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Introduction to Vortex Generation for Frosted-Surface Heat Exchanger Performance

Prof. Mr. Bajirao Patil[1] Prof. Dr. Dhananjay Gupta[2] Prof. Mr. Avinash Patil[3]

[1]Principal, P.V.P.I.T., Budhgaon-- Diploma Wing

[2]HOD & Professor (Retired.), Government, College, of Engg, Kota, Rajasthan

[3]Vice Principal P.V.P.I.T. Budhgaon -- Degree wing

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1. INTRODUCTION

1.1 Background

In many refrigeration applications, the evaporator is a plain-fin-and-tube heat exchanger, with a fin spacing of 5-10 mm. These heat exchangers are widely used because they are reliable, inexpensive, and relatively tolerant to frost accumulation. Unfortunately, this heat exchanger geometry does not provide a very high air-side heat transfer coefficient. Enhancing the air-side thermal-hydraulic performance of plain-fin-and-tube heat exchangers can lead to smaller, lighter, and more energy efficient refrigeration systems. In this research we examine the use of vortex generators as an air-side enhancement technique for refrigeration evaporators.

In essence, streamwise vortex enhancement works by imparting a secondary flow to the mainstream, which brings a highly rotational flow in contact with the boundary layer on the surface as shown in Figure 1.1. The downwash region of the vortex thins the thermal boundary layer; whereas, the upwash region thickens it. These surface-normal inflow and outflow regions occupy nearly the same heat transfer surface area, but the response of the convective heat transfer coefficient is nonlinear and thus allows the heat transfer enhancement associated with the inflow to exceed the heat transfer degradation of the outflow. In this way, vortex enhancement is qualitatively

similar to the effect of blowing and suction on heat transfer from a flat plate. This enhancement, however, comes at the cost of an increased pressure drop, due to the shear forces along the fin surface and the form drag of the vortex generators. Because of the linear relationship between shear stress and the velocity gradient, the inflow and the outflow associated with streamwise vortex generation produce nearly equal regions of increased and decreased shear. As a result, the drag on the vortex generator is the main contributor to the pressure drop penalty and is rather small for a plain fin-and-tube heat exchanger where the major source of drag is the tubes.

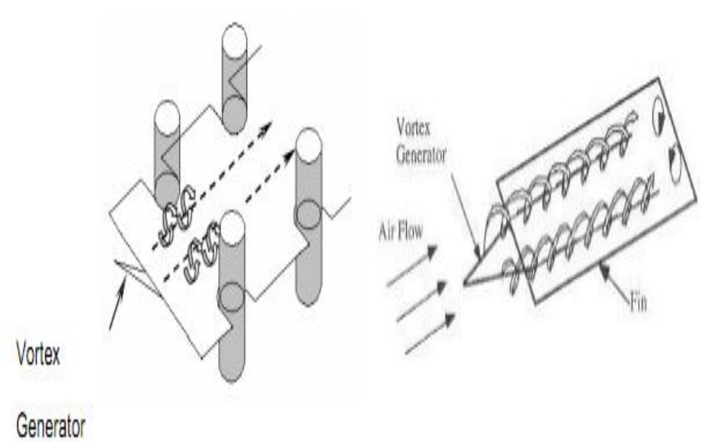

Figure 1.1- Schematic of a vortex generator showing the surface-normal inflow and outflow regions on a fin

The major focus of this research is the impact of accumulating frost on the effectiveness of the vortex generator where the deposition of a frost layer can change the geometry of the vortex generator and affect the flow of the air stream as shown below in Figures 1.2 and 1.3. The major difficulty in studying frost growth on a heat exchanger is the sensitivity of frost growth to environmental parameters (i.e. moisture content, interfacial substrate temperature, surface material, surface roughness, etc.). On an evaporator where the tube wall temperature is continuously changing over the length of the exchanger, it is a real challenge to predict frost properties such as density and thermal conductivity based on interfacial temperature alone. Furthermore, in most evaporators, coolant flow is partitioned into parallel flow and counter flow sections relative to the air stream. This fact, coupled with the observation that frost deposition diminishes with increasing core depth due to a natural reduction in the enthalpy driving potential, makes the use of standard correlations found in the literature very difficult.

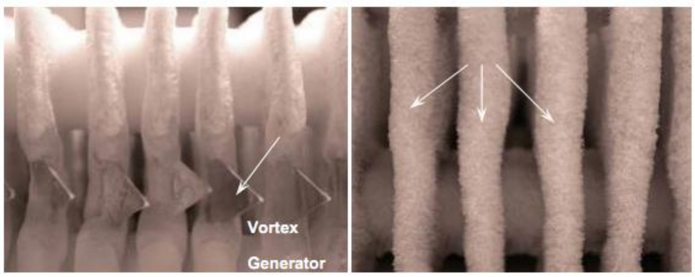

Figure 1.2- Frost deposition on a heat exchanger is known to increase the core pressure drop and degrade thermal performance.

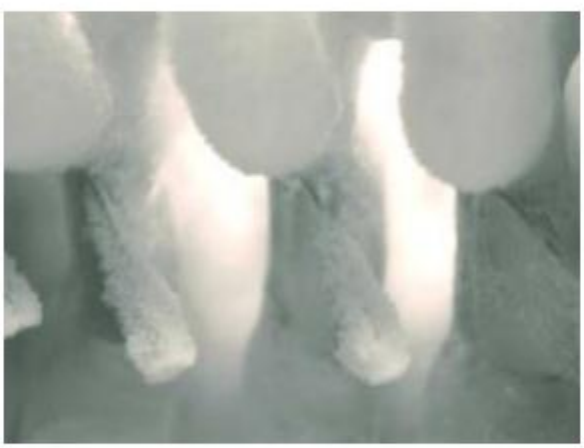

Figure 1.3- Frost growing on a vortex generator can affect the flow geometry.

1.2 Literature Review

1.2.1 Vortex Generator Studies

Several individuals have shown the promise of vortex generation as a means of heat transfer augmentation for flat-plate flows, channel flows, and channel flows with tubes. For example, using unsteady liquid crystal thermography (LCT) to study delta wings in pure channel flow, Fiebig et al. [1991] reported average heat transfer enhancements exceeding 50% with an accompanying 45% increase in the drag coefficient. Using naphthalene sublimation in channel flow for 400< Re <2000, Gentry and Jacobi [1998] found similar enhancements of 20–50% and pressure drop penalties of 50-110% for the delta wing. In a computational study by Brockmeier et al. [1993], the thermal-hydraulic performance of delta-wing vortex generators was found to be superior to conventional heat enhancement methods including plain fins, offset strips, and louvered fins. Experiments conducted on channel flows with tubes have also produced promising results. Fiebig et al. [1994] investigated heat exchangers with 3 tube rows and a delta-winglet pair downstream of each tube. For an inline arrangement, they reported average increases in heat transfer of 55-65% with a pressure penalty of only 20-45%.

Some of the earliest known testing of flow manipulators was performed by Schubauer and Spangenberg in 1959. They studied the effect of forced mixing on boundary layer development in a wind tunnel with slatted wall sections that could be adjusted to generate various back pressures. By using dust injection to demarcate the location of flow separation, they concluded that the general effect of the flow manipulators was equivalent to a decrease in the adverse pressure gradient. Various types of flow mixers were tested, one of which resembled a delta wing that was appropriately identified as a “triangular plow.” The E-3 triangular plow, which had an aspect ratio, = 1.33 and an angle of attack, = 19.5 , was observed to increase the pressure-recovery coefficient at separation from 0.50 to 0.75 as well as extend the point of separation from 4.83 ft to 7.92 ft. The price of this accomplishment was a 78% increase in the momentum thickness.

Critical Reynolds Number

Fiebig [1998] in a technical summary of the literature concluded that for a single vortex generator, heat transfer enhancement increases with the angle of attack reaching a maximum around 45 . He also argued that heat transfer enhancement increases with vortex generator area and decreases with the transverse spacing of the generators. Local heat transfer enhancements of 100% and overall enhancements of 50% were possible, which equates to more than 100 times the area of the vortex generator. These conclusions were primarily deduced from work conducted using delta winglet pairs and rectangular winglet pairs. Fiebig [1998] also reported that vortex generators inserted into channel flow might reduce the critical Reynolds number necessary for onset of turbulence to as low as 350.

Performance Evaluation Criterion Results

In a more recent experimental study of the application of delta winglets to three-row tube bundles, K.M. Kwak et al. [2002] observed heat transfer improvements of 10-25% with a corresponding pressure loss increase of 20-35%. Using performance evaluation criterion (PEC) analysis, they also reported that performance enhancements were higher in the inline arrangement than the staggered arrangement due to the large pressure drop penalty associated with the staggered arrangement. These results spanned a range of Reynolds numbers from 300 to 2700. It should be noted that Kwak et al. [2002] defined the characteristic length used in the Reynolds number as twice the channel height- not the hydraulic diameter.

Optimal Delta-Wing Dimensions

Very few studies have been conducted to optimize the dimensions and construction of the vortex generator. Gentry and Jacobi [1998] performed a parametric study of a single delta-wing vortex generator under developing channel flow using naphthalene sublimation by examining such effects as aspect ratio, angle of attack, and Reynolds numbers common to the HVAC&R industry (i.e. Redh = 400-2000). In this study, Gentry varied the aspect ratio, , between 0.5 and 2.0 while fixing the angle of attack, , at 15 , 35 , or 55 . At low Redh, which is of particular interest for domestic refrigeration research, the Sherwood enhancement ratio was relatively small over the majority of the parameter space. The peak value of approximately 1.25 occurred for = 2.0 and =55 . In fact, Gentry found the greatest enhancement occurred with = 2.0 and =55 for all three Redh in the channel flow.

Effect of Vortex Generator Stamping

Biswas and Chattopadhyay [1992] presented a numerical study on the effect of a punched/stamped hole beneath the delta wing on the spanwise average Nusselt number, friction factor, and vortex strength. In their study, they assumed perfectly aligned holes and imposed spacewise-periodic boundary conditions at the location of the punched holes. Grid refinement was performed to ensure nearly grid-independent results. For the case of stamping, fluid entrainment through the upper hole was observed, and fluid was lost through the hole underneath the wing. The consequence was a decrease in the magnitude of the velocity vectors behind the wing and a decayed circulatory flow pattern for the same axial location. As a result, the enhancement in heat transfer at the channel exit due to the delta wing was 34% in the absence of stamping as compared to only approximately 10% when stamping is used. However, the spanwise averaged friction factor, (f x Re), for the case of the delta wing with stamping was 31% lower than that for the case of the attached delta wing without stamping.

Vortex Breakdown

Using naphthalene sublimation and the heat and mass transfer analogy, Gentry and Jacobi [1997] demonstrated the possibility for a 50% to 60% enhancement in the average heat transfer using delta-wing vortex generators for flow over a flat plate at low Reynolds numbers (Re = 600-1000). Gentry and Jacobi also showed that vortex breakdown occurs approximately four chord lengths downstream of the wing.

Core Pressure Drop

Fiebig et al. [1990] examined small, punched-out delta-winglet pairs in a wind tunnel with a vertical test section. These winglets, which had a winglet-to-fin area ratio of 0.003, were placed in simple channel flow and angled relative to tubes inside the test section. For Reynolds numbers between 2000 and 5300, the winglet pair exhibited an overall heat transfer enhancement of 20% under optimal geometrical conditions. More interesting, however, was the corresponding 7% reduction in drag. This research shows the possibility for a winglet pair in a fin- and-tube geometry to simultaneously increase heat transfer while decreasing flow losses.

Full-Scale Testing

Full-scale implementation and testing of vortex generators in heat exchangers is only sparsely reported in the literature. One of two known tests was performed by Russell et al. [1982] as part of a project for CE-Lummus. Their experiments relied on a transient melt-line method to gauge the effectiveness of various vortex generator configurations in full-scale flat tube heat exchangers. As a result of their work, the rectangular winglet placed in two staggered rows with a 20 angle of attack was identified as the most promising configuration. For a Reynolds number of 500 based on hydraulic diameter, the j factor was enhanced by 47% while the f friction factor increased

by 30%. The results were even more encouraging for Reynolds numbers 1500 to 2200 where the j/f ratio was observed to exceed 0.5. The main weakness of their work, however, was their reliance on existing plain-tube correlations as the basis for their comparison. Full-scale tests on unenhanced but otherwise identical coils were never performed.

A more recent full-scale test of delta-wing vortex generators on a plain-fin-and-tube heat exchanger showed considerable heat transfer augmentation with little to no associated pressure drop penalty [El Sherbini and Jacobi, 2000]. For this study, two different delta wing sizes were tested on a plain-fin heat exchanger common to refrigerator applications. The result of using the smaller wings was a 14% to 18.3% increase in the Colburn j-factor whereas the larger wings produced a 24.7% to 31.3% increase in the j-factor with a maximum uncertainty of 9%. In both cases, the wing-to-fin area ratio was less than 1.5% and thus constituted a negligible addition to the fin material. The most surprising result of this study, however, was the negligible change in the friction factor associated with these heat transfer improvements. Previous research by others has suggested that passive enhancement by vortex generation would almost certainly incur a drag penalty. So, this negligible penalty in pressure was very interesting and attributed to the dominating pressure drop across the tubes in the heat exchanger.

1.2.2 Frost Growth Studies

Because of the breadth of encompassing literature, this topic will be subdivided for ease and convenience into frost properties, growth rate models, and the holistic testing of evaporator coils under frosting conditions. Many more studies on frost growth exist in the literature (White and Cremers 1981; Ogawa, Tanaka, and Takeshita 1993; Schneider 1978; Tao et al. 1993; Gall and Grillot 1997; and Inaba and Imai 1996), and the reader is encouraged to consult these sources as well. What follows is the author's attempt to emphasize those findings deemed especially relevant to this study.

Frost Properties

concluded that the plate surface temperature and the relative humidity of the air stream both affect frost thickness; whereas, the density of the frost largely depends on the air velocity and to a lesser extent on the relative humidity. Density, however, was independent of surface temperature. Similarly, the mass deposition rate of the frost was shown to have considerable dependence upon the relative humidity and air velocity. The mass rate was 3.6 times greater at 72% relative humidity than it was at 31%. The mass rate increased by a factor of 2.4 during tests conducted with an air velocity of 5.7 m/s compared to 2.6 m/s. A transient one-strip method was used to measure the frost properties. A weighing plate was used to measure frost accumulation, and a micrometer fitted with a fiber optic endoscope was used to measure the frost thickness. By taking the partial derivative of frost mass with respect to time, O□□ stin and Andersson also examined the contribution of the mass flux of condensed vapor to frost density and frost thickness. They found that for times greater than 60 minutes, the contribution of the mass flux that went towards increasing the frost thickness varied between 0.41 and 0.65 with an average value of 0.49. This fact suggests that under quasi-steady conditions, the condensing water vapor contributes nearly equally to the increase of frost density and frost thickness. polynomial-based correlation for the thermal conductivity (k = -8.71x10-3 + 4.39x10-4• +1.05x10-6• 2) that yielded conductivities in the range of 0.05-0.2 W/m-K for frost densities in the range of 75-275 kg/m3.

Rite and Crawford [1991] also looked at the impact that various environmental parameters have on the frost rate. The evaporator tested was a top-mount, automatic defrost mechanically fit model with a fin spacing of 5 fpi that employed a parallel-cross/counter-cross flow arrangement. Relative humidity was controlled using a heated, evaporative-pan humidifier. In this study, a maximum discrepancy of 15% existed between calculating the frosting rate by direct measurement of the water level in the pan and the weighing of the frosted coil. This discrepancy suggests that a theoretical frost deposition rate based on experimentally collected upstream and downstream relative humidities should be acceptable. Rite and Crawford also observed that the accumulation of frost on the coil did not significantly influence the frosting rate flux. The average frosting rate flux was essentially the same after 10 hours as it was after 5 hours. Rite and Crawford also explained a discrepancy found in the literature concerning the effect that velocity has on the frosting rate. Earlier work by Senshu [1990] had suggested that the frosting rate decreases with increasing air velocity. Other researchers, however, observed the opposite trend. Rite and Crawford explained this apparent contradiction by examining four parameters linked to the airflow rate that affect the frosting rate. These parameters are the mass transfer coefficient, surface temperature, air temperature, and moisture capacity of the air. Rite and Crawford showed that the mass transfer coefficient, air temperature, and moisture capacity of the air all increase with the airflow rate which tends to promote the mass driving potential. The surface temperature, on the other hand, also increases with the airflow rate, but this effect serves to decrease the driving potential. The net effect of the airflow rate on the frosting rate then is the sum of the relative contributions from these influences.

Theoretical Growth Rate Models

Cheng and Cheng [2001] proposed a theoretical model for predicting the frost growth rate on a flat plate. The Hayashi [1977] correlation was used to calculate the frost density, and the correlation by Brian et al. [1970] based on the mean frost surface temperature and the average frost density was used to calculate the effective thermal conductivity of the frost layer. Assumptions inherent to their model included uniform frost density throughout the frost layer at any instant, orthogonal growth of the frost layer relative to the plate surface, uniform frost thickness, and constant heat and mass transfer coefficients (h and hm) on the frost surface. The derived expression for frost thickness using these forth stated assumptions and correlations is

$$\frac{d\delta_f}{dt} = \frac{h_m (w_a - w_s)}{147.55\,\delta_f \exp[0.277(T_s - 273.15)](dT_s/d\delta_f) + \rho_f}$$

where the first term in the denominator accounts for the water vapor that goes to increase the frost density and is equal to drf /dt. Their model, however, assumes a Lewis number of unity and a driving potential based on a linear difference (instead of a log-mean difference) of the humidity ratios between the air and the frost surface. Comparisons were made with other existing theoretical models by Jones and Parker [1975] and Sherif, et al. [1993].

Cheng and Wu [2003] examined frost formation on a flat plate subjected to atmospheric air flow in a suction-type, open-loop wind tunnel using a CCD camera and a PCI frame grabber at an image-sampling rate of 5 seconds. Cheng and Wu distinguished between three different time periods in the formation of frost as was done previously by Hayashi [1977] and called them the crystal growth period, frost layer growth period, and full growth period, respectively. According to Cheng and Wu, in this last period a multiple-step ascending frost growth pattern emerges, which periodically results in a slight decrease in the frost thickness due to the melting of frost crystals on the surface, the collapse of the frost layer, and the penetration of melted water. The range of the examined environmental parameters were 2V 13m/s, 20 Ta 35 C, 40% 80%, and -13 Tw -2 C. Cheng and Wu also offered several reasons for the disparity of results in the literature concerning the effects of air temperature on frost thickness. One explanation they put forward was that when warmer air arrives at the frost surface, it may not be cooled immediately to below the freezing point but may enter the frost layer and aid in densification instead of surface-level deposition. A second explanation offered by Cheng and Wu was that the higher temperature air raises the frost surface temperature and in this way promotes the melting of the frost columns and branches at the surface. It was also noted, however, that higher temperature air usually can hold more moisture, a phenomenon known to increase the driving potential. Cheng also checked these experimental results against his model described above. The data agreed reasonably well with the model, especially during the frost layer growth period.

Evaporator Performance with Frost

In a separate paper, Rite and Crawford [1991] also extensively and systematically studied the effects of various parameters (i.e. RH, air flow rate, and air temperature) on the UA-value of a mechanically fit, domestic refrigerator evaporator under frosting conditions. They found that while holding the air flow rate constant, the UA- value steadily increased as frost was deposited on the coil. This result differed from earlier studies, which reported an initial increase in UA followed by a decrease in UA with continuing frost deposition. To further substantiate this claim, Rite and Crawford conducted a single 24-hour experiment over which the UA-value eventually leveled off but never showed evidence of decreasing. They also claimed that the thermal conductivity of the frost layer had only a small to modest influence on the heat transfer of the evaporator (contrary to the insulating effect suggested by other researchers) since the UA-value increased for the duration of their testing. Finally, by attaching type-T thermocouples to the fin, Rite and Crawford showed that although the surface resistance decreased by 10% during the test period, the contact resistance only decreased by approximately 2%, suggesting that the filling of the gaps between the tube and fin was negligible.

Mago and Sherif [2002] modeled the process path of an industrial evaporator coil under frosted conditions. The motivation for the study was to determine the thermo-physical properties of the air stream leaving a given row of an n-row coil with the hope of identifying the location where the moist air stream reaches a supersaturated state on the psychrometric chart. Supersaturated conditions lead to the generation of airborne ice crystals, which produce snow-like frost on the heat exchanger surface and degrade the capacity of the coil. In this paper, Mago and Sherif used a log- mean enthalpy difference method that was based on a fictitious saturated air enthalpy evaluated at the refrigerant temperature. Their work confirmed that as the relative humidity of the entering air is increased, the transition to supersaturated air occurs earlier in the coil.

1.2.2 Studies of Vortex Generation Under Frosting

CONDITIONS

Aside from early work by Storey and Jacobi [1999] for a channel flow, no research on the use of vortex generators under frosting conditions has been reported where the accumulating frost can change the geometry of the flow. Moreover, although this research in channel flow qualitatively suggested that the vortex generator should function properly under frosting conditions and should not affect frost thickness, this hypothesis was not tested on a full-scale heat exchanger.

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