Effect of vortex generator on the air-side thermal-hydraulic performance of flat tube heat exchangers

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Abstract— In the current work, the thermal-hydraulic performance of fin and flat tube heat exchangers with and without the addition of vortex generators are experimentally investigated in a relatively low Reynolds number flow. For the experimental data collection, the existing wind tunnel available at the Faculty of Mechanical Engineering (FKM) is used. However, the fins are modified by attaching triangular vortex generators of 9 mm x 9 mm size oriented at 45^{o} to the incoming air flow direction. The fan speed is controlled so that the air flows over the fin-and-tube banks at five different air velocities (1.8 m/s, 2.3 m/s, 2.8 m/s, 3.3 m/s and 3.8 m/s) for both inline and staggered tube configurations. The obtained results show that the temperature distribution increased by a maximum of 26.9% for staggered arrangement when the vortex generator is added compared to that obtained without vortex generator. Moreover, the average heat transfer coefficient of the staggered arrangement with vortex generator is up to 46% higher than the case without vortex generator while the pressure drop for an inline arrangement with vortex generator increased up to 35% compared to the inline arrangement without vortex generator. In general, it is observed from the experimental results that the fin-and-flat tube banks with vortex generator have similar heat transfer performance and pressure drop for both arrangements. Hence, the results obtained from this study can provide information for further investigation of flat tube heat exchangers for industrial applications.

Keywords— flat tube; heat transfer enhancement; vortex generators; pressure drop

1. INTRODUCTION

Fin-and-tube heat exchangers (HEs) are widely used in many industrial applications such as heating ventilation and air conditioning applications (HVAC), petrochemical, automotive, power plant, etc. Since the energy consumption of these applications is very large, the challenge that facing the designer is to reduce the energy consumption by improving the equipment. Thus, an extra effort must be concentrated to improve the thermal hydraulic performance of the compact HEs to meet the target of enhancing the heat transfer rate. Generally, the dominant thermal resistance is commonly occurred on the air side instead of the tube side of the HE [1]. Therefore, fins are employed on the air side of the HEs in order to augment the heat transfer rate. In fact, the extended surfaces (fins) have many shapes, it can be in the continuous form (e.g. plate [2] , plain [3]) or interrupted form like (wavy [4] , louvered [5] , slit [6] , etc.). Wang [7] has reviewed the recent patterns of enhanced surfaces that promote the thermal performance of fin and tube HEs. He revealed that 90% of the surfaces that produced enhanced thermal performance were interrupted fin surfaces. However, these types of fins enhance the heat transfer but the enhancement is accompanied by a considerable pressure drop.

In recent years, a new design of fin known as vortex generator (VG) has been introduced by researchers. This type of fin is an impressive method to augment the heat transfer and pressure drop characteristics of the compact fin and tube HEs. vortex generators can be mounted or punched on the fins surface [8], and can be classified according to the direction of the axes of the vortices in comparison to the main flow direction. So, when the vortices axes are parallel to the main flow direction it called longitudinal vortices and when the vortices axes are perpendicular to the main flow direction it called transverse vortices [9] . Longitudinal vortices performance is better than transverse vortices since it can generate three mechanisms of passive heat transfer enhancement such as increasing the boundary layers, spinning and the flow instability. Although, punched vortex generators can disturb the thermal boundary layer development it also can generate longitudinal vortices to increase the heat transfer near the wall and far away from the wall [10]. Interestingly, compared to the interrupted enhanced surfaces, VGs have the ability to enhance the thermal hydraulic performance with a negligible increase of the pressure drop.

This is due to the fact that, VGs provide a secondary flow (swirling motion) in which the extra transverse velocity component do not contribute directly to the increase of pressure drop as that of longitudinal velocity component. As a result, the heat transfer performance is achievable with a moderate pressure drop penalty [11].

Many researchers have conducted a comprehensive review of VGs heat transfer performance in compact HEs [11, 12]. More recently H. Ahmed et al. [13] have summed up all the recent development of experimental and numerical works related to the VGs. In general, from the open literature, the thermal-hydraulic performance of various VGs with fin and tube heat exchanger has been investigated experimentally by [3, 14-18] and numerically by [1, 19-23]. The use of punched longitudinal vortex generators with wavy fin and flat tube result in a considerable increase in heat transfer between the heated wall and the upcoming cooled air. However, they also increase the pressure drop but the increment is not significant [22]. In 2015, Zdanski et al. [16] have conducted several experiments in order to address the effect of delta winglet vortex generators (DWVGs) on the thermal performance of in-line tube banks. The results showed an increase up to 30% in Nu number and up to 40% in friction factor. In a separate study by Lin et al. [10], the impact of a new fin pattern having curved delta winglet vortex generators (CDWVGs) on the heat transfer and friction characteristics of round tube with a staggered arrangement. They reported that a significant increase in heat transfer was achieved similar to the aforementioned researchers. This is because of the generation of secondary flow behind the tube which reduces the size of wake region and thus, enhances the heat transfer. Similarly, Wang et al. [24] proposed a novel LVGs, which contain adjusted rectangular wing and trapezoidal wings which are known as novel combined winglet pairs (NCWPs). In comparison with the HEs without LVGs, the heat transfer enhanced by 1.8-24.2% for the HEs with NCWPs with a moderate friction factor increment of 1.3-29.1%. Therefore, they recommended that NCWPs should be implemented in thermal applications instead of LVGs in order to achieve higher heat transfer coefficient. More recently, using SIMPLEXQ method Salviano et al. [25] have performed an optimization for several interacting factors of LVGs such as LVGs locations (stream-wise and span-wise), angles of attack and the shape as well in order to get an ideal arrangement of the VGs. The results showed that the optimized arrangement produced the higher heat transfer augmentation than previously published works. Moreover, they found that RWVGs are more appropriate to maximize the thermal performance and the optimal ratio between the height of VGs and fin pitch is found to be 0.6, not 0.5 as mentioned by the previous researcher. Lastly, they illustrated that higher heat transfer enhancement can be achieved for staggered tube arrangement when using VGs in common flow up instead of common flow down and the location of VGs should be adjacent to the minimum flow area in the stream-wise direction.

Most of the published research works are related to fin-and-tube heat exchangers with circular tubes and plain fins with simple and traditional winglet VGs such as delta winglets. Very few investigations have been reported in the open literature to evaluate the functioning of VGs for enhancement of the thermo-hydraulic performance of wavy fin-and-tube HEs. Indeed, most of the published experimental and numerical works are focused on the impact of the simple and traditional sorts of VGs on the performance of fin and round tube HEs. Moreover, the influence of the VGs on the thermal and fluid characteristics of the fin and flat tube HEs has received less attention compared with the circular tube, although of the fact that the flat tube performs better than the round tube in terms of heat transfer and pressure drop. To the best of authors' knowledge, the effect of the mixed delta winglet vortex generators (flow-up and flow-down) on the heat transfer and pressure drop characteristics of the fin and flat tube HEs is not fully examined yet. Therefore, the main purpose of this work is to experimentally investigate the influence of mixed DWVGs on the air side heat transfer and pressure drop characteristics of fin and flat tube HEs. The impact of tube alignment and Reynolds number will also be examined.

2. Experimental Setup

The heat transfer and pressure drop experiments were performed in an open wind tunnel. A schematic diagram of the experimental setup is presented in Fig. 1. The system consists of inlet section, a flow straightener, a test section, fin and tube HEs with and without vortex generators, and measuring devices for air velocity, air temperature and air pressure difference, temperature controller, a suction fan, and frequency inverter. The system was designed to suck the atmospheric air and let it flow over the fin-and-tube HE, while the tube is heated using the electrical heating rod. The wind tunnel is a square duct of 26 cm x 26 cm in cross section and 230 cm in overall length. Through a flow straightener, air flows 100 cm in straight duct before reaching the test unit. The wind tunnel walls are perforated with a two hole of 10 cm before and after the test section in order to measure the upstream and downstream pressures of the moving air. Moreover, the tunnel wall has another hole before the test section to allow measurement of the air velocity. Then, the air leaves the extension section and flows through the fin-and-tube HEs and then to the suction fan where it is discharged to the surrounding. Furthermore, the whole duct system is supported by stands of steel in order to avoid noise and vibration during the operation; hence the wind tunnel is elevated 50 cm above the floor level.

Axial fan model EPM provided the power for the wind tunnel, the fan driven by a 50 W AC motor. The fan speed could be varied using the frequency inverter on an ongoing basis from 1.8 to 3.8 m/s. Therefore, it was possible to alter the air velocity in the permissible range. Digital CENTER 330 ANEMOMETER was used to display the air velocity. REX C-100 temperature controllers were used to control the surface temperature of the flat tubes after being heated up by the heating roads. Each temperature controller has a K-type thermocouple in order to measure the temperature of the tube wall temperature. The fins were manufactured using CNC machine in order to obtain very precise dimensions of the fin holes, where the aluminum flat tube will be inserted. Then, the whole system was assembled to run the experiments and collect the data. The air velocity and temperature measurement were obtained by using digital 330 anemometer. The extendable stick of the probe has a sensing tip in the form of a small fan. The sensor is capable of measuring the air temperature as well. The air temperature was recorded before the test section using a digital anemometer. Moreover, the air temperatures before and after the test section were recorded at eight different locations (see Fig. 2) using T-type thermocouples. All of the thermocouples were calibrated before conducting the experiments by placing the thermocouples in a variable temperature path while the temperature was measured by a very precise digital thermometer. The thermocouples were placed with a great care inside the test section and their positions were fixed by using high-temperature resistant plaster. The air pressure at the inlet and the outlet of the test section were measured using the digital differential pressure manometer of model TESTO 510.

The entire signal data collected from the thermocouples was connected to Data acquisition system (NI 9219). Then the data is transmitted from the data acquisition device to the host computer for further operation through USB cable. Fig. 3 shows the fins with vortex generators layout that was examined in this experiment. The geometrical parameters of both inline and staggered configurations are listed in Table 2. As shown in figure [4] the air temperature at the inlet of the test section between the tube and the outlet of the test section were measured at different locations.

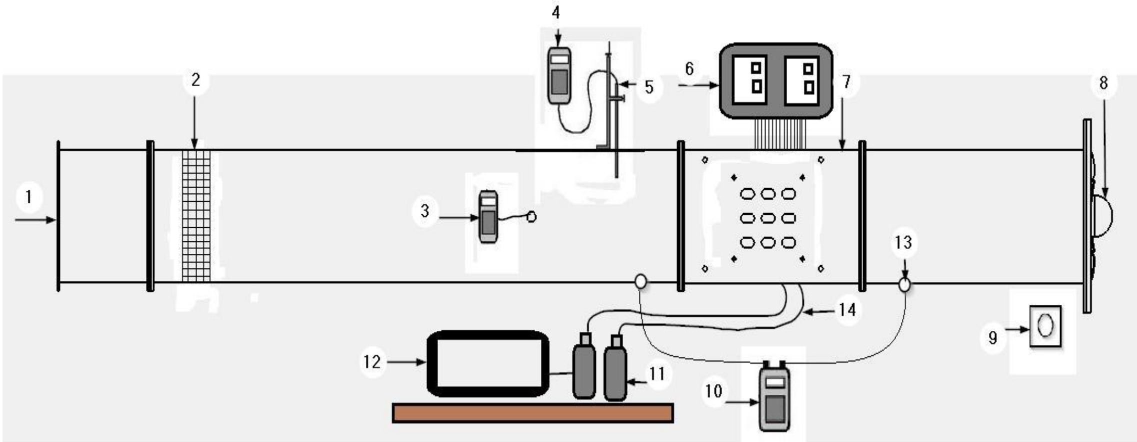

Figure 1: schematic diagram of the experimental setup; 1-inlet, 2-flow straightener, 3- Anemometer, 4- thermometer (testo 110) ,5- Air probe, 6- Temperature controllers, 7- test section, 8- suction fan, 9- frequency inverter, 10- Digital manometer, 11-NI 9219, 12-computer, 13- static pressure tip, 14- thermocouples type T

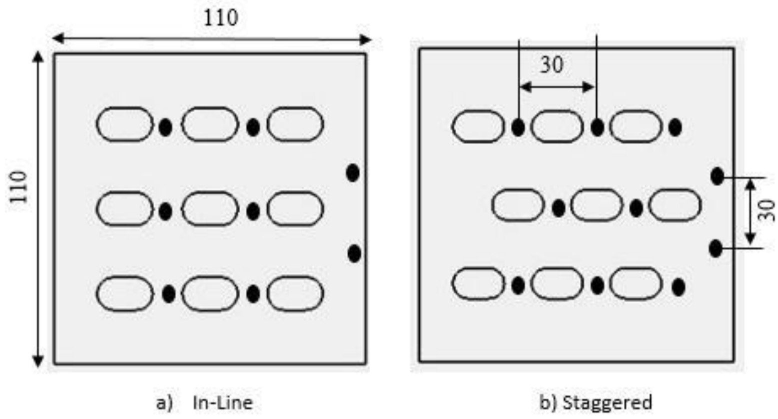

Figure 2: Locations of temperature sensors for (a) in-line, b) staggered arrangements

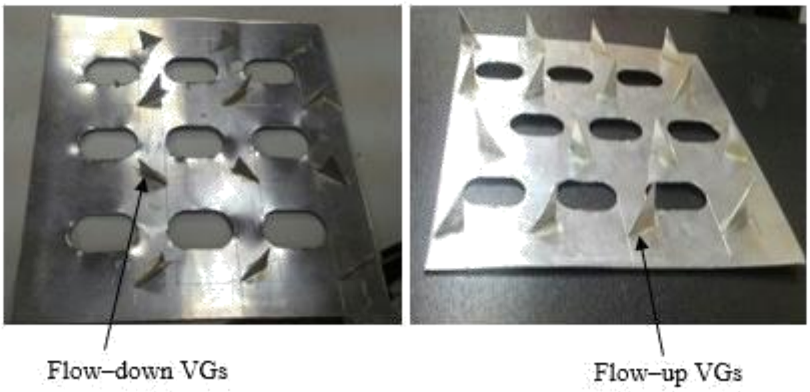

Figure 3: picture of the fins with flow-up and flow down Delta winglet vortex generators

Table 1: Geometrical details of fin and flat tube heat exchangers.

Geometric Parameter	Symbol	Dimension
Fin thickness	t	0.6 mm
Fin pitch	Fp	17.5 mm
Fin collar high outside diameter	Dho	11.60 mm
Fin collar wide outside diameter	Dwo	19.50 mm
Fin collar high inner diameter	Dhi	9.39 mm
Fin collar wide inner diameter	Dwi	17.88 mm
Transverse tube spacing – (Inline & Staggered)	PT	30 mm
Longitudinal tube spacing - (Inline & Staggered)	PL	30 mm
Tube wall thickness	δ	1 mm
Number of tube rows - (Inline & Staggered)		3

3. Parameter Definitions

In compact HEs, the air flow conditions and the geometry limitations are among the factor that affects the performance of the HEs. The behavior of the air flow is determined by Reynolds number which can be defined as:

$$Re = \frac{u_{max}\, D_h}{-} \tag{1}$$

Here u_{max} denotes the maximum velocity at the minimum flow area, D_h the hydraulic diameter of the tube. In this experiments, the heat transfer by conduction between the wind tunnel and the workshop surrounding was neglected and the heat transfer by radiation from the tube surfaces to the surrounding was further neglected. Thus, the total heat transfer was determined using the following equation:

$$q = \dot{m} c_p (T_{out} - T_{in}) \tag{2}$$

Where $\dot{m}$ is the air mass flow rate, c_p is the specific heat at constant pressure, T_{in} is the inlet air temperature and T_{out} is the outlet air temperature. The forced convection heat transfer coefficient can be obtained using the following equation:

$$h = \frac{q}{A_T \Delta T_{LM}} \tag{3}$$

Where A_T is the total heat transfer surface area = $(A_f + A_t)$ and ΔT_{LM} denotes the logarithmic mean temperature difference defined as follows

$$\Delta T_{LM} = \frac{(T_W - T_{in}) - (T_W - T_{out})}{\ln \frac{(T_W - T_{in})}{(T_W - T_{out})}} \quad (4)$$

The average Nusselt number was obtained as followed:

$$\overline{Nu} = \frac{\bar{h}\, D_h}{k} \quad (5)$$

Heat transfer and pressure drop were represented using Colburn j and friction f factors which are defined by the following equations:

$$j = \frac{h}{\_u_{max}\, c_p} . Pr^{2/3} \quad (6)$$

$$f = \frac{D}{L} \frac{2\Delta P}{\rho\, u_{max}{}^2} \quad (7)$$

4. Results and Discussion

This section presents the experimental values of the temperature distribution at different locations, the convective heat transfer coefficient as well as the friction factor of the flat tube with plain fin and with DWVGs. The experiments were carried out using the flat tube with two different tube arrangements (In-line and Staggered) in the range of Reynolds number between 3400 and 7250.The acquired results for the flat tube without the vortex generators for both configurations were used as a reference to estimate the performance enhancement while mounting the DWVGs on the plain fins.

A. Effect of Reynolds Number on the air side temperature

As expected, the temperature values increased from the inlet of the tube banks towards the outlet for both inline and staggered arrangements at all Reynolds number. The reason behind this temperature increment is due to the fact that the air before the first rows of tubes was close to the room temperature, hence, the air gains energy as it flows over the first row of tubes. When the air passes over the second rows of tubes, it gains energy making its temperature increase further. Finally, the third rows of tubes supply energy to the air, hence the air temperature become higher than the previous position. The outlet temperature distribution across the flat tube compact heat exchanger at various Reynolds number for inline and staggered arrangements with and without vortex generators are presented in Fig. 4. For all cases, as the Reynolds number increases the temperature decreases for all configurations. This is due to the fact that as the velocity increases (at high Reynold number), the air may not have enough time to absorb enough energy, hence the temperature decreases compared to that obtained at low Reynolds number. As compared to the results obtained for the flat tube without vortex generators for inline configuration, the temperature gained by the air at all positions and all Reynolds number are higher for the case with vortex generators. The maximum temperature increment is 24.22 % for an inline arrangement with vortex generators. Similarly, the temperature was increased for staggered arrangement with vortex generator maximum of 26.92% compared to without vortex generator. This is due to the reason that vortex generator develops a secondary flow which increases the turbulent intensity of the airflow behind the tube wake area resulting in an increase of air velocity.

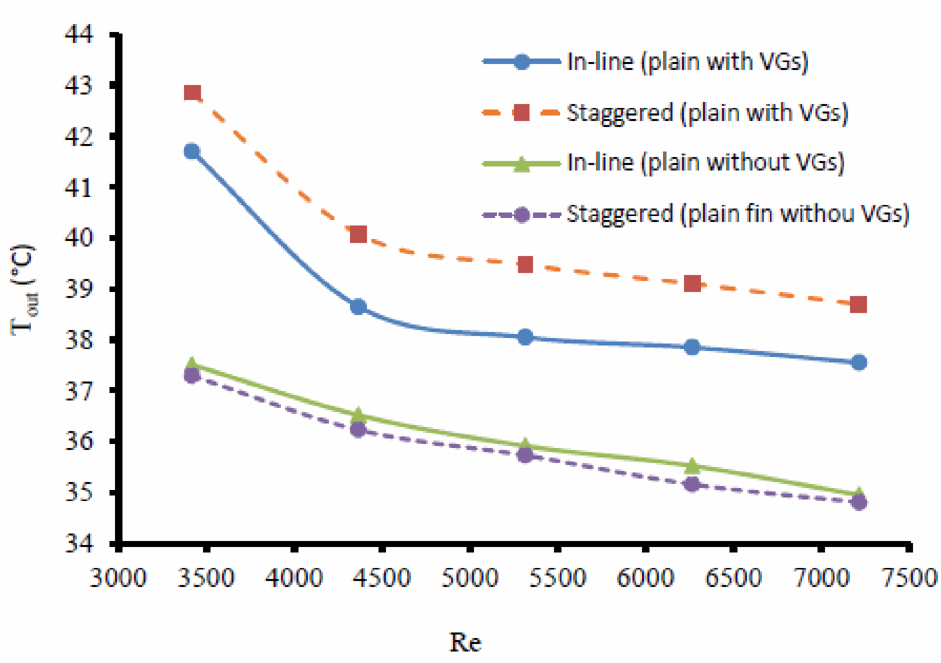

Figure 4: Variation of the outlet temperature against Reynolds number

B. Effect of DWVGs on the heat transfer coefficient

Generally, the area around the tube in finned and tube heat exchangers is very essential. Thus due to the limited space between the flat tubes, the superior and appropriate model for the fin outline should be considered. While the plain fin is not efficient in terms of heat transfer enhancement as louvered, slit, and wavy fin. Thus, there is a desperate need to overcome this disadvantage by combining plain fin with vortex generators which can improve the velocity near the flat tube and therefore, increase the heat transfer near the tube wall [4, 26] Fig. 5 shows the heat transfer coefficient for the flat tube HEs without and with vortex generator for the inline and staggered arrangements. From the figure, it can be seen that the heat transfer coefficient is increasing for all cases with increasing air velocity. As the Reynolds number increases from 3463 to 7312, the heat transfer coefficient increased up to 13.59% for inline and staggered tube arrangements without vortex generators. Correspondingly, when the DWVGs are attached on the fin surfaces for the inline arrangement, the heat transfer coefficient increased up to 45% compared to that obtained without vortex generator. In comparison, the heat transfer coefficient of staggered arrangement with vortex generator increased significantly by 46% (maximum) without vortex generator. The reason for this is that the increasing in heat transfer coefficient for an inline and staggered arrangement with vortex generator is because of the vortex generator itself, where it generates a secondary flow behind the tubes wake area, which increases the velocity of the air flow at the region behind the tube. The staggered arrangement provided the highest heat transfer coefficient for both cases (with and without VGs), this may attribute to the special geometrical structure of the staggered tube arrangement, where it play as additional vortex generators. As a consequence, an additional increase in air mixing caused by a staggered configuration results in further enhancement compared to the inline configuration.

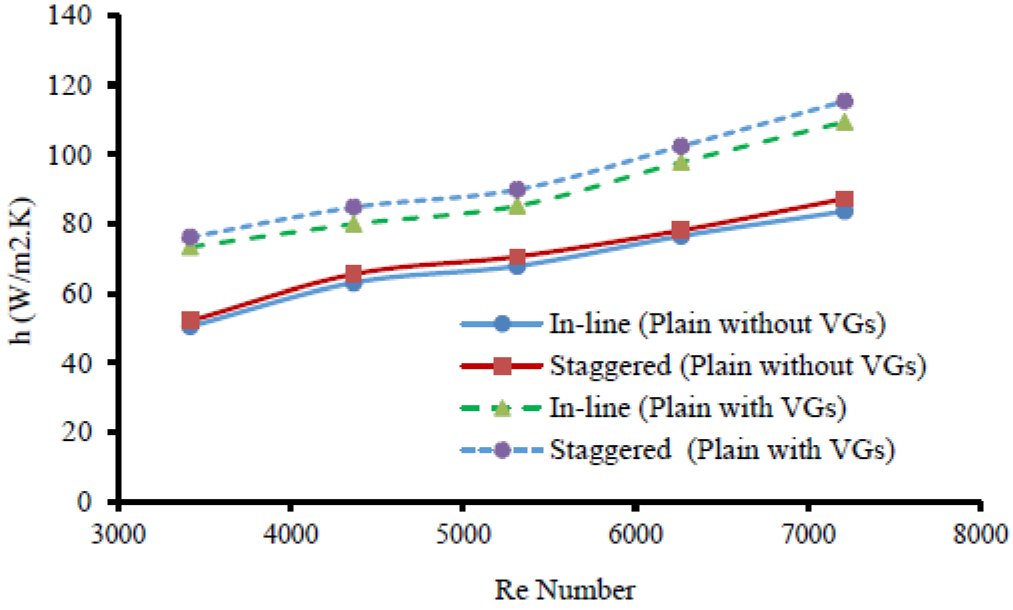

Figure 5: Variation of the heat transfer coefficient against Reynolds number

C. Friction factor

Variation of the friction factor against Reynolds number for inline and staggered configurations with and without DWVGs are depicted in Fig. 6. As expected, the friction factor for both configurations with vortex generators is found to be higher than that obtained from the fin without Vortex generators .This may be due to the fact that the flow blockage due to the existence of the vortex generators. The inline arrangement with vortex generator is increased slightly by up to 35% compared to the inline arrangement without vortex generator. The staggered arrangement with vortex generator increased by a maximum of 30% compared without vortex generator. From the figure, it can be clearly seen that inline configuration with vortex generators provided the highest friction factor among all cases for the Reynolds number ranged between 4300 and 7250. According to Joardar, and Jacobi,[27] vortex generators can enhance the heat transfer performance significantly with inconsiderable pressure drop penalty. Moreover, they found out an interesting result in their study revealed that changing the tube configuration from inline to staggered the thermal performance remain at the same level. Nevertheless, the pressure drop reduced by 8% for staggered arrangement. Similar results have been obtained in this study as shown in figures 5 and 6.

5. Conclusion

In this study, the thermal hydraulic performance of the compact flat tube heat exchangers with different types of fins (with and without VGs) and different tube configurations (inline and staggered) was examined experimentally. The obtained results indicated that the air-side heat transfer coefficient can be enhanced considerably due to the addition of the vortex generators on the plain fin surfaces. The main results of this study are summarized as follows:

- The mounted DWVGs enhanced the air side heat transfer coefficient for both configurations as a result of the development of the secondary flow by the vortex generators, which reduces the thickness of the thermal boundary layer and enhanced the turbulent mixing behind the tube.

- Compared to the flat tube heat exchanger without vortex generators for Inline configuration, the heat transfer coefficient increased by 25.6-45%, while for the staggered with vortex generator the increment is 27-46 %.

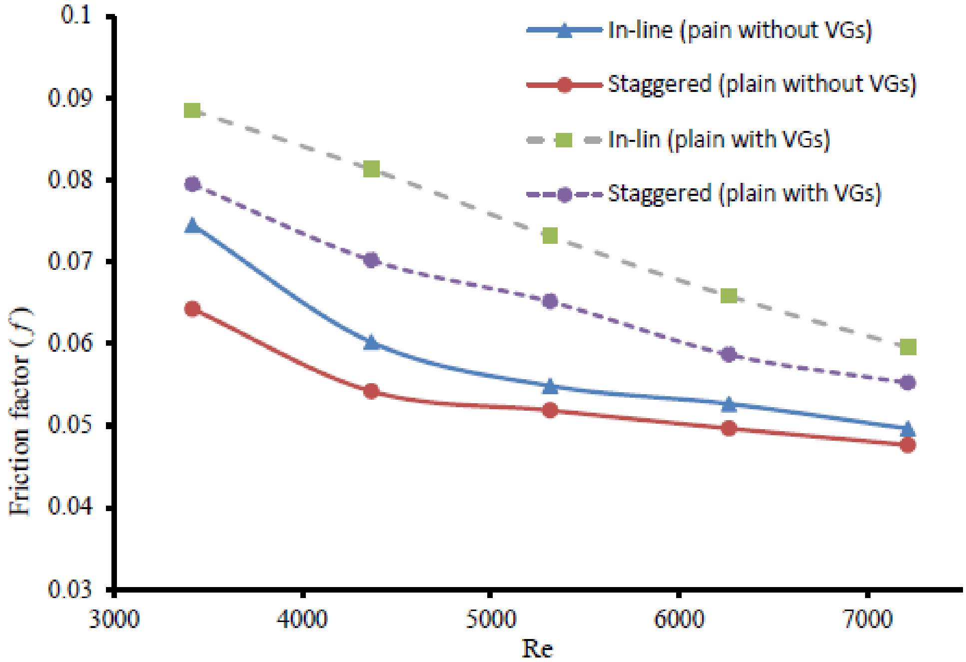

Figure 6: Variation of friction factor against Reynolds number for all cases

- In terms of heat transfer enhancement, staggered configuration provided the highest heat transfer coefficient for the both cases (with and without VGs). In contrast, in-line configuration had the highest friction factor for both cases.

- The impact of tube alignment without vortex generators on the heat transfer characteristics was very little. While significant impact of tube alignment on the heat transfer was observed for an inline and staggered arrangement with vortex generators.

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