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Research Paper

Investigation of flow characteristics and heat transfer enhancement of corrugated duct geometries

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HIGHLIGHTS

- Flow characteristics and thermal efficiency in corrugated ducts were studied.
- Experimental studies were conducted to identify hydrodynamic structures.
- Numerical data were validated experimentally using particle image velocimetry.
- Corrugated walls have substantial effect on the enhancement of heat transfer.

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ABSTRACT

The objective of this study was to determine the flow characteristics and thermal efficiency in various ducts geometries numerically and experimentally. The whole studies were conducted for Reynolds numbers in the range of $3 \times 10^3 \le \mathrm{Re} \le 6 \times 10^3$. Firstly, effects of the aspect ratio, *S/H* on flow structures and heat transfer enhancement were aimed to be examined. Therefore, the corrugated duct geometries were designed for three different aspect ratios such as *S/H = 0.1, 0.2, 0.3.* Thermal efficiency of these geometries were examined numerically in order to optimize the aspect ratio, *S/H*. By increasing the corrugation height, the rate of turbulence intensity on the axis of corrugated channel increases as expected. Heat transfer rate increases with the rise of the aspect ratio, *S/H* and shows a maximum value at *S/H = 0.3* that corresponds to the highest aspect ratio. The highest friction factor, *f* occurs in the corrugated channel with aspect ratio of *S/H = 0.3* and it is followed by *S/H = 0.2*, and *0.1*, respectively. Afterwards, experimental studies were conducted in order to identify hydrodynamic structures and verify findings of numerical solution using the Particle Image Velocimetry (PIV) technique. Velocity distributions, patterns of streamline and corresponding turbulent statistics were determined experimentally and numerically in order to reveal hydrodynamics characteristics and thermal performance of the corrugated channel flow.

1. Introduction

Energy crises experienced in the past and expected to be encountered in the near future have forced most countries to create energy management policies in order to use energy more efficiently. Because of these facts, researchers have started to focus on the optimization of energy systems. Fabbri [1] investigated the convective heat transfer in a channel composed of smooth and corrugated walls under laminar flow conditions. It was found that heat transfer rate of the optimized corrugated profile increases as a function of the Reynolds number, *Re* and Prandtl number, *Pr.* Moreover, Ali and Hanaoka [2] conducted experiments on the parameters operating with a forced convection of heat transfer for laminar flow of air in a channel having a V-corrugated upper plate heated by radiation. The local Nusselt number, *Nu* was directly proportional with the inclination angle, β. The mentioned Nusselt number, *Nu* was varied from 33% to 67.3% while the angle was comprised from 0° to 60°. Gradeck et al. [3] established their main purpose of experimental studies concerning the enhancement of heat transfer for flows with a single phase under the effect of laminar and turbulent forced convections. The results of the experiment revealed the fact that the heat transfer coefficient had a higher degree of sensibility on the top of the corrugation even if the highest disorder was observed at the bottom part of the undulation with its negligible effects.

The numerical work of Bahaidarah et al. [4] reported that enhancement of heat transfer increases with an increase of the

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Nomenclature

c_p	specific heat (J/kg K)
C_μ	turbulence model constant
D_h	hydraulic diameter, (=D), m
f	friction factor
h	heat transfer coefficient (W/m^2 K)
k	turbulent kinetic energy
k_f	thermal conductivity of fluid (W/m K)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
x	streamwise direction
y	transverse direction
u	velocity in x direction (m/s)
v	velocity in y direction (m/s)
U	free-stream velocity (m/s)
u'	streamwise velocity fluctuation
v'	transverse velocity fluctuation
$\langle u \rangle$	time-averaged velocity components in x direction
$\langle TKE \rangle$	time-averaged turbulent kinetic energy
u_{rms}	RMS value of the streamwise velocity fluctuations
v_{rms}	RMS value of the vertical velocity fluctuations
TI	turbulence intensity (%)
L	length of corrugated
S	width of corrugated
H	height of channel
l	inlet length of channel
o	outlet length of channel
C	cases

Greek symbols

φ	phase shift
Γ	thermal diffusivity (m^2/s)
ε	turbulent dissipation rate (m^2/s^3)
η	thermal performance (–)
μ	viscosity (kg/m s)
μ_t	eddy viscosity (kg/m s)
ρ	density (kg/m^3)
τ_{ij}	Reynolds stress, (m^2/s^2)

Subscripts

f	fluid
i	inlet
m	mean
c	channel
s	smooth
t	turbulent
w	water

Reynolds number, *Re* for both sinusoidal and arc-shaped channel configurations. Jaurker et al. [5] reported the rate of heat transfer and friction characteristics on a heated duct wall with a large aspect ratio, *S/H* and different fluid properties. Mohamed et al. [6] performed a numerical study to report the effects of the entrance region of a symmetric wavy-channel on the rate of heat transfer and physics of flow. It was concluded that augmentation of both the shear stress and the Nusselt number, *Nu* depend on the Reynolds number, *Re* and also the highest magnitude of Nusselt number, *Nu* which was acquired in the entrance region. Bilen et al. [7] studied heat transfer and friction characteristics of a fully developed turbulent air flow in a different grooved tubes (circular, trapezoidal and rectangular) and suggested that heat transfer enhancement was around 63% for a circular groove, 58% for the trapezoidal one and 47% for the rectangular duct at the highest Reynolds number, $Re = 38 \times 10^3$. Zhang and Che [8] analyzed the effect of corrugated plates and their flow features numerically. It was proven that the thermal and hydraulic performances were influenced by the corrugated channel profile. Mohammed et al. [9] studied the characteristics of a 2D corrugated channel to carry out for different values of Nusselt numbers, *Nu* as a function of wavy channel angle, φ, and height, *H*. On one hand, the rate of pressure drop increases with raising the angle, φ of the wavy channel. On the other hand, the rate of pressure drop decreases with respect to the channel height, *H*. Wang et al. [10] conducted experiments on a channel flow with periodic ribs placed on one wall having the Reynolds number as 22×10^3 based on the channel height, *H*. It was found that the maximum shear stress occurs at the leading edge of the rib. Sheremet and Miroshnichenko [11] used Boussinesq approach to predict transient natural convection in a differentially heated wavy-walled cavities under the effects of surface radiation. For concave undulations, the average Nusselt number, *Nu* is directly proportional with the Rayleigh number, *Ra* surface emissivity, $\acute{\varepsilon}$ and shape parameter. For convex undulations, the average Nusselt number, *Nu* is inversely proportional to the shape parameter and undulations number. Ahmed et al. [12] numerically investigated laminar forced convection heat transfer in the trapezoidal channel to reveal the differences between copper –water nanofluid and conventional fluids. The average Nusselt number, *Nu* increases with upgrading the Reynolds number, *Re* and nanoparticle volume fraction while pressure drop increases. Also, they found out that the average Nusselt number, *Nu* decreases when the wavelength of the corrugated channel increases. Their results reveal that copper-water nanofluid can be used to enhance the heat transfer in the trapezoidal – corrugated channels rather than the conventional fluids. Ghaddar and El-Hajj [13] studied the steady and time periodic fluid flows, and also heat transfer characteristics in a periodic two dimensional corrugated channels numerically. They concluded from their heat transfer results that the averaged Nusselt number, *Nu* increases with increasing the Reynolds number, *Re*. The corrugated channel provides to augment the heat transfer as much as 120% compared to a straight channel at the same Reynolds number, *R*e They, lastly, indicated an optimized geometric ratio, that is to say width, *W* to length, *L* ratio, *W/L* which is $W/L = 0.35$ which provides maximum rate of heat transfer. Ergin et al. [14–16], conducted a numerical study to scrutinize the turbulent flow characteristics in a corrugated duct carefully. In their results, they interpreted that a corrugated duct would provide a complex flow pattern and influence the fluid flow structures severely in the duct passage. In conclusion, their numerical results using the k–ε model and the wall functions are modestly agreed with the experimental studies. Sawyers et al. [17] combined the analytical and the numerical techniques to investigate effects of three dimensional hydrodynamics on heat transfer in a corrugated channel. They found that in three-dimensional case, mean flow in the transverse direction led to increase heat transfer due to fluid entrainment core and recirculating flows. In addition to these studies, O'Brian and Sparrow [18] reported a correlation of the average Nusselt number, *Nu* of the flow in the corrugated channels with sharp edged peaks. They proved that the friction factor, *f*