WATER SPRAYS: CHARACTERISTICS AND EFFECTIVENESS

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Objective of this paper: to outline a method for assessing the effectiveness of water spray nozzles in "Halon" replacement scenarios.

1 Introduction

The properties of water make it an intrinsically excellent chemical for fighting fire. Water's ability to absorb heat as a liquid and as a vapour is quantified by its relatively high specific heat capacity and latent heat capacity [NFPA (1977)]. The rate of heat transfer can be further increased by increasing the surface area that the water presents to the surroundings (fuel, fire and fire gases). This can be achieved by the break-up of bulk water into the dispersed phase, a spray of fine drops.

Four distinct ways of controlling combustion are described in the Fire Protection Handbook [NFPA (1977)], they are extinguishment by: cooling; oxygen dilution; fuel removal; and chemical inhibition.

Lefebvre [1989] has explained the mechanisms for the evaporation of a fuel spray. The same description is appropriate for the fire fighting water spray.

As the heat transfer takes place the drops heat up, and at the same time lose part of their mass by vaporization and diffusion into the surrounding air or gas. The rates of heat and mass transfer are markedly affected by the drop Reynolds number, whose value varies throughout the lifetime of the drop, since neither the drop diameter nor the drop velocity remains constant. The history of the drop velocity is determined by the relative velocity between the drop and the surrounding gas and also by the drop's drag coefficient. The latter again depends on the Reynolds number. After a certain time has elapsed each drop attains its steady-state or "wet-bulb" temperature corresponding to the prevailing conditions.

The larger drops take longer to attain equilibrium conditions, and their trajectories are different from those of the smaller drops since they are less influenced by aerodynamic drag forces. However, the smaller drops evaporate faster and produce clouds of vapour that move with the air.

The key point to note is that each drop has individual characteristics and will interact with the surroundings according to these characteristics.

2 Spray Characterisation

To quantify the ability of a spray as a fire fighting agent requires a detailed analysis of the individual drops. The characteristics and behaviour of individual drops are unique in space and time. A full analysis of a representative sample of drops is therefore essential. This information can then be used to predict the initial condition of drops at the nozzle head, and subsequent interactions with the fire environment.

Chigier [1983] states that a complete analysis of a spray requires the determination of the following: spray image; drop size distribution; drop number density; drop velocities; drop size/velocity correlation; liquid distribution; air distribution; and vaporisation rates. This approach has been taken at South Bank University, where several nozzles have been extensively characterised to allow three dimensional modelling of their sprays (section 5).

Spray image measurements of the whole spray have been made by photographic and collection techniques. At South Bank University, "splash pattern" photographs [Jackman (1992)]; laser light sheets that illuminate planes in the spray [Lavelle (1993)]; and water collection topography [Glockling (1992)], are the techniques that are used. Figure 1 gives the measured volume distribution of a spray nozzle across a floor in ambient conditions, by Glockling [1992]. The irregular solid cone nature of the spray can be clearly seen.

From the spray image measurements the boundary of the spray envelope and any internal drop flux variations are found.

3 Drop Data

Two drop characterising techniques have been used. A standard laser diffraction technique for particle sizing, and the complete drop characterisation technique developed at South Bank University.

3.1 The Malvern particle sizer

The Malvern 2600C particle sizer is a commercially available instrument that collects diffracted light from particles illuminated with a Helium-Neon laser. A lens situated behind the sample focuses the scattered light onto an array of photo-diodes. The particle sizer is equipped with a range of lenses. To characterise spray nozzles a 300 mm focal length lens was used that permitted drops to be measured within the diameter range 5.8 - 564 μm.

3.2 The South Bank Photographic High-speed Imaging Laser

This technique enables the accurate characterisation of drops without the sometimes questionable use of "black-box" electronics used by LDA and diffraction based laser analysis techniques. The South Bank system [Nolan et al (1991), Jackman et al (1992a)] utilises a synchronised pulsed copper vapour laser and high speed cine camera enabling continuous photographic capture of drops during their time in the focused sampling volume. The apparatus is kept remote from the sampling location by optical fibre for the delivery of the light, and a rigid borescope for the collection of the light. Image analysis of the progression of drops in sequential frames provides, among other parameters, the drop size, velocity, direction and frequency.

The dimensions of the sampling volume and the frequency of the shutter/laser pulse are both adjustable. To characterise water sprays the optics are generally arranged with a sampling volume of 6 x 4.5 x 4 mm that permit drops to be measured within the diameter range 10 - 3000 μm. The camera/laser frequency is generally set to 6000 Hz, allowing velocities in the range 0 - 25 m s^{-1} to be measured.

Accumulation of data from a sizable population of drops results in the calculation of many mean values and estimations of possible mathematical functions that fit the data. Table 1 gives the calculated mean values for three spray nozzles, operated at a pressure of 3 bar. Figures 2,3 and 4 give examples of the drop diameter, velocity and trajectory distributions.

The measurements have been made in ambient conditions. In a fire environment the same water flow rate will result in a reduced volume of water reaching the floor. This is due to the heat released from the fire (conductive, convective and radiative) and associated flow of fire gases. The fire environment results in the evaporation of the water drops, and consequential reduced diameter and momentum. Some of these drops will boil away completely, adding to the volume of evolving water vapour. By finding the initial drop characteristics close to the nozzle, predictions of their flight can be made.

The cine film made at each sampling location ensures there is a permanent record of the drops. This allows any future additional analysis of, for example the level of air entrainment or evaporation, possible. This technique surpasses all others by providing information concerning the drop's shape and geometric behaviour with time.

4 Methods of extinguishing fires

- *"Combustion is a reaction that is a continuous combination of a fuel (reducing agent) with certain elements, prominent among which is oxygen in either a free or combined form (oxidizing agent)".*

The quality that these reactions have in common is that they are exothermic: converting chemical energy trapped in the original molecules into the form of actual thermal energy.

4.1 Extinguishment by cooling

Cooling of a fire's solid fuel will reduce and ultimately stop the rate of release of combustible vapours and gases. The efficiency of an extinguishing agent as a cooling medium depends upon specific and latent heat, as well as upon boiling point.

Water applied as a spray may also remove heat from the combustion gases themselves. Water absorbs the infra-red emissions from the fire, and its cooling action is performed by sequentially conduction, evaporation, and convecting heat away from the solid surfaces that are either burning, or are hot from exposure.

The action of an extinguishant such as water may be improved by the addition of surfactants that promote soaking and penetration, preventing run-off, and leaving residues of flame retardants.

4.2 Extinguishment by oxygen dilution

Oxygen required for combustion may be present as free oxygen gas in the atmosphere or combined, as hypochlorites, such as ClO_2. Dilution can only be applied to the gaseous state since in the combined form oxygen is locked into the molecules and so no dilution is possible.

By artificial injection of gas into the same space as a fire, the percentage of oxygen in the space available for the combustion process is reduced. If the percentage of oxygen remaining is low enough the fire will be extinguished. The necessary degree of oxygen dilution varies greatly with the particular fuel.

A typical example of the efficacious use of the oxygen dilution principle is when carbon dioxide is used in total flooding of closed or semi closed spaces. The application of water to a fire produces large amounts of steam whose diluting effect in an enclosed space will additionally help extinguish the fire.

4.3 Extinguishment by fuel removal and chemical inhibition

Fuel can be effectively removed by blanketing it with water, pre-wetting.

Less significantly water can be used for the physical absorption of fire gases and possibly to react with components of the gas.

Pietzak and Ball [1983] state that the success of a water spray in extinguishing a fire is dependent on the proportion of drops that:

- are blown away before reaching the fire
- vaporize to steam (contributing to cooling and water vapour evolution)
- directly impact on the walls, floor and ceiling (cooling them if they are hot or running to waste)
- penetrate the fire plume, or otherwise reach the burning surfaces beneath, to inhibit pyrolysis by cooling, and to dilute the available oxygen
- cool and pre-wet the surrounding combustibles to prevent fire spread.

5 SPLASH program

A three dimensional particle tracking model has been developed at South Bank University. The interaction between a spray and a uni-directional thermally buoyant layer has been mathematically modelled and developed into a computer program, SPLASH [Gardiner (1988) and Jackman (1992b)]. The model has been successfully compared with results from physical experiments [Ingason and Olsson (1991)], [Williams (1991)], and it has been applied to investigations of sprinkler protection of buildings, LPG storage, and computer cabinets.

A full description of SPLASH is available in Jackman et al [1992b].

The model allows the examination of many variables, particularly the heat and mass transfer effects in the buoyant layer and the consequences of the cooling process.

The output from the program provides details of:

a. the total heat transfer from the fire gases and the consequent reduction in smoke egress from the building

b. the complete physical and thermal drop histories throughout the spray including the number boiled and mass evaporated, and the resulting water distribution on the floor, and where appropriate the walls and ceiling

c. the effects of the sprinkler spray, on the physical profiles of the buoyant layer, as it passes through the spray envelope

d. the changing gas properties within the specified layer volumes and the average gas temperature and drag to buoyancy ratio in the gas layer.

SPLASH contains spray data from several nozzles and sprinklers, all were collected at South Bank University using the Photographic High-speed Imaging Laser technique, PHIL (see section 3.2). This has allowed comparisons between spray types to be made as well as the effectiveness of individual sprays in many fire environments to be assessed.

5.1 The application of SPLASH to the extinguishment problem

For each characterised spray and operating pressure SPLASH outputs quantify the spray's cooling, pre-wetting, and oxygen diluting potential.

5.1.1 Cooling

After the interaction of a spray with fire gases, the heat transfer to the spray is calculated as a single value. This is calculated by considering the interaction in each of the 2100 discrete control volumes of which the defined volume comprises. The values have dimensions of $J\ s^{-1}$.

SPLASH calculates the number and volume of drops that are circulating and travelling in the gas flow. In an enclosed environment these fine drops will be carried in the convective flow until they have fully evaporated.

5.1.2 Cooling and wetting of the fuel

It is necessary to find the amount of water available for wetting the combustibles. That is both the combustibles' still remote from the fire, and those affected by the heat from the fire.

The distribution of the water drops that reach the fuel array and floor is calculated in three ways. The volume across the whole floor is found, the volume distribution in each zone of a grid on the floor is found, and the volume and average drop temperature of water reaching blocks of fuel is found. Figure 5 shows the calculated water distribution at the floor for a nozzle at increasing temperature. It is interesting to notice the amount of deflection of the spray that occurs with the flow of the fire gases (maximum velocity = 2 m s^{-1}).

5.1.3 Dilution

The mass and volume of liquid water converted to water vapour is calculated. These values found with SPLASH can be used to find the increasing proportion of water vapour in a sealed container, and hence the dilution of the oxygen can be calculated.

5.1.4 Application to computer cabinet fires

Heat predictions were made for a spray nozzle at a range of gas temperatures between 1 and 46 K above the ambient gas temperature (296). The nozzle was assumed to be suspended 30 mm under the roof of the cabinet.

Figure 6 illustrates the analysis in the cabinet over the full range of gas temperatures computed for the nozzle. The predictions shown are of: heat transfer; deposition on the floor, walls and ceiling; and volume circulating and leaving in the gas flow. Figure 6 shows the calculated increase in heat transfer is proportional to the increase in environmental temperature.

It was found that two nozzles with different orifice sizes (0.3 mm and 0.7 mm) had different predicted results. At 3 bar pressure and realistic cabinet temperatures, over 26% of the spray produced from the 0.3 mm nozzle was predicted to circulate in the flow, whilst 70% impinged upon the floor. This compares to the dramatically lower figure of around 2% recirculating at equivalent conditions for the spray produced by the 0.7 mm nozzle for which over 85% impinge directly upon the floor. This difference is largely due to the finer spray produced by the 0.3 mm nozzle.

5.1.5 Assumptions

SPLASH is a particle tracking model that calculates the interaction between the spray's drops and thermally buoyant layer considering the conservation of mass, momentum, and energy in discrete control volumes. The description of the thermally buoyant layer is less sophisticated than that of the spray, since it assumes steady state, a uni-directional gas flow, and no heat transfer by radiation. These limitations are understood and use of the program close to a fire source is restricted and the results only considered as indicative.

The model was originally designed for applications sufficiently remote from a fire for the heat transfer by radiation to be small. The closer the spray approaches the fire the less valid is this assumption. In lieu of the completion of the radiation model for the SPLASH code, its predicted results can still give meaningful answers, with under-estimations of cooling, erring on the side of caution.

6 Discussion

To characterise fully, a spray nozzle that is to be used for fire fighting purposes, requires measurements of all the characteristics of the drops in the spray. Therefore, as well as drop diameter measurements, drop velocity, trajectory, and flux are also required.

Commercially available sizing techniques have been found to give perfectly adequate diameter measurements for perfectly spherical drops within the size range limits. Though this single property is not sufficient for a full characterisation.

The Photographic High-speed Imaging Laser technique developed at South Bank University has proved to be a highly successful characterising method, and has been used for characterising aerosols and sprays for several years. The technique can measure the drop histories of size, travel and flux. It is a direct and continuous measuring technique, viewing a defined volume in space, all drops entering and leaving it are recorded. Their properties of length, mass and velocity are measured at a number of positions within the volume, as well as their rate of change with time. It can measure non-spherical drops. Events such as drop collisions, drop oscillations, and break-up have been recorded and evaporation and condensation, can also be recorded.

Photographic characterisation is a well established reliable and accurate technique. It is non-intrusive, non-destructive, continuous and is able to cope in harsh environments. So far the technique has only studied sprays in ambient conditions. This is not because it is incapable of probing "unfriendly" fire environments, in fact the flexible light and lens system allow in-depth investigation in highly hostile environments. Measurements have been collected with a view to the mathematical modelling of the spray. This requires a knowledge of the initial conditions of the drops for their future paths to be tracked. The calculation of this tracking has relied on well established chemical engineering heat and mass transfer equations between the dispersed phase and the gas phase.

A complete database of drop information from spray nozzles and other spray types (fire sprinklers and sprayers, aerosol cans and inhalers), is available for use at South Bank University. Comparisons between spray types and operating pressures have been possible, and assessment of their effectiveness. To optimize the use of fog nozzles in physical fire experiments, such as described by Carhart et al [1992] for navy shipboard compartments, will require the selection of nozzle and operating pressure based on the spray drops' characteristics.

There are many models for the prediction of smoke spread, but few attempt to include the interaction of a water spray. SPLASH models a spray in a fully three dimensional manner, considering all variations at different angles in the spray, and all the characteristics of representative drops in the spray.

Calculations by SPLASH, of particular interest for fire extinguishment by sprays, are cooling of the fuel and fire gases, wetting of the potential fuel and the dilution of the oxygen by the production of water vapour. Therefore the effectiveness of any spray can be found regarding the heat transfer to the spray, volume and distribution of wetting of the fuel load and mass of water evaporating.

7 Conclusions

The Photographic High-speed Imaging Laser is an ideal technique for characterising a spray. All the drop's properties, diameter, velocity, trajectory and shape, are found simultaneously. As well as the flux at different positions around the nozzle. Being a direct photographic technique the measurement does not rely on assumptions about the drops sphericity, or light transmission properties.

Applications of the program SPLASH have shown it to be a suitable method for finding the effectiveness of sprays. This is demonstrated by the calculation of the spray's ability to cool fire gases and fuel, pre-wet other combustibles and dilute the oxygen with water vapour.

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TABLE 1

NOZZLE	Spray Systems TG 0.7 mm	Spray Systems TG 0.3 mm	CAA fog
Malvern results			
Number geometric mean diameter,µm	172.	137.21	
PHIL results			
Number geometric mean diameter,µm	158.	107.	106.
Log values	5.06	4.67	4.66
Numerical mean diameter,µm	177.	114.	116.
Standard deviation	102.	45.	51.
Surface mean diameter,µm	204.	123.	126.
Volume mean diameter,µm	239.	132.	138.
Sauter mean diameter,µm	327.	153.	166.
Number median diameter,µm	148.	106.	106.
Volume median diameter,µm	443.	168.	180.
Rosin-Rammler mean diameter,µm	507.	181.	212.
Numerical mean velocity, m s^{-1}	10.3	7.3	6.5
Number median velocity, m s^{-1}	10.8	7.1	6.5
Volume median velocity, m s^{-1}	13.6	8.9	10.8
Numerical mean trajectory, °	-54.	-87.	-60.
Number median trajectory, °	-86.	-89.	-62.
Volume median trajectory, °	-86.	-89.	-60.
Sampling position elevation, °	-90.	-90.	-63.
radius, m	.15	.15	.11

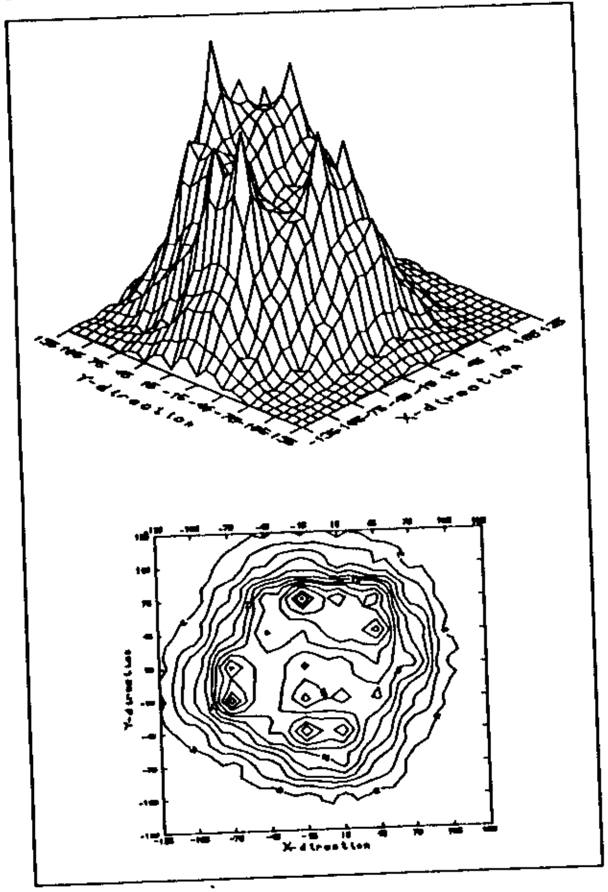

Figure 1 Water collection topography, using the Spray System TG 0.3 mm nozzle, at a height of 150 mm and 3 bar supply pressure.

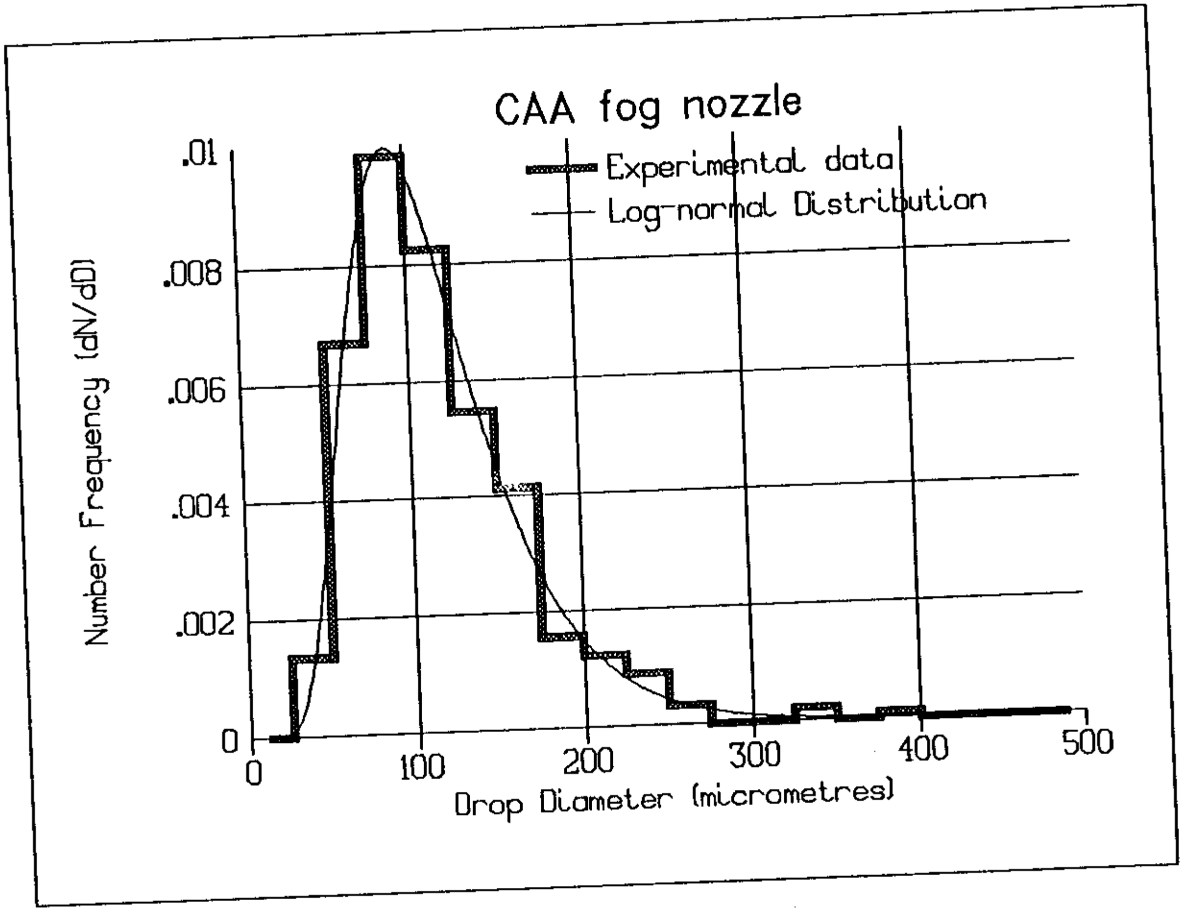

Figure 2

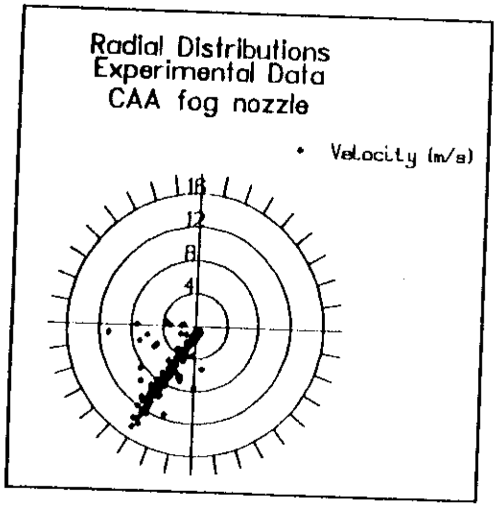

Figure 3

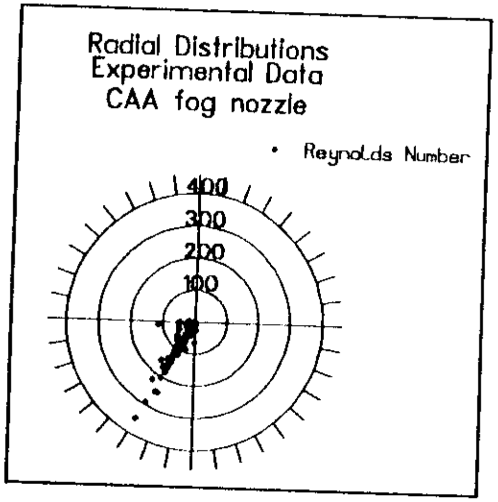

Figure 4

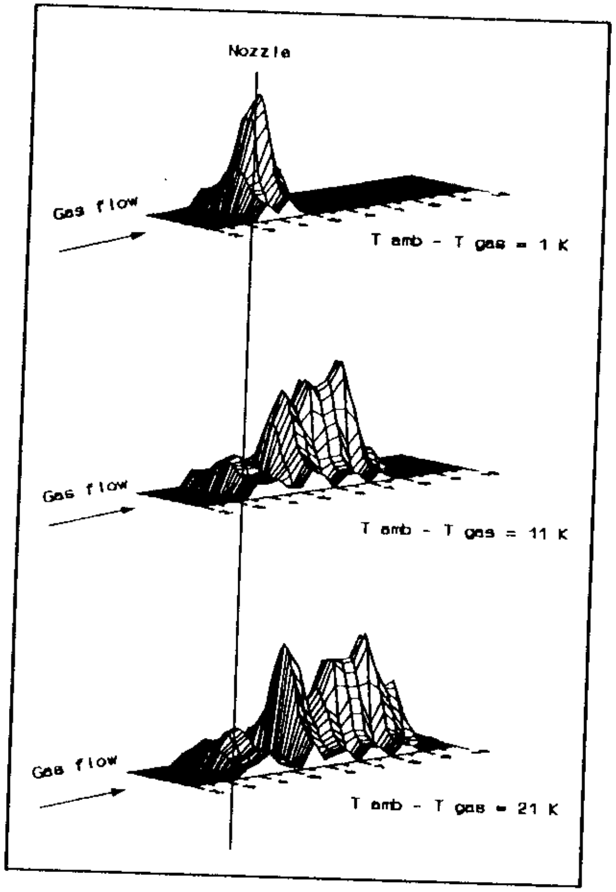

Figure 5 Predicted drop distribution along 10 m corridor (0.5 m wide) from the Spray System TG 0.3 mm nozzle (3 bar) at three gas temperatures.

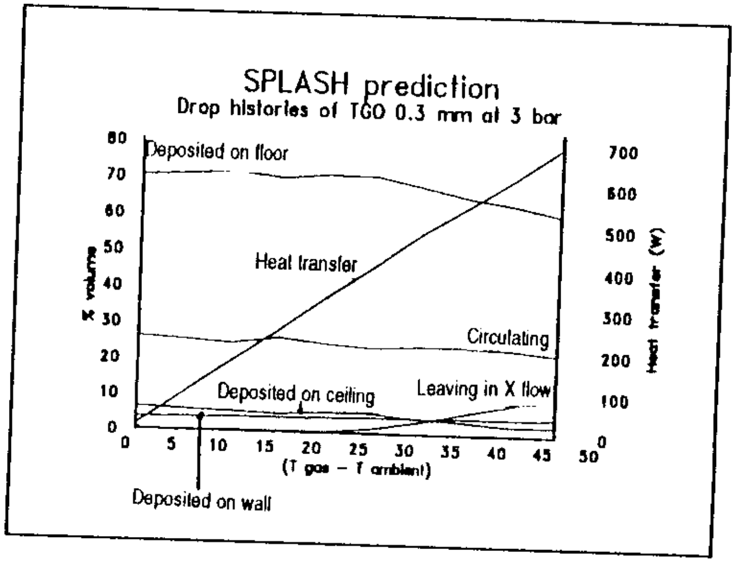

Figure 6 Complete drop histories over a range of gas temperatures computed with SPLASH for the Spray systems nozzle.