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ROLE OF FIRE FIELD MODELS AS A DESIGN TOOL FOR PERFORMANCE-BASED FIRE-CODE IMPLEMENTATION

K.T. Yang
Department of Aerospace and Mechanical Engineering, University of Notre Dame, Indiana, USA

ABSTRACT

The worldwide movement from prescription-based to performance-based fire codes is unmistakable and irreversible. In the implementation of such performance-based fire codes, both basic and innovative engineering design tools are needed to analyze potential fire scenarios for relative fire hazards and risk assessment. Among such innovative design tools are fire models, particularly the fire field models, which will continuously see increased application in fire-safety design of buildings. The current-generation fire field models is assessed regarding their engineering capabilities as well as their shortcomings, and the needed steps to improve them are identified so that they can be applied to performance-based fire-safety design with some confidence. The critical role of the fire field models in the implementation of performance-based fire codes is delineated along with the needs to train fire-safety professionals in the proper use of fire field models as an integral part of the fire-safety engineering educational programs.

1. INTRODUCTION

Despite the many continuing uncertainties in the implementation of performance-based fire codes, the recent movement in the adoption of such codes away from the prescription-based fire codes, particularly in the developed countries, is unmistakable and irreversible. It is true that the speed with which such a major paradigm shift based on this movement is being pursued may be different for different countries. This is, however, not entirely unexpected in view of the fact that different countries have had in the past very different fire-code development and implementation infrastructures based on their own traditional prescription-based codes, and major changes are difficult to make and very time consuming, since such changes would necessarily affect many people such as fire-code developers, fire-safety officials and regulators, building designers, fire-protection industry personnel, fire insurers, fire-protection engineering educators, and others.

Despite the commitment to the performance-based fire-code movement, many of the countries have adopted a more moderate course of action which still retains some of the practices of the prescription-based code in the interim. Nevertheless, it is fair to say that within a decade or two, performance-based fire codes will become the norm among the majority of countries.

The basic concept of performance-based fire codes has been much articulated in the recent past [1-6]. Briefly, the concept specifically addresses much of the shortcomings embedded in the traditional prescription-based fire codes. In such traditional codes, detailed rigid instructions regarding all aspects of fire safety in the building design are given and must be adhered to by the designer without exception. As a result, the codes have no way to allow for any new and innovative fire-safety solutions and are also difficult to upgrade and accommodate new technology advances in the fire protection field. The basic concept of performance-based fire codes, on the other hand, emphasizes on meeting certain fire-protection performance requirements, and does not require the use of any specific solution methodology by the building designer as to how such performance requirements are met. However, the designer must demonstrate credibly the validity of his/her chosen engineering methodology to the regulator. Therefore, also implicit in this basic concept is the fact that the performance-based code developer, the code regulator, the designer, and also others involved in the process of satisfying the fire-code requirements must all be trained professionals well versed in the pertinent fire-protection engineering methodologies and technical advances for building design. It is this requirement of the availability of trained fire-protection engineering professionals that has slowed the implementation of the overall practice of the performance-based fire codes in several countries because of the lack of proper engineering educational infrastructure to train the needed fire-protection professionals [7].

One essential difficulty in the implementation of the performance-based fire code is to determine how performance requirements are specified. This is largely due to the very large number of coupled fire-safety requirements related to the different fire hazards in a given building. Good examples are requirements for fire prevention, human safety, prevention of spreading hazards, and assurance of fire-department accesses. In human safety for instance, requirements are for safe refuges and escape routes, safety from heat, smoke and other toxic gases, safe egress time, and safety from structural hazards. In spreading hazards, there are general requirements for no fire spread to adjacent buildings and other spaces. For fire department operations, there are critical requirements for operational fire-fighting bases in the building and their accesses from outside. All these requirements are related to specific fire scenarios including the fire source and the subsequent fire and smoke spread, and there are a very large number of such scenarios that are all possible in a building. Obviously, it will be next to impossibility in attempting to design a building to satisfy all these requirements. There is, however, a consensus that in the implementation of performance-based fire codes, the building is to be designed for safety to be based on a relatively smaller number of fire scenarios, known as design fire scenarios (DFS), together with fire-safety performance specifications that must be met in each of them [8]. Such scenarios would logically be based on formal risk assessment [9] to be carried out by the building designer. However, the fire code regulator must still have to be convinced that they are the mostly likely and reasonable scenarios for the designed building to insure its fire safety.

Of the broad fire-safety requirements in a building as mentioned earlier, one engineering design tool which can be used to analyze the feasibility and effectiveness of the designed fire-safety measures associated with many likely fire scenarios is the application of fire models (along with models such as evacuation and risk assessment models, among others), which have been under continuing intensive development in the worldwide fire-research community. A fire model represents a quantitative physical (and chemical) description of a fire starting from its ignition and commencement at a certain location, followed by its growth and spread and accompanied by smoke and other toxic gases to other downstream locations, as a function of the presence of combustible materials, existing geometries, and prevailing temperature, velocity, and pressure conditions. Once a design fire scenario is specified, it is generally feasible to apply such a fire model to provide quantitative information on the evolving dynamics of the spreading fire, which can then be used to determine the designed fire-safety measures for that specific fire scenario. It is therefore clear that such fire models represent an invaluable design tool to the building designers to answer many what-if questions regarding fire safety, and also to provide a quantitative basis for relative deterministic or probabilistic risk assessments [9] of the hazards in the various design fire scenarios. In addition, they can also be used to contribute to long-term data bases for fire scenarios and their analyses to support future building designs for fire safety. On the other hand, despite the attractiveness in applying the fire models to analyze fire scenarios, there is still a degree of reluctance in the use of fire models by the building designers, largely due to their current perception that many such fire models are still not sufficiently accurate and robust for general use in fire-safety analyses. It is, however, to be noted that, while the predictive accuracies of the fire models are indeed important, it is even more important to be able to assess the relative degree of fire hazards in different fire scenarios for performance-based design analysis, as long as the uncertainties in the accuracies can be reasonably estimated. Also, the model accuracy issue will become less critical in time, in view of the very large continuing efforts by the fire-modeling community at the present time to improve the predictive accuracies of the fire models.

It is now well known that fire models can be divided into two groups [10], namely, zone models and field models. A zone model is one in which the individual flow regions with unique and distinguishable characteristics are treated as zones (e.g. Chow [11]). Examples are for a room fire scenario the flame zone, the fire plume, hot ceiling and smoke layer, wall layer, and regions next to windows and doorways. Each zone is describable by its own global mass, momentum, species, and energy balances, together with physical submodels from empirical correlations, largely based on stand-alone tests, to be used as either forcing functions or functions to close the conservation equations. The result is a series of coupled first-order nonlinear ordinary differential equations in time, which can then be solved numerically and expediently on personal computers. On the other hand, fire field models are those based on numerical solutions to a series of partial differential equations associated with conservation of mass, momentum, energy, and species [12]. The unique advantages of the fire field models and their applications in analyzing building fire scenarios are their ability to simulate the dynamic fire and smoke movements seamlessly in both space and time in a way very much the same as what is happening in a real fire. These fire field models are inherently more basic and general, since they are not particularly restricted to any specific fire scenarios. With the ever-increasing accessibility to high-powered and fast-CPU computing resources, the fire field models have received ever-increasing attention in simulating real fire scenarios, and despite existing shortcomings and uncertainties in these models, there are positive indications on the basis of the current concentrated research efforts to improve several of the physical submodels such that these models will eventually outperform zone models as the preferred design tool to simulate fire scenarios in the implementation of performance-based fire codes.

The purpose of this paper is then to delineate the critical role of fire field models as a design tool for building design in fire safety, and also to provide a rational basis for properly using such fire field models in performance-based fire code related to analysis and design. As will be shown, such a rational approach is crucial in the fire-safety design of buildings to meet the requirements of performance-based fire codes.

2. CRITICAL ROLE OF FIRE FIELD MODELS AS A DESIGN TOOL

As already mentioned earlier, many relevant fire scenarios for fire safety involve the flow of smoke, particulates, and toxic gases with velocities and high temperatures varying in space and time, as affected by the fire source and the surroundings [8]. This is not surprising in view of the well-known effects of, for instance, the flow of such toxic substances on the physiologocal and psychological impacts on humans inside the buildings. Despite the shortcomings of the current generation of fire field models, as will be elaborated in the following, they are particularly suitable for calculating and analyzing the growth and spread of such toxic substances in the hot gases, taking into account all the complex coupling effects inherent in the real fire phenomena at the same time seamlessly and continuously. Such effects include those from thermal radiation, turbulence, combustion, species generation, and strong buoyancy, and others. However, in view of the very large number of possible building designs that may be encountered in practice by the designers, a series of design fire scenarios [8] which are taken to be the most probable and hazardous scenarios, must be analyzed to provide data for performance-based fire-safety code compliance in all such scenarios. Again, the choice of these design fire scenarios rests with the relative risk assessments and past experience with similar buildings in satisfying the performance-based codes dealing with such fire-hazard-related parameters as, for instance, fire prevention, smoke curtains, smoke layer thickness, flash-over prevention, compartmentalization practices, escape-route design, and the like.

In addition to providing the methodology to analyze the design fire scenarios, the same fire field models can also be utilized to develop quantitative data bases for a collection of fire scenarios and documentation of their analyses to support future building design activities. It is readily appreciated that such data bases would be invaluable also as a design tool to quickly and expeditiously determine the adequacy of fire-safety design of buildings and the associated systems and practices.

Finally, as it will become clear, the fire field models have a basic solution and computational structure which may only require minor changes over time, while the submodels dealing the complex complex coupled-physics phenimena can and should be continually updated as new and better submodels become available. As a result, fire field models can be regarded as "living" (continuously enhanceable) design tool for performance-based fire-code implementation.

3. FIRE FIELD MODEL DEVELOPMENT AND CRITICAL REQUIREMENTS

In order to appreciate the specific role that fire field models can play in the implementation of performance-based fire codes, it is important to have a clear understanding of the various physics that the field models can accommodate and also of how this same physics underpins most of the relevant fire scenarios in the fire-code implementation. For building fires, the hot gas temperatures can be in the range of hundreds of degrees Centigrade, and consequently the hot gas must be taken to be compressible. The high temperatures provide the strong buoyancy that drives the fire and smoke spread phenomena, even where there is forced ventilation. The gas flow in the building is necessarily turbulent in view of the large building characteristic length and the large temperature variations. Therefore, all the field variables such as velocity components, temperature (or enthalpy), and species concentration should be either Reynolds- or Favre-averaged quantities, even though there is a good indication that the latter may be preferred, but more difficult to deal with [13]. The presence of turbulence also dictates the need for coupling with the turbulent-combustion phenomena in the fire, and only then can the heat release rate in the fire be properly estimated. This heat release from the combustion process drives the temperature field and the buoyant flow from the fire source. The temperature field contains another source of heat, the radiant heating, which arises from the fact that the products of combustion in the fire generally contain species such as carbon dioxide and water vapor, both of which participate in the radiative-transfer process. Also it is important to recognize that there are strong coupling all around among combustion, turbulence, and thermal radiation. Turbulence affects combustion through the mechanism of mixing of the reactants. Combustion and hot-gas flow affect the distribution of the species which, in turn, affect radiative transfer. Radiation further affects turbulence through its contribution to the temperature field and buoyancy, which also directly affect the flow field and its mechanism for turbulence generation. Since all these coupling effects are inherent in all the real-fire phenomena, they need to be accounted for in the fire field models. For this purpose, suitable submodels for turbulent combustion, turbulence, radiative transfer, and strong buoyancy are incorporated into the fire field models as represented by the basic time-averaged conservation equations of mass, momentum, energy, and species. These are nonlinear coupled time-dependent three-dimensional partial differential equations, which are solved numerically, mainly by finite-volume schemes involving either finite-difference slovers or somewhat less frequently, by finite-element algorithms, along with initial and boundary conditions according to the geometries of the scenarios.

There has been a very rapid development of such fire field models and the associated computer codes in recent years, largely due to the general accessibility of large-capacity fast-CPU computing resources [12]. Examples of fire field models include such proprietary fire models as UNDSAFE (University of Notre Dame), SAFEAIR (Thames polytechnic), KAMELEON (SINTEF), JASMINE (Fire Research Station), SOFIE (Cranfield University), CESARE-CFD (Victoria University of Technology) and others, and such commercial codes as PHOENICS (CHAM of North America, Inc.), FLUENT (Fluent, Inc.), COMPACT (Innovative Research, Inc.), and FLOW3D (UK AEA Technology). The proprietary codes are essentially those designed by the fire modelers for their own use and with limited use by others, while the commercial codes are the generic CFD (computational fluid dynamics) codes, which nevertheless can be adapted to fire-scenario applications by incorporating default submodels.

While the base computational structure to numerically solving the governing equations within a specific methodology such as either finite differences or finite elements has only minor differences for the various field models, the noticeable differences are generally in the specific physical submodels used in the codes. Unfortunately, most of the currently available fire field models still suffer some important shortcomings and uncertainties. They refer to two essential requirements for the rational and proper development of any fire field model, namely, computer-code verification and model validation. Computer-code verification deals with the discritization errors, numerical consistency, and solution convergence issues of the numerical-solution algorithms [14]. For any fire field model, it must be demonstratable that the discritization errors are known or at least can be closely estimated, that the numerical errors will approach zero as the mesh size is continuously reduced, and that all iterations in the algorithm must converge satisfactorily. The model validation refers to the adequacy of all the submodels in the overall fire model by comparison with experimental data and also the determination of uncertainties and sensitivities in the submodels relative to disturbances associated with uncertain inputs [12]. There are many submodels in the overall fire field model, and their validation with full-scale fire tests is absolutely essential to determine the adequacy and accuracy of the submodels, and also to asses their limits of application. The latter is particularly important in view of the fact that all fire field models do not have the same degree of capabilities. In addition, because of the inherent uncertainties of experimental conditions, there is also a definite need to delineate the submodel sensitivities due to uncertainties in the geometries and other boundary and initial conditions so that the effects of the uncertainties in the experimental input data could also be assessed.

Unfortunately, most of the fire field-model developers have not been very careful in addressing these two requirements in the application of their models. For instance, very little is offered in general in the discussion of mesh-refinement studies and solution convergence. Validation and verification of their models are largely lumped together by comparing the calculated results with that of limited experimental data, which are often their own. At times, the experiments do not have very well-defined test conditions. Another difficulty is that real-scale fire tests are extremely expensive to carry out and difficult to document completely. On the other hand, full-burn real-scale fire tests designed specifically for fire-model validations do exist, but the results, unfortunately, have only been sparsely used for this intended purpose. A good example is the series of tests carried out in a decommissioned nuclear reactor-containment vessel in Germany [15, 16], which represent probably the most significant and complete fire tests ever conducted in view of the extensive pretest planning and the extreme care going into the detailed data acquisition and analysis. One attempt to simulate some of the test results under forced-ventilation conditions in blind postcalculations has been given in [17].

One of the most important submodels, but also the most difficult, in any fire field model is that of turbulent combustion, which is needed to provide the fire heat load in a given fire scenario. Thus it is not surprising that this submodel is regarded as the weakest link in the entire fire modeling effort [12]. Despite the fact that the mechanisms for turbulent combustion are largely known, there is quite a controversy at to how this phenomenon should be quantitatively described, and an even higher uncertainty is the fact that basic intrinsic quantities needed in the submodel, such as reaction kinetics and pyrolysis parameters, are lacking for combustibles normally found in an inhabited building. Consequently, there is a need for estimating the fire heat load (or fire heat release rate) from a fire in a design fire scenario [18] without the use of a combustion submodel so that the analysis by the fire field model can proceed. Fortunately, there is a general agreement in the field of implementing the performance-based fire codes that the fire load in a given fire scenario can be considered as a design parameter, known as the design fire load, which is in general a function of the materials normally found near a given fire source and the nature of the fire source itself. In the analysis of a design fire scenario, the fire heat load is taken to be a value either based on a typical space where fire is likely to start, or based on an estimated justifiable upper bound or a justifiable bounded range. It is of special interest to note that with such a specification, the application of a fire field model becomes much simplified [12].

4. PROPER USE OF FIRE FIELD MODEL FOR PERFORMANCE BASED FIRE-CODE IMPLEMENTATION

As pointed out before, the current-generation fire field models still suffer from some shortcomings and uncertainties, particularly in the verification and validation of the corresponding computer codes. The computer-code verification only requires some self-discipline on the part of the fire-model developers to document and show once for all the results of analyzing their computer codes for accuracy, consistency, and solution convergence and perhaps also show simulation results of some relevant, for instance, natural- and forced-convection problems which have exact or nearly exact solutions, so that the accuracy of the solution methodology can be demonstrated. On the other hand, the fire field model validation would involve more substantial additional effort by the model developer, since this represents a continuing effort either as more experimental data become available to extend its limits of validity, or as the submodels are improved to be able to cover more of the parameter-space applications as new research findings appear. Only is this way can the fire field model be considered up to date and merits its application as a design tool for performance-based fire-code implementations.

In the meantime it is suggested that the current-generation fire field models be applied with certain degree of care. It is absolutely essential that the building designer or any other user does not apply any such models blindly. The designer must be made aware of all the conditions, assumptions, past verification and validations under which the model is developed, and insure that these constraints are all met in the building design being considered. Uncertainty and sensitivity analyses should be an integral apart of applying the fire field model for the performance-based fire-code compliance. The results are needed to provide data to the designer and the fire-code regulator and others to assess the tolerance of the design for fire safety. It is also important to realize that all real fire scenarios in buildings are complex phenomena and the corresponding fire field-model analyses must go hand-in-hand with what is known from the past experience. Such experience, even qualitatively, is invaluable to provide the underpinning of the correctness of the computer-code analysis to insure its validity. In this regard, it is not difficult to appreciate the need for the establishment of a data base to include full documentations of real-life fire-safety and fire-hazard records in buildings and also of the results of fire field-model analyses of the design fire scenarios based on the specific design fire loads for future reference and use.

Furthermore, the fire field model should not be applied too rigidly, but serve as a flexible tool in which the basic fire-field model can be judiciously simplified to adapt to the needs of the specific scenario under consideration. The case of replacing the turbulent combustion submodel in the complete fire model by a justifiable fire heat load, for instance, is a good illustration of a useful flexibility in the application of fire field models. Another similar example is the successful replacement of the combustion submodel with a heat-release rate provided by a separate zone model, as demonstrated in [17]. Another illustration is the simplification of the model when the design scenario is only concerned with the smoke and toxic-gas movement in building corridors and in the smoke filling of rooms, staircase refuges, and elevator shafts. In this case, combustion and radiation submodels can be conveniently shut off, and also likely so can be the temperature field and gas-compressibility effects. Also in some other cases, it may be justifiable to carry out numerical simulations in two dimensions only or without time dependence under either steady or quasi-steady conditions. In either scenario, considerable simplifications will result.

As we begin to appreciate more and more the potential of applying the fire field models as a critical design tool for the implementation of performance-based fire codes and the needs for advanced engineering capabilities to apply such models to real and design fire scenarios, we will start to realize that fire-safety engineers must certainly be properly trained in this developing technology. Therefore, it is imperative that the technology of fire field models and their applications be made a necessary part of the educational and training programs for prospective fire-safety engineers and professionals.

5. CONCLUDING REMARKS

The worldwide movement from prescription-based to performance-based fire codes is unmistakable and irreversible. To implement the performance-based fire codes for building design requires basic and innovative engineering design tools to satisfy the performance requirements for fire safety. Potential fire scenarios must be identified and evaluated for relative fire hazards and risk assessment. One such engineering design tool needed for fire-safety considerations is the use of fire models to simulate a variety of fire-hazard scenarios so that proper fire-safety contermeasures can be designed and implemented. More promising is the fire field models which deal with the dynamic fire phenomena seamlessly in space and time, in a way similar to that occurring in real fires.

They are also more basic and generic, as their computed behaviours satisfy all the physical conservation and geometrical requirements. It is thus clear that we will see increasingly more uses of these fire field models for fire-safety analyses in buildings, particularly in view of the fact that increasingly, computing resources are no longer a critical limitation to such analyses.

The current-generation fire field models, despite their recent advances in both fidelity and capability, still suffers some shortcomings and uncertainties, largely in terms of the computer-code verification and even more importantly, the fire-model validation. There is a certain lack of self-discipline on the part of the model and code developers to demonstrate the numerical accuracy, consistency, and the guarantee to converged numerical solutions of the developed numerical code. Also, there are insufficient effort to validate the fire models, despite the existence of excellent experimental data sets which are specifically designed to validate the fire field models [15,16]. Such validations are necessary and must be taken as continuous efforts to insure the correctness and accuracies of the submodels in the overall fire field model, as well as to constantly assess the limits and uncertainties of these models, when such models are to be upgraded by new and refined submodels.

Also, when fire scenario analyses are carried out by using the fire field models, it is imperative that the results be compared to those of similar scenarios in the past real-fire records and also in the past field-model analysis to insure their correct trends. It is therefore desirable to establish a well-documented data base for this purpose. Furthermore, it is not always necessary to use the complete fire field model to deal with all fire-safety scenarios. In many cases, simplifications are often possible as dictated by the specific scenarios and proper judgement of the building designer.

Finally, similar to the paradigm shift to the performance-based fire codes, the proper use of the fire field model requires specific engineering training and detailed knowledge of the theory and application of the fire field models for the prospective building designers, the code regulator and other professionals in the broad fire-safety industry. Such trainings can best be done in fire-safety educational degree programs along with other fundamental trainings in engineering analysis and design.

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