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A CFD Validation Challenge for Transonic, Shock-Induced Separated Flow: Approach and Metrics

Steven J. Beresh,[1] Matthew F. Barone,[2] Kevin J. Dowding,[3] Kyle P. Lynch,[4] Nathan E. Miller,[5] and Blake Lance[6]
Sandia National Laboratories, Albuquerque, NM, 87185

A blind CFD validation challenge is being organized for the unsteady transonic shock motion induced by the Sandia Axisymmetric Transonic Hump, which echoes the Bachalo-Johnson configuration. The wind tunnel and model geometry will be released at the start of the validation challenge along with flow boundary conditions. Primary data concerning the unsteady separation region will be released at the conclusion of the challenge after computational entrants have been submitted. This paper details the organization of the challenge, its schedule, and the metrics of comparison by which the models will be assessed.

Introduction

The need to establish the accuracy and reliability of numerical simulations for engineering applications has resulted in increased attention to the validation of computational models. Such needs inspire experiments designed specifically to provide data for an unambiguous comparison between experimental and numerical results, as well as to aid the evolution of the underlying physical models. Past efforts have shown that most existing data sets do not meet the rigorous criteria necessary for such validation activities, and therefore it has been recommended that experiments should be conducted explicitly for this purpose, providing not just the main body of data but also the ancillary information necessary for complete specification of the simulation [1-3]. The mathematical closure of the computation requires provision of boundary conditions appropriate to the problem [4-5], and thus reasonable agreement between simulation and experiment cannot be expected without some knowledge of the physical environment in which the experiment resides. This is the principal failing of most archival data sets that otherwise could be employed for validation purposes [3].

A clear example of this is the Bachalo-Johnson experiment conducted in the early 1980's [6,7]. They performed measurements at a high subsonic Mach number over an axisymmetric hump on a cylindrical body, designed to produce an unsteady shock-induced separation. The flow becomes supersonic near the apex of the hump, forming a weak shock that imposes an adverse pressure gradient onto the incoming boundary layer. This causes it to separate, forming an unsteady separation bubble downstream of the hump which later undergoes an unsteady reattachment. A sense of the flowfield can be obtained from Fig. 1, which shows the shock-induced separation region behind the axisymmetric hump of the Sandia revision of the Bachalo-Johnson configuration, described below. These data were measured using PIV [8] and have their axes and contour labels removed to avoid releasing relevant information prior to the validation challenge.

The physics encompassed by the experiment are applicable to a wide variety of aerospace applications, including aircraft wings at cruise condition, engine inlets, and deflected control surfaces. This experiment has been widely used as a source of validation data (e.g., [6,9,10,11]), owing to its relatively simply geometric representation of a complex

[1]Distinguished Member of the Technical Staff, Engineering Sciences Center, AIAA Associate Fellow, correspondence to: P.O. Box 5800, Mailstop 0825, (505) 844-4618, email: sjberes@sandia.gov
[2]Principal Member of the Technical Staff, Engineering Sciences Center
[3]Distinguished Member of the Technical Staff, Engineering Sciences Center
[4]Senior Member of the Technical Staff, Engineering Sciences Center
[5]Senior Member of the Technical Staff, Engineering Sciences Center
[5]Senior Member of the Technical Staff, Engineering Sciences Center

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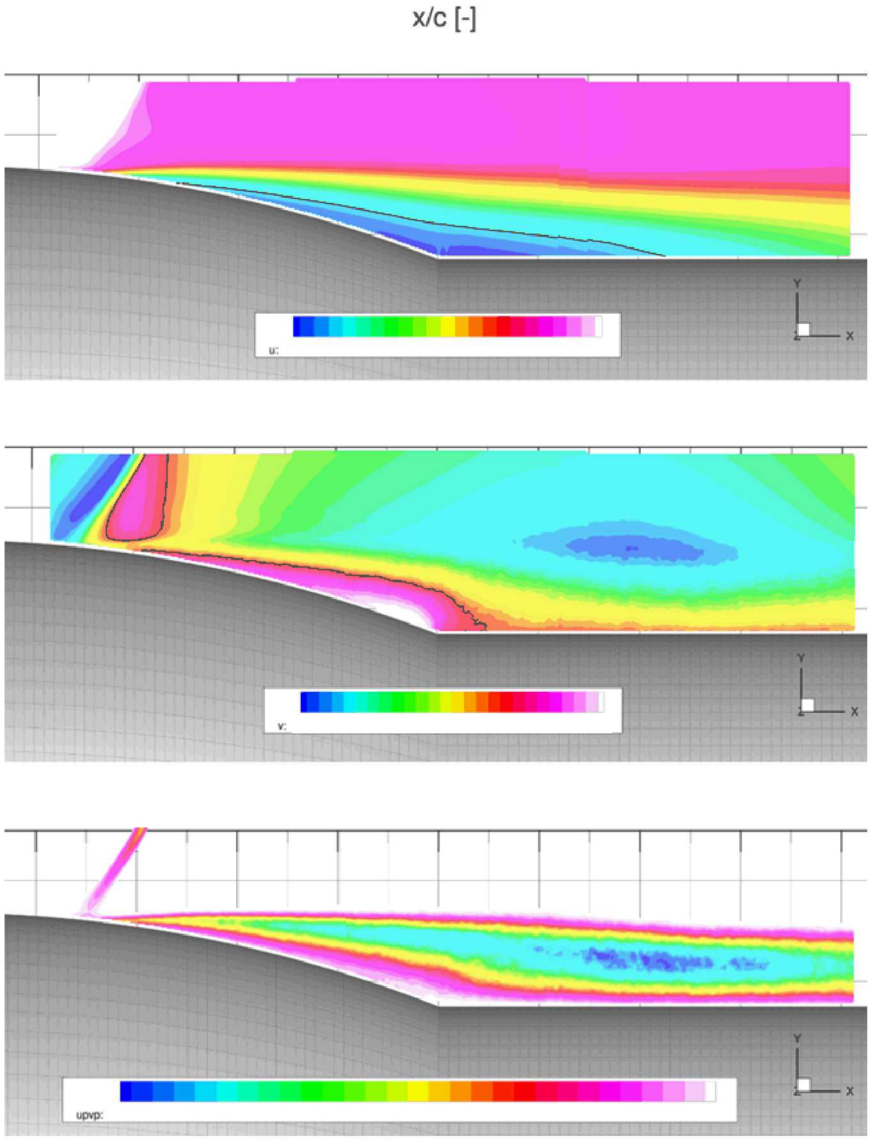

Fig. 1: Time-averaged PIV measurements in the separation region of the Sandia axisymmetric transonic hump model. Top, *u* (streamwise) velocity. Middle, *v* (transverse) velocity, Bottom, *u'v'* Reynolds stress. From [8].

compressible fluid dynamics problem with important flight relevance. Yet, the experiment suffers some deficiencies as a validation experiment. The geometry of the wind tunnel model contains ambiguities as described in the literature and boundary conditions are incompletely defined. Lack of skin friction measurements complicates analysis and interpretation of model deficiencies in prediction of other quantities, such as the surface pressure distribution. The porous-wall boundary condition is difficult to prescribe such that it can be replicated computationally. The Reynolds number based on chord length is too high for current Direct Numerical Simulation capability. In addition, modern diagnostics offer an opportunity to probe the flow-field to much greater fidelity than was possible with contemporary instrumentation. Regardless, this experiment remains a popular source of validation data because no alternative provides as attractive a data set for the relevant physics at this Mach number. Therefore, the Bachalo-Johnson experiment is deserving of a revisit to produce a modern validation dataset.

There have been many attempts to model the Bachalo-Johnson experiment, using a range of computational techniques. Representative RANS results are available on the NASA Langley Turbulence Model Resource website [21]. RANS models have been reasonably successful in predicting the surface pressure distribution, with moderate model-to-model variation. Much more variation is found in prediction of the skin friction coefficient, with as much as 20% difference in prediction of this quantity by different turbulence models, even upstream of the shock wave. Boundary layer re-attachment varies significantly across different models. Mean velocities also can be reasonably predicted by RANS, but with significant discrepancies with the measurements depending on the model and the profile location. Reynolds shear stress predictions by RANS are consistently lower than the measured values, by as much as 50%. The SSG/LRR-omega full Reynolds stress model produces Reynolds stresses much closer to the experiments, but it does not offer a substantial gain in accuracy for other quantities. Aside from the predictive performance of any given *nominal* RANS model on this flow, Spalart has also pointed out the issue of sensitivity of model prediction of surface quantities to calibrated model parameters. Small changes in model constants can cause relatively large changes in the predictions. It remains to be seen if new RANS model approaches, including data-driven models, can improve predictions of the velocity field and Reynolds stresses, while maintaining or improving the accuracy on engineering quantities of interest.Spalart et al. [9] have simulated the Bachalo-Johnson experiment using wall-modeled LES (WMLES) and hybrid WMLES/DNS approaches. The measurements of Reynolds stress were not confirmed by DNS, even upstream of the hump; the root cause of this deficiency could not be identified due to ambiguities in the experimental/computational comparisons. Uzun and Malik [11] have performed wall-resolved LES (WRLES) of the Bachalo-Johnson flow, and obtained improved agreement with the measured Reynolds stresses by considering a larger extent of the domain in the azimuthal direction. They have also highlighted the apparent differences in the experiment as conducted in the 2×2 ft tunnel [7] and the 6×6 ft tunnel [22], such as change in shock position and separation bubble length, that are important to take into account when performing model validation. Several issues and gaps remain in the community's understanding of LES model performance for this class of flows. These include: ensuring proper generation of an accurate representation of the upstream turbulent boundary layer, required azimuthal extent of the domain for accurate prediction of various quantities, required resolution in the outer part of the boundary layer in WMLES, impact of the near-wall model in WMLES on prediction of various engineering quantities, and impact of the sub-grid stress model in both WMLES and WRLES on prediction of these quantities.

A companion paper [12] describes the experiment that revisits the Bachalo-Johnson experiment. *It is not a direct replication of the geometry or flow conditions*, as it seeks to meet additional goals suited for code validation. The present paper will describe the validation challenge wrapped around this experiment. Rather than simply releasing the data to the community for use in validating predictive capability of unsteady transonic shock motion, an organized and scheduled challenge will be implemented. The experimental geometry and all boundary conditions will be released on a specific date to all computational teams wishing to participate. Their simulated results will be submitted by a specific date, only after which will the primary data concerning the unsteady separation region be released. Submissions will be assessed by established metrics of comparison to offer insight into the predictive performance of the computational models for the flowfield quantities of interest. The primary value of the exercise will be generating new information concerning which model characteristics are important to predict different features of this class of flows.

The validation challenge will be initiated at SciTech 2020 by the experimental companion paper [12] and the present paper, which will detail the organization of the challenge, its schedule, and the metrics of comparison by which the models will be assessed. By implementing such a blind validation challenge, we seek to benefit the turbulence modeling community with a clearer understanding of those modeling approaches that well represent unsteady transonic shock motion.

Experiment

A brief summary of the experiment is provided here; full details will be found in the companion paper [12].

The experiment is conducted in Sandia's Trisonic Wind Tunnel (TWT) at a high subsonic Mach number targeted at Mach 0.875. The Reynolds number based on chord length is 1e6, as compared to 2.76e6 for Bachalo-Johnson [7]. The TWT is a blowdown-to-atmosphere facility using a 12 in × 12 in test section that, in the present configuration, uses solid walls rather than porous walls. The model consists of a cylindrical geometry capped by an elliptical nose. Following a constant-diameter forebody, an axisymmetric hump encircles the cylinder, upon which a shock is generated at the apex. Large-scale separation occurs at the shock foot and reattaches downstream in an unsteady manner. Preliminary simulations have shown that the elliptical nose is shock-free and that the unsteady separation region of the experiment is broadly consistent with predictions. A photo of the model installed into the TWT is shown in Fig. 2.

Boundary condition measurements include the wind tunnel wall pressure distribution, the wind tunnel wall boundary layer as measured using Particle Image Velocimetry (PIV), and the freestream turbulence intensity. Stagnation temperature and model wall temperature are measured for their effect on flow velocity. On the model

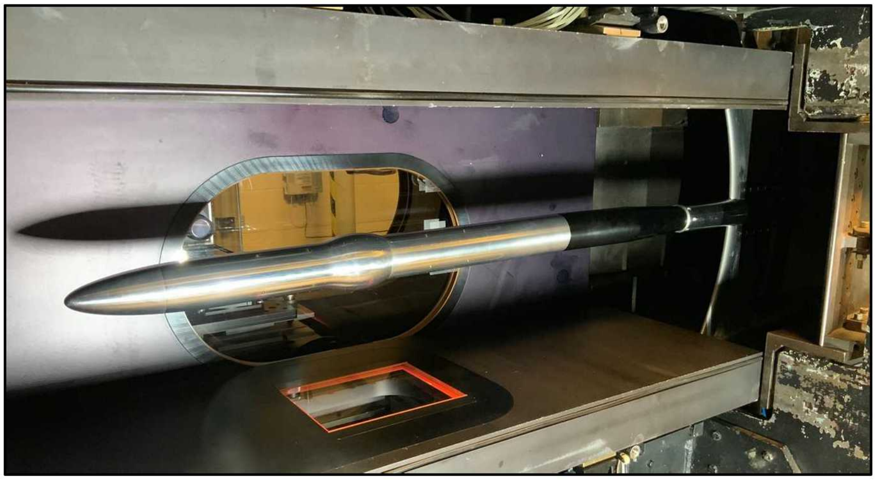

Fig. 2: Photo of the axisymmetric transonic hump model installed into Sandia's Trisonic Wind Tunnel.

itself, the incoming boundary layer has been measured using PIV. The upstream surface pressure distribution and the upstream surface shear stress measured using Oil-Film Interferometry (OFI) are also provided.

Upon the start of the validation challenge, the precise model geometry will be released. The wind tunnel geometry also will be provided, including the contraction section leading into the test section and the diffuser section downstream of the test section. This will allow computational participants to simulate as much of the wind tunnel as they deem appropriate to their modeling approach.

The Validation Challenge

The simplicity of the geometry and the desire for additional data expressed by multiple modeling groups motivated us to propose a 'CFD Validation Challenge' to the community. The Challenge is 'blind,' in that the model and tunnel geometry, inflow conditions, and tunnel turbulence properties are provided to participants, but the experimental data surrounding the hump is initially withheld. These data describing the unsteady region will be revealed only after all simulations have been completed. The primary goal is to assess the efficacy of various simulation approaches, while preventing a biased evaluation by removing the ability to calibrate a model to the experimental data *a priori*. A secondary goal is to evaluate the variability between CFD estimates when the experimental data are unknown.

The idea of a blind CFD challenge is not new. For example, Klausmeyer and Lin [13] performed a blind comparison of methods for estimating aerodynamic performance of a high-lift airfoil. Simms et al. [14] conducted a blind comparison of wind turbine simulation data to experimental data acquired in a collaborative effort between the National Renewable Energy Laboratory and NASA Ames Research Center. Multiple blind comparisons have been performed for laminar, high-enthalpy, hypersonic flow, including Harvey et al. [15], Holden et al. [16], and Holden et al. [17]. Perhaps the best examples of collaborative blind comparisons are the AIAA drag prediction workshops [18] and the high-lift prediction workshops [19], both of which served as excellent forums for assessing the consistency of predictions from numerous contributors and the state of the art in CFD capabilities. From the experimental side, similar challenges such as the international PIV challenges have been valuable for identifying optimal algorithms and their effect on interrogated data [20].

The present flow case provides a compelling benchmark problem for several reasons. First, the Reynolds number of the flow makes it accessible to the full range of simulation approaches, including DNS. We expect DNS results to greatly aid in ultimate interpretation and understanding of the turbulence model predictions. Further, application of a range of approaches of varying fidelity by different groups, ranging from DNS to wall-modeled LES to RANS, should enhance the communities' understanding of how various modeling choices affect the accuracy of the predictions, and how this may vary for different quantities of interest. A successful outcome of this exercise will be not only quantitative assessment of the accuracy of various modeling approaches, but also improved understanding of why the models achieve their level of accuracy. Such insight will help guide the development of next-generation turbulence models.

Secondly, the present experiment dedicates much attention to measurement of the boundary conditions as required to create unambiguous simulations. The fidelity and resolution of these boundary condition measurements will reduce uncertainties associated with unknown boundary condition effects that often plague validation studies and complicate their interpretation. These will include the incoming boundary layer on the model to provide a known input into the unsteady region; participants can assess whether they have simulated the incoming boundary layer adequately before they are expected to get the separation turbulence correct. The principal measurements surrounding the hump include not only mean flow quantities and flowfield Reynolds stresses from PIV, but also unsteady surface pressures via Pressure Sensitive Paint (PSP), thus making the validation exercise highly relevant for those interested in CFD as a tool to predict unsteady, fluid-induced surface loadings. In addition, Oil-Film Interferometry (OFI) for the surface shear stress will be made available, providing a value important to aerodynamic analysis but notoriously difficult to measure. All experimental measurements, whether for boundary conditions or the principal data, will include rigorous quantification of uncertainties.

The geometric information released at the start of the Challenge will include not only the geometry of the wind tunnel model, but also those of the wind tunnel itself. This will include the geometry of the entrance contraction and the immediate exit of the test section into the diffuser. Therefore, computational participants will be able to simulate as much of the flow through the wind tunnel as they wish to ensure the level of fidelity they feel is desirable.

We have identified specific quantities of interest (QOIs) to be predicted by participants as a basis for model comparison. The selected QOIs include those used in past validation studies with the Bachalo-Johnson flow, such as mean velocity and Reynolds stress profiles, mean separation and reattachment locations, and mean surface pressure distribution. The present experiment will add spatial distributions of other single point quantities, such as wall shear stress and surface pressure fluctuation magnitude. We include further comparisons involving spectral information from the wall pressure signal, including temporal and wave-number spectra. We are also introducing QOIs and associated metrics that measure the ability of models to capture topological features of the flow, for example, mean separation bubble volume and separation shear layer vorticity thickness.

The Sandia modeling team already has been simulating this case, both to aid in the experimental design and to test validation methodology. We have compared experimental data to these initial simulations, verifying that both the experiments and the computations produce the same physics and that the QOIs are suitable for interpretation of the flow. As the Sandia team clearly cannot be considered a 'blind' participant in the validation challenge, this feature will be leveraged as a 'control' group. Sandia's modelers, alone amongst entrants, will have advance access to the final data. Can this allow them to achieve more accurate results? Or will the Sandia simulations return similar accuracy as those modeling teams who are truly blind to the data? This will provide a uniquely useful data point amongst the Validation Challenge participants – and perhaps challenge the widespread notion that CFD results can be tuned to the correct answer.

The Validation Challenge is open to any participant, including academic, government, and commercial groups. The Challenge will include two separate categories of simulation: first, a RANS-based solution representative of a fast-turnaround engineering analysis; and second, a scale-resolving solution where any such method, including DES, LES, or DNS can be used. Participants may submit simulations in both categories if they wish, or even multiple entries within the same category. Once simulation results are submitted, their comparison to the data and the assessment of their performance will be guided by an advisory panel of members external to Sandia whose work does not overlap with groups interested in the Bachalo-Johnson case. This will ensure a neutral appraisal of the models.

The Validation Schedule

The timeline of the Challenge is planned as follows:

July 2019, AIAA Aviation (Ref. [8]): Formal announcement of the Challenge.

January 2020, AIAA SciTech: Publication of geometry details, tunnel model, inflow and turbulence information (Ref. [12]). Official beginning of the Challenge.

Mid-August 2020: Submission deadline for RANS-based entries.

Late September 2020: Submission deadline for scale-resolving simulation entries (WMLES/LES/DNS).

December 2020: Experimental data to be released to participants.

January 2021, AIAA SciTech: Invited session(s). 1-2 talks to present the experimental data, 1-2 talks for an assessment of modeling performance to be given by a neutral arbiter (to be determined), and additional talks for participants to describe their simulation approaches and findings.

Subsequent events: A follow-on challenge may be conducted in which participants may refine their simulations based upon access to the experimental data. How can models be improved based on insights from the Challenge?

Metrics of Comparison

The Challenge organizers have identified specific quantities of interest (QOIs) to be predicted by participants as a basis for model comparison. Some of these QOIs include those used in past validation studies with the Bachalo-Johnson flow, such as mean velocity and Reynolds stress profiles, mean separation and reattachment locations, and mean surface pressure distribution. The present experiment will add spatial distributions of other single point quantities, such as wall shear stress and surface pressure fluctuation magnitude. Improved measurement technology developed since the Bachalo-Johnson experiment allows us to add QOIs focused on the unsteady nature of the separated flow such as probability distributions of instantaneous separation and reattachment locations and maxima in Reynolds stresses. Further comparisons involving spectral information from the wall pressure signal are possible as well, including temporal and wave-number spectra. We are also exploring QOIs and associated metrics that measure the ability of models to capture topological features of the flow, for example, mean separation bubble volume and separation shear layer vorticity thickness.

Previous CFD challenges, such as the Drag Prediction Workshop, have illustrated the benefit of requiring participants to provide some demonstration of solution verification for their code, utilizing at least one representative turbulence model. Participants in the present RANS validation challenge will be required to submit results for calculation of the NASA 2D bump-in-channel case [21] on a provided sequence of grids. Solution verification for scale-resolving simulations is often problematic (although more straightforward for DNS than for LES in most cases). No solution verification exercises will be prescribed for participants in the scale-resolving portion of the Challenge. Rather, participants will be strongly encouraged to demonstrate sensitivity to mesh and time-step resolution by performing appropriate sensitivity studies, as well as providing estimates for uncertainties due to incomplete statistical averaging.

A noncomprehensive list of QOIs is given here. Additional QOIs may be added subsequently for follow-on assessments once specific model performance questions have been posed by the experimental/computational comparisons.

To establish accuracy of mean flow predictions, mean pressure and skin friction distributions on the model surface as well as profiles of the mean streamwise and radial velocity will be used as primary QOIs. The Bachalo-Johnson experiment reported mean velocity profiles and surface pressures, but skin friction measurements were not included. The skin friction distribution will aid assessment of turbulence model performance and give increased fidelity of information about the oncoming turbulent boundary layer. Profiles of the streamwise, radial, and shear components of the Reynolds stress will be used as a basis for evaluation of models' ability to predict turbulent stresses and to provide insight into possible model deficiencies in predicting the primary mean engineering QOIs. The positions of these profiles will be assessed not at absolute spatial positions but rather at positions relative to the separation and reattachment points. This will allow simulations to be assessed independently for their predictions of the separated flowfield structure and their predictions of velocity and Reynolds stress quantities within the separation region.

The present validation experiment offers the opportunity to also assess the ability of scale-resolving simulation approaches in predicting unsteady aspects of the flow. Spatial distributions of surface pressure fluctuation amplitude as well as frequency and wavenumber spectrum will be available from unsteady pressure sensitive paint measurements. These QOIs will facilitate an evaluation of simulation methods for prediction of unsteady turbulent-induced pressure loadings within various regimes: an attached turbulent boundary layer experiencing an evolving pressure gradient, both favorable and unfavorable; the shock-wave/turbulent boundary layer interaction with resulting separation; and subsequent reattachment. Amongst other possible uses of these unsteady pressure measurements, it will be interesting to use them to evaluate mesh resolution requirements for their accurate representation using large-eddy-simulation.

Other QOIs we plan to include in the Challenge involve quantities that are derived from the measurements. Examples include the boundary layer separation and re-attachment locations, as derived from the OFI measurements and confirmed by oil flow visualization and PSP. Surface pressure fluctuation measurements will be post-processed to provide not only spectra, but also stream-wise and span-wise correlation lengths. We may also include an integrated measure of how well the separation bubble flowfield is predicted. One candidate for such a QOI is the circulation bubble volume, defined as the volume within the zero streamwise velocity contour.

Conclusions

The Bachalo-Johnson experiments from the early 1980's remain a popular data set for CFD validation of unsteady transonic shock motion and the associated unsteady separation region. Nonetheless, this data set suffers from several deficiencies in use as a validation data set that reflect the state-of-the-art of the era in comparison to modern experiments. These are principally a reflection of the limited conceptualization of validation experiments at the time. Boundary conditions are, at best, only partially specified and the description of the model geometry contains ambiguities. The Reynolds number was too high to enable even modern DNS capabilities, and the porous-wall wind tunnel poses a poorly-defined wall boundary condition. Contemporary instrumentation at the time allowed only mean and fluctuating surface pressures and some profiles of the mean velocities and Reynolds stresses. In contrast, modern instrumentation offers full field of instantaneous velocity using PIV, from which the turbulence properties may be fully described. Fluctuating surface pressure fields may be measured using PSP. OFI measures the surface shear stress at numerous points. And also of great importance, the importance is understood of full specification of boundary conditions within the wind tunnel.

To this end, a revisited Bachalo-Johnson experiment has been conducted and serves as a new Validation Challenge, initiated at the 2020 AIAA SciTech conference. The Challenge is blind, in that participants will receive the model geometry, the boundary conditions, and the wind tunnel specifications, but the primary data surrounding the separation region will be withheld. Participants may submit simulations using RANS, LES, DES, and/or DNS approaches. The primary data will be released only at the conclusion of the Challenge after computational entrants have been submitted. Submissions will be assessed by established metrics of comparison to offer insight into the performance of different computational models and suggest new modeling approaches to improve future success with unsteady transonic flow simulation.

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