

Foam as a Fire Fighting Agent

Introduction

Fire fighting foams are the primary agent for the control and extinguishment of flammable liquid fires, such as water-soluble flammable chemicals and non-water miscible liquids. The latter group of non-water miscible liquids are mainly called hydrocarbons (nonpolar liquids) which are lighter than water and therefore float on top of a water base. The water-soluble (polar) flammable liquids are mostly organic solvents such as alcohols, ethers, amines, and ketones.

One should be aware that it is not the liquid itself that burns, but the vapour above the liquid. Flammable liquids are low molecular weight volatile liquids with high rates of evaporation. The fire zone is above the liquid surface, where evaporated gases from the liquid react with air oxygen in a chemical reaction - a combustion reaction. A fire is an example of such a chemical reaction where combustible material reacts with oxygen under high release of heat (exothermic reaction). Combustion is an oxidation, a chemical chain reaction that requires oxygen (O₂). When foam is applied to a burning surface several different interacting mechanisms will be in force

The Extinguishing Process

The following points outline the extinguishing process:

- The foam layer protects the fuel from heat radiation of the flames.
- Drained liquid from the foam cools the surface of the burning fuel and adjacent hot surfaces and thus reduce the evaporation rate of the fuel. The cooling occurs because the liquid in the foam absorbs heat from the flames. Some of this liquid evaporates and the heat of vaporization absorbed contributes considerably to the cooling.
- The foam layer forms a barrier that prevents migration of molecules from the liquid fuel to the gaseous fire zone above. It separates the fuel source and the air above.
- For the film forming foams (AFFF and FFFP), the barrier is a very thin film (about 1 µm, or 0,001 mm) of drained foam solution spreading across the fuel surface due to this solution's exceptionally low surface tension of about 16 mN/m. In comparison, the surface tension of pure water is 72 mN/m.
- For the polymer-containing alcohol resistant fluorochemical based foam types used on flammable polar solvents, the barrier will be a gel-like coating of dehydrated polysaccharides. This is a polymer membrane that is extracted from the foam solution when it comes in contact with the polar solvent, and which will prevent the foam from being solved in the fuel.
- The degradation rate of applied foam slows down in correlation with reduced flame intensity as more of the fuel area gradually is covered with foam.

Some common terms/definitions before we go on further :

- **Foam concentrate** a foaming agent to be mixed with water to a foam solution. Foam concentrate and Foam liquid are synonym terms.
- **Foam solution** is a certain amount of foam concentrate mixed with water, usually 1, 3 or 6 percent by volume. It can be mixed as the foam is applied by means of a proportioning device, or it can be made on beforehand as a premixed solution.
- **Foam** is generated by entering air into the foam solution. This is done by sucking air into the solution through a foam nozzle, or it may be accomplished in other ways. All foams are two-phased mediums showing so-called non-newtonian flow characteristics.
- **Foam characteristics** describing the generated foam from its drainage rate and expansion ratio. Foam number is another term for expansion ratio.
- **Expansion ratio** expresses how much a given volume of foam solution is expanded when it is generated into foam by addition of air. 10 litres of foam formed by 1 litre of foam solution gives a foam with expansion ratio 10:1 (Foam Number 10).
[Low expanded foam: foam number up to 20, Medium expanded foam: foam number between 20 and 200, High expanded foam: foam number >200]
- **Spreading /Fluidity** of a foam says something about how frictionless it spreads across a surface. This depends on the foam type, the rheology of the foam (rheology is the study of a fluid's flow characteristics), the application rate, the foam stability, and partly on the nature of the underlying fuel.
- **Foam Stability** is the stability of finished generated foam and a measure for its persistency. The drainage rate of liquid out of the foam is an expression of the foam's stability.

The Extinguishing Mechanism

The following explanation is a step by step generic description of the extinguishing mechanism of any type of class B fire fighting foams.

1. The initial foam discharge hits the surface of the burning liquid and foam degradation starts immediately. The flames are now at the most intense and the heat flux highest, and the foam degradation is at its maximum. The rate of degradation is not linear, but will vary during the course. (See section **B. Foam degradation**, page 5.) The fuel will also, to a certain degree influence on the rate of foam breakdown.
2. After sufficient cooling a foam blanket starts to form. The area of the blanket will gradually increase because the application rate, $V_{\text{application}}$, must be greater than the breakdown rate, $V_{\text{degradation}}$, which is an absolute condition for the fire to be extinguished. The foam has gained 'foothold' and begins gradually to spread.
3. Foam coverage increases and evaporated combustible material into the fire zone decreases concurrently with a reduction of heat flux from the flames. The inequality $V_{\text{application}} > V_{\text{degradation}}$ (see page 5) is greater now than at the beginning. Remember, $V_{\text{application}}$ is more or less constant while $V_{\text{degradation}}$ is a variable parameter.

4. Some of the heat is absorbed by the fuel and adjacent hot surfaces, while some is absorbed by the liquid in the foam as heat of evaporation when it evaporates. In physical terminology this means that the enthalpy change ΔH , is negative, - the fire's thermodynamic potential decreases.
5. The flames, and therefore the heat flux, decreases. Heat is absorbed by the foam, the temperature in the fire zone drops, and the foam barrier that prevents combustible gases to reach the fire zone is getting bigger and stronger. Until the concentration of combustible gases in the fire zone falls below the lower ignition limit for that fuel. The fire is extinguished.

The complete extinguishment process is physico-chemically complex and affected by many variable factors. Although the inequality $V_{\text{application}} > V_{\text{degradation}}$ mentioned above is essential and must apply anyway, the following will influence on how easy or difficult a liquid fire can be put out, - or if at all being possible:

- *The quality of the foam*
- *Type of fire / scenario*
- *Type of flammable liquid – flash point, polarity, vapor pressure, boiling point*
- *Foam application rate*
- *Application method / equipment and technique*
- *Quality and type of foam concentrate the foam is made of*
- *Weather conditions - wind and temperature*
- *Logistics / competence – well trained firefighters*
- *Thermal updraft (chimney effect)*
- *Adequate supply of fire water and foam agent*
- *Sufficient water pressure*

A. Foam Application

The foam agent - or the foam concentrate - is proportioned into the water flow at a given percentage, usually as 1%, 3% or 6%, depending on the type of concentrate used. The resulting mixture is referred to as a *foam solution*, and it is this which in turn is generated to finished foam by mixing with air, to produce an expanded foam structure through the use of an air-aspirated foam nozzle.

A generated foam has given *foam characteristics* of a specific drainage rate and foam expansion ratio. The foam characteristic is determined primarily by the type of nozzle/monitor used, but also the choice of concentrate will contribute. In addition, water pressure, water quality and temperature will influence. Note that the terms *Foam Quality* and *Foam Characteristics* are used interchangeably as synonyms.

At least that is how the concept foam quality is presented in much of the published literature that exists on foam rheology. Accordingly, the same foam concentrate can provide foam with quite different 'foam qualities', depending on what equipment one chooses to use. This may sound somewhat strange, as one might associate 'foam quality' with good extinguishing performance, which is not necessarily the case. The Foam Quality measurement defines how many litres of foam you get out of one liter of foam solution (expansion ratio) together with how stable this foam is (drainage rate). Therefore, it is important to distinguish between the concepts *Foam* and *Foam Concentrate*.

The foam may contain varying amounts of liquid, depending on how much the solution has been expanded. By so-called non-air aspirated equipment, such as conventional water nozzles or open sprinkler heads, almost no foam forms at all. One is at the bottom of the expansion range, with expansion values below 2 – 3 to 1 foam expansion. The amount of foam what formed this way takes place as some air goes into the solution on its way through the air from the nozzle.

Many types of foam agents, however, require the use of air-aspirating equipment to provide a foam with a higher expansion ratio necessary to perform effectively on a fire. Monitors and other nozzles may be constructed with an air inlet to induce additional foam generation.

Foam application can be direct or indirect. Direct application, where the foam jet hits the burning surface is the harshest method with respect to fuel pick-up into the foam. However, in many situations this is the only method available to fire fighters. For example, in fighting fires in large storage tanks, where big monitors have to shoot low expanded foam with long throwing distances on to the top of a burning tank fire.

At indirect application the foam first hits a wall or something else solid so that it is 'slowed up' and therefore flows more gently across the surface. This gives less fuel uptake in the foam, and is often preferred in a fire situation, in particular with water miscible fuels such as ethanol and other alcohols.



Application method- and technique is determined by the choice of equipment and type of fire to be extinguished. All units making up the total extinguishing system must be designed and dimensioned so that it is adapted, or suitable, to the potential scenario one would be confronted.

The application rate is calculated in litres of *foam solution* applied per minute per square meter of the burning surface (ltr/min/m²). The litres of generated *foam* per minute per m² is influenced by the equipment used. Foam expansion factors of 10 would result in 10 times the volume of the foam solution if the expansion ratio is 10, or 5 times the volume of foam solution if the equipment generates a foam expansion factor of 5.

[The exception is generator-produced High Expansion foam without any throwing length at all, where measuring the foam volume is used to find the application rate. Here are discussed the mechanisms of Low Expansion and Medium Expansion foams, which is relevant in this context].

Once a freshly generated foam hits the burning surface and gets foothold, it begins to spread. At the same time foam breakdown starts immediately (foam degradation is described in section B below). There are two 'forces' that oppose each other, foam build-up *and* spreading on the one hand and foam breakdown on the other. If these two 'forces' are in equilibrium, a successful extinguishment is absolutely impossible. Again it should be emphasized that the criteria: $V_{\text{application}} > V_{\text{degradation}}$ must be in force. The foam must be able to cool, resist heat, and flow outwards, forming a sealing barrier.

The spreading property will vary from foam to foam. It will obviously increase with increasing application rate, but also vary with the concentrate type the actual foam is made of, with type of burning fuel, with the foam's density and viscosity, and not at least with the degradation rate of the applied foam. Viscosity is the internal friction between the bubbles as well as friction between the foam and fuel surface – in other words, how 'sticky' the foam is. Foam density is determined by its expansion ratio.

B. Foam Degradation

Fire fighting foam with a film forming foam is a two-phase system consisting of air bubbles dispersed in a continuous water phase. It is unstable and will eventually collapse, regardless of whether the foam is applied to a burning liquid surface or just on the ground. Applied on a burning liquid surface, the break down rate will naturally be much faster than on a non-burning surface due to heat radiation, and it will be greatest in the beginning when the radiation is strongest.

If we let V stand for rate, the following inequality must – as mention before – always apply if a fire should be extinguished with foam:

$$V_{\text{application}} > V_{\text{degradation}} \quad (1)$$

Foam breakdown is caused by three factors: **a)** evaporation of the liquid in the foam, **b)** drainage of fluid out of the foam due to thermal radiation from the flames, and **c)** so-called conventional drainage. The latter is non-thermal related drainage, or drainage that would occur even without flames present, - a drainage that takes place anyway and that is energetically conditioned ('drainage by gravity').

The rate of foam breakdown is the equal of drainage rate plus evaporation rate:

$$V_{\text{foam degradation}} = [V_{\text{evaporation}} + V_{\text{drainage-thermal}} + V_{\text{drainage-conv.}}] \quad (2)$$

(1) then becomes: $V_{\text{foam degradation}} > [V_{\text{evaporation}} + V_{\text{drainage-thermal}} + V_{\text{drainage-conv.}}]$

[In cases these rates should be equal, $V_{\text{application}} = V_{\text{foam degradation}}$, we talk about the critical application rate. Then we will not be able to put out any fire, no matter how long we keep on applying foam].

The $V_{\text{drainage-thermal}}$ value would be large in the beginning because of the heat radiation, and as would the value for $V_{\text{evaporation}}$. Therefore, given a constant application rate, the inequality above will increase as function of time. Remember that foam breakdown is a mass transfer, where the liquid in the foam disappears due to evaporation and drainage, accounting for all of the mass change.

The drainage rate is not a linear function of time. Its initial value is zero, gets its maximum after a certain time, and then gradually decreases. Low expansion foam has a higher drainage rate than higher expanded foams, or a shorter drainage time.

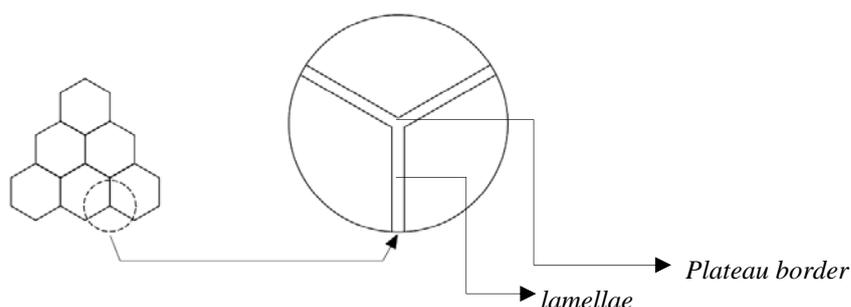
The terms drainage time and drainage rate are different terms. The first is a measurement of time, the second is the time derivative of mass change (d/dt). Further defined, the rate of mass transfer of fluid out of the foam, - or mass transfer per unit time.

The density of the foam decreases as it ages because it loses mass; therefore expansion ratio increases. The foam expansion can increase by up to several times its original value, which is consistent with data from measured drainage rates on different foams.

Expansion ratio, drainage rate and density are key concepts in foam rheology.

The foam consists of bubbles of different sizes. The bubbles are separated by a thin two-sided liquid film of foam solution, called lamellae. This film is very thin, and as the liquid phase is drained out, it stretches. At a certain critical thickness of around 50-100 Ångstrom, Å (one Å = 10^{-7} mm) it collapses and bubbles merge. Since the pressure is greatest in the small bubbles, these diffuse into the larger ones. Foam bubbles have a more or less stable polyhedric structure where three or more

bubbles meet in what is called the Plateau border (see figure). The liquid pressure is lower here than elsewhere in the lamellae, and the drainage will occur at these.



Two-dimensional illustration of a three-dimensional polyhedral structure

Although the polyhedral ('honeycomb') structure is the most energetically favorable configuration, in practice bubbles varies a lot, both in shape and size because of physical-chemical laws and different external influences. Foam is not a static, but highly a dynamic medium.

The contribution of the foam agent. Foam breakdown is to a great extent influenced of the type of chemical components present in the water phase in the lamellae. That is, the composition of the foam concentrate that has been used to make the foam solution the finished foam is generated from.

Different types of foam concentrate provide different foams, even if they are generated with the same equipment and at the same temperature. This is obvious, and depends of course on the chemicals the foam liquid is composed of. Foam characteristics, degradation rate (stability), cohesive strength, tolerance to heat radiation, flow properties, etc. will vary.

For example, foams able to form polymer membranes on polar flammable liquids will generally be more stable and slow-draining than those who are not. This has to do with the fact that they often contain macromolecules of carbohydrates, which in interaction with other components, - surfactants, electrolytes, other additives - contribute to increased viscosity on the lamellae liquid. The friction increases, the elasticity of the lamellae changes, and the mobility of the liquid is affected. Both mechanical and chemical 'forces' are involved.

The composition and selection of types of chemicals in the foam concentrate means a lot, maybe most, of how easily a given foam solution can be generated to foam using a given equipment. The same can be said with regard to the permeability of the underlying flammable gases, - that is, to what extent they are able to penetrate the foam blanket. Foams that easily pick up volatile flammable gases are poor extinguishing foams. The concentrate they are made of contains 'wrong' chemicals, - or component composition. Such fuel pick-up will also play a considerably part in rate of foam breakdown.

Reidar Ladehaug

Solberg Scandinavian,
October 2010