ASME V&V 20-2009

Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

ASME SETTING THE STANDARD

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This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Periodically certain actions of the ASME V&V 20 Committee may be published as Cases. Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

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FOREWORD

This Standard addresses verification and validation (V&V) in computational fluid dynamics (CFD) and computational heat transfer (CHT). The concern of V&V is to assess the accuracy of a computational simulation. The V&V procedures presented in this Standard can be applied to engineering and scientific modeling problems ranging in complexity from simple lumped masses, to 1-D steady laminar flows, to 3-D unsteady turbulent chemically reacting flows. In V&V, the ultimate goal of engineering and scientific interest is validation, which is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. However, validation must be preceded by code verification and solution verification. Code verification establishes that the code accurately solves the mathematical model incorporated in the code, i.e., that the code is free of mistakes for the simulations of interest. Solution verification estimates the numerical accuracy of a particular calculation.

The estimation of a range within which the simulation modeling error lies is a primary objective of the validation process and is accomplished by comparing a simulation result (solution) with an appropriate experimental result (data) for specified validation variables at a specified set of conditions. *There can be no validation without experimental data with which to compare the result of the simulation*.[*] Usually a validation effort will cover a range of conditions within a domain of interest.

Both the American Institute of Aeronautics and Astronautics (AIAA) and the American Society of Mechanical Engineers (ASME) have published V&V Guides that present the philosophy and procedures for establishing a comprehensive validation program, but both use definitions of error and uncertainty that are not demonstrated within the guides to provide quantitative evaluations of the comparison of the validation variables predicted by simulation and determined by experiment. ASME V&V 10-2006, for instance, defines error as "a recognizable deficiency in any phase or activity of modeling or experimentation that is not due to lack of knowledge" and defines uncertainty as "a potential deficiency in any phase or activity of the modeling, computation, or experimentation process that is due to inherent variability or lack of knowledge."

In contrast, this Standard presents a V&V approach that is based on the concepts and definitions of error and uncertainty that have been internationally codified by the experimental community over several decades. In 1993, the Guide to the Expression of Uncertainty in Measurement was published by the International Organization for Standardization (ISO) in its name and those of six other international organizations.[†] According to the Foreword in the ISO Guide, "In 1977, recognizing the lack of international consensus on the expression of uncertainty in measurement, the world's highest authority in metrology, the Comite International des Poids et Mesures (CIPM), requested the Bureau International des Poids et Mesures (BIPM) to address the problem in conjunction with the national standards laboratories and to make a recommendation." After several years of effort, this led to the assignment of responsibility to the ISO Technical Advisory Group on Metrology, Working Group 3, to develop a guidance document. This ultimately culminated in the publication of the ISO Guide, which has been accepted as the de facto international standard for the expression of uncertainty in measurement.

The V&V approach presented in this Standard applies these concepts to the errors and uncertainties in the experimental result and also to the errors and uncertainties in the result from the simulation. Thus, the uncertainties in the experimental value and in the simulation value are treated using the same process. Using the approach of the ISO Guide, for each error source (other than the simulation modeling error) a standard uncertainty, u, is estimated such that u is the standard deviation of the parent population of possible errors from which the current error is a single realization. This allows estimation of a range within which the simulation modeling error lies.

The objective of this Standard is the specification of a verification and validation approach that quantifies the degree of accuracy inferred from the comparison of solution and data for a specified variable at a specified validation point. The scope of this Standard is the quantification of the degree of accuracy for cases in which the conditions of the actual experiment are simulated. Consideration of the accuracy of simulation results at points within a domain other than the validation points (e.g., interpolation/extrapolation in a domain of validation) is a matter of engineering judgment specific to each family of problems and is beyond the scope of this Standard.

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[*]This is implicit in the phrase "real world" used in the definition of validation.

[†]Bureau International des Poids et Mesures (BIPM), International Electrotechnical Commission (IEC), International Federation of Clinical Chemistry (IFCC), International Union of Pure and Applied Chemistry (IUPAC), International Union of Pure and Applied Physics (IUPAP), and International Organization of Legal Metrology (OIML)

ASME PTC 19.1-2005 "Test Uncertainty" is considered a companion document to this Standard, and it is assumed the user has both so many of the details of estimating the uncertainty in an experimental result are not repeated herein. ASME PTC 19.1-2005 illustrates the application of the ISO Guide methodology in straightforward and also in complex experiments.

Ideally, as a V&V program is initiated, those responsible for the simulations and those responsible for the experiments should be involved cooperatively in designing the V&V effort. The validation variables should be chosen and defined with care. Each measured variable has an inherent temporal and spatial resolution, and the experimental result that is determined from these measured variables should be compared with a predicted result that possesses the same spatial and temporal resolution. If this is not done, such conceptual errors must be identified and corrected or estimated in the initial stages of a V&V effort, or substantial resources can be wasted and the entire effort may be compromised.

Finally, as an aid to the reader of this Standard, the following guide to the topics and discussions of each section are presented. It is recommended that the reader proceed through the Standard beginning in Section 1 and successively read each subsequent section. The presentation in this Standard follows a procedure starting with verification (code and solution), proceeding to parameter uncertainty assessment, experimental uncertainty assessment, simulation validation, and concluding with a comprehensive example problem. As stated, this Standard follows an overall procedure; however, each section of this Standard may also be viewed as a standalone presentation on each of the relevant topics. The intent of this document is validation in which uncertainty is determined for both the experimental data and the simulation of the experiment. However, the material in Sections 2, 3, and 4 can be studied independently of the remainder of the document as they are important in their own right. A reader's guide follows:

Section 1 presents an introduction to the concepts of verification and validation, the definitions of error and uncertainty, and the introduction of the overall validation methodology and approach as defined in this Standard. The key concepts of this Section are the validation comparison error and the validation standard uncertainty. It is shown that validation standard uncertainty is a function of three standard uncertainties associated with errors due to numerical solution of the equations, due to simulation inputs, and due to experimental data.

Section 2 presents two key topics:

(a) the details of a method for code verification based on the technique of the method of manufactured solutions

(b) the details of a method for solution verification based on the technique of the Grid Convergence Index (an extension of Richardson Extrapolation).

The outcome of Section 2 is a method for estimating the standard uncertainty associated with numerical errors.

Section 3 presents two different approaches for estimating the standard uncertainty associated with errors in simulation input parameters. One approach evaluates response of the simulation or system in a local neighborhood of the input vector, while the other approach evaluates response in a larger global neighborhood. The first approach is commonly referred to, for example, as the sensitivity coefficient method, and the second approach is generally referred to as the sampling or Monte Carlo method.

Section 4 presents a brief overview of the method presented in the ASME PTC 19.1-2005 Test Uncertainty standard for estimating uncertainty in an experimental result. At the conclusion of this Section, the reader will have methods for estimating the key uncertainties required to complete a validation assessment.

Section 5 presents two approaches for estimating the validation standard uncertainty given the estimates of uncertainty associated with numerical, input, and experimental data errors as developed in the three previous sections. At the conclusion of this Section, the reader will have the necessary tools to estimate validation standard uncertainty and the error associated with the mathematical model.

Section 6 presents a discussion of the interpretation of the key validation metrics of validation comparison error and validation uncertainty. It is shown that the validation comparison error is an estimate of the mathematical model error and that the validation uncertainty is the standard uncertainty of the estimate of the model error.

Section 7 summarizes the methods presented in the previous sections by implementing them in a comprehensive example problem working through each element of the overall procedure and results in a complete validation assessment of a candidate mathematical model.

Finally, several appendices are included in this Standard. Some are considered as part of the Standard and are identified as mandatory appendices. Other included appendices are considered as nonmandatory or supplementary and are identified as such.

ASME V&V 20-2009 was approved by the V&V 20 (previously PTC 61) Committee on January 9, 2009 and approved by the American National Standards Institute (ANSI) on June 3, 2009.

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Edition:	Cite the applicable edition of the Code for which the interpretation is being requested.
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ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not approve, certify, rate, or endorse any item, construction, proprietary device, or activity.

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STANDARD FOR VERIFICATION AND VALIDATION IN COMPUTATIONAL FLUID DYNAMICS AND HEAT TRANSFER

Section 1
Introduction to Validation Methodology

1-1 GENERAL

This Standard addresses verification and validation (V&V) in computational fluid dynamics (CFD) and computational heat transfer (CHT). The concern of V&V is to assess the accuracy of a computational simulation. The V&V procedures presented in this Standard can be applied to engineering and scientific modeling problems ranging in complexity from simple lumped masses to 1-D steady laminar flows to 3-D unsteady turbulent chemically reacting flows. In V&V, the ultimate goal of engineering and scientific interest is validation, which is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. However, validation must be preceded by code verification and solution verification. Code verification establishes that the code accurately solves the mathematical model incorporated in the code (i.e., that the code is free of mistakes for the simulations of interest). Solution verification estimates the numerical accuracy of a particular calculation. Both code and solution verification are discussed in detail in Section 2.

The estimation of a range within which the simulation modeling error lies is a primary objective of the validation process and is accomplished by comparing a simulation result (solution) with an appropriate experimental result (data) for specified validation variables at a specified set of conditions. *There can be no validation without experimental data with which to compare the result of the simulation.*[1] Usually a validation effort will cover a range of conditions within a domain of interest.

1-2 OBJECTIVE AND SCOPE

The objective of this Standard is the specification of a verification and validation approach that quantifies the degree of accuracy inferred from the comparison of solution and data for a specified variable at a specified validation point. The approach, proposed by Coleman and Stern [1], uses the concepts from experimental uncertainty analysis [2–4] to consider the errors and uncertainties in both the solution and the data.

The scope of this Standard is the quantification of the degree of accuracy of simulation of specified validation variables at a specified validation point for cases in which the conditions of the actual experiment are simulated. Consideration of solution accuracy at points within a domain other than the validation points (e.g., interpolation/extrapolation in a domain of validation) is a matter of engineering judgment specific to each family of problems and is beyond the scope of this Standard.

Fluid dynamics and heat transfer are the areas of engineering and science that are specifically addressed, but the validation approach discussed is applicable in other areas as well. Discussion and examples are centered on models using partial differential equations, but simpler models also fall within the purview of the validation approach.

1-3 ERRORS AND UNCERTAINTIES

Pertinent definitions from metrology are as follows:

(a) error (of measurement), δ: "result of a measurement minus a true value of the measurand" [5]

(b) uncertainty (of measurement), u: "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [5]

These concepts were extended in reference [1] to apply to the value of a solution variable from a simulation as well as a measured value of the variable from an experiment.

In that context, then, an error, δ, is a quantity that has a particular sign and magnitude, and a specific error, δ_i, is the difference caused by error source i between a quantity (measured or simulated) and its true value. In the approach outlined in this Standard, it is assumed

[1] This is implicit in the phrase "real world" used in the definition of validation.