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Effect of a delta-winglet vortex pair on the performance of a tube–fin heat exchanger

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Abstract

The experimental analysis of the effects of delta-winglet vortex generators on the performance of a fin and tube radiator is presented. The winglets were arranged in flow-up configuration, and placed directly upstream of the tube. This is a hitherto untested configuration, but is thought to have certain advantages. In addition to vortex generation the flow is guided onto the tube surface increasing the localised velocity gradients and Nusselt numbers in this region. The study includes dye visualisation and full scale heat transfer performance measurements. The results are compared to a standard louvre fin surface. It was found that the winglet surface had 87% of the heat transfer capacity but only 53% of the pressure drop of the louvre fin surface.

Keywords: Compact tube–fin heat exchanger; Delta-winglet vortex generator

1. Introduction

Tube–fin heat exchangers are used in a broad range of applications including industrial and chemical processes, air conditioners for domestic or industrial applications and automotive radiators. Generally, the application of these heat exchangers, involves either a temperature or phase change of a fluid, resulting in the absorption or rejection of energy in the form of heat. Because of their widespread applications, they are responsible for transferring enormous amounts of energy. Since global energy consumption is starting to impact negatively on the environment, as well as causing depletion of our existing fuel stocks, energy utilisation has come under close scrutiny. Heat exchangers are an integral component of the dissemination of energy and their effectiveness is becoming crucial to our lifestyle sustainability. Energy costs and environmental considerations continue to motivate attempts to derive better performance over the existing designs.

The basic tube–fin design consists of a stack of closely spaced fins through which tubes have been inserted, and this configuration has changed little since their introduction over 40 years ago [1]. On the other hand, the increasing technological improvements and cost reduction in manufacturing processes may offer increased versatility in heat exchanger design.

It is well known that the major resistance to efficient heat exchange in tube–fin heat exchangers is the air side heat transfer convection coefficient. In typical applications the air-side resistance comprises over 90% of the total thermal resistance [2]. Therefore the major area of current research is in attempting to reduce this resistance through variations in fin surface design.

There have been numerous fin surface variations trialled over recent years. These have evolved from wavy fins to slit fins and presently louvre fins are widely used. However in general, modifications to the fin surface have resulted in an increase in pressure drop with little improvement in heat transfer performance [3].

Ali and Ramadhyani [4] investigated the heat convection in the entrance region of 2D corrugated channels. They found that the corrugated channels increase the Nusselt

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Nomenclature

a	width of flat tube
b	length of flat tube
DW	delta-winglet
FD	flow-down
FU	flow-up
f	fanning friction factor
f_R	reference fanning friction factor
fpi	fins per inch
H	winglet height
j	Colburn j factor
j_R	reference Colburn j factor
$S1$	transverse tube pitch
$S2$	longitudinal tube pitch
VG	vortex generator
jf	dimensionless factor $= (j/j_R)/(f/f_R)^{1/3}$

number by 140–240% and the pressure drop by 130–280%. Yoshii et al. [5,6] presented dry and wet surface experimental data for two wavy-finned cooling coils with aligned and staggered tube arrangements. They found that under wet surface conditions the wavy-finned cooling coil exhibited a 20–40% increase in heat transfer coefficient and 50–100% increase in the pressure drop.

Recently there has been much interest in enhanced surfaces having punched delta-winglets [7–10]. These winglets are designed to generate longitudinal vortices which increase turbulence levels and improve convection resulting in improved heat transfer performance, albeit with a minimal pressure drop penalty. The vortices generated are a result of the introduction or exploitation of secondary flows, rather than the manipulation or alteration of the main flow. Jacobi and Shah [3], performed a thorough review of the progress made in the application of longitudinal vortex generators. They suggested two alternative classifications for heat transfer enhancement: main-flow enhancement and secondary flow enhancement. In main-flow enhancement the gross characteristics of the flow are altered through geometric changes, pressure variations, or by other means. However, in secondary flow enhancement, local flow structures are deliberately introduced.

Gentry and Jacobi [7] reported on heat transfer enhancement by various vortex generators mounted at the leading edge of a flat plate. They demonstrated a 50–60% improvement in average heat transfer over the surface of the plate, using delta-wing vortex generators. It is worth noting that a delta-wing is like an isosceles triangle mounted symmetrically to the flow, and the angle of attack is measured between the plate and the lean of the delta. A delta-winglet on the other hand is like a right-angled triangle (or half delta) mounted perpendicular to the plate, but at an incident angle measured parallel to the inlet flow. Gentry and Jacobi varied the angle of attack from 25° to 55°, with the optimum enhancement occurring at an angle of attack of 40°.

A description of the flow field formed by a delta-winglet vortex generator is given by Yanagihara and Torii [8]. They identified three distinct vortices. There is a main vortex that is formed as a result of the flow separating in the tip of the half-delta wing and rolling up due to the lower pressure in the back side of the vortex generator. Then there is the corner vortices that are horseshoe-like vortices formed in the corner between the front side of the wing and the fin. Finally, there is an induced secondary vortex which is formed in the corner between the back side of the wing and the fin as a result of the redirection of the near wall flow caused by the lower pressure behind the generator.

Torri et al. [9,10] have proposed a novel technique that can augment heat transfer, but nevertheless can reduce pressure-loss in a fin–tube heat exchanger. They performed an experimental study to evaluate heat transfer and pressure loss in a test section comprising delta-winglet pairs arranged in a “common flow-up” configuration. Flow up refers to the streamwise alignment of a pair of winglets to form a converging channel and conversely for flow-down they form a diverging channel. In this case the winglets were mounted on the fin surface slightly behind the round tubes. Note that they only used one row of winglets which was mounted behind the first tube row. They argue that the nozzle-like flow passages created by the winglets and the aft region of the circular tube promote acceleration to bring about a separation delay and form drag reduction of the tube, and hence reduce the zone of poor heat transfer from the wake. They reported a 10–30% improvement in heat transfer and the pressure loss was reduced by 55%.

Punched longitudinal vortex generators forming winglets in staggered arrangements on the fin surface have been studied by Chen et al. [11] and found to increase heat transfer by 50% and 87% with 2 or 4 staggered delta-winglet pairs, respectively. Staggered winglets were more effective than in-line winglets, obtaining a 20% increase in heat transfer and 14.5% lower additional pressure loss. In the staggered arrangement, the winglet further away from the tube was more effective for heat transfer.

Zhang et al. [12] conducted an experimental and numerical parametric study to investigate the effect of span position of vortex generators on the local heat transfer coefficient for three-row flat tube bank fin. The vortex generators in his case where all of flow-down type and were not punched through. They used the naphthalene sublimation method to infer heat transfer. They concluded that vortex generators should be mounted as close as possible to the tube surface and that vortices generated upstream converge at the wake region of the flat tube.

Several studies have also been performed in order to examine the performance of louvered surfaces combined with vortex generators. Lozza and Merlo [13] experimentally compared a louver fin coil with one combined with punched winglets. They found that there was marginal improvement in heat transfer but the pressure loss becomes higher than for a conventional louvered fin of comparable *j*. Better results were obtained by Joarder and Jacobi[14] who compared a louvered radiator with one having delta-wing vortex generators placed at the entrance to the fins. Note however that the fins were of the triangular duct type introduced by Davenport [15]. They reported heat transfer improvement of up to 21% and a pressure drop penalty of less than 8%.

In typical trials, the delta-winglet pair is arranged in a flow-down configuration when located in front of the tube. Mounting the winglets in this diverging manner may cause a significant portion of the bulk flow to be diverted around the tube thereby giving the tube, which is primary heat transfer surface, a wide berth. On the other hand mounting them in a flow-up or converging manner in front of the tube may give rise to a significant portion of the flow impinging on the tube stagnation zone increasing Nusselt numbers in this region. An additional effect is that the flow has to accelerate between the winglet edge and the tube side increasing velocity gradients and hence Nusselt numbers along the tube side. It appears that no investigation has been undertaken to examine the thermo-hydraulic characteristics of a delta-winglet pair arranged in the flow-up configuration positioned in front of each tube.

In this paper, we report on a study which is focussed on a flat tube arrangements with delta-winglet vortex generators. A parametric study was conducted to investigate the effect of the delta angle on the flow structure using a water tunnel dye visualisation technique. In addition we experimentally tested the flow-up delta-winglet pair arrangements positions immediately in front of the tubes. Full scale coil was dry tested for a wide range of Reynolds numbers and the results were compared to a current production coil having exact similar tube geometry but with a louvered fin surface.

2. Flow visualisation study

A flow visualisation study was conducted using several delta profiles. The delta profiles were cut out of 0.5 mm PVC sheet and bent through 90° to form the winglets. The resulting PVC fin and winglets were mounted on a Perspex tube bundle and trialled in a low speed water tunnel. The tube bundle and fins were scaled up from the real coil prototype by a factor of six. The water Reynolds number flows were chosen to be similar to those of the air Reynolds numbers used for the prototype evaluation. The Reynolds numbers used were 2600, 3400 and 4600 based on the tube transverse pitch which is commonly the length scale used for such heat exchangers. Scaling the Perspex model up by a factor of 6 had several advantages. At this size the tube bundle almost completely filled the water tunnel cross section which measured 350 mm high by 175 mm wide. This reduced the need for pressure compensation dampers to ensure a uniform velocity profile entering the model in the vertical plane. Dampers were still required however for the horizontal flow plane because the fins only occupied the centre portion of the tube bundle and therefore the flow had to be prevented from bypassing the fins. By adjusting the position of these dampers for each water flow rate, it was possible to ensure that the velocity profile entering the model was uniform. Another advantage is that as the model increases in size, the water flow velocities can be reduced. Even at the highest water velocity of 0.15 m/s the free stream turbulence was low enough to allow the dye to be introduced by a Pitot tube without any vortex shedding from the Pitot tube diameter. It was established that at all flow rates a free stream dye trace remained laminar for a flow length that was greater than the model length.

It was established that a delta profile with a delta angle of 39° and angle of incidence of 30° displayed distinctive and coherent vortices at the inlet velocities of interest. These were then compared in both a flow-up as well as a flow-down configuration. The various observations were captured with a video camera, and various frames selected for presentation. Samples of these frames are depicted in Figs. 1 and 2 which show the resulting longitudinal vortices generated by each configuration. Note that the dark oblong shaped areas in the photographs represent the tube cross section.

Observing Fig. 1, it can be seen that the flow-down delta-winglet configuration generates a distinctive and well formed longitudinal stream wise vortex which has an approximate diameter of about a third of the tube height. However, the vortex longevity is uncertain as it is insinuates obliquely onto the bulk free stream flow and ends up impinging on the adjacent delta-winglet row. On the other

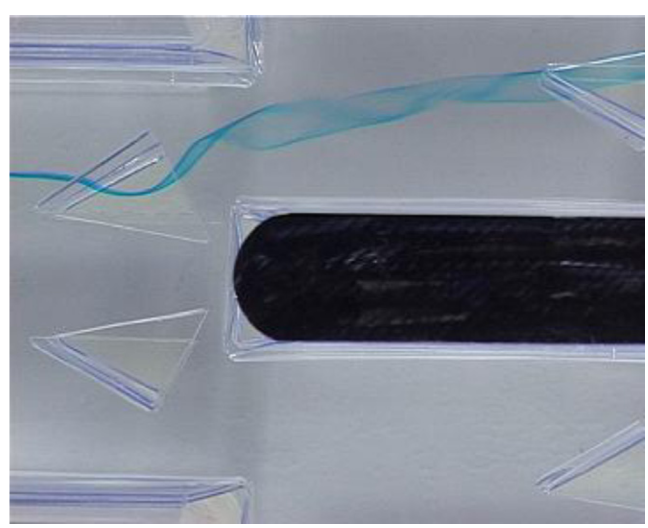

Fig. 1. Longitudinal vortex street generated by a delta-winglet vortex generator using a flow-down configuration.

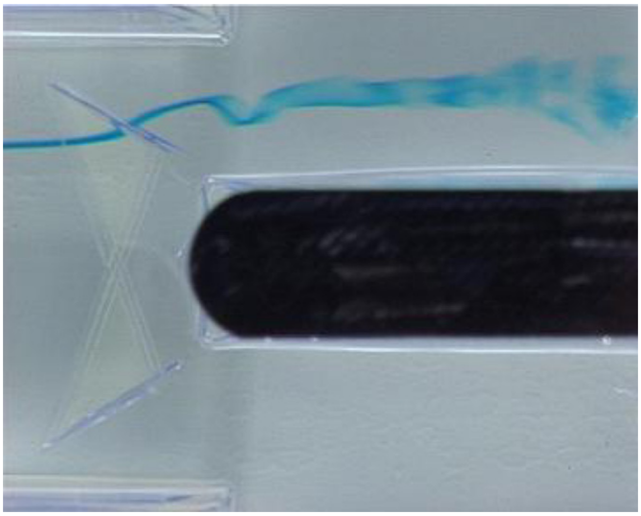

Fig. 2. Longitudinal vortex street generated from a delta-winglet vortex generator using a flow-up configuration.

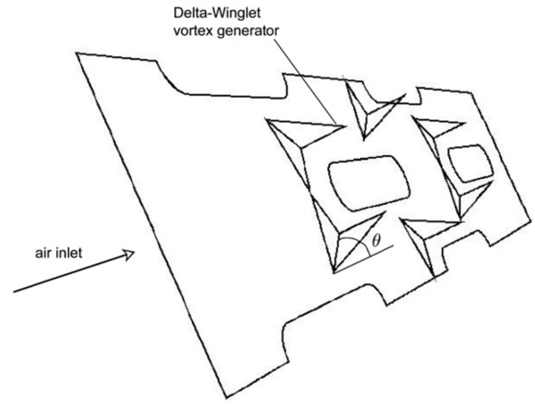

Fig. 3. Schematic representation of the delta-winglet pair arranged in a flow-up configuration.

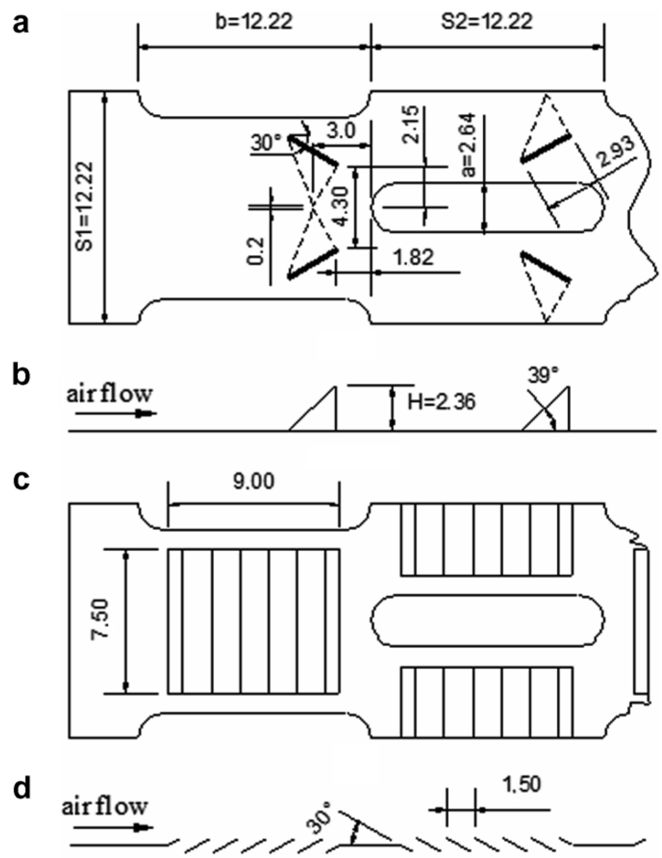

Fig. 4. Schematic view of the surface geometry of each of the fin types tested (a) delta-winglet vortex fin, the dashed lines demarcate the cut lines due to punching (b) winglet profile (c) louvre fin (d) louvre profile.

hand the flow-up configuration as seen in Figs. 2 creates a vortex which flows parallel to the tubes. Although the diameter of this vortex is smaller, about a quarter of the tube height, it has a higher rotational velocity and appears to have a higher intensity than the former. The preceding observation was made while studying the video footage, and is not as apparent in the still photographs.

Both configurations generate vortices which display desirable characteristics which may increase the turbulence and hence heat transfer. However, the flow-up configuration possibly has additional advantages. The positioning of this winglet pair creates a converging channel which may encourage a large portion of the bulk flow to be directed onto the tube stagnation surface. This will increase velocity gradients and result in increased Nusselt numbers along the tube surface. Since the tube surface is a primary heat transfer surface, the increased convection from this source may be significant. Conversely the flow-down orientation has the opposite effect and may actually cause a proportion of the bulk flow to be diverted outwards creating a wide berth around the tubes. Considering the above reasons, the flow-up configuration was selected as a basis for a prototype coil.

3. Prototype coil description

The proposed delta-winglet fin surface configuration is schematically depicted in Figs. 3 and 4. In order to punch out the delta-winglet profiles, a hand punch and dye was custom built for this purpose. The delta-winglet pair was then manually punched into the plain fin surface which had the tube slots pre-punched. Dowel rods protruding from the dye surface were used to locate the tube slots thereby accurately positioning the punch with respect to the tube. Fig. 5 shows a comparison of (a) the flow-up delta-winglet surface and (b) the standard louver surface. The louver angle of the standard fin surface is 30°.

Each test coil measured 760 mm wide by 260 mm high, and had four rows of tubes, 74 in total with single circuiting. The standard louver fin coil and the delta-winglet prototype each had a fin pitch of 9 fpi.

4. Test apparatus and procedure

The prototype and standard coils have been tested experimentally using a purpose built coil test rig, schemat-

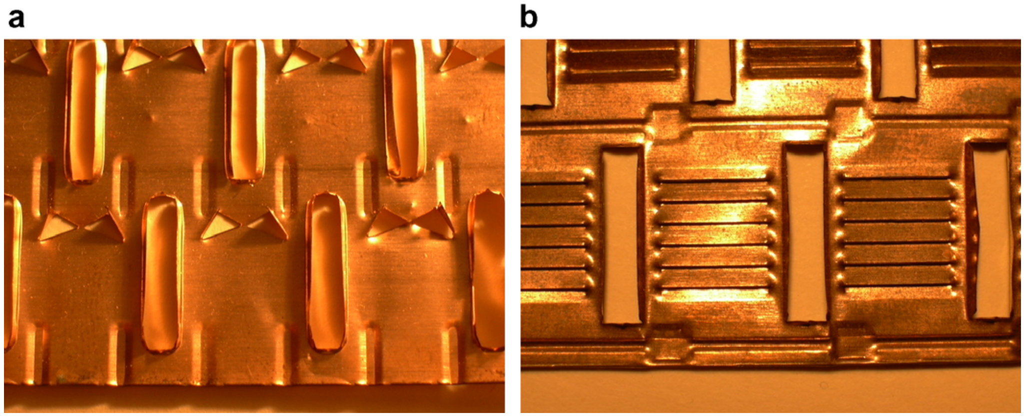

Fig. 5. Comparison of the test coil fin surfaces: (a) flow-up delta-winglet (left) and (b) louvre fin surface (right).

ically shown in Fig. 6. The system forms a closed loop cycle which maintains the preselected on-coil conditions at a steady state condition by virtue of the feedback control system. Chilled water is supplied to the coil from the storage tank, kept at the desired temperature of 11.5 °C by the refrigeration system which has a variable speed compressor. The on-coil air temperature was maintained at 40 °C by the electric duct mounted heaters. These on-coil conditions were chosen to ensure that no precipitation and hence no latent heat exchange occurred. Since the test coils were intended for radiator applications, only the sensible heat capacity was required. The supply and return chilled water temperatures were measured with PT100 temperature sensors. The water flow Reynolds Numbers based on the hydraulic diameter varied from 2500 to 7500, and the velocity was measured using an ABB Magmaster Flowmeter for measuring the water velocity through a calibrated pipe section. The ABB Magmaster is fitted with a CalMaster diagnostic monitoring tool and has an accuracy of approximately 1%. The air flow rate was varied to provide coil face velocities of 2.9, 4.8 and 6.2 m/s which are inclined to be more in line with radiator applications rather than

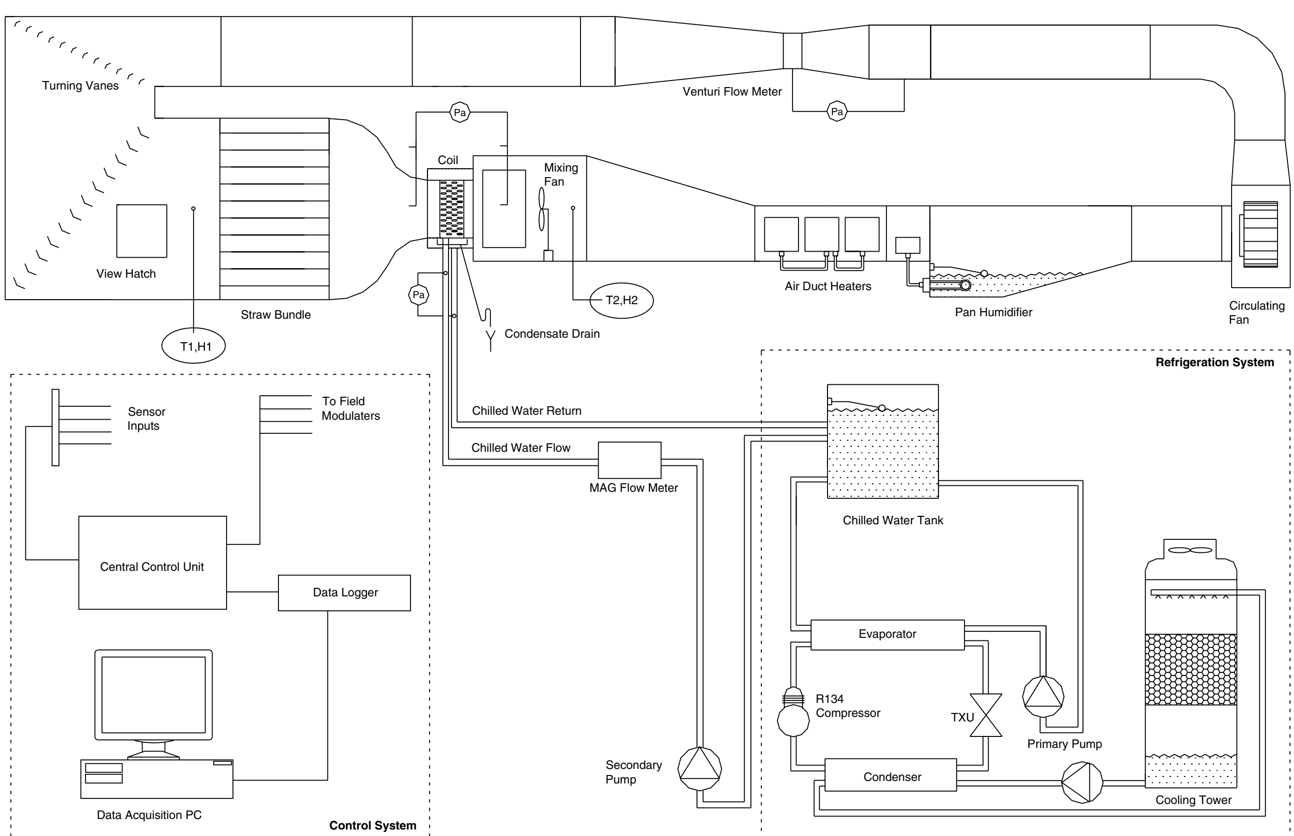

Fig. 6. Closed loop coil test apparatus.

cooling coil applications. The air on-coil and off-coil temperatures were measured with VAISALA combined temperature and humidity sensors. The water and air temperature sensors had an accuracy of 0.1 °C. The desired air flow rate was controlled by the venturi pressure drop measurement which was fed back to the control system. The air pressure drop across the test coil was measured with Pitot tubes connected to an electrical pressure transducer. Water pressure tapings were located adjacent to the coil inlet and outlet manifolds. The digital pressure transducers had an accuracy of 0.5%. All the measured variables were recorded by a data logger and displayed on a PC as an instantaneous readout. The energy balance was less then 5% in all cases. The collected Data was reduced using the procedure recommended by Wang [16], and shall not be repeated here. Only one modification was necessary, concerning the conversion of flat tube perimeter into an equivalent circular tube diameter.

5. Prototype test results and discussion

Fig. 7 shows the resulting *j*-factor and *f*-factor performance comparison plots.

Note that the Reynolds number plotted along the *x*-axis is based on the tube dimension across the tube flats, plus the fin collar thickness, which is the length scale that is most appropriate to influence the velocity field. It can be seen that on average the heat transfer coefficient is about 70% of the louver fin surface. On the other hand the fanning friction factor is only 53% of that of the louver fin surface. Therefore, although the heat transfer capacity is reduced, the overall effectiveness of the surface is significantly improved.

This is further demonstrated by observing the comparison in goodness factors shown in Fig. 8. The DW coil has 87% of the heat transfer capacity but 53% of the pressure drop of the louvered fin surface. This implies that a 15% increase in coil area will achieve the same heat transfer but with almost half the pressure drop. There is then a direct saving in energy, because the fan power consumption is the product of flow rate and pressure drop. Although the air flow rate increases by 15%, the pressure reduces by 47%. The resulting power consumption $P_2 = 1.15 \times 0.47\ P_1 = 0.54\ P_1$.

Following the suggestions of Yen et al. [17] and Zhang et al. [12], the *jf*-factor was plotted versus the Reynolds number as another way to compare the performance of our new design with that of a reference design. Fig. 9 shows this comparison for the three air side velocities. It is clear that the *jf*-factor increases with the increase of the Reynolds number and that the maximum value is 0.87. This finding is consistent with the goodness factor reported earlier in Fig. 8.

It is worth noting that direct comparison with data from the literature was not possible. Firstly, the majority of studies reported in the literature used coils with round tubes. The tubes will also shed vortices themselves and the interaction of the vortex generated upstream with the tube, especially in the wake region is totally different [18]. Secondly, most researchers compared their coils with those

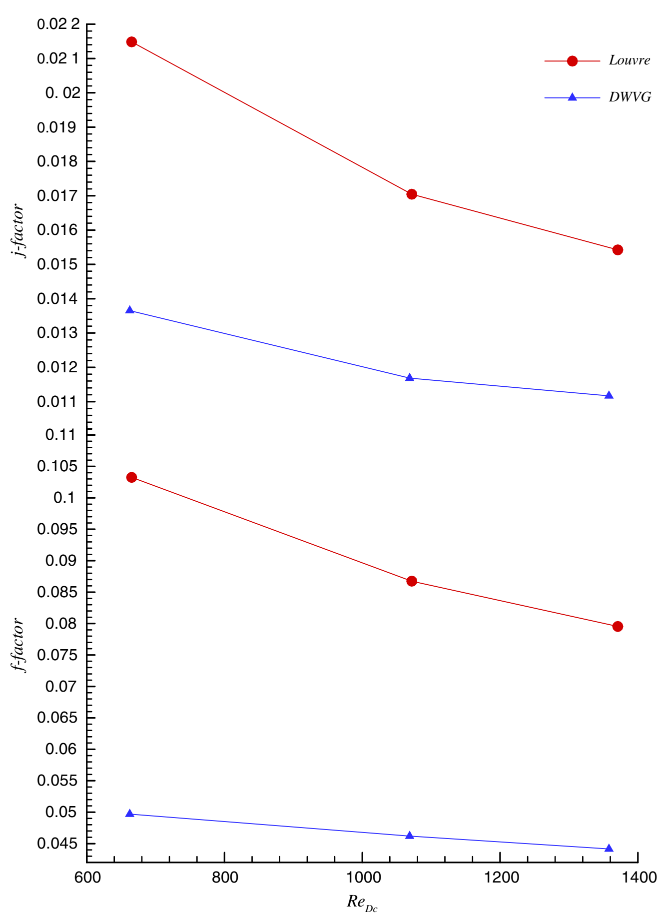

Fig. 7. *j*-Factor and *f*-factor performance comparison plots between the delta-winglet coil and the louvre fin coil.

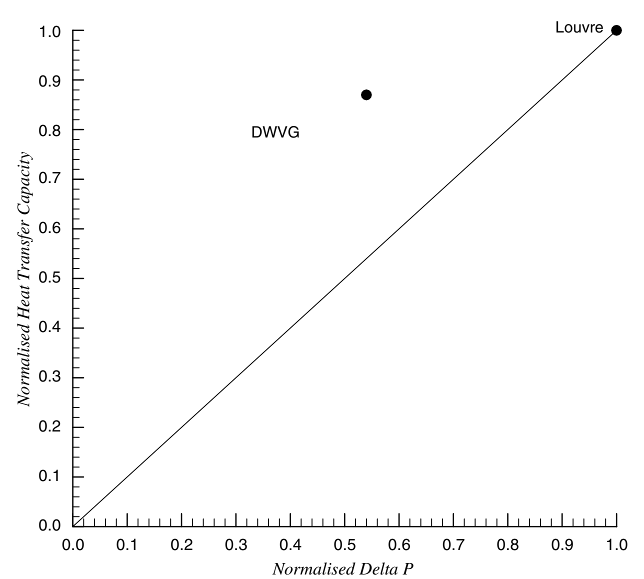

Fig. 8. Goodness factor comparison between the delta-winglet coil and the louvre fin surface.

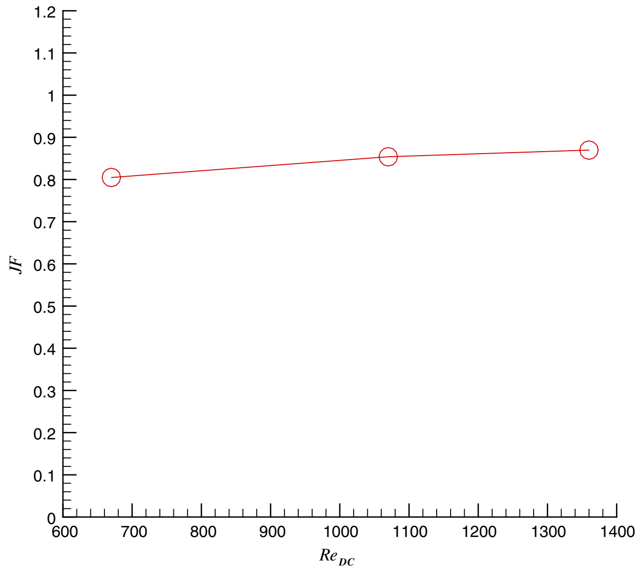

Fig. 9. *jf*-Factors plotted vs. the Reynolds number for all three air velocities.

having flat fins which are hardly the norm for any practical application. Comparison with current production coils was used in this study as it provides a more meaningful comparison with an existing design. Such comparison was also performed recently by Jordar and Jacobi [14] where they investigated the effect of leading edge fins addition on the performance of a louvered fin heat exchanger. Very few studies reported on-coils with flat tube arrangements notably that of Fiebeg et al. [18,19] and Zhang et al. [12]. However, their data were recorded using different tube arrangements and fins design.

A comparison with Fiebeg et al. [18], who used flat tubes, reported a heat transfer increase of 100% and a similar increase in the pressure drop. This result agree partially with our findings on the heat transfer part (we achieved 87% improvement in heat transfer) and is in total disagreement with many other studies findings, e.g. Kwak et al. [10], on the pressure drop part. While, Zhang et al. [12] have investigated the flow-down configuration with delta-winglets attached to the top of the fins rather than punched through. This has major implication on the pressure distribution and the boundary layer especially close to the tube which make any meaningful comparison very difficult.

It is clear from the data presented in that paper that the heat transfer mechanisms of the two fin surfaces differ dramatically. The louver fin surface facilitates boundary layer renewal and has numerous leading edges. The delta-winglet fin has fewer leading edges and relies predominantly on increasing convection through vortex generation. According to the results, the louver fin is superior to the delta-winglet fin. Although coherent vortices were generated from the first row of winglets, we doubt wether the downstream winglets produce the same level of vorticity. This implies that only the first row of winglets may be effective in producing vortices which can improve heat transfer. In addition, the longevity of the vortices produced by the first row of winglets may be compromised by interference from the tubes and downstream winglets. Hence, it is probable that only the fin surface area near to the first row of winglets experiences any major improvement in heat transfer coefficient. This finding necessitates the further exploration of ways to improve heat transfer at the downstream tube rows in order to fully utilise the potential of this type of fin.

6. Conclusions

It was demonstrated through flow visualisation that the proposed delta-winglet orientation generated distinct coherent stream wise vortices. It was found that a delta angle of 39° gave the best flow structure. Test of a full scale coil with flow-up delta-winglet geometry exhibited 87% of the capacity the louver fin surface. On the other hand it showed a substantially lower pressure drop, approximately 53% of the louver surface. This configuration appears to be the best arrangement yet published in the literature. In many applications the capacity deficit can be compensated for by an increase in coil face area. The resulting fan energy consumption is only 54% of that of the equivalent louver fin surface. Although, the capital cost of the coil may increase, the energy savings are significant, and will be result in energy saving throughout the life of the coil.

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