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COMPUTATIONAL LAMINAR FLOW CONTROL OVER A POROUS FLAT PLATE

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Abstract
The history of laminar flow control (LFC) from 1930s to present has been surveyed and the current state of the technology is assessed. The focus has been on the development of suction type LFC techniques for aerofoil surfaces and their use in aircraft design. As a preliminary investigation, the compressible Navier-Stokes equations have been solved for flow over a porous flat plate using a high-resolution TVD scheme. Computational results were in good agreement with the analytical solutions of Blasius and Iglisch using several suction rates. The skin friction coefficient and the drag coefficient have been accurately predicted.

Keywords: LFC – TVD Schemes – Navier-Stokes Equations.

Introduction
The main key in the flow control is to exploit the natural tendency of the flow to behave against its normal behavior. LFC is a boundary layer flow control technique employed to maintain the laminar state over the aerofoil surfaces, but it does not imply the relaminarization of a turbulent flow state. Although the same control concept may be employed for both regimes, the energy requirement for relaminarization of turbulent flows could be typically greater than that for LFC. For the purpose of flow control, some devices are needed either active or passive. In active control, some sensors and an algorithm based on flow principle are used whilst for passive control fixed or static devices that modify the flow are used. For engineering application passive control seems more feasible than active feedback control [1, 2].

Beginning with the realization that skin friction drag could amount to approximately 45 percent of the total drag [3] and also laminar skin friction can be as much as 90 percent less than turbulent at the same Reynolds number, an aerofoil with laminar flow would have much less skin friction drag than the one with turbulent flow. This shows the significance of LFC in aircraft design. Unfortunately achieving laminar flow over entire aerofoil configuration is impractical. Because of the sensitivity of the laminar flow to disturbances (joints, doors, etc.), drag reduction due to laminar flow over a portion like wings is achievable. Experimental investigation of NASA proved that full chord length laminar flow can be obtained by suction through holes or strips [3]. NASA high speed research (HSR) program aims to achieve laminar or smooth airflow over the surface of an aircraft`s wing at supersonic speeds. The F-16XL laminar flow test panel [4] was designed for this purpose. Experimental data from F-16XL will provide useful test cases for validation of CFD tools that can be used for the design of future high-speed airplanes with laminar flow characteristics.

History of LFC
The earliest known experimental work on LFC for aircraft took place in the late 1930s and 1940s primarily in wind tunnel. In 1939 NACA performed some tests for the design of multiple suction slots

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and produced the first aerodynamic criteria for obtaining laminar flow up to a Reynolds number of 7 millions, a large value at that time. The first LFC flight experiment was happened in 1941. Seventeen suction slots between 20 to 60 percent of the chord of a B-18 wing (glove) were installed [5]. But the test was unsuccessful because of limitations in achieving the designed length Reynolds number for transition. Experiments in NACA on LFC ceased during world war years in order to develop natural laminar flow control (NLFC) on 6- and 7- digit series aerofoils. In Germany and Switzerland efforts to develop LFC technology with suction was under way during the war. They emphasized the stability of laminar flow with continuous suction rather than discrete suctions. Tollmein and Schlichtling discovered theoretically that continuous suction resulted in a very stable boundary layer in 2D type disturbances (TS waves). German researchers derived methods for calculating boundary layer characteristics and drag reduction resulting from continuous suction, but they were unable to produce smooth surfaces suitable for continuous suction.

Release of German report after war renewed the interest in the USA [5]. The NACA initiated wind tunnel tests that attained full chord laminar flow on both surfaces of an aerofoil with continuous suction through porous bronze surfaces, with 1" diameter holes. Boundary layer measurements were made on the upper surface to 83% chord and laminar flow was observed up to 83% of the chord at Reynolds numbers up to 8 millions. The measured drag for LFC aerofoil was roughly one third of the model without suction (1951). After that, wind tunnel experiments verified the theoretical results that the attainment of full chord laminar flow with continuous suction can not be prevented by further increase in Re, airplane size, and speed at subsonic level [5].

A problem in attainment of laminar flow is an increase in sensitivity of laminar flow to discrete 3D type disturbances than 2D theoretical disturbances, which causes an increase in the wind tunnel Reynolds number. Pfenniger (Northrop Corp report NAI-57-317 Feb 1957) boundary-layer research group have obtained some experimental results which show the cross flow instability (one of the 3D disturbances) can be controlled by reasonable amount of suction initiated sufficiently close to the wing leading edge. When the speed of F-94 aircraft was increased to the value that the local Mach number on the aerofoil surface exceeded 1.09, a potentially problem raised that full chord flow laminarization was lost using the tested slots. This was probably due to the steep pressure rise through the shock wave than the effects of aerofoil surface roughness.

Research continued by designing X-21 experimental wings in 1963. In March 1974 the American Institute of Aeronautics and Astronautics (AIAA) gathered a group of 91 research members in a workshop conference. The objective was technological aspects for short term and long term impacts of aircraft fuel conservation methods. One of the interesting conclusions was to employ LFC technology in the design of future long-range transport aircraft [5]. Langley research center immediately established LFC working group to define a program of required activities. Based on the success of pervious experimental program in attaining large scale of laminar flow and more recent advances in material and manufacturing technology, very extensive support from industry was gained. An important outcome was active participation of people from industry in an LFC technology workshop held at Langley research center on April 1976. The objective was to bring the LFC to a state of readiness for application in transport aircraft. Improvements in computational capabilities are the key element for success of this.

In late 1980s Langley research center considered LFC for commercial supersonic transport as part of NASA technology development program. The benefits of application of LFC to supersonic transports include increased range, improved fuel economy and reduced airplane weight. The improved fuel consumption not only has economical benefits but also reduces the impact of supersonic engine emissions at high altitudes to the ozone layer. The skin friction of laminar flow boundary layer is also much lower than turbulent boundary layer in supersonic speeds. Furthermore, the associated aerodynamic heating of the surface by skin friction is another important factor to be considered for LFC design.

In the Boeing and Douglas aircraft companies, the aerodynamic modification of supersonic LFC was investigated. Some exploratory flight tests on two prototypes F-16XL airplanes were performed. The main objectives were to determine the capability of active LFC to obtain large extent of chord wise laminar flow at supersonic speeds and to validate computational codes, design methodology and suction system design criteria for application to supersonic transport aircraft. The investigators have installed an extensive array of hot-film, pressure and temperature measurement instruments and provided real time display of measurements. They completed 38 flights with active boundary layer suction and experienced very few problems with the suction system. The laminar flow data is currently forbidden for distribution.

Transition Prediction

The process of transition in the boundary layer for external flows was qualitatively described in [1] as shown in Figure 1. Disturbances in the freestream enter the boundary layer as steady or unsteady fluctuations of the basic state. This part of the process is called receptivity. As shown schematically in Figure 1, the initial amplitude increases from left to right. If a weak disturbance is imposed and the path A is followed, then the initial growth of these disturbances is described by linear stability theory of primary modes (i.e. the linearised and unsteady Navier-Stokes equations).

For 2D boundary layers, this growth is slow and occurs at a long stream wise length scale, and can be modulated by pressure gradients, surface mass transfer, temperature gradients, or other flow properties. As the amplitude grows, 3D and nonlinear interactions occur in the form of secondary instabilities. The disturbance growth is very rapid at this stage and the breakdown to turbulence occurs. It is often assumed that the transition follows the path A with the linear regime. This is justified on the assumption that external flows typically have weak free stream disturbances and the stream wise extent of the linear growth region is large compared to that of the nonlinear region. For 3D boundary layers (e.g. swept wings), nonlinear distortions of the basic flow may occur early on due to the action of the primary instabilities. In this case, the linear stability theory does not accurately model disturbance growth. In this case the free stream disturbances are so strong that the growth of linear disturbances is bypassed and the flow quickly becomes turbulent (path E). Depending on the amplitude, the transient growth can lead to span wise modulations of 2-D waves (path B), direct distortion of the basic state which leads to secondary or subcritical instabilities (path C), or direct bypass (path D).

The three most widely used transition CFD tools are the linear stability theory (LST), the parabolised stability equations (PSE), and the direct numerical simulations (DNS). Direct numerical simulations (DNS) play an important role in the investigation of transition. But there are problems associated with this technique. These are (a) a large amount of computer resources (CPU and memory) is usually required and (b) it is needed to impose a no intrusive downstream boundary condition. The later one is based on the periodic assumption associated with temporal simulations, which is no longer used. Langley Stability and Transition Analysis Code (LASTRAC) is a general purpose, physic based transition prediction code released by NASA for laminar flow control studies and transition research [6].

An incompressible CFD code was developed in [7] for calculating boundary layer properties over a porous flat plate. A porous 3D flat-plate was also investigated experimentally in [8]. The aim here is to extent these investigations for aerofoils and in a wide range of Mach speeds using a compressible CFD code discussed next.

Governing Equations

Neglecting body forces and volumetric heating the non-dimensional form of compressible Navier-Stokes equation in the transformed coordinate system for two dimensional flows can be written as:

$$\frac{\partial \hat{U}}{\partial t}+\frac{\partial \hat{F}}{\partial \xi}+\frac{\partial \hat{G}}{\partial \eta}=0 \qquad (1)$$

where

$$\hat{U}=U/J$$
$$\hat{F}=(\xi_x F+\xi_y G)/J\ ,\ \hat{G}=(\eta_x F+\eta_y G)/J \qquad (2)$$
$$J=\xi_x \eta_y-\xi_y \eta_x$$

$\xi=\xi(x,y)$, $\eta=\eta(x,y)$ are coordinate transformation function and J is the Jacobian of the transformation. The vectors U , F and G are given by:

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ e\end{bmatrix}\ ,\ F=\begin{bmatrix}\rho u\\ P+\rho u^2-\tau_{xx}\\ \rho uv-\tau_{xy}\\ (e+P)u-u\tau_{xx}-v\tau_{xy}+q_x\end{bmatrix},$$

$$G=\begin{bmatrix}\rho v\\ \rho uv-\tau_{xy}\\ P+\rho v^2-\tau_{yy}\\ (e+P)v-u\tau_{xy}-v\tau_{yy}+q_y\end{bmatrix} \qquad (3)$$

where ρ , u , v , e , q are respectively density, velocity components along x, y direction, total energy and heat flux. The components of shear stress tensor are as follow:

$$\tau_{xx}=\frac{\mu}{\mathrm{Re}}\left(\frac{4}{3}\frac{\partial u}{\partial x}-\frac{2}{3}\frac{\partial v}{\partial y}\right)$$
$$\tau_{yy}=\frac{\mu}{\mathrm{Re}}\left(\frac{4}{3}\frac{\partial v}{\partial y}-\frac{2}{3}\frac{\partial u}{\partial x}\right) \qquad (4)$$
$$\tau_{xy}=\frac{\mu}{\mathrm{Re}}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)$$

The governing Navier-Stokes equations have been used in non-dimensional form.

Analysis of Suction Region

For the analysis of suction region, a non-zero suction velocity at the surface (v_w <0) and the no slip condition (u_w =0) can be assumed. The governing equations can be simplified by setting up the 2D steady state boundary layer equation and neglecting the terms with small order of magnitude as seen below.

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{5}$$

Momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\frac{\partial^2 u}{\partial^2 y} \tag{6}$$

From the momentum equation in y direction $\left(\frac{\partial p}{\partial y}=0\right)$ is obtained. This implies that the pressure is constant across the boundary layer in y direction.

The compatibility condition for the wall with suction, i.e. $u(x,0)=0, v(x,0)=v_W(x)$, can be determined by:

$$\mu\left(\frac{\partial^2 u}{\partial y^2}\right)_W=\frac{dp}{dx}+\frac{\tau_W}{\upsilon}v_W \tag{7}$$

With $\tau_w=0,$ the curvature of velocity profile at the wall can be related to the pressure gradient in the x direction.

For the favorable pressure gradient, i.e. $(\partial p/\partial y)<0,$ the compatibility condition in Equation 7 yields $(\partial^2 u/\partial y^2)_W<0$ and therefore $(\partial^2 u/\partial y^2)<0$ over the entire boundary layer thickness. The more negative the value of $(\partial^2 u/\partial y^2)<0,$ the more stable the flow will be and the transition will be delayed (Figure 2). This is the concept that Natural Laminar Flow Control (NLFC) is based on [9, 10].

The second term in the right hand side of Equation 7 represents the concept of suction type LFC. With a suction over flat plate ($v_w<0$), it will be shown that the skin friction coefficient, C_f, will be increased. However this increase in C_f will be adjusted by a limited amount of suction to the values lower than a turbulent skin friction coefficient. For an aerofoil, the delay in the transition would decrease drag coefficient.

The boundary layer can be affected by suction in two ways. First, the suction acts to decrease the boundary layer thickness and a thinner layer is less likely to become turbulent than a thick one. Second, the suction induces a laminar velocity profile that is more stable.

An important question in retaining a laminar boundary layer is the amount of required suction. If the amount of suction is increased then the boundary layer thickness is decreased and the critical Reynolds number will be increased. However a large amount of suction is not economical because the part of energy saved in drag reduction has to be used again for the suction.

Numerical method

A class of implicit, second order accurate, total variation diminishing (TVD) scheme has been adopted here for computation of two dimensional compressible flows. The method is based on upwind and symmetric TVD schemes reported by Yee [11] and further modified by Sedaghat [12, 13] for computation of viscous flows. In this work, the symmetric TVD method with the Minmod limiter function was selected due to better predictability for low subsonic flows.

For computation of 2D compressible flows over a porous flat plate, an algebraic grid generator with clustering mesh points in the boundary layer was used. In Figure 3, a 62*62 mesh generated over the flat plate is shown. The computational domain consists of a rectangle with unit length and the height equals to five times of laminar boundary layer thickness.

As the initial condition (t=0), all quantities was set to their free stream values, which means that the plate is inserted suddenly into an undisturbed flow with free stream condition specified everywhere. The free stream Mach number and the Reynolds number are specified as input parameters.

In order to measure convergence rate of the numerical procedure, the Root Mean Square (RMS) of density residual may be utilized which is defined by:

$$RMS=LOG_{10}\left(\sqrt{\frac{\sum_{i=1}^{n_\xi}\sum_{j=1}^{n_\eta}(\rho_{ij}^{new}-\rho_{ij}^{old})^2}{n_\xi n_\eta}}\right) \tag{8}$$

where n_ξ and n_η are the number of mesh points in the ξ and η directions, respectively and ρ_{ij}^{new} and ρ_{ij}^{old} correspond to the density at the current and previous time steps.

Results and Discussion

A porous flat plate has been considered as a test case to investigate effects of suction on a laminar boundary layer. The free stream condition is set to the values of $M_\infty=0.2$ and $\mathrm{Re}_\infty=10^4$.

The computational velocity contours over the solid flat plate are shown in Figure 4. The growth of laminar boundary layer and its thickness can be observed in this figure.

The local wall shear stress was obtained computationally for solid flat plate and compared with the exact solution of Blasius($C_f = 0.664 / \sqrt{\mathrm{Re}_\infty}$) in Figure 5. It is observed that the wall shear stress become infinite at the leading edge (x=0). The singularity in the leading edge has caused this rapid change and therefore the boundary layer theory is not directly applicable at this point. A grid dependency check was performed for the case with suction of $V_s = -0.01$ and three sets of meshes consisting of 31*31, 62*62, and 124*124 as shown in Figure 6. This indicates a satisfactory trend for all mesh sizes investigated the quality that was expected from high resolution TVD schemes.

Iglisch[14] has studied boundary layer flow past a flat plate with uniform suction. Iglisch has solved a simplified boundary layer equation at the constant pressure, $dU/dx = 0$, and the following wall boundary conditions

$$\begin{aligned} &u(x,0) = 0 \\ &u(x,\infty) = U_\infty \\ &v(x,0) = v_0 = \text{const.} < 0 \end{aligned} \tag{9}$$

The results shown in Figure 7 obtained by Iglisch [14_15] indicate that by increasing suction rates the flat plate drag will increase also for the turbulent flows which we are trying to avoid with suction. The dashed lines illustrated in Figure 7 gives the limits for transition from laminar to turbulent flow and also fully turbulent flow regions. The difference between the fully turbulent drag curve and a curve corresponding to $C_Q = \text{const.}$ gives the drag reduction. This can be achieved by suppressing turbulence through suction and keeping the boundary layer stable and laminar. The drag coefficient due to swallowing tangential momentum through the wall can be determined by:

$$C_D = \frac{1}{L} \int_0^L C_f(x)dx + 2C_Q \tag{10}$$

where $C_Q = -v_0 / U_\infty$ and C_f is the local skin friction coefficient. The drag coefficient was calculated by integrating C_f over the plate surface and tabulated in Table 1 for suction rates of $-0.001, -0.002, -0.005,$ and -0.01. These values were compared with the analytical values obtained in [14] at $\mathrm{Re} = 10^4$ and for the prescribed suction rates. The drag coefficient has been increased by increasing the suction rates; however, this will prohibit the flow regime from becoming turbulent by delaying transition and its corresponding high drag values. Remarkably, the data corresponding to the transition line in Figure 7 has been accurately computed as indicated in Table 1. This confirms that transition will occur in the presence of suction at higher values of the Re number.

As shown in Figure 8, the local velocity profiles at a cross section situated in 0.75% of the flat plate length were compared under different suction rates. It is apparent from Figure 8 that by increasing suction rate, the curvature $(\partial^2 u / \partial y^2) < 0$ becomes strictly negative and therefore the point of inflection in velocity profiles will be prevented.

The convergence history (RMS) of the numerical values of density for $\mathrm{Re} = 10^4$ and $M_\infty = 0.2$ was also shown in Figure 9 using different suction rates. Convergence trends indicate a smooth convergence rate also significantly independent from the suction rates on the flat plate surface. Two level drops of residuals can be easily obtained after 1000 iterations.

Conclusion

A class of high resolution TVD schemes was used for solving the compressible Navier-Stokes equations over a porous flat plate. To characterize the laminar flow control, several suction rates were applied and the corresponding computational results were compared with the analytical solutions of Blasius and Iglisch. By increasing suction rates, the skin friction and its corresponding drag coefficient has been increased. This increase in the drag coefficient with suction will overweight the undesirable high values of the drag coefficient in turbulent flows. Thus, an appropriate amount of suction rate is crucial to avoid transition from laminar to turbulent and also to maintain a laminar boundary layer over the desired length of a wing.

From this preliminary investigation, it is obvious that the current CFD code can be used to predict values of the skin friction drag accurately for a wing model. However, transition has to be known from measurements or other numerical transition prediction tools. Knowing or assuming this, the overall flow characteristics of an actively controlled LFC wing can be determined particularly for supersonic transport aircrafts. This is the subject of current research.

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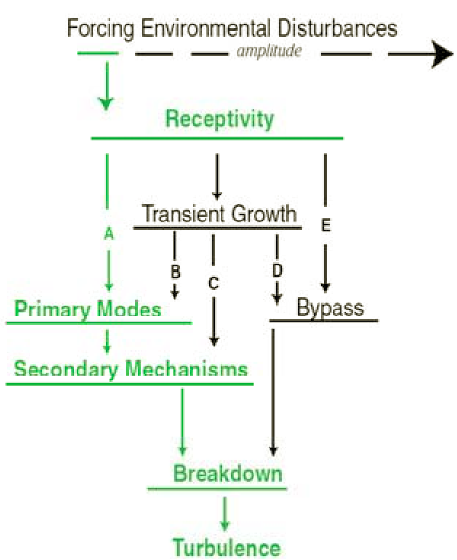

Fig. 1- Roadmap to transition [1].

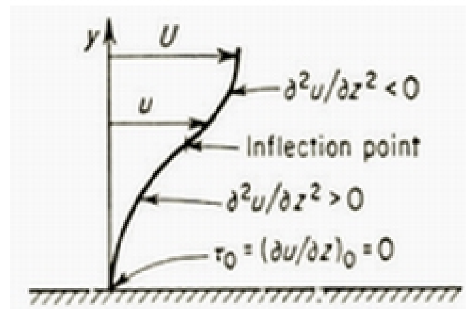

Fig. 2- The velocity profile with curvature and inflection point.

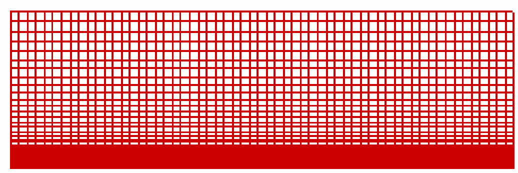

Fig. 3- The structured grid points for the porous flat plate.

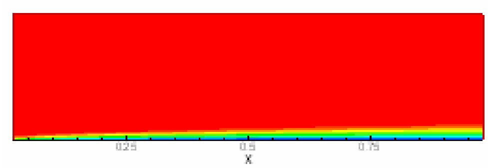

Fig. 4- The growth of boundary layer over the solid flat plate (velocity contours).

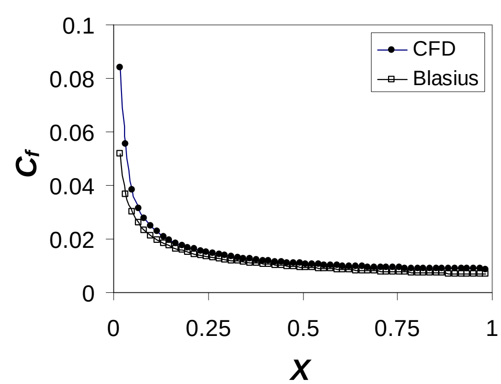

Fig. 5-Comparison of the computed and the analytical skin friction coefficient, C_f, for the solid flat plate.

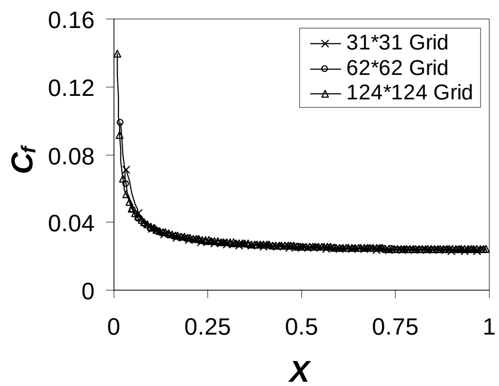

Fig. 6- Grid dependency check for the test case with suction (Vs=-0.01).

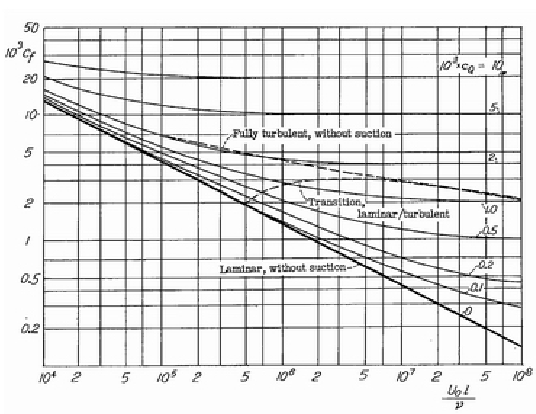

Fig. 7-Total friction drag is given as a function of Reynolds number at various suction rates [14].

Table 1- Comparison of drag coefficient obtained from the CFD code with the data by Iglisch.

The Suction Rate (Vs)	The CFD Code	Iglisch [14]
-0.001	**0.015038**	**0.014619**
-0.002	**0.016299**	**0.0162142**
-0.005	**0.02168**	**0.020320**
-0.01	**0.02922**	**0.0278853**

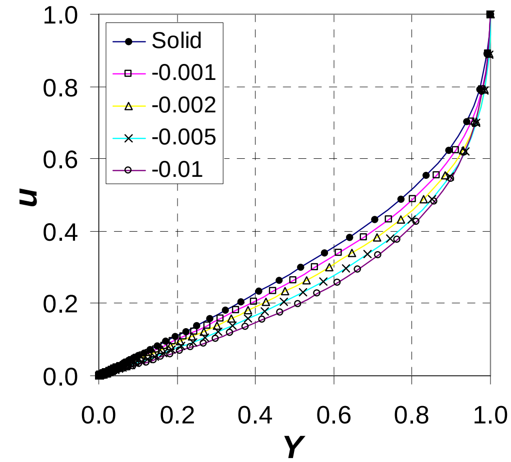

Fig. 8- Velocity profiles for different suction rates at X=0.75.

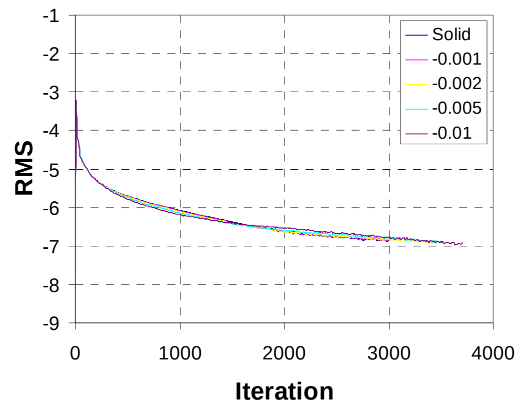

Fig. 9- The convergence history of the numerical procedure.