CHAPTER 5
EXPERIMENTAL RESULTS

5.1 Introduction

In this chapter, the experimental results for forced convection heat transfer in triangular corrugated-plate channels with corrugation aspect ratio of 0.5 (45^o corrugation angle) under constant heat flux boundary conditions are presented. Five different corrugated-plate channels with relative spacing ratios of 1, 1.5, 2, 2.5 and 3 are investigated. For this corrugation shape, the effects of mass flow rate represented by Reynolds number and channel inter-plate spacing represented by relative spacing ratio on the wall temperature distributions, air temperature profiles, local and average Nusselt number and isothermal fanning friction factor are investigated. The wall and air temperature distributions, Re-Nu and Re-f characteristics for flat duct under constant heat flux boundary conditions are also experimentally investigated to be considered as a reference geometry for the sake of comparison with the corrugated-plate channels performance.

5.2 Flat Duct Performance

5.2.1 Wall Temperature Distributions

The wall and air bulk temperature distribution for flat duct at Re = 500 under constant heat flux boundary conditions is illustrated in Fig. 5.1. It is observed from the Figure that the wall temperatures at a succession of points separated from each other by the same axial distance lie on a straight line in the thermally fully developed region which is parallel to the fluid bulk temperature line. The vertical displacement between the two lines yields the fully developed wall to bulk temperature difference.

The wall temperature distributions for flat duct under constant heat flux boundary conditions is illustrated in Fig. 5.2 at different Reynolds number.

As Re increase, the wall temperature was decreased and this is more observed in the thermally fully developed region. Increasing Reynolds number leads to a considerable increase in the fluid velocity and hence higher heat transfer rates which is expressed by decreasing the wall temperatures.

5.2.2 Air Temperature Profile

The air temperature profile normalized with respect to its mean value across the duct cross section for flat duct under constant heat flux boundary conditions is illustrated in Fig. 5.3. The thermocouples used for measuring the air temperature profile are located at a distance equal to 0.75 of the duct length from the inlet to ensure that the flow is in the thermally fully developed region. The air temperature profile for flat duct was symmetry around the duct center line, and the point of lowest temperature lying on the duct center line (Y/S=0.5). Also, the temperature profile shows very lower uniformity, as the extreme points of lowest and highest temperature equal to 0.76 and 1.27 from the average value which represent very high deviations.

5.2.3 Average Nusselt number and Isothermal Fanning Friction Factor

The Re-Nu and Re-f relationship for flat duct is illustrated in Fig. 5.4. Lower values of Nusselt number was obtained in the Reynolds number ranged from 100 to 1000 and these values is nearly constant and is lightly dependent of the Reynolds number. The Re-f relationship for flat duct shows an inverse correlation. Although the pressure drop per unit length increase with Re, the isothermal fanning friction factor decrease as Re increase due to the inverse relationship between the friction factor and the velocity square which has the dominant effect on the friction factor rather than the pressure drop.

5.3 Corrugated-Plate Channels Performance

5.3.1 Reynolds number Effect

5.3.1.1 Wall temperature distributions

The wall temperature distributions along with the air bulk temperature lines are depicted for Reynolds number having values of 100, 300, 500, 700 and 1000 as shown in Fig. 5.5(a), 5.5 (b), 5.5 (c), 5.5 (d) and 5.5 (e) respectively for triangular corrugated-plate channels with fixed corrugation aspect ratio, $\gamma = 0.5$, and fixed relative spacing ratio ($\varepsilon = 2$). The thermocouples were fixed on the center of the upward and downward facing facet of each pitch of the lower wall to measure the average wall temperature for each pitch while the air temperature was measured at inlet and outlet of the test section. In the thermally fully developed region the points of the same phase which is separated from each other by the same axial distance that is equal to the corrugation pitch lie on a straight line. The curve that fitting the upward and downward wall temperature points become parallel to the air temperature line in the thermally fully developed region and the displacement between the two parallel lines yields the fully developed wall to bulk temperature difference. It is shown from Fig. 5.5 that the displacement between the wall and air temperature lines which represent the fully developed wall to bulk temperature difference decrease as Re increase. This leads to an increase in the heat transfer coefficient and hence the Nusselt number with increasing Re as discussed later.

Fig. 5.6 display the effect of flow Reynolds number on the wall temperature distributions in triangular corrugated-plate channels at γ = 0. 5, and ε = 2.

As Re increase, the average wall temperature decreases as a result of increasing the heat transfer rate with the air velocity.

5.3.1.2 Air temperature profiles

The air temperature profiles across the corrugated-plate channel cross section is illustrated in Fig. 5.7. at X/P having a value of 0.25, which represents the peak-and-valley plane along with that for flat duct. For fixed channel inter-plate spacing, the normalized temperature profiles with respect to its mean value are illustrated for Re = 100, 300, 500, 700 and 1000 at ε = 1 as shown in Fig. 5.7(a), and at ε = 2 as shown in Fig 5.7(b). As mentioned previously for flat duct, the temperature profile shows very lower uniformity, as the extreme points of lowest and highest temperature equal to 0.76 and 1.27 from the average value which represent very higher deviations. These higher deviations were damped for corrugated passage, where the temperature profile is found to be more uniformity with increasing Re. This is observed from the reduction of the temperature profile deviation around its average value with increasing Re. For triangular passage with relative spacing ratio of 1, the lowest point having values of 0.92, 0.95, 0.99, 1.05, 1.1 for Re = 100, 300, 500, 700 and 1000 respectively. While for relative spacing ratio of 2, the corresponding values are equal to 0.85, 0.88, 0.92, 0.96, 1.04 for, Re = 100, 300, 500, 700 and 1000 respectively. These values represent a considerable uniformity from the flat duct value (0.76). This is due to the mixing effect which occurs by the fluid recirculation in the in the troughs of corrugated-plate channels (discussed in detail in chapter 6). This mixing effect makes the thermal boundary layer more thinner. So the convection heat transfer rate is increased.

While for flat duct, the temperature profile was symmetry around the duct center line, and the lowest temperature point lying on the duct center line (Y/S=0.5), this similarity decrease for corrugated-plate channel as the temperature profile gets shifted towards the wall exposed to flow acceleration (The wall side opposite to that exposed to flow recirculation) with increasing Re and higher temperature gradients near the walls are observed. The peak point positions (Y/S) for corrugated-plate channels ranged from 0.25 to 0.37 which represent a considerable deviation toward the inner wall from the flat duct value (0.5)

5.3.1.3 Local Nusselt number

Nine thermocouples are fixed at different equally-spaced locations of one corrugation pitch to measure the local temperature distribution in order to evaluate the local Nusselt number distribution of that pitch. As result the effects of Re on the local Nusselt number distribution in triangular corrugated-plate channel is shown in Fig. 5.8. where the local Nusselt number distributions at Re = 100, 300, 500, 700 and 1000 are displayed for a fixed relative spacing ratio (ε = 2), and a fixed corrugation aspect ratio (γ = 0.5) along with the Re-Nu relationship for flat duct. At low Re there is a small variation of the local Nu over the pitch and the profile is similar to the flat duct profile (constant value), and the flow is unaffected by the wall corrugation. As Re increases, the variation of the local Nu increased and varied according to the onset and growth of the lateral vortex. Higher values of Nu is obtained at the part of the wall exposed to flow acceleration and these values are increased with Re. Increasing Re causes a considerable increase in the velocities and hence in the wall velocity gradient as a result of increasing Re in a passage with constant hydraulic diameter and constant fluid properties. So an increase in the heat transfer rate occurres. Also increasing Re cause higher values of Nusselt number due to the growth of the lateral vortex with Re in the recirculation zone which promote flow mixing, so the boundary layer thickness become more thinner, also the growth of the lateral vortex in the recirculation zone is accomplished by the smaller cross flow area in the acceleration zone (the side opposite to acceleration zone), and hence higher wall velocity gradient is occurred in the acceleration zone which increase the heat transfer rate. At higher Re very higher fluctuation of the local Nu profile and higher peaks value are observed. The profile shows a very high peak at X/P=0.25 which occur due to the sudden impact of air flow to the sharp edged corner of the triangular corrugated-plate channel which cause a sudden increase in the wall velocity gradient

5.3.2 Channel Inter-Plate Spacing Effect

5.3.2.1 Wall temperature distributions

The wall temperature distributions along with the air bulk temperature lines are depicted for relative spacing ratios having values of 1, 1.5, 2, 2.5 and 3 as shown in Fig. 5.9(a), 5.9 (b), 5.9 (c), 5.9 (d) and 5.9 (e) respectively with fixed corrugation aspect ratio, $\gamma = 0.5$, and fixed Reynolds number, Re = 500,. It is shown from Fig. 5.9 that the displacements between the wall and air temperature lines which represent the fully developed wall to bulk temperature difference increase with ε. This leads to a reduction in the heat transfer rate as ε increase as discussed later.

Fig. 5.10 displayed the effect of relative spacing ratio on the wall temperature distributions in triangular corrugated-plate channels at $\gamma = 0.5$, and Re = 500. As ε increase, the average wall temperature increases as a result of decreasing the heat transfer rate with increasing ε. This is due to the considerable reduction in the air velocity and hence in the wall velocity gradient with increasing ε as a result of increasing ε in a passage with constant Reynolds number and constant fluid properties.

5.3.2.2 Local Nusselt number

The effects of variations in the channel inter-plate spacing represented by relative spacing ratio on the local Nusselt number distribution is shown in Fig. 5.11 where the local Nusselt number distributions at ε = 1, 1.5, 2, 2.5 and 3 are displayed at a fixed Re (Re=300), and at a fixed corrugation aspect ratio (γ=0.5). High values of Nusselt number was obtained at narrow channel (ε=1). As the channel inter-plate spacing increases, the local Nusselt number decreases, this is due to the reduction in the velocities and hence the wall velocity gradients with increasing inter-plate spacing. These lower velocity gradients cause an increase in the thermal boundary layer thickness. So, lower Nusselt number is reached. The peak of the local Nusselt number profile is reached at X/P = 0.25 due to the sudden impact of the air flow to the sharp edged corner of the triangular passage which cause a sudden increase in the wall velocity gradient

5.3.2.3 Average Nusselt number

The variation of the average Nusselt number with Reynolds number for different relative spacing ratios (1, 1.5, 2, 2.5 and 3) is presented in Fig. 5.12 compared with the Re-Nu relationship for flat duct. Average Nusselt number in the corrugated channels is enhanced several folds, depending upon the values of Re and ε at any given γ. The increased Nusselt number with Re is predominantly due to the transverse vortices induced in the troughs of the plate surface corrugations which promote flow mixing resulting in more uniform core region temperature profiles, and much sharper wall temperature gradients with thinner boundary layer thickness. So, the convection heat transfer rate is increased. Also, due to the increase in the effective flow length or surface area of the corrugated plate-channels over the flat duct, an increase in the convection heat transfer rate for corrugated channel is occurred. As the channel inter-plate spacing increases, the velocity gradient decreases as discussed previously. This reduction in the velocity gradient cause an increase in the thickness of the thermal boundary layer, and the wall temperature gradients is less sharper and the core flow becomes less uniform, so, the Nusselt number decreases with increasing ε.

5.3.2.4 Isothermal fanning friction factor

The variation of the isothermal fanning friction factor with Re and relative spacing ratio are presented in Fig.5.13. Results for channels with ε = 1, 1.5, 2, 2.5 and 3 are presented, along with the Re-f relationship for flat duct. The increasing of the friction factor of the corrugated plate-channels over the flat duct is clearly evident. The increased friction factor is predominantly due to the onset and growth of the lateral vortices in the channel troughs that enhance fluid momentum transfer thereby increasing the wall shear stress, also, due to the increase in the effective flow length or surface area of the corrugated plate-channels over the flat duct.

As mentioned previously, at narrow channel (ε = 1) higher values of velocity gradient occurred, and hence higher shear stress and friction factor values are observed. As the channel relative spacing ratio increases, the shear stress decreases, as a result of decreasing the velocity gradient with increasing channel inter-plate spacing. Therefore, lower values of pressure gradient and friction factor are observed.