High Expansion (HiEx) Aqueous Foam Suppression of a Cup-burner Flame

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High expansion (HiEx) aqueous foam has great potential for extinguishing fires in confined, obstructed, inaccessible shipboard spaces [1]. In a highly obstructed space, fires collect behind obstructions or underneath machinery and are difficult to be reached by traditional water or foam (low expansion) spray systems. Despite a long history of HiEx aqueous foams for hangar bay applications, very few studies addressed the chemical and physical interactions between the foam and a fire. Specifically, the extinction pathways by which the foam suppresses the fire are not known. How do the flow properties (viscosity and yield stress) and thermal properties (evaporation rates, radiation absorption) affect foam entrainment and fire extinguishment? How does the foam structure (bubble size distribution, expansion ratio) affect the thermal and flow properties? The relationship between foam structure and yield stress at ambient conditions is a subject of active research [2], but, very little work is available on thermal properties of the foam.

We have developed a multiphase, computational model for 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. The overall flame extinction model development follows closely the methodology described by Ananth and Mowrey [4], who adapted the cup-burner for the water mist problem. In the present work, we will adapt the co-flow configuration to foam suppression for the first time. Foam is assumed to be generated outside the burner with Ex=1000 using ambient air. A stable diffusion flame is established first, before the foam 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. Fluent does not contain models, which are designed for foam. Therefore, a pseudo-fluid foam sub-model is developed separately, and coupled to Fluent.

Simulations were performed for foam injected at the base of the annular region between two concentric tubes (10 and 2.5 cm diameter) at a velocity of 1 cm/sec (2 fpm) and for pure propane gas injected at the base of the inner tube at 1 cm/sec (STP). As the foam approaches the flame, hot layer builds up in the top half of the outer tube (18 cm long) due to large vortices in the plume, which extends the entire width of the chimney (outer tube) unlike the case without the foam. The vortices are also closer to the base of the flame and cause puffing instabilities. The foam begins to evaporate at the outer edges of the inner tube due to heat transfer from the flame to the foam surface. The base of the flame lifts up and widens beyond the lip of the inner tube extending along the foam surface. The flame base appears to spread along the foam surface and fill the width of the outer tube. Further computational work is needed to fully understand the extent of spreading. However, it is clear that the flame is not extinguished at the foam injection

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rate of 1 cm/sec (2 fps). At this low injection rate, the foam evaporates at the rate it is being fed and the foam is unable to fill the space. Therefore, the extinguishment time is very long. This appears to be consistent with the pilot studies performed by Wilder [5] for pool fires. Wilder observed that the fire is extinguished at high foam injection rates and fails to extinguish at low injection rates. His measurements show that the extinguishment time approaches a large value (> 3.5 min) as the injection rate falls below a critical value of 1.12 cm/sec (2.25 fpm), which is close to the injection rate in our simulations. Also, Boyd and Di Marzo [6] performed bench-scale experiments to measure foam regression rates when a stationary slab of foam is subjected to uniform radiant heat flux from gas fired panels. They reported 0.126 mm/sec foam surface velocity due to applied surface heat flux of 18 KW/m^2 for a foam with Ex=17. Based on their data, we estimate that the foam evaporation rate to be 0.7 cm/sec for Ex=1000. Therefore, the predicted evaporation rates in our computations are in reasonable agreement with their experimental values. Unfortunately, very little information was reported on the dynamic aspects of the foam-fire interactions in the literature. Detailed measurements in bench-scale experiments are needed for quantitative comparisons with our theory.

Figures 1a-d show the effects of increased injection rate (8 cm/sec or 16 fpm) on the flame suppression. Figure 1b shows that the vortices (plume) descend significantly towards the base as the foam approaches the flame base compared to that in Figure 1a. Figures 1c-d show that the foam flow constricts around the fuel jet, cutting off air supply to the base of the flame from the surroundings. This smothering effect causes suppression of the flame as indicated by the lower temperatures. The maximum reaction rate decreases by a factor of 3 at 3.58 sec compared to that at 3.06 sec. There is also significant foam evaporation. The simulations show that the water vapor formed by the evaporation form an envelope around the fuel jet and contributes to flame extinction in that region. It is clear that increasing the foam injection rate above the evaporation rate enables the foam to surround and radially isolate the fuel jet to a small volume to extinguish it. Therefore, increased foam injection rate is found to have a significant effect on the extinction of the flame.

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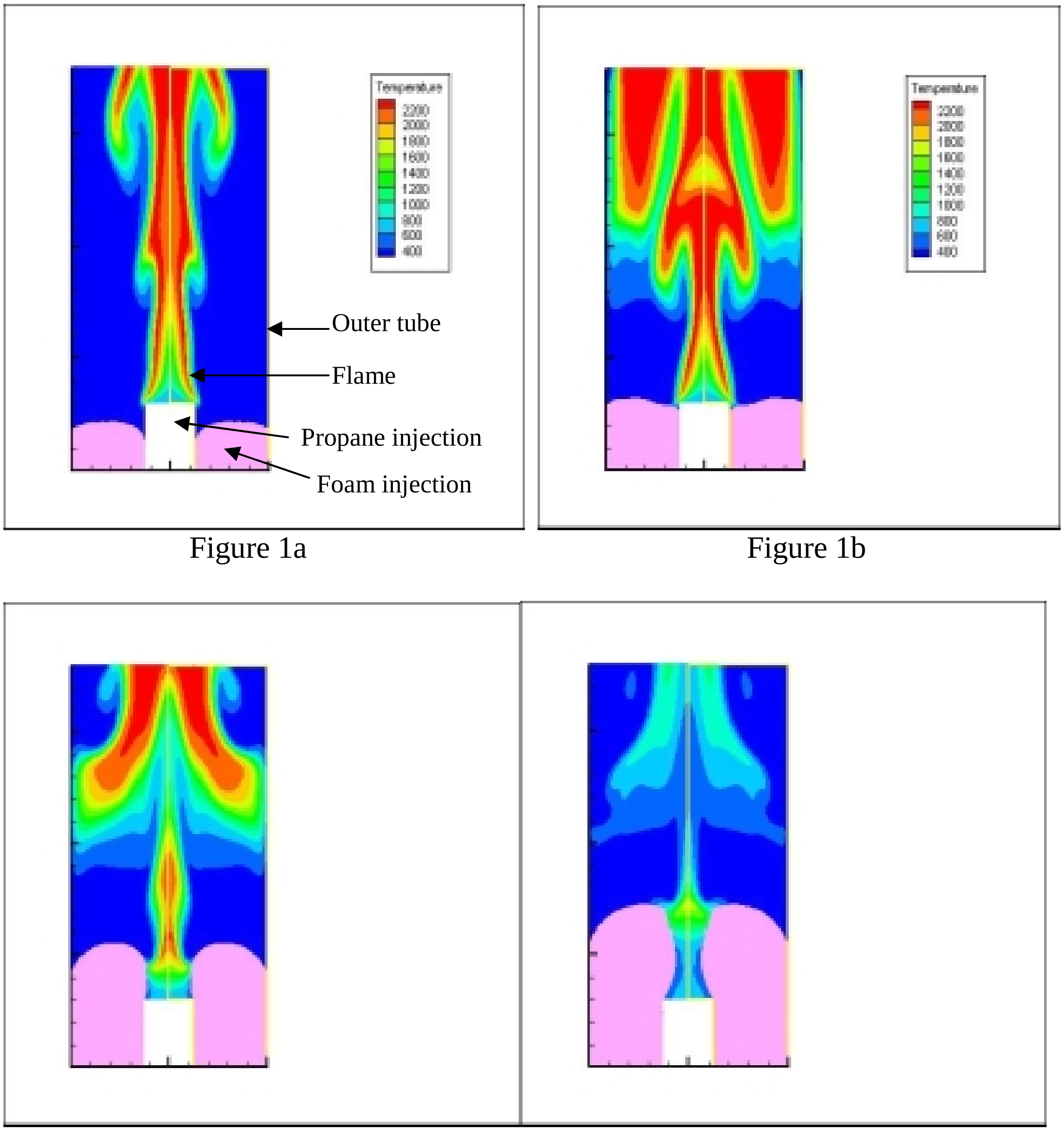

Figure 1a

Figure 1b

Figure 1c

Figure 1d

Figure 1. Contours of foam density and flame temperature for a foam injection rate of 8 cm/sec (16 fpm) and at times (a) 2.02, (b) 3.06, (c) 3.32, and (d) 3.52 sec from the start of the foam injection.