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Aerodynamic Studies on automobile structures

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Abstract: *Flow over skewed steps is an interesting practical problem with wide range of applications such asaerodynamic vehicles and structures. A closed view of any automobile gives an idea that it has been derived from step pattern. Now a day's researchers are concentrating on increasing of fuel economy and minimization of noise by eliminating undesirable drag forces and aerodynamic instabilities particularly in high speed vehicles. Fuel economy is mainly depends on induced drag which is a dependent of step inclination angle. This study investigates the variation of flow behavior with step inclinations on different models at different velocities. Based on the literature review nine models were designed by using CATIA. The models used in this study are forward facing step, backward facing step and combination of forward and backward facing step with step inclination angles of 90^0, 50^0, 30^0 respectively. All these nine models were fabricated and tested in a low speed wind tunnel at different velocities to identify various flow zones and to understand the pressure distribution on the surface of the models and influence of velocity on flow zones are also determined.*
Key words: *forward facing step, backward facing step, wind tunnel, coefficient of pressure, coefficient of drag*

I. Introduction

The crises of energy in global has been encourage researchers to look for new techniques which improve the performance. One of common methods to increase efficiency of energy system equipment is by change the design geometry of channel. The fluid flow over forward or backward-facing steps found in many practical applications. A closed view of any automobile shape gives an idea that it has been derived from step pattern. The body shape of a car combines both forward facing and backward facing step. It also finds applications in automobiles, heat exchangers, chemical process, turbine blades, and power plants etc. The study of backward-facing step flows constitutes an important branch of fundamental fluid mechanics. The phenomenon of flow separation in a backward-facing step channel has received considerable attention owing to its geometric simplicity, physical abundance and its close relevance to some fundamental engineering flows. For instance, heat exchanging equipment, aerodynamic performance of airfoils or automotive vehicles. Although the flow exhibits a three-dimensional nature, the major benchmarks are two dimensional. The configuration of a forward facing step has been investigated much less than its counterpart, the backward facing step. This is mainly due to the fact that the backward facing step is often used as a benchmark test for computations, whereas the calculation of the forward facing step is quite a delicate task. In other words, very little has been published on the problem of the flow separation on a forward facing step, and neither its topology nor its relevant scales are known in a predictable form. Although forward facing stepconfigurations are used to enhance heat transfer rates and are often encountered in geophysical problems. Forward-facing step which can easily be found in most of the aerodynamic vehicles or structures play an important role in noise generation. A backward-facing step has extensively been studied at least for the flow field but the forward-facing step problem is relatively new in the study of flow and acoustics. Recently, experimental studies were conducted to find the noise source by examining the correlations between flow and acoustics. The investigations are still on-going and no decisive conclusions have been made yet.

R.B.Sharma et.al [1], proposed an effective numerical model using the Computational Fluid Dynamics (CFD) to obtain the flow structure around a passenger car with different add-on devices. A model of generic passenger car was developed using solid works, generated the wind tunnel, and applied the boundary conditions in ANSYSworkbench platform, and then testing and simulation have been performed for the evaluation of drag coefficient for passenger car. The aerodynamics of the most suitable design of vortex generator, spoiler, tail plates, and spoiler with VGs are introduced and analyzed for the evaluation of drag coefficient for passenger car. The addition of these add-on devices are reduces the drag coefficient and lift coefficient in head-on wind. Rounding the edges partially reduces drag in head-on wind but does not bring about the significant improvements in the aerodynamic efficiency of the passenger car with add-on devices. Hence, the drag force can be reduced by using add-on devices on vehicle and fuel economy, stability of a passenger car can be improved.

From their analysis, they found that spoiler with VGs is more effective add-on device to reduce the drag coefficient and lift coefficient which are applied on the passenger car when the car is running on the road.

The drag coefficients and drag forces are proportional to each other so when the drag forces are reduced, lift forces are also reduced because it is proportional to the lift coefficient.

Ram Bansal et.al [2], developed a model of generic passenger car in solid works-10 and generated the wind tunnel and applied the boundary conditions in ANSYS workbench 14.0 platform then after testing and simulation are performed for the evaluation of drag coefficient for passenger car. They introduced aerodynamics of the most suitable design of tail plate and analyzed for the evaluation of drag coefficient for passenger car. The addition of tail plates results in a reduction of the drag-coefficient 3.87% and lift coefficient 16.62% in head-on wind.

B.f. armaly et.al [3], reported Laser-Doppler measurements of velocity distribution and reattachment length to downstream of a single backward-facing step mounted in a two-dimensional channel. They presented results for laminar, transitional and turbulent flow of air in a Reynolds-number range of $70 < Re < 8000$**.** They reported that laser-Doppler measurements do not only yield the expected primary zone of recirculating flow attached to the backward-facing step but also show additional regions of flow separation downstream of the step and on both sides of the channel test section. These additional separation regions have not been previously reported in the literature. Although the high aspect ratio of the test section (1 : 36) ensured that the oncoming flow was fully developed and two-dimensional, their experiments showed that the flow downstream of the step only remained two-dimensional at low and high Reynolds numbers.

Three-dimensional stationary structure of the flow over a backward-facing step is studied experimentally by Olivier Cadot et.al [4] and they investigated Visualizations and Particle Image Velocimetry (PIV) measurements. They showed that the recirculation length is periodically modulated in the span wise direction with a well-defined wavelength. Visualizations also reveal the presence of longitudinal vortices. In order to understand the origin of this instability, a generalized Rayleigh discriminant is computed. Their study reveals that actually three regions of the two-dimensional flow are potentially unstable through the centrifugal instability. However both the experiment and the computation of a local Gortler number suggest that only one of these regions is unstable. It is localized in the vicinity of the reattached flow and outside the recirculation bubble.

Bahram Khalighi et.al [5] investigated the unsteady flow around a simplified road vehicle model with and without drag reduction devices. They performed experiments in a small wind tunnel which includes pressure and velocity fields measurements. The devices are add-on geometry parts (a box with a cavity and, boat-tail without a cavity) which are attached to the back of the square-back model to improve the pressure recovery and reduce the flow unsteadiness. Their results show that the recirculation regions at the base are shortened and weakened and the base pressure is significantly increased by the devices which lead to lower drag coefficients (up to 30% reduction in drag). Also, their results indicate a reduction of the turbulence intensities in the wake as well as a rapid upward deflection of the under body flow with the devices in place. The baseline configuration (square-back) exhibits strong three-dimensional flapping of the wake. Finally, they investigated a blowing system numerically. In this case they realized drag reduction up to 50%.

Young J. Moon et.al investigated [6] aerodynamic noise from a forward-facing step numerically for Reynolds number based on the step height, Re_h=8,000 and flow Mach number, M=0.03. They calculated Flow over the forward-facing step by the incompressible large eddy simulation (LES), while its acoustic field is solved by the linearized compressible perturbed equations (LPCE). They investigated aerodynamic noise from a forward-facing step numerically. From the computed results, they concluded that the space-time characteristics of the surface pressure over the step and the low dimensionalized flow structures by filtered proper orthogonal decomposition (POD) method indicate two different noise generation mechanisms. The low frequency noise is generated by a flapping motion of the shear layer, while the High frequency noise is generated by the breaking-off of the shear layer, due to the Kelvin-Helmholtz instability.

The actual noise of forward-facing step from an extended span will be generated more dominantly from the region around the step-corner rather than from a region close to the shear layer reattachment point.

Durst et al. [7] observed the formation of secondary separation zones in the two-dimensional numerical simulations of a symmetric sudden-expansion flow. Both the experiments and the predictions confirm a symmetry-breaking bifurcation leading to one short and one long primary separation zone.

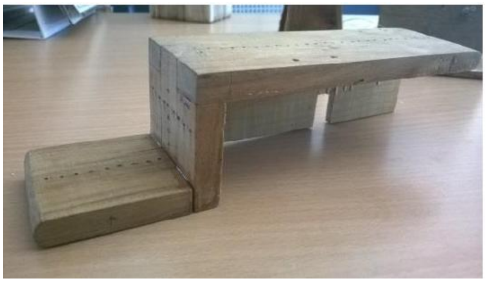
j.tihon et.al [8] used the electro diffusion technique to investigate reattaching and recirculating flows behind a backward facing step. They identified two recirculation zones downstream of the step experimentally. They concluded that reattachment length was practically constant after reaching turbulent flow conditions. The size of the secondary recirculation zone was quiet important. The intensity of velocity fluctuations parallel to the wall in the near wall region was found to be of the order of magnitude of local mean velocity. The high magnitude of skin friction inside of the recirculation zone was strongly Reynolds number dependent. Despite strong fluctuations, the reverse flow appearing in this region seems to be a viscous dominated and laminar like one.

Hyoung et.al [9] visualized Backward facing step flow with a 1:5 expansion ratio in a micro channel using theμPIV technique. They concluded that the flow hardly gets separated from the wall in normal flow rates used in microfluidic devices even with geometrically favorable features for recirculation and separation to occur. Onset of recirculation was observed at relatively large flow rates. This reconfirms that fluid flows are highly ordered and laminar at reduced scales and cannot be disrupted easily.

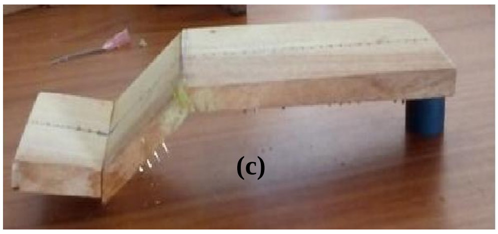
II. Experimental Setup

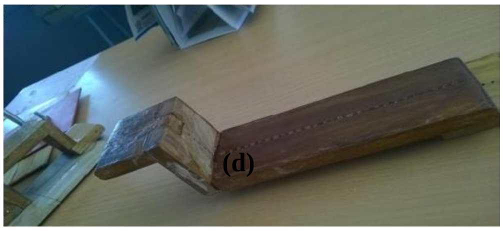
The experiments were conducted in low speed wind tunnel (shown in fig. 1). The size of the test section is 600 mm long and 300 mm side square cross- section. The models used in this work are forward facing step, backward facing step and combination of forward and backward facing steps with step inclination angles of 90^0, 50^0, 30^0 respectively (shown in fig2 (a), (b), (c), (d),(e),(f),(g),(h)&(i). The length of all the models is 200 mm, width of models is 50mm, step height is 40 mm, plate length ratio is 3 and thickness of the models is 10mm. These models contain ports at its center at a distance of 5 mm each to measure the pressure acting on its surface. The experimentation is done for all the models at different velocities 15 m/s, 20 m/s, 25 m/s. Values of drag and pressure on the surface of the models are measured using wind tunnel.

Fig 1. Low Speed Wind Tunnel



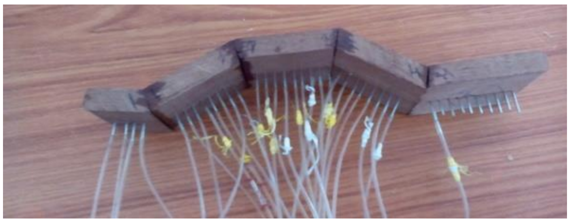
(a) **(b)**





(e) **(f)**

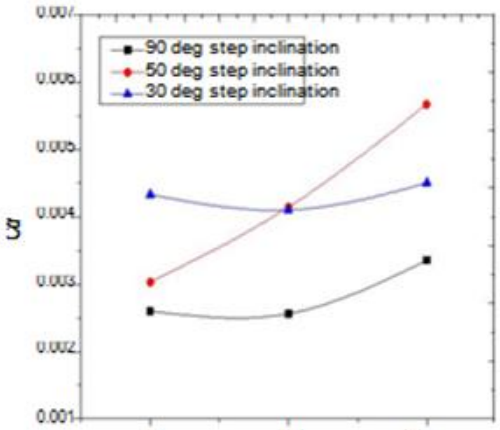
(g) **(h)**



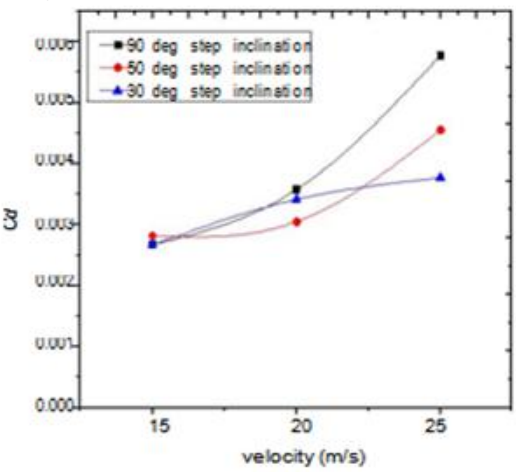
(i)

Fig 2.represents the fabricated models a) ffs with 90^0 inclination, b) ffs with 50^0 inclination, c) ffs with 30^0 inclination, d) bfs with 90^0 inclination, e) bfs with 50^0 inclination, f) bfs with 30^0 inclination, g) combination of ffs & bfs with 90^0 inclination, h) combination of ffs & bfs with 50^0 inclination, i) combination of ffs & bfs with 30^0 inclination

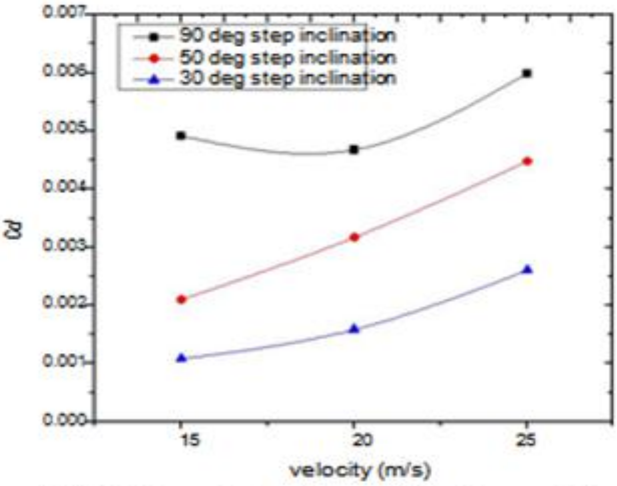
III. Results And Discussions



a) Variation of Drag for ffs models



b) Variation of Drag for bfs models

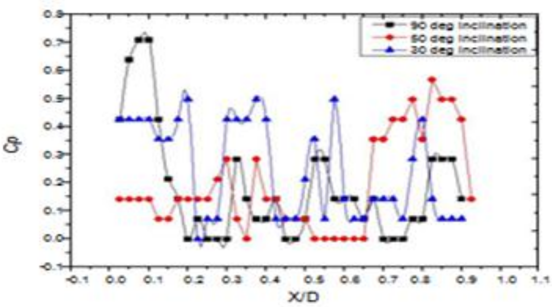


c) Variation of Drag for combination models

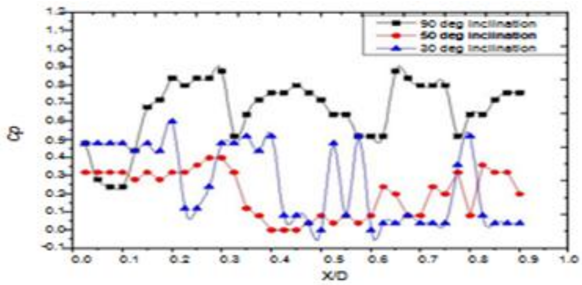
Fig 3. Variation of drag coefficient for different step angles at different velocities

The plot (fig 3 (a), (b), (c)) shows the variation of coefficient drag for different step models with inclinations of 90^0, 50^0, 30^0 at different velocities 15 m/s, 20 m/s, 25 m/s.

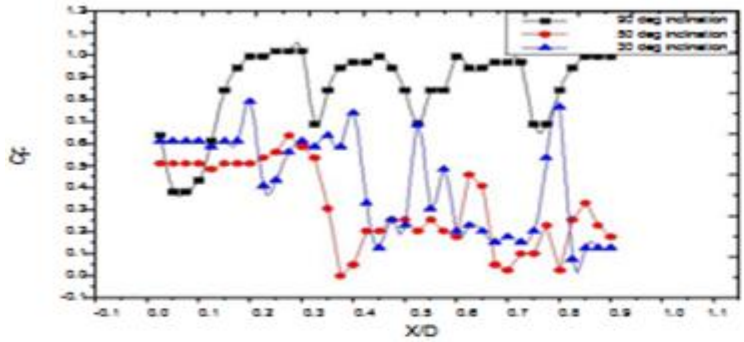
The plot in fig 3. (a) Shows the coefficient of drag variation for forward facing step models with various stepinclination angles at different velocities. Forward facing step with step inclination shows the least possible drag coefficient compared to remaining models and ffs with step inclination shows the maximum coefficient of drag comparatively and linear increase in coefficient of dragwith velocity is also o served. or ffs with step inclination the coefficient of drag is almost uniform with the increase in velocity and effect of velocity is also not that much significant on ffs model with step inclination. The plot in fig 3. (b) Shows the coefficient of drag variation for backward facing step models with various step inclination angles at different velocities. At a velocity of15 m/s the coefficient of drag is almost same for the three geometries, as the velocity increases the value ofcoefficient of drag also increases. For ffs model with step inclination least coefficient of drag is identified andfor ffs model with step inclination highest drag is identified comparatively. For ffs models we can conclude that as the step angle decreases the coefficient of drag also decreases. The plot in fig 3. (c) Shows the coefficient of drag variation for combination of forward and backward facing step models with different step inclination angles atdifferent velocities. Combination model with step inclination shows the least coefficient of drag compared to the remaining models whereas Combination model with step inclination shows the highest coefficient of drag comparatively, finally we can conclude that as the step inclination angle decreases the coefficient of drag also decreases this is because of increase in recirculating zone length which is responsible for drag reduction.



(a)



(b)



(c)

Fig.4. Variation of coefficient of pressure for ffs models at velocities of 15m/s(a), 20m/s (b), 25 m/s (c).

The plot in fig 4 (a) shows the coefficient of pressure distribution for forward facing step with step inclinations of90^0,$50^0$and 30^0respectively at a flow velocity of 15m/s. from the plot it is observed that pressure distribution isuniform at forward plate for both the models with step inclinations of $50^0$and 30^0.for a step with 90^0 there is a drasticraise of pressure at the mid of the forward plate and drastic pressure loss is observed at the step surface, a recirculation zone is formed at the beginning of the rear plate there after vortex shedding is observed, a secondary recirculation zone is also observed at the mid of the rear plate. for a step with 50^0 there is a small pressure drop at the beginning of the step and pressure raise is observed at the step surface, a vortex zone is identified at the beginning of the rear plate and gradual pressure drop takes place and became uniform at the mid of the rear plate and then pressure recovery takes place which is responsible for the formation of secondary recirculation zone and gradual pressure drop is observed at the end of the rear plate. for a step with 30^0there is a small pressure drop at the end of the forward plate and drastic pressure drop is identified at the step surface and a recirculation zone is identified at the beginning of the rear plate and totally four zones are identified till the end of the rear plate, as X/D increases thestrength of the zone is found to be decreases. The plot in fig 4(b) shows the coefficient of pressure distribution forforward facing step with step inclinations of90^0, $50^0$and 30^0respectively at a flow velocity of 20 m/s. from the plot it is observed that for both the steps with $50^0$and 30^0there is a small pressure drop at the end of the forward plate and for step with 90^0gradual decrease of pressure takes place from the beginning of the forward plate and pressure recovery takes place at the step surface a small vortex zone is identified at the beginning of the rear plate and at theend of the rear plate in between there is a small pressure raise is found for step with 50^0,pressure is slightly increased at the step surface and a pressure drop is identified at the beginning of the rear plate and a continues vortex shedding is identified till the end of the rear plate for step with 30^0sudden drop in pressure is identified at the step surface and a recirculating zone is identified at the end of the step and drastic pressure loss is observed at the beginning of the rear plate which is responsible for the formation of secondary recirculating zone, after this zone pressure is uniform up to the end of the rear plate and another recirculating zone is identified at the end of the rear plate after this zone again the pressure is uniform. The plot in fig 4(c) shows the coefficient of pressure distribution for forward facingstep with step inclinations of90^0,$50^0$and 30^0respectively at a flow velocity of 25m/s.From the plot it is observed that for both the steps with $50^0$and 30^0pressure is almost uniform at the forward plate and for step with90^0 gradual decrease of pressure takes place from the beginning of the forward plate and pressure recovery takes place at the step surface and a small vortex zone is formed at the end of the step and one more zone are identified at the end of the rear plate as X/D increases the length of the recirculating zone is found to be increased. for step with 50^0 a small pressure raise is observed at the end of the step and drastic pressure drop is identified at the beginning of the rear plate and pressure recovery takes place and continuous vortex shedding is identified up to the end of the rear plate and a small recirculating zone is identified at the end of the rear plate. for step with 30^0 sudden rise and fall of pressure is identified at the step surface and gradual increase of pressure takes place at the beginning of the rear plate, recirculation zone is identified at the mid of the rear plate and at end of the rear plate after this zone pressure is found to be uniform.

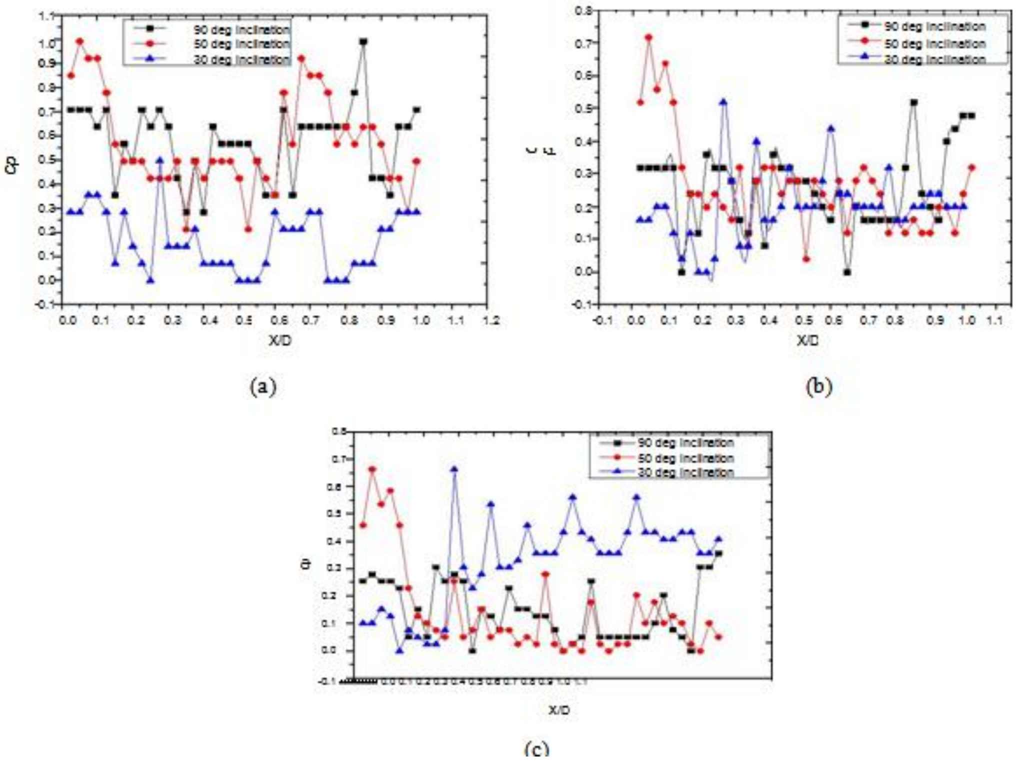
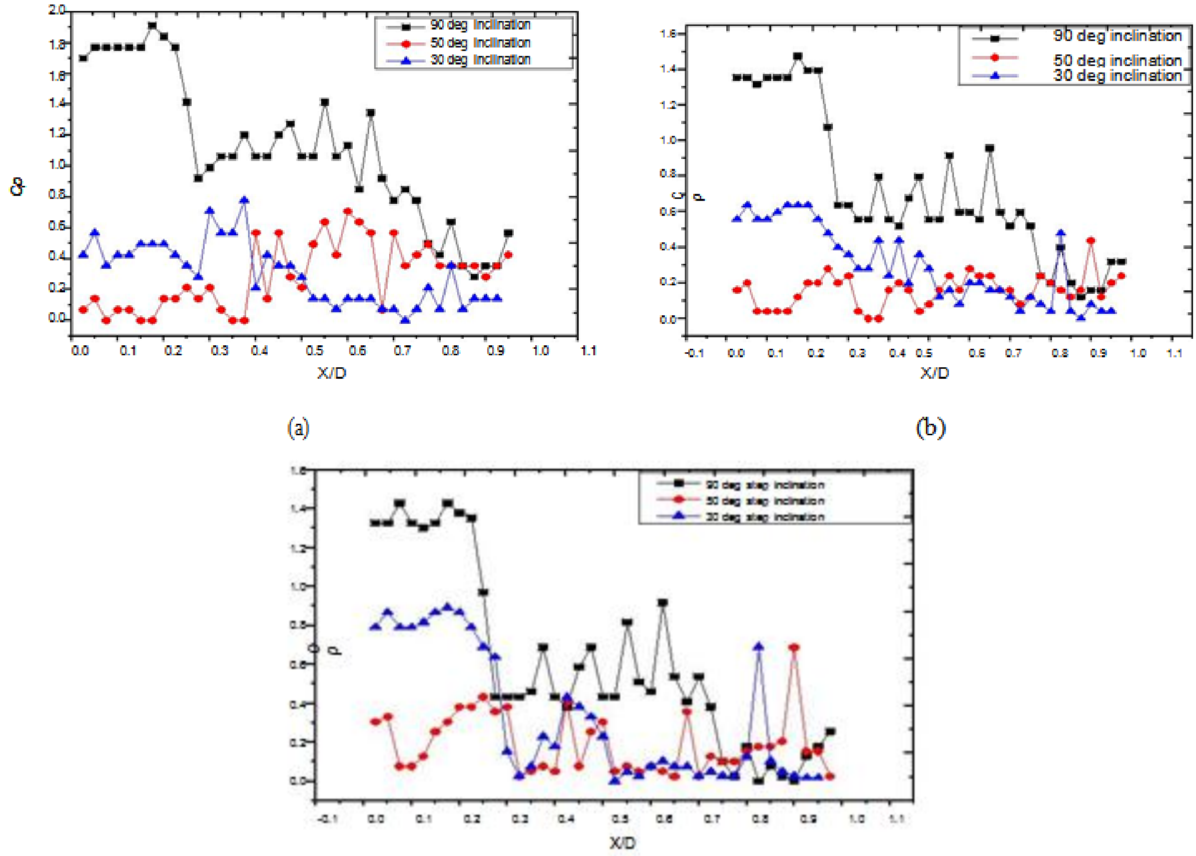


Fig.5. Variation of coefficient of pressure for bfs models at velocities of 15m/s (a), 20m/s (b), 25 m/s (c).

The plot in fig 5. (a) Shows the pressure distribution for backward facing step with step inclinations of 90^0,50^0and30^0respectively at a flow velocity of 15 m/s. for step with90^0small pressure drop is observed at the end of theforward plate and sudden pressure drop takes place at the beginning of the step surface and pressure recovery takes place up to the end of the step surface, a recirculating zone is identified at the beginning of the rear plate and pressure is found to be uniform after this zone and another recirculating zone is identified and here also pressure is uniform after the zone and a sudden rise and fall of pressure is observed at the end of the rear plate which is responsible for formation of recirculating zone. For step with 50^0 inclination pressure rise is observed at the forward plate and drastic pressure loss is observed at the surface of the step and recirculating zones are identified at thebeginning of the rear plate and continued with vortex shedding up to the rear plate and gradual pressure drop is identified at the end of the plate. For step with 30^0 inclination pressure rise isobserved at the beginning of the step and pressure drop is identified at the surface of the step which is responsible for the formation of recirculating zone and gradual rise and fall of pressure is found on entire length of the rear plate. The plot in fig 5(b) shows thepressure distribution for backward facing step with step inclinations of90^0,50^0and30^0respectively at a flow velocityof 20m/s.for step with90^0pressure is uniform at the forward plate and drastic pressure drop is identified at thestepsurface.Recirculation zones are identified at the end of the step and at thebeginning of the rear plate this zones arecontinued up to the end of the rear plate by recovering the pressure. for step with 50^0inclination there is a pressurerise at the beginning of the forward plate and pressure drops drastically at the surface of the step and recirculation zones are identified at the beginning of the rear plate and at the mid position of the rear plate and then continues vortex shedding is identified up to the end of the rear plate. for step with 30^0inclination pressure drop is observed at the end of the forward plate and pressure recovery takes place at the step surface where recirculation zone is identified and these zones are continued up to the mid position on the rear plate and pressure is found to be almost uniform at the end of the rear plate. The plot in fig 5(c) shows the pressure distribution for backward facing step with step inclinations of 90^0, 50^0and30^0 respectively at a flow velocity of 25m/s. for step with 50^0 pressure is almost uniform at the forward plate and pressure drop is identified at the beginning of the step surface and recirculationzones are identified at the rear plate and at the mid position of the rear plate after this zone pressure is found to uniform and pressure recovery takes place at the end of the rear plate and another recirculation zone is formed. forstep with 50^0inclination pressure rise is observed at the beginning of the forward plate and a small recirculation zoneis found at the forward plate and pressure is drastically reduced at the step surface and recirculating zone is identified at the end of the step surface and this zones are continued up to the mid of the rear plate and then vortex shedding is identified up to the end of the rear plate. for step with30^0 inclination small pressure drop is identified at the end of the forward plate, pressure recovery takes place at the end of the step surface and a recirculation zone is formed, these zones are identified up to the end of the rear plate with decrease in length of the zones and pressure is found to be uniform at the end of the rear plate.



(a) (b)

(c)

Fig.5. Variation of coefficient of pressure for combination models at velocities of 15m/s(a), 20m/s (b), 25m/s(c).

The plot in fig 5(a) shows the pressure distribution for combination of forward and backward facing step models with step inclinations of 90^0,50^0 and30^0 respectively at a flow velocity of 15m/s. for a model with 90^0inclination pressure is almost uniform at the forward plate and small pressure raise is observed at the step surface and pressure drops drastically at the end of the step surface and pressure recovery takes place at the middle plate and continuous vortex shedding is identified up to the end of the rear plate and recirculating zone is identified at the backward step surface and gradual pressure drop is identified at the end of the rear plate. For a model with 50^0inclination a small vortex shedding is identified at the forward plate and pressure recovery takes place at the end of the step which is responsible for formation of recirculating zone and these zones are continued up to the beginning of the rear plate. At the end of the zone pressure is found to be uniform. for a model with30^0 inclination small pressure rise is observed at the beginning of the step and gradual drop of pressure takes place up to the end of the forward step, pressure recovery takes place at the end of the step and a recirculating zone is identifiedat the beginning of the step and gradual decrease of pressure takes place up to the end of the middle plate and small recirculating zone is identified at the beginning of the backward step and at the end of the rear plate pressure is found to be constant. The plot in fig 5(b) shows the pressure distribution for combination of forward and backwardfacing step models with step inclinations of90^0, 50^0and30^0respectively at a flow velocity of20m/s. for a model with90^0inclination pressure is almost uniform at the forward plate and drastic pressure loss is observed at the forwardstep surface and a recirculating zone is observed at the end of the step and this zone is continued up to the end of the backward step and gradual pressure loss is identified at the end of the rear plate. For a model with 50^0inclination initially pressure raise is identified later pressure is found to be uniform at the forward plate, gradual rise and fall of the pressure takes place at the forward step surface, a small recirculating zone is identified at the end of the forward step and continuous vortex shedding is observed at middle plate and backwardstep a recirculating zone is identified at the end of the rear plate.for a model with 30^0inclination a small pressure raise is identified at the beginning of the forward plate, pressure drops drastically at the end of the forward step and pressure recovery takesplace which is responsible for formation of recirculation zone, continues vortex shedding is identified at the middle plate and at the backward step, and a recirculating zone is identified at the end of the rear plate after this zone pressure is observed to be constant. The plot in fig 5(c) shows the pressure distribution for combination of forwardand backward facing step models with step inclinations of 90^0, 50^0and30^0respectively at a flow velocity of 25m/s.for a model with 90^0inclination small rise in pressure is observed at the beginning of the forward plate and pressuredrops drastically at the forward step surface a recirculating zone is identified at the end of the forward step, the formation of this zones are continued on middle plate and at the backward step and vortex shedding is identified at rear plate. for a model with 50^0inclination sudden pressure drop is identified at the beginning of the forward plate and pressure recovery takes place and a recirculation zone is formed at the end of the step, vortex shedding is identified at the middle plate and a recirculation zone is identified at the backward step and pressure is found to be uniform at the beginning of the rear plate and a recirculation zone is identified at the end of the rear plate. for a model with 30^0inclination a small pressure drop is identified at the beginning of the forward plate and pressure drops drastically at the end of the forward step, a recirculating zone is identified at the end of the step surface, pressure recovery takes place at the middle plate and continuous vortex shedding is identified at the middle plate and at the step surface and a recirculating zone is identified at the end of the rear plate.

IV. Conclusion

In this work the experiments are conducted on nine models, the models chosen are: forward facing step, backward facing step and combination of forward and backward facing step with step geometries of 90^0 ,50^0 and 30^0 respectively. The experiments were conducted to find the drag and co – efficient of pressures on the surface of the models at different flow velocities. From the above experiments the following conclusions are made.

The drag is found to be increase with the increase of velocity, for ffs models least coefficient of drag is identified at the ffs model with 50^0 step inclination, as the step angle decreases coefficient of drag is observed to be increased for forward facing steps. For bfs models least coefficient of drag is identified at the bfs model with 30^0 step inclination and compared to remaining models model with 30^0 step inclination shows better results. For combination of forward and backward facing step models least coefficient of drag is identified at the model with 30^0 step inclination. Finally we can conclude that coefficient of drag is mainly influenced by step geometries as the step inclination decreases coefficient of drag decreases.

For ffs models it is inferred that the influence of flow velocity is predominant in dictating the strength of the recirculating zone and the strength of recirculating zone not only depends on the velocity but also influenced by the angle of inclination. As the step inclination angle decreases more number of zones are identified after the step surface. For bfs models it is inferred that the strength of the recirculating zone is increased with decrease of step inclination angle. And this recirculating zone is also depends up on velocity of the flow, as the velocity of the flow increased the strength of the zone is found to be decreased. For combination of forward and backward facing models it is observed that maximum pressure drop takes place at the forward step with 90^0 inclination model. Strength of the recirculating zone is increased with the decrease of step inclination angle and found good at steps with 30^0 inclination, which is reason behind the reduction of coefficient of drag. Hence from this analysis we conclude that combination of forward and backward facing step with 30^0 inclination is preferable.

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