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A Review of Experimental Study of Turbulent Heat Transfer in Separated Flow

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Abstract: This paper presents review of experimental studies of turbulent heat transfer in separation flow. Enhancement of turbulent heat transfer rate in separation region with sudden expansion in passage or flow over backward and forward facing steps have been chronologically presented with experimental observations. Augmentation of turbulent heat transfer rate in separation flow by introducing swirl generators in pipes, annular pipes, and with sudden expansion in passage has been high lighted. Different geometries of rib with rectangular and square ducts in turbulent flow in a number of studies have confirmed increase of heat transfer coefficient in separation flow behind ribs.In the review, detail effect of Reynolds number, heat flux, expansion ratios, and twisted tape on heat transfer and pressure drop are considered along with experimental studies that included only turbulent flow range with heat transfer. Further works on sudden expansion along with ribs at different intervals and geometries at particular portion of a channel or all through could be conducted to see the augmentation effect in different consequences.

Key words: Separation flow, Sudden expansion, Facing step, Bluff plates, Ribs channel, Swirl generators

INTRODUCTION

Turbulent heat transfer in separated flow fields is an attractive and important phenomenon. The separation flow generated by sudden expansion or contraction in passage, flow over forward and backward facing step, in channel ribs, and used swirl generators in passage, occurs in many different practical flow geometries such as heat exchangers, nuclear reactors, combustors and cooling channels. Separation occurs in turbulent and laminar flows. In the present paper, the turbulent flow separation has been studied to a greater extent. This is because:
a) Turbulent flows are more frequently encountered than laminar flows.
b) Separation is more likely to occur when the flow is turbulent.
c) Due to inertial effects, separation has a much greater influence in turbulent flows.

There is a great change of the local heat transfer rate in the separated flow regions and considerable heat transfer augmentation may result up to the reattachment region. Knowledge of convective heat transfer rate in separation flow regions has been consolidated in this review paper and provided more information and precise analysis associated with heat transfer as well as a complete physical understanding of the flow. For turbulent heat transfer in separated flow, all analyses are preferred eventually depended on experimental. The published experimental papers related to turbulent heat transfer in separated flow, could be categorized into: Sudden expansion, forward and backward facing step, Blunt body, Ribs channel, and Swirl generators. Some results of their investigation have been incorporated in this paper.

Experimental studies:

There are many researchers, who investigated experimental study of turbulent heat transfer in separation flow with different geometries such as separation flow for sudden expansion in passage, backward or forward facing step, blunt body, rib channels, and swirl generators. We selected the summary of references which graduated from the earliest studies to recent studies and included more detail about turbulent heat transfer in separation flow.

Sudden expansion:

Boelter *et al*. (1948) presented results of investigations conducted to observe the distributions of the heat transfer rate of air flowing in a circular pipe in the separated and reattached regions downstream of an orifice. The investigation was performed in Re range of 17,000 to 26,400 and the test pipe having 2 inch outside and 1.78 inch inside diameters respectively. They used various entrance sections as shown in Figure 1 which makes variation of point of reattachment at entrance pipe. From the experimental data obtained, they found maximum heat transfer coefficient near the point of reattachment which is about four times away of the length of fully developed flow.

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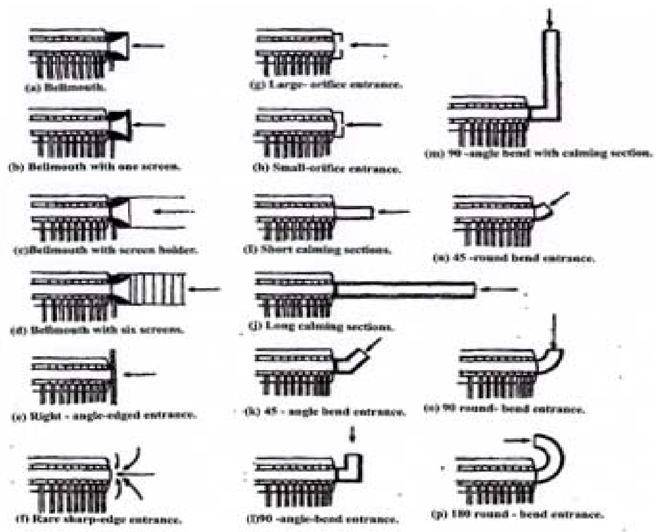

Fig. 1: Circular pipes with various entrance sections.

Ede *et al*. (1956) have investigated the effect of an abrupt convergence of straight pipe on the local heat-transfer coefficient for flowing water. The experimental covered for Reynolds numbers from 800 to 100,000 corresponding to a smaller pipe of diameter 1 inch. The pipe was heated through the longitudinal passage with intense direct current during the wall. They have observed comparatively small disparity in local heat transfer coefficient. It does not differ significantly with the variation created in the entrance regions of pipes under more normal entry conditions. They also determined effect of an abrupt divergence at Reynolds numbers from 3,700 to 45,000 and they observed a considerable variation in local heat transfer coefficient. Koram and Sparrow (1978) had performed experimental study of turbulent heat transfer of water flowing in circular pipe with unsymmetric blockage (segmental orifice plate) for range of Reynolds number from 10,000 to 60,000.

Krall and Sparrow (1966) conducted experiments to determine the effect of flow separation on the heat transfer characteristics of a turbulent pipe flow. The water flow separation was drive by an orifice situated at the inlet of an electrically heated circular tube. The degree of flow separation was varied by employing orifices of various bore diameters. The Reynolds and Prandtl numbers were varied from 1000 to 130000 and from 3 to 6 respectively and ratios of the orifice to the tube diameter ranged from 2/3 to 1/4. Results show that the augment of the heat transfer coefficient due to flow separation accentuated with the decrease of Reynolds number decreases as shown in Figure 2. They have also found the effect of expansion ratio on the distribution temperature. The point of flow reattachment, which corresponds to maximum value of the heat transfer coefficient was found to occur from 1.25 to 2.5 pipe diameter from the onset of flow separation. Suzuki *et al*. (1982) performed experiment to study heat transfer and visulation of flow and surface temperature in the recirculating flow of an orifice in tube where they obtained results similar to (Krall and Sparrow 1966).

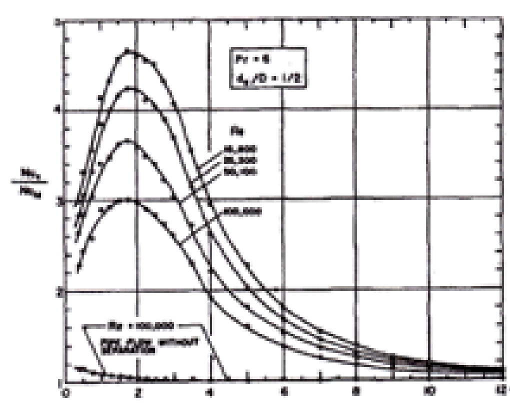

Fig. 2: Local Nusselt number distribution Ref.

Filetti and Kays (1967) presented experimental study on separation flow and heat transfer through flat duct with double step. They showed the highest heat transfer occurs in both long and short stall on sides at the point of reattachment, followed by decay towards the achievement of fully developed duct flow also they observed at different distances on the two walls of the duct the boundary-layer reattachment occurred and these distances are independent of Reynolds numbers. Again the long and short stalls can be moved to the opposite walls by use of a vane well upstream of the separation point. Figure 3 presents Nusselt number versus normalized distance downstream step for expansion ratio (2.125). Also Seki *et al*. (1976, 1976) performed experimental study on effect stall length and turbulent fluctuations on turbulent heat transfer for separation flow behind double step at entrance flat duct.

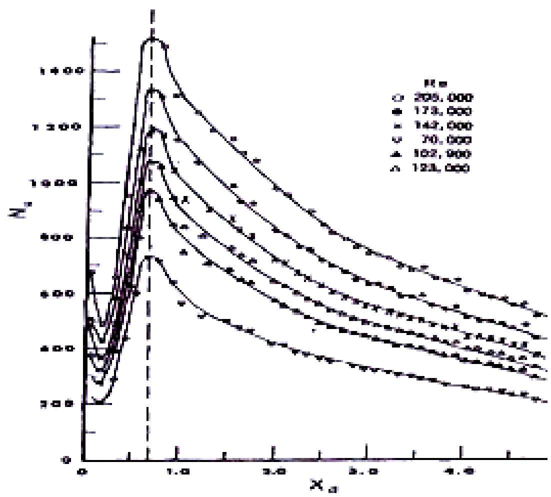

Fig. 3: Local Nusselt number distribution.

Zemanick and Dougall (1970) carried out experimental study of heat transfer to fluid flow in abrupt expansion of circular channel. Three expansions maintained during the test ratios of upstream –to- downstream diameter of magnitudes 0.43, 0.54 and 0.82 were considered with air as the working fluid. They have presented data for Reynolds numbers from 4000 - 90000, corresponding to the geometry of the ducting. For the range of the Reynolds numbers and expansion ratios studied, the following conclusions could be drawn from the test data:

1-The flow beyond an abrupt expansion in a circular duct shows a significant augmentation (over the fully developed value) of the average convective heat transfer coefficient in the separated flow region.

2-The degree of heat transfer coefficient enhancement increase with the increase of diameter ratio.

3-The location of highest heat transfer moves downstream as the ratio of downstream to upstream diameter increases.

4-The peak Nusselt number observed a apparent dependence on upstream.

5-In the **Nu-Re** expression, the Reynolds number exponent raised to a magnitude of approximately 2/3. The equation (1) reasonably represents the maximum Nusselt number data of all three geometries tested:

$$Nu_{max} = 0.20{Re_d}^{0.667} \quad (1)$$

Smyth (1974) conducted experiments to study of the physical effects of separation and the associated reattachment and redevelopment, on the heat transfer characteristics of turbulent flow in pipes and to compare the results of these flow conditions with the fully developed one-dimensional flow condition. He also compared results with a recently developed numerical technique for the solution of recirculation flows. Separation of the flow was induced in a 4 ft length of 2 in. internal diameter tube of wall thickness 0.001 in. by means of a sudden enlargement of diameter at the entry of the tube. The tube was electrically heated by the passage of a current along its length. The first 25 in. of the tube was monitored by thermocouples which gave the wall temperatures and from these the local heat transfer rates were measured at Reynolds numbers up to 5 x 10^4 using air as the working fluid. There is a comparison between prediction and experiment as presented in Figure 4, he found modest agreement at points near the peak of Nusselt number but greatly poorer agreement in the developed region after reattachment of the flow.

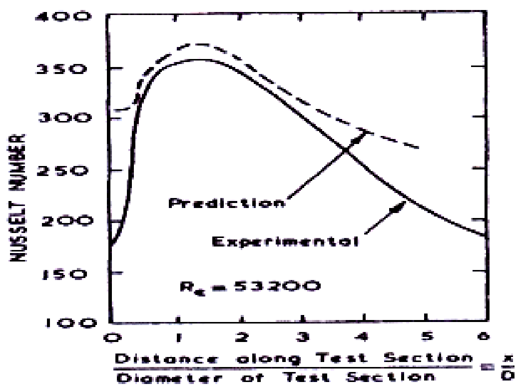

Fig. 4: Experimental and predicated Nusselt numbers.

Baughn *et al*. (1984) presented experimental study of the local heat transfer coefficient to an air flow downstream of an axisymmetric abrupt expansion in a circular channel with constant heat flux. They used a range of expansion ratios (d/D), small diameter to large diameter of 0.266 to 0.800 over the Reynolds number range of 5,300 to 87,000. From the experimental data obtained for all expansion ratios, the value of Nu/Nu_{DB} falls monotonically for d/D= 0.266 with the increase of Reynolds number as shown in Figure 5. This behavior is qualitatively satisfying the water tests (Ede *et al*. 1956) but differs with the out come of air study (Zemanick and Dougall 1970) for downstream Reynolds numbers above 30,000, where the ratio of peak to fully developed Nusselt numbers became independent of Re. Further details are shown in Figure 6, they have obtained the Reynolds number dependency on the maximum Nusselt number compared to the equation suggested by (Zemanick and Dougall 1970) using Re_d instead of Re_D in order to find the effect of expansion ratios on the Nusselt number. Also Runchal (1976), Baughn *et al*.(1985, 1987a, 1987b, 1989), Iguchi and Sugiyama (1988), and Habib *et al*.(1992, 1992) have investigated effects of Schmidt numbers, Reynolds number, expansion ratio, velocity, segmented baffles, baffle spacing, baffle material and heat flux on the local heat transfer coefficient where they obtained on the augmentations of heat transfer.

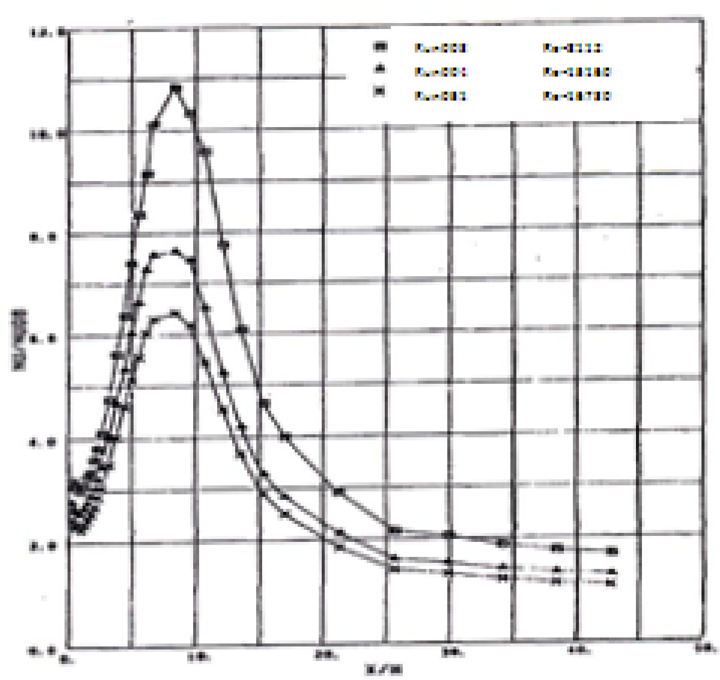

Fig. 5: Heat transfer at the downstream of the abrupt expansion, d/D=0.266 and various Re.

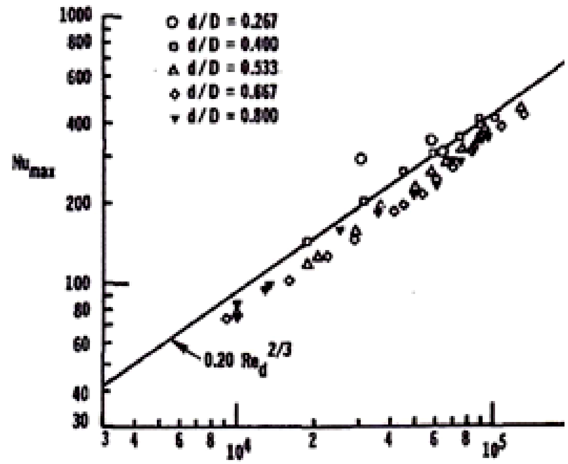

Fig. 6: Reynolds number dependency on the maximum Nu number compared to an equation. suggested by Zemanick and Dougall (1970).

Khezzar *et al*. (1999) performed experiments to study the combustion of premixed fuel and air downstream of a plane sudden-expansion. They used an area expansion ratio of 2.86 and a Reynolds number of 20,000, and the combusting flows comprised of premixed methane and air over a range of equivalence ratios with emphasis on values of 0.72 and 0.92. The results showed that the degree of asymmetry of the isothermal flows was decreased by pairing the pressures between the two recirculation regions, and by striking oscillations at the half-wave or full-wave frequency of the duct, and by combustion. Periodic variations of velocities, acceleration, temperature and flame shape were showed in understanding with the main pressure fluctuation of rough combustion, and the length of the recirculation zones varied from less than 0.5 to 3 steps and those results confirmed the experimental data reported by De Zilwa *et al*. (1997).

Jing and Chun (1996) carried out experimental study of heat transfer from a hot stream flowing during a sudden expansion where cold air injected from its porous base. The combustor entrance used have 30 mm high and 200 mm wide and the aspect ratio (channel width to step height) for the step height (15mm) was 13.3. The results indicated, increase in the length of recirculation zone about 7.8 times of the step height when the Reynolds number go over 6300 so that the length of recirculation zone was in the same variety in comparison with Tsou *et al*. (1991), and Soong and Hsueh (1993). They have also reported that by decreasing the temperatures in the recirculation zone obtain from cooling effects of the injected fluid were more considerable in the recirculation zone than other regions due to the velocity in that region was much smaller than the measured velocity in the free stream and the redeveloped boundary layer. On the other hand they have found that the maximum and average Nusselt numbers were larger in a higher Reynolds number.

Sang and Ota (2010) presented experimental results on study of turbulent separation flow and heat transfer in a symmetric expansion plane channel. The step used was 20 mm high and 200mm wide and the Reynolds number maintained from 5,000 to 35,000. From the experimental measurements of the mean and turbulent fluctuation of temperatures and velocities, they obtained that local Nusselt number profile was significantly different at the lower and upper walls result the Coanda effect caused by instability between the lower and upper separated shear layers. These results show relevant agreement with Ohori-Yuki *et al*. (2004). In this study (Sang and Ota 2010) they used the empirical formulas (2, 3) and obtained the difference between heat transfer from the lower and upper walls which increased with an increase in Re and reached up to about 45%.

$$Nu_{max} = 0.079\left(U_{ref}\frac{H}{\upsilon}\right)^{0.071}\text{(Upper wall)} \tag{2}$$

$$Nu_{max} = 0.053\left(U_{ref}\frac{H}{\upsilon}\right)^{0.0712}\text{(lower wall)} \tag{3}$$

While Dae-Hee Lee *et al*. (2011) performed numerical and experimental study of heat transfer at axisymmetric sudden expansion followed by an sudden contraction called (cavity) in a circular channel with uniform wall temperature. The experimental results revealed that the maximum Nusselt numbers appeared between 9 and 12 step heights from expansion step as shown Figure 7. They also obtained a good agreement with numerical results evaluated by using equation (4) for local Nusselt numbers.

$$Nu(x) = \frac{h(x)D}{k_s} = \frac{V_s^2 D}{[A_s(T_s(x) - T_b(x))K_s R_s]} \quad (4)$$

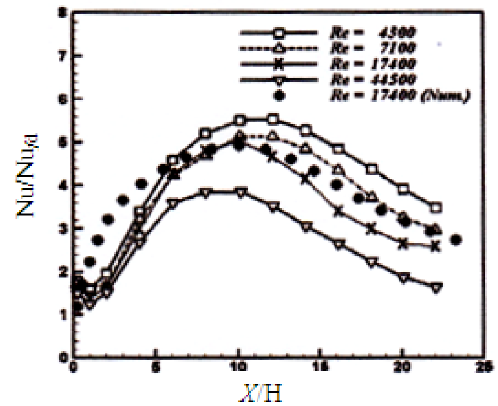

Fig. 7: Distribution of local Nusselt number in the axisymmetric abrupt.

Hussein *et al*. (2011) carried out experimental study of turbulent heat transfer and separated flow in annular passage. They found of effect separation flow on the average and local convective heat transfer and observed augmentation of local heat transfer coefficient occurred with increase heat flux and or Re while step height effect was clear at separation region and obtained increase in the local heat transfer coefficient with increase of step height.

Forward and backward facing step:

Seban *et al*. (1959) studied experimentally heat transfer in the separated, reattached, and redeveloping flow regions around the downward facing step. They found that the heat transfer coefficient reached a highest value at the reattachment point, and after that decreases as shown in Figure 8. To demonstrate the relative effect of the suction and injection, Seban (1966) investigated experimentally the heat transfer and fluid flow in a separated region downstream of a backward facing step for fixed rates of suction and injection through a slot at the base of the step, with air velocities in the free stream varied in the range from 15 to 45 m/s. The apparatus was constructed providing a top wall of rectangular duct as test surface of the cross section 117.5 mm height by 300 mm width having a plate of 300 mm wide and 457.5 mm long at its forward edge a 5 mm slot providing a tangential inlet for injected flow. The slot was surmounted by a 25 mm step making the total step height at this location 30 mm .With fixed suction , the length of the separated region decreases as the free–stream velocity is reduced and the maximum value of the group (h/k) (υ/Ua) 0.8 is also increased. With injection, there is no region of separated flow at the wall when the free–stream velocity is of the same order of the injection velocity and the local heat transfer is at first influenced primarily by the injection velocity.

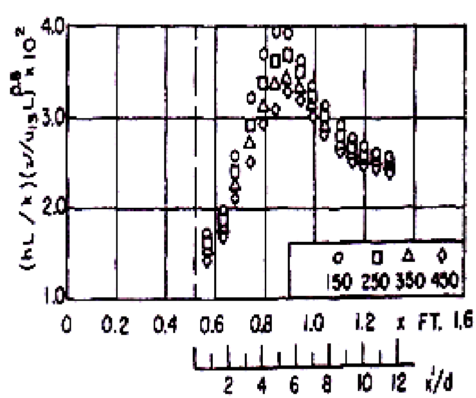

Fig. 8: Local heat transfer coefficient.

Sogin (1964) performed experiments on a bluff flat plate stripe in two dimensional flows. It was instrumented to measure local heat flux and temperature distribution under steady–state conditions. Different configurations were obtained by changing angle of incidence or modifying its cross–sectional profile. Air speed ranged from 12 m/s to 47.5 m/s and the Reynolds number based on 170 mm chord length ranged from 100000-440000. The nominal blockage ratio was (0.21) when the angle of incidence was 90 degree. The local heat transfer by forced convection from the base surface of a bluff obstacle presented for a variety of configuration. The data were satisfactorily represented by equation of type (5).

$$Nu = C.\, Re^{0.667} \tag{5}$$

The coefficient (C) of equation (5) depends upon the configuration and the location. Its value was formally 0.2 on the rear of flat plate strip at 90 degrees angle of attack. It diminishes wherever any device can come close to the dead air space, or reduce its size. Results concluded that the device which increased the size of or open the dead air region had increased the heat transfer and those which reduced confinement had also reduced the heat transfer. Habib *et al*. (1994) also presented experimental study of turbulent flow and heat transfer over baffles of different heights staggered in rectangular duct.

Mabuchi *et al*. (1986) studied effect of free stream turbulence on heat transfer in the reattachment region on the bottom surface of a backward facing step (for different angles of separation) also Suzuki *et al*. (1991) have studies of effects of cylinder mounted near the top corner of the step, while Ota *et al.* (1995) performed investigation to observe the effect of inclined downstream step on turbulent separated and reattached flow, and Oyakawa *et al.* (1996) made estimate of thermal performance on heat transfer improvement by passive and active methods at downstream region of backward-facing step. The effect of the step height on the turbulent mixed convection flows over a backward-facing step reported by (Abu-Mulawah *et al*., 2002 and Abu-Mulawah, 2002) studied effects of backward and forward facing steps on turbulent natural convection flow along a vertical flat plate where they showed that the highest local Nusselt number occurred at the reattachment region.

Vogel and Eaton (1985) studied combined fluid dynamic and heat transfer measurements in separated and reattaching boundary layer, with emphasis on the near – wall region. A constant heat flux surface behind a single sided sudden expansion to flow was made to obtain Stanton number profiles as a function of Reynolds number and boundary layer thickness at the separation region at Reynolds number ranged from 13000 to 42000 with the expansion ratio 1.25. Investigation considering Reynolds analogy to determine heat transfer coefficient using the local skin friction, revealed that the reattachment causes a local augmentation of the heat transfer coefficient, so it recovers fairly and rapidly the flat plate behavior at the downstream of reattachment. Well downstream of reattachment, the near wall layer behaves like that under an ordinary turbulent boundary layer. Results also showed that the peak in the Stanton number around reattachment varies as the (- 0.4) power of the Reynolds number ($Nu_d \times Re^{0.6}$), while for the flow over flat plate, Stanton number varies as the (- 0.2) power of Reynolds number ($Nu_d \times Re^{0.8}$).

For measuring details of the heat transfer near the reattached point of the separated flows, Mori *et al.* (1986) used the thermal tuft probe while Kawamura *et al*. (1987, 1991) designed new heat flux probe to determine time and spatial characteristics of heat transfer at the reattachment region of a two dimensional backward facing step deign. Oyakawa *et al*. (1994, 1995) also used jet discharge at reattachment region downstream of backward facing step. While Tsou *et al*. (1991) carried out experimental study of the starting of heat transfer at downstream of a backward-facing step by using a Ludwieg tube wind tunnel to produce an incompressible flow.

Terekhov *et al.* (2003) reported experimental study of hydrodynamic characteristics of the gas flows past a rib and a downward step in feature separation flow regions, and distributions of temperatures, heat transfer coefficients and pressures behind the obstacles. They determined the effect of improved external turbulence on dynamic and thermal features of the separated flow and they also showed the results obtained agree with previous data for a downward step (Alemasov *et al.* 1989) where a 10-5% augmentation obtained at the maximum recirculation velocity. They have seen a decrease in the obstacle height results in a significant augmentation of the heat transfer and the maximum is located closer to the obstacle. For the flow with separation past a rib, the maximum heat transfer is shifted also in the downstream direction from the flow separation point compared to the case of a downward step.

Abu-Mulaweh (2005) studied experimentally the turbulent fluid flow and heat transfer of mixed convection boundary-layer of air flowing over an isothermal two-dimensional, vertical forward step. They studied the effect of forward–facing step heights on local Nusselt number distribution as shown in Figure 9, and obtained that the local Nusselt number increases with increasing step height and reaching a greatest value at the reattachment region. The present results indicated that the increase of step height leads to increase of intensity of temperature fluctuations, the reattachment length transverse velocity fluctuations and the turbulence intensity of the streamwise.

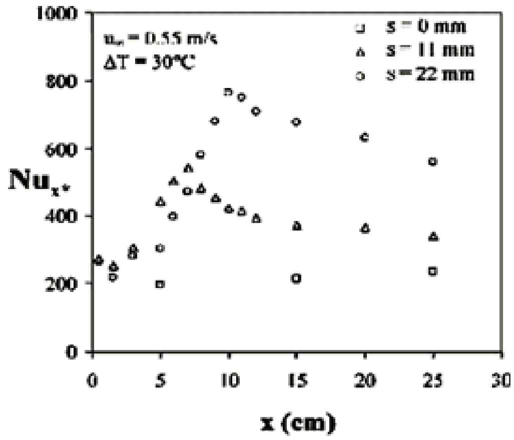

Fig. 9: Local Nusselt number variation downstream of the step.

Sano Masatoshi *et al*. (2009) presented experimental results of the turbulent channel flow over a backward-facing step by using suction through a slit at the bottom corner of the step and the direction of the suction was perpendicular and horizontal to the main flow. They measured local heat transfer coefficient and wall static pressure behind the backward-facing step and the results indicated the enhancement of the heat transfer coefficient in the recirculating region by suction and reduction of the pressure drop. Also they observed improvement of the heat transfer coefficient occurred with the increase in turbulent energy.

Blunt body:

Sorenson (1969) performed experimental study of Local and average mass transfer coefficients on a sharp-edged plate and on truncated slabs of various thicknesses. The results showed that the mass transfer coefficients did not only dependent on the air velocity and the distance from the leading edge, but also the thickness of the slabs are significant Ota and Kon (1974) studied the heat transfer measurements in the separated, reattached and redeveloped regions of the two dimensional air flows on a flat plate with blunt leading edge. The used test plate (20 mm thick, 100 mm wide and 400 mm long) was made from stainless steel sheet (0.05 mm thick and 100 mm wide) Bakelite, and plywood. Heating of the plate was done by means of electric current at both sides of the plate causing an axisymmetric of flow and temperature fields involved. Heat flux was controlled with sliders and the temperatures on the heating surface were measured with 0.07 mm copper- constantan thermocouple soldered on the back of the stainless steel sheet. The experiments were carried out under the condition of constant heat flux. The flow reattachment occurs at about four plate thickness downstream from the leading edge and the heat transfer coefficient becomes maximum at that point. This behavior is dependent on the Reynolds number which ranged from 2720 to 17900 in this investigation. It is reported that the heat transfer coefficient increases sharply near the leading edge as indicated in Figure 10.

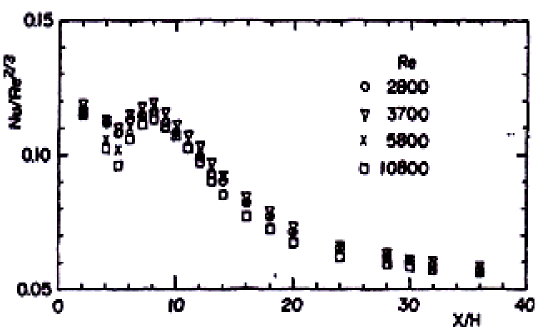

Fig. 10: Local Nusselt number distribution.

Ota and Kon (1977) and Ota *et al.* (1980) measured the turbulent shear stress and heat flux in an axisymmetric separated and reattached flow over a longitudinal blunt circular cylinder. Test and Lessmann (1980) conducted experimental observation of heat transfer during forced convection over rectangular body while Cormick *et al.* (1984) studied experimentally heat transfer to separated flow region from a rectangular prism in a cross stream. For further details Ota *et al.* (1980), Ota and Kon (1980), Bellows and Mayle (1986), Ota and Nishiyama (1987), Ota and Kato (1991), Hourigan *et al.* (1991), Dyban *et al*.(1994), Ota and Ohi (1995), and Jungho (2004) have conducted experimental studies about turbulent momentum, heat transfer, temperature and velocity in separated and reattached flow over blunt plates.

Sparrow *et al.* (1987) studied relation between the points of flow reattachment and maximum heat transfer for regions of the flow separation where they showed the maximum heat transfer occurred upstream of the reattachment point. Cooper *et al.* (1986) presented effect of sound on forced convection from a flat plate further Mehendale *et al.* (1991) conducted experimental study effect of injection hole geometry on the leading edge heat transfer coefficient and film cooling effect, where they showed when mainstream turbulence increase that the leading heat transfer coefficient increase and the film effectiveness decrease also they obtained the heat transfer with coolant injection for the four hole diameters is higher than that for the three hole diameters at low mainstream.

Salman and Abdul-Rissole (1992) performed experiments to study the effect of external flow separation on heat transfer to the two dimensional axisymmetrical, turbulent separated flow. The air flow separation was induced by a sharp edged disc facing cylindrical test tube situated horizontally in the wind tunnel. Reattachment and, redeveloping of the flow occurred behind the point of separation (disc sharp edge) on the surface of an electrically heated cylindrical test tube. The degree of flow separation varied with varying discs of various outer diameters. The Reynolds number at separation encompassed a range of about 2400 to 4500. The results indicated that the heat transfer coefficients in the region of flow reattachment were significantly larger than those obtained for fully developed flow, also, the point of flow reattachment varies with disc diameter and coincide with the position of maximum local heat transfer coefficient.

Ribs Channel:

There are many investigations conducted to enhance the heat transfer from a surface by roughening the surface with different geometries of ribs on the surface. Williams *et al.* (1970) conducted a study on heat transfer from surfaces roughened by ribs where they obtained augmentation of heat transfer due to chamfering of head of the rectangular section ribs on the outer surfaces of an inner tube of annular flow. Han (1984) presented observation of heat transfer and friction in channels with two opposite rib-roughened walls to obtain the effect of the rib pitch to height and rib height to equivalent diameter ratios on friction factor and heat transfer coefficients with Reynolds number range of 7000-90,000. He obtained the Stanton number of the ribbed side wall about 1.5 to 2.2 times of that for the four sided smooth duct for the range of the tested data. There is an increase of 25% of the Stanton number for the smooth side wall due to the presence of the ribs on the adjacent walls. On other hand the friction increases 2.1 to 6.0 times of those for the four sided smooth duct. Han and Park (1988) performed study on the effect of the channel aspect ratio and rib angle of attack on the heat transfer coefficient for Reynolds number from 10,000 to 60,000 with a pair opposite rib roughened walls where they obtained significantly useful results for design of turbine blade cooling channels. Further, Han *et al.* (1991) used in their experimental a square channel with parallel, crossed, and v-shaped angled ribs where they found that the maximum and minimum heat transfer augmentation occurs with v-shaped and crossed ribs respectively. Chandra *et al*. (1997; 2003) performed experimental study of heat transfer and friction behaviors in rectangular channels with varying number of ribbed wall and they observed the effect on heat transfer and flow structures with the increase of number of ribs. Further Lei Wang and Bengt Sunden (2007) presented experimental investigation on local heat transfer in a square duct with various–shaped ribs, where they used different rib configurations consisting of A-Square ribs, B-Equilateral-triangular, C-Trapezoidal ribs with decreasing height in the flow direction, and D-Trapezoidal ribs with increasing height in the flow direction. They showed that the highest heat transfer augmentation occurred with the trapezoidal-shaped ribs at decreasing height in flow direction as shown in Figure 11. Thianpong *et al.* (2009) have conducted experimental study of turbulent heat transfer and friction in a channel with different triangular rib heights. The experimental results indicated that the higher heat transfer enhancement occurs with uniform rib height compared to the non-uniform rib height.

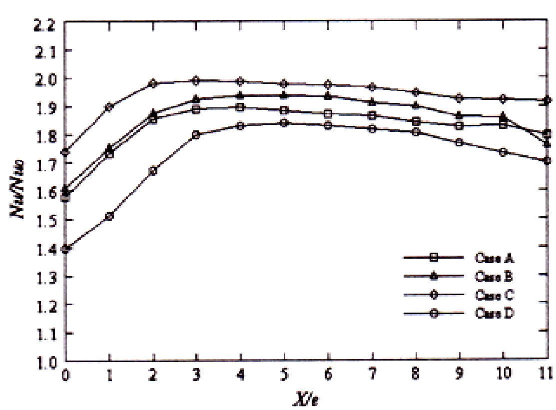

Fig. 11: Local heat transfer increase along the centerline for P/e =12, Re =20,000.

Recommendations:

This paper provided review of many experimental and studies related to turbulent heat transfer in separation flow. It is recommend to use nonofluid in experimental and numerical studies, because currently nonofluid is widely spread in more applications.

Taslim and Wadsworth (1997) have experimentally study the heat transfer coefficients of the rib surface in a square duct roughened with staggered 90 deg ribs. They used three rib geometries corresponding to blockage ratios of 0.133, 0.167, and 0.25 for pitch to height ratios of 5, 7, 8.5, and 10. Results obtained from the experimental observation revealed average heat transfer coefficient much higher than that for the area between the ribs. They also found the decrease of thermal performance with increase of blockage ratio. The investigation was performed with a focus on enhancement of heat transfer due to ribs staggered on the opposite wall of flow. Terekhov *et al.* (2002, 2003) have studied experimentally heat transfer and flow structures in separated flow behind a step and rib where they obtained effect of obstacle height on heat and mass transfer in separation region and they also obtained the resultant heat transfer is proportional to step height. Terekhov *et al.* (2003) further studied experimentally heat transfer coefficients and pressure distributions of the gas flows past a rib and past a downward step thus the results reveal that the position of maximum heat transfer coefficients, separation region length, and pressure drop depend on the geometry of the separation flow. Rong *et al.* (2007) carried out experimental study on the heat transfer properties and flow characteristics of water flowing through the rectangular channels with staggered transverse ribs on two opposite walls. The experiments covered the Reynolds number range from 4000 -20,000, the heat flux used from 700-1560 W/m^2 and the rib height to channel height ratio ranged (h/B) from 0.15-0.61(rib height to channel hydraulic diameter ratio(h/D_{hyd}) from 0.09-0.38 and the pitch to rib height ratio covered(P/h) from 2.5-26. They have also extended their experiments in wind tunnel, where the results indicated that the turbulence intensity, circulation, vortices, and friction factor all show larger values at h/B>0.4 or h/D_{hyd} =0.25 and P/h<8, than those in the regime of thru flow. They have also found increased Nusselt number by several times caused by the increase of turbulent transport of physical quantities. Akhilesh *et al.* (2010) have studied heat transfer enhancement in rectangular channels with axial ribs or porous foam under through flow and impinging jet, whereas increase in heat transfer between 50-90% caused by the use of axial rib in impingement and channel flow cases.

Isak Kotcioglu *et al.* (1998) have studied the enhancement of heat transfer using winglet-type vortex generators (VG) in a rectangular channel. Recently there are researchers who developed associated studies using vortex generator, such as Pongjet Promvonge *et al.* (2010) performed experimental study on heat transfer enhancement and friction in a triangular ribbed channel with winglet type vortex generators (WVGs). They employed staggered and in-line ribs with different angled WVGs where the results revealed that the higher value of thermal enhancement factor around 1.67 occurs with staggered ribs at 30° WVGs at the lowest value of Reynolds number while lower value obtained for the in-line ribs at 30° WVGs was about 1.6. They have also compared results with similar trend obtained by Thianpong *et al.* (2009) as shown Figure 12

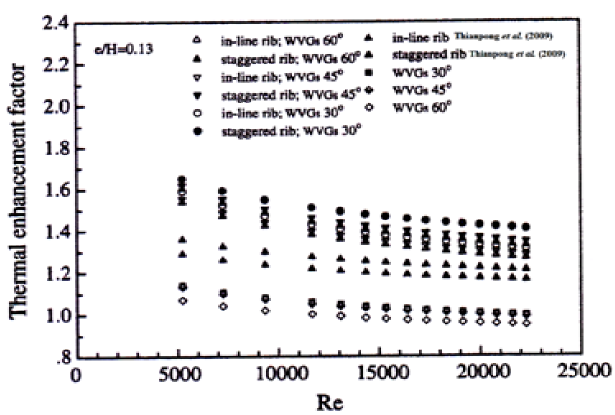

Fig. 12: Variation of thermal enhancement factor with Reynolds number for various turbulators.

Conclusions:

For sudden expansion, forward and backward facing steps, and blunt body, the augmentations of heat transfer rate in separation flow is affected by several factors, which includes steps height, Reynolds number, heat flux, and angle of step height (divergent or convergent). Increase of heat transfer coefficient is obtained with increase of step height, Reynolds number, and heat flux, and the maximum heat transfer coefficient occurs at the reattachment point.

On other hand for ribs channel, the number of ribs, shape of ribs and angle of ribs effect on the enhancement of heat transfer rate in separation region along with the Reynolds number and heat flux.
It is evident that for swirl generators the shorter length of twist tape has better effect on heat transfer enhancement in comparison to longer ones.

Henze *et al.* (2011) investigated experimentally the wall heat transfer distributions and velocity field for internal flows in the presence of longitudinal vortices. They used PIV system to characterize the vortex flow structure and TLC to a transient measuring technique for obtaining the wall heat transfer where they found effect of the longitudinal vortices induced by the VG and observed the characteristic of heat transfer distribution. Eiamsa (2010) studied experimentally thermal and characteristics of turbulent channel flows with multiple twisted tape vortex generators. While Teerapat *et al.* (2010) presented experimental investigations of heat transfer augmentation in a wedge ribbed channel using winglet vortex generators (WVGs). They used two pairs of the WVGs with the attached angle of 60° and mounted on the test channel entrance having aspect ratio, AR= 10 and height, H= 30 mm with a rib height, e/H= 0.2 and rib pitch, P/H= 1.33 and the range of Reynolds numbers from 5000-22,000. The results indicated a considerable enhancement of heat transfer for the WVG and two rib shapes in comparison to smooth channel and further enhances with the increase of Reynolds number as shown in Figure 13.

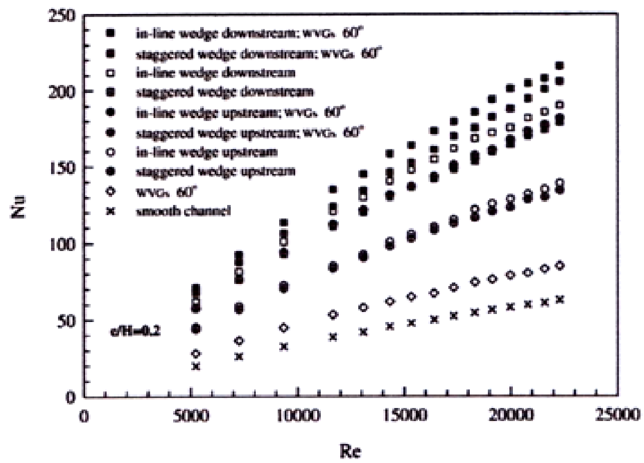

Fig. 13: Variation of Nusselt number with Reynolds number.

Swirl generators:

There are many experimental investigations on enhancement of heat transfer related to use of swirl generators in passage. Smithberg and Landis (1964) was the pioneer of those experiments. They used tape swirl generators in tubes of experimental studied of forced convection heat transfer and friction, where they showed effect of tape swirl generators on enhancement heat transfer. Kidd (1969) conducted experimental study on turbulent heat transfer and pressure drop in heated tubes with Nitrogen flow in tubes containing twisted tapes. He focused on the effect of various length of twisted tape in tube on temperature and pressure distributions and obtained a good agreement with previous studies. Due to consideration of different geometries in engineering applications therefore there are numerous publications where different swirl generators were employed in order to rais enhancement of heat transfer, whereas those investigations represented by Gau and Chen (1998) performed experimental study of enhancement of heat transfer with swirl flow issued into a divergent pipe. For convergent pipe Yan et al. (2010) reported a pre-swirl effect on the heat transfer process in the entry region. Also, Chang (2003) presented experimental investigation heat transfer characteristics with swirling flow in 180 degrees circular section with uniform heat flux. Gul (2006) used tangential swirl generators in circular tube for improvement of heat transfer. Further, there are studies on the effect turbulent decaying swirl flow on heat transfer enhancement in passage reported byBlackwelder and Kreith (1970), Sparrow and Chaboki (1986), Yilmaz *et al.* (1999, 2002, 2003), Kittisak Yonsiril *et al.* (2006), Tulin Bali and Betul Ayhan Sarac (2008), and Ahmadvand *et al.* (2010), while there are researchers focused on turbulent heat transfer in annular passage with swirl generators and those studies are represented by Ehsan Shoukry (1985), Toshiaki Kanemoto (1992), Ahan *et al.* (1993), Solnordal and Gray (1994), Tae and Kwon (2003), Smith *et al.* (2006), Ali (2007), and Ahmadyand *et al.* (2010). For more details, Paisarn (2006) carried out experimental study on turbulent heat transfer and pressure drop in concentric annular pipes with and without twisted tape. The experimental results showed that the effect heat transfer rate and pressure drop augments due to insertion of twisted tape. Finally they presented correlations (6 ,7) for the heat transfer coefficient and pressure drop in terms of the Nusselt number and friction factor based on experimental data.

$$Nu = \frac{hiDi}{K} = 0.648Re^{0.36}\,[1 + \frac{D}{H}]^{2.475}\,Pr^{1/3} \tag{6}$$

Where $7000 \leq Re \geq 23{,}000$, $Pr \geq 3$, $3.1 \leq H/D \leq 5.5$

$$f = 3.517Re^{-0.414}\,[1 + \frac{D}{H}]^{1.045} \tag{7}$$

Where $7000 \leq Re \geq 23{,}000$, $3.1 \leq H/D \leq 5.5$

For further improvement of heat transfer in sudden expansion in pipe flow, Zohir *et al.* (2011) conducted experiments on heat transfer characteristics and pressure drop for turbulent airflow in a sudden expansion pipe equipped with propeller type swirl generator or spiral spring with several pitch ratios. The investigation was performed in a Re range of 7500 to 18,500, and three pitch ratios for the spiral spring, P/D = 10, 15 and 20 respectively, where they focused on effects of using a propeller rotating freely and inserted spiral spring on heat transfer enhancement and pressure drop. Results obtained from propeller swirl generators, indicated increase of the average Nusselt number ratio approximately, 0.83-1.65, 1.35-1.69, and 1.0-1.23 times over those of sudden expansion plain pipe for X/H = 1, 5, and 10, respectively as shown in Figure 14. For the helical vortex swirl generators also there are increases in the average Nusselt number ratio, approximately, 1.06-1.14, 1.12-1.23, and 1.05-1.37 times over those of sudden expansion plain pipe for P/d = 10, 15 and 20, respectively as shown in Figure 15. They have also got modest agreement with the data of El-Shazly *et al*. (2005) and Smyth (1974) for sudden expansion in pipe.

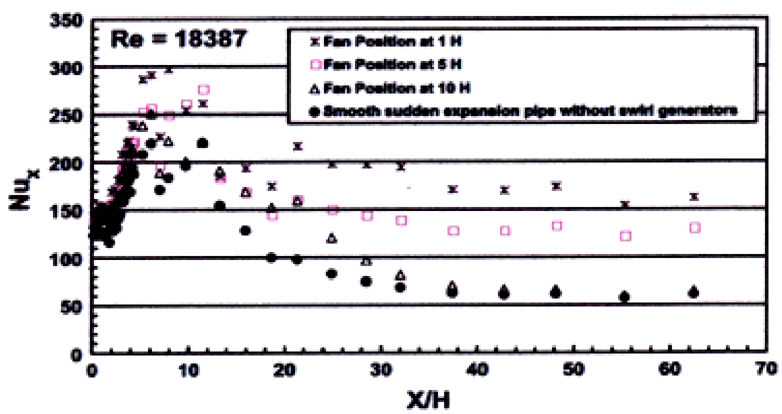

Fig. 14: Comparison of local Nusselt number variations versus dimensionless tube length for sudden expansion pipe with and without propeller type swirl generators and at Re= 18,387.

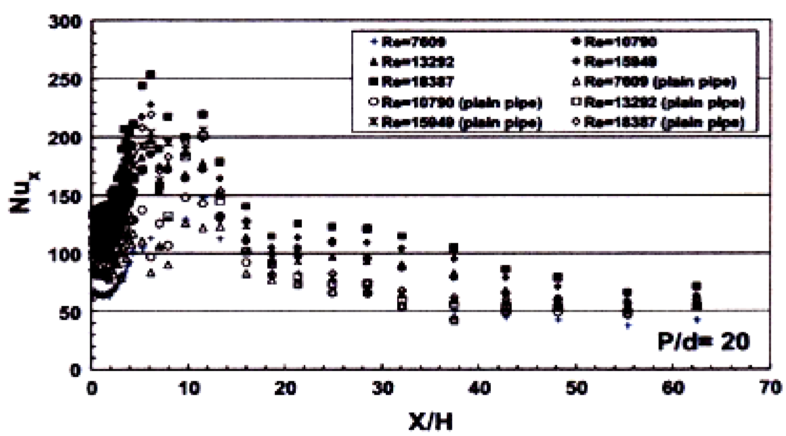

Fig. 15: Comparison of local Nusselt number variations versus dimensionless tube length for helical vortex swirl generators P/d = 20 and for plain pipe at different Reynolds number.

Nomenclature

Symbol	Description	Units
A_s	Surfaces area	m^2
CRZ	Corner recirculation zone	
C_f	Friction factor coefficient	
D	Diameter of heated tube in the sudden expansion region	m
ER	Expansion ratio	
h	Heat transfer coefficient	$W/m^2.K$
H	Height	mm
Hr	Height ratio	
K	Thermal conductivity	W/m.K
Ka	Thermal conductivity of air	W/m.K
Nu	Nusselt number	
Pr	Prandtl number	
Re	Reynold number	
T_b	Air bulk temperature	°C
T_s	Surface temperature	
U_{ref}	Free stream velocity	m/sec
Vs	Voltage	Volt

REFERENCES

Abu-Mulaweh, H.I., 2002. Effects of backward- and forward facing steps on turbulent natural convection flow along a vertical flat plate. Int. J. Therm. Sci., 41(4): 376-385.

Abu-Mulaweh, H.I., 2005. Turbulent mixed convection flow over a forward-facing-step the effect of step heights. International Journal of Thermal Sciences, 44: 155-162.

Abu-Mulaweh, H.I., T.S. Chen and B.F. Armaly, 2002. Turbulent mixed convection flow over a backward-facing step—the effect of the step heights. Int. J. Heat Fluid Flow., 23(6): 758-765.

Ahan, S.W., Y.P. Lee and K.C Kim, 1993. Turbulent fluid flow and heat transfer in a concentric annuli with square-ribbed surface roughness. J. of KSME (B).17(5): 1297-1303.

Ahmadvand, M., A.F. Najafi and S. Shahidinejad, 2010. An experimental study and CFD analysis towards heat transfer and fluid flow characteristics of decaying swirl pipe flow generated by axial vanes. J. Meccanica., 45. 111-129.

Ahmadvand, M., A.F. Najafi and S. Shahidinejad, 2010. An experimental study and CFD analysis towards heat transfer and fluid flow characteristics of decaying swirl pipe flow generated by axial vanes. J. Meccanica., 45: 111-129.

Akhilesh, P., Rallabandi, Dong-Ho Rhee, Zhihong Gao, Je-Chin Han, 2010. Heat transfer enhancement in rectangular channels with axial ribs or porous foam under through flow and impinging jet. Int. J. Heat and Mass Transfer, 53: 4663-4671.

Alemasov, V.E., G.A. Glebov and A.P. Kozlov, 1989. Thermo-anemometric methods for studying flows with separation. Kazan'Branch of the USSR Academy of Sciences, Kazan, (1989)1-178.

Ali M., Jawarneh, 2007. Heat transfer enhancement in swirl annulus flows. 5th Wseas int. Conf. on Environment, Ecosystems and Development, Tenerife, Spain, December (2007) pp: 14-16.

Baughn, J.W., M.A. Hoffman, B.E. Launder, D. Lee and C. Yap, 1989. Heat transfer, temperature, and velocity measurements downstream of an abrupt expansion in a circular tube at a uniform wall temperature. J Heat Transfer, 111: 870-876.

Baughn, J.W., M.A. Hoffman, D. Lee and C. Yap, 1987a. Turbulent velocity and temperature profiles downstream of an abrupt expansion in a circular duct with a constant wall temperature. In the Proceedings of the 1986a ASME-JSME Thermal Eng Conference, pp: 449-454.

Baughn, J.W., M.A. Hoffman, R.K. Takahashi and B.E. Launder, 1984. Local heat transfer downstream of an abrupt expansion in a circular channel with constant wall heat flux. J Heat Transfer, 106: 789-796.

Baughn, J.W., M.A. Hoffman, R.K. Takahashi and D. Lee, 1987b. Heat transfer downstream of an abrupt expansion in the transition Reynolds number regime. J. Heat Transfer, 109: 37-42.

Baughn, J.w., R.K. Takahashi, M.A. Hoffman and A.A. McKillop, 1985. Local heat transfer measurements using an electrically heated thin gold-coated plastic sheet. J Heat Transfer, 107: 953-959.

Bellows, W.J. and R.E. Mayle, 1986. Heat transfer downstream of a leading edge separation bubble. J. Turbomachinery, 108: 131-136.

Blackwelder, R. and F. Kreith, 1970. An experimental investigation of heat transfer and pressure drop in a decaying swirl flow. In: Augmentation of convective heat and mass. ASME: 102-108.

Boelter, L.M.K., G. Young and H.W. Iversen, 1984. An investigation of Aircraft Heaters XXVII - Distribution of heat transfer rate in the entrance section of a circular tub. NACA-TN-1451.

Chandra, P.R., C.R. Alexander and J.C. Han, 2003. Heat transfer and friction behaviors in rectangular channels with varying number of ribbed walls. Int. J. Heat Mass Transfer, 46(3): 481-495.

Chandra, P.R., M.E. Niland and J.C. Han, 1997. Turbulent flow heat transfer and friction in a rectangular channel with varying numbers of ribbed walls Journal of Turbomachinery, 119: 374-380.

Chang, T.H., 2003. An investigation of heat transfer characteristics of swirling flow in a 180 degrees circular section bend with uniform heat flux. KSME Int. J. 17(10): 1520-1532.

Cooper, PI., J.C. Sheridan, C.J. Flood and M.C. Welsh, 1986. The effect of sound on forced convection from a flat plate. 8th Australasian Fluid Mech. Conf, Univ. of NSW.

Dae hee lee, Jun Sik Lee, Hyun Jin Park and Moon Kyung Kim, 2011. Experimental and numerical study of heat transfer downstream of an axisymmetric abrupt expansions and in a cavity of a circular tube. Journal of Mechanical Science and Technology, 25(2): 395-401.

De Zilwa S.R., S. Sivasegaram and J.H. Whitelaw, 1997. Active control of isothermal and combusting flows in plane sudden-expansions. Proc. 1997 Transport Phenomena in Thermal Sci and Process Eng. pp: 325-330.

Dyban, E.P., E.Y. Epik and L.E. Yushina, 1994. Heat transfer on the surface of longitudinally streamlined bodies in the presence of closed separation and external flow turbulization. Heat Transfer, 4EC7: 25-30

Ede, AJ., C.I. Hislop and R. Morris, 1956. Effect of the local heat transfer coefficient in a pipe of an abrupt disturbance of the fluid flow: abrupt convergence and divergence of diameter ratio 2:1. Proc Inst Mech Engrs., 170: 1113-1130.

Ehsan Shoukry and Leslie W. Shemilt, 1985. Mass transfer enhancement in swirling annular pipe flow. J. Ind. Eng. Chem. Process Des. Dev., 24(1): 53-56.

Eiamsa-ard, S., 2010. Study on thermal and fluid flow characteristics in turbulent channel flows with multiple twisted tape vortex generators. International Communications in Heat and Mass Transfer, 31: 644–651.

El-Shazly, K.M., A.E. Zohir, A.A. Abdel Aziz and M.Abdel Mohiomen, 2005. Heat transfer characteristics of pulsated flow downstream of abrupt expansion through pipes, In. 2nd International conference on advanced in Engineering science and Technologies, National research center, pp: 12-14.

Filetti, E.G. and W.M. Kays, 1967. Heat transfer in separated, reattached and redeveloped regions behind a double step at entrance to flat duct. Journal of Heat transfer, 89: 163-168.

Gau, C. and H.R. Chen, 1998. Enhancement of heat transfer with swirling flows issued into a divergent pipe. Journal of Thermophysics and Heat Transfer, 12 (1): 87-93.

Gul, H., 2006. Enhancement of heat transfer in a circular tube with tangential swirl generators. J. Exp Heat Transfer 19: 81-93.

Habib, M.A., A.M. Attya and M.M. Khalifa, 1992. Measurements of augmented heat transfer downstream of an abrupt rectangular channel expansion. J. Modeling, Measurement & Control B, 44(1): 33-46.

Habib, M.A., A.M. Mobarak, A.E. Attya and A. Aly, 1992. An experimental investigation of heat transfer and flow in channels with streamwise-periodic flow. Journal of Energy, 17(11): 1049-1058.

Habib, M.A., A.M. Mobarak, E. Abdel-Hafez, M. El-Sallak and R. Affify, 1994. Experimental investigation of heat transfer and flow over baffles of different heights. ASME J. Heat Transfer, 116: 363-368.

Han, J.C. and J.S. Park, 1988. Developing heat transfer in rectangular channels with rib-turbulators. Int. J. Heat Mass Transfer, 31: 183-195.

Han, J.C., 1984. Heat transfer and friction in channels with two opposite rib-roughened walls. Journal of heat transfer, 106: 774-781.

Han, J.C., Y.M. Zhang and C.P. Lee, Augmented heat transfer in square channel with parallel, crossed, and V-shaped angled ribs. Journal of Heat Transfer, 113: 590-596.

Henze, M., J. Von Wolfersdorf, B. Weigand, C.F. Dietz and S.O. Neumann, 2011. Flow and heat transfer characteristics behind vortex generators-a benchmark dataset. Int. J. Heat and Fluid Flow, 32(1): 318-328.

Hourigan, K., L.W. Welch, M.C. Thompson, P.I. Cooper and M.C. Welsh, 1991. Augmented forced convection heat transfer in separated flow around a blunt flat plate. Exp Thermal Fluid Sci., 4: 182-191.

Hussein Togun, Y.k., Salman, Hakim, S. Sultan Aljibori and S.N. Kazi, 2011. An experimental study of heat transfer to turbulent separation fluid flow in an annular passage. Int. J. Heat and Mass Transfer, 54: 766-773.

Iguchi, M. and T. Sugiyama, 1988. Study on the flow near the wall of the larger pipe, downstream of a sudden expansion. Trans JSME B, 54(507): 3010-3015.

Isak Kotcioglu, Teoman Ayhan, Hayati Olgun, Betul Ayhan, 1998. Heat transfer and flow structure in a rectangular channel with wing-type vortex generator. J. of Engineering and Environmental Science, 22: 185-195.

Jing-Tang, Yang and Chun-Hung, Tsai, 1996. High temperature heat transfer of separated flow over a sudden expansion with base mass injection. Int. J. Heat Mass Transfer, 39: 2293-2301.

Jungho Choi, 2004. An experimental investigation of turbine blade heat transfer and turbine blade trailing edge cooling. PhD Thesis, Texas A&M University.

Kawamura, T., A. Yamamori, J. Mimatsu and M. Kumada, 1991. Time and spatial characteristics of heat transfer at the reattachment region of a two-dimensional backward-facing step. Proc. of the 1991 ASME-JSME Thermal Eng Conf.3 pp: 197-204

Kawamura, T., S. Tanaka, I. Mabuchi and M. Kumada, 1987-88. Temporal and spatial characteristics of heat transfer at the reattachment region of a backward-facing step. Exp Heat Transfer, X: 299-313.

Khezzar, L., S.R.N., D.E. Zilwa and J.H. Whitelaw, 1999. Combustion of premixed fuel and air downstream of a plane sudden-expansion. J. Experiments in Fluids, 27(4): 296-809

Kidd, J.R.G.C., 1969. Heat transfer and pressure drop for nitrogen flowing in tubes containing twisted tapes. AIChE J. 15: 581-585.

Kittisak Yongsiri1, Smith Eiamsa-ard, Chinaruk Thianpong and Pongjet Promvonge, 2006. Effect of turbulent decaying swirl flow on heat transfer enhancement in a tube. The 2nd Joint International Conference on Sustainable Energy and Environment Bangkok, Thailand.

Koram, K.K. and E.M. Sparrow, 1978. Turbulent heat transfer downstream of an unsymmetric blockage in a tube. J. Heat Transfer, 100: 588-594.

Krall, K.M. and E.M. Sparrow, 1966. Turbulent heat transfer in the separated, reattachment, and redevelopment regions of a circular tube. J Heat Transfer, 88: 131-136.

Lei Wang and Bengt Sundén, 2007. Experimental investigation of local heat transfer in a square duct with various-shaped ribs. Journal Heat and Mass Transfer, 43: 759-766.

Mabuchi, I., T. Murata and M. Kumada, 1986. Effect of free-stream turbulence on heat transfer characteristics in the reattachment region on the bottom surface of a backward-facing step (For different angles of separation). Trans JSME B52: 2619-2625.

McCormick, D.C., R.C. Lessman and F.L. Test, 1984. Heat transfer to separated flow regions from a rectangular prism in a cross stream. J. Heat Transfer, 106: 276-283.

Mehendale, AB., J.C. Han and S. Ou, 1991. Influence of high mainstream turbulence on leading edge heat transfer. J. Heat Transfer, 113: 843-850.

Mori, Y., Y. Uchida and K. Sakai, 1986. A study of the time and spatial micro- structure of heat transfer performance near the reattaching point of separated flows. Trans JSME B52: 3353-3361.

Ohori Yuki, Nakamura Atsuhito, Yoshikawa Hiroyuki and Ota Terukazu, 2004. Turbulent Heat Transfer in a Symmetric Sudden Expansion Channel. Proceedings of the Thermal Engineering Conference, pp: 409-410.

Ota, T. and H. Kato, 1991. Turbulent heat transfer in a separated and reattached flow over a blunt flat plate. Proc. of the 1991 ASME-JSME Thermal Eng Conf, 3 pp:191-196.

Ota, T. and H. Nishiyama, 1987. A correlation of maximum turbulent heat transfer coefficient in reattachment flow region. Int. J. Heat Mass Transfer, 30: 1193-1200.

Ota, T. and N. Kon, 1974. Heat transfer in the separated and reattachment flow and a blunt flat plate. Journal of heat Transfer, 96: 459-462.

Ota, T. and N. Kon, 1977. Heat transfer in an axisymmetric separated and reattached flow over a longitudinal blunt circular cylinder. J. Heat Transfers, 99: 155-157.

Ota, T. and N. Kon, 1980. Turbulent transfer of momentum and heat in a separated and reattached flow over a blunt flat plate. J. Heat Transfer, 102: 749-754.

Ota, T. and N. Ohi, 1995. Turbulent heat transfer in a separated and reattached flow over a blunt flat plate. Proc of the 1995 ASME-JSME Thermal Eng Conf, pp: 363-370

Ota, T., N. Kon and S. Kikuchi, 1980. Temperature and velocity fields in the separated and reattached flow over blunt flat plates. Bull JSME 23: 402-408.

Ota, T., N. Kon, S. Hatakeyama and S. Sato, 1980. Measurements of turbulent shear stress and heat flux in an axisymmetric separated and reattached flow over a longitudinal blunt circular cylinder. Bull JSME 23: 1639-1645.

Ota, T., N. Nakamura and T. Hirayama, 1995. Turbulent separated and reattached flow around an inclined downward step. Turbul. Heat Mass Transfer, 1: 286-293.

Oyakawa, K., I. Teruya, I. Senaha, M. Yaga and I. Mabuchi, 1996. Evaluation of thermal performance on heat transfer enhancement by passive and active methods at downstream region of backward-facing step. Trans JSME B62: 1104-1110.

Oyakawa, K., T. Saitoh, I. Teruya and I. Mabuchi, 1995. Heat transfer enhancement using slat at reattachment region downstream of backward facing step. Trans JSME B61: 4426-4431.

Oyakawa, K., T. Taira and E. Yamazato, 1994. Studies of heat transfer control by jet discharge at reattachment region downstream of a backward facing step. Trans JSME B60: 248-254.

Paisarn Naphon, 2006. Heat transfer and pressure drop in the horizontal double pipes with and without twisted tape insert. International Communications in Heat and Mass Transfer, 33: 166-175

Pongjet Promvonge, Teerapat Chompookhama, Sutapat Kwankaomenga and Chinaruk Thianponga, 2010. Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators. Energy Conversion and Management., 5: 1242-1249.

Rong Fung Haung, Shyy Woei Chang, Kun-Hung Chen, 2007. Flow and heat transfer characteristics in rectangular channels with staggered transverse ribs on two opposite walls. Journal of Heat Transfer, 129: 1732-1736.

Runchal, A.K., 1976. Mass transfer investigation in turbulent flow downstream of sudden enlargement of a circular pipe for very high Schmidt numbers. Int. J. Heat Mass Transfer, 14: 781-792.

Salman, Y.K. and A.A. Abdul-Rissole, 1992. Turbulent heat transfer measurement in external separation and reattached flows. Eng and Technology Journal, 4: 15-27.

Sang-Kyu, Park and Terukazu, Ota, 2010. An experimental approach to turbulent heat transfer using symmetric expanded plane channel. J. Mechanical science and Technology, 24(4): 857-863.

Sano Masatoshi, Suzuki Ippei and Sakuraba Kenichiro, 2009. Control of turbulent channel flow over a backward-facing step by suction. Journal of Fluid Science and Technology, 4(1): 188-199.

Seban, R.A., 1966. The effect of suction and injection on the heat transfer and flow in a turbulent separated air flow. Transaction of the ASME: 276-284.

Seban, R.A., A. Emery and A. Levy, 1959. Heat transfer to separated and reattached subsonic turbulent flows obtained downstream of a surface step. J. Aerospace Sci., 2: 809-814.

Seki, N., S. Fukusako and T. Hirata, 1976. Effect of stall length on heat transfer in reattachment region behind a double step at entrance to an enlarged flat duct. Int. J. Heat Mass Transfer, 19: 700-702.

Seki, N., S. Fukusako and T. Hirata, 1976. Turbulent fluctuations and heat transfer for separated flow associated with a double step at entrance to an enlarged flat duct. ASME J. Heat Transfer, 98: 588-593.

Smith Eiamsa-ard, Chinaruk, Thianpong and Pongjet Promvonge, 2006. Experimental investigation of heat transfer and flow friction in a circular tube fitted with regularly spaced twisted tape elements. International Communications in Heat and Mass Transfer., 33: 1225-1233.

Smithberg, E. and F. Landis, 1964. Friction and forced convection heat transfer characteristics in tubes with twisted tape swirl generators. J. Heat Trans, Trans ASME, 86: 39-49.

Smyth, R., 1974. Heat transfer in turbulent separated flow. Journal of Nuclear Science and Technology 1(12): 545-553.

Sogin, H.H., 1964. A summary of experiments on local heat transfer from the rear of bluff obstacle to a law speed Air stream. J. of heat transfer ASME Trans., 86: 200-202.

Solnordal, C.B. and N.B. Gray, 1994. An experimental study of fluid flow and heat transfer in decaying swirl through a heated annulus Experiments in Fluids., 18: 17-25.

Soong, C.Y. and W.C. Hsueh, 1993. Mixed convection in a suddenly-expanded channel with effects of cold fluid injection. Int. J. Heat and Mass Transfer., 36: 1477-1484.

Sorensen, A., 1969. Mass transfer coefficients on truncated slabs. Chem. Eng Sci., 24: 1445-1460.

Sparrow, E.M. and A Chaboki, 1986. Swirl-affected turbulent fluid flow and heat in a circular tube. J. of Heat Transfer ASME 106: 766-773.

Sparrow, E.M., S.S. Kang and W. Chuck, 1987. Relation between the points of flow reattachment and maximum heat transfer for regions of flow separation. Int. J. Heat Mass Transfer, 30: 1237-1246.

Suzuki, H., K. Suzuki, S. Kida and T. Nakamae, 1991. Heat transfer augmentation in the region downstream of a backward-facing step (Effects of a cylinder mounted near the top comer of the step). Trans JSME S7B: 1410-1415.

Suzuki, K., Y.M. Kang, T. Sugimoto and T. Sato, 1982. Heat transfer in the downstream region of an orifice in a tube. Trans JSME B48: 132-140.

Tae-Hyun, Chang and Kwon-Soo, Lee, 2003. An experimental study on heat transfer characteristics with turbulent swirling flow using uniform heat flux in a cylindrical annuli. Journal of Mechanical Science and Technology, 17(12): 2042-2052.

Taslim, M.E. and C.M. Wodsworth, 1997. An experimental investigation of the rib surface-averaged heat transfer coefficient in a rib-roughened square passage. Journal of Turbomachinery, 119: 381-389.

Teerapat Chompookham, Chinaruk Thianpong, Sutapat Kwankaomeng and Pongjet Promvonge, 2010. Heat transfer augmentation in a wedge-ribbed channel using winglet vortex generators. Int. Communications in Heat and Mass Transfer., 37: 163-169.

Terekhov, V.I., N.I. Yarygina and R.F. Zhdanov, 2002. Some features of a turbulent separated flow and heat transfer behind a step and a rib 1- Flow structures. Journal of Applied Mechanics and Technical Physics, 43: 888-894.

Terekhov, V.I., N.I. Yarygina and R.F. Zhdanov, 2003. Heat transfer in turbulent separated flows in the presence of high free stream turbulence. Int. J. of Heat and Mass Transfer, 46: 4535-4551.

Terekhov, V.I., N.I. Yarygina and R.F. Zhdanov, 2003. Some features of a turbulent separated flow and heat transfer behind a step and a rib 2-Heat transfer in a separated flow. Journal of applied Mechanics and Technical Physics, 44: 522-531.

Terekhov, V.I., N.I. Ymygina and R.F. Zhdanov, 2003. Heat transfer in turbulent separated flows in the presence of high free-stream turbulence. International Journal of Heat and Mass Transfer, 46(2003) 4535-4551.

Test, F.L. and R.C. Lessmann, 1980. An experimental study of heat transfer during forced convection over a rectangular body. J. Heat Transfer, 102: 146-151.

Thianpong, C., T. Chompookham, S. Skullong and P. Promvonge, 2009. Thermal characterization of turbulent flow in a channel with isosceles triangular ribs, International Communications in Heat and Mass Transfer., 36: 712-717.

Toshiaki Kanemoto, Takashi Kubota, Haruo Ishibashi, 1992. Swirling flow in a straight draft tube with annular and rectangular cross section. 11th Australasian Fluid Mechanics Conference, pp: 14-18.

Tsou, F.K., S.J. Chen and W. Aung, 1991. Starting flow and heat transfer downstream of a backward-facing step. Journal of Heat Transfer., 113: 583-589.

Tulin Bali, Betul Ayhan Sarac, 2008. Exergy analysis of heat transfer in a turbulent pipe flow by a decaying swirl generator International Journal of Exergy, 5(1): 64-77

Vogel, J.C. and J.K. Eaton, 1985. Combined heat transfer and fluid dynamic measurements downstream of a backward–facing step. J. of heat transfer ASME Trans., 107: 922-929.

Williams, F., M.A.M. Pirie and C. Warburton, 1970. Heat transfer from surfaces roughened by ribs. in: A. Bergles R.L.Webb (Eds,) Augmentation of Heat Transfer\ ASME\ New York\ pp: 36-43.

Yang, C.S., D.Z. Jeng, Yaw-Jou Yang, Hong-Rong Chen and C. Gau, 2011. Experimental study of pre-swirl flow effect on the heat transfer process in the entry region of a convergent pipe. Experimental Thermal and Fluid Science, 35(1): 73-81.

Yilmaz, M., O. Comakli, S. Yapici and O. Nuri Sara, 2003. Heat transfer and friction characteristics in decaying swirl flow generated by different radial guide vane swirl generators. Energy Conversion and Management., 44: 283-300.

Yilmaz, M., O. Comaklia and S. Yapici, 1999. Enhancement of heat transfer by turbulent decaying swirl flow. J. Energy Conversion and Management., 40(13): 1365-1376.

Yilmaz, M., S. Yapici, O. Comakli and O.N. Sara, 2002. Energy correlation of heat transfer and enhancement efficiency in decaying swirl flow. Heat Mass Transfer, 38(4–5): 351-358.

Zemanick, P.P. and R.S. 1970. Dougall, Local heat transfer downstream of abrupt circular channel expansion. J. Heat Transfer, 92: 53-60.

Zohir, A.E., A.A. Abdel Aziz and M.A. Habib, 2011. Heat transfer characteristics in a sudden expansion pipe equipped with swirl generators. International Journal of Heat and Fluid flow, 32: 352-361.