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Reduction of Flow Separation from a Fuselage for Subsonic and Transonic Flows

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Abstract: - This paper discusses research variables that directly impact the ability to obtain laminar flow and techniques to reduce flow separation. Laminar flow control has long been considered as a potentially viable technique for increasing aircraft performance. Previous studies have demonstrated that laminar flow control could reduce takeoff total weight, mission fuel, and structural temperatures.

This paper will show flow over fuselage using active and passive designs. Active design uses a porous boundary condition, whereas, passive design without a porous boundary condition. A primary goal of the passive design is to obtain detailed surface pressure–distribution data. These data were obtained for a Mach range of 0.4 – 0.9. This paper demonstrated that laminar flow and flow separation-reduction can be achieved on a blunt fuselage configuration for a Mach range of 0.4 - 0.9. Pressure-distribution and transition data were obtained for a Mach range of 0.4 - 0.9. The results show that large regions of laminar flow can be achieved when active laminar flow control is used. This paper shows that slower moving air on the upper surface can be increased in speed by bringing air from the high pressure area on the bottom of the fuselage through slots. One can conclude from this study, also that the porous boundary condition should be at least 2/3 of the incoming free stream velocity and in the axial direction. Pressure will decrease on the top so the adverse pressure gradient which would cause the boundary layer separation reduces.

Key- Words: Boundary layer, flow separation, blunt body flow, numerical analysis.

Nomenclature

Symbol	Meaning
c_v	Specific heat at constant volume
e	Internal energy
$\overline{\overline{e}}$	Deformation Tensor
f_{ij}	Viscous forces
$\overline{\overline{I}}$	Identity tensor
h^o	Stagnation enthalpy
k	Thermal conductivity
m	Mass
p	Static pressure
Q	Heat generation
t	Time
T	Static temperature
$\overline{\overline{T}}$	Stress tensor
U	Mean velocity component
V	Mean velocity component
W	Mean velocity component
W	Molecular Weight
ε_{ij}	Rate of strain tensor
γ	Ratio of specific heat
δ_{ij}	Kronecker delta
ρ	Density of fluid
λ	Bulk viscosity
τ_{ij}	Shear stress
μ	Coefficient of viscosity

1 Introduction

Flow separation is a phenomenon of special interest in boundary layer theory and its understanding was advanced considerably by [1] who showed that regular separation could occur by an interactive process. Since then, triple deck theory has contributed much to the understanding of boundary layer separation [2-3]. Excellent reviews may be found in [4-10].

In most situations it is inevitable that the boundary layer becomes separated from the surface of a body. This detachment of the boundary layer results in a large increase in the drag on the solid body. This can be understood by studying the inviscid flow over a cylinder. The pressure distribution is the same on the upstream and downstream sides of the cylinder. Hence, thus, there are balanced forces on the cylinder and therefore no drag the d'Alembert's paradox. One of the most famous results of the inviscid flow theory is d'Alembert's paradox which states that a rigid body does not experience any drag in incompressible flow. It is well known that this contradiction is associated with the assumption of a fully attached form of the flow; this situation almost impossible in practice.

However, for viscous fluid, if the boundary layer separates from the cylinder, then the pressure on the downstream side of the cylinder is essentially constant, and equal to the low pressure on the top and bottom points of the cylinder. This pressure is much lower than the large pressure which occurs at the stagnation point on the upstream side of the cylinder, leading to a pressure imbalance and a large pressure drag on the cylinder. For high Reynolds number one might think that the viscosity could be ignored, however, once again encounter d'Alembert's paradox and therefore unable to balance and to explaining aerodynamic drag forces. The important insight in resolving this paradox is due to Prandtl (1904), who suggested that the viscosity could be ignored everywhere except in a thin layer close to the surface of a body. Understanding the behavior of this boundary layer has been crucial to the development of modern fluid mechanics.

The difference between a separated flow and its theoretical inviscid flow concerns not only the form of trajectories of fluid particles, but also the magnitudes of aerodynamic forces acting on the body. Boundary layers tend to separate from a surface of a solid body when there is an adverse pressure gradient that is increasing fluid pressure in the direction of the flow. For a large pressure gradient the shear stress can be reduced to zero, and separation often occurs. The fluid is no longer sticking on the wall, and opposing flow can develop which effectively separates the boundary layer off of the wall.

The study of flow separation from the surface of a solid body, and the determination of global changes in the flow field that develop as a result of the separation, are among the most fundamental and difficult problems of fluid dynamics. Separation imposes a considerable limitation on the operating characteristics of aircraft wings, helicopter, and turbine blades, leading to a significant degradation of their performance. It is well known that the separation is normally accompanied by a loss of the coefficient of lift, drastic increase of the drag, and an increase of the heat transfer at the reattachment region.

The traditional approach of studying the separation phenomenon for high Reynolds is based on seeking possible simplifications that may be introduced in the governing Navier-Stokes equations. The first studies at describing separated flows past bluff bodies are due to Helmholtz (1868) and Kirchhoff (1869) in the manifest of the classical theory and application of non-viscous flows, but it was incomplete explanation as to why separation occurs. Prandtl (1904) who was the first to recognize the physical cause of separation at high Reynolds numbers as being associated with the separation of boundary layers that must form on all surfaces of the solid bodies.

2 Theoretical Analysis

The main problem here is to determine velocity field and the states of the fluid: its pressure, density, and temperature at all time and all space. There are six unknowns u, v, w, p, ρ and T. with four independent variables x, y, z, and t. Hence six independent equations for these six unknowns are needed.

The equations for the conservation of mass, momentum, and energy, are written in terms of the dependent variables velocity, pressure and enthalpy. In steady laminar flow, the instantaneous value of a variable at any given position and time in space is equal to its mean value.

Thermodynamic properties of a substance are not independent variables in a compressible flow. The manner in which any thermodynamic property is related to any two independent thermodynamic properties is referred to as an Equation of State. One equation of state for a perfect gas is the Ideal Gas Law:

$$p = \rho RT \qquad \text{Eq. 1}$$

Where R is the universal gas constant divided by the molecular weight of the fluid. This simple linear relationship is important for a wide class of gaseous problems at sufficiently high temperatures and low pressures. However, at low temperature and high pressure near phase change, significant error can result by using the perfect gas equation. At these conditions, the gas is considered to exhibit real gas effects. Several models exist to model real gases, such as Van der Waals equation and the compressibility correction factor.

2.2 Conservation of Mass

Equation of continuity expresses the conservation of mass of the medium. Conservation of mass requires that mass can neither be destroyed nor created. In many engineering applications sometime it is preferable to write the natural equation, by using the index notation, especially when dealing with numerical analysis. The continuity equation in index notation is therefore:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho \overrightarrow{V_j}\right) = 0 \qquad \text{Eq. 2}$$

In this equation, $\overrightarrow{V_j}$ represents the three-dimensional velocity vector components of the flow.

2.1 Conservation of Momentum

There are three equations of motion which express the conservation of momentum.

$$\overrightarrow{F} = m\overrightarrow{a} = \frac{d}{dt}\left(m\overrightarrow{V}\right) \qquad \text{Eq. 3}$$

The differential form of the momentum equation is:

$$\rho \frac{D\overline{V}}{Dt} = \rho \overline{F} + \overline{\nabla} \bullet \overline{\overline{T}} \qquad \text{Eq. 4}$$

Where $\overline{\overline{T}}$ is the stress tensor, and the constitutive model is:

$$\overline{\overline{T}} = \left(-P + \lambda \overline{\nabla} \bullet \overline{V}\right)\overline{\overline{I}} + 2\mu \overline{\overline{e}} \qquad \text{Eq. 5}$$

Where, p is thermodynamic pressure, λ is the bulk viscosity where ($\lambda = \frac{2}{3}\mu$), $\overline{\overline{I}}$ is the identity tensor and $\overline{\overline{e}}$, is the deformation tensor. The momentum equation is therefore:

$$\rho \frac{D\overline{V}}{Dt} = \rho \overline{F} + \overline{\nabla} \bullet \left[\left(-p + \lambda\left(\overline{\nabla} \bullet \overline{V}\right)\overline{\overline{I}}\right) + 2\mu \overline{\overline{e}}\right] \quad \text{Eq. 6}$$

One may write the shear stresses (viscous forces) as:

$$\tau_{xx} = \lambda \nabla.\vec{V} + 2\mu \frac{\partial u}{\partial x} \quad \text{Eq. 7}$$

$$\tau_{yy} = \lambda \nabla.\vec{V} + 2\mu \frac{\partial v}{\partial y} \quad \text{Eq. 8}$$

$$\tau_{zz} = \lambda \nabla.\vec{V} + 2\mu \frac{\partial w}{\partial z} \quad \text{Eq. 9}$$

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) \quad \text{Eq. 10}$$

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) \quad \text{Eq. 11}$$

$$\tau_{yz} = \tau_{zy} = \mu\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right) \quad \text{Eq. 12}$$

The x-momentum therefore is:

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad \text{Eq. 13}$$

The y-momentum therefore is:

$$\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad \text{Eq. 14}$$

The z-momentum therefore is:

$$\frac{\partial(\rho w)}{\partial t} + \nabla.(p w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad \text{Eq.15}$$

The momentum equation can be written in tensor form where the shear stress tensor is used. The shear stress (viscous) tensor for Newtonian (linear fluid) therefore is:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \delta_{ij}\lambda \overline{\nabla} \bullet \overline{V} \quad \text{Eq. 16}$$

Where δ_{ij} is the kronecker delta and δ_{ij} =1 for i=j and δ_{ij} =0 for i≠j, the momentum equation in tensor form is:

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \quad \text{Eq. 17}$$

The three terms on the right-hand side of Eq. 17 represent the x-components of all forces due to the pressure, p, the viscous stress tensor, τ_{ij} , and the body force, f_i .

2.3 Conservation of Energy Equation

The differential form of the energy equation is written in the same way as the continuity and the momentum equation, namely, by using Green's theorem, hence:

$$\rho \frac{D}{Dt}\left(\frac{\overline{V} \bullet \overline{V}}{2} + e\right) = \rho \overline{F} \bullet \overline{V} + \overline{\nabla} \bullet \left(\overline{V} \bullet \overline{\overline{T}}\right) + \rho Q - \overline{\nabla} \bullet \overline{K} \quad \text{Eq. 18}$$

Therefore the differential form of the total energy equation can be written in the following form, where the stress tensor is used and the assumption of the Newtonian fluid applied implicitly:

$$\rho \frac{D}{Dt}\left(e + \frac{V^2}{2}\right) = \rho Q + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$
$$-\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y}$$
$$+\frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z}$$
$$+\frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} + \rho \vec{f}.\vec{V} \quad \text{Eq. 19}$$

In some engineering applications, sometimes one wishes to deal with the internal energy alone or in another instance one may wish to evaluate the mechanism of transferring energy from one mode to another, such as in turbulent flow or in viscous situations therefore it will be helpful to develop the energy equation in terms of the internal energy alone. One way to derive the internal energy is to subtract the kinetic energy equation from the total energy equation.

The kinetic energy equation is obtained by using the dot product between two vectors namely the momentum equation and the velocity vector. Therefore the kinetic energy equation is:

$$\rho\frac{D\frac{V^2}{2}}{Dt} = -u\frac{\partial p}{\partial x} - v\frac{\partial p}{\partial y} - w\frac{\partial p}{\partial z} + u\left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right)$$
$$+v\left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right) + w\left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right)$$
$$+\rho\left(uf_x + vf_y + wf_z\right)$$

Eq. 20

One may subtract the kinetic energy obtained from dotting the velocity vector with the three directions of the momentum, therefore the internal energy equation may be written as:

$$\rho\frac{De}{Dt} = pQ + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$
$$-p\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \lambda\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)^2$$
$$+\mu\left[\begin{array}{l} 2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 \\ + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \end{array}\right]$$

Eq. 21

For incompressible fluid, $e = c_v T$, therefore,

$$\rho c\frac{DT}{Dt} = div(k\ grad\, T) + \tau_{xx}\frac{\partial u}{\partial x} + \tau_{yx}\frac{\partial u}{\partial y}$$
$$+\tau_{zx}\frac{\partial u}{\partial z} + \tau_{xy}\frac{\partial v}{\partial x} + \tau_{yy}\frac{\partial v}{\partial y} + \tau_{zy}\frac{\partial v}{\partial z}$$
$$+\tau_{xz}\frac{\partial w}{\partial x} + \tau_{yz}\frac{\partial w}{\partial y} + \tau_{zz}\frac{\partial w}{\partial z} + \rho Q$$

Eq. 22

For compressible fluid, therefore:

$$\frac{\partial(\rho h^{\circ})}{\partial t} + div(\rho h^{\circ} u) = div(k\ grad\ T) + \frac{\partial p}{\partial t}$$
$$+\left[\begin{array}{l} \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} \\ + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} \\ + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \end{array}\right] + \rho Q$$

Eq. 23

In tensor form the energy equation therefore is:

$$\frac{\partial}{\partial t}\left(\rho h^o\right) + \frac{\partial}{\partial x_j}\left(\rho u_i h^o\right) = \frac{\partial p}{\partial t} - \frac{\partial}{\partial x_j}\left(u_i \tau_{ij} + Q_j\right) + \rho u_i f_i$$

Eq. 24

Considering an infinitesimal control volume, the two terms on the left-hand side of this equation describe the rate of increase of h^o and the rate at which h^o is transported into and out of the control volume by convection. The first term on the right-hand side describes the influence of the pressure on the total enthalpy. The second term describes the rate at which work is done against viscous stresses by distortion of the fluid. The gradient of Q is the rate of energy transfer into the control volume by conduction, and the last term describes the rate of work done by body forces.

If the Navier-Stokes equations do not hold an equation of the stress tensor must be found and solved simultaneously with the four basic equations. Even when the Navier-Stokes relations hold, the relation of the coefficient of viscosity must be given with respect to the state variables of the fluid such as temperature and density.

There are many other cases where the basic equations of fluid dynamics are not sufficient or should be modified such as in the cases of the two-phase flow, multi-fluid flow theory, relativistic fluid mechanics and biomechanics.

3 Numerical Analysis

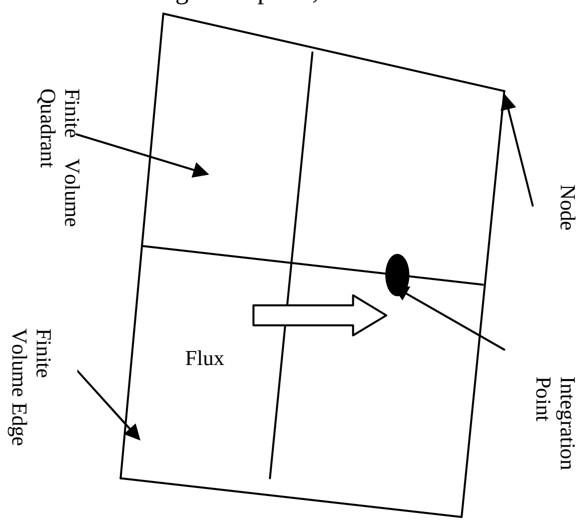
Now, after stating all the flow equations, mass, momentum, energy, and the constitutive laws that govern the transport relations, it is time to formulate a solution. But, since, these equations are coupled nonlinear, partial differential equations, it is impossible to have a closed form of solution. In order to formulate or approximate a valid solution for these equations they must be solved using computational fluid dynamics technique. In order to solve these equations numerically with a computer, they must be discretized. That is, the continuous control volume equations must be applied to each discrete control volume that is formed by the computational grid. The integral equations are substituted with a set of linear algebraic equations solved at a discrete set of points [11-15].

In a finite element discretization the grid breaks up the domain into elements over which the changes of the fluid variables are evaluated. Adding all the variations for each element then gives an overall visualization of how the variables vary over the entire domain. The primary advantage of the finite element method is the geometric flexibility allowed by a finite element grid. In a finite volume discretization the grid breaks up the domain into nodes, each associated with a discrete control volume. The fluxes of mass, momentum, and energy for each control volume are then calculated at each node. An advantage of the finite volume method is that the principles of mass, momentum, and energy conservation are applied directly to each control volume, so that the integral conservation of quantities is exactly satisfied for any set of control volumes in the domain. Thus, even for a coarse grid, there is an exact integral flux balance.

A numerical analysis must start with breaking the computational domain into discrete sub-domains, which is the grid generation process. A grid must be provided in terms of the spatial coordinates (x, y and z location) of grid nodes distributed throughout the computational domain. At each node in the domain, the numerical analysis will determine values for all dependent variables including pressure, velocity components and temperature.

The nodes must be distributed throughout the volume enclosed by the exterior boundary surface of the domain such that they form a complete three-dimensional matrix of nodes. Each node in the matrix will be referred to by the index triplet (i, j, k).

Fig.1 Schematic view finite volume cell showing integration point, flux and node



3.1 Flux Elements

To complete the description of the distribution of nodes in the computational domain, it is useful to introduce the concept of a flux element. A flux element, such as shown in Figure 1, is a linear, hexahedral element defined by eight nodes. Conforming to the finite element approach, linear shape functions representing the variation of variables within the flux element are applied.

Each flux element has four octants for two-dimensional domain and eight octants for three-dimension region. The six sides of each octant are divided into two groups; those that are coincident with the flux element sides and those that are in the interior of the flux element. Because the latter group will form the surfaces of the control volume over which surface integrals will be evaluated, they are referred to as, integration point surfaces, as shown in Figure 1.

3.2 Control Volumes

In finite volume method a control volume exists for each node, with the boundary of each interior control volume defined by eight line-segments in two dimensions and 24 quadrilateral surfaces in three dimensions. To solve the governing or the natural equations that were derived in theoretical section they must be converted to their discrete or algebraic form.

3.3 Discretization

Discretization is the process whereby the governing equations are converted by their discrete form. Discretization identifies the node locations and flux elements to model the flow problem. The differential equations are transformed to algebraic equations, which should correctly approximate the transport properties of the physical processes.

Next, the fluxes are evaluated at integration points, which are shared by adjacent control volumes. The same flux that leaves one control volume enters the next one. Thus, even with a low accuracy advection scheme numerical conservation is guaranteed. This is the fundamental advantage of a finite volume method. The discretization is evaluated in an elemental basis.

4 Results and Discussion

Laminar flow control and flow separation-reduction have been considered as a potentially viable technique for increasing aircraft performance. Many studies have demonstrated that laminar flow control could reduce takeoff total weight, fuel weight, and structural temperatures [16-22].

Minimizing the pressure drag amounts to preventing or delaying boundary layer separation. Since adverse pressure gradients are the cause of separation. Trailing stagnation points are bound to cause problems, so separation can often be delayed by placing the trailing stagnation point so that the fluid can leave the body smoothly. [16-22] Another way of delaying separation is by forcing the boundary layer to become turbulent. The more efficient mixing which occurs in a turbulent boundary layer reduces the boundary layer thickness and increases the wall shear stress, often preventing the separation which would occur for a laminar boundary layer under the same conditions [16-20].

One can see that there is a trade-off between the turbulent boundary layer and the laminar boundary layer. The turbulent boundary layer produces a greater drag due to skin friction, but can often reduce the pressure drag by preventing, or reducing, boundary layer separation. The turbulent boundary layer usually dominant at high Reynolds numbers, various schemes have been invented for producing turbulent boundary layers. [22-27]

In accordance with the Prandtl's theory, a high Reynolds number flow past a rigid body has to be subdivided into two characteristic regions. The main part of the flow field may be treated as inviscid. However, for all Reynolds numbers, no matter how large, there always exists a thin region near the wall where the flow is predominantly viscous. Prandtl termed this region the boundary layer, and suggested that it is because of the specific behaviour of this layer that flow separation takes place. Flow development in the boundary layer depends on the pressure distribution along the wall. If the pressure gradient is favourable, i.e. the pressure decreases downstream, then the boundary layer remains well attached to the wall. However with adverse pressure gradient, when the pressure starts to rise in the direction of the flow, the boundary layer tends to separate from the body surface. Since the velocity in the boundary layer drops towards the wall, the kinetic energy of fluid particles inside the boundary layer appears to be less than that at the outer edge of the boundary layer, in fact the closer a fluid particle is to the wall the smaller appears to be its kinetic energy. This means that while the pressure rise in the outer flow may be quite significant, the fluid particles inside the boundary layer may not be able to get over it. Even a small increase of pressure may cause the fluid particles near the wall to stop and then turn back to form a recirculating flow region characteristic of separated flows.

There are many examples of fluid flows in technology and engineering where imposed boundary conditions or geometries results in flow separation. In applications where thermal effects are significant, such as cooling or insulating systems, such separations can have important consequences for the heat transfer properties of the system. Laminar flow control and flow separation-reduction have been considered as a potentially viable technique for increasing aircraft performance. Many studies have demonstrated that laminar flow control could reduce takeoff total weight, fuel weight, and structural temperatures [16-22].

This paper will show flow over fuselage using active and passive designs. Active design uses a porous boundary condition, whereas, passive design without a porous boundary condition. A primary goal of the passive design is to obtain detailed surface pressure–distribution data. These data were obtained for a Mach range of 0.4 – 0.9. This paper demonstrated that laminar flow can be achieved on a blunt fuselage configuration for a Mach range of 0.4 - 0.9. Pressure-distribution and transition data were obtained for a Mach range of 0.4 to 0.9. The results show that large regions of laminar flow can be achieved when active laminar flow control is used.

Figure 2 shows path lines for flow over fuselage with Mach number of 0.4 of an active design. One can see that the flow is attached to the surface of the body almost every where, on the other hand figure 3 shows path lines for passive design where it is evident that the flow is separated from the top surface.

Fig.2 Path lines for flow over fuselage Mach =0.4 with active design

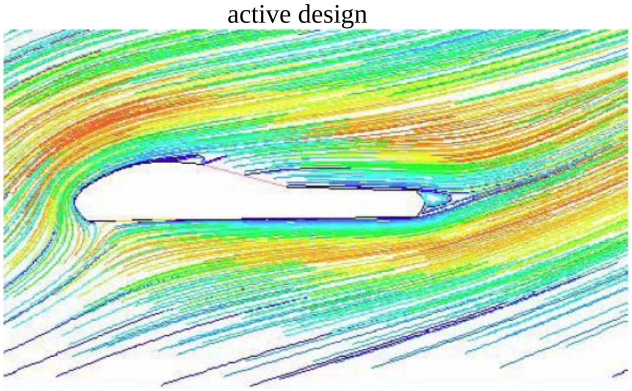


Fig.3 Path lines for flow over fuselage Mach =0.4 with passive design

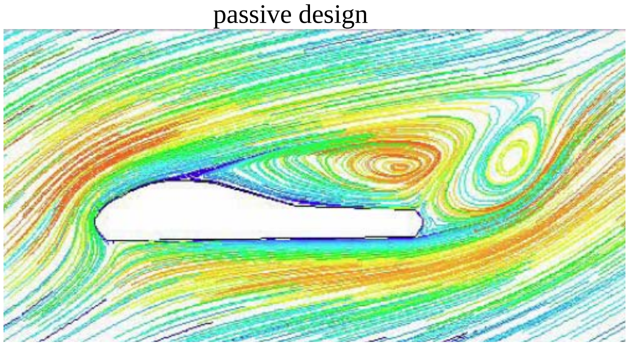


Figure 4 shows velocity vectors of the active design for flow over fuselage with Mach number of 0.4 where one can see the direction of the flow as it flows over the body. Figure 5 shows velocity vector for flow over fuselage with passive design; one can see the circulation of the flow in regions of the separated flow.

Fig.4 Velocity vectors for flow over fuselage Mach =0.4 with active design

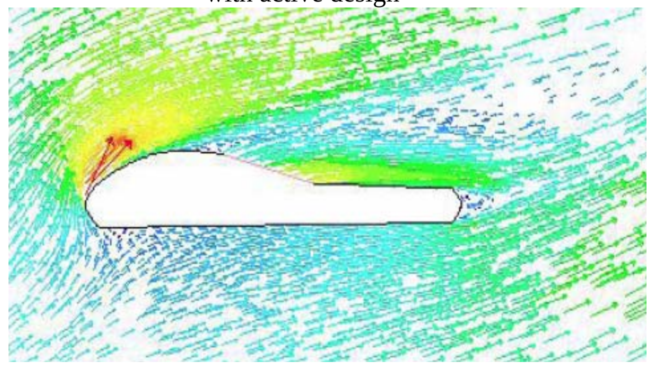


Fig.5 Velocity vectors for flow over fuselage Mach =0.4 with passive design

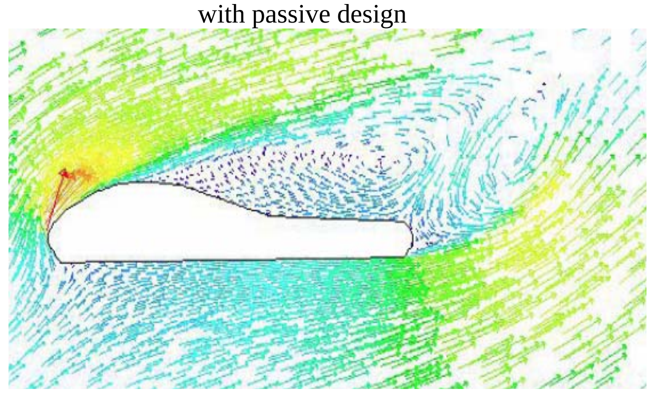


Figure 6 shows path lines for flow over a fuselage with active design of Mach number of 0.9, one can see that the flow is attached to the body. Figure 7 shows path lines for the flow over fuselage with passive design of Mach number of 0.9, one can see that the flow is separated from the body. Figure 8 shows flow over fuselage with active design but one can see there is some circulation and separation in the flow. One can conclude from this study that the porous boundary condition should be at least 2/3 of the incoming free stream velocity and in the axial direction.

Figure 9 shows contour plots of Mach number of flow over fuselage with active design of Mach number of 0.9, one can see the shock wave is generated on the top surface. Figure 10 shows contour plot of Mach number of flow over fuselage with passive design of Mach number of 0.9; one can see the shock wave is generated on the top surface of the solid body.

Fig.6 Path lines for flow over fuselage Mach =0.9 with active design

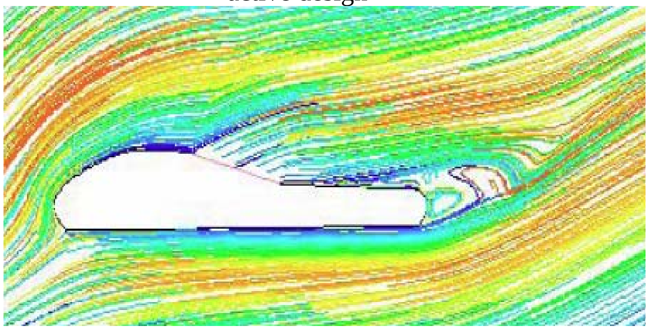


Fig.7 Path lines for flow over fuselage Mach =0.9 with passive design

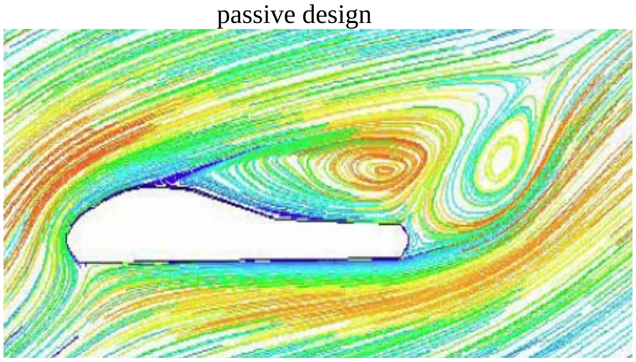


Fig.8 Path lines for flow over fuselage Mach =0.9 with active design different velocity

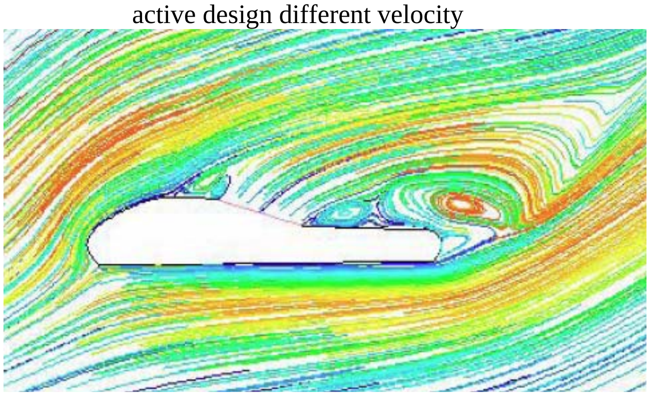


Fig.9 Contour Plot flow over fuselage Mach =0.9 with active design

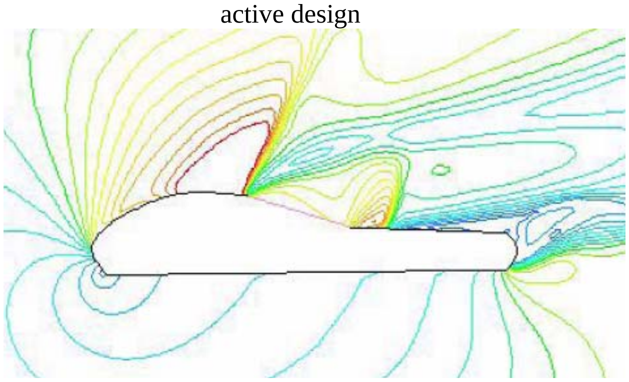
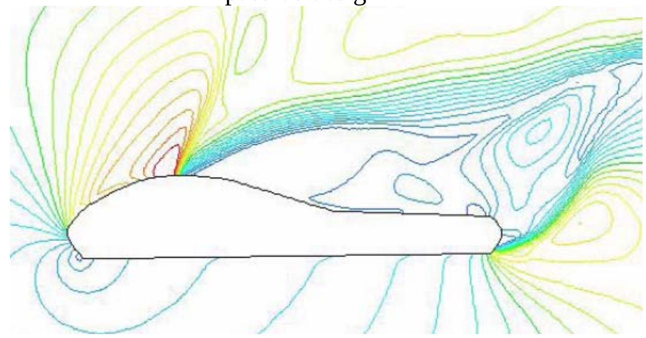


Fig.10 Contour Plot flow over fuselage Mach =0.9 with passive design



5 Conclusion

The study of flow separation from the surface of a solid body, and the determination of global changes in the flow field that develop as a result of the separation, are among the most fundamental and difficult problems of fluid dynamics. Laminar flow control and flow separation-reduction have been considered as a potentially viable technique for increasing aircraft performance. Many studies have demonstrated that laminar flow control could reduce takeoff total weight, fuel weight, and structural temperatures.

Minimizing the pressure drag amounts to preventing or delaying boundary layer separation. Since adverse pressure gradients are the cause of separation, one wants to avoid these or at least make the gradients small. This paper shows that slower moving air on the upper surface can be increased in speed by bringing air from the high pressure area on the bottom of the fuselage through slots. Pressure will decrease on the top so the adverse pressure gradient which would cause the boundary layer separation reduces. One can conclude from this study also that the porous boundary condition should be at least 2/3 of the incoming free stream velocity and in the axial direction.

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