Experimentalist's requirements for a safe methodology in CFD code validation

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Abstract

In spite of the spectacular progress in CFD there is still a strong need to validate the computer codes by comparison with experiments. The first validation step is the assessment of the code numerical safety and the physical models accuracy. This validation step requires carefully made building block experiments. To be calculable, such experiments must satisfy conditions such as the precise definition of the test set-up geometry, the absence of uncontrolled parasitic effects, a complete information on the flow conditions and indication on the uncertainty margins. Under these conditions, the experiment can be put into a database which will be precious to help in the development of reliable and accurate codes. The paper provides also an overview of modern measurement techniques allowing a precise and thorough description of complex separated flows. Recommendation for the constitution of experimental databases are provided as a conclusion.

Introduction

Methods for verifying the capability of a code to solve given equations have been the object of close examinations. Identification and elimination of various types of errors and use of precision criteria, methods for convergence testing, rules for establishing grid convergence, are all required when one has to assess the quality of the numerical tool. The various stages of the general process of verification that will give to the code a confidence label permitting to use it for testing theoretical models have been summed up by Roache with references to many authors[1]. The ERCOFTAC association has issued Best Practice Guidelines giving strict recommendations to asses code quality for industrial computational fluid dynamics[2]. The code verification process constitutes by itself a complex program often partially carried out but that should be completely satisfied in the ideal cases. A second step is devoted to the validation of models aimed at predicting flows that cannot be presentable as clearly identified solutions of well known mathematical problems. At this stage, comparison with experimental data is mandatory.

In the past, predictive methods were validated by comparison of the computed results with some measured global quantities, such as forces and moments, and with wall properties, namely the pressure and the heat-transfer for hypersonic applications. The skin friction was more rarely available, this quantity being difficult to measure (even now) in compressible flows. However, the flow prediction landscape has completely changed over the past 40 years with the advent of numerical methods solving the Navier-Stokes equations or approaches such as DSMC to predict rarefied flows. However, in their present state the CFD codes are still far from being free of critics, since many difficulties persist both on the numerical and physical sides. There is thus a strong need to validate CFD codes, more particularly from the physical point of view before their routine use for design purposes[3].

A comparison restricted to the wall properties is in general insufficient to validate the most advanced predictive methods. In particular, information on the Mach number, temperature, density fields is essential to elucidate the cause of discrepancies affecting, for example, the wall quantities distribution. Such a requirement is still more demanding in hypersonic flows where one has to represent complex thermo-chemical processes and/or strongly interacting and shock-separated turbulent flows. In this case, information on turbulence quantities is also needed, which is a formidable challenge in high Mach number flows! The prediction of shock/shock interferences which can have destructive effects on a nearby structure necessitates an accurate prediction of the complex structures resulting from shock intersection. The problem of code validation is crucial in three-dimensional applications where the Navier-Stokes approach becomes mandatory. Due to the complexity of such flows, it is clear that the consideration of the surface pressure alone is inadequate, this information giving a very partial view of the flow (in three-dimensional flows, it is no longer possible to infer separation from an inspection of the wall pressure distributions).

In these conditions, the validation of computer codes requires well documented experiments providing not only wall quantities but also flow field measurements. It is remarkable that the breakthrough in our predictive capacity has been paralleled by spectacular developments in measurement techniques over approximately the same period, mainly with the advent of laser based optical methods, optical techniques having operated a true revolution in our capacity to investigate flows containing shock waves, concentrated expansions, thin shear-layers and recirculating regions[4].

The validation methodology

Code requirements : reliability or accuracy?

Before considering a validation action, the aim of the calculation must be clearly stated.

- If calculation is used to predict the performance of a system or a sub-system, accuracy is mandatory.
- In the design of devices involving complex flows whose experimental simulation is not possible a calculation showing the flow field topology is of great help. In this case, accuracy is not essential, but reliability is crucial since one must be confident on the physical features of the computed field.
- The physical understanding of complex flows must be based on a theoretical analysis whose aim is to help in the interpretation of the phenomena and in the establishment of a consistent topological description. In this case, accuracy is not needed since theoretical analyses are most often derived from simplifying assumptions rendering quantitative results questionable.
- In the last issue, a code is used as a tool to test a new physical model. Then, numerical accuracy is mandatory since it would be vain to implement a good model in an inaccurate code.

The methodology different steps

The verification/ validation procedure has to be submitted to a four step methodology.

First step: Assessment of the code numerical accuracy. A conclusive assessment of this point is not a straightforward issue in the sense that the numerics involves many aspects. When possible, a first firm answer can be obtained from comparison with analytical solutions in laminar flow or well established empirical results. In turbulent flow, the question is not so clear since numerical and physical modelling problems are closely linked. Verification by confrontation with other codes is not always conclusive since the codes may use different numerical techniques, discretization schemes and solution algorithms. A further step is to run the code on a configuration for which reliable experimental results are available. This point is far less obvious that it would appear at first sight, since the experimental data should allow to draw clear conclusions.

Second step: Validation of the physics implemented in the code on elementary configurations. This is the most important point for the specialist in flow physics, the first step being only a preliminary step simply aiming at verifying the tool. In the second step, the code is used to compute what can be considered as the elementary components of an aerodynamic flow: attached boundary layer, laminar-turbulent transition on a flat plate, separation induced by an obstacle, flow past a base, shock wave/boundary layer interaction, start and development of a vortex structure, vortex breakdown, shock/shock interference or shock crossing, etc. Two-dimensional - preferably axisymmetric - as well as three-dimensional basic situations have to be considered. For this first validation step, the numerical results are compared with *building block* experiments focusing on a specific elementary phenomenon.

Third step: Validation on more complex sub-systems. Once the code and its physical model(s) have been validated on basic cases, a more complete configuration must be considered consisting in a sub-system of a complete vehicle, where several elementary phenomena are combined. This is the case of a profile on which one encounters laminar-turbulent transition, attached boundary layers, transonic shock wave/boundary layer interaction, separation, wake development, etc. The wing constitutes a three-dimensional extension with the additional problems of the vortices emanating from the wing and control surfaces extremities. The supersonic air-intake involves shock/shock interference, shock wave/boundary layer interactions, corner flows with vortex development. After-bodies combine supersonic jets with complex shock patterns (Mach disc formation), shock induced separation, either inside the nozzle (overexpanded nozzle) or on the fuselage (jet pluming at the exit of an underexpanded nozzle). Many other examples can be cited: propulsive nacelle, compressor/turbine cascade, helicopter rotor, etc.

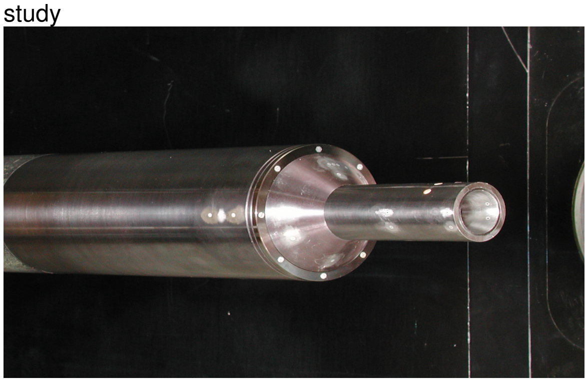
Fourth step: Validation on the complete vehicle or object. This is the ultimate target in which the code is applied to a complete vehicle.

Each of the above steps implies an iterative procedure between computation and experiment to adapt or correct the code from inspection and interpretation of the discrepancies between the computed and experimental results. This exercise is not entirely safe for the experimentalist, since a persistent discrepancy may be due to measurement errors or ill defined experimental conditions.

Requirements for good test cases constitution

Definition of the geometry. A first condition for an experiment aiming at code verification/validation is to focus on a configuration whose geometry is representative of a typical situation, precisely defined and as simple as possible while avoiding singularities leading to meshing difficulties. When possible, an analytical definition of the contour should be provided. It is preferable to give the dimensions in metric units to avoid risk of confusion in the reference length used to compute a Reynolds number. When possible, a two-dimensional geometry should be adopted - even for three-dimensional problems - since it offers many advantages to visualise the phenomena and to execute measurements, in addition of the lower cost of the test-set up fabrication. Furthermore, the original set-up must frequently be modified before arriving at a fully satisfactory flow; such modifications are far easier on a two-dimensional/ axisymmetric arrangement. Two typical models are shown in Fig. 1.

a – double cone model for hypersonic separation study



b – Axisymmetric model for powered base flow Investigation

Fig. 1: Two typical simple models for code validation purposes

The first one is a double cone configuration used to produced shock-induced separation at high Mach number, the second one is a model used to validate codes predicting the flow past an axisymmetric afterbody equipped with a propulsive jet.

Boundary conditions. The boundary conditions must be well identified and accurately known. This concerns the upstream flow conditions (Mach number, velocity, pressure, density) when a uniform incoming flow exists. In transonic experiments executed in a channel type arrangement, one often considers phenomena taking place on the channel walls, the test section itself being the model. In this case, a well defined origin with a uniform state at upstream infinity does not exist. Then, the data should provide all the flow conditions in a section located sufficiently far upstream of the region of interest, including the boundary layer properties (mean velocity profile, turbulent quantities). If LDV measurements now permit to know with a good approximation the Reynolds stress profiles in moderate supersonic flows, a method must be conceived for deducing from these data the dissipation rate of two-equation turbulence models.

In all cases the stagnation conditions (pressure, temperature) and the incoming stream thermodynamic properties must be given. Downstream boundary conditions leading to a well posed problem must be provided. If the flow leaving the zone of interest is supersonic, then no-conditions have to be imposed to perform the calculation. The question of the downstream conditions is more delicate if the configuration is such that the flow leaving the test region is subsonic. When the outgoing flow is again uniform, most often a downstream pressure is given, since this quantity is easily obtained. It is far more difficult to provide the pressure field in a complete plane, as some theoreticians sometimes ask for. In transonic channel experiments where a shock is produced by the choking effect of a second throat, the best way is to provide the geometry of the second throat and, in the calculation, to impose downstream conditions insuring the choking of this throat. The photograph in Fig. 2 shows a test set-up which has been extensively used to analyse shock wave/boundary layer interaction in a transonic channel[5]. The entrance of the test section has a converging-diverging upper wall constituting a first sonic throat. At this location, the flow conditions, including the boundary layer profiles, are provided. In the present arrangement, an oscillating shock is produced by a rotating shaft placed in the downstream part of the channel. The shaft has also a choking effect, thus providing well defined downstream conditions.

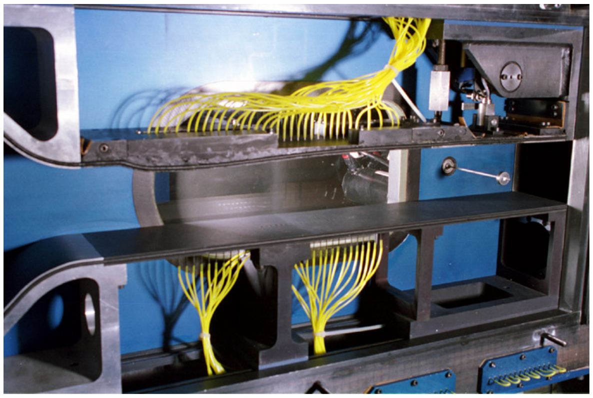


Fig. 2: Test set up arrangement for transonic interaction studies

Parasitic effects. Side effects or uncontrolled perturbations must be avoided, except if they can be taken into account by the calculation. The side effects due to the finite span of any experimental arrangement strongly affect the flow when separation occurs. Then, the experimented flow can be very different from the assumed ideal two-dimensional flow which would correspond to the infinite span condition.

Fig. 3: Surface flow pattern in a nominally 2D transonic channel (IMP/PAM document)

As an illustration Fig. 3, shows a surface flow visualisation realised in a nominally two-dimensional transonic channel. In the vicinity of the side-walls, two foci which are the traces of two tornado-like vortices are clearly visible. Confrontation of such an experiment with a planar two-dimensional calculation can be deprived of any signification and lead to erroneous conclusions. When the boundary layer is attached or weakly separated this effect is small and 2D calculations remain acceptable. If one desires to keep the mathematical simplicity of two space dimensions, the best is to compute an axisymmetric flow, as the one past the hollow cylinder-plus-flare model shown in Fig. 4, which has been much used to validate both laminar and turbulent shock wave/boundary layer interactions[6]. Even in this case, the flow adopts a three-dimensional structure at a "microscopic" scale, as it can be seen in the surface flow pattern in Fig. 5.

Fig. 4 : Hollow cylinder-plus-flare model for axisymmetric flow investigation

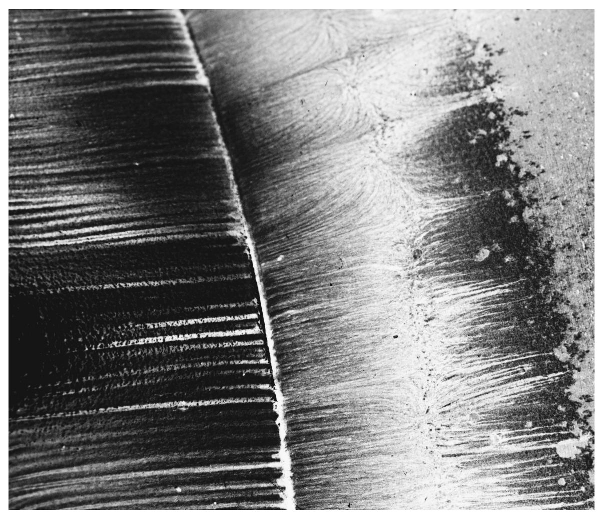


Fig. 5 : 3D micro structures in an axisymmetric reattachment region

When the goal of an experiment is to reproduce closely the behaviour of an aircraft, the coincidence of the wind tunnel's Reynolds number with that of real flight tests is a condition often hard to satisfy. Even if this condition is fulfilled, premature transition can occur on the model. The boundary layers on the walls of classical wind tunnels are generally turbulent and unsteady perturbations radiate from the wall to the whole test channel. Such perturbations lead to transition of the flow around the model at Reynolds numbers significantly lower than those where it occurs in real flying tests. The conception of quiet wind tunnels, at NASA, ONERA and Purdue University[7], has been undertaken to overcome this difficulty. Inversely, when a plainly turbulent regime is searched for code validations, it is preferable that the wind tunnel be naturally turbulent without the help of auxiliary means like transition strips. The transition in general is indeed far from being treated satisfactorily by the methods of calculation presently at our disposal and transitional effects are often present when turbulence is set up artificially.

Experimental needs. The description of the flow must be as complete as possible to provide all the information useful to understand its physics and to help in the elucidation of disagreements. Flow visualisations are desirable to give a precise idea of the flow topology. Surface flow visualisations are mandatory in three-dimensional flows to indicate the location of separation/attachment lines.

Measurements reliability and accuracy. The experimental data must be reliable, which means that the experiment is not "polluted" by an extraneous phenomenon due to a bad definition of the test arrangement or an ill functioning of the facility. The risk is at its maximum when such an influence has not been identified and is interpreted as a proper basic feature of the flow under investigation. Measurements must be safe, as for the calculations, this aspect being distinct from the problem of accuracy which must also be carefully assessed. Measurement accuracy must be in proportion with the calculation purposes and the modelling present status. Precision has a very high cost; in most circumstances what is important is to be confident in the experimental results and to known (even approximately) the uncertainty margins.

The physical interpretation. Constitution of safe data base is not restricted to the execution of hopefully good experiments in relation with code development. The experimentalist must also be a physicist able to interpret its findings and to understand the physics of the investigated flow field. This interpretation, which must be based on theoretical arguments, is essential to insure the safety of the results. It must precede any numerical exploitation.

The above conditions lead to reject of a large quantity of existing experiments for validation purposes. In particular, nearly all the two-dimensional ramp flow experiments have to be considered with suspicion when separation occurs. Also, in a large number of published experiments some information is missing to execute the calculation or the boundary conditions are not *clean* in the sense that the conditions on the frontiers of the zone of interest affect the phenomenon in a complicated and unclear manner. In the present context, any experiment should satisfy a *calculability* criterion meaning that the experiment is not useful if it cannot be calculated.

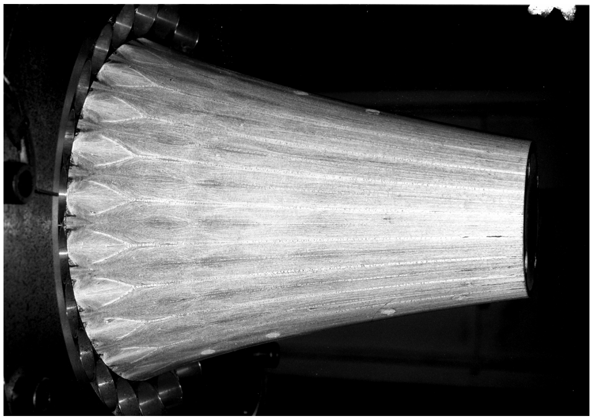
Validation of experiment by calculation. Calculation is also used by the experimentalist to control his results. There are simple situations where theory can be considered as safe and accurate, so that a good way to check a new experimental method is to compare its results with the theoretical ones. In situations where the calculation cannot be considered as entirely safe, an important, persistent and unexplained discrepancy should provoke a reconsideration of the experimental results. In hypersonic flows, measurements executed with optical techniques like Laser Doppler Velocimetry (LDV), Coherent Anti-Stokes Raman Scattering (CARS), Electron Beam Fluorescence (EBF) have been in great part validated by comparison with theoretical results, no other techniques being available to perform such measurements.

An overview of modern measurement techniques

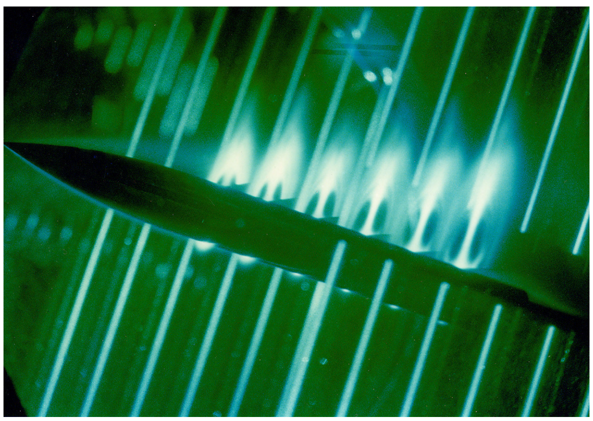
The purpose of this section is to briefly present modern measurement techniques which are used (or could be used) to investigate complex flows, mare particularly at high Mach number. The classical and well proven methods will not be mentioned, even if they are still routinely used!

Flow visualisations

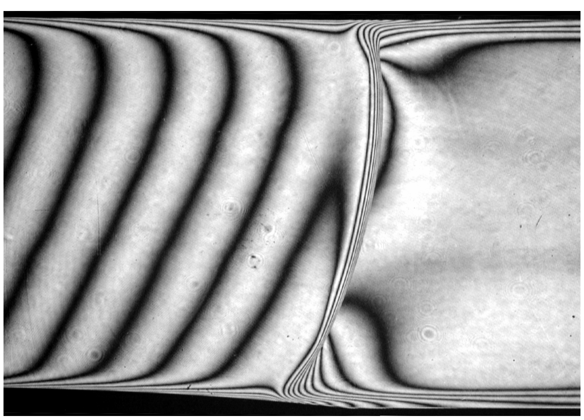
Fortunately, most flow phenomena can been visualised, which is a great help for their physical understanding and modelling[8]. Flow visualisations must be attempted in all circumstances where they are possible, specially on three-dimensional configurations for which they are nearly mandatory. The first step consists in making a visualisation of the surface flow pattern in order to localise the critical points that it contains and the accompanying separation/ attachment lines[9]. The photograph in Fig. 6a shows the complex surface flow pattern produced by the impingement on the central body of the 24 primary jets of a plug nozzle. Flow field visualisation can be achieved by several techniques, including the laser sheet method (both in low and high speed streams, see Fig. 6b), shlieren, shadowgraph of interferometry in compressible flows (see Fig. 6c), electron beam fluorescence (EBF) in low pressure high Mach number flows (see Fig 6d). Particle Image velocimetry (PIV, see below) can also be considered as a sophisticated visualisation method for separated flows.



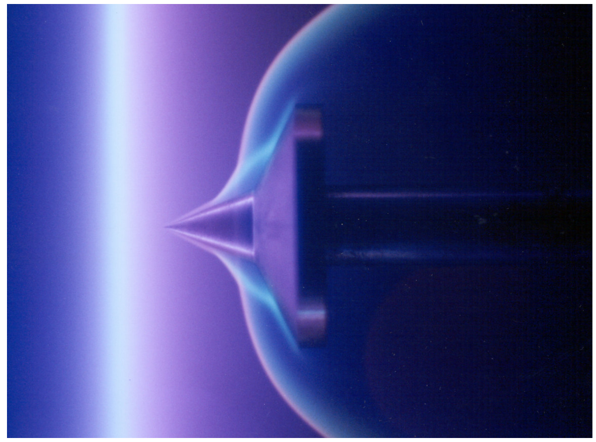
a – surface flow on the central body of an aerospike nozzle



b – laser sheet visualisation of the vortices past an elongated body



c – interferogram of a transonic shock wave



d - EBF visualisation of the flow past a double code model at Mach 10

Fig. 6: Different techniques of flow visualisation

Wall measurements

Pressure Sensitive Paint. This method (known as PSP) which allows to determine the complete pressure distribution over a model, is based on the fact that some compounds emit light (luminescence) when excited by a suitable source, the emitted light having a longer wave-length than the excitation light[10,11]. The quantity of light emitted depends on the oxygen diffused into the paint because oxygen quenches and deactivates the excited molecules. The internal concentration of oxygen being a linear function of the external pressure of the same gas, one can measure the pressure acting on the paint by detecting some of its luminescent parameters. A difficulty with PSP's is their simultaneous response to change in temperature, which could restricts their use in hypersonic flows. The difficulty can be circumvented either by using a paint nearly insensitive to temperature or by making a correction from measurement of the wall temperature. Convincing PSP measurements have been performed at high Mach number on a plug nozzle with a PSP component having a low sensitivity to temperature[12] (see Fig. 7).

Skin-friction measurement. In a recent technique, the skin-friction is determined by measuring the rate of deformation of a thin oil film deposited on the model surface[13-15]. If the film of oil is thin compared to its length, its surface takes the shape of a small wedge whose thickness y at any time t can be accurately measured by an interferometric technique (see Fig. 8). Knowing the location x of the measurement point and the time t, the determination of the wall shear stress is in principle straightforward.

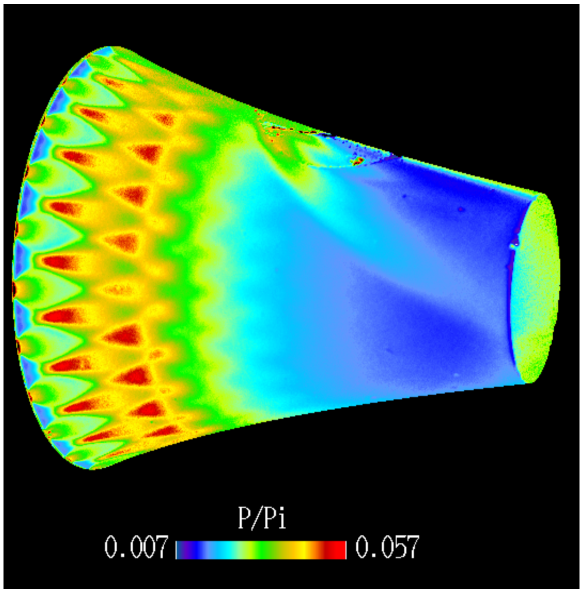


Fig. 7: PSP measurements on a plug nozzle central body

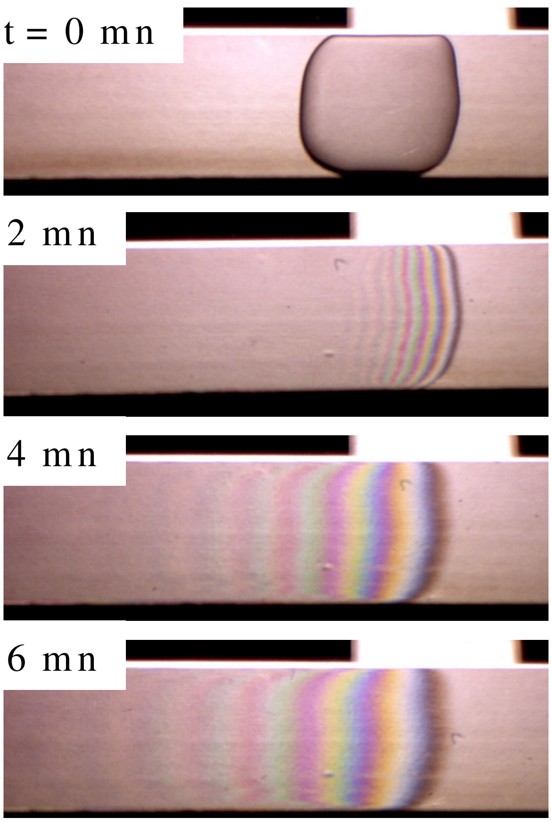


Fig. 8 : Skin friction measurement by the thin oil film technique

Heat flux measurements. Over the past 20 years, quantitative infrared thermography has experienced a strong development in a large number of laboratories[16-18]. As it is well known, a body emits a radiative signal whose intensity is a strong function of its temperature. In infrared thermography, the model is observed by an infrared camera containing a detector element sensitive to infrared radiations at a certain wave-length. By processing a series of pictures taken at known time intervals, it is possible to construct the time history of the model temperature and to deduce the surface heat flux distribution by means of the heat equation. The example of infrared image (in false colour) in Fig. 9 shows the heat flux distribution on a hemisphere in a Mach 5 flow. Infrared pictures also provide a convenient way to detect laminar-turbulent transition.

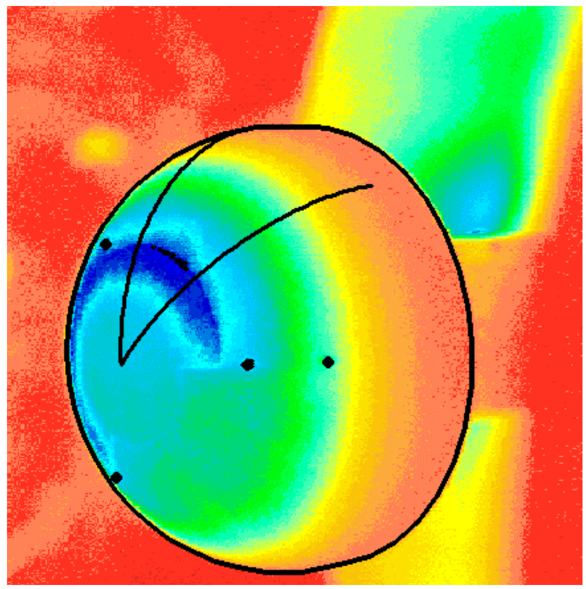


Fig. 9: Infrared measurements of the heat flux distribution over an hemisphere in a Mach 5 flow.

Field measurements

Measurement of field quantities such as velocity, temperature, density, gas species concentration,etc is a difficult task. However, the advent of laser sources in the early 60s has given a dramatic impetus to the development of non intrusive methods allowing an in-situ determination of the properties of a gas, including its velocity

Laser Doppler Velocimetry

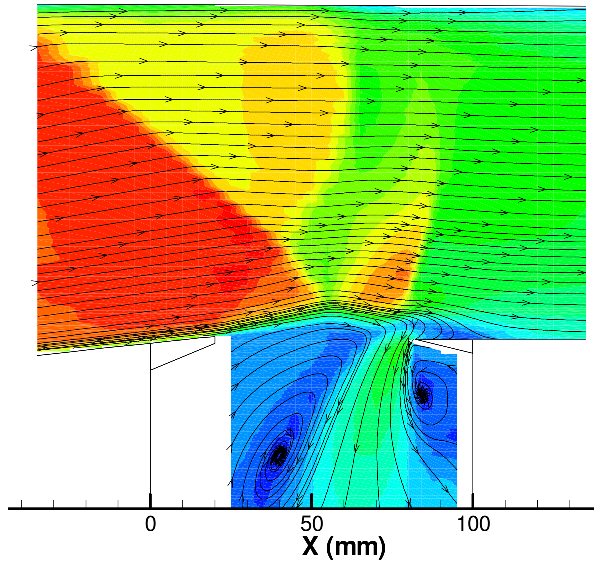
The basic idea underlying LDV, which is now a well known technique, is to measure the velocity of tiny particles transported by the flow[19-21]. If these particles are small enough, their velocity is assumed to be that of the stream and LDV provides a measure of the local instantaneous velocity. A statistical treatment of a sample acquired at one point permits to determine the mean velocity as well as the turbulent quantities. The basic postulate of LDV is not always true in highly decelerating or accelerating flows in which the particles do not instantaneously adjust their velocity to that of the fluid. The problem of particle lag is at the heart of LDV and one should be cautious in the use of results obtained in regions where the velocity undergoes a large variation over a short distance, situations frequently met in hypersonic flows. Reliable LDV measurements have been obtained in shock-separated flows up to Mach number 5; above measurements become hazardous.

Developed since 1991, Doppler global velocimetry (DGV) - also called planar Doppler velocimetry (PDV) - is a particle based velocity measurement system giving the velocity of particles injected in the flow, as LDV. The difference is that LDV determines the velocity at one point in space, whereas DGV has the capacity to give the velocity at a multitude of points in a given region of space[22-24]. The basic principle consists in determining the Doppler shift of the light scattered by a moving particle.

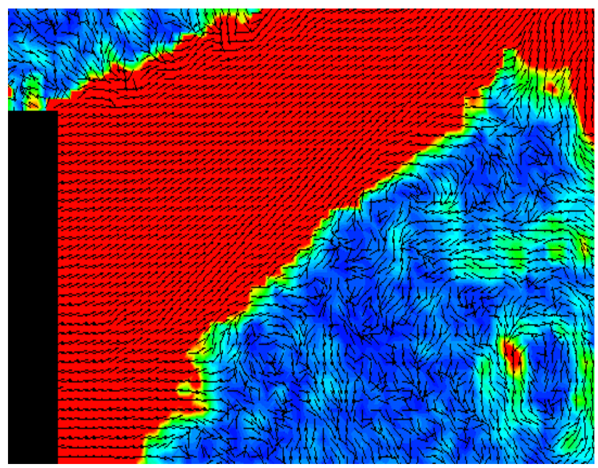
Particle Image Velocimetry

The principle of PIV is to illuminate particles injected in the flow by a laser sheet and to observe the scattered light[24-26]. In order to perform velocity measurements, two laser pulses, separated by a short and known time interval Δt, are emitted to provide two images recorded on the same photographic plate (in practice, the photographic plate is replaced by a CCD camera providing the image in a numerical form). During the interval Δt, each particle has moved over a distance proportional to its velocity (assumed to be that of the flow) giving two images on the plate. The velocity components contained in the plane of the image are deduced by measuring the displacement of the particles which is done by automated procedures using sophisticated algorithms.

Particle image velocimetry is a very powerful technique since it provides a complete velocity field in a large number of points for a whole region of space, whereas LDV is restricted to measurements at one point. PIV is very precious for the study of unsteady phenomena since it allows to freeze the velocity field at a given instant. On the other hand, the access to the averaged field quantities (mean velocity) necessitates to operate an averaging procedure over a large quantities of pictures. This can become problematic for the Reynolds tensor components whose determination requires averaging several thousands of instantaneous values. In this case LDV if still more effective (see in Fig. 10a an average LDV velocity field in the vicinity of the bleed system of a supersonic air-intake and in Fig. 10b, the instant PIV velocity field in a rotating jet).



a – LDV measurement in the bleed region of a supersonic air intake (average Mach number)



b – PIV velocity field in a rotating jet

Fig. 10: Velocity measurements by laser techniques with flow seeding

Laser Spectroscopic Flow Diagnostic

These methods are based on fundamental physical processes related to the interaction between light and matter an do not need seeding by heavy particles of relatively big size. Laser spectroscopic measurements are based on the radiative interaction of a laser beam with spectroscopic properties of the investigated flow. Depending on the interaction process, the laser light is either absorbed or scattered by those species which are radiatively active at wave-length used.

The measurements are made on selected populations from which it is possible to deduce the local gas properties. The intensity of the radiative signal gives a measure of the species concentration (or atom/molecule number density). The temperature is most often deduced from the broadening of a spectral line due to the Doppler effect induced by the motion of the atoms or molecules (the energy contained in this motion being proportional to the square root of the translational temperature). The velocity of the flow is deduced from the shift of the central frequency of the signal coming from the Doppler effect produced by the bulk motion of the gas. Rotational and vibrational temperatures can also be deduced from an analysis of the reactive signal.

Laser absorption. In this technique, the laser beam is tuned to a wave-length which is resonant with an absorbing transition of a selected species. The attenuation of the beam passing through the test region is measured, the absorption of two or more wave-lengths being used to determine both the gas temperature and the density of the absorbing species. This technique is simple to implement since it requires an optical access which is just sufficient to allow the laser beam to pass through the test region. Production of a detectable and usable signal does not depend on the laser power, so that small power lasers can be used.

Among these methods, the *diode laser absorption* technique consists of illuminating a transverse section of the gas to be studied by an infrared light beam[27,28]. Doppler broadening and shift in wave-length of the species absorption lines is used to obtain a measure of translational temperature and flow velocity

Rayleigh scattering. In Rayleigh scattering the light from a laser beam is scattered at nearly the same frequency as that of the incident light. By measuring the intensity of the scattered light and its spectral properties, it is possible to determine the density, pressure and velocity of the gas. Rayleigh scattering is probably the simplest method giving a local measurement of flow properties, since it does not rely on any spectral resonance of a seed material (see LIF below). On the debit side, the method lacks spectral difference between the light scattered by the gas and the background light so that it is difficult to distinguish the useful signal from parasitic light.

Raman scattering. When a photon strikes a molecule, it leaves a fraction of its energy to the molecule which is then raised to a higher energy state. When de-excitation occurs, a photon is released which has a longer wave-length, or lower energy, than the incident photon. This process is called Raman Stokes scattering. The scattered light has a spectrum whose frequencies are characteristic of the molecule. Thus, analysis of the emitted spectrum constitutes a way to measure the vibrational and rotational temperatures in this particular state. Species concentration is determined from the amount of light contained in a certain narrow spectral band.

If the photon emerges from the interaction at a shorter wave-length, hence higher energy, the process is called Raman Anti-Stokes scattering. This scattering process takes place with molecules of a higher energy level whose relative number is small; thus the Raman Anti-Stokes signal is naturally fainter than the Stokes signal. Raman signals are at a wave-length different from that of the laser and consequently are affected very little by background scattering. In addition, the Raman effect is an interaction driven by the radiation field and, for this reason, is not affected by collisional quenching (see below). The disadvantage of the technique is that the signal is very weak and that the laser beam is scattered in all directions of space. In order to eliminate this serious disadvantage, stimulated Raman spectroscopy has been developed.

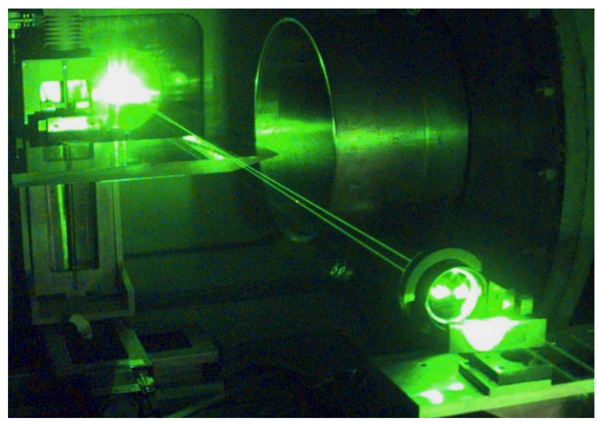
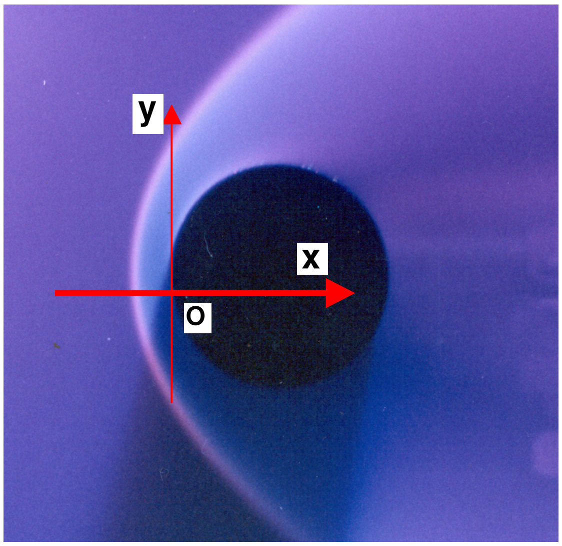
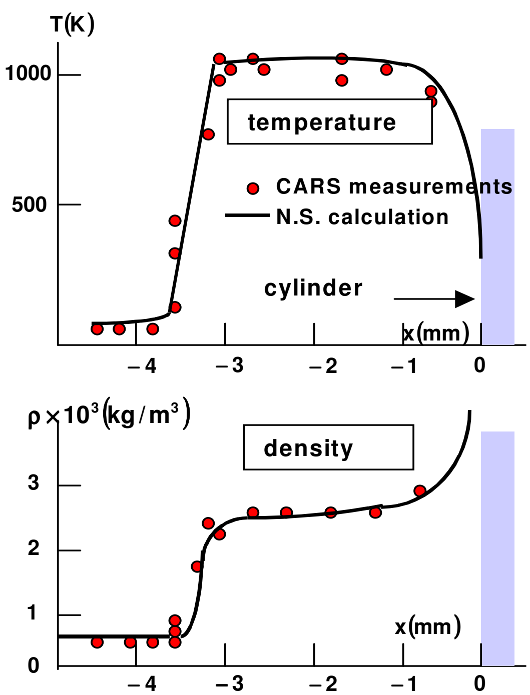


Fig. 11: CARS measurements in a hypersonic wind tunnel

Stimulated Raman scattering. This technique is analogous to spontaneous Raman scattering, the scattering being produced by a first laser called the pump laser. The system now includes a second laser, the probe laser, whose frequency is shifted so that the differences in wave-length with the pump laser matches a resonant frequency of the molecule. This arrangement is used in Coherent Anti-Stokes Raman Scattering (CARS) in which measurements are made with the Anti-Stokes radiation[29] (see Fig. 11). The main advantage of CARS is that the scattering cross section is much higher than that of the spontaneous Raman effect by several orders of magnitude. In addition, the emitted light leaves in a preferred direction defined by the directions of the incident beams. Thus, the useful light is collected more efficiently than in ordinary Raman scattering. Analysis of the CARS signal allows the determination of the nature of the species, of their concentration, temperature, etc. Also, the gas velocity can be determined from Doppler shift. There are several variants of CARS, for example in Dual Line CARS (DLCARS) four beams are used to excite two energy levels of the studied molecule which allows a more direct determination of the density and temperature of the gas[30].



a – EBF visualisation of the flow



b – density and temperature distributions

Fig. 12: DLCARS measurements in front of a cylinder at Mach 10

Density and temperature measurements by DLCARS in front of a cylinder placed in a Mach 10 flow are shown in Fig. 12, along with a comparison with a Navier-Stokes calculation which was used here to validate the measurements.

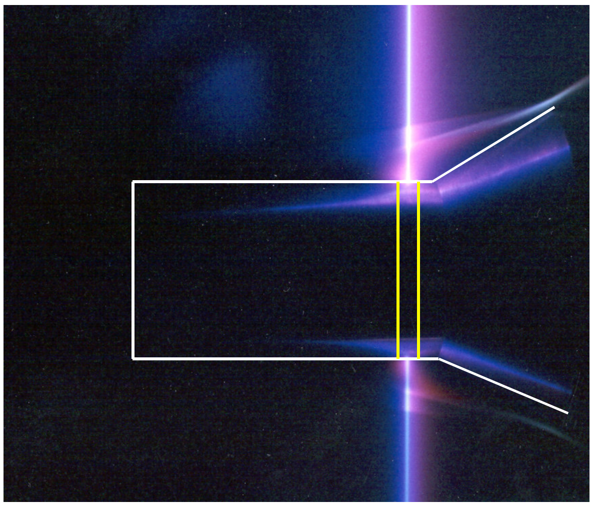
Laser induced fluorescence. In Laser Induced Fluorescence (LIF) the measured signal is obtained from the subsequent spontaneous emission of absorbed energy or fluorescence[31]. In this process, the emission takes place after a relatively long time, several seconds in some cases, whereas in other types of interaction emission occurs after 10^{-8}s for most molecules. Due to this long relaxation time, the signal analysis must consider the effect on some species of non-radiative energy transfers taking place through collisions between molecules (quenching). Quenching depends on temperature and species concentration. Proper operation of LIF requires the presence of species For aerodynamic research in non reacting fluids, the flow is seeded with a small concentration of sodium, iodine, nitric oxide, acetone, etc.

Fluorescence properties are also used to obtain a picture of an entire flow region by using planar laser induced fluorescence (PLIF)[32]. In this technique, the zone of interest is illuminated by a laser sheet and the fluorescence picture recorded by a camera containing a two-dimensional array of photo-detectors.

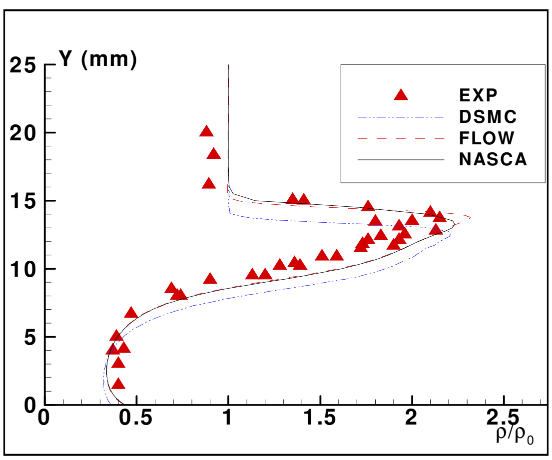
Electron beam fluorescence

Electron Beam Fluorescence (EBF) is a well-established technique to perform local and non intrusive measurements of density, vibrational and rotational temperatures in a low density flow of nitrogen or air[33]. The technique is based on the formation of N_2^+ excited ions by an energetic electron beam (typically 25keV energy) traversing the flow. The almost immediate drop to a lower energy state gives rise to fluorescence whose intensity is proportional to the density. At high densities, quenching destroys the linearity of the response. Tomographic imaging with a sweeping electron beam creating a visualisation plane is a classical application of EBF (several examples are shown in this paper). The photograph in Fig. 6d is an EBF visualisation of the flow past a double-cone model. In this case, the electron beam is fixed, the visualisation being obtained by post-luminescence.

Density measurements using electron-beam-excited X-ray detection. In order to obtain quantitative density results, even when quenching occurs, a variant based on the detection of *brehmstrahlung* and characteristic X-rays can be employed[34-36]. These X-rays are emitted by electrons which are decelerated when passing close to an atom. The method has the advantage that the signal is emitted instantly and shows no collisional quenching. The X-ray radiation at the point of measurement is collimated and detected with X-ray counters equipped with preamplifiers. The photograph in Fig. 13a shows the electron beam used to perform X-rays measurements on a cylinder-flare configuration (see below). The beam traverses the model (though a small tube) to avoid the intense X-rays production which would result from the impact of the beam on the surface. Density profiles obtained in the interaction region are compared to Navier-Stokes and DSMC calculations in Fig. 13b.



a – EBF visualisation of the flow and electron beam



b – comparison between computed and measured density profiles

Fig. 13: Measurements by X-rays detection in a laminar shock-separated boudary layer

Velocity measurements using an electron-beam-assisted glow discharge. This technique uses a miniature pseudo-spark type electron gun to perform velocity measurements through a time of flight principle. The miniature pseudo-spark developed at Onera generates an intense pulsed electron beam, emitted by an electron gun[27,37] which penetrates within the flow from a hole across the surface of the model and traces the path of a high voltage glow discharge in some 10ns. At a precise delay time (5µs) after the electron gun actuation, a CCD camera is opened briefly (250ns) to image the position of the luminous column convected by the flow. The local velocity of the stream is deduced from the horizontal displacement of a given point during the selected delay time.

Unsteady flow qualification

A greater attention is now paid to flow unsteady aspects, since unsteadiness is intrinsically linked to any phenomenon (the steady state is as illusory as 2D assumption!) and since flow fluctuations can generate vibrations, noise and other disagreements. The discovery of flow fluctuations is not new, but now there exist CFD methods in measure to compute unsteady flows with increasing accuracy. One can cite the URANS (Unsteady Reynolds Averaged Navier-Stokes), LES (Large Eddy Simulation), DES (Detached Eddy Simulation), DNS (Direct Numerical Simulation) approaches In parallel to this progress, there is a need for more complete and more accurate descriptions of typical unsteady flows to validate the codes.

Instant visualisations (schlieren, shadowgraphy) coupled with high speed cinematography are precious to “follow” the fluctuating phenomenon. The local velocity fluctuations (in particular turbulence) are classically measured with hot-wire anemometry in conjunction with unsteady pressure measurement at the wall with appropriate transducers. PIV is a precious tool to obtain an instant picture of the flow field showing the large structures generated by separation (see Fig. 10b). A sequence of such pictures allow to follow the structures in space and time (in fact, the time interval between two consecutive pictures is still too long for rapid phenomena but rapid progress is made in the field). As we know, LDV gives the instant velocity at one point which provides the Reynolds tensor components by suitable averaging. If the unsteadiness is driven by a periodic mechanism (like in transonic shock oscillation, cavity flow or air-intake buzz), conditional sampling and appropriate processing permits to establish the organised motion from local instant measurements (hot-wire, LDV).

Database constitution

Constitution of a database is not a straightforward operation. In addition of technical skill to fabricate a test set up, to operate the wind tunnel and execute the experiment, to perform the measurements, it requires a solid background in fundamental fluid mechanics. The database constitution is not limited to the acquisition of a vast amount of results, but must be accompanied by an in depth analysis of the flow physics. Because of the investment needed by such operations and their strategic importance for the development of predictive methods, the question of the database test cases dissemination inevitably arises. It is now realised that a good database can be as precious as a code and cannot be freely transmitted. Even basic experiments have now an economic weight and cannot be put on the market without something in exchange. Thus, dissemination rules have to be more precisely defined according to the more or less precious nature of the database contents.

In addition of the permanent scientific concern about more accurate, safer and less expansive predictive methods, the problem of the constitution of valuable, safe, well identified and permanent databases is now considered as a strategic issue and addressed seriously. In this perspective, the ONERA Fluid Mechanics and Energetic Branch has started the constitution of a database containing the most prominent experimental results obtained in its research wind tunnels of the Meudon-Centre over the last 30 years[38]. This task will be actively pursued and the database contents fed with new experiments satisfying the quality criteria here above defined. At the European level, the ERCOFTAC association has constituted a database containing 82 test cases, stored by the University of Surrey, which can be obtained through the ERCOFTAC website[39]. In the framework of the FLOWNET European-Union project a database has been constituted which can be accessed through the INRIA website[40]. Thus, several national and international initiated have been initiated in the past years to build complete, well documented and safe databases in order to help in the development of accurate predictive methods both for research end industry.

Concluding Remarks

The confidence in code predictions is still limited because of the uncertainties in the numerical handling of the equations and of the lack of accuracy of the physical models implemented in the codes. This is particularly true in separated high Mach number flows which contain both intense shock waves, thin shear layers, separated regions (laminar, transitional and turbulent) and are affected by real gas effects. A consequence of the intense development of the CFD activity has been to urge experimentalists to execute more complete experiments, including the definition of all the flow properties. This demand has motivated an important effort to develop advanced and non intrusive methods for detailed flow investigation, such as PSP, infrared thermography, LDV, DGV, laser spectroscopic diagnostic techniques, etc.

Thus, during the past years a strategy has emerged to organise more efficiently the dialectics between computation and experiment. To validate their codes, numericians need an as complete as possible information on some representative test cases. This information constitutes what is called a database which must respect certain rules to be useful. Thus, the database must contain a precise description of the configuration, along with all the necessary flow and boundary conditions. The measurements must be considered as safe, and if possible accurate, these objectives being difficult to reach in hypersonic facilities because of the extreme flow conditions and the short useful test duration. Uncertainty margins must be provided in order to allow meaningful conclusion on the accuracy of physical models.

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