Computational Study of Effect Viscosity on Shock Wave Angle at Mach Number 2.5 by Using FLUENT Code

Ali A. A. Abaas and Ahmed H. Jassim

Abstract—The major object of this project is to research effect of viscosity on shock wave angle of supersonic inflow with a Computational Fluid Dynamics (CFD) as a commercial code. It will display of inviscid and five turbulence samples flow will be met the best of the published wind tunnel experimentally by Lepicovsky et al. [10]. Realizations founded on Fluent Inc as the CFD-Code and contain inviscid flow and the standard and Realizable k-ε, Spalart-Allmaras, Reynolds (Ensemble) Averaging and Large Eddy Simulation turbulent samples. A C-type grid is employed as a two-dimensional triangular to agree the researches mensuration at a 25° wedge at Mach-Number of 2.5 with 0.0° angle of attack. The results of numerical showed the samples flow fully prophesy the shock wave angle but the best results were at inviscid flow and then k-ε standard and realizable sample of flow, but Spalart-Allmaras, Reynolds (Ensemble) Averaging and Large Eddy Simulation. At supersonic flow the effect viscosity was slightly. The effect of viscosity showed on Drag, Lift Force Coefficients and skin friction distribution. The shock wave interaction with the boundary layer was clear.

Index Terms—Computational study, viscosity, shock wave, Mach number, FLUENT.

I. INTRODUCTION

To study effect viscosity on shock wave angle, it must be needed to compare between experimental and computational results. While experiments provide data about the flow, they often lack the possibility of having a direct and detailed prudence into the physics of the flow field, so that the employed of computational fluid dynamic to prophesy external flow has been dramatically increased in the past decade. The common availability of special computer with each other effectiveness solution algorithms and advanced pre- and post-processing facilities capable the employ of commercial CFD codes by engineering for search, development and designing duty in manufacture. In order to validate the results of the computer code, the work is extended to use the available well established computer code FLUENT which is powerful code to prophesy the fluid flow and heat transfer. FLUENT code has a capability of investigating two samples of flow, viscous and inviscid. HUSSAINI [1]. The rapprochement of the emitted experimental datum with the chosen samples in flow include inviscid and viscous the standard k-epsilon, Realizable, Reynolds Averaging, Large Eddy Simulation and Spalart-Allmaras turbulent samples is one of the major themes of the realizations. The compression shocks, lift and drag force coefficient were used to contrast the results of the present sample with results of the wind tunnel test. Kumar [2] developed a computational sample by employing a delayed detached-eddy simulation to check the different part of shock-wave/vortex interactions; it was specified condition of naturally created bow shock wave production during a sonic injection into a supersonic cross flow. The sample was comprised with experimental results gained formerly and was diffused to exam the effects of shock/vortex interaction on mixing properties of supersonic flows. A vortex producing, in the shape of a semispan wing part, was placed at an angle of attack upstream of an injection position. The resultant vortex interacts with the bow shock, and for a sufficiently powerful interaction, there was breakdown of the supersonic vortex. The vortex break observed during the computational study was in a so perfect convention with a past physical sample.

Duraisamy et al. [3] comprised between experimental and theoretical founded on the equations of Reynolds-averaged of Navier Stokes (RANS) where improved in bounding uncertainties in RANS samples via physical limits. Statistical inference chose to characterize sample coefficients and in employing machine teaching to develop turbulence samples. Physical limits and turbulent sampling employed to predictive models

Coderoni [4] studied numerical analysis a high-order Simulation of Large Eddy and a set of Reynolds Averaged Navier-Stokes (RANS) simulations as comprising with experimental work for capturing shock wave from jet. The changes of thrust was analyzed because of activating the injectors where indicated the heated and unheated jet cases and the specific thrust decreased 3% when the injectors are used.

1.1. Theory

A. FLUENT is an ultimate useful computer program for sampling heat transfer and fluid flow in complicated shapes. FLUENT supply whole mesh elasticity, to solve troubles of flow by unstructured meshes which may be produced about

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The standard samples qualified in The Standard k-epsilon Sample, FLUENT code supplies the so-called k-ε realizable sample [9]. The term "realizable" represent the sample accepts mathematical of certain chains on the stresses of normal, regular with the turbulent flows physics. The k-ε realizable sample suggested for Shih et al. [9] which meant for heading lacks the classic k-ε samples at embrace as followed: (a) the formula of eddy-viscosity including the changeable of Cµ primarily suggested by Reynolds. (b) the dissipation (ε) equation sample founded in the equation of dynamic of fluctuation represented the mean-square of vorticity.

\[
\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x} \left( \mu + \frac{\mu_l}{\sigma_k} \frac{\partial k}{\partial x} \right) + G_k + G_b - \rho \varepsilon - \rho YM \quad (7)
\]

\[
\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x} \left( \mu + \frac{\mu_l}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x} \right) + \rho C_\varepsilon \varepsilon - C_k \rho \frac{\varepsilon^2}{k} + C_{\mu} \frac{\varepsilon}{k} C_{\varepsilon} G_b \quad (8)
\]

Where \( k \) is the turbulent kinetic energy, \( \varepsilon \) is the dissipation rate of kinetic energy, \( G_k \) is the production of turbulent kinetic energy by mean velocity gradients, \( G_b \) is the production of turbulent kinetic energy by buoyancy effect, \( \rho YM \) is the rate of dissipation associated with the buoyancy effect, \( \rho \varepsilon \) is the rate of dissipation of turbulent kinetic energy, \( C_\varepsilon \) is a constant, usually taken as \( 1.44 \), \( C_k \) is a constant, usually taken as \( 1.92 \), \( C_{\mu} \) and \( C_{\varepsilon} \) are empirical constants, \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers for laminar viscosity and dissipation, respectively. The constants have the following values:

<table>
<thead>
<tr>
<th>Coef.</th>
<th>( \sigma_k )</th>
<th>( \sigma_\varepsilon )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.0</td>
<td>1.30</td>
<td>1.44</td>
<td>1.92</td>
<td>0.09</td>
</tr>
</tbody>
</table>

2.3. The Realizable k-epsilon sample (K-E-Realiz)

The kinetic energy of turbulence \( (k) \) with its rate of dissipation \( (\varepsilon) \) which represent the differential equations of transport display model shape containing the accumulation term a time depend, a term of spread as well as terms of dissipation and production [7].
as qualified in Sampling Production Turbulence in the k-epsilon Samples. Gb is the production of kinetic energy of turbulence for buoyancy, where the Turbulence is effected of buoyancy on the k-epsilon Samples are calculated. YM performs the assistance of the oscillating in turbulent of compressibility to the rate of overall dissipation , the Effects of Compressibility on Turbulence is calculated in, the k-epsilon Samples. C2, C1e, C3ε are Constance σk and σε are the Prandtl numbers turbulent for k and ε, respectively.

2.4. Sampling the Effective Viscosity

For The k-epsilon Standard Sample and The Realizable k-epsilon sample The turbulence “eddy” viscosity, μi adds k and ε as supposed by Kolmogorow and Prandtl with equilibrium hypothesis resulting to

\[
\mu_i = C_\mu \rho \frac{k^2}{\varepsilon}
\]

2.5. Spalart-Allmaras Sample(S-P)

The Spalart - Allmaras sample represent the one equation group of eddy viscosity samples. This group is founded on the supposed that stress-tensor of Reynolds 

\[-\rho U V\]

which represent relation to the average rate of strain through an visible viscous of turbulence called eddy viscosity

\[v_i = \frac{-U V}{V} \left( \frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X} \right) \] ..............................................(9)

In fact the calculation employs a medium transfer variable \( v \) with the function of damping \( f_{vl}(v) \) relation to viscous of turbulence by \( v_i = v \cdot f_{vl}(v) \) to find the solution of the following transfer equation

\[
\rho \frac{Dv}{Dt} = G_v + 1 \sigma_v \left( \frac{\partial \mu}{\partial \varepsilon} \frac{\partial v}{\partial \varepsilon} + C_{S\kappa} \rho \left( \frac{\partial v}{\partial \varepsilon} \right) ^2 \right) - Y_v \] ..............................................(10)

The medium changeable \( v \) is in common conformable to the kinematic viscosity of turbulence \( v_i \) unless in the near-wall part [11]. Gv and Yv are the destruct and product terms viscous of turbulence. Both are powerful in the near-wall because of blocking of wall and damping of viscosity. Aside from \( \sigma_v \) indicates thePrandtl number of turbulent,Cb2 a standardization constant and v is the kinematic viscosity of molecular.

2.6. Sampling the Viscous of Turbulence

The viscous of turbulence, \( \mu_i \) is calculating as the following equation:

\[
\mu_i = \rho \nu \cdot f_{vl} \] ..............................................(11)

wherever the function of damping viscosity, \( f_{vl} \), is offered by

\[
f_{vl} = \frac{x^3}{x^3 + C_{vl}^3} \] with, \( x = \frac{v}{\nu} \)..............................................(12)

2.7. Reynolds (Ensemble) Averaging (REA)

The averaging of Reynolds, the resolution changeable in the immediate (perfect) equations of preyed Navier-Stokes in the purpose (time-averaged or ensemble-averaged) with compounds of oscillating. To the compounds of velocity:

\[
u_i = \bar{u_i} + u_i'
\]

wherever \( \bar{u_i} \) with \( u_i' \) is the average with instant components of velocity (where i is 1, 2, 3,……).

Also, for pressure with another amounts of scalar:

\[
\phi = \phi + \phi' \]

where f indicates the scalar like energy, pressure, or condensation of species , replacing terms of this shape for the variables of flow into the instant momentum and continuity equations and occupation an ensemble(or time) medium (and the over bar of dropping in an average velocity, u(bar)) produces the equations of ensemble-averaged of momentum . Cartesian tensor form which can be written in as

\[
\partial \frac{\partial \rho}{\partial t} + \frac{\partial \rho \nu_i}{\partial x_i} = 0 \] ..............................................(13)

The equations 10 and 11 call "Reynolds-averaged" equations of Navier-Stokes (RANS). They include the common shape as the instant equations of Navier-Stokes, with the speeds and another resolution changeable now perform time-averaged or ensemble-averaged amounts. Extra terms now show that perform the turbulent effects. The "Reynolds stresses", 

\[
\rho \nu_i u_j
\]

should be sampled near the equation 11.

For changeable-intensity flows, Equations 10 and 11 may explain as equations of Navier-Stokes for Favre-averaged [9], and velocities perform amounts of mass-averaged. And then, the equation 10 with equation 11 may use for intensity - changing flow.

2.8. The Large Eddy Simulation (LES) Sample

The equations of governing employed LES are gained by filtrate the time-following equations of in either Fourier (wave-number) for equation Navier-Stokes arrangement (physical) space or space. A filtrate procedure effective for the eddies which are the scales least than the grid spacing or width of filter employed in the calculations. The equations of resulting thus rule the dynamics of big eddies. A filtrate changeable (indicated by an over-bar) is knew by

\[
\bar{\phi}(x) = \int_D \phi(x')G(x,x')dx'
\]

Here D represent fluid field, and G represent a function of filter which limits the scale of the solved eddies.
In FLUENT, discretization of finite-volume solve implicit, supplies the process of filter:

\[ \overline{\phi}(x) = \frac{1}{V} \int_{\Omega} \phi(x') dx' \]

Here V represent the cell volume computational. Function of filter, \( G(x,x') \), implied here is then

\[ G(x,x') \begin{cases} 1/V \text{ for } x' \in \Omega \\ 0 \text{ otherwise } \end{cases} \]

Since the usage of LES to flows of compressible is yet in its childhood, the theory is approached here for flows of incompressible. It is supposed that the LES sample in FLUENT will be employed to basically incompressible (but not necessarily fixed-intensity) flows. Filtering the incompressible equations of Navier-Stokes, one gained [12]

\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \]

and

\[ \frac{\partial \rho u_j}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} \]

where \( \tau_{ij} \) is the sub grid-scale stress knew by

\[ \tau_{ij} \equiv \rho u_i u_j - \rho u_i u_j \]

III. RESULTS AND DISCUSSION

The computation of flow is desired by 800 restorations to convergence. At the finish of each calculation run, residuals of flow are decreased three orders more than of number. The shock wave angle was obtained experimentally equal to 51° by J. Lepicovsky et al [13] as shown in figure (1). A triangular Mesh, C-Type is used to generate grid of a 25° wedge and 0.0° angle of attack as cleared in figure (2). The common viscous effects and Mach number velocity magnitude by using inviscid flow where neglected viscosity, the shock wave angle was 51° are shown in Figures (3 and 4). By using different kinds of viscosity shock angle gave 52° at k-ε standard and realizable, while shock angle was 53° at Spalart-Allmaras, Reynolds (Ensemble) Averaging and Large Eddy Simulation, all of these cases at of viscosity was used the boundary layer was appeared on the surface of sample in velocity magnitude contours as shown in figures (5,6,7and 8). The pattern of flow vectors before and after the wave was cleared as shown in figures (9 and 10).

The magnitude of pressure coefficient as shown in figure (11) which illustrated the comparison between the inviscid flow curve and flow viscosity curves (k-ε standard and realizable, Spalart-Allmaras, Reynolds (Ensemble) Averaging and Large Eddy Simulation).

The value of lift force coefficient as shown in figure (12) which clearance the maximum value of (CL) at inviscid flow and decreased gradually to reach Reynolds (Ensemble) Averaging

The value of drag force coefficient as shown in figure (13) which clearance the minimum value of (CL) at inviscid flow and increased gradually to reach Reynolds (Ensemble) Averaging

The check of the coefficient of skin friction marks one of the most serious variation between the turbulent investigated samples figure (20) showed differences values on the upper surface for three cases the standard k-ε, Realizable, Reynolds Averaging.

The magnitude of shock wave angle where exactly specified for a 25° wedge with Mach-Number 2.5 and 0.0° angle of attack, at comparative the experimental results with FLUENT Code the inviscid flow was the best choose after that k-ε standard and realizable sample of flow. At last, Spalart-Allmaras, Reynolds (Ensemble) Averaging and Large Eddy Simulation. At supersonic flow the effect viscosity was slightly. Changing viscosity type doesn’t affect on pressure coefficient results, while neglecting the viscosity effect will show significance difference. The shock wave interacting with the boundary layer is very clear in this study. The magnitudes of (CL) and (CD) are opposite, the boundary layer which is found as result the effect of viscosity gave these differences as shown in skin friction coefficient.

IV. CONCLUSION

The goal of design of airfoil for supersonic flow, the value of shock wave angle does not effect of viscosity so it can be used FLUENT code to calculate values do not find it easily such as (CL), (CD) and skin friction coefficient for build supersonic airfoil sample before used experimental sample. The viscosity of supersonic flow is the least effect so the behavior of supersonic flow is the nearest from inviscid flow and other types of viscosity.

References


Fig. 1. Shadowgraph of an oblique shock wave

Fig. 2. The section with (triangular Mesh, C-Type)

Fig. 3. Mach No. contour for inviscid flow

Fig. 4. Velocity magnitude contour for inviscid flow

Fig. 5. Mach No. contour for k-ε standard flow

Fig. 6. Velocity magnitude contour for k-ε standard flow
Fig. 7. Mach No. contour for Large Eddy Simulation (LES) flow

Fig. 8. Velocity magnitude contour for Large Eddy Simulation (LES) flow

Fig. 9. Velocity vector colored by velocity magnitude contour for inviscid flow

Fig. 10. Velocity vector colored by velocity magnitude contour for k-ε standard flow

Fig. 11. Pressure coefficient on a 25° wedge with Mach-Number of 2.5 and 0.0° angle of attack by using inviscid and different kinds of viscosity
Fig. 12 Lift force coefficient (CL) on a 25° wedge with Mach-Number of 2.5 and 0.0° angle of attack by using inviscid and different kinds of viscosity.

Fig. 13 Drag force coefficient (CD) on a 25° wedge with Mach-Number of 2.5 and 0.0° angle of attack by using inviscid and different kinds of viscosity.