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A WAY TO CHARACTERIZE THE RANGE OF VALIDITY OF A FIRE MODEL

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The use of fire models currently extends beyond the fire research laboratories and into the engineering, fire service and legal communities. Sufficient evaluation of the models is necessary to ensure that users can judge the adequacy of its technical basis, appropriateness of its use, and confidence level of its predictions. The model evaluation process consists of two main components: verification and validation [1]. Verification is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate; only that the equations are being solved correctly. Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Differences that cannot be explained in terms of numerical errors in the model or uncertainty in the measurements are attributed to the assumptions and simplifications of the physical model.

It is commonly assumed by model users that verification and validation (V&V) is the responsibility of the model developers. Certainly, developers do a considerable amount of this type of work, in particular verification, but it is impossible to ensure that the model is "validated" for every conceivable application. Indeed, the very point of numerical modeling is to predict the outcome of fire scenarios that have not, or cannot be, replicated in a controlled laboratory environment. Thus, the burden of V&V must be shared by the model developer and user. The benefit to the user is two-fold: first, it confirms that the user can use the software properly, at least for the given application; and second, it assures the user that the model can address the given fire scenario, even providing the user with some estimate of its accuracy.

This paper presents a relatively simple way that a user can determine if a particular application of the model has been validated. For example, suppose the problem at hand is a fire in a warehouse with a 10 m ceiling, sprinklers, roof vents, and HVAC system. There is probably no experimental data set that is exactly like it, and it would be too expensive to conduct new experiments. How does one determine if any validation work is appropriate for this scenario? The approach taken in a recent validation study conducted by the U.S. Nuclear Regulatory Commission (NRC) and the Electrical Power Research Institute (EPRI) was to characterize the experiments used in the study in terms of a handful of commonly used non-dimensional quantities from the fire literature [2]. This essentially defines the "parameter space" for which the model was validated. The fire protection engineers using the models as part of their PRAs (Probabilistic Risk Assessments) are warned that the models can only be applied within this parameter space. This prevents the tendency by users to simply declare that the model has been validated and can be used for any application.

The non-dimensionalized parameters used in the NRC/EPRI study are:

Fire Froude Number, $\dot{Q}^*$

$$Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{gD} D^2} \tag{1}$$

where $\dot{Q}$ is the peak heat release rate of the fire and D is the equivalent diameter of the base of the fire. The Fire Froude Number is a useful non-dimensional quantity for plume correlations and flame height estimates. A large value of $\dot{Q}^*$ describes a fire for which the energy output is relatively large compared to its physical diameter, like an oil well blowout fire. A low value describes a fire for which the energy output is relatively small compared to its diameter, like a brush fire. Most common accidental fire scenarios have $\dot{Q}^*$ values on the order of 1.

Flame Height relative to Ceiling Height, L_f/H, is a convenient way to express the physical size of the fire relative to the size of the room. A value greater than one indicates that there is flame impingement on the ceiling, an important consideration when evaluating devices such as sprinklers and smoke detectors. The Flame Height, L_f, is the height of the visible flame, based on Heskestad's correlation:

$$L_f = D\left(3.7\,(\dot{Q}^*)^{2/5} - 1.02\right) \tag{2}$$

Global Equivalence Ratio, ϕ, is the ratio of the mass flux of fuel from the fire to the mass flux of oxygen into the compartment, divided by the stoichiometric ratio.

$$\phi = \frac{\dot{m}_f}{r\,\dot{m}_{\mathrm{O}_2}} \equiv \frac{\dot{Q}\,(\mathrm{kW})}{13,100\,(\mathrm{kJ/kg})\,\dot{m}_{\mathrm{O}_2}} \quad ; \quad \dot{m}_{\mathrm{O}_2} = \begin{cases} \frac{1}{2}\,0.23\,A_0\sqrt{H_0} & \text{Natural Ventilation} \\ 0.23\,\rho\,\dot{V} & \text{Mechanical Ventilation} \end{cases} \tag{3}$$

Here, r is the stoichiometric ratio, A_0 is the area of the compartment opening, H_0 is the height of the opening, ρ is the density of air, and $\dot{V}$ is the volume flow of air into the compartment. If $\phi < 1$, the compartment is considered "well-ventilated" and if $\phi > 1$, the compartment is considered "under-ventilated." In general, under-ventilated fire scenarios are more challenging for the models because the combustion physics are more complicated.

Relative Distance along the Ceiling, r_{cj}/H, indicates the distance from the fire plume of a sprinkler, smoke detector, *etc.*, relative to the compartment height, H. The maximum ceiling jet temperature, important in determining device activation, has been shown to be a function of this ratio.

Relative Distance from the Fire, r_{rad}/D, indicates whether a "target" is near or far from the fire. In general, it is more challenging to predict the radiative heat flux to objects near the fire.

Room Length and Width relative to the Ceiling Height, L/H and W/H, are useful mainly when assessing an empirical or zone model because most of the correlations used by these models are limited in terms of compartment aspect ratio. For CFD, extreme values of these ratios might indicate unusual fire behavior.

Ceiling Height relative to the Fire Diameter, H/D^*, is a non-dimensional measure of the height of the fire plume. D^* is length scale that incorporates the heat release rate of the fire.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \tag{4}$$

The larger this ratio, the more important the plume becomes in the overall scenario. For empirical and zone models, it indicates whether or not the plume entrainment correlation is appropriate. For CFD, it indicates how "high" the plume actually is, in non-dimensional terms.

The ranges of these parameters for the current set of experiments in the FDS validation suite is included in Table 1. Essentially, these parameters answer basic questions about the nature of the fire scenario. For example, is the fire large relative to the enclosure? Is it a jet fire? Is the compartment unusually shaped? At the extremes of the parameter space, the physical assumptions in the model may or may not be expected to be valid.

The purpose of Table 1 is to ensure that those citing the FDS Validation Guide determine whether or not their particular application of the model falls within parameter space for which the model has been evaluated. This is a necessary, but not sufficient, condition for saying the model is validated. These parameters help the user narrow down the list of relevant fire experiments. The next step in the validation process is to study the comparisons of model predictions and experimental measurements for these experiments to determine if the predictions are of sufficient accuracy for the application at hand.

Table 1: Summary of the major experimental parameters in the FDS Validation Suite.

Test Series	$\dot{Q}$ (kW)	D (m)	H (m)	Q^*	D^* (m)	L_f/H	ϕ	H/D^*	$W/H - L/H$	r_{cj}/H	r_{rad}/D
Arup Tunnel	5344	1.6	7	1.4	1.8	0.8	0.03	3.8	1.1 – 42.9	0 – 1.1	N/A
ATF Corridors	50 – 500	0.5	2.4	0.3 – 3.1	0.3 – 0.7	0.3 – 1	0.01 – 0.07	8.5 – 3.4	0.8 – 7.1	0.8 – 6	N/A
Bryant Doorway	34 – 511	0.3	2.4	0.4 – 6.4	0.2 – 0.7	0.3 – 1	0.01 – 0.16	9.9 – 3.4	1 – 2.1	0.6 – 0.8	N/A
CSTB Tunnel	1965 – 2484	0.8	1.9	2.9 – 3.7	1.2 – 1.3	2.1 – 2.4	0.04 – 0.05	1.5 – 1.4	1.3 – 28.4	1.6 – 12.6	N/A
FM/SNL	470 – 516	0.9	6.1	0.5 – 0.6	0.7	0.3	0.2	8.8 – 8.5	2 – 3	0.2 – 0.3	N/A
Hamins Burner	0.4 – 162	0.1 – 1	Open	0.1	0 – 0.5	Open	Open	Open	Open	N/A	0.1 – 12
Heskestad	$10^2 – 10^7$	1.1	Open	$10^{-1} – 10^4$	0.4 – 44	Open	Open	Open	Open	N/A	N/A
LLNL Enclosure	50 – 400	0.6	4.5	0.2 – 1.4	0.3 – 0.6	0.1 – 0.4	0.03 – 0.22	15.9 – 6.9	0.9 – 1.3	0.3 – 1	N/A
McCaffrey Plume	14 – 57	0.3	Open	0.2 – 0.7	0.2 – 0.3	Open	Open	Open	Open	N/A	N/A
NBS Multi-Room	110	0.3	2.4	1.4	0.4	0.4 – 5.2	0.12	6.2	1	0.5 – 0.7	0.9 – 2.4
NIST RSE	50 – 600	0.15	1	4.9 – 58.4	0.3 – 0.8	1 – 2.9	0.1 – 1.15	3.5 – 1.3	1 – 1.5	N/A	N/A
NIST/NRC	350 – 2200	1	4	0.3 – 1.9	0.6 – 1.3	0.4 – 1	0.04 – 0.7	6.5 – 3.1	1.8 – 5.4	0.3 – 2	2 – 4
NRCC Facade	5000 – 10300	4.3	2.8	0.1 – 0.2	1.8 – 2.4	1 – 1.8	2.5 – 5.2	1.5 – 1.2	1.6 – 2.2	N/A	0
NRL/HAI	50 – 520	0.3 – 0.7	Open	1 – 1.1	0.3 – 0.7	Open	Open	Open	Open	N/A	0.3 – 8
Sandia Plume	2025 – 5450	1	Open	1.7 – 4.6	1.2 – 1.8	Open	Open	Open	Open	N/A	N/A
SP AST	450	0.3	2.4	5.7	0.7	1	0.13	3.5	1 – 1.5	N/A	N/A
Steckler	31.6 – 158	0.3	2.1	0.7 – 3.5	0.2 – 0.4	0.3 – 0.7	0.01 – 0.6	9.1 – 4.8	1.3	N/A	N/A
UL/NFPRF	4400	1	7.6	3.7	1.7	0.8	0	4.5	4.9	0.1	N/A
Ulster SBI	30 – 60	0.2	Open	1.4 – 2.8	0.2 – 0.3	Open	Open	Open	Open	N/A	1 – 7.5
USCG/HAI	250 – 1000	0.3	3	5.6 – 22.4	0.5 – 0.9	0.6 – 1.1	0.26 – 1.02	5.6 – 3.2	1.7 – 2.3	0 – 0.8	6 – 15
USN Hawaii	100 – 7700	0.3 – 2.5	15	1.3 – 0.7	0.4 – 2.1	0.1 – 0.4	0	40.3 – 7.1	4.9 – 6.5	0 – 1.2	N/A
USN Iceland	100 – 15700	0.3 – 3.4	22	1.3 – 0.6	0.4 – 2.8	0.1 – 0.4	0	59 – 7.8	2.1 – 3.4	0 – 1	N/A
Vettori Flat	1055	0.7	2.6	2.3	1	1.2	Closed	2.8	2.1 – 3.5	0.8 – 2.9	N/A
Vettori Sloped	1055	0.7	2.5	2.3	1	1.2	0.23	2.6	2.2 – 2.9	N/A	N/A
VTT Large Hall	1860 – 3640	1.4 – 1.8	19	0.7	1.2 – 1.6	0.2	0	15.8 – 12.1	1 – 1.4	0 – 0.6	N/A
WTC	965 – 1460	1	3.8	0.8 – 1.2	0.9 – 1.1	0.7 – 0.9	0.5 – 0.7	4.1 – 3.5	0.9 – 1.8	0.1	0.5 – 2

References

[1] *ASTM E 1355-04, Standard Guide for Evaluating the Predictive Capabilities of Deterministic Fire Models*, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 2004.

[2] K. Hill, J. Dreisbach, F. Joglar, B. Najafi, K. McGrattan, R. Peacock and A. Hamins, *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, NUREG-1824, United States Nuclear Regulatory Commission, Washington, D.C., 2007.