\, grad w) + S_{Mz} \quad (3)$$

Governing equations of the flow of a compressible Newtonian fluid

Continuity

$$\frac{\partial \rho}{\partial x} + div(\rho u) = 0$$

x-momentum

$$\frac{\partial(\rho u)}{\partial x} + div(\rho u u) = -\frac{\partial p}{\partial x} + div(\mu\, grad u) + S_{Mx} \quad (4)$$

y-momentum

$$\frac{\partial(\rho v)}{\partial y} + div(\rho v u) = -\frac{\partial p}{\partial y} + div(\mu\, grad v) + S_{My} \quad (5)$$

z-momentum

$$\frac{\partial(\rho w)}{\partial z} + div(\rho w u) = -\frac{\partial p}{\partial z} + div(\mu\, grad w) + S_{Mz} \quad (6)$$

Energy

$$\frac{\partial(\rho i)}{\partial t} + div(\rho i u) = -p\, div u + div(k\, grad T) + \Phi + S_i \quad (7)$$

Using various correlation FEV results are been compared analytically

$$h_f = f\frac{LV^2}{D_h 2g}$$

Where,
f is the friction factor for fully developed laminar flow
L: length of the channel, duct, pipe
V: mean velocity of the flow
d: diameter of the pipe

$f = \frac{64}{Re}$ (For Re<2000) $Re = \frac{\rho u_{avg} d}{\mu}$

C_f is the skin friction coefficient or Fanning's friction factor.

For Hagen-Poiseuille flow: $C_f = \tau_{wall} l \frac{1}{2}\rho u_{avg}^2 = \frac{16}{Re}$

For turbulent flow: : $\frac{1}{\sqrt{f}} = 1.74 - 2.0\log_{10}\left[\frac{\varepsilon_p}{R} + \frac{18.7}{Re\sqrt{f}}\right]$

Moody's Chart
R: radius of the channel, duct, pipe
ε_p: degree of roughness (for smooth channel, duct, pipe, $\varepsilon_{p=0}$)
$Re \to \infty$: Completely rough channel, duct, pipe.

3. Literature Survey

Kafel et al. 2017 compares the performance of smooth, corrugated shell and corrugated tube exchanger. They also analyzed the distinct arrangements of concave and convex type of corrugated tubes.

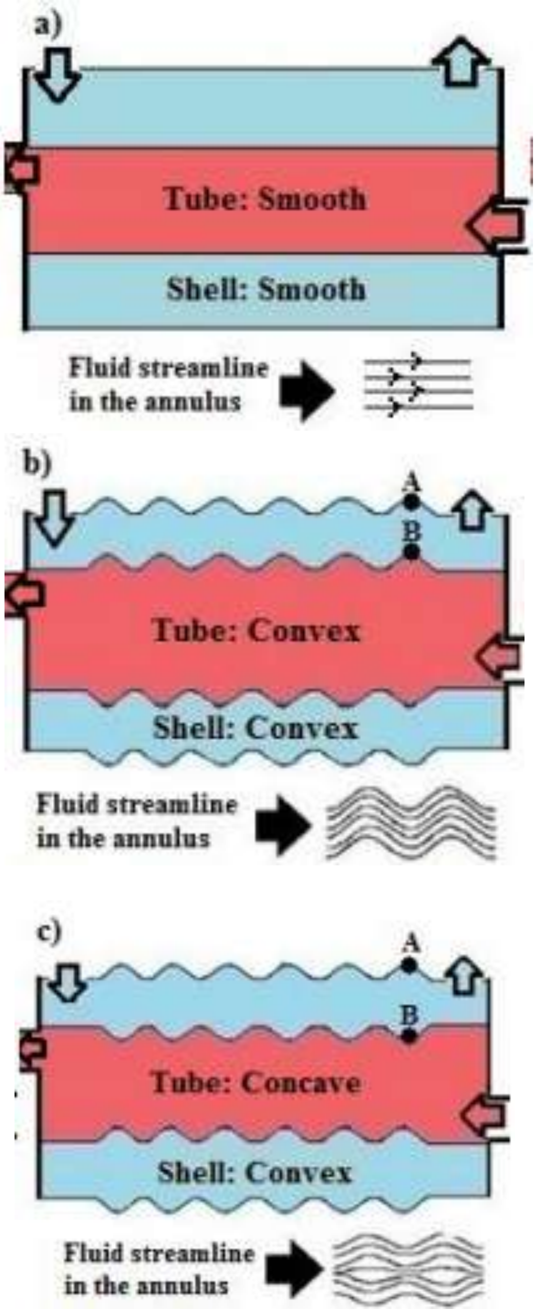

Figure 1: The effect of arrangement type on annulus fluid streamline [1]

The exergy losses due to simultaneous employing of corrugated tubes as the inner and outer tube in heat exchanger have been reported. In their work experimental based parametric exergy analysis has been carried out. The result reveals that the corrugations lead to enhancement in both exergy loss and NTU. Moreover they also observed that heat exchanger made of convex corrugated tube and concave corrugated shell.

Wongwises [2] experimentally examined the influence of corrugation pitch on the condensation heat transfer and pressure drop of R-134 inside horizontal corrugated tube. Their results illustrates that the corrugated tube has heat transfer coefficient and pressure drop in comparison with smooth tube.

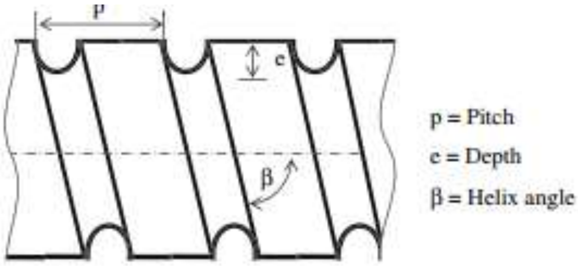

Figure 2: Drawing of a helically corrugated tube

Aroonrat et al. [3] performed an experimental investigation on evaporation heat transfer and pressure drop of R-134 through a vertical corrugated tube. With having varying corrugation pitches. The heat transfer and pressure drop between smooth and corrugated tube have been compared and result shows that in corrugated tube have higher heat transfer coefficient and frictional pressure drop than smooth tube. They also concluded that as the corrugation pitch decreases, heat transfer coefficient and frictional pressure drop increases.

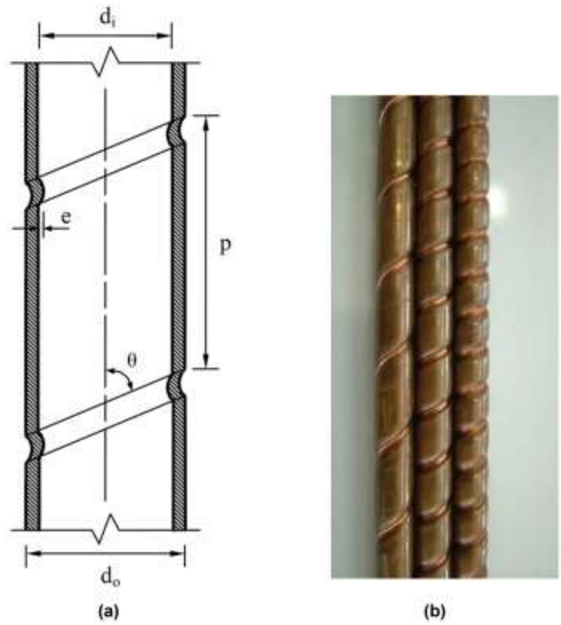

Figure 3: Corrugated tube: (a) sketch and (b) actual photograph. (color figure available online) [3]

Zhenping et al. 2017 examined the heat transfer and flow characteristics of half-corrugated microchannels. They compare the thermal performance and pressure drop between flat-bottom copper and half-corrugated microchannels. They found that the half-corrugated microchannels have superior thermal-hydraulic performance.

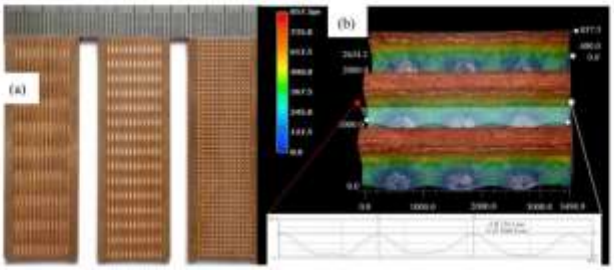

Figure 4: Morphologies of different microchannels: (a) appearance of half-corrugated microchannels with different wave length;(b) surface profile of microchannel of MCH-31 [4]

Zhang and Che [5] numerically examined the thermal hydraulic performance of corrugation shape influence of corrugated plates. The governing equations and have been solved by using finite volume method and Lam-Bremhorst low Reynolds number turbulence model has been considered. A CFD analysis was carried out by using commercial software such as GAMBIT/FLUENT. It was observed that for sharp corrugations pressure drop and heat transfer coefficient was higher as compared to the smooth corrugations. They also conclude that the average Nusselt numbers and friction factor were about 1–4 times superior for the trapezoidal corrugated channel as compared to the elliptic corrugated channel.

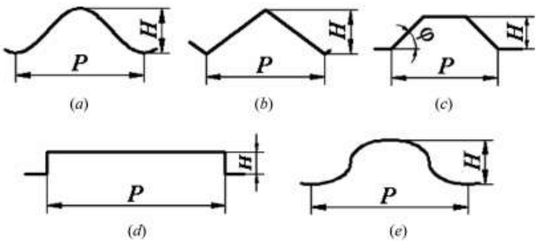

Figure 5: Corrugation profiles. (a) Sinusoidal curve, (b) triangular curve, (c) trapezoidal curve, (d) rectangular curve, and (e) elliptic curve. [5]

Islamoglu et al.2008 experimentally examined the airflow within a corrugated channel with sharp and rounded corrugations where the convective heat transfer performance characteristics have been analyzed. At Reynolds number2000–5000, the height of channel was 5 mm, the corrugation angle was 30° the flow characteristics have been studied. They revealed that the performance of rounded corrugation is 100% superior than the sharp corrugation of corrugated channel. The flow characteristics and heat transfer of air flow in corrugated channels under constant surface.

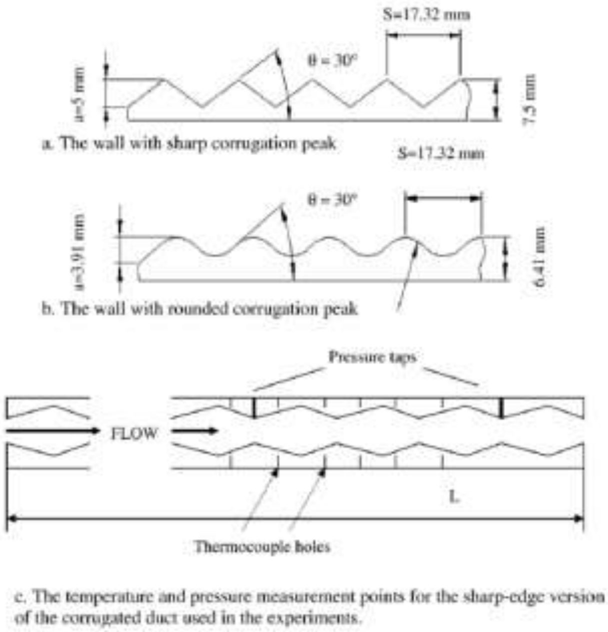

Figure 6: The converging–diverging channel with the representative parameters. [6]

Naphon et al. 2008 studied numerically and experimentally the heat transfer and fluid flow in the V-corrugated channel. The heat flux and Reynolds numbers were in the ranges of 0.5–1.2 kW/m2 and 400– 1600 respectively. The convection terms of governing equations were considered by upwind scheme and the SIMPLEC algorithm was used for coupling the velocity and pressure. The numerical simulation was implemented using commercial software NASTRAN/CFD. Results showed that the numerical simulation has agreed with the experimental measurement. It was found that the corrugated channel had significant influence on the heat transfer augmentation and the pressure drop penalty.

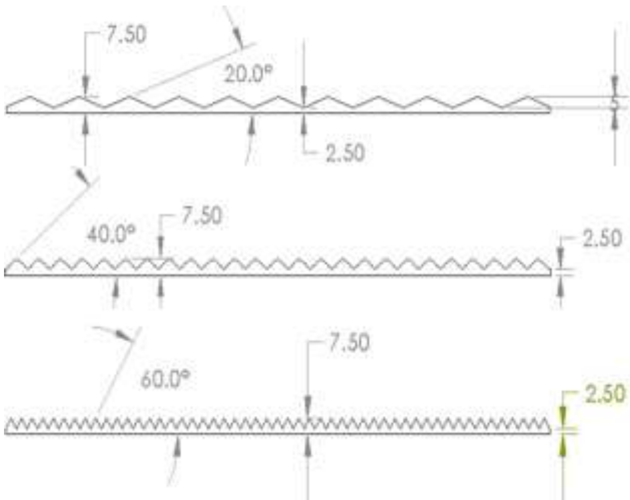

Figure 7: Schematic diagram of the corrugated plate. [7]

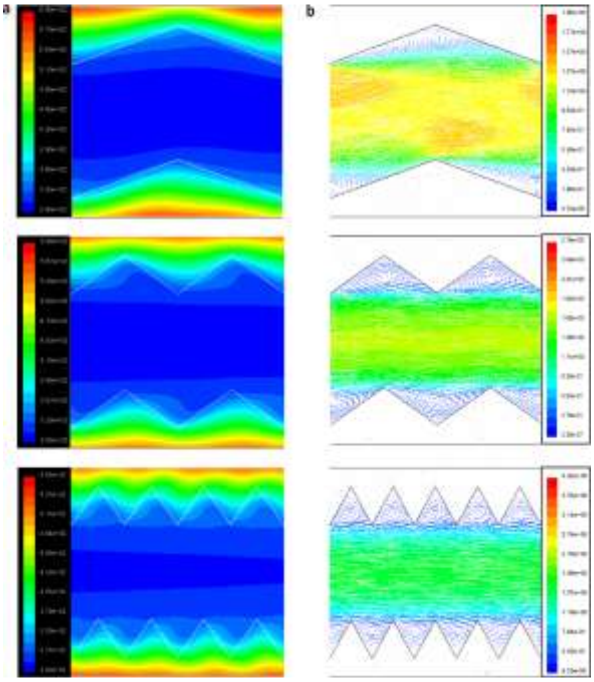

Figure 8: Variation of (a) temperature contour, (b) velocity vector for different channel heights at the same Re (918), wavy angle = 40^0, q = 0.83 kW/m^2 [7]

Metwally and Manglik 2004 performed numerically on the laminar convection in a sinusoidal corrugated channel with a constant temperature walls. The governing equations for mass, momentum and energy have been solved by the finite difference approach over a nonorthogonal grid. The results indicated that the transverse vortices became more severe as the aspect ratio increased with a particular Reynolds number. Likewise, the mixing fluid was produced with the vortices enhancing significantly the rate of heat transfer that was dependent on the channel corrugation aspect ratios, Reynolds number and Prandtl number. It was noticed that the area goodness factor for the sinusoidal channel was up to 5.5 times of the straight channel.

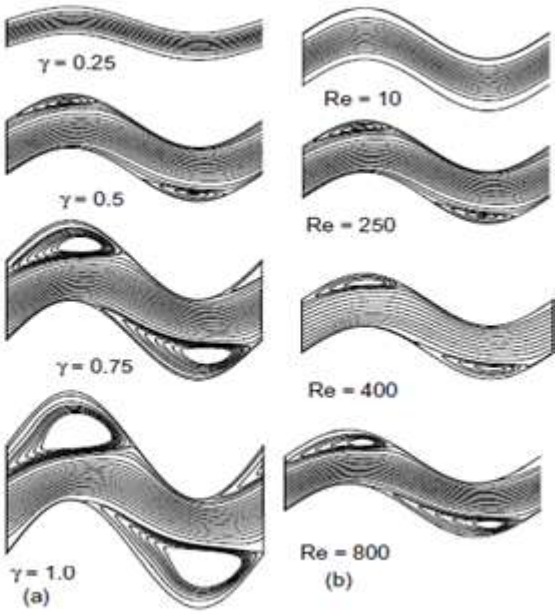

Figure 9: Streamline distributions in steady laminar flows in sinusoidal corrugated-plate channels [8]

Rush et al. 1999 experimentally performed the heat transfer and flow characteristics under sinusoidal wavy laminar flows through channel. Water tunnel was used to study the flow field using visualization methods while wind tunnel has been used to conduct heat transfer experiments in the range of Reynolds number 100 to 1000. It was observed that the geometry of the channel and Reynolds number have effected directly the location of the mixing onset. The heat transfer has been significantly increased by the onset of macroscopic mixing.

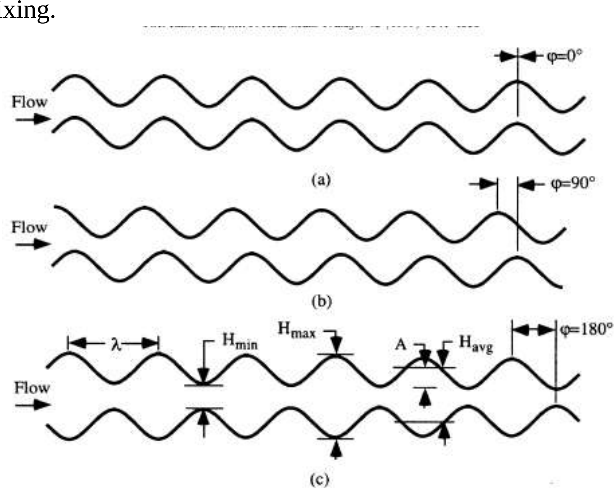

Figure 10: Schematic of wavy passage configurations and the definition of important geometric parameters "depth of channel is L"

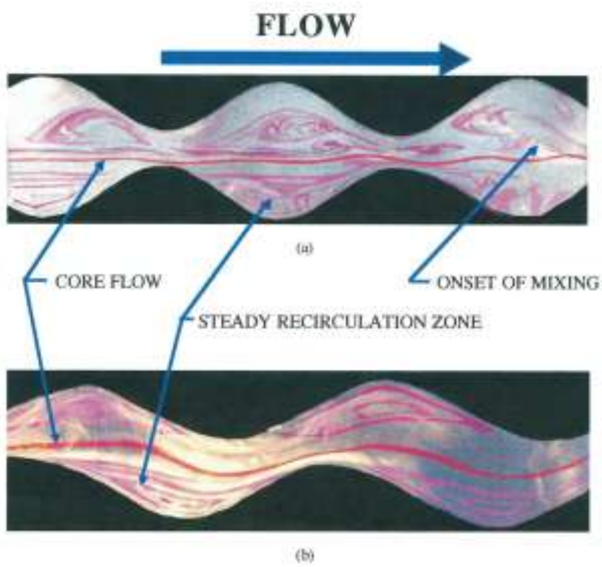

Figure 11: Typical images from the flow visualization study

Wang and Chen 2002 investigated theoretically the heat transfer through a sinusoidal-wavy channel under the range of Reynolds number 100 to 700. The governing equations have converted the Cartesian coordinate to curvilinear coordinate by employing a simple coordinating transformation. Additionally, there was a slight heat transfer augmentation at smaller value of amplitude-wavelength ratio, while at larger value of amplitude-wavelength ratio. A significant enhancement in the heat transfer for higher Reynolds numbers was observed.

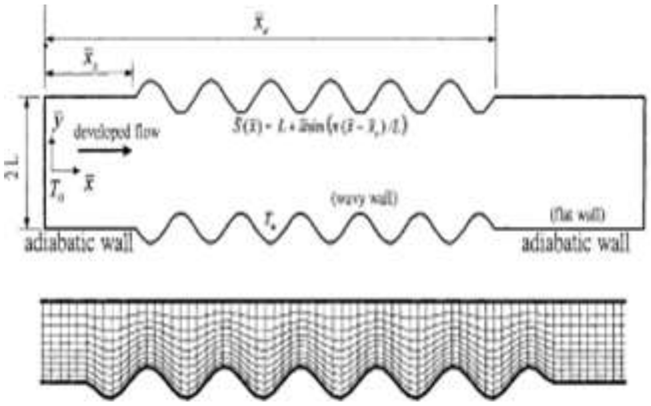

Figure 13: Physical model, coordinates and grid system [9]

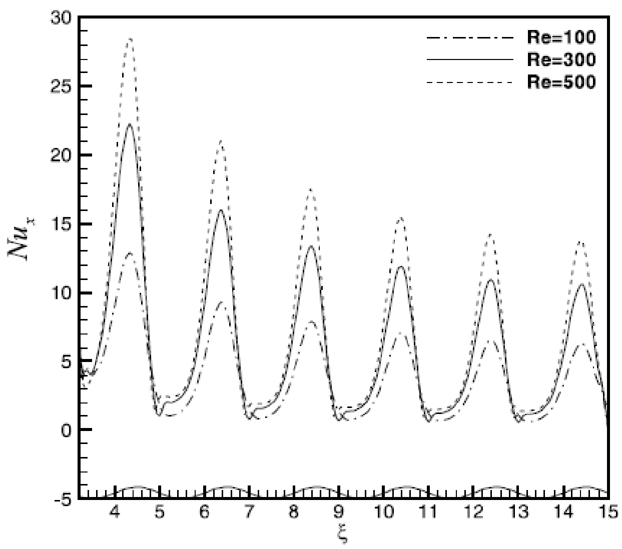

Figure 14: Distribution of local Nusselt number for a = 0:2 and Pr= 6:93. [10]

4. Conclusion

- The frictional pressure drop increases with increasing vapor quality, while it decreases significantly as the evaporating temperature increases. The two-phase friction factor decreases with increasing equivalent Reynolds number. The frictional pressure drops for the corrugated tube is higher than that for the smooth tube. In addition, the higher frictional pressure drop is obtained from the tube with lower corrugation pitch.
- The heat transfer coefficient tends to increase with increasing average vapor quality and mass flux. The heat transfer coefficient obtained from the corrugated tube is higher than that from the smooth tube. Moreover, the heat transfer coefficient increases with the decrease of corrugation pitch.
- A significant enhancement in the heat transfer for higher Reynolds numbers was observed.
- The average heat transfer coefficient and pressure drop increase with increasing mass flux as well as average quality.
- The corrugation pitches have a significant effect on the heat transfer coefficient and pressure drop augmentations.
- The heat transfer has been significantly increased by the onset of macroscopic mixing.

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