Development and Validation of a Modified Hold Time Model for Total Flooding Fire Suppression

Todd M. Hetrick[1]*, Ali S. Rangwala[1], Paul E. Rivers[2]

[1] Worcester Polytechnic Institute
100 Institute Rd., Worcester, MA 01609

[2] 3M Company
St. Paul, MN 55144-1000

* Corresponding author is currently employed by Exponent, Lisle, IL.
email: thetrick@exponent.com; phone: 508.963.5833

Abstract

This study analyzes the validity of theoretical models used to predict the duration (hold time) for which a halon-replacement suppression agent will remain within a protected enclosure. Two current models and one new formulation are investigated; the sharp descending interface model (as applied in NFPA 2001, Annex C), the wide descending interface model (implemented in ISO 14520.1, Annex E), and the thick descending interface model (introduced herein). Experimental data from 34 full-scale tests designed to characterize the discharge and draining dynamics of seven clean extinguishing agents (CEA) are used to validate the thick descending interface model. Results show that the validity of the wide and sharp interface models is highly sensitive to the threshold of agent concentration decay being modeled; whereas the thick interface prediction method is not greatly susceptible to this input parameter. When the hold time is determined as a 15% decay in agent concentration, experimentally obtained hold time values are roughly 10% shorter than sharp interface predictions, 60% longer than wide interface predictions, and 30% longer than the thick interface model predicts.

Introduction

The sharp descending interface and the wide descending interface models use well established theory on orifice flow and worst case assumptions to model the decay of Clean Extinguishing Agents (CEA) concentration as a function of time and elevation. Theoretical considerations and model construction are discussed elsewhere [1-9]. A previous paper by Hetrick and Rangwala [Hetrick, SUPDET08] showed experimental data from 34 full-scale tests designed to characterize the discharge and draining dynamics of seven clean extinguishing agents (CEA), and to validate these models. Results show that the validity of the wide and sharp interface models is highly sensitive to the threshold of agent concentration decay being modeled. With this in mind, this study develops a new model called the *thick interface model* that captures the draining of CEA better than the sharp and wide interface models.

Figure 1 shows the agent concentration profiles in three hold time models considered in this study. The thick interface model is a newly proposed model developed in this study.

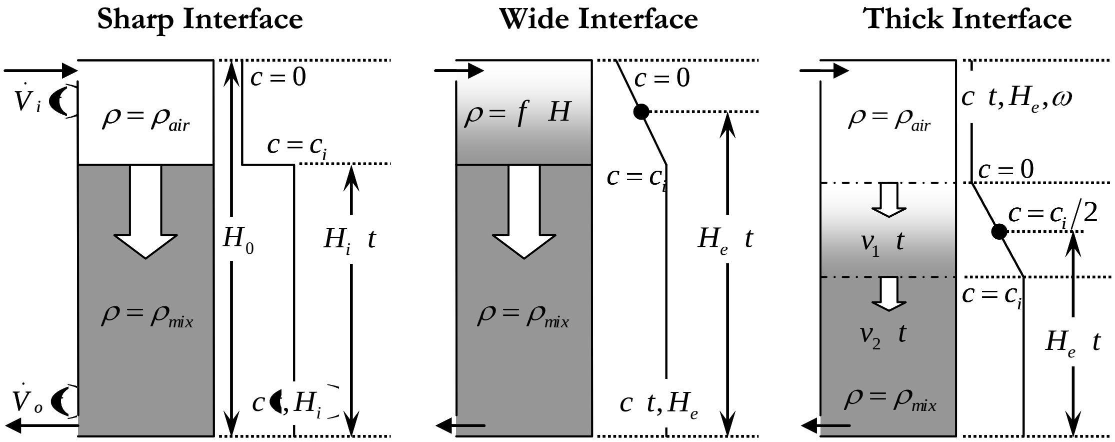

Figure 1 – Concentration distribution of agents in the sharp, wide and thick interface models. The thick interface is a new model proposed in this study. The thickness of the interface is estimated from test data of 34 full scale tests. The volumetric gas flow in and out of the enclosure is designated by V_i and V_o. Volumetric agent concentration, *c*, is initially equal to c_i at time zero. The gas density, ρ, is given for 'air' and the 'mix' of agent and air at the discharge concentration, c_i. The interface's elevation is given by the variable, *H*, where the subscripts '0' and 'e' stand for initial and equivalent.

Assuming that gas species do not diffuse results in an infinitesimally thin interface between inflowing fresh air and the agent-air mix resulting after discharge. The wide interface model assumes that inflowing fresh air mixes instantaneously with the agent-air mixture to form a linear decay of agent concentration from the leading edge of the interface, H_i, to the uppermost elevation in the protected enclosure. These two conditions represent theoretical extremes of a stratified model formulation. In this study gas diffusivity is formulated such that it provides a compromise between the sharp and wide models. The *thick descending interface* model assumes that the interface has a characteristic thickness across which the agent concentration is assumed to decay linearly. At time zero the interface does not exist. As fresh air begins to flow in it mixes with the top of the column of agent air, forming a linear concentration decay through elevation. Given enough time, the interface grows to a maximum characteristic thickness and begins to descend towards the floor. When the leading edge of the interface reaches the floor's elevation the interface gradually begins to decay in thickness. Eventually, the interface disappears, all agent has drained from the enclosure, and only fresh, atmospheric air remains.

The interface thickness arises from a balance between gravity and gas diffusion. The resulting agent profile from these forces is transient and forms a highly nonlinear interface between two gas species. The clean agent type, enclosure dimensions, enclosure obstacles, buoyant plumes above heat sources, and leaks located at various elevations in the walls pose too many unknowns. Given our current state of knowledge, a concise theoretical formulation for the characteristic thickness is not possible and as such, the characteristic thickness must be evaluated experimentally. After conducting 34 tests on 7 agent types, it is found that the characteristic thickness is a constant in time and also nominally has the same value for various agent types [5].

Thick Interface Model

Figure 2 illustrates a method of assessing the time resolved interface thickness. HFC-23 experimental data is used as a sample case to analyze the thick interface model proposed in this work[1]. The relationship between elevation and concentration is assumed to be linear. At each time step a linear regression is computed for all data points that exist within a concentration range of 15% to 85%. Inclusion of all available data points would skew the linear regression and result in poor interface

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[1] This experiment's data is arbitrarily chosen for demonstration purposes in Figures 2 and 3. The sharp interface model is used to predict a 13 minute hold time; indicating that this particular test is similar to typical total flooding systems in use today.

representation. Additionally, at each time step a linear regression is computed with at least 3 data points (no regression lines appear for the uppermost and lowermost data series).

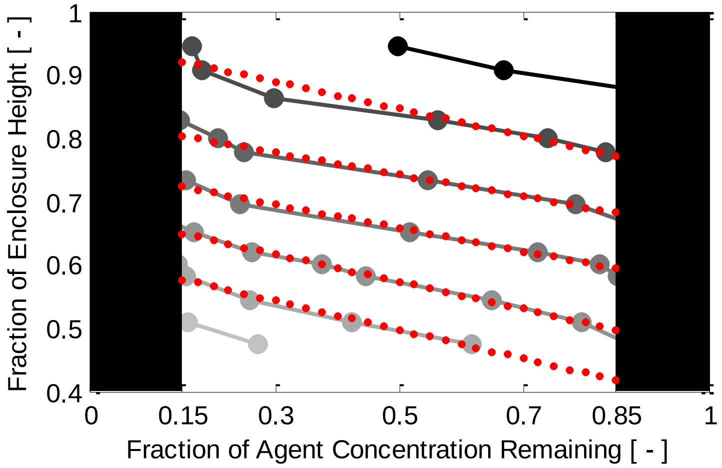

Figure 2 – Diagram of interface thickness analysis procedure. Agent concentration data is transformed onto fractional elevation and concentration axes. Each data series represents a single snapshot in time; time progression is indicated by the change in color from black towards white. At each snapshot in time, the red data series approximate the agent concentration profile as being adequately represented by a linear relationship between elevation and concentration.

The slope of the regressed line (red dotted lines),

$$\omega = \frac{\left(\Delta H/H_i\right)}{\left(\Delta C/C_i\right)},$$

is equal to the ratio of the fractional change in elevation to the fractional change in concentration. When the denominator is assumed to equal one (representing the change from null to full agent concentration), the characteristic interface thickness, ω, is equal to the fractional interface width, $\Delta H/H_0$.

Figure 3 shows the regressed dimensionless interface thickness as a function of the dimensionless time for the exemplar HFC-23 data set[1]. The interface slope analysis procedure (demonstrated in Figure 2) can be repeated at each data acquisition time step (5 second intervals in this study) to determine the dependency of the interface thickness to time. In general, the dimensionless interface thickness ranges between 0.15 and 0.25. This represents an interface thickness between 15% and 25% of the enclosure's maximum height.

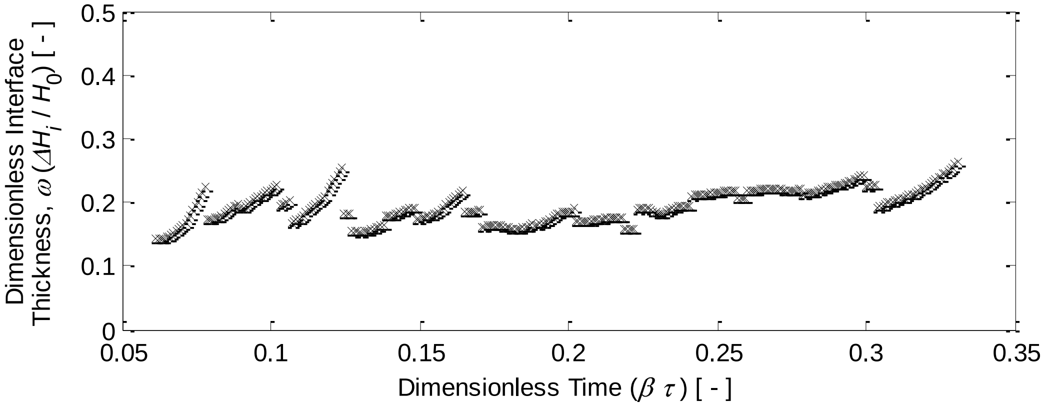

Figure 3 – Dimensionless interface thickness versus dimensionless time. The analysis method of Figure 2 is repeated at each data collection time step (every 5 sec. herein); yielding the transient, observed behavior of the interface thickness as the interface itself descends through the enclosure's elevation. The dimensionless time, $\beta\tau$, is presented elsewhere [4,5,8].

It is observed that the characteristic thickness is relatively constant as the agent drains out of the enclosure. Figure 3 shows that the interface thickness is nominally a constant throughout the experimental duration. One would expect the agent-air interface region to widen with progressing time; however, this is not well supported in Figure 3.

Figure 3 is compiled from the results of a single experiment. The same exercise can be completed for each of the 34 hold time tests conducted as part of this study. Analysis of the regressed parameter, ω, in conjunction with other influential, controlled, experiment variables does not yield a reliable method of predicting its value. Further insight into the observed behavior of the parameter, ω, is divulged elsewhere [5]. It is found however, that a value of 0.25 reasonable represents the observed data set. For this reason, hold time predictions for the thick descending interface are computed assuming that $\omega = 0.25$ in this study.

Results and Discussion

The hold time model is validated by comparing the theoretical and experimentally observed hold times as shown in Figure 4. In order to provide direct comparisons between experiments with various agent types and differing amounts/distributions of leakages the hold time is best expressed in dimensionless units[2]. Due to the semi-subjective nature of the *hold time*, three plots are provided; each assuming a different threshold for agent concentration. The elevation threshold at which the hold time is defined need not be incremented in the plots below as all elevations are simultaneously visualized (a dimensionless hold time value of 0 represents the hold time at the maximum elevation and a value of 1 represents the hold time at the minimum elevation).

A line of 'exact correlation' and dashed lines representing incremented error thresholds are included in each subplot of Figure 4. Data values on the line of exact correlation represent when experimental and theoretical hold times are equal. The error threshold lines represent percent deviations in the experimentally observed hold time values relative to the theoretical prediction. Data points lying below the line of perfect correlation represent a conservative condition where the experimental hold time duration is longer than the predicted value. Data values above this line represent a non-conservative scenario where the models predict an overly optimistic hold time.

All experimental hold time values are depicted three times in each plot; once for each of three hold time models under consideration. Plotted data points are colored by theory type and assume a marker shape based on agent type. The affect of agent type on model validity is difficult to discern. In general, no particular agent type can be observed to stand out from the others. This indicates that the clean agent type being modeled does not have a significant affect on model validity. On the other hand, the theoretical model used has a significant impact on model validity.

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[2] Both experimental and theoretical values of the hold time are charted as the quantity, $\beta\tau$, which is presented in depth elsewhere [4,5,8].

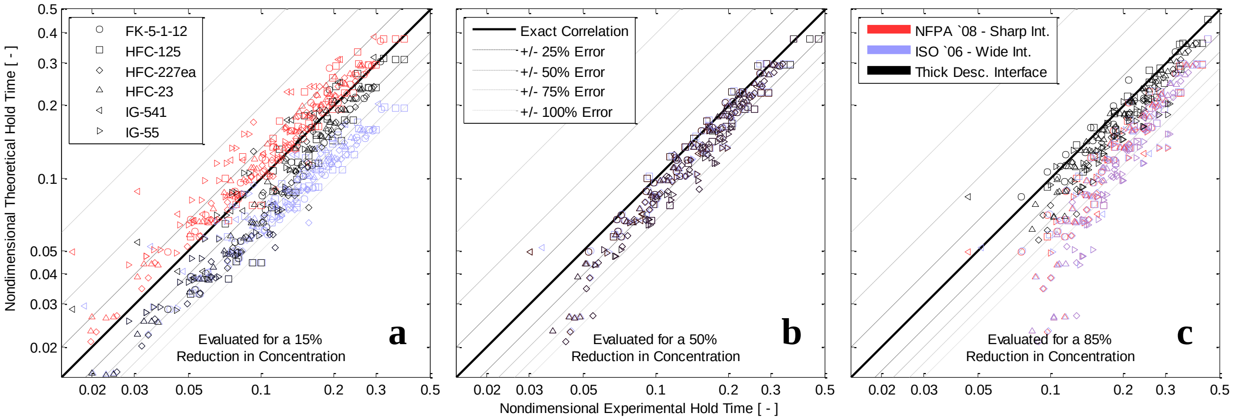

Figure 4 – Validation plots of the dimensionless theoretical hold time versus the dimensionless experimental hold time for a 15%, 50% and 85% decay in agent concentration. Plotted values are calculated as the quantity $\beta\tau^2$. Error lines represent percent deviations from the theoretical hold time prediction. Each legend is applicable to each of three charts.

A significant portion of the data shown in Figure 4a lies in the non-conservative region (above the 45° solid line). The newly introduced, thick descending interface model is shown to provide more accurate predictions of the hold time for a 15% drop in agent concentration than the other existing theories. Thick interface data points (black) populate the region of the axes between that of the sharp and wide theories. Hold times at lower left (measurements taken from upper elevations) are commonly one-and-a-half to two times the predicted value but as the interface descends to approximately one half of the enclosure height (advancing to the upper right) the data center at the line of exact correlation.

The thick interface formulation behaves identically to the wide interface, as the thickness initially develops, and then transfers to that of the sharp interface's descent once the characteristic thickness is met. This crossover in behavior is apparent in Figure 4a. Initially, the thick interface data overlaps that of the wide interface and eventually it is observed to populate a different region of the chart. This appears to occur at a dimensionless theoretical time of ~0.05, which represents the interface passing an elevation of ~85% of maximum enclosure height.

The wide descending interface model (ISO 14520) results in experimental hold times that are up to 75% longer than predicted when the hold time is regarded as a 15% decay in concentration. This overly conservative trend is mostly constant through time/elevation as the interface descends and results in system designers not being able to justify whether a 10 minute hold time can be met; even when many total flooding systems can easily retain the necessary clean agent concentration for this duration.

Figure 4b assumes the hold time to represent a 50% decay in agent concentration. Because each of the three theories models this concentration threshold equally, most data points directly overlap one another. ISO and NFPA standards adopt slightly different values of the vapor density of agents, the density of atmospheric air, and methods of measuring the amount of leakage present in an existing structure. Due to this, slight jitter is observed between wide and thick data points. The thick interface model is operated with the same assumptions as the sharp interface model, thus perfectly overlapping all of these data points (no red data visible).

Figure 4c assumes the hold time to represent an 85% decay of the initial agent concentration or, in other words, only 15% of the total agent remains in the enclosure. From an industrial application, an 85% decay of agent is usually not applicable. However, hold time results are presented in this case as well to demonstrate the versatility of the thick descending interface model. In Figure 4c, the plotted theoretical hold time values of the sharp and wide theories are the same as those in Figure 4b. Either of these existing theories do not support a 15% agent remaining input value and therefore are not meant to be applicable in this range.

Conclusions

The inadequacy of the analytical models stated above is partially mitigated through use of the *thick descending interface model*. This model reformulates the simplifying assumption for where the suppressant accumulates within the design enclosure as resolved in elevation. A result of this is the need for users to define an additional input parameter, the characteristic interface thickness. For the purposes of model validation herein this parameter is regressed from the experimental data although further work may be required to establish the independence of this parameter from other system design and environmental variables.

References

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