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Recent Results on Two-Dimensional Airfoils Using a Lattice Boltzmann-Based Algorithm

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There have been significant advancements made in the lattice Boltzmann-based software PowerFLOW during the last couple of years for computational fluid dynamics. Recently, the newest version, PowerFLOW 3.2, was used to simulate two NACA airfoil benchmark cases. The results are compared with available experimental data as well as other numerical results. It is shown that PowerFLOW predicts lift rather well, although the drag predicted is higher than experiment. Most important, it is also shown that the algorithm/software is capable to give an excellent prediction of stall at high Reynolds numbers for these airfoils.

Introduction

OVER the past 10 years, there have been significant advances made in the lattice Boltzmann method (LB) as an alternative approach for computational fluid dynamics (CFD).[1] A solid theoretical foundation for this new method as a viable alternative for hydrodynamic computations has been established over this period. There have also been careful direct numerical simulations (DNS) using LB on various flow benchmarks.[2–5] All of these efforts have removed many of the misconceptions associated with using a kinetic-based method such as LB for hydrodynamic computations, including high Reynolds number simulations. Furthermore, many of its key advantages, such as parallel computation and handling complex fluids and complicated geometries, have been gradually recognized in the mainstream CFD community. There has also been increasing theoretical interest in viewing Boltzmann-level descriptions as a potentially more suitable representation than Navier–Stokes for fluid physics, especially for turbulence.[6]

To extend an LB approach to engineering applications, which often involve extremely high Reynolds numbers, the LB-based, time-dependent, very large eddy simulation (VLES), algorithm PowerFLOW has been developed. In the past couple of years, significant progress has been made from earlier versions, particularly in the development of models for subgrid-scale turbulence effects and the corresponding LB extensions. These include LB enhancements in both the bulk flow and near-wall regions.[7,8] The bulk turbulence physics in the most recent version, PowerFLOW 3.2, is based on an extension of the two-equation model originally derived from the renormalized group method.[9,10] PowerFLOW also incorporates a generalized turbulence wall model in the boundary-layer region. This is an extension of the usual law of the wall formulism,[11] including appropriate effects of the pressure gradient. Thus it has shown to widen substantially the applications beyond attached flow situations and to give predictions for separations.[10,12] Extensive validation of PowerFLOW, both on simple academic problems and on cases involving extremely complex dynamic or geometric properties, has been performed.[10] As a matter of fact, PowerFLOW has now become a very useful tool in a variety of engineering CFD communities, particularly for external aerodynamics simulations around automotive bodies worldwide.

In this paper, we present results specifically on some typical two-dimensional airfoil benchmarks, NACA airfoils, using the recently released version, PowerFLOW 3.2. The results are compared with available experimental data, as well as with results from the Institute for Computer Applications in Science and Engineering (ICASE) Navier–Stokes slover CFL3D.[13] It is shown that PowerFLOW gives satisfactory predictions for lift. Drag, however, is overpredicted compared to experiment. Note that PowerFLOW 3.2 is able to give an accurate prediction of stall for these airfoils at high Reynolds numbers. Similar predictions were not found with CFD3D. Case setups are described, including resolutions and boundary conditions, followed by a detailed analysis. Note that all of these simulations were performed consistently. There have been no adjustments of the physics model or the algorithm for different flow situations involving various angles of attack or Reynolds numbers, nor for different types of airfoils. It is important that a useful algorithm be capable to provide reliable predictions to flow properties in general circumstances, rather than just being good in narrowly defined situations. The same software and algorithm have also been extensively validated on automotive aerodynamics cases with excellent results.[14]

Simulation Results on NACA 0012

The NACA 0012 airfoil was simulated at two different Reynolds numbers, $Re = 5 \times 10^5$ and 6.6×10^5. The former has available data from the Navier–Stokes solver CFL3D,[13] whereas the latter has available experimental data.[15] All of the numerical simulations were run at a Mach number of 0.2 to ensure that compressibility effects remain minimal.

Because of the symmetry of the NACA 0012 airfoil, it is sufficient to run simulations involving positive angles of attack only. To reduce the computation size while avoiding blockage effects, the resolution setup as shown in Fig. 1 was used. Each rectangular box represents a resolution domain in which the mesh is uniform and Cartesian. The inner boxes have higher resolutions by a factor of two over the outer box in which it is contained. The innermost region surrounding the airfoil corresponds to a resolution of 850 mesh points across the cordal length. The surface geometry of the airfoil is decomposed into piecewise planar, that is, linear for two dimensions, elements that intersect cubic cells at the neighborhood. Hence, the near-surface cells are no longer cubic but naturally fit the shape of the surface. PowerFLOW incorporates a kinetic-based algorithm that can accurately determine the hydrodynamic fluxes on these surface elements.[8] Note that, although this may not be so important for two-dimensional NACA airfoils, this capability is extremely desirable for being able to deal with cases involving extremely complex three-dimensional geometries: No elaborate body-fitted griding is required.

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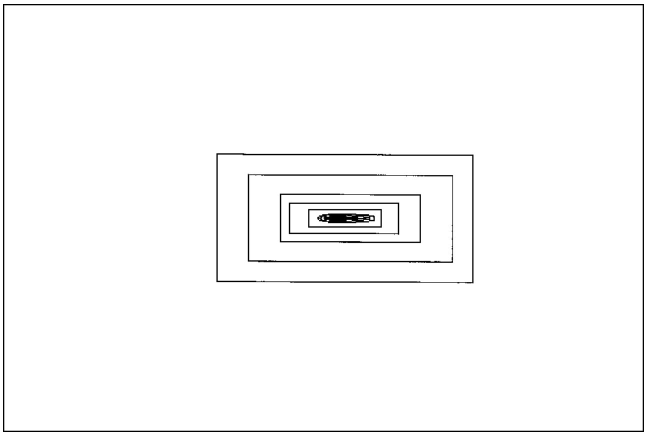


Fig. 1 Setup of outer VR regions for NACA 0012 airfoil; boundary condition at inlet is fixed velocity and outlet is fixed static pressure condition. Total of eight different grid scales.

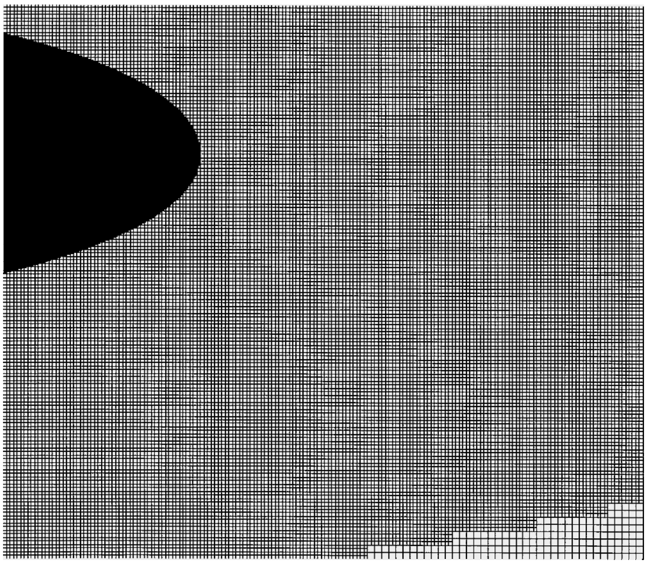


Fig. 2a Closeup of VR regions for NACA 0012 airfoil.

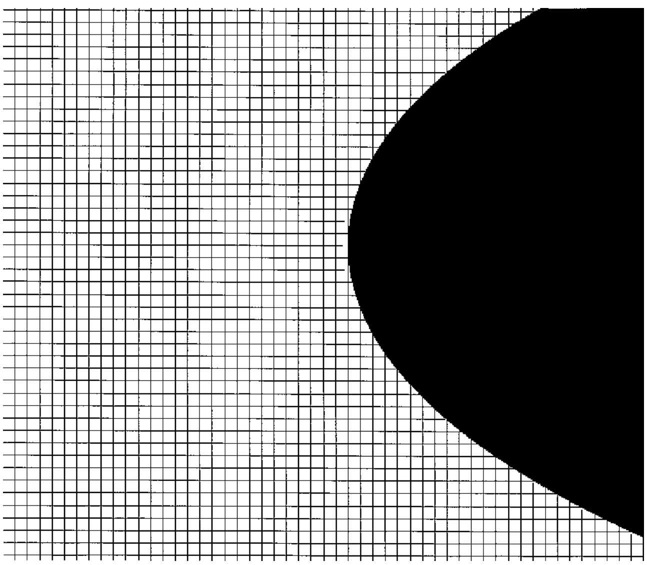


Fig. 2b Closeup of surface resolution on leading edge of NACA 0012 airfoil.

The inlet/freestream flow velocity corresponds to Mach number 0.2, and the turbulence intensity is 0.1% of the freestream velocity. Several variations in resolution were examined (Fig. 2). Resolutions ranging from 500 mesh points along the chord, corresponding to a total domain of 160,000 cells, all the way up to 850 mesh points along the chord, corresponding to a total domain of 800,000 cells, were investigated. From this we ensure the essential resolution insensitivity is observed for the highest resolution simulations and are presented here. Quantitatively, this resolution yields $y_+ \sim 100$.

Results

Simulations for a range of attack angles from 0 up to 16 deg were performed. The reason this range of angles was chosen is that the experimentally predicted stall angle for NACA 0012 is around 13 deg. Figures 3 and 4 show the lift C_l and drag C_d at various attack angles. These are compared with experimental data and with results from CFL3D.[13] It is unfortunate that the available experimental data known to us is at $Re = 6.6 \times 10^5$, whereas the numerical results presented by the other numerical code was at 5×10^5. It is known that both C_l and C_d are Reynolds-number-dependent, as shown in Fig. 5 (based on available experimental data of closest possible Reynolds numbers).[15] To avoid errors in comparison, we performed simulations at both Reynolds number values. These are shown in Figs. 3 and 4. From Fig. 3, it can be seen that PowerFLOW gives accurate lift prediction for all attack angles. More interesting, it gives an accurate prediction of stall. Compare this with the other results: CFL3D seems to give reasonable results at smaller attack angles;

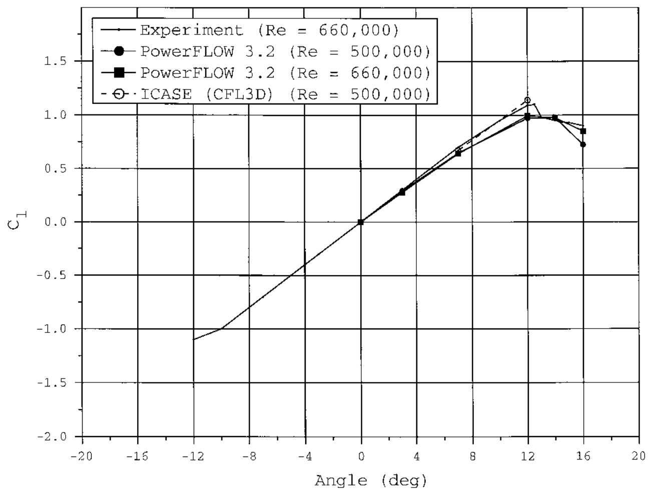


Fig. 3 Coefficient of lift vs angle of attack, comparing PowerFLOW 3.2p4 to both experiment and CFL3D, at $Re = 5 \times 10^5$ and 6.6×10^5 for NACA 0012.

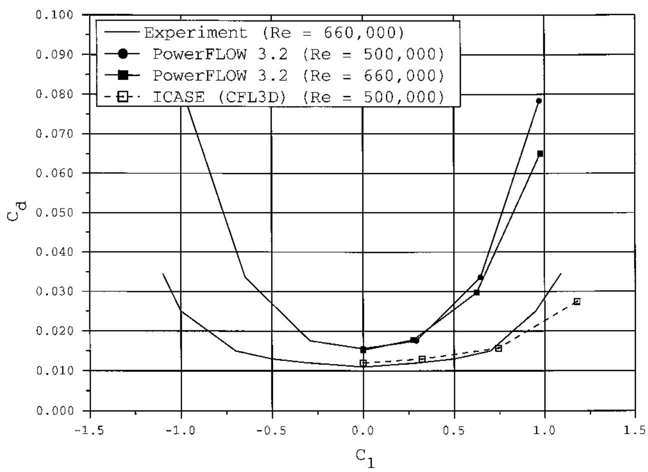


Fig. 4 Coefficient of drag vs angle of attack comparing PowerFLOW 3.2p4 to both experiment and CDF3D, at $Re = 5 \times 10^5$ and 6.6×10^5.

however, it overpredicts the lift at higher angles, and no indication for stall is provided. Similar conclusions can also be made for C_d.

Nonetheless, PowerFLOW 3.2 is shown to overpredict the drag values. We are in the process of further improving the physics in PowerFLOW. One essential development underway is the wall model generalization. This is being done so that the wall model can capture fully self-consistently and automatically both laminar and turbulent near-wall properties and their transitions. For the Reynolds numbers simulated, this has an important effect on lift and drag because there likely exists a laminar region at the leading edge of the foil. Figure 6 contains a series of plots of pressure distributions, C_p, along the surface at several typical attack angles. It indicates that the maximum suction pressure is underpredicted. This is due in part to the application of a turbulent wall model over the entire surface of the foil. Figure 7 gives comparison of the pressure profiles at some representative vertical sections. Figure 8 presents streamlines in the neighborhood of the airfoil at prestall and poststall angles, respectively. It is shown that although the flow is fully attached at the prestall angle there is a clear separation at the leading edge for those angles that are beyond the critical stall angle.

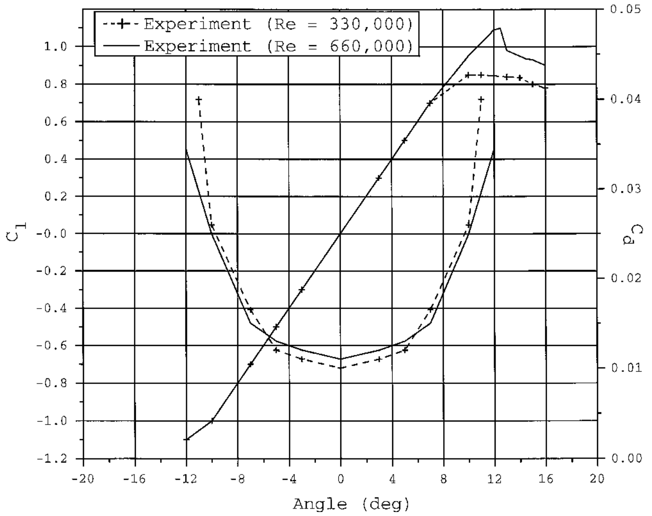


Fig. 5 Experimental values for lift and drag at $Re = 3.3 \times 10^5$ and 6.6×10^5 for NACA 0012.

Simulation Results on NACA 4412

To examine the reliability of the PowerFLOW algorithm for CFD, simulations have also been performed on another NACA airfoil, NACA 4412. This is an even more interesting airfoil because of its asymmetric shape. Consequently, the properties at negative attack angles are not the same as for positive angles. The setup is done similar to that for NACA 0012 described earlier. The simulations were done for Reynolds number at 3×10^6, where there exists available experimental data.[15] On the other hand, we are not aware of any corresponding results from CFL3D. Figures 9 and 10 give C_l and C_d comparisons to experiments at a range of attack angles including negative ones. PowerFLOW 3.2 also predicts the stall angle for this airfoil, as indicted in the drop off of the lift value at larger angles. Furthermore, PowerFLOW results also have indicated a local minimum in lift at −12 deg, seen clearly in the experimental data. The streamlines are shown in Fig. 11.

Discussion

There has been significant progress in the development of the LB-based algorithm, PowerFLOW 3.2. Much of the improvement

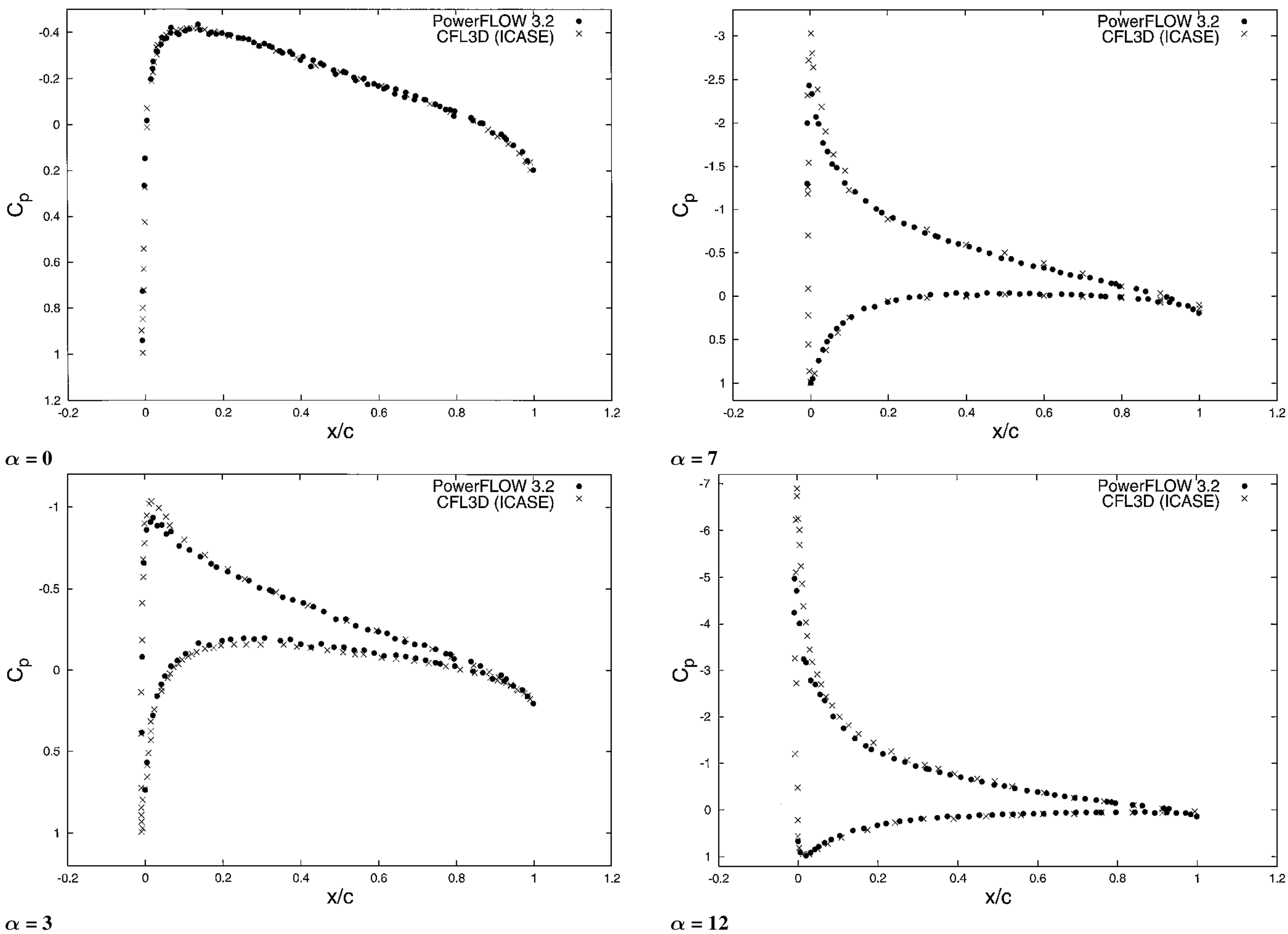


Fig. 6 Surface C_p plots at various angles of attack.

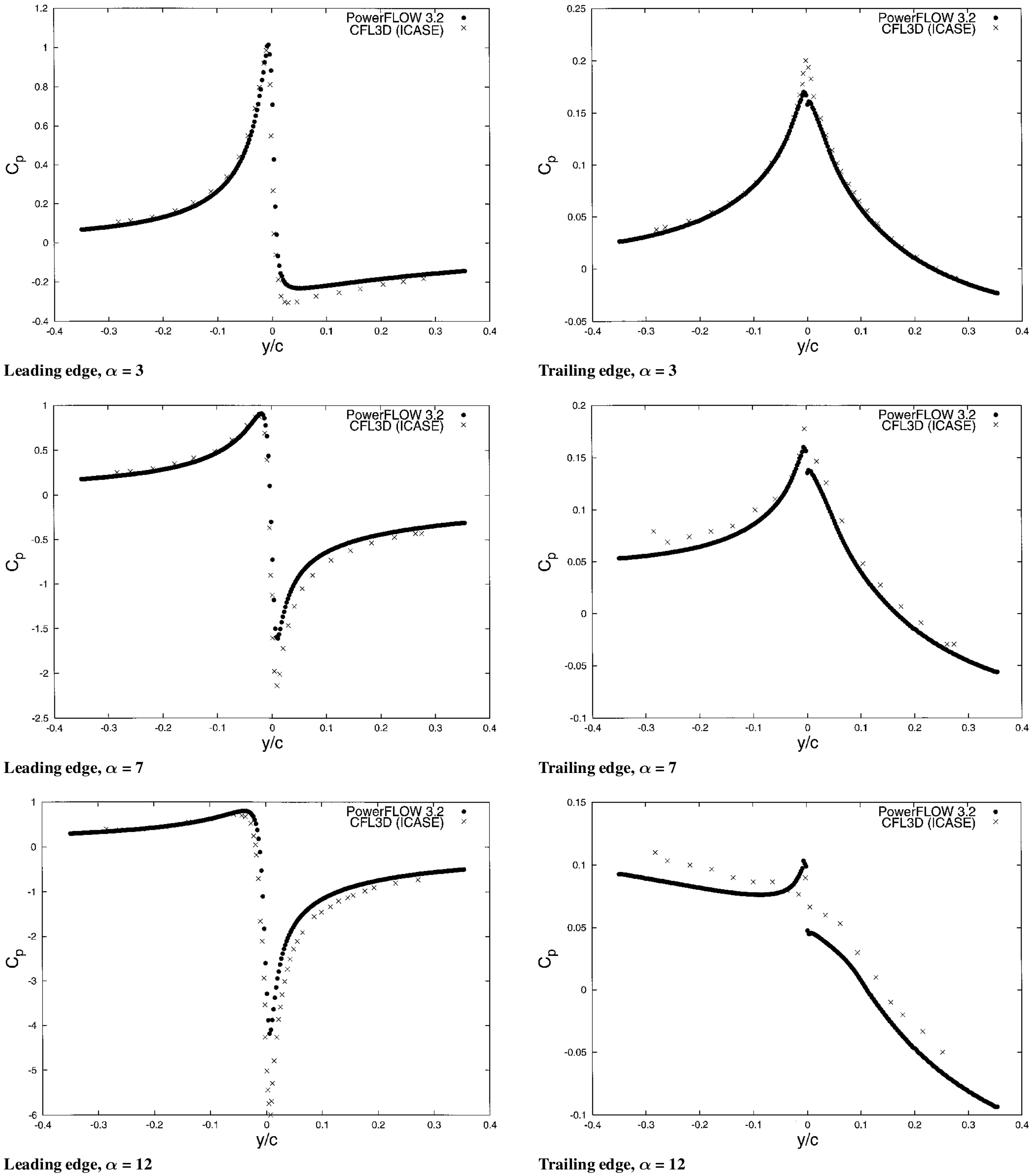
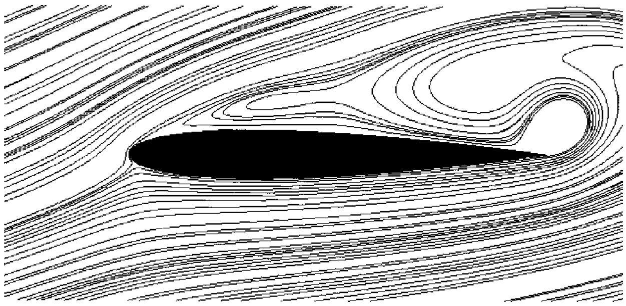


Fig. 7 **C_p vs y in the fluid at both the leading edge and the trailing edge, for various angles of attack as compared to CFL3D.**

to the code can be credited to the use of a two-equation turbulence model instead of a Smagorinski-type algebraic model. It has shown good results for variety of flows around a number of different geometries, particularly for automotive shapes.[14] Recently, to assess its applicability to aerospace problems, extensive simulations on some two-dimensional NACA airfoils were performed using this code. Based on the results, we conclude that the PowerFLOW 3.2 algorithm is able to give reliable results for an overall range of attack angles, including negative angles and poststall angles. PowerFLOW has provided prediction of stall angles for both NACA 0012 and NACA 4412, involving both moderate and high Reynolds number values. This demonstrates its applicability to study flow properties around streamlined bodies in general. In addition, the new version (PowerFLOW 3.2) is significantly robust to case setup so that no unphysical phenomenon of negative drag has been seen.[13] Because no elaborate gridding is required in case setup, as compared with other CFD software and algorithms, PowerFLOW is especially desirable for simulations for turbulent fluid dynamics involving extremely complex flows including separations and geometries in both two- and three-dimensional situations.

a)



b)

Fig. 8 Streamlines around a NACA 0012 airfoil at angle of attack of a) 7 deg (prestall) and b) 16 deg (poststall).

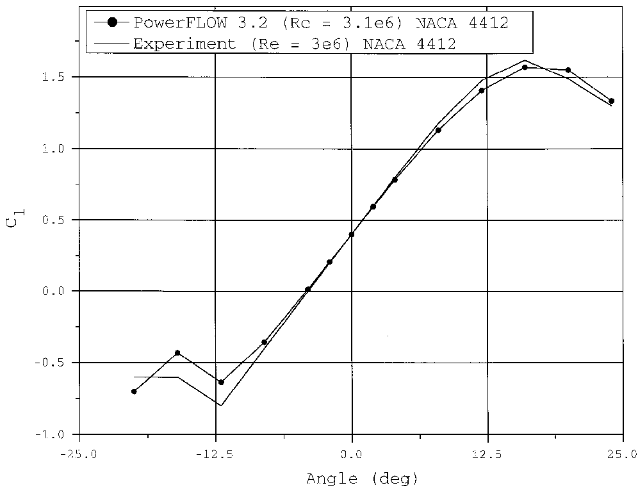


Fig. 9 Coefficient of lift vs angle of attack, comparing PowerFLOW 3.2p4 to experiment for NACA 4412 airfoil.

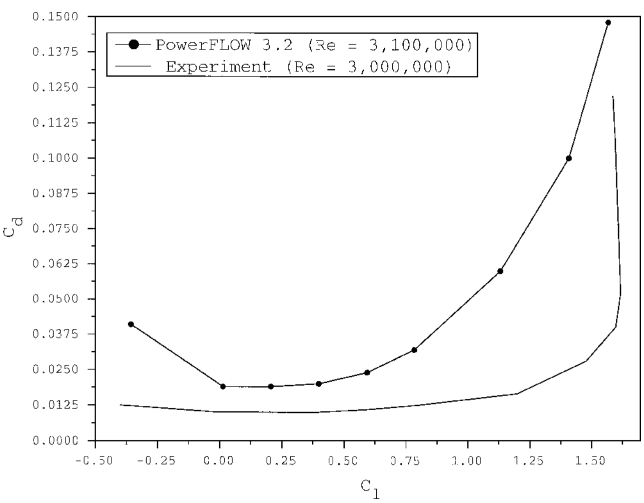
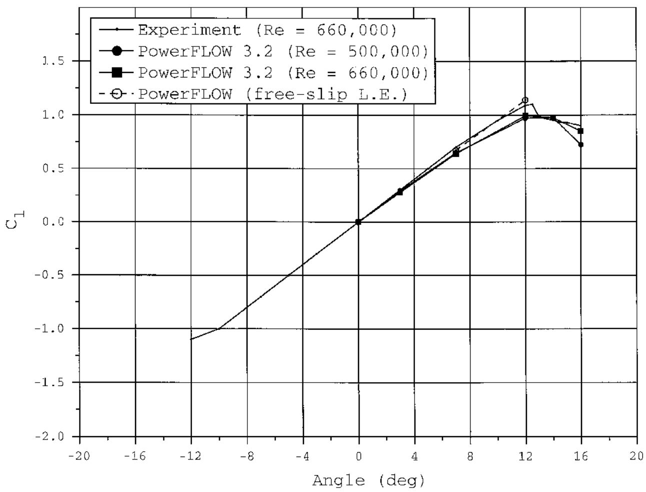
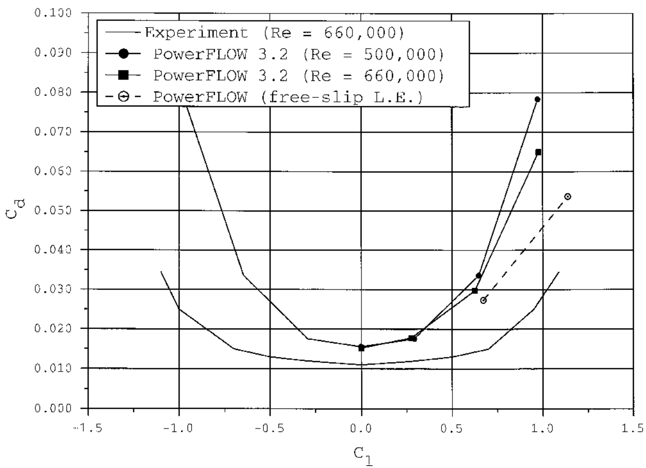


Fig. 10 Coefficient of drag vs angle of attack, comparing PowerFLOW 3.2p4 to experiment for NACA 4412 airfoil.

Fig. 11 Streamlines for NACA 4412 airfoil at an angle of attack of − 12 deg.



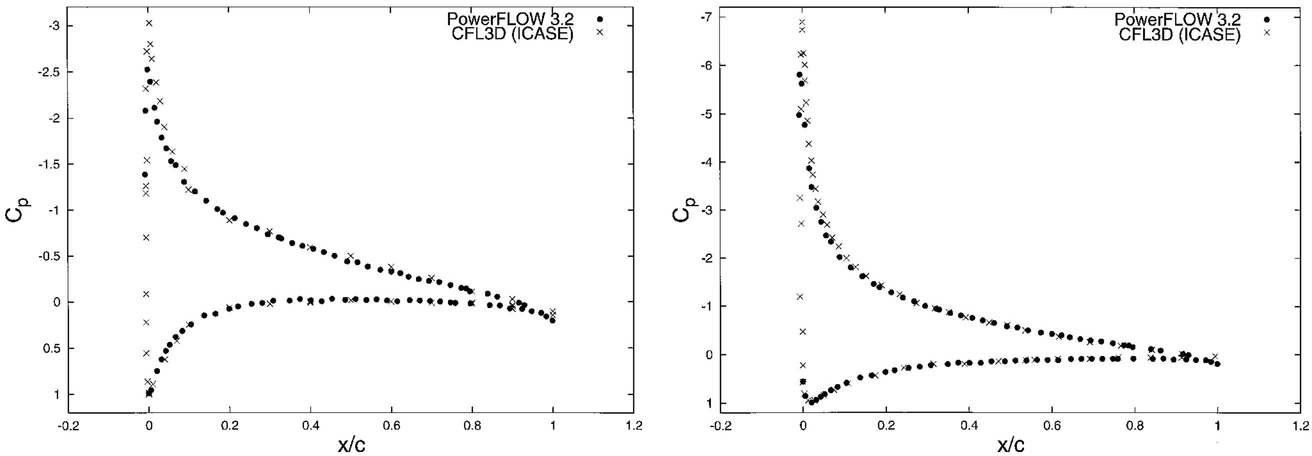
Coefficient of lift vs angle of attack



Coefficient of drag vs angle of attack

Fig. 12 Lift and drag of NACA 0012 airfoil predicted by PowerFLOW with a free slip wall condition applied to the leading edge, as compared to a fully turbulent leading edge.

We are currently in the process of further generalizing the existing physics model and the algorithm in PowerFLOW. One of the essential development areas is to incorporate a fully self-consistent capability for capturing laminar to turbulence transitions. This is important for flow regimes where the Reynolds number is low or moderate. As a demonstration, Figs. 12 show another set of PowerFLOW NACA 0012 simulations. Here, a section, starting from stagnation point up to approximately the suction point that was originally modeled by the normal PowerFLOW turbulence wall model, is replaced with a free-slip boundary condition. This is to mimic the effect of existing laminar layer where the wall stress is minimal.[16] As one can see, both the lift and drag are substantially improved. (Note that CFL3D seems to have overpredicted these at higher angles.) Figure 13 shows the pressure distribution along the surface. It can be seen that the maximum suction point is considerably improved.



$\alpha = 7$ $\alpha = 12$

Fig. 13 C_p along the surface of a NACA 0012 airfoil with a free slip leading edge.

Conclusions

In conclusion, the LB-based algorithm has demonstrated its increasing capabilities in CFD. It is not only an effective computational tool, but it also has certain fundamental theoretical implications for turbulence modeling.[6] PowerFLOW is a software code that is based on an LB approach with a combination of advanced turbulence models. It has been demonstrated as a useful and reliable tool for a wide variety of flow simulations both in academic benchmark cases and engineering CFD applications.

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