A Review on Heat Transfer Enhancement by Longitudinal Vortices

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The study of the influence of longitudinal vortices on heat transfer is related to the present day development of high-performance thermal systems. The recent researches have shown that these vortices play an important role in enhancing heat transfer. One example is the flow within a turbine cascade that involves complex vortex interactions on the turbine endwall and at the base of the turbine and compressors blades. These vortices create hot spots that significantly reduce the life of a turbine. On the other hand, the use of longitudinal vortices to enhance the heat transfer in the air side of plate-fin heat exchangers has been considered promising. Streamwise vortices also occur frequently in aerodynamic flows such as the trailing vortex's shedding from the wings of aircraft, or embedded vortices introduced into boundary layers on aircraft wings to prevent separation.

Until the last decade, few works have focused on the potential use of vortex generators to enhance the heat transfer in compact heat exchangers. Most of the earlier works dealt with longitudinal vortices and heat transfer as related to turbine blade cooling. By contrast, studies of the fluid dynamical aspect of streamwise vortices in their many forms constitute a large body of literature. Longitudinal vortices have deserved attention primarily due to their connection to aeronautical engineering. In the recent years, however, many research works have been conducted to study the influence of longitudinal vortices on heat transfer.

The present review aims to focus on the effect of longitudinal vortices generated by wings on the heat transfer enhancement in boundary layers, ducts and plate fin-tube geometries. Longitudinal vortices present in curved surfaces (Taylor-Görtler vortices), and secondary flows generated by active techniques ("corona wind") are not considered here. Complimentary information about the topic of this review can be found in the detailed review papers that were presented recently by Fiebig (1995) and Jacobi and Shah (1995).

1. The interaction between longitudinal vortices and its adjacent flow

The early work involving longitudinal vortices in boundary layers was oriented toward their utility as a mixing mechanism to prevent separation in an adverse pressure gradient. The standard technique was to produce an array of vortices near the edge of the boundary layer that would mix the high-velocity fluid from the inviscid stream with the shear layer near the surface. Schubauer and Spangenberg (1960) investigated many different types of generators to find out which were the most effective to prevent boundary layer separation. They concluded that different vortex generating mechanisms produced about the same degree of mixing. Sedney (1973) reviewed studies investigating effects of small protuberances on boundary layer flows and concluded that for three-dimensional protuberances the general effect is the production of vortex patterns. He subdivided these vortex systems into the vortex system upstream of the separated flow, the spiral vortices in the near wake, and the horseshoe vortex system. The most prominent feature distinguishing three-dimensional disturbances from two-dimensional disturbances was the remarkable streamwise persistence of the structures generated. Kitchens et al. (1981) calculated the
streamwise vorticity decay downstream of a three-dimensional protuberance for a laminar boundary layer. Ersoy and Walker (1986) computed the motion of a counter-rotating pair of two-dimensional vortices above a plane wall to explain the viscous-inviscid interaction that produced eruption and ejection of secondary vortices near the wall.

Recent work on vortex/boundary layer interactions has focused on the details of the mean and turbulence structure of the boundary layer to relate these measurements to the modification in turbulent boundary layer transport processes. The structure of turbulent boundary layers with embedded streamwise vortices has been studied extensively by Bradshaw and co-workers at Imperial College and Stanford University. Vortices were generated by placing delta winglet vortex generators in a wind tunnel settling chamber, upstream of the contraction nozzle, to reduce the wake effects of the delta winglet while conserving the circulation. Mean flows, Reynolds stresses, triple products, and skin friction measurements were obtained at two streamwise locations in a turbulent boundary layer with zero pressure gradient. Shabaka et al. (1985) reported the results for single longitudinal vortices embedded in a turbulent boundary layer. Skin friction measurements revealed that in regions where the secondary flow was directed toward the wall the skin friction increased. Decreased skin friction was observed where the secondary flow was directed away the wall. The Reynolds shear stress \( \langle u'v' \rangle \) distribution was severely distorted by the presence of the vortices and is very small or slightly negative in the downwash region. Significant induced vorticity was produced by viscous interaction between vortices and the surrounding boundary layer flow. The shear correlation coefficient and the stress-energy ratio, which are usually constant for a two-dimensional boundary layer, were drastically changed in the region of the vortices. Correlation coefficients for the shear stresses \( \overline{w'w'} \) and \( \overline{v'v'} \) achieved numerical values similar to those for \( \overline{u'v'} \), indicating that the secondary shear stress is strongly organized and important. Introduction of vortex pairs with the common flow upward produced significant inward lateral divergence of the boundary layer, as reported by Mehta and Bradshaw (1988). Vortex pairs produced stronger distortion of the boundary layer than the single vortices. Boundary layer fluid is lifted up by the vortices, and entrained into them, but there was very little direct interaction between the vortices. The distance of the vortex cores above the surface grew downstream, and was roughly twice the boundary layer thickness. In the vortex region, they found large changes in all the dimensionless structural parameters of the turbulence, to the extent that the concept of large eddies controlling transport could not be applied, as the eddy viscosities and diffusivities behaved ill. They concluded that the prediction of embedded-vortex flows will require the solution of a full Reynolds-stress-transport equation. The behavior of longitudinal vortices generated by similar half-wings without the presence of a wall was reported by Mehta and Cantwell (1988).

Westphal et al. (1985) investigated the effect of a moderate adverse pressure gradient on the interaction between a single streamwise vortex and a turbulent boundary layer. The vortex was generated by a delta winglet placed in the centerline of the test section. They measured the three-components of the mean velocities and the five of the six independent components of the Reynolds shear stress tensor. They observed a growth of the vortex core, followed by a flattening of the core shape that occurred when the core radius became comparable to the distance of the vortex center from the surface. The adverse pressure gradient was found to cause an increase in the rate of core growth and, therefore, a stronger distortion of the core shape. Turbulence properties were even more strongly disturbed by an adverse pressure gradient than by constant pressure.

Liandrat et al. (1987) performed a numerical simulation of longitudinal vortices interacting with a flat plate boundary layer. They used a forward marching scheme and different models for the transport terms of the Reynolds stress governing equations. The calculated mean and turbulent
quantities in a boundary layer with embedded vortices were compared to the experiments reported in Shabaka et al. (1985) and Mehta and Bradshaw (1988). Simple models based upon the Boussinesq hypothesis provided good estimates of overall flow properties but more elaborated models using second-moment closures were required for detailed prediction. Using these models they were able to reasonably predict the anisotropy of normal stresses \( \bar{\nu}^2 - \bar{\nu}^2 \) necessary to capture the shear stresses \( \bar{\nu}^2 \) and \( \bar{\nu}^2 \). By integrating along streamlines they were also able to significantly reduce the time needed for the computation. Mehta and Bradshaw (1988) noted that the above calculation was not able to predict the \( \bar{\nu}^2 \) stress satisfactorily. They noted that for the vortex pairs, the calculation fails to predict even the mean flow distribution. They concluded that a competent application of existing models is still not adequate for accurate engineering calculation. Detailed discussion can also be found in the report by Bradshaw (1987) who reviewed the present understanding of turbulent flows with longitudinal mean vorticity, with the emphasis being placed on the turbulence modeling. More recently, Cutler and Bradshaw (1993a, 1993b) reported experimental results on the interaction between a longitudinal vortex pair, produced by a delta-wing at angle of attack, and a turbulent boundary layer developing on the plate. They observed that the flow near the separation line and in the vortices is complicated, constituting a more challenging test case for three-dimensional turbulent calculation.

There are many recent experimental studies on the vortex structure downstream different kinds of wing geometries. Kita et al. (1994) studied the effect of a flat-plate wing with low aspect ratio present in a side wall boundary layer, reporting that secondary vortices present in the flow suppresses separation near the wing root and tip. Wendt and Hingst (1994) examined the vortex structure in the wake of a low-profile "wishbone" vortex generator and concluded that the flow in the cross plane can be well represented by the two-dimensional Oseen model. Hoang et al. (1995) studied the temporal evolution of a pair of streamwise vortices generated by a delta wing, based on LDV experimental data, and described the process of vortex breakdown.

2. Earlier work on heat transfer enhancement by longitudinal vortices

Studies relating longitudinal vortices and heat transfer enhancement are relatively recent. One of the earliest is reported by Edwards and Alker (1974), who investigated the effect of both counter-rotating and co-rotating vortices on heat transfer of boundary layers. Spatially resolved heat transfer rates were determined by passing the flow over a uniform heat-flux wall and measuring the local surface temperature using a luminescent phosphor technique. They used cubes and vortex generator blades to create the longitudinal vortices, and found that cubes produced the highest local improvement (up to 160%) while the effect of vortex generators extended further downstream. The counter-rotating vortex pairs were more effective than the co-rotating pairs, with a maximum increase in the heat transfer of 65% over flat-plate values for the counter-rotating vortex generators with 15° angles of attack. The type of boundary layer existing before addition of the vortex generators was not given.

Russel et al. (1982) carried out experiments with sensitive paints to determine the spanwise temperature distribution of alternating rows of closely spaced co-rotating vortex generators on a plate fin-flattened tube geometry. They found that considerable enhancement of heat transfer occurs, with a modest pressure loss penalty. Increases of up to 50% in heat transfer coefficient and 40% in pressure drop were reported. Through flow visualization and a yaw meter, the peak heat transfer location was associated with the downwash region between vortices. Minimum heat transfer was linked to the upwash flow between neighboring vortices.

Turk and Junkhan (1986) measured the enhancement of convection coefficients on the surface of a flat plate by using blade-type vortex generators,
with the emphasis being placed on the relationship between the geometry and the augmentation of the local and overall coefficients. The spanwise local coefficients were found to vary with the spanwise spacing of generator blades. Span-averaged heat transfer data revealed a region of minimum enhancement a short distance downstream of the blade row, rising to enhancements of up to 150% over the laminar value further downstream.

3. Heat transfer in laminar boundary layers

Although the initial work on heat transfer enhancement through longitudinal vortex generators indicated that the technique would be promising, the research focus was essentially on global results, with little useful information on the basic mechanisms that enhanced the heat transfer. In order to clarify this aspect, Torii and co-workers at Yokohama National University started working with the clarification of the heat transfer mechanism by measuring the velocity field and the local heat transfer coefficient distribution of an otherwise laminar boundary layer in the presence of a delta winglet (or delta winglets). The characteristics of the flow field were grasped by local velocity measurements using hot-wire anemometry and by flow visualization with smoke-wire. The distribution of the local heat transfer coefficient was measured by the heat plate technique and the naphthalene sublimation technique. Some numerical calculations were also performed to analyze the development of the longitudinal vortices.

Torii and Yanagihara (1989) report an experimental work in which the heat transfer effect of longitudinal vortices generated by a delta winglet were evaluated at a certain distance downstream the winglet. The main conclusion is that in this region of the boundary layer, the effect of the transition for the turbulent regime was predominant, although it was possible to verify that the longitudinal vortices persist downstream. Yanagihara and Torii (1990a) modified the experimental apparatus to study the effect of the longitudinal vortices just downstream the generator, where the vortex system has a larger intensity. In this case, the local boundary layer thinning in the downwash region, due to the entrainment of high-speed outer layer flow caused by the vortical motion, was the primary reason for the local heat transfer enhancement. An expressive value of the heat transfer coefficient, 80% above the two-dimensional result, was found in a region clearly dominated by a laminar structure. On the other hand, the heat transfer augmentation in the upwash region was insignificant. In this region, the velocity fluctuations indicated that there is an onset of local turbulence transition. The three-dimensional velocity field measurements by hot-wire anemometry and the smoke-wire flow visualization results indicated that the following vortical structure, shown in Fig. 1, significantly affect the flow field and the heat transfer coefficient.

Figure 1 Vortical system generated by a delta winglet.

Distribution: (1) the main vortex formed as a result of the flow separating at the tip of the delta winglet and rolling up due to the lower pressure in the back side of the generator, (2) the corner vortices that are horseshoe-like vortices formed in the corner between the front side of the wing and the duct plate and (3) the induced secondary vortex that is formed between the main and corner vortices. These results were confirmed by naphthalene sublimation experiments that showed clear peaks and valleys related to these vortices (Torii et al., 1991). More-detailed local velocity and
temperature measurements conducted by Torii et al. (1994) suggested that the increase of the heat transfer coefficient in the downwash region was higher than the increase of the local skin-friction coefficient, in the region just downstream the vortex generator. On the other hand, in the upwash region, there is a clear onset to local turbulence transition with similar turbulence characteristics (power spectra, probability density distribution) of the flat-plate laminar-turbulence transition.

Parametric studies with the winglet generators height, attack angle and geometry (Yanagihara and Torii, 1992) indicated that configurations that produce stronger main and corner vortices are more effective for heat transfer enhancement (higher attack angle and geometry with larger frontal area). In another work (Yanagihara and Torii, 1990b), higher local heat transfer coefficients were reported for pairs of delta winglets where the common flow between the generators directs toward the surface (downwash). The effect of the angle of attack and the distance between generators were analyzed (Yanagihara and Torii, 1991), with better results for pairs with the common flow downwash, higher angles of attack and smaller distance between generators. Extending the work for rows (Yanagihara and Torii, 1993), the counter-rotating pattern for the longitudinal vortices was more effective for heat transfer enhancement.

4. Heat transfer in turbulent boundary layers

Eaton and co-workers developed a research program in Stanford University to study the influence of longitudinal vortices generated by delta winglets on the flow structure and heat transfer of turbulent boundary layers. The work of Eibeck and Eaton (1985, 1986, 1987) examined in details the isolated influence on heat transfer of a longitudinal vortex of various strengths embedded in a turbulent boundary layer by measuring the resolved heat transfer coefficient and the three-component velocity measurements. Their results show that the longitudinal vortex imposes local modifications in the heat transfer coefficient through distortion of the mean flow rather than by modifying the turbulence field or by the larger skin friction magnitude caused by the spanwise flow. The data of Westphal et al. (1985) have shown that the turbulence levels are lower than normal in the downwash region of a longitudinal vortex and higher than normal in the upwash region. If these turbulence effects were dominant, the heat transfer behavior should be opposite to that observed in the Eibeck's experiments. The crossflow component of the skin friction would also have a small effect on local heat transfer because the vortices are weak. The validity of the law-of-the-wall in each spanwise station indicated that the flow seems to be dominated by two-dimensional mechanisms near the wall. The local heat transfer coefficients were well predicted by using the local boundary layer thickness and the two-dimensional flat-plate correlation. They concluded that the prediction of the mean flow within the boundary layer may be sufficient for local heat transfer predictions. The measured average heat transfer augmentation was modest when compared to the two-dimensional flat-plate value, although a peak augmentation of up to 23 percent was observed.

Pauley and Eaton (1987, 1988a) extended the above-mentioned work to include the case of a pair of vortices. They observed a broad region of enhanced heat transfer between the vortices, leading to a substantial increase in the spanwise averaged heat transfer. They found that a pair of longitudinal vortices induces stronger distortion in the boundary layer structure. Correlations relating integral boundary layer parameters to the local heat transfer rate were found not to be accurate in the vicinity of a vortex, unlike the case of one single vortex. It was observed that a strong correlation exists between the turbulence intensity near the wall and the local Stanton number even in regions of strong three-dimensional effects. This suggests that the turbulence intensity near the wall plays an important role in controlling the heat transfer rate. Pauley and Eaton (1988b, 1989) also present detailed measurements of the turbulent quantities for pairs of longitudinal vortices generated in a turbulent boundary...
layer to better characterize this kind of that interaction. They observed that the Reynolds stresses in the central vortex core are imposed by the fact that the vortex is generated within an existing boundary layer. The low momentum, highly turbulent boundary layer fluid is concentrated in this core. They found also that the combination of highly turbulent wall fluid and induced vorticity leads to a region of significant turbulent diffusion of vorticity where the secondary flow is directed away from the wall. In an extension of this work, Pauley and Eaton (1994) studied the effect of a vortex arrays on the turbulent boundary layer heat transfer.

Ligrani and co-workers at Naval Postgraduate School have studied the influence of embedded longitudinal vortices on heat transfer of film-cooled turbulent boundary layers. Their primary goal was to offer aids for the thermal design of gas turbines. In their experiments (Ligrani et al., 1988; 1989) the film coolant was injected from a single row of film-cooling holes with a single longitudinal vortex induced upstream using a delta winglet attached to the wind tunnel floor. Measurements of mean temperatures and mean velocities in spanwise planes show that near the downwash side of the vortex, heat transfer was augmented, vortex effects dominated flow behavior, and the protection from film cooling was reduced. Near the upwash side of the vortex, coolant was pushed to the side of the vortex, locally increasing the protection provided by film cooling. The local heat transfer distributions and fluid flow behavior was found to change significantly as the spanwise locations of the vortex is changed with respect to the film-cooling hole locations (Ligrani and Williams, 1990). The experimental results showed that the injection hole centerline must be at least 2.9-3.4 vortex core diameters away from the vortex center in the lateral direction.

Suzuki and co-workers at Kyoto University have dealt with the heat transfer characteristics of a turbulent boundary layer disturbed by a large eddy breakup manipulator (LEBU plate) and a delta winglet type vortex generator. In previous works, Suzuki et al. (1990) verified that the insertion of a LEBU plate in the turbulent boundary layer reduced the heat transfer coefficient and the skin friction coefficient. Therefore, the main idea consisted in using the vortex generator to enhance the heat transfer deteriorated by the use of the LEBU plate. With a convenient combination of the geometric parameters of the LEBU plate and the vortex generator, they found that the net effect would be positive in terms of heat transfer enhancement (Inaoka et al., 1992). The vortex generator's height and attack angle were found to affect the magnitude of heat transfer augmentation, while the cross-sectional position of the LEBU plate was not considered an important factor. In order to further investigate the mechanism of heat transfer enhancement by this combination, Inaoka and Suzuki (1995) measured the three-dimensional mean and fluctuating velocity field by using five-hole pitot yaw-meter and triple V-shaped hot-wire anemometer, and the temperature field by using thermocouples. They concluded that the main reason for the heat transfer enhancement was the changes of mean velocity and temperature fields by the action of the longitudinal vortices. The activation of the near wall turbulence was found to play some role on heat transfer enhancement, particularly in the upwash fluid region.

5. Heat transfer in channel flow

Fiebig and co-workers at Ruhr-Universitat Bochum have conducted experimental and numerical works about the influence of wing-type vortex generators on heat transfer and fluid loss in duct flows. Their main target was to improve the performance of plate-fin heat exchangers. All experimental heat transfer data reported by this group was measured using the liquid-crystal thermometry and the transient technique. The pressure loss data were evaluated by pressure or drag force measurements, depending on the experimental conditions. In one of their first work, Fiebig et al. (1986) reported an experimental work in which the local heat transfer and friction coefficients for channels with various kinds of wing-type vortex
generators were measured. Delta wings, rectangular wings and delta winglets were punched out from the channel wall as vortex generators (Fig. 2). In the experiments with the Reynolds number (ReH, based on the channel height) from 1360 to 2270, the span-averaged Colburn-factor enhancement ranged from one to two with modest increases in friction coefficients. They concluded that the delta wing exhibits the best performance of all shapes. The increase in friction factor was associated to the increase of the projected cross flow area. An extension of this work was reported by Fiebig et al. (1991) in which the same experimental work was carried out focusing on the influence of an isolated generator with different geometry (delta wing, rectangular wing, delta winglet, rectangular winglet, delta winglet pair and rectangular winglet pair). The aspect ratio of the generator was varied from 0.8 to 2 and the attack angle from 10° to 60°, with the Reynolds number (ReH) ranging from 1000 to 2000. The global heat transfer enhancement, considering only the heated plate downstream the generator, was about 50% higher in comparison to the smooth duct, while the friction factor increased 45%. Tiggelbeck et al. (1992) studied the influence of two pairs of delta winglet vortex generators aligned to the flow, with the common flow down. They concluded that the vortical structure generated downstream the delta winglet is not dependent of the flow approaching the vortex generator. The global heat transfer coefficient was augmented by 80% for two rows of delta winglet pairs at ReH = 5600. In an extension of this work, Tiggelbeck et al. (1993) studied the effect of changing the configuration of the downstream winglet pair from the common flow down configuration to the common flow up configuration. The aligned geometry, with both delta winglet pairs with the common flow up configuration, indicated a higher heat transfer performance because of the tendency of the longitudinal vortices pair to remain near the wall. In another work, Tiggelbeck et al. (1994) extended the work of Fiebig et al. (1991) to make a thorough analysis about the influence of the geometry of the vortex generators in the channel flow. The attack angle was varied from 30° to 90°, and the Reynolds number (ReH) from 2000 to 8000. Their result showed that the delta winglet pairs presents better heat transfer results.

One of the first numerical investigation regarding the influence of longitudinal vortex generators on heat transfer was done by Fiebig et al. (1989) who studied the structure of the velocity field and temperature field in a laminar flow inside a channel with the presence of delta-wing type and a pair of delta-winglet type vortex generators. They report a global heat transfer enhancement of 84% in a channel with a pair of delta-winglets with an attack angle of 30° and ReH = 4000. Different values of the attack angle were simulated and the conclusion is that the vortical structure generated by a wing positioned in a channel is different of the structure generated in a free flow. Biswas and Chattopadhyay (1992) studied the same problem numerically, considering also the influence of the stamping hole in the plate after forming the vortex generator. The presence of a pair of winglet type vortex generators with an attack angle of 26°, positioned in a long channel, increased the Nusselt number by 34% and friction factor by 79%, relative to the smooth duct. When the stamping hole is considered, the increase in the Nusselt number is about 10% and the friction factor about 48%. This difference occurs because without the hole, the boundary layer separates upstream the generator, forming the horseshoe and longitudinal vortices. Biswas et al.
(1996) conducted a numerical and experimental study to determine the detailed flow structure and heat transfer effects of longitudinal vortices in a channel flow. The vortical structure consisting of a main vortex, a corner vortex and induced vortices was confirmed also for channel flows.

For turbulent flows in channels with vortex generators, Zhu et al. (1993) studied numerically the influence of the geometry of the vortex generators on the heat transfer and pressure drop. They used the SOLA algorithm and the conventional $\kappa$-$\varepsilon$ turbulent model to simulate the flow and heat transfer. The results for $Re_H = 5000$ indicate that the heat transfer enhancement is strongly related to the increase of the turbulent kinetic energy near the wall. The global heat transfer enhancement was around 16 to 19% for a winglet pair with an attack angle of 25°. For the same case, the increase in the pressure drop was fourfold. The comparison among the four most commonly used types of vortex generators (delta wing, rectangular wing, pair of delta winglet and pair of rectangular winglet) did not indicate a clear superiority of any geometry although the delta winglet pair presented a slightly better performance. Deb et al. (1995) conducted a similar numerical work using a pair of delta winglets positioned in a channel, for laminar and turbulent flow regimes. They used the $\kappa$-$\varepsilon$ turbulent model and compared the numerical results with the experimental data of Pauley and Eaton (1988a, 1988b). For $Re_H = 5000$, they calculated a heat transfer enhancement of 16% in the channel. The authors considered that the conventional $\kappa$-$\varepsilon$ model is accurate enough to simulate the development of the longitudinal vortices. This conclusion is different from that of Liandrat et al. (1986) who conducted a numerical simulation of a turbulent boundary layer in the presence of a skew-induced longitudinal vortex. Their results indicate that only the more complex Reynolds stress models would be able to predict the behavior of the various turbulent quantities.

6. Heat transfer in fin-tube configuration

As mentioned before, Russel et al. (1982) was the first group that focused on the use of vortex generators to enhance heat transfer in fin-tube configurations. Their experimental result, although rough, was very promising because it indicated that vortex generators could enhance the heat transfer without a great additional pressure drop.

In the same way, Fiebig et al. (1990) proposed to enhance the heat transfer of a fin-tube heat exchanger by punching a pair of delta winglet vortex generators ahead and behind the tube, in the plate fin. Their objective was to augment the heat transfer in the recirculating zone behind the tube which has low heat transfer coefficients. In the experiments with the $Re_H$ ranging between 2000 and 5000, they found an increase of the local heat transfer coefficient up to 100% and an increase of the mean heat transfer coefficient up to 20%. By contrast, the flow losses were found to decrease in up to 10% due to form drag reduction caused by the delayed separation on the tube, as shown in Fig.3. These effects had the tendency to increase for higher Reynolds numbers. A similar geometry was studied by Sanchez et al. (1990) who investigated numerically the conjugate heat transfer problem in an element of a plate-fin cross flow heat exchanger consisting of a rectangular channel with a
built-in cylinder. On the bottom wall, that also acted as a fin, two longitudinal vortex generators in the form of delta winglets have been mounted in the cylinder wake. The flow and temperature fields in this channel were calculated by solving the complete unsteady Navier-Stokes and energy equations for incompressible fluid with constant properties. Results for $Re_{\infty} = 1000$ showed that a steady separation bubble appears downstream of the cylinder. Even when the thermal conductivity of the fin was 7500 times larger than the fluid (air), the fin was still not isothermal.

In another numerical work, Biswas et al. (1994) studied the flow structure and heat transfer enhancement in channel with a built-in circular tube and a pair of delta winglet vortex generators positioned downstream. The unsteady laminar three-dimensional numerical calculation was performed by using the SOLA algorithm. Their results indicate that the presence of the winglet type longitudinal vortex generator in the wake region behind the cylinder enhanced the heat transfer of this region by 200%. They also identified a strong interactions between the horseshoe vortices and the longitudinal vortices, yielding a delay in the boundary layer separation on the cylinder and consequently enhancing the heat transfer. A recent work by Fiebig et al. (1995b) considered a similar geometry with heat conduction in the fin. This work is an extension of a previous work (Fiebig et al. 1995a) in which a phenomenon called heat transfer reversal was observed in the channel, formed by conducting walls, with a built in cylinder. The introduction of a pair of the winglet type vortex generator downstream the cylinder enhanced the global heat transfer by 31% for a $Re_{\infty} = 300$ and a fin efficiency of 55%.

In a more application focused experiment, Fiebig et al. (1993, 1994) studied the influence of the winglet type vortex generators in fin-tube configurations with three tubes rows. They measured the heat transfer and pressure loss for different fin spacing, tube arrangement (inline or staggered) and tube form (round or flat tube), as shown in Fig. 4. The results of Fiebig et al (1993) indicate that the heat transfer coefficient was enhanced by 55% to 65% for circular tubes with an inline arrangement and by 9% for staggered arrangement, as shown in Fig. 5. On the other hand, the friction factor was 20% to 44% higher for the inline arrangement, while for the staggered arrangement the friction factor increased only 3%. Their work for flat tubes (Fiebig et al. 1994) resulted in a heat transfer enhancement of 100%, with a similar increase of the pressure loss. The influence of the vortex generators on the flat tube configuration was higher because the overall heat transfer coefficient in the base case (without the vortex generator) for this configuration is smaller than for the circular tube configuration. The vortical system (horseshoe and

Figure 4 Vortex generators in a three-row round tube arrangement

Figure 5 Heat transfer results for a three-row round tube arrangement
wake) behind the circular tube is stronger because of its larger frontal area, yielding a higher heat transfer coefficient in the base case. In this particular case, the flat tube was positioned near the leading edge of the fin, with no local boundary layer growth, which did not allowed the formation of strong horseshoe vortices.

Yanagihara and co-workers at the University of São Paulo have conducted a research program with both experimental and numerical studies dealing with the heat transfer enhancement, by winglet type vortex generators, of fin-tube geometries. The primary application is the compact heat exchangers for the refrigeration and air-conditioning industry. The model consisted in a single-row plate fin tube heat exchanger model, with the delta winglet pairs fixed in different positions over the fin surface. The main difference with the previous works was the Reynolds number ranging from 300 to 2000, which is more realistic considering the industrial application. Yanagihara and Sabanai (1996) performed an experimental analysis in a open-loop velocity controlled wind tunnel using an electrically heated tube with several plate-fins. The global heat transfer coefficient was determined for several locations of the vortex generators on the plate-fin. A maximum intensification factor of 14% (Re = 1000) was achieved positioning the winglets 1.0 D apart and 0.4 D behind the centerline of the tube. The work of Yanagihara and Bayon (1996), using the naphthalene sublimation technique for a similar configuration, indicated that the heat transfer augmentation is dependent on the generator's aspect ratio and attack angle. A winglet type generator with aspect ratio of 1.0, positioned 1.0 D apart and 0.4 D behind the centerline of the tube, yielded an augmentation rate of 18%. For the same generators' position, the best attack angle was close to 52°.

The numerical work of Yanagihara and Rodrigues Jr. (1996a, 1996b) also dealt with a similar configuration. The steady-state analysis was carried out for the Reynolds number ranging from 284 to 1000. The conjugate heat transfer problem was not considered in these cases. The results indicate that flow losses reduction and heat transfer enhancement can be achieved simultaneously. At Re = 284 a reduction of flow losses of about 12% was obtained with vortex generators positioned at r/D = 0.9 and θ = 80° (angle taken from the tube centerline in the main flow direction) while a global heat transfer enhancement of 3% and a local heat transfer enhancement of 350% were achieved. The numerical results for the same geometry with Re = 1000 indicate a flow losses reduction of 20% and a global heat transfer enhancement of 7%. The influence of the attack angle and aspect ratio of the generators was also studied. The numerical results present good agreement with the naphthalene sublimation results, indicating that both approaches are reliable. Fig. 6 shows the influence of the vortex generator on the local heat transfer coefficient, for a vortex generator with aspect ratio A = 1, positioned at r/D = 0.7 and θ = 130°. It is noteworthy how the recirculation region behind the tube, with low Nusselt number, is affected positively by the vortical flow structure. Further numerical and experimental work have been conducted at the University of São Paulo dealing with the influence of fin-tube configuration parameters in a two-row heat exchanger with vortex generators.

Figure 6 Influence of the vortex generator on the local heat transfer coefficient (circled Nusselt number, with V.G.)

7. Concluding remarks

The topic reviewed in this paper concerning the influence of vortex generators on the fluid losses and heat transfer is very interesting and relatively little explored. Although a large amount of research work appered in the recent years, there are many questions...
that can be addressed concerning the applicability of this kind of heat transfer enhancement device in industrial equipments. The flow and heat transfer in industrial equipments are very complex, with many influential parameters. Placing a vortex generator in such kind of channel means adding many other geometrical parameters whose influence should be clarified further. Generally speaking, the research works presented until now deals with some very specific geometrical and flow conditions. Many additional research work should be conducted to study the combined influence of the channel and generators' geometry on heat transfer and pressure loss. Experimental and numerical work in the low Reynolds number regime, for channel geometries simulating compact heat exchangers, are specially important.

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