■ Research Paper ■

Phenomenological Model and Experimental Comparisons on Static Foam Drainage for Fire Fighting Foams

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ABSTRACT

This paper is concerned with the development of a phenomenological model for drainage from static foams used in standard fire-foam qualification tests for low expansion ratio commercially available foams. The fact that operational foam heights (30 mm) are much smaller than foam drainage apparatus heights (200 mm) has been the inspiration to determine the height dependence of static drainage. This is done by constructing a model of foam drainage based on momentum flux balance and conducting experiments with an apparatus with foam drainage through a fuel layer. The results show a linear relationship of quarter drainage time with the height consistent with the theoretical expectations. The constants are related to viscosity and liquid film thickness. Microscopic examination on bubble movement and the pictures are used to infer that the bubble size distributions between three commercial foams are not distinctively different and so are the film thicknesses. It is argued that the strong dependence on quarter drainage time on the film thickness can be consistent with the experimental results only if the variation of these thicknesses between different foams is not significantly large. Assuming a constant film thickness, the constants of the relationship between quarter drainage time and height are obtained from the experimental data. The constants derived from the experimental data show dependences in which lower concentration foams have a behavior different from those with higher concentrations beyond known influences of viscosity and surface tension. The need for longer duration drainage as a qualifying measure is argued to be important to correlate with fire extinction behavior.

Keywords: Static Foam Drainage, Fire Extinction Foams, Foams

1 INTRODUCTION

Static foam drainage in fire fighting foams is the first element in the fire extinguishment process. Typical low expansion ratio foams used in Underwriters laboratories-based standard - UL 162 that the present authors have been working with have expansion ratios of 6 to 10. The liquid in the foam held inside the foam structure drains via thin films between gas bubbles by gravity also affected by viscosity largely and at later times surface tension forces as well. Drainage time which is a part of the specification of the foam measured in a standard apparatus for draining a quarter of

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the liquid in the foam. Typical quarter drain time, t_{qD} is about 120 to 180 s for AFFF (Aqueous film forming foams) and about 270 to 350 s for AR-AFFF (Alcohol Resistant AFFF). The standard apparatus uses a cylindrical container 100 mm dia and 200 mm height with a volume of 1.6 liters. The foam that is deposited on the pan in pan-fire test (2.16 m × 2.16 m) measures 30 mm high. One would have expected that there would be test results or at least experimental investigations concerning height effects on drainage reported in literature. There have been many studies on static drainage behavior. References[1-2] have reported experiments on several foams and also presented complex models for the prediction of the static drainage behavior. The reported experiments are at foam heights of 0.18 to 0.7 m height chosen arbitrarily with different foams; hence, no deductions of foam height effect can be made. The foams have also been prepared in the laboratory to evaluate various other effects and their value to use of commercial foams for fire application appears very limited. The reported procedure for the evaluation of drainage rates has so many correlations and values that no general deductions on the behavior seems possible. Two foams - AFFF and FFFP (Film forming fluoro-protein) were characterized for the bubble distribution in Magrabi et al [3] and the drainage behavior compared in Magrabi et al [4]. They performed experiments at a fixed height of 0.2 m with expansion ratios from 5 to 30 using a compressed air foam generator. The two foams behaved radically differently with expansion ratio even though their viscosity (μ) and surface tension (γ) values did not differ much. In order to explain the differing behavior, they invoked a quantity called velocity coefficient which is characterized by using the data of time-to-drain from experiments. For foams, it is understood that if the liquid fraction in the bottom of a foam column has to reach a critical value (~ 0.26) before drainage starts. This process takes time. This time information is used to deduce the velocity coefficient which is considered as a representative of surface viscosity. It appears that an important part of the experimental information is used the predictive model. Thus, to the best of authors' understanding of the literature, the effect of the height of the foam has not been examined.

The behavior of foam flow through the nodes and the Plateau border has been described succinctly by Cohen Addad et al [5] (see *Figure 3* of this article); the flow through the channels with complex geometry is influenced by the surface viscosity in a manner that the effective flow rate is reduced with larger surface viscosity for foams of the FFFP kind studied by Magrabi et al [3]. The fact that surface viscosity is not a well characterized quantity and accounting for it is involved, it is not obvious if it cannot be treated as an enhanced bulk viscosity because the drainage rate is a combination of reduced area and increased surface viscosity. Further, Simon-Cox [6] invokes a factor 3 to multiply the viscosity to account for the geometry. Thus the use of enhanced viscosity is very inviting due to its simplicity. Most theories [2,7-10] involve the use of Plateau border radius which is connected to the bubble radius which is not a predictable quantity. Arguments are made by Stevenson [10] on whether geometric average is appropriate or classical sauter mean diameter is appropriate. In a recent study, Sabastien G., et al [12] examined forced drainage with model surfactant solutions and suggest that both rigid and mobile bubble surfaces are controlled by surface shear viscosity and shear thinning behavior and indicate that Marangoni effect cannot completely explain their results. One of the other issues with most of the above work (excepting reference [2]) is that they concentrate on high expansion ratio foams not very important for the focus of this work related to low expansion foams. However, practical fire fighting foams have also multiple bubble sizes and a method of picking up the relevant value that changes during the drainage process is unclear. It is also not clear if bubble radius even if attractive, is a more appropriate physical quantity to attempt to correlate the drainage rates. It appears to the present authors that the film thickness is a more appropriate quantity. Multiple bubble sizes may still coexist with a single average film thickness. In view of these factors, a simple minded phenomenological model is intended to be developed here and a simple experimental approach to estimating some of the key parameters is described.

2 THEORY

The approach chosen to determine the drainage from a static foam is to write the momentum flux balance between the exit at the bottom and the top of one channel of size equal to the mean thickness of the liquid layer, say r_m. It is taken that this is a representative size and the drainage volume from this describes the entire behavior. The equation is

$$\dot{m}V_e = \pi r_m^2 h\rho g - \mu \frac{du}{dy} 2\pi r_m h - 2\gamma\pi r_m \tag{1}$$

where $\dot{m}$ is the flow rate through the channel of thickness r_m given by $\dot{m} = \rho\pi r_m^2 V_e$, h is the channel height, ρ is the liquid density, V_e is the liquid velocity at the bottom, g, the acceleration due to gravity (9.81 m/s^2) and γ, the surface tension. The velocity gradient du/dy is given by the solution of Poiseuille flow gives $du/dy = a_1 \mu V_e / r_m$ where V_e is the mean velocity through the channel. By introducing the expressions for $\dot{m}$ and du/dy, we can recast the equation as

$$V_e^2 = gh - \frac{a_1 \mu V_e}{r_m} \frac{h}{\rho r_m} - \frac{2\gamma}{\rho r_m} \tag{2}$$

We now identify V_e by $-dh/dt$ and introduce another constant a_2 to account for geometric effects on the influences of surface tension to obtain

$$\left[\frac{dh}{dt}\right]^2 = gh + \frac{a_1 \mu}{\rho r_m^2} h \frac{dh}{dt} - \frac{2a_2\gamma}{\rho r_m} \tag{3}$$

Most experimental data show that the left hand side term is an order of magnitude smaller than other terms and hence, can be ignored. One then gets a result for dh/dt as

$$\frac{dh}{dt} = -\rho g \frac{r_m^2}{a_1 \mu} + \frac{2a_2\gamma r_m}{\mu h} \tag{4}$$

In earlier literature on foams (references 6-10), the equation for drainage is a non-linear partial differential equation. It is perhaps of value to see the connection between the equation derived here and the standard form. This is set out in the Appendix.

In the early part of the drainage process, the first term on the right hand side can be expected to play a major role. This is consistent with the results indicated by [7,10-11]. We non-dimensionalise height and time as

$$z = h/h_0\,; \quad \tau = t/t_r\,; \quad t_r = a_1 h_0 \mu/(\rho g r_m^2) \tag{5}$$

where h_0 is the initial foam height, t_r is the reference time scale. We can now rewrite the equation as

$$\frac{dz}{d\tau} = -1 + \frac{2a_2\bar{\gamma}}{z};\ \ \bar{\gamma} = \frac{\gamma}{\rho g h_0 r_m} \tag{6}$$

The solution of this equation subject to $z = 1$ at $\tau = 0$ gives an implicit solution

$$\tau = (1-z) + \bar{\gamma}\, ln\left[\frac{(1-\bar{\gamma})}{(z-\bar{\gamma})}\right] \tag{7}$$

Experimental observation discussed later show that the effects of surface tension are very small in the early part of the drainage, certainly up to quarter drainage time. This implies that at least up to quarter drainage time (we believe that this may be valid even till about half drainage time), the role of surface tension is much smaller than gravity-viscosity induced effects. This implies that we can take $\bar{\gamma} << 1$. We can expand the solution around $\bar{\gamma} \to 0$ and obtain an expression for quarter discharge time as

$$t_{qD} = \frac{a_1 \mu h_0}{\rho g r_m^2} + \frac{2a_1 a_2 \gamma \mu}{(\rho g)^2 r_m^3} \tag{8}$$

This expression shows that the time for discharge bears a linear relationship with the initial height of the foam, but in an algebraic expression rather than as a scaling law. Both the terms are strongly dependent on the radius for a cylindrical channel, r_m that can also be interpreted as a film thickness. The second term is the time scale invoked for rendering time dimensionless in the analysis of Koelher et al [8]. In his work largely concerned with high expansion ratio foams, surface tension plays a significant role much as can be expected from the drainage behavior at times much later than quarter drainage time.

3 EXPERIMENTS

3.1 The Apparatus

It was aimed that the drainage process must have features similar to what is done in practice - the liquid must drain through the foam, form drops that fall through n-heptane (or through diesel). In the UL foam test apparatus, one liter of foam is deposited. At an expansion ratio of 5 to 6, the drained amount of liquid is about 150 ml. One should design the apparatus to collect about 100 ml at the maximum. At the lower end, the foam height is one-seventh the maximum, the liquid collection of 30 ml would also be required to be measured accurately. This combination decides the nature of the apparatus; it is shown in *Figure 1*. The drainage occurs through the formation of a large number of drops. They leave the foam, pass through the n-heptane layer by gravity in a duration that is much smaller than time for discharge and hence, accurate measurements are possible. The foams that are tested in the present work are shown in *Figure 2* and *Table 1*. The various foams are those produced by the companies Integrated Fire Protection Pvt. Ltd (IFP), K. V. Fire Chemicals (India) Pvt Ltd (KV), Fluid Equipments Pvt Ltd (FE). Broadly three classes of foams were tested. These are Aqueous Film forming foam (AFFF), Alcohol resistant AFF (AR-AFFF), and IFP - AFFF foam. The foam concentrates are available in 3 % concentration usually; one company FE produces 1 % concentrate also. When used for firefighting, these are diluted to 3 % usually. In order to determine the effects of viscosity and surface tension, additional experiments with 6 % concentration are also conducted. The measured values of viscosity and surface tension are set out in *Table 1*. As can be noticed, several of them have viscosities not very different from water, but some of them like AR - AFFF and IFP foams have viscosities higher by a factor of 2 or more. Surface tension values differ by no more than 13 % between them.

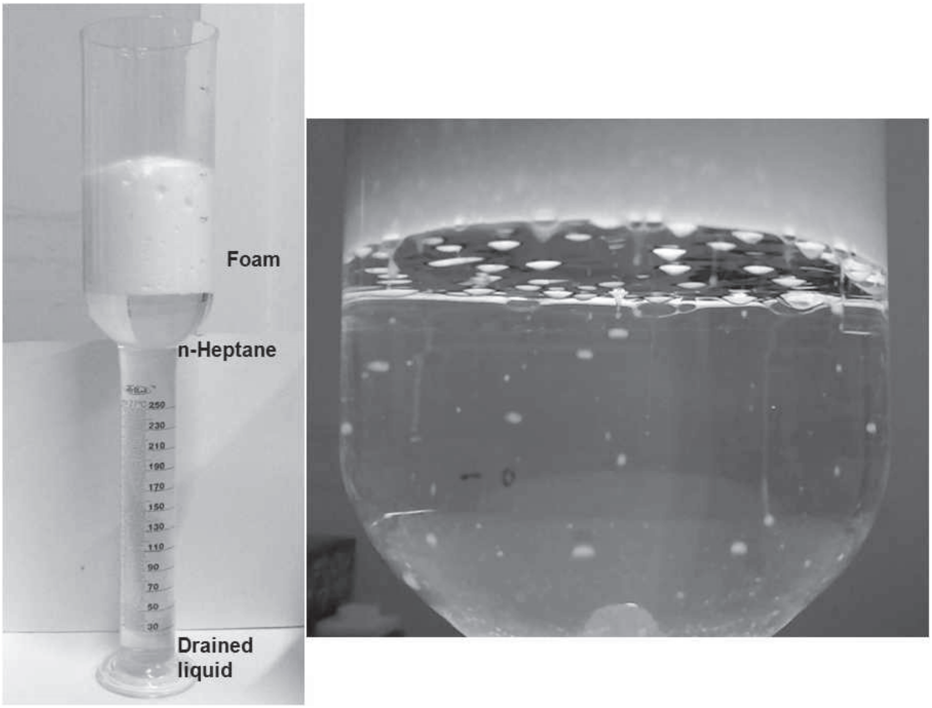

Figure 1 The foam drainage apparatus (left) and the drainage process (right)

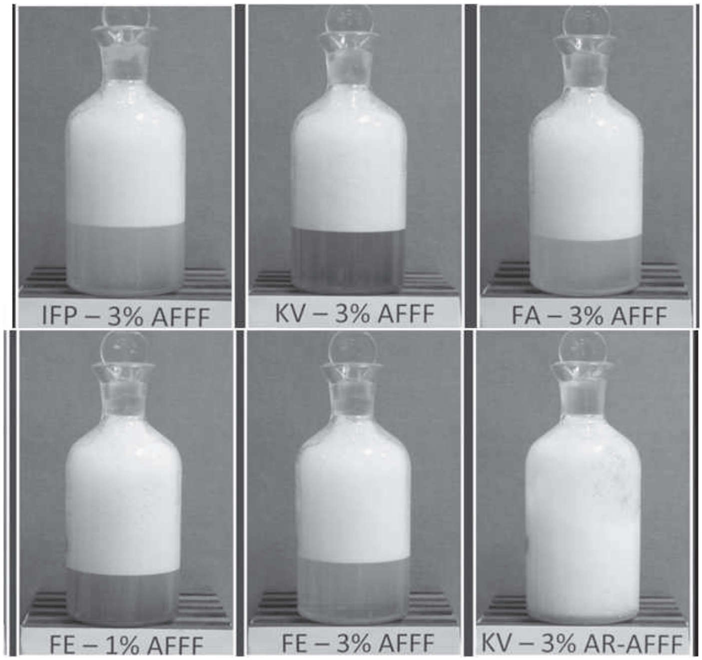

Figure 2 The commercial foams used in the experiments

Table 1 The commercial foams tested and the final constants; KVAFFF-3-3 means KVAFFF 3 % foam concentrate diluted further to 3 % and similarly others

No	Foams	μ mPa. s	γ mN/m	C_1 s	C_2 s
1	KVAFFF-3-3	0.80	23.4	33	44
2	FEAFFF-1-1	0.86	23.6	31	38
3n	IFPAFFF-3-3	0.81	22.3	33	44
3	IFPAFFF-3-3	1.08	22.3	93	62
4	KVARAFFF-3-3	1.65	24.9	18	82
5	KVAFFF-3-6	0.80	24.5	110	0
6	FEAFFF-1-3	0.91	25.4	170	0
7	FEAFFF-1-5	0.91	25.4	180	0
8	KVARAFFF-3-5	2.55	25.5	215	0
9	IFPAFFF-3-5	0.99	24.8	165	0
10	IFPAFFF-3-6	1.10	24.5	190	0

3.2 Foam Generation Process

Two methods of foam generation have been used. The first one is the same as used in UL tests - using an aspirated nozzle that has a 2.3 to 2.5 mm nozzle through which the foam solution passes at 0.11 lit/s at velocities of 20 to 25 m/s. A sketch of the nozzle is shown in *Figure 3*. Foam solution at high pressure enters orifice 1 and exits orifice 2 as high velocity jet at atmospheric pressure. The jet draws air through four air holes 3, 90 degrees apart. The entrained air and foam solution mixture impinge on splitter 4 resulting in vigorous mixing and agitation. Foam air mixture thus formed will pass through a short length of barrel, 5 and finished foam will exit the barrel. The foam solution moving through the nozzle entrains an amount of air to produce foam with expansion ratio, *ER*. The foam is formed after passage through a 12 mm dia, 50 to 75 mm long duct inside which is located a sharp conical splitter to induce turbulence to the incoming stream. Thus the residence time taken to form the foam, the ratio of the volume of the duct to the volumetric flow rate is about 3 to 5 ms. The highly turbulent flow conditions impose large strain rates on the interfaces between the foam solution and entrained air leading to bubbles of various sizes from tens of microns to about hundred microns. A second method adopted at the laboratory is to use a mixer to churn the foam solution at high speeds and generate the foam. A kitchen mixer running at 3000 rpm is operated with about 50 to 200 ml of foam solution for one minute before use in the drainage experiment; it is observed that foam formation occurs satisfactorily only after about 30 s and therefore the mixer is run for 1 min. All foams excepting IFP (3 and 4 in *Table 1*) behaved the same way with either of the techniques. With IFP, in particular, the results of the nozzle approach followed in practice behaved the same way as other AFFF foams (alcohol resistant variety apart), but the mixer generated foam of IFP behaved as a fluid with higher viscosity than was measured earlier to use in the mixer. This matter is discussed later.

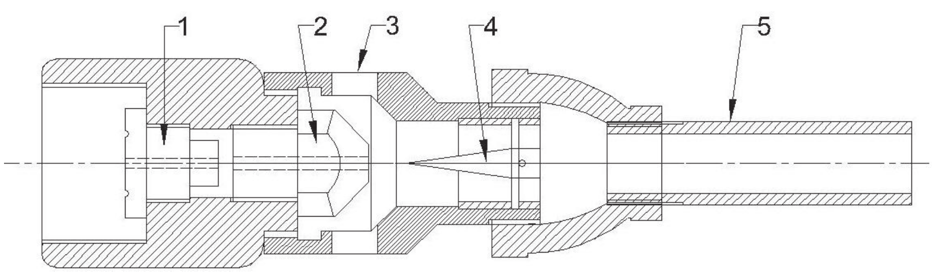

Figure 3 Foam nozzle used to generate the foam

3.3 Foam Drainage Process

After the foam is prepared, it is immediately transferred to the foam drainage apparatus kept ready with n-heptane loaded to the appropriate height. The foam pouring process takes between 5 to 10 s depending on the amount to be transferred. A timer is started immediately after a substantial amount is transferred. The drainage process is then watched for collection at the bottom zone. It takes a definite time for the drainage process to start. This is typically 15 to 150 s over all the foams and foam heights considered. The drainage process then begins with the formation of drops at the interface between the foam and th n-heptane layer and falling off into the liquid as drops. These drops them pass through n-heptane and collect at the bottom. The right part of *Figure 1* shows the details of the phenomena at the interface. The drops form at several locations at different times and drop down through n-heptane when their size increases to an extent that surface tension forces can no longer hold them on to the interface. The time required for increasing amounts of collection at the bottom will be noted. In early experiments the near-full drainage regime was covered. This took between 60 to 90 mins. In subsequent experiments, the time required for discharge of quarter the amount filled in was noted. This would be in the range of 1 - 15 mins.

In order to examine the details of drainage, smaller amounts of the prepared foam were placed below a microscope (Magnum T - Trinocular Microscope with epifluoroscence illumination) and movement of the bubbles was videographed. These were very revealing (see supplementary material uploaded on the website). The liquid movement through the channels and nodes was vividly seen, particularly when very tiny bubbles of 10 to 20 microns size moved along these pathways. Occasionally, bubbles readjusted their position indicating vacancy created due to drainage. One of important observations made on an examination of videos that lasted for about 2 minutes is that there was only movement of small bubbles through the channels and larger size bubbles - of diameters of 50 to 400 microns remained unaltered in their positions. There was an occasional very minor readjustment of positions with no visible break-up or coalescence. Thus the early part of the drainage is largely controlled by gravitational-viscous forces. These results are consistent with those of [4] who have presented the results of bubble size distributions over time and these indicate very little change over a 2 minute period. *Figure 4* shows the foams of IFP and KV AFFF foams under a microscope. These are the stills from the video taken of these samples. The bubble sizes vary widely from about 50 to 500 microns and the channels seem to be around 50 to 150 microns. The broad parameters do not depend on the bubble size distribution that seems not the same in the two cases considered. Similar data have been obtained for other foams and *Figure 5* shows it for KV ARAFFF and FE foams (5 and 7 in *Table 1*). The film thickness is typically about 100 μm ($\pm$ 50 μm). The conclusion from these data is that the film thickness particularly in these multi-size bubble generating situations is not very simply linked to any directly controllable parameter and hence either the bubble sizes. Hence the film thickness that controls the discharge times very strongly as in the equation above (inverse square of the film thickness) is perhaps not directly responsible for the drainage time behavior. The fact that bubbles readjust their positions as seen from the videos of the foams under the microscope continuously in a random way may be allowing the pathways for the drainage to occur. While this new view point is worthy of being pursued for modeling purposes, more information on the behavior of the low expansion ratio foams is to be obtained before such a task can be undertaken.

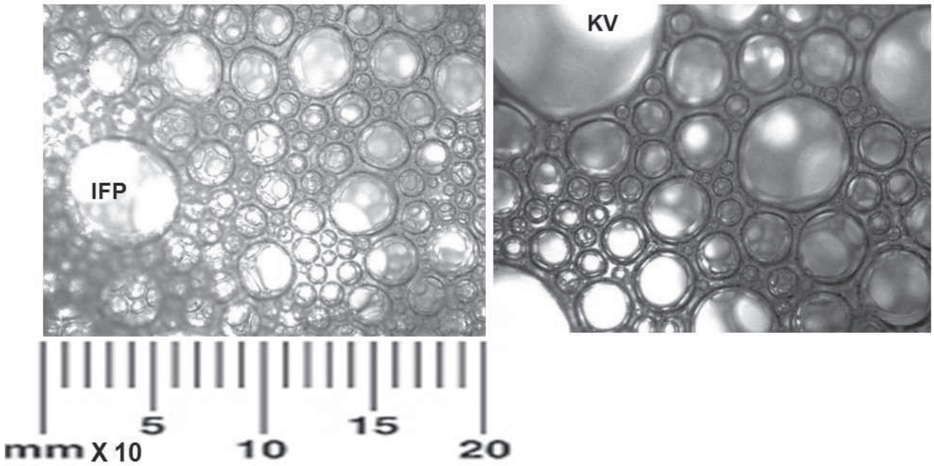

Figure 4 Foam bubbles under a microscope - IFP and KV AFFF

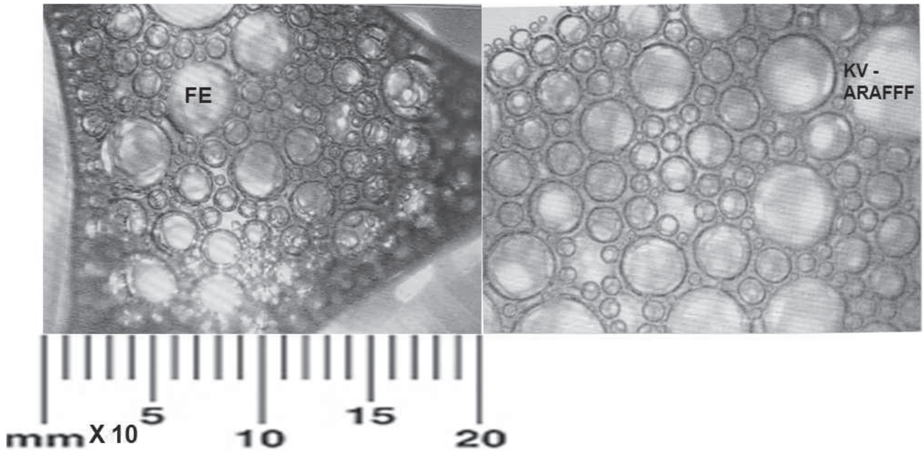

Figure 5 Foam bubbles under a microscope - FE and KV AR-AFFF

4 RESULTS AND DISCUSSION

The amount drained (z) with time as determined from the experiments is shown in *Figure 6*. As can be noticed the rate of drainage up to quarter drainage point, typically around 150 to 175 s for both KV, AFFF and IFP, AFFF class of foams. From this figure, it is clear that IFP foam takes longer to drain compared to KV foam. The data obtained from the experiments is summarized in *Table 2*. The results of select cases is presented in this table. The range of heights considered vary from 30 to 150 mm and the expansion ratios (ER) obtained for these experiments varies from 5 to 8. Because the expansion ratio varied even up about 10 in some experiments, it was necessary to account for this variation in the results for examining the dependence on foam height. In a multi-size bubble distribution, the liquid layer thickness is obtained by expecting that a uniform liquid layer covers all the bubbles (of diameter d_i). The amount of liquid is $1/(ER$-1) times air volume. Therefore, characteristic dimension representing the film thickness, r_m is obtained as $r_m = \Sigma f_i d_i^3/[6(ER\text{-}1)\Sigma f_i d_i^2]$ where f_i is the fraction of bubbles of diameter, d_i. Since the bubble size distribution represented by f_i is also dependent on the expansion ratio *ER*, it might simply be useful to adopt a simpler approach. We just take $t_{qD}/t_{qD,ref} = [ER/ER_{ref}]^m$. Data from a number of experiments have shown $m \sim 1$ in a range of *ER* from 5 to 10. This is utilized to correct for variations in *ER* in the experiments. The data obtained thus is represented as t_{qDC} in *Table 2* by using a reference value of $ER = 6.2$. The equation for quarter drainage time is expressed in a normalized manner as follows. All the quantities are normalized by nominal values to enable the constants to reflect deviations for specific cases of interest. This is particularly useful since the actual values vary widely. The nominal values used are $h_0 = 30$ mm, $\rho = 1000$ kg/m^3, $g = 9.81$ m/s^2, $\mu = 0.001$ *Ns*/m^2 (*Pa s*), $\gamma = 0.025$ *N*/m, $r_m = 100$ μm, $ER = 6.2$. It may be noted that for most applications discussed here the deviations from the chosen values will be within one order of magnitude and this helps better appreciation of the values involved. Towards this, the *Equation 8* can be recast as

$$t_{qD} = A(h_0/30) + B \tag{9}$$

$$A\ (s) = \frac{C_1(\mu/0.001)(ER/6.2)}{(\rho/1000)(g/9.81)(r_m/10^{-4})^2} \tag{10}$$

$$B\ (s) = \frac{C_2(\gamma/0.025)(\mu/0.001)(ER/6.2)}{(\rho/1000)^2(g/9.81)^2(r_m/10^{-4})^3} \tag{11}$$

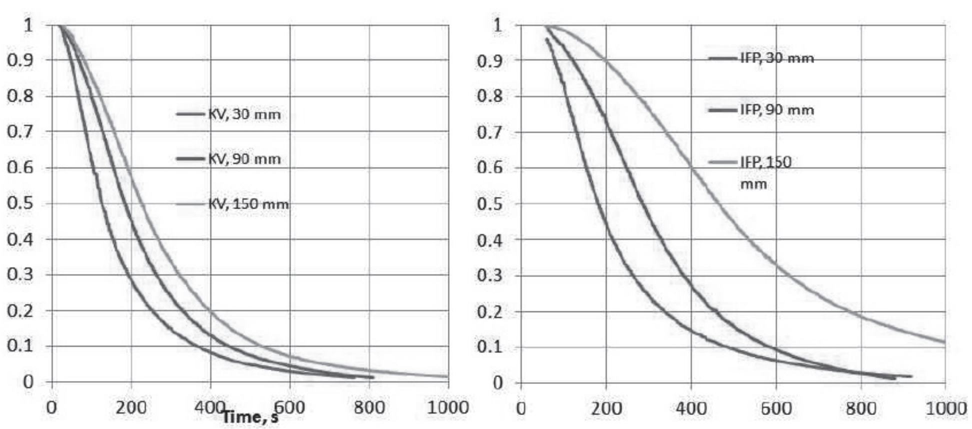

Figure 6 The drainage, z vs. time (s) for KV, AFF and IFP, AFFF foams

Table 2 Sample results from experiments on static drainage, t_0= time duration for the onset of drainage, t_{qD}= time duration for discharge of quarter the liquid, t_{qDC}= Quarter discharge time corrected for differences in expansion ratio.

No	Foams	μ mPa. s	γ mN/m	h_0 mm	ER -	t_0 s	t_{qD} s	t_{qDC} s
1	KVAFFF-3-3	0.81	22.3	37	6.2	15	63	63
				59	6.4	17	89	92
				80	6.6	18	112	119
				100	6.5	21	129	136
				113	6.1	17	132	129
2	FEAFFF-1-1	0.86	23.6	32	5.3	13	66	56
				49	5.3	14	83	71
				68	5.5	15	109	97
				102	5.4	13	140	123
3	IFPAFFF-3-3	0.80	23.4	42	7.4	31	135	181
				42	7.4	27	129	155
				71	8.8	40	205	266
				106	7.1	43	280	319
				112	7.4	48	283	340
4	KVARAFFF-3-3	1.65	24.9	34	5.8	23	179	169
				55	6.0	23	152	148
				76	6.2	29	209	211
				115	6.3	36	303	306

The data are set out in *Figure 7*. The foams KVAFFF-3-3 and FEAFFF-1-1 show up similar behavior. The foam IFPAFFF-3-3 produced using a the mixer jar shows a much higher drain time and slope. Since all these foams were derived from those used for qualification in pan fire tests and in these tests, the behavior of IFPAFFF-3-3 was no different from the others, the foam drainage tests using a nozzle were repeated. These are set out in the same figure under the notation 3*n*. As can be noticed, these drainage time seems the same as for other foams and different from that of itself derived from the mixer. This appeared very puzzling and one possible reason was thought to be enhanced viscosity due to the foam generation process in the mixer that is far more "strain" inducing than the nozzle. Hence viscosity was measured before and after the mixer operation (of 1 minute) at various times after that. The viscosity had increased from 0.8 mPa s to 1.08 mPa s and remained steady for over an hour. It is believed that the structure of the foam had changed including the film thickness as well as the channel geometry. These induce the classical Boussinesq effects due to surface viscosity described vividly in Figure 3 (b) of Cohen Addad et al [5]. This appears to be the only possible reason since the change of viscosity by 25 % cannot account for the increase in slope (by about 300 %). This has an important bearing in foam preparation process practiced in the laboratories using mixer generated foams. It is possible that some foams (like KVAFFF-3-3 or FEAFFF-1-1) do not behave differently when they are generated by one or the other means, but some do, like IFPAFFF. It is suspected that the IFPAFFF foam may have some protein component that gets affected by the enhanced temperature and strain in the mixer jar. Further verification is limited by the fact that these are commercial foams whose composition has been unavailable for study. For static drainage experiments to have meaning, it is desirable that the process used in applications be also adopted for laboratory experiments. The constants C_1 and C_2 in the *Equations 9*, are now determined from the viscosity and surface tension values provided in the *Table 1* and the values of the slopes from the experimental data (A and B). These are listed in *Table 1*. The constant C_1 varies widely even after accounting for variations in viscosity; it is therefore inferred that the film thickness or channel geometry is different in these cases. In order to understand the behavior of the foams at different concentrations, the same foams are processed at different dilution levels and drainage times vs. foam heights were determined. These are presented in *Figure 8*. These display a different behavior with the constant C_2 near 0. This implies that the domination of viscous effects (or even Boussinesq effects) are significant. A question came up whether the drainage rate of the foam through the layer of n-heptane, petrol and diesel would be different. Drained liquid fraction is plotted as a function of time in *Figure 9*. Results show that interface effects have little influence on drainage rates.

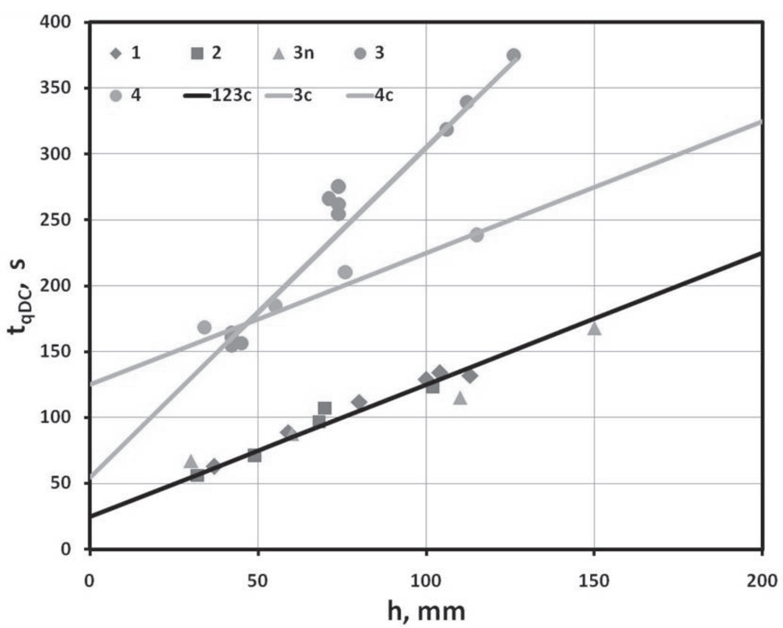

Figure 7 The quarter drain time (s) corrected for expansion ratio with foam height (mm) for the foams KVAFFF-3-3 (1), FEAFFF-1-1 (2), IFPAFFF-3-3 (produced using a nozzle, 3n) along with correlation named 123c, IFP-3-3 (3) and KVARAFFF-3-3 (4)

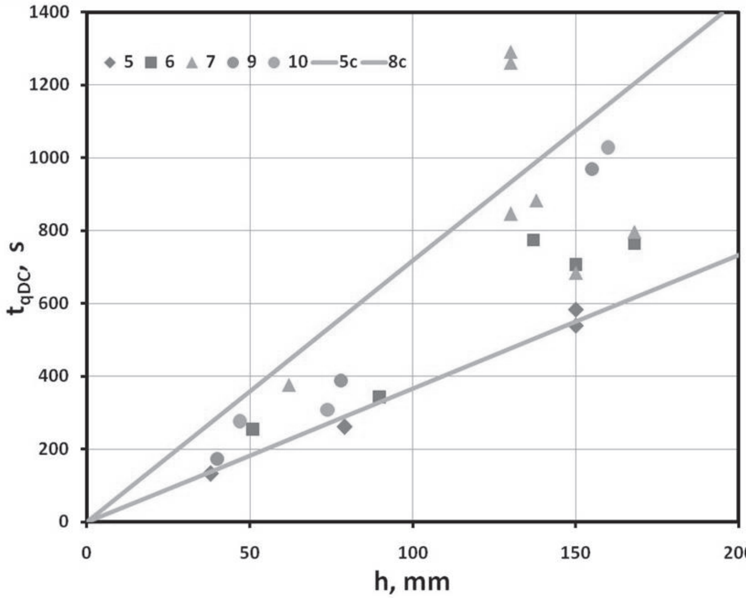

Figure 8 The quarter drain time (s) corrected for expansion ratio with foam height (mm) for the foams KVAFFF-3- 6 (5), FEAFFF-1-3 (6), FEAFFF-1-5 (7), KVARAFFF-3-5 (8), IFPAFFF-3-5 (9), and IFPAFFF-3-6 (10) along with correlation lines for KVAFFF-3-6 (5c) and KVARAFFF-3-5 (8c)

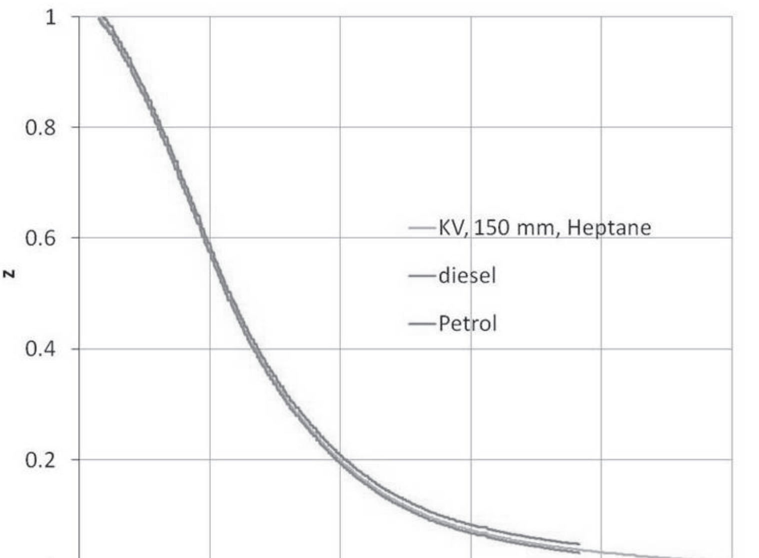

Figure 9 Drained fraction vs time, for KV AFFF foam with heptane, petrol and diesel liquid-foam interfaces.

It is appropriate to speculate on the results of Magrabi et al [3] in the light of the above findings. Amongst the two foams experimented by them, FFFP foam is made significantly of proteins. The method of foam formation used by them is compressed air. The expectation is that the strain rates induced by the foam generation process have altered the foam structure much different from that in aspirated nozzle. This effect is thought to be different from the changes in the bubble size distribution that is finer with compressed air foams as evident from their results as well. This effect is speculated to be limited to bio-origin substances as they undergo degradation with temperature and strain effects more than substances with chemical origin. The work of Magrabi et al [3] has been limited to one height (0.2 m) and hence some insight that can be obtained from studies on the influence of foam height cannot be obtained.

5 SUMMARY

This paper has considered the static drainage behavior of three commercial foams. This study arose because the standard foam drainage tests use a foam height of 200 mm, but the foam that spreads over the fuel during extinguishment process is 30 mm. Determination of the drainage behavior with foam height augmented by a simple theory shows a linear behavior of quarter drainage time with height. While classically, foam bubble diameter has been invoked in seeking the differences in behavior, it is argued that bubble size distributions that can vary within the foam with time would be better replaced by foam thickness as a measure of drainage process. The high sensitivity of drainage time on foam thickness is a complicating factor in dealing with simple correlations. The dependence of static drainage behavior of some commercial foams on foam thickness has been experimentally obtained and set out within this view. However, Boussinesq effects seem to dominate foams at larger concentrations (of dilution) and select foams (IFP-AFFF).

The results of the quarter drainage time studies performed as a part of standard fire test (of UL kind, say) covers a 2 minute period for AFFF class of foams and five minute period for ARAFFF class of foams where as the fire extinguishment tests require a nine minute cool off period before the back burn protocol begins. In this period, it is expected that coarsening, coalescence and bubble break-up processes occur since during this period, because the linearity of drainage with time becomes exponential in character as the amount drained approaches values beyond 50 %. Thus it is unclear if what is observed in the quarter drainage period will be of any significance for fire extinguish even if it is relevant a quality confirmatory check. This indicates to the need for a study of correlating the early behavior with the extinguishment process.

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Notes: Videos of the foam behavior under microscope are posted at
https://drive.google.com/folderview?id = 0B36tyTSxGfU3NlZ3NFZVdjBnUnc&usp = sharing

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APPENDIX

Standard approach to foam drainage modeling is to use the following equation (drawn from Koehler et al, Physical review E, v. 58, August 1998):

$$\frac{\partial A}{\partial t} + \frac{\rho g}{\eta}\frac{\partial A^2}{\partial z} - \frac{\gamma \delta^{1/2}}{2\eta}\frac{\partial}{\partial z}A^{1/2}\frac{\partial A}{\partial z} = 0 \qquad (12)$$

In order to determine if the equations obtained in the present study have any relationship with the above equation, it is useful to examine the derivation of the above form with supporting explanations by Simon Cox (*http : //www.maths.tcd.ie/foams/PRESENTATIONS/Thursday19/Thursday19 Lecture1 Simon.pdf*). The equiv-alent form presented by Simon Cox is

$$3\eta f\frac{\partial A}{\partial t} + \frac{\partial}{\partial z}\left[\rho g A^2 - C\gamma\frac{\sqrt{A}}{2}\frac{\partial A}{\partial z}\right] = 0 \qquad (13)$$

which is the same as the one presented earlier barring some constants. Simon Cox presents the arguments to derive the above equation. He sets out

$$Q = < u > \ A = \frac{\rho g}{\eta f}A^2 - \frac{1}{2}\frac{C\gamma}{\eta f}\sqrt{A}\,\frac{\partial A}{\partial z} \qquad (14)$$

Where Q is the flow rate, the product of mean velocity $< u >$ and A is the plateau border cross section = 0.161 r^2. Here r is the characteristic radius of curvature of the channel through which flow takes place (this is also set out in Koehler et al, Langmuir 2000, 16, pp 6237 - 6241. A generalized view of foam drainage: experiment and theory and Stevenson in his paper dimensional analysis of foam drainage, Chemical engg science, 61, pp 4503 - 4510, 2006). Since the above equation is valid all over the foam, it can be invoked at the bottom where the drainage enters the fuel layer. We take that $< u >= -dh/dt$, the velocity with which the flow comes out and rearrange the terms to get

$$\frac{dh}{dt} = -\frac{\rho g}{\eta f}0.161 r^2 - \frac{1}{2}\frac{C\gamma}{\eta f}\frac{1}{\sqrt{A}}\frac{\partial A}{\partial z} \qquad (15)$$

The first term on the right hand side is the same as derived in our paper where momentum arguments were directly used.

$$\frac{dh}{dt} = -\rho g\frac{r_m^2}{a_1\mu} + \frac{2a_2\gamma r_m}{C\mu h} \qquad (16)$$

The question then is of the second term in the immediately above equation. Firstly, it must be noted that the term due to surface tension is dimensionally consistent with the term involving partial derivatives. In the sense of dimensional arguments of the kind advanced by Stevenson (ref. 10 in the paper) and the scaling arguments prevalent in fundamental physics, the consistency is established. However, we can ask a question as to under what circumstances the partial derivative term can be shown to lead to what is in our paper. In the term

$$-\frac{1}{2}\frac{C\gamma}{\eta f}\frac{1}{\sqrt{A}}\frac{\partial A}{\partial z} \tag{17}$$

We can choose $A = Const.r^2(z/L)^2$ as the variation of A with respect to r and z. The variation with respect to r is the known one from earlier literature. The variation with respect to z is chosen to be valid near $z \sim 1$ consistent with the approach chosen in profile techniques very standard in fluid flow and heat transfer problems. Introducing this into the equation gives a term

$$-\frac{1}{2}\frac{C\ Const.\ \gamma}{\eta f}\frac{r}{L} \tag{18}$$

If we choose the characteristic length L as h, we get the same expression as inthe present paper for the second term barring constants which are always uncertain and need calibration against known data. Finally, the quantities r and r_m in the above equations can be taken as equivalent and barring constants, the correct physics is recovered from the analysis the authors have presented.