Effects of Moving Boundary and Expansion Ratio of High Expansion (HiEx) Aqueous Foam on Fire Suppression

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High expansion (HiEx) aqueous foams are only 3x heavier than air and contain 500x more air than water by volume. It can fill a hangar bay in less than a few minutes. They are being considered for fighting three-dimensional fires in large, confined, obstructed, inaccessible shipboard spaces [1] with relatively small mass of water. Despite a long history of HiEx aqueous foams for hangar bay applications, the extinction pathways by which the foam suppresses the fire are not known. Wilder [2] performed pilot scale tests on HiEx suppression of Class A, B, and C fires inside an 8 ft^3 compartment. He reported that below a critical value of foam injection rate or above a critical value of foam's expansion ratio, fires were not extinguished. The precise mechanisms responsible for the observed limiting behavior remain unclear. It is also not clear how the critical values of the application rate and expansion ratio depend on other parameters.

We have developed a multiphase, computational model for HiEx extinction dynamics of a laminar, co-flow, diffusion flame formed in a cup-burner. The cup-burner is a bench-scale apparatus commonly used to evaluate suppression agents (Sheinson *et al.* [3]). A diffusion flame is formed by the combustion of a steady jet of propane gas rather than a liquid pool. The propane jet flame is expected to be more difficult to extinguish than the liquid pool because the fuel flow is fixed, independent of the heat feedback from the flame to the burner surface. We adapted the co-flow configuration to foam suppression for the first time. Foam is assumed to be generated outside the burner using ambient air. A stable diffusion flame is established first, before the foam of prespecified expansion ratio is injected at a pre-specified rate. We obtain numerical solutions of the laminar, transient, Navier-Stokes and energy equations using volume of fluid (VOF) conservation equations with the computational fluid dynamics (CFD) software package Fluent in cylindrical geometry [4]. Fluent does not contain models, which are designed for foam. Therefore, we developed a pseudo-fluid foam sub-model separately, and coupled to Fluent.

Figure 1 describes interactions between aqueous HiEx foam and a flame, which entrains surrounding air to sustain combustion reactions. The foam consists of a network of air bubbles with water contained mostly at the bubble intersections known as Plateau borders. As the foam is injected, it quickly surrounds the flame and forms a barrier to the air entrainment at the flame base. This cuts off oxygen supply and "smothers" the flame. The foam's viscosity is much larger than that of water and has significant effect on foams ability to flow radially into the flame. As the foam flows towards the flame, it evaporates and causes four effects, which are; (1) latent heat absorption from hot gases, (2) oxygen dilution by the water vapor formed by evaporation, (3) sensible heat absorption by the water vapor due to its higher specific heat (twice) than air, and (4) evaporation of foam also releases air from foam bubbles and supplies oxygen to the flame. Clearly, evaporation of foam causes competing effects on the combustion reactions. Our simulations [4] showed that as the foam injection rate is increased, the smothering effect dominates and causes flame extinction. On the other hand, as the foam injection velocity is

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decreased below a minimum value, the flame spreads across the foam surface to obtain oxygen, and the flame is not extinguished for a fixed foam expansion ratio of 1000 [4].

In Figure 2, we scale the extinction time by dividing with the time (cold fill time) it takes to fill the cup-burner in the absence of a flame. At a fixed foam injection rate 16 feet per minute, the ratio (extinction time)/(fill time) is equal to the ratio (quantity of foam needed to extinguish the flame)/(quantity of foam needed to fill the burner in the absence of the flame). Extinction time is the time required to completely drive the flame and all the associated hot gases (plume) out of the cup-burner. Figure 2 shows the effect of foam expansion ratio (Ex) on the scaled extinction time. It shows the best fit to the computations as a solid line, and the actual computations are shown as solid dots. As Ex increases from 200 to about 1200, the scaled extinction time increases from 0.5 to 2. When the scaled extinction time is half, only half of the full quantity of foam is needed to extinguish the flame. Figure 2 shows that at Ex>625, the scaled extinction time is greater than 1. Figure 2 also shows the pilot scale data of Wilder [2] for class A and B fuels. The foam injection rate was not reported for these data. But, it could be between 2 to 5 feet per minute (fpm). At these low injection rates, our computations predicted no extinction for the cup-burner flame. Therefore, the cup-burner computations over predict the scaled extinction time relative to Wilder's pilot data for Class A and B fuels as one might expect.

Figures 3 and 4 illustrate temperature contours for the computations shown in Figure 2 at Ex = 250 and 2000 respectively. The foam injection rate is fixed at 16 fpm in both simulations. It shows that the foam has completely covered the inner fuel tube. The fuel gas is ejected from the foam surface as a very thin jet because fuel is continued to be supplied at a constant rate. Even though the combustion reaction rate is completely suppressed to near zero, the hot gases are still being driven out by the foam at a time just before extinction. At extinction, the entire burner is at ambient temperature. As Ex is increased to 2000, Figure 4 shows no extinction. The flame base spreads along the surface of the foam, and the hot gases occupy essentially the entire burner. Clearly, the increased Ex reduces the effectiveness of the foam at a fixed injection rate.

Conclusions

Moving boundary solutions to the Navier-Stokes equations are obtained by volume of fluid (VOF) approximation. The simulations show that increased foam injection rate and decreased expansion ratio favor flame extinction. At low expansion ratios, less than full quantity (for cold-fill) of foam is required to extinguish the flame.

Acknowledgements

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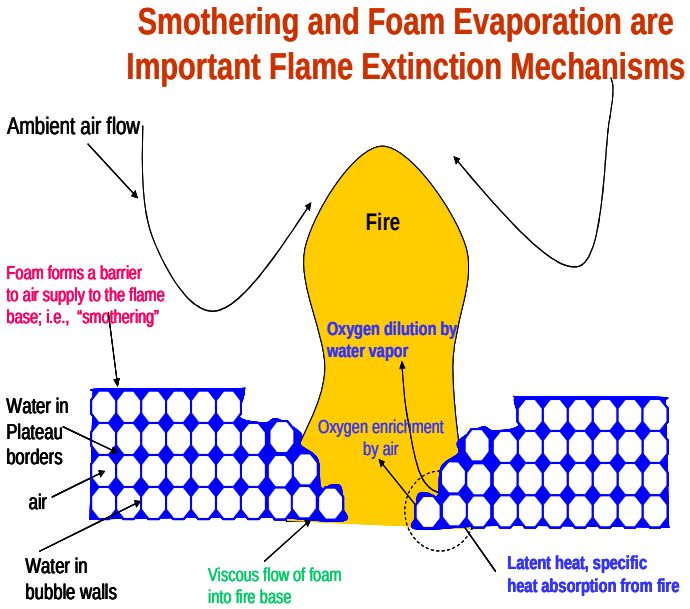

Figure 1. Schematic of extinction mechanisms

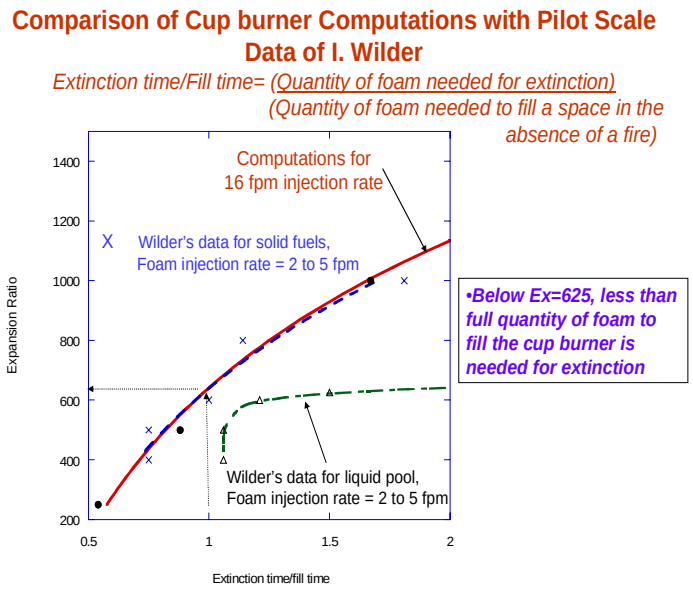

Figure 2. Effect of Ex on scaled extinction time

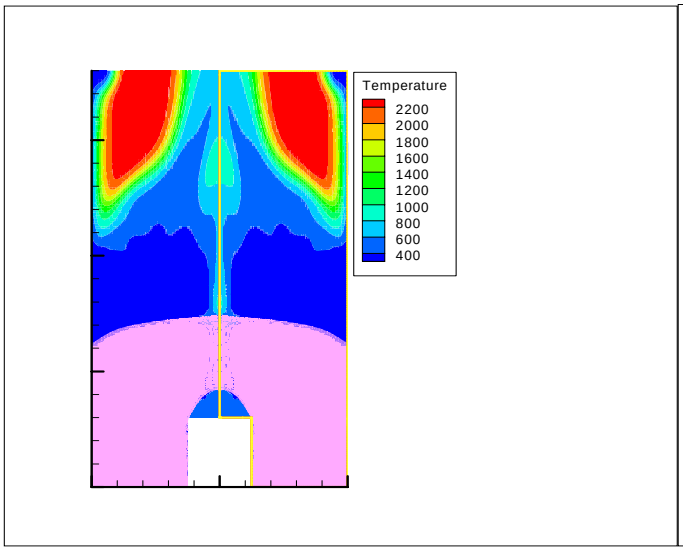

Figure 3. Contours of gas temperature for Ex=250

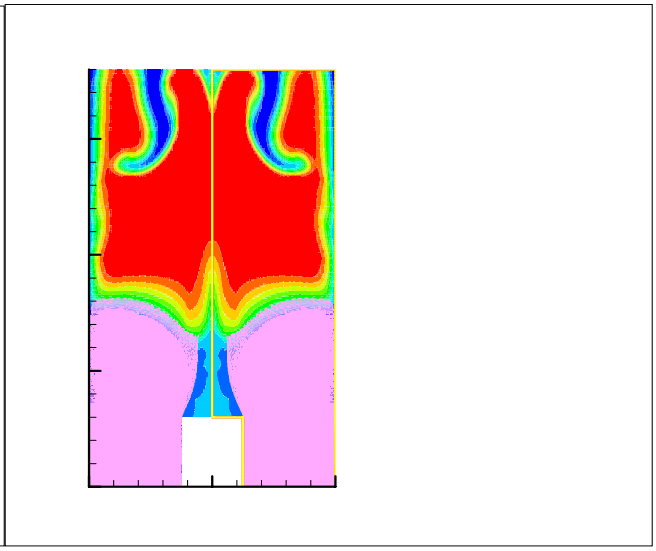

Figure 4. Contours of gas temperature for Ex=2000