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WIND TUNNEL REQUIREMENTS FOR COMPUTATIONAL
FLUID DYNAMICS CODE VERIFICATION

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SUMMARY

The role of experiment in the development of Computational Fluid Dynamics (CFD) for aerodynamic flow field prediction is discussed. Requirements for code verification from two sources that pace the development of CFD are described for: (1) development of adequate flow modeling, and (2) establishment of confidence in the use of CFD to predict complex flows. The types of data needed and their accuracy differs in detail and scope and leads to definite wind tunnel requirements. Examples of testing to assess and develop turbulence models, and to verify code development, are used to establish future wind tunnel testing requirements. Versatility, appropriate scale and speed range, accessibility for nonintrusive instrumentation, computerized data systems, and dedicated use for verification were among the more important requirements identified.

1. INTRODUCTION

Computational fluid dynamics (CFD) is expected to play a prominent role, along with wind tunnel testing, in the design of aerospace vehicles.[1,2] Such expectations and optimism are based on the premise that the continued development of CFD, coupled synergistically with the new developments in instrumentation and test techniques, will provide a clearer understanding of complex flow phenomena and lead to more efficient and more ambitious designs. However, the pace of CFD introduction in the design process, and the sophistication of its application, will depend largely on the designer's confidence in the computational method. Experiments that verify CFD are an essential part of the confidence-building process because mathematical approximations, limited computer capacity, and uncertainty in modeling various physical processes lead to compromised solutions to the complete set of governing equations.[3]

The topic of CFD verification is currently being debated. It is a relatively new concept that depends on closely coordinated planning between computational and experimental disciplines. Because the code applications are becoming more complex and the regions of interest are diverse and wide-ranging, it no longer suffices to use experimental data from integral or surface measurements alone to provide the required verification. Flow-physics, flow-field, and boundary-condition measurements emerge as critical information in this regard. Furthermore, measurement accuracy requirements must be examined from a new perspective.

As a consequence of this evolutionary status of code verification, before defining the wind tunnel requirements it is important to establish what we mean regarding the role of experiment in the development of CFD. The author and his colleagues have experience in this regard, as our experimental effort has for some time been closely allied with the CFD effort at Ames Research Center.

This paper, therefore, will begin by briefly describing the status, future direction, and pacing items of CFD technology development. Requirements for code verification from two sources that pace the development are then described. The first of these requirements involves experiments to establish phenomenological input for situations in which understanding of the flow physics is limited. The important problem of turbulence modeling for aerodynamic flows will be used as an illustration, but other examples (such as high-temperature, reacting-gas physics with simplifications to account for radiation and mass transfer, or vortex interactions within developing flow fields over aircraft at high incidence) also could have been used. The second requirement involves experiments that establish the confidence limits on CFD predictions of complex flows over parametric variations such as Mach and Reynolds number. Examples for external aerodynamic flows are used, but internal flows, rotating flows, or unsteady flows would also provide good illustrations. The wind tunnel and accuracy requirements naturally ally themselves with these verification requirements and they are discussed in the final sections of the paper.

2. STATUS AND FUTURE DIRECTION OF CFD

2.1 Status

CFD has experienced volatile growth and a measurable degree of maturity over the past decade. The point can be illustrated by referring to Fig. 1. In the mid 1970's, to predict the entry heating environment over the Space Shuttle at flight conditions (which could not be duplicated in the wind tunnel), it was necessary to reduce the problem to manageable proportions. This was done by approximating the complete configuration with simple geometries (Fig. 1a) that were amenable to computation. The choices were based on extensive wind tunnel test data from the complete configuration compared with inviscid computations over the simple configurations, coupled with boundary-layer solutions. Leeside, separated flow computations were not possible. Today (in contrast), calculations of the entire Shuttle flow field and surface heating, including the leeside, are being accomplished by solving the Reynolds-averaged, Navier-Stokes equations.[4,5] A computer-generated surface geometry used for one such calculation is illustrated in Fig. 1b. Solutions of the time-dependent form of the equations are made in the subsonic regions, and solutions of the parabolized thin-layer laminar form of the equations are used in supersonic regions. Equilibrium gas properties have been incorporated and the results compared with flight data.[4] The main driving forces in the advancement were access to large, fast computers and significant advances in algorithm development.

2.2 Future Direction

The future direction of CFD is toward even more ambitious applications involving complex geometries and their attendant flow fields. For example, pathfinder computations employing Reynolds-averaged, Navier-Stokes equations will be obtained for a complete fighter aircraft,[6] the flow around a hypersonic vehicle, the internal flow in the turn-around duct of the Shuttle main engine[7] and the unsteady flow through a compressor stage.[8] Such computations test the limits of CFD technology development and the spinoffs from the successes and failures of such computations are expected to spur new development. But the ultimate success of such technology development depends, to a large extent, on addressing and solving the important issues still pacing the development of CFD.

2.3 Pacing Issues

Some of the more important issues pacing the development of CFD are shown in Fig. 2. Solution methodology, grid generation, and computer power were discussed by Kutler.[9] Flow modeling and code verification, which rely heavily on experiment, are two additional issues that establish the important link between computation and experiment. Flow modeling is required in instances in which the physics is poorly understood or is so complex as to make "brute-force" computation impractical. Important examples are turbulence models for closure of the Reynolds-averaged, Navier-Stokes equations[10,11]; transition from laminar to turbulent flow; and high-temperature gas physics related to hypersonic flows. Code verification is required to establish the limits of accuracy of the computations, particularly as the complexity of the flow increases.

3. EXPERIMENTAL REQUIREMENTS

3.1 Role of Experiments

A framework for describing the important links between experiment and computation is shown in Fig. 3. Experiments are required at each stage of code development. Research codes refer to those in which the ability to predict a particular, and usually idealized, flow phenomena is first established. One or two researchers are involved in developing the code, and no documentation is available. At this stage, experiments that are referred to as "building blocks" are needed. These provide the phenomenological data required to understand the flow physics, to guide flow-modeling processes, and to ultimately verify the computational development for the particular problem at hand. Pilot codes refer to a more advanced stage. Documentation is more complete, the code may be operated by others besides the researchers involved in the original development, and the envelope of problem application is expanded. At this stage, benchmark experiments peculiar to the various applications are required to provide the parametric data that establish accuracy limits on the computations. Subsequently the code would advance to its ultimate development stage when it could be used alone (or even be combined with codes from other disciplines such as structures or propulsion) and applied confidently in the design process. Configurational data from wind tunnel experiments would be needed to verify performance.

The distinction between the various stages of development outlined here is idealized, and not always evident in practice, because of the dynamic nature of CFD and its wide-ranging possibilities for solving many different problems; but the framework depicts how experiment and computation, working together, could accelerate the pace of development at each stage and even between the various stages. Of course, the implication here is the need for close coordination between experimental and computational disciplines. For the remainder of this paper, the first two stages of development will be emphasized along with their wind tunnel requirements.

3.2 Measurement Requirements

Each experimental stage must provide specific information that will enable a critical assessment of computational capability and accuracy. Some examples of key measurement requirements are listed in Fig. 4. These measurements are only representative and are germane to the technological development for Reynolds-averaged, Navier-Stokes equations for fully developed turbulent flows.

Building-block experiments must document sufficient information on flow phenomena to provide 1) an understanding of the flow physics, 2) guidance for modeling the turbulence, and 3) a critical test of the code's ability to simulate the flow. Surface variables and flow variables, including turbulence information, are essential. Some phenomenological experiments that focus on new flow physics or basic understanding of turbulence may be performed at incompressible flow conditions, but measurements will be required ultimately at representative flight Mach numbers and Reynolds numbers if simulations of actual flow phenomena are to be tested.

Benchmark experiments must provide sufficient information to test the ability of codes to perform adequately over a range of flow conditions or for a variety of geometries. Detailed measurements on turbulence modeling physics are not essential, but parametric testing over as full a range of flight Mach numbers and Reynolds numbers as possible will be necessary to provide an accuracy assessment of the computational methods. With the renewed emphasis on hypersonics, flight experiments may become essential elements of the process because ground based facilities may lack adequate flight simulation capability. Code failures at this benchmarking stage may suggest further need for building-block experiments and a synergistic evolutionary development may follow.

Design experiments at the final stage provide the optimal configuration data necessary for performance evaluation and the experiments should be carried out as close to flight conditions as practical. CFD is expected to expedite the execution of these experiments by eliminating the need for very fine increments in parametric variations and by helping resolve any anomalous data sets.

Careful measurements of free-stream and boundary conditions are required at all stages because they may influence the flow field around the test models. This is particularly important for transonic flows. Moreover, these measurements are often required to initiate computation or are approximated in the computation.

3.3 Instrumentation Trends

The outlook is promising for making the measurements required to guide and verify computations, such as those listed in Fig. 4, because impressive advances in instrumentation development and data acquisition have taken place over the past decade. Some examples of this development trend are shown in Fig. 5. Prior intrusive techniques are being replaced by nonintrusive ones and the laser has emerged as the device that makes such applications possible. Measurements, such as velocity and its fluctuations,[12] density[13,14] and temperature and its fluctuations,[14] skin friction,[15] and model position and attitude[16] are now possible. These advances will have an impact on future wind tunnel requirements to be discussed later in this paper.

3.4 Building Blocks

An example of a building-block experiment is shown in Fig. 6. This experiment, in conjunction with CFD, was used to guide the development of an improved turbulence model for airfoils at transonic flow conditions where strong shock-wave boundary-layer interactions occur. The test model consisted of a cylindrical body, fitted with a circular-arc section. A transonic flow developed over the circular-arc section similar to that on an airfoil, and shock wave interactions of varying strengths were studied by varying free stream Mach numbers. The choice of an axisymmetric geometry and the long cylindrical section was made to eliminate three-dimensional effects and to develop a viscous interaction region of sufficient scale to allow detailed nonintrusive measurements. Mean flow and turbulence profiles, obtained with a Laser Doppler Anemometer System (LDA), and surface quantities such as pressure and oil-streak data were documented.[17] The model was tested in two facilities, the Ames' 2-ft by 2-ft and 6-ft by 6-ft wind tunnels, to evaluate the influence of wind tunnel boundary conditions. (No significant influence occurred.)

Computations of the flow field from a Reynolds-averaged, Navier-Stokes code revealed deficiencies in the turbulence modeling. By using a model developed by Cebeci and Smith, primarily for attached boundary layers, the shock wave location was predicted incorrectly and consequently the pressure recovery was seriously overpredicted. The mean-and-turbulence-profile data from the LDA measurements were used to explain the differences and guide modeling improvement. The primary cause of the pressure recovery overprediction was the failure of the eddy viscosity model to adequately reflect the lag of turbulence adjustment through the shock wave and the resultant underprediction of the displacement thickness influence. By using modeling concepts in conjunction with the turbulence data, a significant model improvement was developed. In particular, the "history effects" of the turbulence changes through the shock wave were accounted for by prescribing and solving an ordinary differential equation for the maximum shear stress development.[18] Modeling constants were determined using the turbulence data in conjunction with computations. The improved model results are shown in Fig. 6. The model has been introduced in two airfoil codes.[19,20] Additional studies are under way to determine the range of applicability by making comparisons with other benchmark experimental airfoil data.

3.5 Benchmarks

An example of one of these benchmark experiments[21] is illustrated in Fig. 7. The test model consisted of a supercritical airfoil section. It was mounted in a specially designed test section with solid walls. Boundary layer suction was applied ahead of the airfoil on the sidewalls to minimize interference; the upper and lower walls were contoured to stream-line shapes that were predetermined by computation to account for the presence of the model, which further minimized interference. Tests were performed at a Reynolds number of $6 \text{ v } 10^6$, based on chord, and angle of attack and Mach number were varied over a range sufficient to produce transonic flows covering weak and strong shock-wave boundary-layer interaction and attendant displacement effects. The boundary layer was tripped on the upper and lower model surface to ensure turbulent flow beyond 7% chord. Model pressures, wall boundary pressures and shapes, total drag, lift, and flow field and wake velocities from an LDA system were documented. A data base of this type (with minimal interference from a tunnel with solid walls) provides an ideal basis for evaluating the development of codes for the transonic speed range because the codes can include the wall boundary conditions more precisely than interference corrections can be made to the data sets.

The data are being used to assess the influence of turbulence modeling on transonic airfoil computations and to verify the development of a transonic code.[20] At present the code does not include the solid tunnel wall boundary conditions, but a preliminary assessment using this benchmark data indicates that the code provides very good simulation for the strong interaction cases when the Johnson-King turbulence model[19] is employed. Results of the comparisons for one strong interaction case (where separation occurred at the trailing edge) are shown in Fig. 7. The airfoil pressures, flow field velocities at constant heights above the model, and a wake profile at the trailing edge are compared with computations using two different turbulence models, a two-equation (q-w) model,[20] and the Johnson-King (J-K) model.[19] The comparison shows that the computations using the improved Johnson-King turbulence model simulates the measurements very well. It is important to emphasize that this conclusion could not have been drawn without the complete data set composed of total drag, lift, boundary conditions, and flow field surveys.

4. WIND TUNNEL REQUIREMENTS

The requirements for future wind tunnels used to verify CFD naturally result from our previous discussions on the role of experiment in the development of CFD. The most important of these requirements are: 1) versatility, along with well-defined test and boundary conditions; 2) appropriate scale and speed range; 3) accessibility of nonintrusive instrumentation; 4) provision for high-speed data systems; and 5) dedication of use to verification-experimentation. Some examples should help to develop these points further.

4.1 Versatility

As discussed previously, CFD applications are expected for a variety of aerodynamic flows over a wide speed range. Use of large, fast computers, which can timeshare among problem applications, means that the time needed to perform a variety of cost-effective computations will be far less than the time to design and perform companion experiments. Nevertheless, the computations still should be verified to ensure confidence in the results, and a limited number of well-thought-out, cost-effective experiments will be needed. Versatility must be kept in mind when considering facilities to accommodate these experiments. This is particularly true for the building-block studies in which phenomenological information will be required for a wide variety of flows and for the verification studies in which wind tunnel boundaries are critical (as in the transonic-speed regime) and may have to be modified from test to test.

The Ames High Reynolds Number Channel facilities provide an example of versatile design. These facilities, shown in Fig. 8, operate in a blow-down mode over a speed range from subsonic to supersonic (Mach = 3 maximum). Test section dimensions are 10 in. by 15 in. and 16 in. by 24 in. for channels I and II, respectively. In subsonic application, speed is varied through a downstream choking device. At supersonic speeds individual nozzles designed for the desired Mach numbers are used. Air from a large, high-pressure storage system provides the capability to operate at high Reynolds number, and run times are sufficient to collect the types of data required for modeling and benchmark experiments. The test sections are replaceable and are considered to be part of the test model. In this way, separate experiments dedicated to a particular test section can be interchanged without dismantling the entire setup, and reentry into the facility can be made to clarify or expand upon certain data sets. Savings in setup time, and the ability to perform several experiments in series, are the obvious advantages of such an arrangement.

Key building-block and verification experiments have been performed in these tunnels. Figure 9 shows geometries for some of the experiments performed in channel I, which can be equipped with either a rectangular or a circular stagnation chamber inlet. Some of these experiments were used by the international community at the 1981-2 Stanford Conference as test cases for evaluating the ability of codes to predict complex turbulent flows. Channel II is now configured for airfoil experiments. It uses shaped, solid, upper and lower walls and side-wall, boundary-layer removal as mentioned in the previously described benchmark experiment.

4.2 Appropriate Scale and Speed Range

Similitude is an important aspect of testing to validate CFD development. Applications of CFD will encompass internal as well as external aerodynamic flows, so the anticipated ranges of scale and speed in facilities employed for verification will be broad, indeed. An example of the Mach-number, Reynolds-number domain for external aerodynamic flow over an aerospace vehicle is shown in Fig. 10. A mean aerodynamic chord was used as the length scale in the Reynolds number. The hypersonic regime is typical of vehicle entry conditions. In this case it depicts the nominal Space Shuttle vehicle trajectory conditions. CFD applications and attendant verification studies are certain to arise over the speed regime from subsonic through hypersonic. A critical need for high Reynolds number capability occurs in the transonic and low supersonic regions, and in the hypersonic regions for exit trajectories associated within the latest aerospace plane concepts. It should also be noted that at hypersonic speeds the associated enthalpy and vehicle scale may preclude ground-based similitude, so flight verification experiments of important flow phenomena (such as reacting chemistry, radiation, and transition) may be necessary. Fortunately the viscous phenomena, important to vehicle stability and control, can usually be duplicated in ground-based verification experiments that test at the appropriate Mach and Reynolds numbers, in the absence of true enthalpy simulation.

Although scale is reflected in the test Reynolds number, actual model dimensions are also important because details of the viscous regions must be measured in some experiments. In this regard, model sizing must take account of the achievable resolution scale of the instruments to be employed. We have found that facilities with test section areas of 1 to 2 ft^2 have been quite satisfactory for use in building-block experiments. In our LDA applications, we achieved spatial resolution to within 0.01 in., which was sufficient to provide viscous profile data. But in some of these experiments, the viscous region under study had to be developed along the tunnel walls to achieve adequate profile resolution. For verification in experiments of complex aerodynamic geometries, model dimensions of about 1 to 2 ft may be required to resolve viscous regions, so larger tunnels may be more appropriate.

4.3 Optical Access

Nonintrusive instrumentation will play an increasingly important role in experiments performed to verify CFD. Therefore another important requirement for facilities performing such experiments will be a provision for optical access. Furthermore, three-dimensional flows will comprise a majority of future studies, and accessibility for a wide range of viewing perspectives is desirable. Open-jet, test-section facilities provide the best access, but confined test sections are more conventional. Access requirements for the latter may present a formidable challenge, but successes have been achieved, as illustrated next.

The two-component laser velocimeter system,[12] which was used to measure the flow field velocities and turbulence quantities in the airfoil experiments performed in High Reynolds Number Channel II discussed previously, is shown in Fig. 11. The requirement was to provide nonintrusive test data in a high-Reynolds-number transonic test tunnel environment. The facility utilized a pressurized test cabin. The laser and its dual-beam-sending optics are mounted outside and on the top of the cabin, and a translating mechanism (equipped with inner optics and located inside the cabin) provides accurate, rapid, preprogrammed positioning. Fiber optics are used to collect the forward-scattered light from the focal volume in the test stream and to transmit it to the photomultiplier tubes located outside the cabin. Optical access into the test stream is provided by glass windows located in the model turntable and in the side walls downstream, in the vicinity of the model far wake. Experience to date with the system shows that stable optical alignment can be maintained during blowdown runs and from blowdown-to-blowdown.

It should be noted that there is a need for developing nonintrusive measuring devices with better spacial resolution, especially for three-dimensional applications.

4.4 Computerized Data System

The quantity and scope of the data needed for verification, the sophistication of new instrumentation, and the need for close coordination between experiment and computation all require that a computerized data system be provided. The system should provide control for tunnel and instrument functions, acquire data, perform arithmetic operations, and act as an interface between CFD users and the experimentalists. It should provide real-time data acquisition, especially if the time-dependent phenomena are encountered. Expert systems could be incorporated for faster and more accurate data acquisition.

An idealized system is depicted in Fig. 12. The kernel is a main computer with sufficient capacity and speed to perform multifunction tasks. For example, it would have command and control functions for smaller computers used to control and/or command tunnel and instrumentation operations; acquire low- and high-level data directly or indirectly; perform arithmetic operations to reduce the data to the desired form; direct data to storage or output devices; and make comparisons with computations. Importantly, it would interface with both the experimental fluid dynamics (EFD) and CFD user networks so that data comparisons and test decisions could be made in a synergistic fashion.

4.5 Dedication to Verification

Accurate, redundant (in some instances), and detailed measurements, often employing state-of-the-art instrumentation, are required in the experiments used to verify CFD. Inevitably, equipment breakdowns and data anomalies will arise so that retesting for clarification, and even further investigations using different instrumentation, may be needed. Sufficient time to conduct the comprehensive experiments will have to be provided. Therefore, dedicated equipment and test time, specifically for these experiments will have to be provided if timely developments are to occur.

5. DATA COMPLETENESS AND ACCURACY REQUIREMENT

Assessing the accuracy and predictability of CFD codes and their turbulence models requires special attention to data completeness and accuracy.

5.1 Completeness

The completeness requirements for a building-block experiment to study turbulence modeling of a supersonic shock-wave, boundary-layer interaction in the vicinity of a compression corner is shown in Figs. 13 and 14. In such flows unforced shock unsteadiness occurs,[22] and laser velocimeter measurements of mean and fluctuating flow quantities must take account of the unsteadiness to avoid misleading interpretations regarding modeling.

A typical joint probability distribution function (JPDF) of velocities is shown in Fig. 13 (which is taken from Ref. 22). The geometry is an axisymmetric cylinder flare. The JPDF was obtained at a location in the outer boundary layer along the flare and downstream of the mean position of a separation shock wave. The bimodality of the distribution is particularly evident and is strongly indicative of unsteady shock wave motion. The two peaks, labeled s_1 and s_2, are representative of velocity states upstream and downstream of the separation shock wave. With each of these states is associated a total probability of occurrence (p_1 and $P_2 = 1 - p_1$), mean velocities (u_1, u_2 and v_1, v_2), turbulent normal stresses, and turbulence shear stresses. A straight-forward analysis reveals that the difference in mean values ($u_2 - u_1$) and ($v_2 - v_1$) for the two states contributes to the stresses. The shear stress contribution due to unsteadiness is $-p_1p_2(u_1 - u_2)(v_1 - v_2)$ and was measured to be 75% of the total shear stress. This contribution to the total Reynolds stresses is due to an organized or coherent motion of the shock rather than to incoherent or dissipative turbulence.

Figure 14 shows zero-drag particle paths in a plane of symmetry for a three-dimensional compression surface achieved geometrically by tilting the flare axis relative to the cylinder axis. Velocity measurements from an LDA were used to construct the paths by conditionally sampling the data on the basis of shock position (e.g., shock forward, shock back) and by using all data representing the long-time mean. These are compared with solutions from the Reynolds-averaged, Navier-Stokes equations which employ an eddy viscosity turbulence model. The separation location moves considerably, and even the long-time mean computer simulations do not compare favorably with the experiment. Turbulence data are also available so that flow unsteadiness can be separated from the random turbulence, and these data will be used to guide improvements in modeling.

5.2 Accuracy

CFD validation will ultimately depend on a thorough understanding of the algorithm limitations, and the influence and physical basis of grid density. It will require experiments that verify the ability of the code to accurately model, for a range of practical parameters, the critical flow physics and its consequent flow behavior around aerodynamic shapes. The latter can occur only when the accuracy and limitations of the experimental data are known and thoroughly understood. We have already discussed the various types of experiments in our idealized scenario for development that are depicted in Fig. 3. Currently, the validation process is hampered somewhat by the lack of adequate instrumentation and ground-based facilities to cover the range of anticipated applications. Therefore, redundant measurement techniques, similar experiments performed in more than one facility, and careful substantiation and specification of experimental accuracy limits will be necessary. Such requirements make it essential that the computational and experimental disciplines be carefully coordinated.

6. CONCLUDING REMARKS

Experiments play a critical role in the development of CFD. They provide the phenomenological data to help in the process of flow modeling and they provide the verification necessary to instill confidence in the computations.

A synergistic approach, comprising closely coordinated experiments and computations at all levels of computational development, was described in order to set the groundwork necessary to develop requirements of facilities to be used to verify CFD. Building-block experiments, which address fundamental phenomenological questions, were described. Experiments of this type require more comprehensive sets of data. In these instances, more sophisticated instrumentation would be the norm rather than the exception. Benchmark experiments were described next. These experiments identify the accuracy and limits on our ability to compute complex flows. The types of data required differ from the more fundamental experiments in the sense that phenomenological issues are not investigated in detail sufficient to identify their causes. Data accuracy and completeness requirements were also noted.

The idealistic breakdown of the experiments and measurements described helped to identify the more important requirements for wind tunnels to be used to verify CFD. Versatility, appropriate scale and speed range, accessibility for nonintrusive instrumentation, computerized data systems, and dedicated use for verification were among the more important requirements identified.

REFERENCES

1. Chapman, D. R., "Computational Aerodynamics-Development and Outlook," AIAA J., Vol. 17, Dec. 1979, pp. 1293-1313.

2. Reinecke, G. "Forecasting the 80's," Astronautics & Aeronautics, Vol. 19, Jul/Aug. 1981, pp. 46-47.

3. Committee on Computational Aerodynamics Simulation Technology Developments, "The Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities, A Fifteen Year Project," National Research Council, National Academy Press, Washington, D.C., 1983.

4. Prabhu, D. K., and Tannehill, J. C., "Numerical Solution of Space Shuttle Orbiter Flow Field Including Real Gas Effects," AIAA J. of Spacecraft and Rockets, 1987.

5. Rizk, Y., M., and Ben-Shmuel, S., "Computation of the Viscous Flow Around the Shuttle Orbiter at Low Supersonic Speeds," AIAA Paper 85-0168, Reno, NV, Jan. 1985.

6. Holst, T. L., Kaynak, U., Gundy, K. L., Thomas, S. D., Flores, J., and Chaderjian, N. M., "Numerical Solution of Transonic Wing Flows Using an Euler Navier-Stokes Zonal Approach," AIAA Paper 85-1640, Cincinnati, OH, Jul. 1985.

7. Chang, J. L. C., and Kwak, D., "A Three-Dimensional Incompressible Flow Simulation Method and Its Application to the Space Shuttle Main Engine, Part II - Turbulent Flow," AIAA Paper 85-1670, Reno, NV, Jan. 1984.

8. Rai, M. M., "Navier-Stokes Simulations of Rotor-Strator Interaction Using Patched and Overlaid Grids," AIAA Paper 85-1519-CP, Cincinnati, OH, Jul. 1985.

9. Kutler, P., "A Perspective of Theoretical and Applied Computational Fluid Dynamics (SP)," AIAA J., Vol. 23, No. 3, Mar. 1985, pp. 328-341.

10. Marvin, J. G., "Turbulence Modeling for Computational Aerodynamics," AIAA J., Vol. 21, No. 7, Jul. 1983, p. 941.

11. Lakshminarayana, B., "Turbulence Modelling for Complex Flows (Invited Paper), AIAA Paper 85-1652, Cincinnati, OH, Jul. 1985.

12. Seegmiller, H. L., Bader, J. B., Cooney, J. P., DeYoung, A., Donaldson, R. W., Jr., Gunter, W. D., and Harrison, D. R., "Development of a New Laser Doppler Velocimeter for the Ames High Reynolds Channel No. II," ICIASF '85 Record, IEEE Publication 85CH2210-3, Stanford Univ., CA, Aug. 1985.

13. Dunagan, S. E., and Brown, J. L., "A Holographic Interferometric Study of an Axisymmetric Shock-Wave/Boundary-Layer Strong Interaction Flow," AIAA Paper 85-1564, Cincinnati, OH, Jul. 1985.

14. Logan, P., and McKenzie, R. L., "Uncertainty in Hot-Wire Measurement of Compressible Turbulent Flows Implied by Comparison with Laser-Induced Fluorescence," AIAA Paper 86-0502, Reno, NV, Jan. 1986.

15. Monson, D. J., "A Laser Interferometer for Measuring Skin Friction in Three-Dimensional Flows," AIAA Paper 83-0385, Reno, NV, Jan. 1983; AIAA J., Vol. 22, No. 4, Apr. 1984, pp. 557-559.

16. Holmes, H. K., "Model Measurements in the Cryogenic National Transonic Facility - An Overview," ICIASF '85 Record, IEEE Publication 85CH2210-3, Stanford Univ., CA, Aug. 1985.

17. Bachalo, W. D., and Johnson, D. A., "An Investigation of Transonic Turbulent Boundary Layer Separation Generated on an Axisymmetric Flow Model," AIAA Paper 79-1479, Williamsburg, VA, 1979.

18. Johnson, D. A., "Predictions of Transonic Separated Flow with an Eddy-Viscosity/Reynolds-Shear-Stress Closure Model," AIAA Paper 85-1683, Cincinnati, OH, Jul. 1985.

19. Johnson, D. A., and King, L. S., "Transonic Separated Flow Predictions Based on a Mathematically Simple, Nonequilibrium Turbulence Closure Model," IUTAM Symposium, Paris, France, NASA TM 86826, Oct. 1985.

20. Coakley, T. J., "Numerical Simulations of Viscous Transonic Airfoil Flows," AIAA Paper 87-0416, Reno, NV, Jan. 1987.

21. Mateer, G. G., Seegmiller, H. L., Coakley, T. J., and Hand, L. A., "An Experimental Investigation of a Supercritical Airfoil at Transonic Speeds," AIAA Paper 87-1241, Honolulu, HI, Jun. 1987.

22. Brown, J. L., Kussoy, M. I., Coakley, T. J., "Turbulent Properties of Axisymmetric Shock-Wave/Boundary-Layer Interaction Flows." In Turbulent Shear Layer/Shock Wave Interactions, Springer-Verlag, Berlin Heidelberg, 1986.

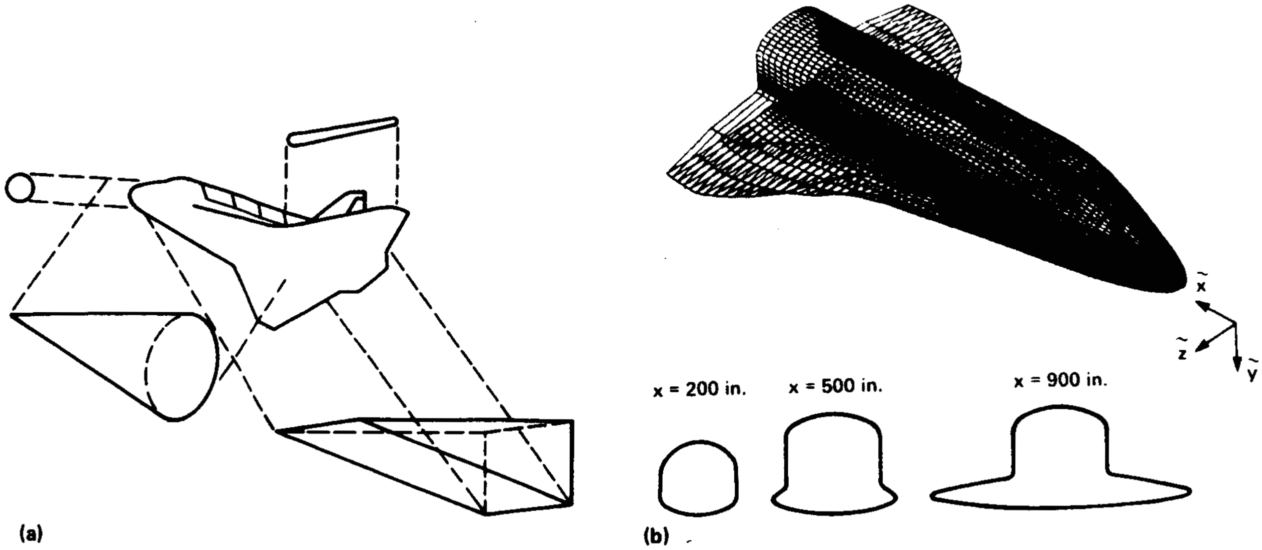


Figure 1. Maturation of CFD over the past decade for Space Shuttle Aerothermodynamics. a) Circa 1974: equivalent shapes and solutions from inviscid and boundary-layer equations. b) Present: complete geometry and solutions from Reynolds-averaged, Navier-Stokes equations.

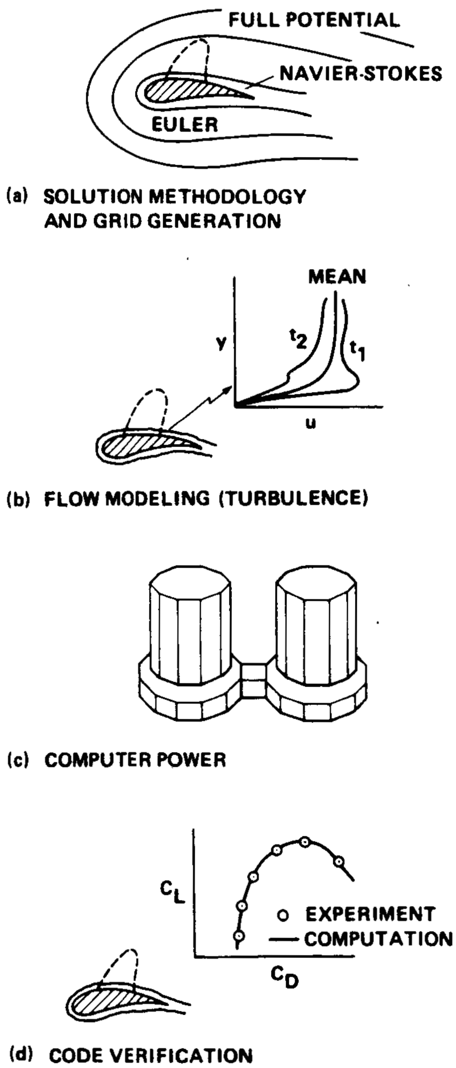


Figure 2. Issues pacing the development of CFD.

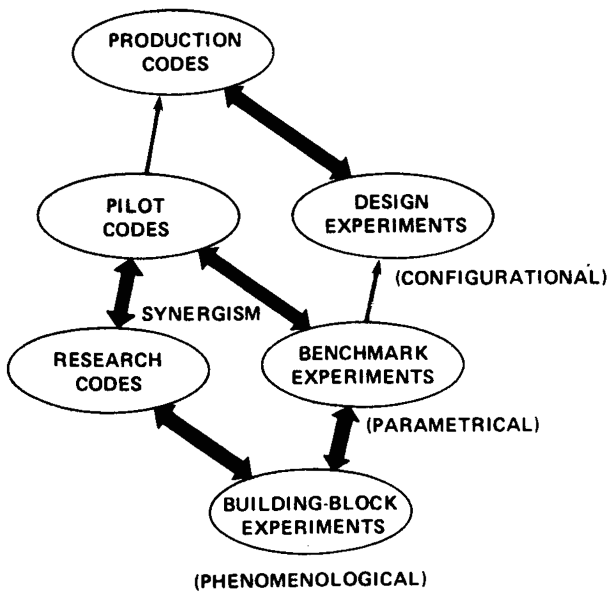


Figure 3. The role of experiment in the development of CFD.

EXPERIMENT	MEASUREMENTS (REPRESENTATIVE FOR TURBULENCE MODELING)	TEST CONDITIONS
BUILDING BLOCK (PHENOMENOLOGICAL)	SURFACE QUANTITIES FLOW FIELD QUANTITIES TURBULENCE INDIVIDUAL STRESSES CORRELATION LENGTHS STRUCTURE BOUNDARY CONDITIONS	REPRESENTATIVE FLIGHT M_∞, Re_∞
BENCHMARK (PARAMETRICAL)	SURFACE QUANTITIES FLOW FIELD QUANTITIES (SELECTED LOCATIONS) BOUNDARY CONDITIONS	VARY M_∞, Re, α OVER FLIGHT RANGES
DESIGN (CONFIGURATIONAL)	DRAG, LIFT, MOMENTS, HEAT LOADS, SHEAR LOADS BOUNDARY CONDITIONS	AS CLOSE TO FLIGHT M_∞, Re, α AS PRACTICAL

Figure 4. Key measurement requirements of experiments supporting development of Reynolds-averaged, Navier-Stokes codes for fully developed turbulent flows.

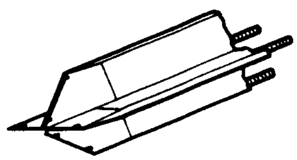
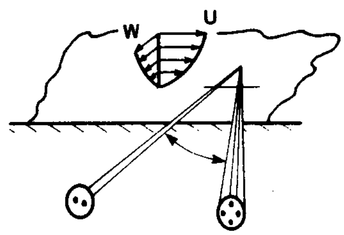
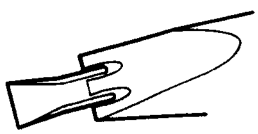
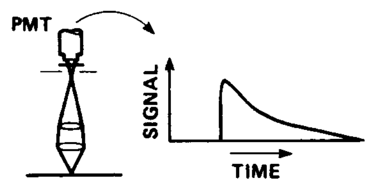
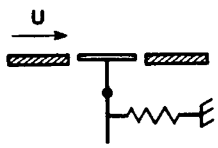
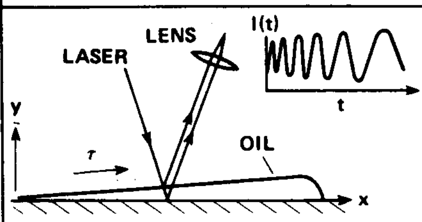
MEASUREMENT	CIRCA MID '70's	PRESENT (NONINTRUSIVE)
VELOCITY MEAN FLUCTUATING	 HOT WIRES PITOT-STATIC TUBES	 3-D LASER VELOCIMETER
TEMPERATURE MEAN FLUCTUATING	 HOT WIRES THERMOCOUPLES	 LASER-INDUCED FLUORESCENCE
LOCAL SKIN FRICTION	 BALANCES FENCES	 LASER-OIL INTERFEROMETER

Figure 5. Advances in instrumentation development over the past decade.

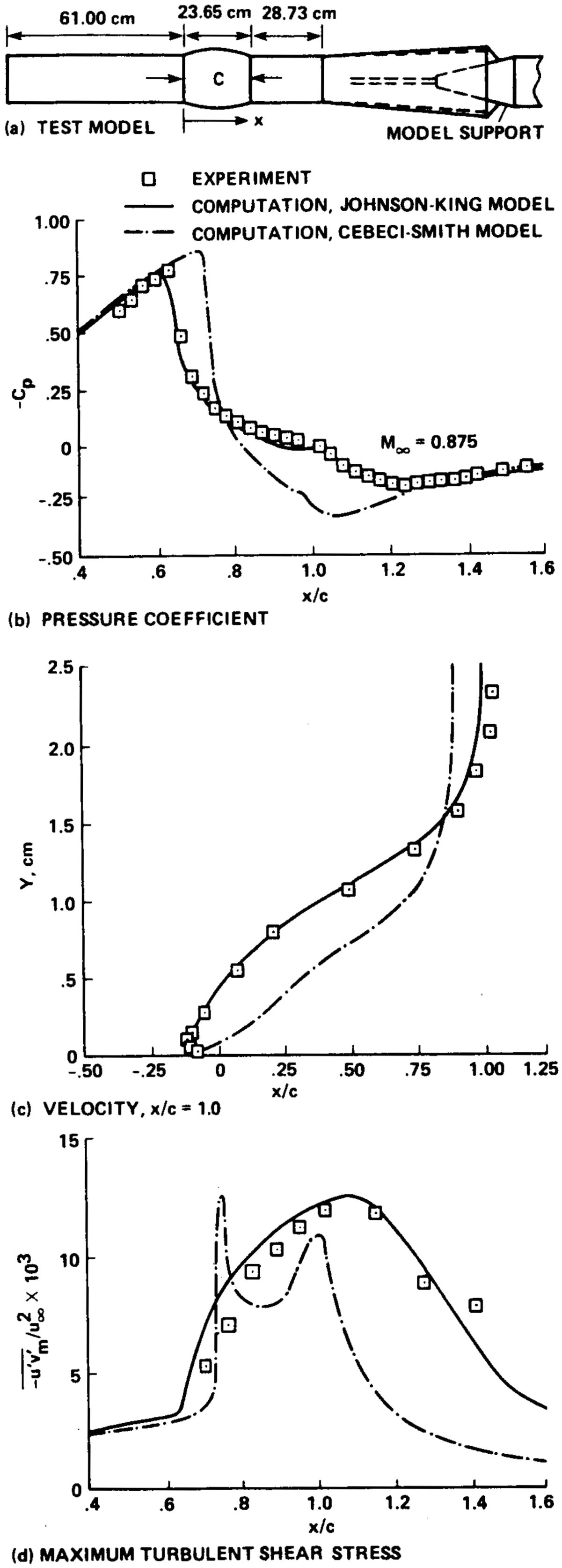


Figure 6. A building-block experiment used to develop an improved turbulence model.

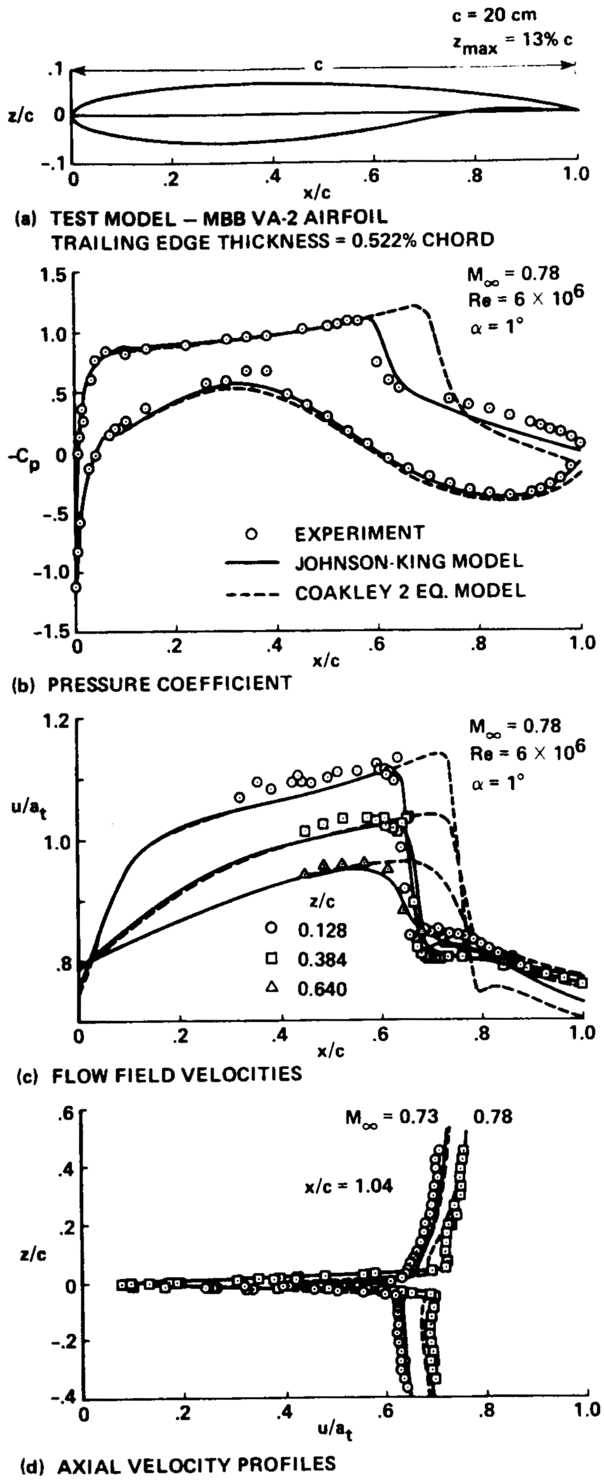


Figure 7. A benchmark airfoil experiment used to verify development of an improved turbulence model.

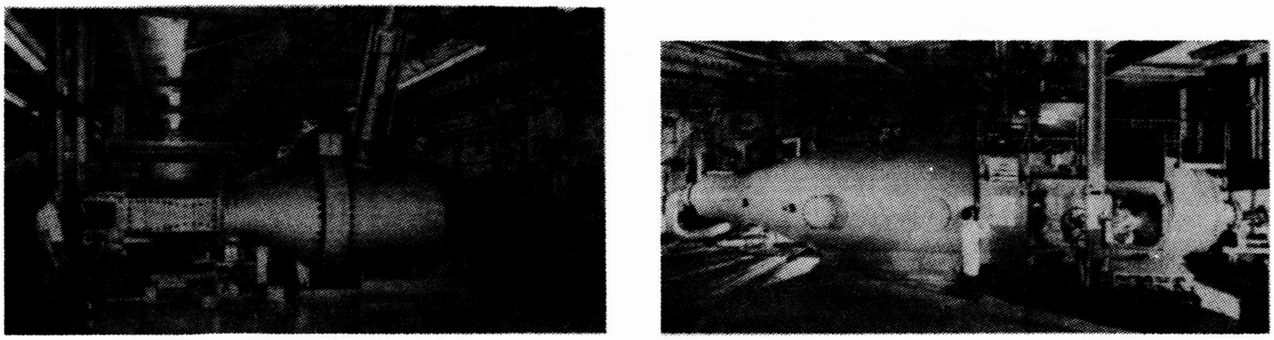


Figure 8. Ames High Reynolds Number Channels. a) Channel I. b) Channel II.

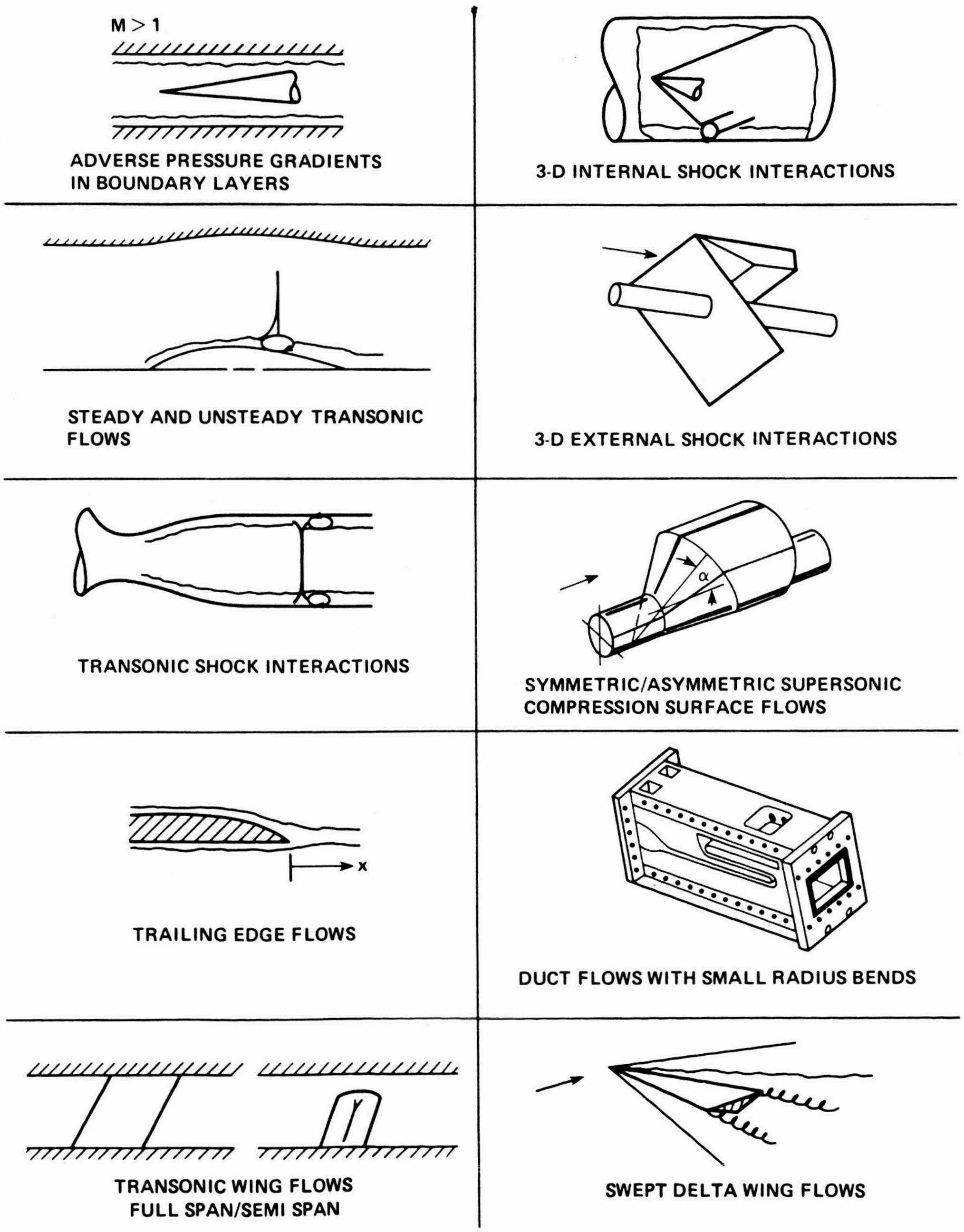


Figure 9. Experiments performed in a versatile wind tunnel.

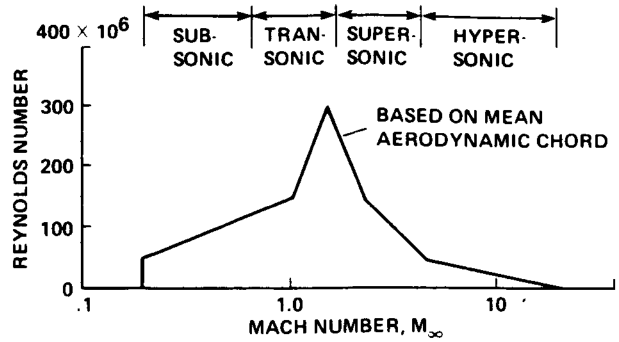


Figure 10. Mach-number, Reynolds-number domain for aerospace vehicles.

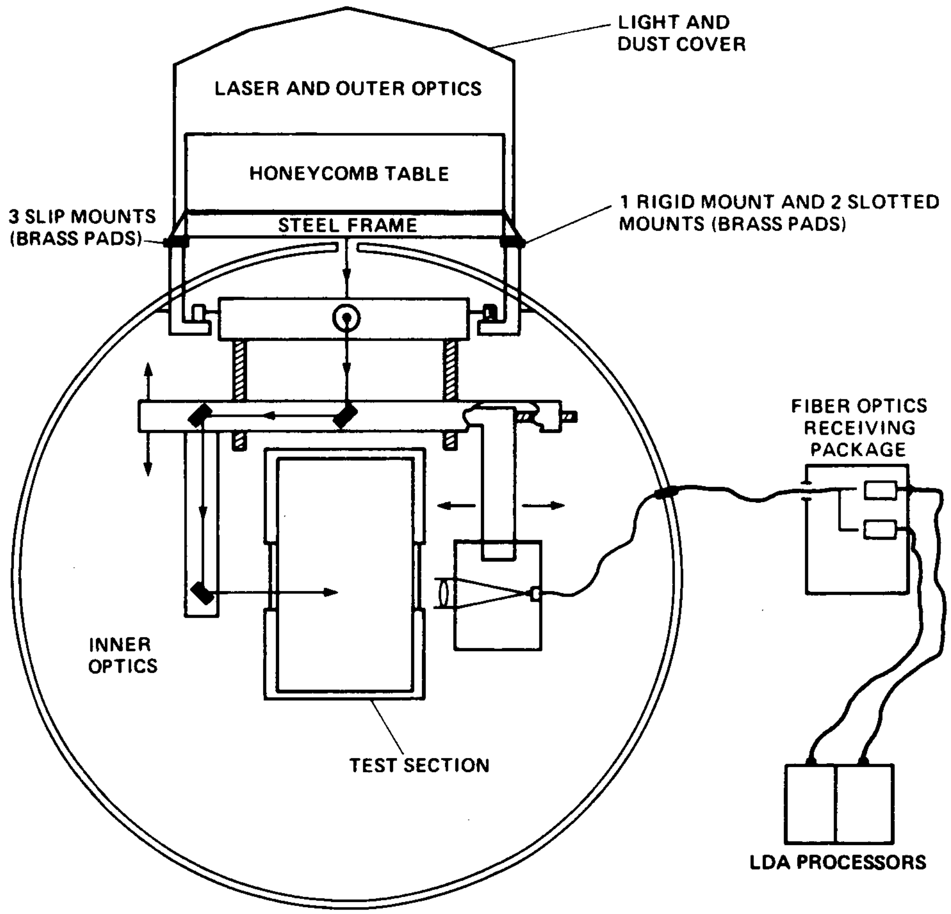


Figure 11. A dedicated laser anemometer system for the Ames High Reynolds Number Channel II.

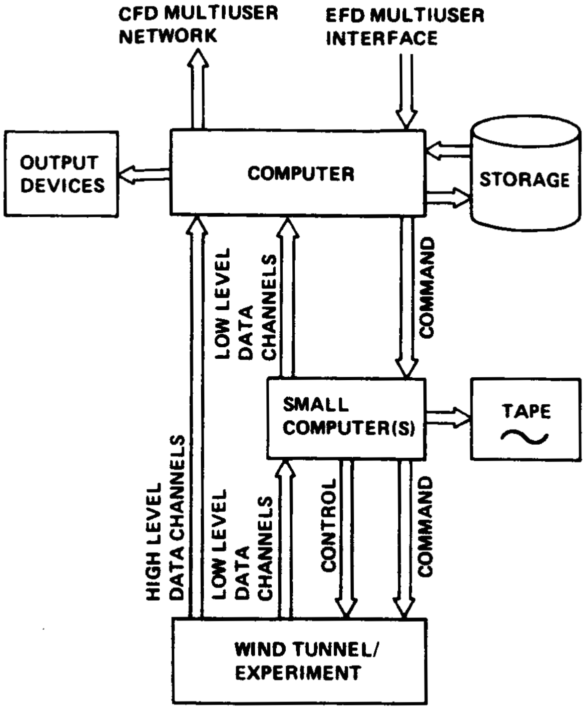


Figure 12. An ideal computerized data system.

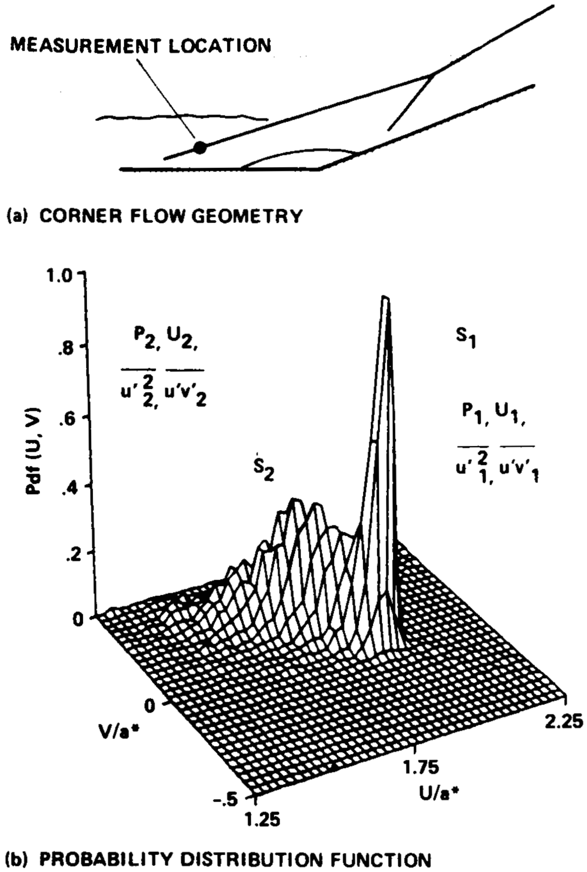


Figure 13. Joint probability distribution function JPDF) for u and v for a 30° axisymmetric compression corner.

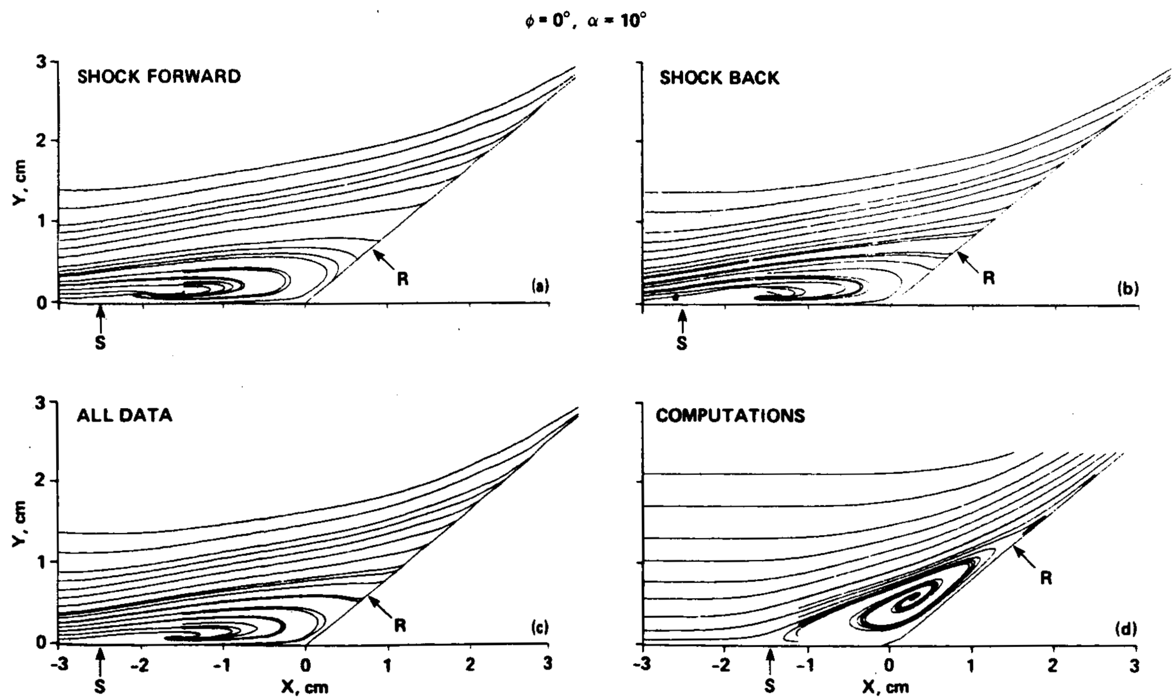


Figure 14. Particle paths over a skewed 30° axisymmetric compression corner from conditionally sampled laser velocimeter data and from a Reynolds-averaged, Navier-Stokes code computation.

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15. Supplementary Notes

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16. Abstract

The role of experiment in the development of Computational Fluid Dynamics (CFD) for aerodynamic flow field prediction is discussed. Requirements for code verification from two sources that pace the development of CFD are described for: (1) development of adequate flow modeling, and (2) establishment of confidence in the use of CFD to predict complex flows. The types of data needed and their accuracy differs in detail and scope and leads to definite wind tunnel requirements. Examples of testing to assess and develop turbulence models, and to verify code development, are used to establish future wind tunnel testing requirements. Versatility, appropriate scale and speed range, accessibility for nonintrusive instrumentation, computerized data systems, and dedicated use for verification were among the more important requirements identified.

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