Fuel Pick-up and Flammability of Fire-fighting Foams

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Abstract

This paper re-analyses data from the FOAMSPEX project that reported the fuel pick-up for a range of foam types and fuels. We identify a distinct cut-off for fuel pick-up based on the plastic number as well as a strong correlation between fuel pick-up and the Reynolds number at impact. We also present new measurements on the level of fuel pick-up that can be tolerated by fluorine-free foams and foams that contain fluorosurfactants. This research should help inform future development of fluorine-free foams.

Keywords: Foam, Fire Fighting, Fuel Pick-up, Fluorine-Free Foams, Fluorosurfactant, PFAS, AFFF, F3, FFF, Film Forming, Plastic Number, Herschel-Bulkley Reynold Number

Background

For the last 50 years fire-fighting foams have been based on the use of fluorosurfactants. This technology makes the extinguishment of flammable-liquid fires extremely practical and efficient. For well-formulated concentrates, fluorosurfactant based foams, such as aqueous film-forming foams (AFFF), film-forming fluoroprotein (FFFP) foams and fluoroprotein (FP) foams, are surprisingly versatile and capable of being applied to fires in a variety of ways with little difference in fire-fighting performance within each foam class. They are also relatively insensitive the fuel involved, and for AFFF and FFFP, they are relatively indifferent to foam expansion.

Due to growing concerns about FPAS, fluorosurfactant based fire-fighting foams appear to have a limited future. We need to prepare for a transition to a new fire-fighting foam technology, or a range of technologies, some of them based on fluorine-free foams (FFF). While the optimised formulations of FFF satisfy the standard performance tests, such as

UL 162 or EN 1568, they require application rates that may exceed those of AFFF by a factor of two to three [1]. Fluorine-free concentrates and FFF solutions are significantly more viscous in comparison to those of AFFF, displaying non-Newtonian behaviour that normally manifests itself as thinning of these liquids with increasing rate of shearing. Both, the elevated application rates and their non-Newtonian behaviour require that fire-suppression engineers design new foam systems suitable for FFF.

From a fundamental perspective, the lack of perfluorocarbon chains, which impart the aqueous lamellae in foams with fuel repellence, makes the lamellae particularly susceptible to breakage by hot fuels, during the application of foams against fires. This behaviour is now well understood, mainly due to the work performed at the US Naval Research Laboratories [2]. Fuel pick-up, that is, the amount of fuel that mixes with foam as the foam collides with the burning liquid, constitutes another manifestation of the chemical composition of foam solutions.

This contribution studies the amount of fuel entrained by the foam, re-analysing the previously published measurements, as function of dimensionless numbers. Whereas large-scale fire tests were conducted during the development of film-forming foams to ensure that small-scale fire testing was also representative of large-scale fire performance, no similar testing has currently been published for fluorine-free foams [3, 4]. Our work aims to identify possible scaling problems for new foam technologies without the need for large-scale testing. Ultimately, the risk of fuel pick-up depends on how flammable are the formed fuel-foam mixtures. For this reason, we also perform several experiments that probe flammability of mixtures of foams and foam solutions with aviation gasoline.

Methodology

SP Fire Research (now part of the Research Institutes of Sweden) conducted a series of tests to estimate the fuel pick-up for different fuels and at impact velocities ranging from 1.3 to 6.3 m/s, as part of the FOAMSPEX project [5-6]. We have re-analysed the SP fuel pick-up data as function of plastic and Herschel-Bulkley Reynolds numbers. *The SP reports define the fuel pick-up as the ratio of the volume of the fuel picked up divided by the volume of foam solution (not the volume of aerated foam), expressed as percentage, the convention that we follow in the present article.* Foam was generated using a small-scale UNI-86 nozzle (the UNI-86R, 2.5 l/min flowrate) and the experiments involved foams with expansions in the window of 5.9 to 7.3 (E = volume of foam/volume of foam solution). The experiments performed by SP Fire Research involved aviation gasoline (Avgas) and heptane fuels and four foam types, AFFF, AR-AFFF (i.e., alcohol-resistant-AFFF), FFFP and FP foams.

We define the plastic and Herschel-Bulkley Reynolds numbers [7] as

$$Pl = \tau_y/(\tau_y + K(V/L)^n) \qquad Re_{HB} = \rho V^2/(\tau_y + K(V/L)^n) \qquad [1,2]$$

where the quantities introduced in the definition of the dimensionless numbers apply at the point of foam stream impacting the fuel. That is, L represents the diameter of foam stream at impact with the fuel (m, typical values 0.007 – 0.018 m) and V the velocity of foam stream impacting the fuel (m/s, typical values of 1.0 - 6.3 m/s), and n, K, ρ and τ_y stand for the flow index of foam (dimensionless), consistency index of foam (Pa s$^{1/n}$), its density (kg/m^3) and its yield stress (Pa), respectively. Using the consistency index and yield stress in Eqs 1 and 2 implies the adoption of the Herschel-Bulkley model in the description of the rheological properties of the foam [8,9].

The diameter of the foam stream at the point of impact with the fuel was estimated as the solution flow rate times expansion ratio divided by velocity. The range of Reynolds number for these experiments fell in a range of between 11 and 250. The test method allowed a foam stream to fall vertically into fuel from a range of heights. This afforded an estimate of foam velocity from $V^2 = 2gh$, where g denotes the gravity and h the height.

In our experiments, we dispersed the fuel droplets in aspirated foam generated using a UK Fire Research 5 l/min nozzle, also called a branchpipe [10]. This branchpipe produced expansion ratios in the range of 5.5 to 9.5. Foam was collected in a 600 ml glass container, with stopper, leaving enough space for the fuel. For the higher expansion ratios, this was about 40-50 g of aerated foam. We placed 12 plastic cylindrical beads (8 mm in length x 10 mm in diameter) in the container to disperse the fuel through the foam. Then a measured volume of fuel was added and the stopper fitted. The container was shaken for between 5 and 10 s (sufficiently to disperse the fuel) and then the contents were poured into an aluminium pan of 200 mm in diameter. A lighted match was passed over the mixture for about 10 s. If ignition occurred and was sustained for more than 10 s, the mixture was considered flammable. The fuel used for these experiments was the aviation gasoline.

In a separate series of experiments, we dispersed fuel in the foam solution, forming an emulsion. Foam solution and fuel (100 ml total) were poured into a 100 ml measuring cylinder and shaken vigorously for around 10 s to create an emulsion. This emulsion was then poured into the same metal pan and a lighted match was passed over the liquid. We applied the same criterion for flammability of the emulsions. Emulsions based on high viscosity (non-Newtonian) foam concentrates (AR-AFFF and most FFF products) were very uniform and stable. Emulsions for low viscosity foam concentrates (AFFF and FFFP products and one FFF formulation, viscosity < 0.1 Pa s) were less stable. The emulsions formed

when using fluoroprotein foams appeared to be very unstable and separated rapidly.

At low fuel pick-up levels, flickering flames appeared that self-extinguished rapidly. As the fuel loading increased, eventually, a fuel volume fraction was reached where the flames self-sustained themselves. We define the fuel-pick that corresponds to this level as the flammability level. In the next part of this article, we report dramatic differences between the film-forming foams (AFFF, AR-AFFF and FFFP) and other foam types (fluoroprotein and FFF). Film-forming foams tolerated extremely high fuel levels within the mixtures, both for fuel/foam mixtures and emulsions of fuel and foam solution. We hypothesise that, an aqueous film forms around the fuel droplets which provides an effective vapour barrier even at high fuel loads. A relatively small amount of foam solution is needed to form the film.

Results and Discussion

As illustrated in Fig. 1, our analysis of the data generated by SP Fire Research demonstrates that, when foams impact the fuel at relatively low Reynolds numbers, they can pick up a large amount of fuel and that the fuel pick-up level increases rapidly with increasing Reynolds number, to reach a plateau value. However, for this to occur, the foam plastic number needs to exceed between 0.05 and 0.5 (see Fig. 2). Values of the yield stress ranged from 1.8 Pa to 13.6 Pa.

When the foam collides gently with the fuel, without exceeding its yield stress, the foam acts as a solid object preventing the fuel pick-up. However, once the yield stress is exceeded by around 5 to 20 times, fuel mixes with the foam, with the extent of mixing increasing with the energy of the impact; i.e., with the Reynolds number.
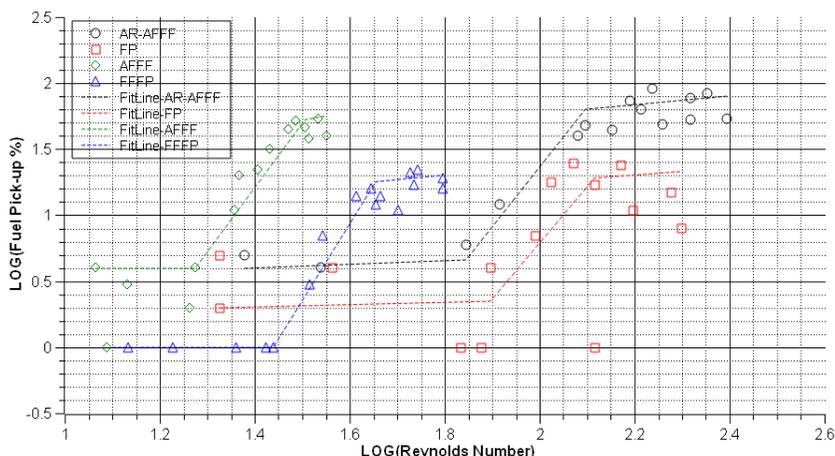

Fig. 1. Fuel pick-up depends on the Herschel-Bulkley Reynolds number.

Fig. 1 demonstrates the fuel-pick as function of the Reynolds number displaying strong correlation between these two quantities, for each foam class. Evidently, a transitional regime exists between elevated fuel pick-up at high Re_{HB} and low pick-up at small Re_{HB}. It is possible that, the elevated fuel pick-up represents an artefact of the experimental design, or there may be a practical limit to the amount of fuel pick-up. From this perspective, one of the FOAMSPEX reports [5] mentions that, stream break-up occurred at the highest fall height. The present analysis applies to a continuous stream of foam, but at, high Re_{HB}, the foam stream breaks into flakes. One readily remarks that, the results are sensitive to the type of foam but not to the type of fuel. We conclude this paragraph by remarking that, the current measurements reflect what is possibly the worst-case application method, vertical impact of a compact foam stream.

Fig. 2 illustrates an evident cut-off for fuel pick-up above a plastic number of 0.05 for AFFF and FFFP, 0.2 for AR-AFFF and 0.5 for FP, with the fuel pick-up as high as 90 % for AR-AFFF below the critical value of PI. FFFP and FP show much lower overall fuel pick-up levels than AFFF and AR-AFFF, while their critical PI differ significantly. Actual handline foam and monitor foam nozzles may have Reynolds numbers greater than 1000, as defined at the nozzle exit, which exceed the Reynolds number at the point of impact, due to slowing of the foam stream because of foam break-up into flakes after the foam left the nozzle. The measurements of SP Fire Research included fuel pick-up for a range of commercial handline nozzles which flowed up to 900 l/min with the fuel pick-up exceeding 50 % [11].
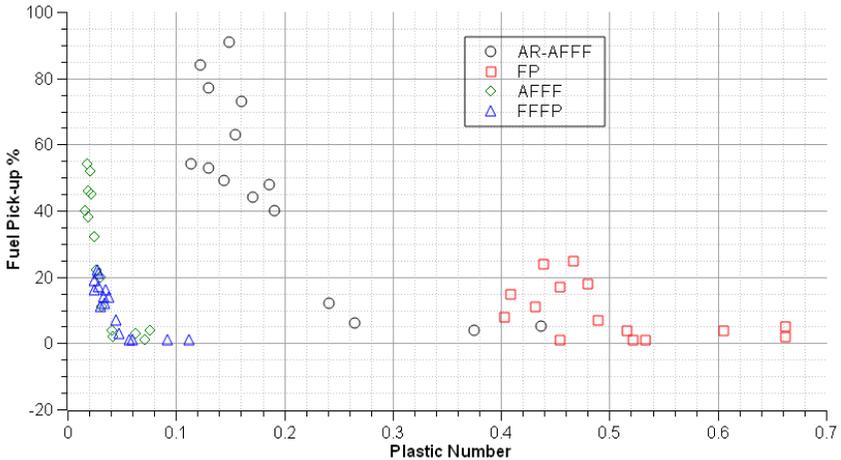

Fig. 2.   Fuel pick-up displays a critical plastic number.

Our experiments demonstrate that, film-forming foams tolerate high content of aviation gasoline (volume of fuel/volume of foam solution > 100 %) before becoming flammable and other types of foams afford only 25 % before becoming flammable (see Fig. 3). These results indicate significant inerting ability of film-forming foams against the picked-up fuel. The results for emulsions demonstrate a similar trend. While film-forming foams produce very stable emulsions of fuels with foam solutions, with considerable fuel loading (> 60 %), such emulsions remain non-flammable. However, emulsions formed with small amount of fuel dispersed in solution of FFF display flammability even for 25 % fuel loading. All foams investigated in the FOAMSPEX project demonstrated the fuel pick-up levels in excess of 20 %, above the critical plastic number.

One of The FOAMSPEX reports [5] included experiments of the ignitability of the foam from the perspective of long-term foam application and vapour sealing. The FOAMSPEX measurements did not comprise the results for fluorine-free foams as these foams were not available at that time. The present data on flammability of foam-fuel mixtures incorporates several concentrates of fluorine-free foams. The fuel loading at which the foam becomes flammable provides a clearly defined maximum level of pick-up that a foam can tolerate. Above this critical loading, foams may become ineffective. As Fig. 3 demonstrates, the critical loading of fuel in the foam can be 10 - 20 times higher for film-forming foams than for fluorine-free and fluoroprotein foams.
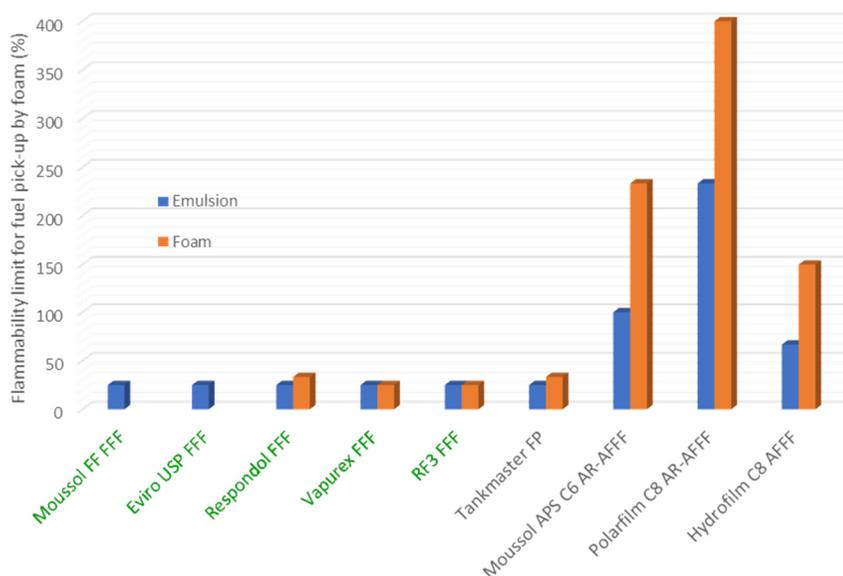

Fig. 3.   Flammability limits for various foam types.

It seems to us that, this behaviour must be the key reason for FFF requiring two to three times higher application rates than film-forming foams. Depending on the fuel pick-up characteristics of FFF products, this may also lead to higher application rates for larger fires under some circumstances. It may be important to design systems in order to maintain a low Reynolds number at the point of impact.

Conclusions

The substantial differences in fuel tolerance of FFF when compared to film-forming foams and the strong plastic and Reynolds numbers dependence of fuel pick-up suggest the following conclusions:

1. A transitional regime exists between elevated fuel pick-up at high Re_{HB} and low pick-up at small Re_{HB}. At high Re_{HB}, the foam stream breaks into flakes, a behaviour that appears to limit effectively the fuel pick-up. Film-forming foams, especially AR-AFFF, exhibit fuel pick-up as high as 100 %.

2. The viscoplastic behaviour of foams leads to the appearance of the critical plastic number of between 0.05 and 0.5, depending on the foam formulation. Above this critical number, the fuel pick-up remains less than 10 %.

3. While film-forming foams pick up significant amount of fuels, their fuel-foam mixtures show considerable resistance to ignition. Even a pick-up of 100 % results in non-flammable fuel-foam mixtures. We suggest that, this is a main reason for effective suppression of large-scale fires by film-forming foams.

4. Mixtures of fuels with fluorine-free foams ignite for the pick-up levels of less than 25 %. In other words, these mixtures are very flammable, even for small fuel pick-up. This behaviour may indicate problems in suppression of large-scale fires by fluorine-free foams, and the requirement for increased foam application densities. That is, suppression of fires by fluorine-free foams may not scale up the same way as for film-forming foams.

5. Application methods that involve high Reynolds numbers for the foam stream, such as by monitors or high volume foam makers, may exhibit high levels of fuel pick-up and fluorine free foams may not perform as effectively, while foam that is applied as small flakes, such as by sprinklers and sprayers, may exhibit lower levels of fuel pick-up, thereby enabling more effective suppression by fluorine free foams.

Acknowledgements

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