INVESTIGATION INTO THE EFFECT OF WIND ON FIRE PROTECTION SPRAYERS, USING THE MODEL SPLASH

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Water spray systems are used to protect chemical plant installations, particularly storage tanks from external fire. The systems are designed to spray water over a predetermined area defined by BS 5306 part 2 and NFPA 15. Storage vessels tend to be located in areas of relatively high wind and this may affect both the extent of wetting and the cooling of the tank walls and contents. Experimental data to characterise water drops from medium velocity sprayers has been obtained using a novel synchronised metal vapour laser - high speed cine system. This data has been employed in a trajectory tracking multi-layered mathematical model, SPLASH, to examine the interaction between the spray drops, the fire gases and air flow. The effectiveness of spray systems has been predicted for a range of fire profiles and in terms of the prevailing wind conditions.

KEY WORDS: three-dimensional, spray model, fire gases, water coverage, LPG protection, wind.

BACKGOUND

Water spray (deluge) systems are used to protect plant structures and machinery against fires caused by highly flammable liquids, gases and solids. They are operated to facilitate: fire extinction; fire control; fire prevention; explosion prevention; and health hazard area scrubbing.

Sprayers

There are high, medium, and low velocity spray systems. The high velocity nozzles produce a course drop spray with good capabilitites of penetration through fire gases and plumes. The low velocity water fog nozzles produce a fine drop size with a high capacity for heat absorption. The medium velocity sprayer is a general purpose nozzle used in all categories of protection.

Sprayer models are identified by orifice size and spray cone angle. The orifice size governs the 'K' factor, which gives the relationship between the pressure at the spray head and the water flow rate. The cone angle specifies the angle of deflection of the spray at the head. Changing either or both, alters the area of water coverage on the target.

Standards

The spray system is operated in the event of a fire, to apply a discharge density of water over a predetermined area. The primary function of fire spray protection of vessels is to reduce the heat input to the vessel by wetting its surface. The water film provides a barrier absorbing radiative and convective heat from the fire. In the case of a Liquid Petroleum Gas (LPG) tank the film of water around the tank attempts to keep the temperature of the tanks surface and contents below 100°C; above this temperature the tank may rupture.

The British Standard British Standard, BS 5306 part 2 [1990], classifies oils and flammable liquid hazards as high hazard. The recommendation for such substances is for the use of deluge installations with medium and/or high-velocity sprayers. Discharge densities are not given in this specification for oil and flammable liquid hazards, but high hazard type 4 cites a minimum design density of 10mm/min of water.

Minimum requirements of water coverage for particular hazards are given in NFPA Standard 15, and are of the order of 10 mm/min (l/min) over an area of 1 m^2. "In addition to the theoretical coverage of a risk there is a marginal wastage which needs to be taken into account. The wastage factor comprises of water losses caused by slippage, overshoots, windage etc, and is taken as a minimum of 25% of the theoretical water requirement". Further discussion of spray systems and related standards is given by Reimer [1990].

LPG tanks are often sited outside, where meterological effect need to be considered. They are frequently placed in areas with blustery or severe wind. For instance on the coastline 10 m/s wind occur over 10 % of the time [Catom (1976)], therefore actual water coverage might be expected to be significantly reduced should water be entrained in the wind.

Two additional considerations are the reduced coverage due to the drop evaporation and deflection by the convection currents of the hot fire gases, and obstructions causing spray shadows.

Related work

Research into spray protection of LPG tanks has investigated the characteristics of spray systems for specific problems and risks.

Lev [1990] studied the protection afforded by the water coverage of surfaces when subject to impinging LPG jet fires. His theoretical work demonstrated how the path of water drops to the surface of, for instance, a tank, could be modelled. He took account of in-flight evaporation losses (including a simplistic radiation model), and the subsequent removal of heat from the surface of the tank. He discussed the applicability of medium and high velocity spray systems. The study considered a range of jet fire temperatures, velocities, radiative heat fluxes, and surface temperatures. He suggested that "the current medium velocity (MV) spray nozzles, which produce a large proportion of drop sizes of less than 0.5 mm diameter, may prove unsuitable for use in water cooling installations where the risk of jet fire impingement exists".

Schoen and Droste [1988] detailed a series of full scale fire tests that determined the water requirements to prevent the failure of LPG storage tanks when engulfed in fire. They compared the water spray systems' (WSS) pipe arrangements. Their conventional WSS, which applied the water from directly above the tank, was unable to protect the vessel with a spraying rate of 16.7 mm of water per min per m^2. The upgraded WSS which sprayed both sides of the tank protected it with 6.7 mm of water per min per m^2. They found that "those parts of the tank wall which had been cooled by the water spray system had a maximum temperature of 100 °C. At non-cooled local points (in the case of the wind effect) the wall-temperature rose up to more than 300 °C."

Stark [1961] conducted an experimental study that measured the rate of water flow at an outdoor fire risk. The dimensions of the target used were 0.6 m wide by 1.3 m length by 2.5 m high. Effects due to the spray nozzle type, operating pressure, arrangement, and the prevailing wind condition were found. Generally there was a proportional relationship between the decreasing water coverage and increasing wind velocity, upto their measured maximum wind velocity (5 m/s). An example array of 4 nozzles operating at 3.3 bar were found to have a 10 % reduction of water coverage, at a wind of 5 m/s.

The aim of this work

The related work reported that the water coverage protection is dependent on the fire characteristics, the spray(s) characteristics, and external interference by wind. This study aims to illustrate through the use of a developed 3 dimensional spray model, SPLASH, the significance of some of the influencing parameters, namely, spray cone angle, spray operating pressure, fire gas temperature, and wind.

An example layout of sprayers protecting an LPG tank from fire gases evolving from a pool fire is considered. This arrangement is used to compare the effects due to different sprayer operating parameters, temperature and wind conditions.

THE SPRAY MODEL SPLASH

A three dimensional particle tracking model has been developed at South Bank University. The interaction between the spray drops and fire gases has been mathematically modelled and developed into a computer program, SPLASH [Gardiner (1988) and Jackman (1992)]. The model has been successfully compared with results from physical experiments [Ingason and Olsson (1991), Williams (1991), Morgan and Baines (1979) and You et al (1986)], and has been applied to the investigations of sprinkler protection of buildings, and mist protection of computer cabinets [Glockling (1992)].

The model allows the examination of many variables, particularly the heat and mass transfer effects in the fire gases and the consequent cooling process.

The output from the program provides details of:

the total heat transfer from the fire gases to the spray,

- the complete physical and thermal drop histories throughout the spray including the number boiled and mass evaporated, and the resulting water distribution on surface (walls, floor, tanks)
- the changing gas properties within the fire gases.

SPLASH contains spray data from several nozzles and sprinklers, collected at South Bank University using the Photographic High-speed Imaging Laser technique [Nolan et al (1988), Jackman et al (1992a)].

Program structure

Explanation of the mathematics of gas/drop interactions used in the SPLASH model are given in the appendix. A full description of SPLASH is available in Jackman et al [1992b], included in this paper are details the theory for the gas flow and spray modelling.

Essentially SPLASH considers a "defined volume" in which all interactions are examined (see figure 1). The "defined volume" is divided into a number of discrete units (2800 maximum). These subdivisions are called "control volumes".

The hot fire gases are described by temperature, velocity and mass flow rate profiles. The gas properties vary continuously with horizontal and vertical distances. Each "control volume" can have different temperature, velocity, mass flow rate and associated physical properties. The sprays are operated, and all drop/fire gas interactions occurring in each "control volume" are calculated and recorded (see figure 2).

Operation of the program

The program requires the definition of the "defined volume" geometry, the positioning of the sprayers and the characteristics of the fire gases and sprayers.

Defined Volume/Gas layer Dimensions The width (Z-direction) and height (Y-direction) of the "defined volume" are specified, the length (X-direction) is preset to 10 metres. The number of "control volumes" required is adjustable with a present maximum of 20 volumes in the width, and maximum 7 volumes in the height. The length again is defaulted, to 20 volumes. The boundaries of the "defined volume" can be open to the ambient air or solid, eg ceiling, floor or walls.

Several definitions of gas layer are available. The simplest form defines the fire gas as a homogeneous layer of a single temperature and velocity component. The other gas profiles available are triangular, and various curves. These were originally developed to specify the characteristics of a smoke layer in a building. For unconfined fire environments, eg outside, the homogeneous layer is the best available profile and is similar to a 'top hat' plume profile which is commonly assumed [Hinkley (1989)].

The wind, forced velocity vector, is a specifiable variable that is assigned to each "control volume".

Any obstructions, eg pipework or panels, can be specified in the program input, and any water reaching them is collected and recorded. The characteristic mass and temperature of this water and the subsequent reduced water coverage of a surface are reported in the program output.

Spray parameters

The sprayer is positioned singularly in the "defined volume" or as part of an array of sprayers. This is achieved by specifying co-ordinates for each sprayer. The sprayer can be orientated in either a pendent mode, directing water towards the floor, or facing a wall and directing water towards it.

SPLASH requires many representative drops to fully characterize the spray envelope from the sprayer. The individual drops' initial characteristics required, are: diameter, velocity, trajectory, and frequency at all angular locations.

A detailed study of sprinkler sprays used in buildings [Jackman (1992)] highlighted large irregularities in the envelope from these spray types. Vast amounts of drop data were required to represent these sprays. Sprayers and nozzles have more uniform spray envelopes and a reduced data set may fully represent them.

Source drop data The drop data used in this work came from a small study intending to measure the diameter distribution of drops falling with terminal velocity.

The drop diameter distribution is used directly in the program and the velocity and trajectory components are estimated at all angular positions around the sprayer.

The details of a typical sprayer, eg the Wormald Medium Velocity sprayer MV 25, are: nominal bore 8.3 mm, spray cone angle 125°, operating pressure approximately 2 bar ('K' factor = 38.2 and water flow rate of 0.81×10^{-3} m^3/s).

The Wormald medium velocity sprayer data file diameter distribution is shown in figure3.

The spray is generated from the raw drop data file by projecting the drop from a number of emission positions at the edge of the sprayer. The separation of these positions is generally set to 10°.

The emission points use the drop data 4 times to form a data set with 4 different trajectory components. The limiting angles are the spray cone angle, and the base angle. Source data came from a sprayer with a cone angle of 125°. The base angle used for this sprayer is 60°. This is defined as the solid angle beneath the sprayer where very few drops are found.

The initial velocity of drops leaving the sprayer is taken to be the water velocity in the pipe as it leaves the sprayer bore hole. At the break-up point of the spray, this over-estimates the velocity of some of the drops. The method of particle tracking used in SPLASH quickly corrects these values. For the experimentally tested sprayer the water velocity is 15.4 m/s.

Sprayer characteristics As previously mentioned, sprayers can be operated over a range of pressures, and are manufactured to produce different cone angles.

The source spray data can be used to generate hypothetical sprayers with different cone angles. This assumes that the drop diameter distribution is little changed. No evidence is available to either support or not support such an assumption. The results from such a sprayer can be used to indicate the significance of such a change.

An algorithm has been introduced that produces an estimated diameter distribution for an increase in the operating pressure of the sprayer. This uses the fact that as the operating pressure of a sprinkler increases, the diameter distribution changes in shape. The peak of the distribution occurs at a smaller diameter; the proportion of drops close to this value increases, and the range of the diameter distribution decreases. When a spray is operated at a higher pressure the associated flow rate increases and initial drop velocity increases.

For the Wormald MV sprayer operating at a higher pressure, 3 bar, the following changes are made. The new peak occurs at a drop diameter of 350 μm. The distribution tail is also reduced, this is achieved by scaling the drops with diameters larger than 350 μm , by 0.75 (ie reduced them to 75% of their former size). Figure 4 shows the new diameter distribution. The flow rate is increased to 1.15×10^{-3} m^3/s. The water velocity is found to be 20 m/s.

Program output

The program reports discrete "control volume" values and global outcomes for the "defined volume". These are the summation of the results of interactions in individual "control volumes", for pre-sprayer and post-sprayer. For example the total heat transferred by all the sprayers is reported, as in the cooling at a specific location in the "defined volume".

The generated file also contains information about the fate of the drops that are tracked through the gas environment. These are quantified in terms of number and volume of drops. The fate of the drop is described as:

a) boiled
b) left at top of "defined volume"
c) hit wall/tank surface
d) left at bottom of "defined volume"
e) left in gas flow (beyond the "defined volume")
g) circulated, after many iterations (4 secs) the drop has failed to reach any of the above end conditions.

The total volume evaporating is also reported.

Water distribution patterns, of drops landing on a surface wall/floor are reported. These come in two forms, number and volume of drops' distributions. Values are given for each "control volume" at the surface of the wall or base of the "defined volume". The water distribution is given in millimetres of water per minute over the "contol volume" surface area. These volume rates can be compared to the required British Standard minimum design density of water over the surface for protection.

The size distribution of drops reaching the wall/floor can also be reported for each "control volume".

APPLICATIONS

To investigate the effects of wind and elevated temperature on the spray protection of an LPG tank, a series of program runs have been conducted.

Example1 - MV Sprayer operating in quiescent conditions

Sprayers are used to protect many different containers' geometries, eg cylinder of varying diameter and length, and spheres. In each case the sprayers are arranged so that the separation of the sprayers on the range pipes is 2.44 m (8 feet). The sprayers are mounted aiming towards the tank at a distance of 0.71 m from the tank wall (2 feet 4 inches).

An academic example has been considered. This was a cylindrical LPG tank (assumed to be 7.3 m in length and 3 m in diameter) whose side wall is protect by 3 sprayers. Each sprayer had a flow rate of 0.81×10^{-3} m^3/s, this protects an area of 4.8 m^2 with a design discharge density of 10 mm/min. Since the separation on the horizontal range pipes was 2.44 m, the area protected by 3 sprayers was 7.32 m, the length of the tank, by 2 m of the wall height, corresponding to 14.4 m^2. The design discharge density is achieved by the overlapping of spray envelopes from each sprayer.

Program Input values The "defined volume" is defined as 10 m by 1.42 m by 3.5 m (X,Z,Y), ie 32' 10'' in length; 4' 8'' wide; and 11' 6'' high. The wall in the X-Y plane is used to represent the LPG tank wall. The design area of protection is 7.32 m in the X-direction and 2 m in the Y-direction. Drop data is collected on the wall surface around the design area of protection to ascertain the contribution of these sprayers to the overlap with other lines of sprayers. In the Y-direction the 0 to .5 m and 2.5 m to 3 m are used for this purpose. The area on the "defined volume" wall below 3 m in the Y-direction and in the X-direction, 0 to 2.8 m and 7.6 to 10 m represents open space, ie water that has missed the tank.

The 3 sprayers are positioned in the "defined volume". The sprayers are orientated towards the rectangle that represents the wall of the tank. The sprinklers are positioned 1.5 m in the Y-direction (below the 3rd "control volume", and at 1.5 m, 3.94 m, and 6.38 m in the X-direction.

The spray data file used, the Wormald MV25, is described in section 2.3.1.

The sprayers are operated in quiescent conditions, with an ambient temperature of 296K and with no wind velocity.

Program output values The volume of drops reaching the tank wall is given as the volume of water per second. This is found to be 2.169×10^{-3} m^3/s from a possible water volume of 2.43×10^{-3} m^3/s from the three sprayers, ie 89%. The lost water was collected at the floor of the defined volume and can be considered to have overshot the tank.

The distribution pattern of water coverage on the wall of the tank with no wind is given in figure 6. Each "control volume" gives the reported application rate of water at the surface of the tank in millimetres of water per minute per "control volume".

This gives an application rate of 8.9 mm/min over the protected area assuming overlapping of sprays occur.

Example 2 - MV Sprayer operating in ambient temperature with a range of wind velocities

The same arrangement as example 1 is used, except wind velocities were introduced. Wind velocities between 4 m/s and 20 m/s were studied.

The wind effect Results showed that with an air velocity of 7.82 m/s the water coverage with this sprayer arrangement had been reduced by 20 %. Such an air velocity could easily be achieved by a rising plume, as well as by the wind in coastal regions. At a wind velocity of 20 m/s the coverage is reduced to 48 %.

Examination of the water distribution pattern with a cross wind reveals possible positions of local heating in the fire, see figure 7. The 7.8 m/s water distribution pattern is compared with the no wind case. Downwind, beyond the first 0.75 m of the tank, water coverage is generally maintained, though at 3.5 m and 6 m the discharge density has been significantly reduced (from 10.2 mm/min to 2.7 mm/min). Upwind of the 1st sprayer the tank has become unprotected by water coverage due to the effect of the wind. It should be noted that this wind blowing will aid the cooling of the tank.

Example 3 - MV sprayer operating in elevated temperatures

Using the same sprayer arrangement different fire gas temperatures were tested for selected wind velocities. Temperatures between 296 and 1396 K and winds 0 to 20 m/s were examined.

The effect of fire gas temperature As expected the use of SPLASH shows how the temperature increase reduces the water coverage. At a wind velocity of 7.8 m/s water coverage is reduced from 78 % to 70 %, when the temperature rises from 396 K to 796 K, see figure 7.

The amount of heat removed is found to increase with both an increase in temperature and wind velocity, see figure 8.

The water distribution pattern of the scenario, with a gas temperature of 796 K and wind velocity of 20 m/s is shown in figure 9. Here SPLASH finds the first 2 metres of the tank unprotected and areas at 4.5 m and 7 m unprotected.

Example 4 - Changes in MV sprayer/operating parameters

Operating pressure The LPG tank scenario was modelled with the sprayers operating at a higher pressure. The 3 bar spray data was generated using the scenario described in section 2.3.2.

It was found that an increase in pressure resulted in more water reaching the tank, but this was a smaller proportion of the original water, than with a 2 bar spray. With a fire gas temperature of 796 K and wind velocity of 7.8 m/s the results in Table I were found.

TABLE I - Comparing two operating pressures of a sprayer when used in identical fire scenarios

Operating pressure (bar)	Water coverage $x10^{-3}$ (m^3/s)	Heat transferred (MW)	Water evaporating $x10^{-3}$ (m^3/s)
2	1.49 (61 %)	0.61	0.86 (35 %)
3	1.81 (51 %)	1.01	1.69 (48 %)

The increased pressure can be seen to significantly increase the amount of heat removed.

Cone angle Two other sprayer cone angles were tested, these were 90° and 160° (the limits of the Wormald MV sprayer range).

It was found that as the cone angle was reduced from 160° to 125° to 90°, the water coverage increased, but the heat transfer decreased.

For a fire gas temperature of 796 K and velocity of 7.8 m/s the results in Table II were found.

TABLE II - Comparing three sprayers with different cone angles when used in identical fire scenarios

Cone angle (°)	Water coverage $x10^{-3}$ (m^3/s)	Heat transferred (MW)	Water evaporating $x10^{-3}$ (m^3/s)
90	1.80 (74 %)	0.54	0.63 (26 %)
125	1.5 (61 %)	0.61	0.86 (35 %)
165	0.97 (40 %)	0.69	1.11 (46 %)

As can be seen the primary role of the sprayer, ie to supply an even water layer onto the surface of the tank, is enhanced with the decreasing cone angle.

PRINCIPAL FINDINGS

'Wastage factor'

The design discharge density is generally achieved over a larger area with a reduced application rate of water. A minimum of 25 % wastage factor [NFPA 15] appears to be a sensible percentage since SPLASH found that with a 796 K gas temperature and 7.8 m/s velocity the coverage is reduced by 30 %.

10 % water coverage reduction with 5 m/s wind

Stark's [1961] experimental measurement can only be used as an indicator of the magnitude of the wind effect, neither sprayer type or arrangement are the same. However, it was found that when SPLASH was operated with a 4.7 m/s wind, and temperature of 296 K, the water coverage was reduced by 13.5 % (or 3 % if offshoots are removed), ie a similar magnitude.

Non-cooled local points

Schoen and Droste [1988] found points where the LPG tank was not cooled below 100°C, they explained that this was due to the effect of the wind. SPLASH found that when an LPG tank was exposed to wind velocities greater then 5 m/s areas at the windward side of the tank surface was nolonger covered by water. Under 'worst case' conditions specific locations of the tank surface, including downwind locations, received no direct water coverage.

Sprayer arrangement

The 'best' positioning of sprayers for the hazard and fire scenario (distance between spray head and tank and separation of the sprayers) can be found not just by experiment but by using a code like SPLASH.

Proportion of drops < 0.5 mm

The MV sprayer data used did contain a large proportion of drops < 0.5 mm as stated in Lev's work [1990], and the event of failed protection by the sprayer was also found with

SPLASH. SPLASH could be used to find existing sprayer/arrangement that would succeed in protecting an LPG tank, or predict the drop characteristics required.

Source data

The drop data used in this work was the product of a small study.The technique used for its collection is unique to South Bank University and has been used successfully to model complex sprinkler sprays. The technique could in the future be utilized to gather more drop data from different sprayers and operating parameters, thus adding more useful data to SPLASH and validate/or otherwise the pressure and cone angle algorithms.

SPLASH assumptions

SPLASH primarily is a particle tracking model, that accounts for the heat and mass transfer of many representative drops as they travel in a fire gas. The description of a fire gas in unconfined conditions is considered simplistic, it assumes a uniform temperature throughout its "defined volume", and one directional air velocity. The model also considers the interactions to occur at steady state. The use of the program may be jusified by its successful prediction of experiments.

CONCLUSIONS

The operation of the 3 dimensional particle tracking model has resulted in agreement with general conclusions of experimental investigations of LPG tank protection. Water coverage is reduced by increasing wind and fire gas temperature. The spray characteristics, due operating pressure and sprayer cone angle affect the protection provided.

The SPLASH program was used to illustrate one arrangement of sprayers. It was found that this arrangement would inadequately protect the LPG tank on the windward side. Local points on the tank wall with no water coverage were also found, in certain fire gas temperature/wind conditions.

This study was conducted purely to illustrate the use of one sprayer type in one arrangement. With source data from other sprayers/nozzles other existing arrangements and future arrangements could be tested for their protection ability.

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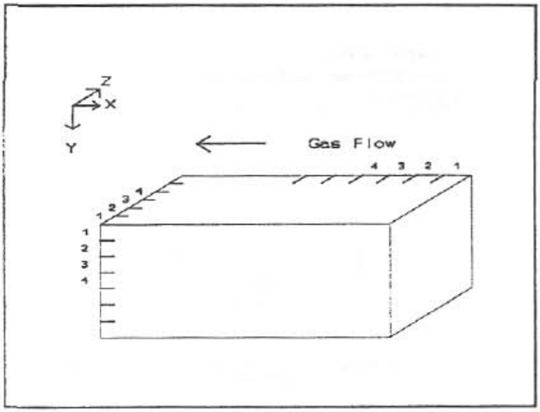

Figure 1 - The "defined volume" divided into smaller, numbered "control volumes"

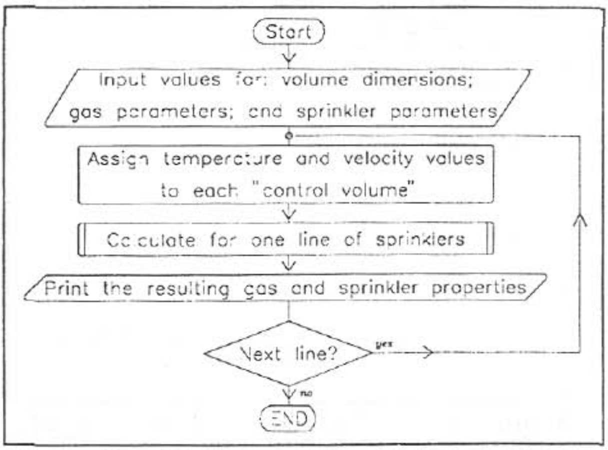

Figure 2 - Outline of the Fortran program, SPLASH

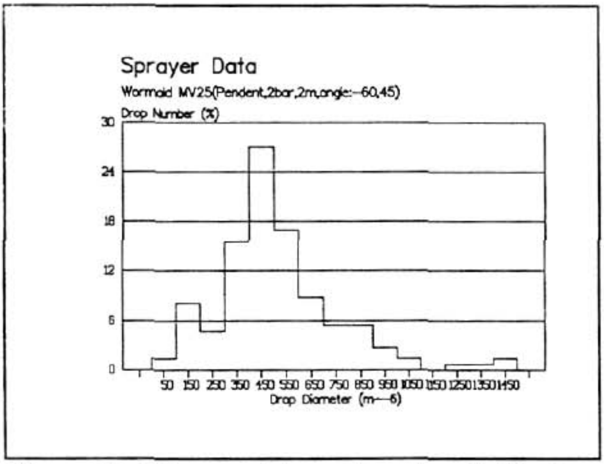

Figure 3 - Measured drop diameter distribution of the sprayer operating at 2 bar

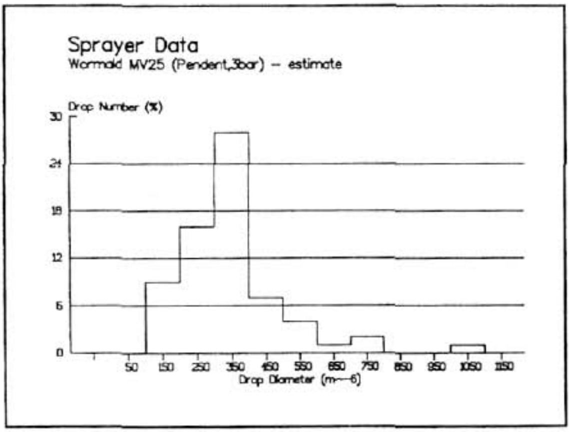

Figure 4 - Estimated drop diameter distribution of the sprayer operating at 3 bar pressure

Figure 5 - Water coverage across a perpendicular wall in quiescent conditions .example1

To help visualize the discharge density over the surface, values with no water coverage are in *italics*, values > 3 mm/min are **highlighted**.

KEY .... = TANK BOUNDARY, ▬ = DESIGN AREA OF PROTECTION BOUNDARY, + = SPRINKLER LOCATION

↓Y (metres) \ X (metres)→	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.
0.5 ..	0.0	1.5	**3.1**	**3.1**	1.5	0.0	1.5	**3.1**	**4.2**	0.3	0.0	1.5	**4.6**	3.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0 ..	1.5	**5.5**	**9.3**	**9.3**	**5.5**	**3.5**	**6.5**	**8.5**	**9.2**	**6.1**	2.4	**6.7**	**10.2**	**8.7**	**4.8**	0.1	0.0	0.0	0.0	0.0
1.5 ..	**4.2**	**9.4**	**8.0**	**8.0**	**9.4**	**8.7**	**10.2**	**8.0**	**8.1**	**8.7**	**9.3**	**11.9**	**6.3**	**8.5**	**7.6**	**4.2**	0.0	0.0	0.0	0.0
2.0 ..	**3.4**	**8.1**	**7.0**	+ **7.0**	**8.1**	**6.6**	**8.9**	**6.6**	+ **7.0**	**7.5**	**8.1**	**9.7**	+ **4.9**	**7.6**	**6.3**	**3.3**	0.0	0.0	0.0	0.0
2.5 ..	**3.5**	**5.7**	**8.8**	**8.8**	**5.7**	**7.0**	**7.0**	**8.1**	**8.6**	**6.1**	**6.0**	**7.4**	**9.1**	**8.5**	**5.2**	2.0	0.0	0.0	0.0	0.0
3.0 ..	0.1	**3.5**	**3.9**	**3.9**	**3.5**	0.7	**3.1**	**3.9**	**4.6**	2.4	0.7	**3.1**	**5.7**	**3.3**	2.0	0.2	0.0	0.0	0.0	0.0
3.5 ..	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.5	0.1	0.1	0.1	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Figure 6 - Water coverage across a perpendicular wall with a 7.8 m/s crosswind, example 2.

To help visualize the discharge density over the surface, values with no water coverage are in *italics*, values > 3 mm/min are **highlighted**.

KEY .... = TANK BOUNDARY, ▬ = DESIGN AREA OF PROTECTION BOUNDARY, + = SPRINKLER LOCATION

↓Y (metres) \ X (metres)→	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.
0.5 ..	0.0	0.0	0.5	**3.3**	2.3	1.3	0.5	0.7	**4.1**	2.1	1.0	0.3	0.7	**4.1**	2.5	0.8	0.3	0.2	0.3	0.2
1.0 ..	0.0	0.0	2.9	**10.1**	**7.3**	2.9	1.1	**4.3**	**10.4**	**6.8**	2.7	1.1	**4.9**	**11.7**	**5.2**	2.5	0.8	0.6	0.3	0.1
1.5 ..	0.0	0.0	**7.2**	**9.9**	**16.6**	**5.9**	2.7	**7.3**	**12.0**	**16.3**	**4.3**	**3.1**	**7.9**	**12.8**	**15.9**	**3.3**	1.4	0.3	0.3	0.1
2.0 ..	0.0	0.0	**5.9**	**8.5**	**15.5**	**5.4**	2.0	**6.2**	**10.8**	**15.1**	**3.7**	2.2	**6.4**	**12.0**	**14.3**	**3.1**	0.9	0.3	0.2	0.2
2.5 ..	0.0	0.0	**4.2**	**9.2**	**8.0**	2.4	0.7	**5.2**	**10.4**	**6.7**	2.3	1.2	**5.9**	**10.7**	**5.4**	2.1	0.6	0.3	0.1	0.0
3.0 ..	0.0	0.0	0.5	**5.2**	**2.8**	1.8	0.5	1.3	**5.6**	2.2	1.8	0.6	1.3	**6.0**	2.4	1.5	0.5	0.3	0.2	0.2
3.5 ..	0.0	0.0	0.0	1.0	1.0	1.0	0.4	0.9	0.8	1.1	0.6	0.3	1.0	0.8	1.3	0.5	0.4	0.3	0.1	0.2

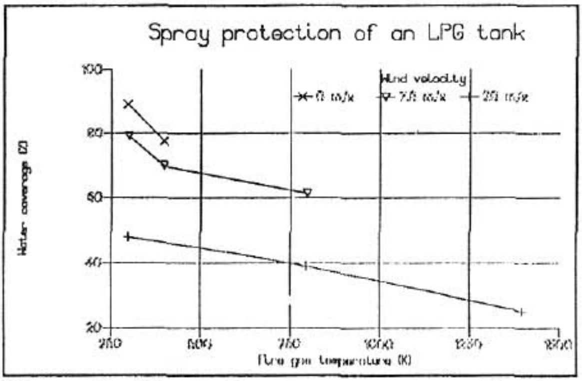

Figure 7 - The tank water coverage reduction caused by a range of fire gas temperatures and wind velocities.

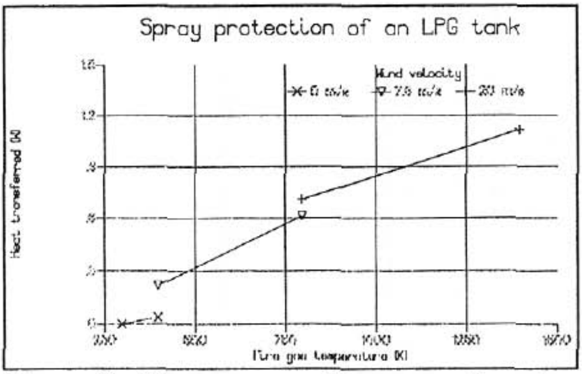

Figure 8 - The amount of heat transferred to a spray with a range of fire gas temperatur es and wind velocities.

Figure 9 - Water coverage across a perpendicular wall in fire gas temperature of 796 K and with a 20 m/s crosswind, example 3.
To help visualize the discharge density over the surface, values with no water coverage are in *italics*, values > 3 mm/min are **highlighted**.

KEY .... = TANK BOUNDARY, —— = DESIGN AREA OF PROTECTION BOUNDARY, + = SPRINKLER LOCATION

↓Y (metres) \ X (metres)→→	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.
0.5 ..	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.2	2.0	2.4	0.4	0.7	0.2	2.6	1.8	0.5	0.7	1.2	2.4	1.1	0.9	0.1
1.0 ..	*0.0*	*0.0*	*0.0*	*0.0*	1.6	**6.3**	2.7	0.3	0.9	2.3	**5.9**	2.7	0.4	0.7	3.4	**5.2**	2.5	0.4	0.7	0.1
1.5 ..	*0.0*	*0.0*	*0.0*	*0.0*	**13.4**	**4.4**	1.1	0.8	*0.0*	**14.2**	**4.4**	0.6	0.8	*0.0*	**15.0**	**3.8**	0.5	0.8	0.1	0.1
2.0 ..	*0.0*	*0.0*	*0.0*	*0.0*	**11.7**	**3.5**	0.5	1.0	0.1	**12.3**	**3.2**	0.5	1.0	*0.0*	**13.1**	2.5	0.4	1.1	0.1	*0.0*
2.5 ..	*0.0*	*0.0*	*0.0*	*0.0*	**3.2**	**6.5**	2.1	0.7	*0.0*	**4.1**	**6.6**	1.6	0.8	*0.0*	**5.0**	**6.0**	1.4	0.8	*0.0*	0.1
3.0 ..	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.8	2.9	1.4	0.6	0.0	0.8	3.2	1.6	0.3	*0.0*	1.9	2.1	1.6	0.4	*0.9*
3.5 ..	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	1.5	0.8	*0.0*	*0.0*	*0.0*	1.0	0.9	*0.0*	*0.0*	1.0	*0.0*	0.8	0.1

APPENDIX - Water drop interactions with fire gases

DROP AERODYNAMICS

Masters (1972) stated that the physical motion of the fluid within a falling drop can be predicted from its Reynold's number. This physical motion can be described in three ways [Jeffreys and Mumford (1974), Winnikow and Chao (1966)].

For drops with Reynold's numbers less than 80, heat transfer to the centre of the drop is by conduction, and mass transfer to the drop's surface is by molecular diffusion [Coulson and Richardson (1977)]. Consequently, all theoretical transport properties are modelled on a rigid sphere.

For drops with Reynold's numbers between 80 and 300, streamlines are formed around the surface of the drop [Renksizbulut and Yuen (1983)]. The shear forces at the interface causes the internal fluid to circulate [Chung and Ayyaswamy (1977)]. These forces are not large enough to deform the drop significantly and so it remains spherical.

Above a Reynold's number of 300, drops have been observed to deform [Garner and Lane (1959), Srikrishna et al. (1982)]. These investigations revealed that the drops do not have a stable or equilibrium shape, but oscillate around a mean shape. The oscillations are sustained by vortex discharge behind a moving drop and result in intense mixing of the contents and a periodic change in the drop's surface area. The frequency of these oscillations was predicted by Rose and Kintner (1966).

MASS TRANSFER TO DROPS

The overall rate of evaporation is a function of the temperature, humidity, and transport properties of the gas: and the diameter, temperature, and relative velocity of the drop [Marshall (1970)]. The overall mass transfer coefficient, K, is the inverse sum of the drop side and gas side mass transfer coefficients:

$$\frac{1}{K}=\frac{1}{K_d}+\frac{1}{K_g} \qquad (1)$$

Evaporation from a spherical drop into a still atmosphere has been treated theoretically by Maxwell (1890), Langmuir (1918), and Fuchs (1959) as a case of molecular diffusion.

The more practical case of mass transfer from spheres for forced convection has been investigated by Froessling (1938), Ranz and Marshall [1952], Garner and Tayeban [1960] and Pasternak and Gauvin [1961].

Investigations involving measurement of mass transfer from freely falling drops, are few in number, but has been approached by Finlay (1957), and more recently Ahmadzadek and Harker (1974).

The results of the above experiments deviated from that of Ranz and Marshall (1952) most noticeably where drop diameters were in excess of 0.003 metres. This effect has been attributed to surface oscillations of the drop which, as described above, will lead to higher heat and mass exchange rates.

These differences in drop behaviour are reflected in the drop side mass transfer coefficient. The algorithms to calculate this for the SPLASH code used by Gardiner (1988) are listed below:

Internal fluid stagnation

Mass transfer to the surface of the drop is by diffusion only and so may be compared with rigid spheres. Rose and Kintner (1966) used a mass transfer coefficient of:

$$K_d = \frac{\phi}{6\Delta t} \ln \frac{6}{\pi} \sum_{n=1}^{2} \frac{1}{n^2} \exp \frac{-4n^2 Df \pi^2 \Delta t}{\phi^2} \quad (2)$$

Internal fluid circulation

Mass transfer to the drop surface is primarily by convection. Following experimental comparisons carried out by Jeffreys and Mumford (1974), it was suggested that the most reliable expression to quantify this process was given by Kronig and Brink (1950):

$$K_d = \frac{17.9 Df}{\phi} \quad (3)$$

Surface oscillation

Mass transfer to the surface is by convection and coupled to the phenomenon of surface stretching. Following extensive experimental evidence [Jeffreys and Mumford (1974)] the expression of Rose and Kintner [1966] was chosen to calculate the drop side mass transfer coefficient:

$$K_d = 0.45 (Df\omega)^{\frac{1}{2}} \quad (4)$$

where the frequency of oscillation and empirical amplitude of the drop are calculated by:

$$\omega^2=\frac{\sigma b}{r^3}-\frac{n(n-1)(n+1)(n+2)}{(n+1)\rho_d+n\rho_g} \tag{5}$$

where n is the number of oscillating drops and b is:

$$b=\frac{d_e^{0.225}}{1.242} \tag{6}$$

A review of the Sherwood number correlations by Yuen and Chen [1978] stated that for Reynold's numbers below 2000 the data of Ranz and Marshall [1952] represent the best of the literature. Thus, by inclusion of the drop side mass transfer coefficients, the overall coefficient of mass transfer can be calculated and applied to the Ranz and Marshall [1952] correlation to calculate the overall rate of mass transfer from the drop:

$$Sh=2.0+0.6Re_d^{\frac{1}{2}}Sc_d^{\frac{1}{3}} \tag{7}$$

where

$$Sh=\frac{K_g\phi}{Df} \tag{8}$$

HEAT TRANSFER TO DROPS

The evaporation of drops in a hot gas stream is a simultaneous heat and mass transfer operation. Heat is transferred by conduction and convection from the hot gases to the drop's surface; and vapour is transferred by diffusion and convection back into the gas stream. An energy balance can be constructed over the drop-gas interface [Chung and Ayyaswamy (1977), Yao and Schrock (1975), Tanaka (1980)].

$$\dot{q}=h(T_g-T_{d_{i_s}})+\lambda_g K(c_g-c_{d_{i_s}}) \tag{9}$$

It should be noted that in the SPLASH model, radiative heat transfer has been ignored. Chen and Trezek [1977] reported that even in extreme conditions the radiation effect is only of the order of 9% of the total heat flux. Thomas [1952] theoretically studied the high radiation penetration of water sprays.

Heat transfer from an evaporating drop is described by the Nusselt, Reynold's, and Prandtl numbers as [Ranz and Marshall (1952)]:

$$Nu=2+0.6Re^{\frac{1}{2}}Pr^{\frac{1}{3}} \tag{10}$$

where the Nusselt number is given by:

$$Nu=\frac{h\phi}{k_g} \tag{11}$$

As with mass transfer, the rate of heat transfer is similarly affected by the physical behaviour of the drop. Heat transfer to stagnant drops will be by conduction, whereas that to circulating and oscillating drops will be primarily by convection.

The temperature change at the surface of a rigid sphere was mathematically modelled by Chung and Ayyaswamy [1977], Yao and Schrock [1975], and Tanaka [1980] using a partial differential technique between the limits of the centre of the drop and the surface. The following equation was derived:

$$\Delta T=\frac{4\dot{q}}{\rho_d Cp_d\phi}\Delta t \tag{12}$$

The fluid mixing of a circulating or oscillating drop can be described by Hill's spherical vortex [Milne-Thomson (1969)]. Chung and Ayyaswamy [1977] used Hill's vortex model to calculate the temperature change in a drop. The resulting algorithm was complex and proved no better than the simpler 'complete mixing' model used by Tanaka [1980] which assumes internal motion to be so strong that complete mixing is achieved giving a flat temperature profile: the resistance to heat transfer is on the gas side of the boundary layer. Tananka [1980] expressed the temperature difference as:

$$\Delta T=\frac{6\dot{q}}{\rho_d Cp_d\phi}\Delta t \tag{13}$$

DRAG FORCES ACTING ON DROPS IN A GAS

Drops emitted from a spray nozzle will have a range of sizes and velocities. Depending on the initial speed of the drops they will either accelerate or decelerate through a thermally buoyant layer. This change in momentum is a result of gravitational and drag forces on the drop.

which is a function of the drag coefficient. The net force acting on a drop is the vectorial sum of the frictional and external forces and so from Newton's third law, there must be an equal force exerted on the gas stream.

For a drop moving in a gravitational field, with an initial velocity, it can be shown that the velocity change, in the vertical and horizontal directions, can be found from a balance of forces [Lapple and Shepherd (1940)].

$$\frac{dV_h}{dt} = -\frac{F_d \cos\alpha}{m_d} \tag{14}$$

$$\frac{dV_v}{dt} = g\,\frac{(\rho_d-\rho_g)}{\rho_d} - F_d \sin\alpha \tag{15}$$

The force on the drop is given as:

$$F_d = \frac{1}{2}\rho_g V_{d_{tot}}^2 C_d A_d \tag{16}$$

where

$$V_{d_{tot}}{}^2 = V_h{}^2 + V_v{}^2 \tag{17}$$

Drops moving relative to a slower moving gas experience a retarding force due to surface friction and pressure drag. Surface friction is caused by the viscous resistance of the gas at the drop's surface; whereas pressure drag is caused by the aerodynamic shape of the drop. This produces back eddies in the wake of the drop owing to separation of the boundary layer [Marshall (1970)]. The action of the two retarding forces are reflected in the overall drag coefficient.

The overall drag coefficient for an evaporating drop exhibiting internal circulation will be different from that of a solid sphere due to:

(a) the friction drag being altered due to decreasing velocity shear at the top surface;
(b) the pressure drag being affected by retarding the separation of the boundary layer;
(c) radial mass efflux affecting the flow field around a sphere, particularly at the stagnation point, and reduces frictional drag due to evaporation causing separation of the boundary layer.

Gillaspy and Hoffer [1983] quoted expressions which related the drag coefficient to the internal circulation of a drop falling through air. The effect was much less than one percent.

Gillaspy and Hoffer [1983] made an experimental study of the effect of evaporation on drag force to support a theoretical study made by Hamielec et al [1967]. Yuen and Chen [1976] also measured the pressure drag on evaporating drops and showed that the decrease in frictional drag was offset by the increase in pressure drag from flow separation. They also demonstrated that adjustment to the viscosity coefficient was necessary to account for the two phase mixture; which has local effects on a drop within a spray. Viscosity was calculated by the one-third rule of Hubbard et al [1975] which calculates the viscosity at the adjusted temperature of:

$$T_r = T_d + \left(\frac{T_g - T_d}{3}\right) \tag{18}$$

Nearly all particle drag investigations compared their results to the 'standard drag coefficient curve' produced by Lapple and Shepherd (1940) which represents the drag coefficient as a function of the Reynold's number for a solid spherical particle. There have been many attempts to express this curve as an equation [Tanaka (1980), Chen and Trezek (1977), Cliffe and Lever (1984), Bird et al. (1960), Dickenson and Marshall (1968)]. All of them have divided the Reynold's number ranges into three regions:

- Stoke's law region - Reynold's number less than one;
- Intermediate region - Reynold's numbers between one and 1000;
- Newton's law region - Reynold's numbers greater than 1000.

The chosen mathematical function to calculate the drag coefficient over a range of Reynolds numbers is that given by Chen and Trezek [1977]. This function predicts an increase in the calculated drag coefficient at Reynolds numbers greater than 1000, as expected.

$$C_d = \frac{24}{Re} + \frac{6}{1+\sqrt{Re}} + 0.27 \tag{19}$$

valid from $1 \leq Re \leq 1000$;

$$C_d = 0.6449 - 0.271210^{-3}Re + 1.22\times10^{-7}Re^2 - 10.919\times10^{-12}Re^3 \tag{20}$$

valid from $1000 \leq Re \leq 3600$.

GAS/DROP INTERACTION

The cooling effect of the drop on the hot gases causes an increase in density, which consequently causes a decrease in gas velocity (assuming a constant mass flow rate). The gas velocity is also altered by the momentum of the drops as they pass through the gas stream. The subsequent change in velocity is found by using the energy balance equation [Welty et al (1984)].

$$\frac{\delta Q}{\delta t}-\frac{\delta W'}{\delta t}=\left[\frac{(V_2^2-V_1^2)}{2}+(U_2-U_1)+\frac{p}{(\rho_2-\rho_1)}\right]\dot{m} \tag{21}$$

NOMENCLATURE

A	area, m^2
b	empirical amplitude of drop oscillation
c	mass concentration of water vapour, kg m^{-3}
C_d	drag coefficient
C_p	specific heat capacity, J/kg K
d_e	equivalent spherical area, m^2
Df	diffusivity of water vapour in air, m^2/s
F	force, N
g	acceleration due to gravity, m/s^2
Gr	Grashof number
h	heat transfer coefficient, J/m^2 s K
H	ratio of equilibrium values of concentrations in two phases
k	thermal conductivity, W/m^2
K	coefficient of mass transfer, kg/m^2 s
m	mass, kg
$\dot{m}$	mass flowrate, kg/s
n	drop or iteration number
Nu	Nusselt number
p	pressure, N/m^2
Pr	Prandtl number
q	rate of heat transfer or flow, J/s
$\dot{q}$	heat flux, J/m^2 s K
Q	heat transfer or content, J
r	radius of drop, m
Re	Reynold's number
Sc	Schmidt number
Sh	Sherwood number
t	time, s
T	temperature, K
U	internal energy, J/kg

V	velocity, m/s
W'	work, Nm

Greek symbols

α	vertical angle of trajectory, radians
α	constant
Δ	*incremental period*
ϕ	drop diameter, m
λ	*latent heat of vapourisation, J kg^{-1}*
ρ	density, kg m^{-3}
σ	*interfacial tension, N/m*
ω	frequency of drop oscillation

Subscripts and superscripts

d	pertaining to the drop variables
g	pertaining to the gas variables
h	pertaining to the horizontal component
r	pertaining to the reduced variable according to the 1/3 rule
v	pertaining to the vertical component

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