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# Computer model for the design and validation of directed water deluge systems for the protection of plant containing pressurised flammable materials against fire

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# Computer model for the design and validation of directed water deluge systems for the protection of plant containing pressurised flammable materials against fire

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A project has been undertaken in response to a research brief to develop a computer model to predict the water distribution on the surface of vessels containing pressurised flammable materials protected by directed water deluge systems. The model is intended to be an integral component of new improved guidelines, currently under development, for the design of such water deluge systems. The aims of the project were to build on an existing basic model, extending its range of applicability to a wide range of tank sizes and water deluge designs. The model would be built into a user-friendly computer code enabling it to be widely applied in industry by non-specialist users. This report discusses the standardisation of techniques for practical measurement of the water distribution on the tank surface, and describes development of the model to deal with large diameter horizontal, cylindrical tanks, and water deluge system designs comprising up to 5 rows of nozzles. The development of a user-friendly front-end interface for the model, which has been incorporated into a stand-alone Windows software program is also described in this report. Predictions of water distributions across the surface of storage vessels obtained using the model, have been validated against measured (experimental) data and a close level of agreement to within 7% has been demonstrated.

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# CONTENTS

## Executive Summary

A project has been undertaken to develop a computer model as part of improved guidance for the design and evaluation of water deluge systems for the protection of liquefied petroleum gas (LPG) tanks against fire.

The current guidelines for the design of water deluge systems are based on meeting a single, overall water application rate value for the whole tank i.e. 9.8 $dm^3\ m^{-2}\ min^{-1}$. A wide range of combinations of water deluge design parameters are permissible under the current guidelines, producing a wide range of water distribution patterns, while meeting the overall water application rate requirement. However, it has been demonstrated that the water distribution across the tank surface is often highly irregular; the degree of irregularity depending on the particular combination of water deluge design parameters used. In the case of highly uneven water distributions, regions of low water coverage and consequently poor fire protection were found. Basing the design of water deluge systems on a single, overall water application value is therefore inappropriate. There is a need for improved guidance on the combinations of water deluge parameters that should be permitted to ensure adequate protection against fire, taking into account the expected water distribution on the tank surface.

The combination of water deluge parameters producing the best water coverage varies from case to case, depending on the range of water deluge design parameters available e.g. for an existing water deluge system, and the level of protection required. A model has therefore been developed to predict the combination of water deluge parameters required to produce the optimum water coverage for any given horizontal (LPG) tank and water deluge system. The model is validated for the cylindrical section of such vessels and is capable of extension to the hemi-spherical/toroidal tank ends, as well as spherical and vertical cylindrical vessels. However, further study would be required to obtain experimental data to enable model evaluation of the prediction of the water coverage in such circumstances.

A standardised method of measuring the water coverage on the tank surface involving the collection of water at a range of locations across the surface has been devised. The rate of water collection per unit width of the collection vessel was selected as the most appropriate parameter for characterising the water flow across the tank surface, and has been termed the “surface water flow rate”.

The developed model consists of a number of empirical relationships between surface water flow rate distributions and the water deluge parameter settings and operating conditions producing each distribution. By interpolation of these relationships, surface water flow rate distributions can be predicted for any intermediate combination of deluge design and operating parameters.

Prior to the start of the current project, the model was only applicable to 3 and 4-row water deluge systems and 1.2 and 2.2 m diameter tanks. However, the model has now been extended by the acquisition of additional empirical relationships to include: (i) 5-row water deluge systems; (ii) 3.0 m diameter tanks.

The model has been incorporated into a Visual Basic (VB) software code, which provides a user-friendly, front-end interface, facilitating application of the model to the optimization and evaluation of deluge designs.

Validation of the model has been carried out by comparing predicted and measured surface water flow rate values at a range of locations for a 3.0 m diameter tank. An average percentage difference between predicted and measured values of 7.0% was demonstrated.

# 1 INTRODUCTION

There have been a number of well documented fires and explosions involving liquefied petroleum gas (LPG) (e.g. Feyzin, 1966; Mexico City, 1984; Humberside, 2001). Current recommendations (Liquefied Petroleum Gas Association Code of Practice 1, 2001) for directed water deluge protection of LPG storage vessels are largely based on data obtained from experiments using pool fires (Bray, 1964; Billinge *et al*, 1986). A number of investigations of the water distribution produced by a variety of water deluge configurations across the surface of a range of experimental and industrial LPG tanks have been carried out (Davies and Nolan 1997; 2004a; 2004b). These studies indicated that extrapolation from the original experimental data has led to a wide variability in design performance, and in many cases the water distribution across the tank surface was found to be uneven. The adequacy of the current design of directed water deluge systems is further questioned by recent research into the effect of jet fires on storage vessels (e.g. Djium, 1997; Roberts *et al*, 1997). This suggested that jet fires pose a greater threat than pool fires and that the current guidance may be inadequate in the event of jet fire impingement.

As a result of the earlier work by Davies and Nolan (1997), together with more recent studies (e.g. Davies & Nolan, 2002), both design and operating procedures have been evaluated with respect to the factors affecting the water distribution across the vessel surface. It was found that the water distribution across the tank surface was often highly irregular and that a substantial number of deluge design and operating parameters influence the water distribution. In addition, many of these parameters interact. It was concluded that it would be difficult to devise simple guidelines for the design of water deluge systems which would ensure an optimum water distribution on the surface of a storage vessel, but a computer model might achieve this. Ideally, the model would predict the water distribution on the tank surface for any given combination of water deluge design and operating parameters.

Due to the complexity of the interactions between the large numbers of parameters identified as affecting the water distribution on the tank surface, it was decided to employ an empirical model, relying on the input of data obtained using experimental LPG tank water deluge systems. The development of two such models has been described previously (Davies & Nolan, 2002), namely for:

(a) a 1.2 m diameter replica LPG tank and 3-row water deluge system.
(b) a 2.2 m diameter replica LPG tank and 4-row water deluge system.

The surfaces of the two replica tanks were divided into a network of zones, each with a zone width of 0.35 m. The zone heights were selected to represent the same arc i.e. 0.31 radians, around the circumference of both tanks. The water flow on the tank surface was determined for each zone by means of a water collection device, providing water collection rate (and water collection rate per unit area) values for each zone.
The principle underpinning the empirical model was that the water distribution on the tank surface (measured in terms of water collection rate and water collection rate per unit area data) was related to a matrix of combinations of water deluge parameter settings. An interpolation of the empirical relationships obtained was then carried out, to predict the water distribution for many other combinations of water deluge parameters. The main assumption used in carrying out the interpolation was that the water distribution would vary in a consistent manner when one deluge parameter only was varied, with all other parameters held constant. A number of tests were carried out which were found to support this assumption, and indicated that the relationship between the parameter varied and the water distribution (i.e. the water collection

rate or water collection rate per unit area for each zone), could be described satisfactorily by a simple polynomial relationship in each case.
The main inputs for the model were:

(i) tank characteristics e.g. tank diameter
(ii) deluge design e.g. number of rows, stand-off distances
(iii) nozzle characteristics e.g. bore size, discharge angle
(iv) water supply characteristics e.g. pressure
(v) particular features e.g. walkways

The output from the model was the predicted water distribution (i.e. water collection rate or water collection rate per unit area distribution) across the tank surface for the specified combination of water deluge parameter values.

The empirical modelling approach lent itself to a modular format, whereby the individual empirical models for particular tanks and water deluge designs could be combined to produce an overall generic model, which would permit predictions of water distributions for a wide variety of tanks and water deluge designs.

The envisaged generic model would permit the prediction of water distributions for all possible combinations of the water deluge parameter settings for a given tank size, which would be evaluated to determine the optimum water coverage. The optimum water distribution for a new deluge design (or the distribution for an existing system), predicted by the model, could be compared with a predetermined minimum water coverage requirement to evaluate the effectiveness of the water deluge system. The model would be applicable to all types (not just LPG) of horizontal, cylindrical pressure vessels and could be extended to vertical cylindrical and spherical vessels.

# 2 PROJECT AIMS AND OBJECTIVES

## 2.1 AIMS

To develop an existing deluge design model for predicting the water coverage from directed water deluge systems protecting pressurised plant (e.g. LPG storage vessels) into a user-friendly computer code, and to extend the range of tank sizes and water deluge designs to which the model can be applied. The developed model should permit the user:

(a) To determine the performance of existing industrial water deluge systems.
(b) To determine the optimal design of directed water deluge systems for the protection of pressure vessels against specified (severe) fire scenarios.

## 2.2 OBJECTIVES

(a) To develop a standardised nomenclature and experimental method to measure the water distribution on a tank surface, generated by a water deluge system.
(b) To obtain the experimental data necessary for the development of the existing code into a generic computer model, including extension of the range of parameters studied to enable the development of:
    (i) a 5-row (pentagonal) water deluge model.
    (ii) a 3.0 m diameter tank model.
(c) To develop a user-friendly front-end interface for the model.
(d) To validate the model's water coverage predictions against measurements obtained using experimental and industrial directed water deluge systems.
(e) To use the model to aid in the design of experimental water deluge systems for full-scale fire trial experiments to be conducted at HSL, Buxton.

# 3 DEVELOPMENT OF STANDARDISED NOMENCLATURE AND EXPERIMENTAL METHOD TO MEASURE THE WATER DISTRIBUTION ON A TANK SURFACE

## 3.1 REQUIREMENT FOR STANDARDISED PROCEDURE FOR DETERMINING WATER FLOW RATE ON VESSEL SURFACE

Current guidelines for the design of water deluge systems specify a minimum water application rate onto the tank surface to protect the vessel against fire e.g. 9.8 $dm^3\ m^{-2}\ min^{-1}$ (LP Gas Association, Code of Practice 1, 2001) or 10.2 $dm^3\ m^{-2}\ min^{-1}$ (National Fire Protection Association, 1996). These figures are generally interpreted as relating to the total quantity of water exiting the nozzles divided by the surface area of the tank. Furthermore, it is implied in the codes that all of this water reaches the tank surface, and that if similar rates of water are applied from nozzles evenly spaced around the tank, the water distribution on the tank surface will be uniform. However, recent research e.g. Davies & Nolan (2004a; 2004b), has demonstrated that this is not the case. In fact, only 35 to 45% of the water exiting the nozzles was found on the surface of the tank. The water distribution was also shown to be uneven. Reasons for the non-uniform water distributions observed, include:

(a) water running down the tank surface. This leads to greater quantities of water on the lower surfaces of the tank i.e. below the tank equator.
(b) interaction between the water films generated by adjacent nozzle spray envelopes, on the surface of the tank. This produces regions of high water concentration, and adjacent regions of low water concentration, across the tank surface.
(c) loss of water from the tank surface due to streamlets of water running off the tank, particularly at the tank equator. Thus, not all of the water running down from the upper surfaces of the tank i.e. above the tank equator, reaches the lower surfaces of the tank.
(d) water spray droplets bouncing off the tank surface. This is particularly significant at the highest water pressures used e.g. 3.5 barg, which give the greatest spray droplet impact velocities at the tank surface.

The current guidelines aim for a uniform water distribution on the tank surface by ensuring that the water droplets arriving at the tank surface are evenly distributed all across the surface. However, due to the subsequent movement and losses of water from the tank surface, for the reasons listed above, the resulting water distribution on the surface that is observed, is likely to be very different from the application distribution, and to be non-uniform. The observed water distribution is effectively a pseudo-steady state distribution, whereby the rate of water arriving at the tank surface from the spray nozzles is equal to the rate of water running off the surface (from a variety of locations).

With respect to protection of the vessel surface against fire, only the pseudo-steady state (observed) water distribution is relevant, since this reflects the quantity of water available at any particular location on the tank surface, which in turn determines the degree of protection provided.

The water application rate parameter used in the current guidelines provides only a very crude measure of the quantity of water on the tank surface, and the degree of protection against fire. There is clearly a need therefore, for a characterising parameter of the water flow rate on the tank surface that reflects the pseudo-steady state water distribution. The water collection rate measurement device used in the water film characterisation work described previously (e.g. Davies & Nolan, 2004a), would appear to fulfil this role. There is a need, however, to standardise the technique, to make it generally applicable and generate comparable measurements for all types of tanks and water deluge systems. The basic technique and the proposed standardisation procedures are described in the following sections.

## 3.2 DESCRIPTION OF WATER COLLECTION RATE MEASUREMENT TECHNIQUE, AS APPLIED TO A 1.2 M DIAMETER TANK AND WATER DELUGE SYSTEM

Since the water collection rate measurement technique was first introduced for the measurement of water flow rates on tank surfaces (e.g. Davies & Nolan, 1997), the water collection device used has undergone a number of evolutionary changes in its design.

The latest, and to date, the most convenient water collection device consists of an inverted triangular hopper, constructed from aluminium sheet of 1 mm (i.e. 0.001 m) thickness, with a rectangular opening at the top (i.e. the base of the triangle) of dimensions 0.35 m (width) by 0.05 m (depth). The sloping sides of the triangular hopper are 0.25 m in length, giving an overall height for the device of 0.31 m. Close to the (inverted) apex of the triangular hopper are two holes of 0.02 m diameter, with plastic tubes attached, which drain the water from the hopper. These tubes are then combined into a 0.04 m diameter (i.e. large), flexible PVC hose, which carries the collected water from the hopper to a collection vessel sited outside the spray zone surrounding the tank. Water is collected for a set period of time and the water collection rate, corresponding to the flow rate of water across the tank surface for the selected location, is thereby determined. A minimum volume of water of 0.5 $dm^3$ is collected for a time period ranging from a minimum of 30 seconds up to 3 minutes, depending on the flow rate found.

A schematic of the water collection device is shown in Figure 1 below.

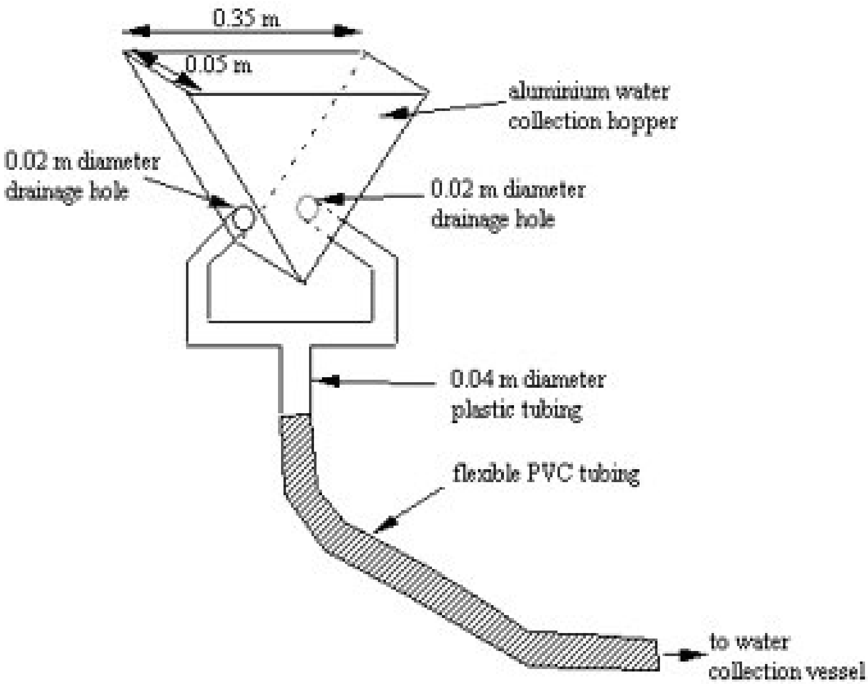



**Figure 1** Schematic of water collection device

The aluminium water collection hopper is attached to the surface of the tank by means of PVC adhesive tape of 0.05 m width. The collection hopper is supported at its apex i.e. the base of the hopper, by means of a frame, which is attached to the tank surface using a magnet. The adhesive tape provides a smooth passage for the water running down the tank surface into the collection vessel, virtually eliminating the step caused by the thickness of the hopper wall i.e. 1 mm. The tape also prevents water passing beneath the hopper.

The dimensions of the water collection hopper and tubing system leading to the water collection vessel have been selected on the following basis:

(1) The opening at the top of the water collection hopper is of dimensions 0.35 x 0.05 m. The depth of the opening i.e. 0.05 m, was an order of magnitude greater than that needed to collect all of the water running down the tank surface, including any ripples or regions of high water concentration e.g. due to interaction between the water films generated by adjacent spray nozzles on the tank surface. (N.B. The maximum water film depth was of the order of 3 mm (i.e. 0.003 m). However, it was found necessary, in practice, to have a hopper depth of this order, to enable the water collected to drain at a sufficiently rapid rate to prevent the hopper from overfilling. At lesser hopper depths, the rate of drainage would have been reduced e.g. due to the surface tension of the water against the walls of the hopper, and due to the reduced volume/mass of water present in the hopper. The width of the opening i.e. 0.35 m, was selected on the basis of providing a compromise between being sufficiently small to capture any horizontal variation in water flow rate across the tank surface, and being sufficiently large that the number of water collection measurements across the tank surface would be kept to a minimum. As a result, characterisation of the whole tank surface (by measurement of water collection rates) was reduced to a manageable task.
(2) The shape of the hopper i.e. triangular, and the length of the sides i.e. 0.25 m, were selected on the basis of providing a sufficient hopper size to collect water at the maximum flow rate expected, without overfilling or splashing out of the hopper. The triangular shape of the hopper ensured that the collected water was channelled towards the drainage holes at the bottom.
(3) The size of the drainage holes at the bottom of the hopper i.e. 0.02 m, and the flexible PVC tubing of diameter 0.04 m, leading to the water collection vessel were selected on the basis of providing sufficient drainage (at the maximum water flow rate), to prevent the water collected from backing up and overflowing the hopper.

One critical factor with respect to the interpretation of any measured water collection rate value on the tank surface, and relating it to the predicted values generated by the model, is the location at which the measurement is made on the tank surface. The water flow rate measurement location is defined with respect to the nozzles comprising the water deluge system. For the 1.2 m diameter replica LPG tank constructed in the laboratory, the water deluge system comprised 3 nozzles in each row, spaced at a longitudinal distance of 1.5 m between nozzles. The replica LPG tank was 3.2 m in length. For the purposes of characterising the water flow rate across its surface, the whole of the tank surface was divided into a series of zones, at each of which water flow rate measurements were carried out. The width of each zone was designated as 0.35 m i.e. the width of the collection hopper, permitting the tank to be divided into 9 slices along its 3.2 m length. The 1.2 m tank was divided into 5 horizontal intervals of 0.02 m around the circumference of the tank, starting from the centre (axial) line at the top of the tank, to just below the tank equator. This was the main region of interest with respect to the potential development of dry spots/hot spots in the case of jet fire impingement on the tank surface, with the water deluge operating. Similarly to the selection of a 0.35 m zone width, the spacing for the horizontal divisions of 0.20 m around the circumference of the tank was a compromise. The 0.20 m spacing was selected to be small enough to capture any variation in water collection rate in a vertical direction around the circumference of the tank, but large enough to minimize the number of zone divisions used. Thus, the total number of zones at which water collection measurements were needed was maintained at a practical level. A schematic showing the division of the replica tank surface into measurement zones is shown in Figure 2 below.

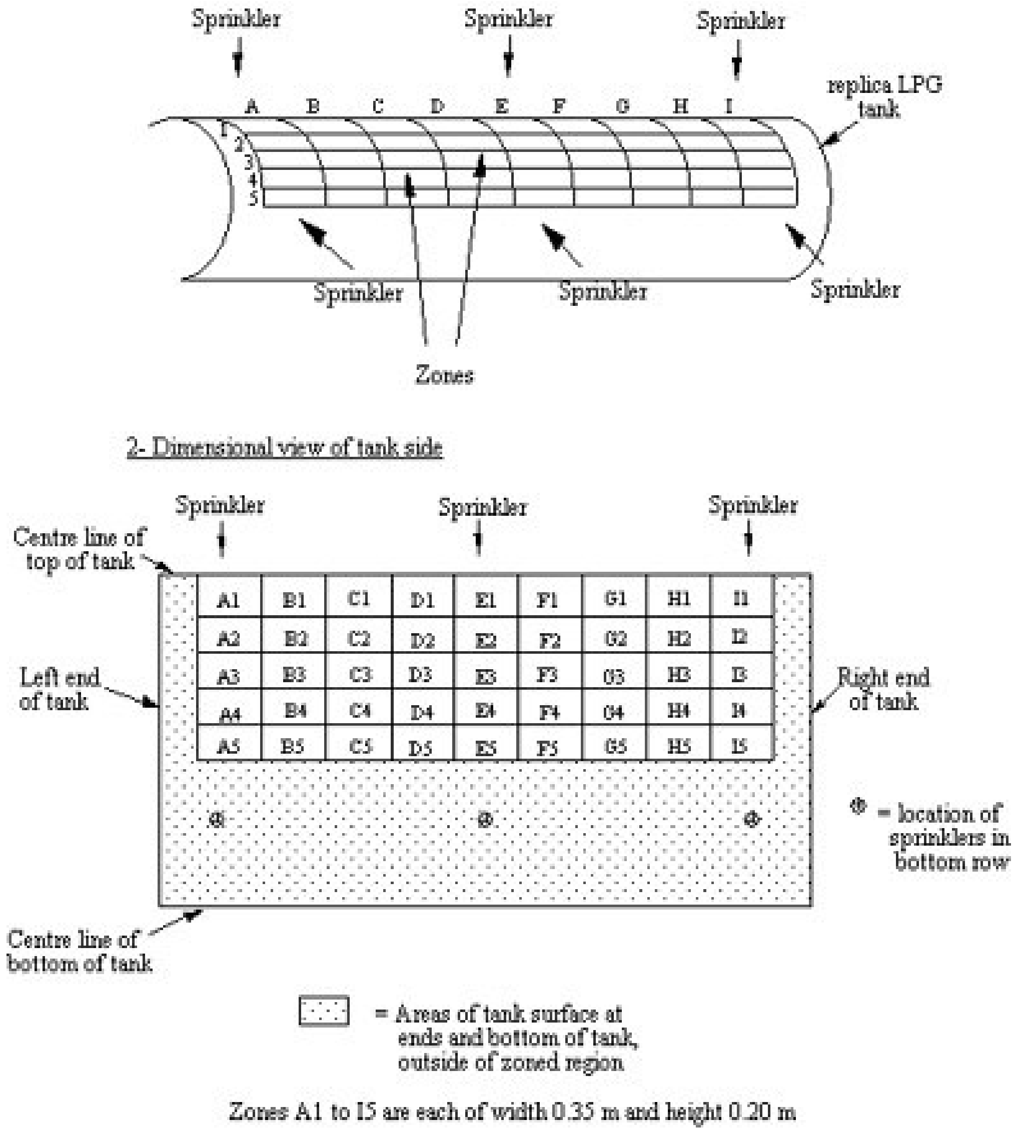



**Figure 2** Schematic showing the division of the replica tank surface into zones

The location of the zones relative to the sprinkler nozzles was designated as follows. Starting with zone column E, the centre of this column of zones was lined up with the centre nozzles within each row. Additional columns of zones (of 0.35 m width) were then allocated on either side of zone column E, until the whole of the tank surface was divided into zones.

The 0.35 m zone width used did not provide an exact multiple of divisions between the 1.5 m spaced nozzles (i.e. 4.28), such that the outer nozzles for each row were located just outside the centres of zones columns A and I. However, the results for measured water collection rates across the complete range of zones i.e. A1 to I5 (Davies & Nolan, 2004a), indicated symmetrical water distribution patterns across the two inter-nozzle regions i.e. for zone columns

A to E and zone columns E to I. Thus, the slight discrepancy between the collection zone widths and the longitudinal distance between nozzles was not considered to be significant.

Each of the inter-nozzle regions on the tank surface was therefore covered by 5 columns of zones i.e. A to E and E to I, but with a half zone overlap into the adjacent inter-nozzle region in each case. Therefore, each inter-nozzle region was effectively covered by 4 zone widths, consisting of half a zone width, followed by 3 full zone widths, and then a further half zone width.

### 3.3 STANDARDISATION OF WATER COLLECTION RATE MEASUREMENT TECHNIQUE

As concluded previously (Davies & Nolan, 2003), the flow rate of water on the surface of the tank is considered to be best characterised by a simple measure of the water collected by the hopper in unit time i.e. the water collection rate. The water collection rate per unit area (i.e. the area between the top of the tank and the collection line) could also be used. However, the water collection rate per unit area parameter is not considered to reflect the degree of fire protection afforded at any selected location on the tank surface. As a result of water running off the tank (e.g. at the tank equator), locations below the tank equator may indicate a low water collection rate per unit area value, although the total quantity of water covering this region of the tank surface may be substantial. Conversely, for locations above the tank equator, high values for water collection rate per unit area may be indicated, although the actual quantity of water present may be small. The actual quantity of water present at any selected location, as indicated by the water collection rate, is considered to more accurately reflect the degree of fire protection afforded.

The disadvantage of using water collection rates alone to characterise the water flow on the tank surface is that these values are dependent on the width of the water collection vessel used. Therefore, to remove this dependency, it is suggested that the water collection rate should be divided by the width of the collection vessel. The water collection rate per unit width value will be independent of the size of the collection vessel, but should reflect the degree of fire protection afforded at any selected location. A comparison of water collection rate per unit area, water collection rate and water collection rate per unit width values for the same locations on the tank surface under identical operating conditions is shown in Table 1. The results relate to the 1.2 m diameter LPG tank and 3-row water deluge system described previously (Davies & Nolan, 2004a).

**Table 1** Comparison of water collection rate per unit area, water collection rate and water collection rate per unit width measurements for a 1.2 m diameter LPG tank and 3-row water deluge system

| ***Water application data*** | |
|---|---|
| ***Parameter*** | ***Value*** |
| Operating pressure (bar) | 2.0 |
| Total water application rate ($dm^3\ m^{-2}\ min^{-1}$) | 475 |
| Surface area of tank ($m^2$) | 15.6 |
| Water application rate ($dm^3\ m^{-2}\ min^{-1}$) | 30.44 |
| Water present on tank ($dm^3\ m^{-2}\ min^{-1}$) | 10.93 |
| % Water present on tank | 36 |

| ***Water collection rate per unit area ($dm^3\ m^{-2}\ min^{-1}$)*** | | | | |
|---|---|---|---|---|
| | ***Left*** | ***Centre*** | ***Right*** | ***Mean*** |
| Above equator | 12.3 | 26.0 | 5.9 | |
| Equator | 8.1 | 17.6 | 5.2 | 10.93 |
| Below equator | 4.9 | 15.1 | 3.3 | |

| ***Water collection rate ($dm^3\ min^{-1}$)*** | | | | |
|---|---|---|---|---|
| | ***Left*** | ***Centre*** | ***Right*** | ***Mean*** |
| Above equator | 0.9 | 1.8 | 0.4 | |
| Equator | 2.3 | 4.9 | 1.5 | 2.6 |
| Below equator | 2.4 | 7.4 | 1.6 | |

| ***Water collection rate per unit width ($dm^3\ m^{-1}\ min^{-1}$)*** | | | | |
|---|---|---|---|---|
| | ***Left*** | ***Centre*** | ***Right*** | ***Mean*** |
| Above equator | 2.6 | 5.2 | 1.1 | |
| Equator | 6.6 | 14.1 | 4.3 | 7.4 |
| Below equator | 6.9 | 21.1 | 4.6 | |

The current guidelines for the design of water deluge systems are based on meeting a single water application rate requirement of 9.8 $dm^3\ m^{-2}\ min^{-1}$, based on the total quantity of water exiting the nozzles divided by the total area of the tank surface. The results for water collection rate per unit area, water collection rate and water collection rate per unit width recorded in Table 1, however, all show a wide variation in values across the tank surface. These results indicate a highly irregular water distribution, with some regions of the tank surface receiving very low water coverage. This demonstrates the inadequacy of using a single overall rate of water application as the criterion for the level of fire protection afforded by a given water deluge system.

It is self evident that the effectiveness of a deluge generated water film, in protecting any particular location on the tank surface against fire, is dependent on the quantity of water flowing over the tank surface at this location. However, the total quantity of water flowing across any selected location is a combination of: (a) the (rate of) water applied to that region of the tank surface by the nozzles; and (b) the quantity of water running down into this region from above, and/or the horizontal migration of water to this region, from adjacent regions of the tank surface. It is apparent therefore, that in general, the lower regions of the tank surface will have higher quantities of water flowing over them, and consequently be better protected, than those near the top of the tank. In fact, the bottom surfaces of the tank are least in need of water film protection, since they are self-cooling due to contact with liquid LPG i.e. inside the tank. The top of the tank, which has least surface water protection, does not receive internal self-cooling, since the LPG is in gaseous form above the ullage level. This means that vessel failure is most likely to occur at the top of the tank, and indeed this was found to be the case, in the jet fire trials of Roberts (2004) and Shirvill (2004). The uneven distribution of water between the top and bottom surfaces of the tank is reflected in the water collection rate and water collection rate per unit width results shown in Table 1, for which increasing values were found with distance from the top of the tank. In contrast, however, the results for water collection rate per unit area indicate decreasing values with distance from the top of the tank. The reason for this is that the area over which the water has been collected for the selected location (which is used in calculating the water collection rate per unit area), is assumed to be the width of the collection hopper multiplied by the distance around the circumference of the tank, from the centre line at the top of the tank to the selected location. However, for the lower surfaces of the tank, a proportion of the water running down the tank from above is lost by run-off at the tank equator, and this assumption is no longer valid. In effect, the area from which the water has been collected is overestimated, resulting in a low water collection rate per unit area value. Thus, the values for water collection rate per unit area for the lower surfaces of the tank underestimate the quantity of water that is available to protect the tank against fire.

The most appropriate measurements for the water flow across the tank surface are therefore the water collection rate and water collection rate per unit width, which indicate that the locations above the tank equator are the least protected regions of the tank with respect to fire. As indicated above, this concurs with the findings from the fire trials reported by Roberts (2004) and Shirvill (2004), in which dry spots/hot spots were always found at locations above the tank equator. As discussed earlier, however, the water collection rate per unit width is the preferred parameter, since it removes the dependency of the water flow measurement on the width of the water collection vessel used. The water collection rate per unit width of collection hopper parameter has been termed the "surface water flow rate" (Davies & Nolan, 2004c). A requirement for a minimum value for the surface water flow rate across the whole of the tank surface will be specified in the revised (improved) guidelines, however, this value and the level of protection provided will need to be established in future fire trials work.

Using the water collection rate per unit width (or surface water flow rate) has additional advantages, for example one of the parameters that will need to be incorporated into the generic model in the future, is the longitudinal distance between the nozzles within each row, comprising the water deluge system. Under the FOC Tentative Rules (1979), a range of longitudinal distances between nozzles of 1.57 to 2.65 m is suggested. (The longitudinal spacing of 1.5 m for the replica LPG tanks and water deluge systems modelled to date is effectively at the lower limit of this range.)

In order to obtain the empirical data needed for the model at greater longitudinal distances, it is suggested that instead of increasing the number of zones measured, the width of the collection zones (and the water collection hopper) is increased. In this way, the same number of zones may be used for measurements. Thus, for a longitudinal nozzle spacing of 2 m, a zone width of 0.5 m would be used, giving 3 full zone widths and two half zone widths i.e. a total of 4 zone widths, across the inter-nozzle region on the tank surface. The number of zones would therefore be the same as for a longitudinal spacing of 1.5 m, as described in section 3.2. The width of the water collection hopper used would be increased to correspond to the width of the designated zones.

Providing the water collection rate per unit width parameter is used, as discussed above, the greater quantities of water that can be expected to be collected in a 0.5 m width collection hopper as compared with a 0.35 m width collection hopper will be effectively normalised, and comparable data should be obtained.

A similar procedure to that described above (i.e. for specifying zone widths for deluge systems with different longitudinal spacing distances) can be used to deal with tanks of different sizes (i.e. larger diameters), with respect to the horizontal divisions defining the number of zones around the circumference of the tank. The number of rows of zones used to cover the region between the centre axial line at the top of the tank to just below the tank equator can be maintained at 5. Thus, for the 1.2 m diameter tank, a zone height of 0.2 m was used, representing an arc of 0.31 radians i.e. 17.6°, around the tank circumference, and for the 2.2 m diameter tank a zone height of 0.34 m was used (also representing an arc of 0.31 radians). Similarly, for a 3 m diameter tank, a zone height of 0.46 m would be needed. By limiting the number of zones used to "map" the tank surface, the number of water collection rate measurements needed to generate the empirical model could be obtained within a practical time frame.

The standardised procedure for measurement of water flow rates on the surface of a LPG tank protected by a water deluge system will therefore consist of dividing the tank surface into a network of theoretical zones, each with a width of ¼ the longitudinal distance between adjacent nozzles within rows. The region of the tank surface between adjacent nozzles is then covered by 5 columns of zones, with the 1$^{st}$ and 5$^{th}$ zone columns centred beneath the nozzles. Half of the 1$^{st}$ and 5$^{th}$ zone columns overlap into the adjacent nozzle to nozzle regions along the tank surface. Horizontal divisions between zones are made at an arc of 0.31 radians (i.e. 17.6°) around the circumference of the tank, starting from the centre axial line at the top of the tank and extending to just below the tank equator. Therefore, a total of 5 rows (and 5 columns) of zones covers the main region of the tank surface of interest with respect to the development of dry spots/hot spots, in the case of impinging jet fires.

In fact, it was only necessary to carry out water collection rate per unit width of collection vessel (i.e. surface water flow rate) measurements for 3 zone columns i.e. 3 x 5 = 15 zones, to characterise the water distribution across the entire tank surface. This was due to the symmetrical nature of the water distribution within each inter-nozzle region across the tank surface, demonstrated in earlier studies (Davies & Nolan, 2004a). The 15 zone region used to characterise the water distribution across the whole tank surface is shown in Figure 3.

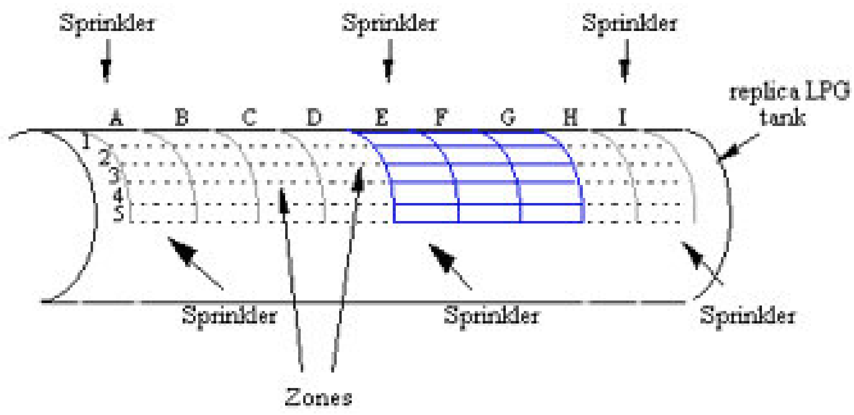



**Figure 3** 15 zone representative region of tank surface for 1.2 m tank and 3-row water deluge

Zones were designated similarly to those shown in Figure 3 above, for all of the tanks for which water distribution characterisations have been carried out. The zone height (i.e. horizontal division spacing) was varied with the tank diameter, and the zone width varied with the longitudinal spacing between nozzles, as described above. Therefore, the surface water flow rates measured for any particular zone, for different tank diameters or different longitudinal spacing between nozzles, represented geometrically comparable regions of the tank surface.

# 4 EXPERIMENTAL DATA NEEDED FOR THE DEVELOPMENT OF A GENERIC MODEL

During earlier work (e.g. Davies & Nolan, 2004a), a wide range of water deluge design parameters and operating conditions were investigated with respect to their effect on the water distribution on the tank surface. A large number of factors/parameters were identified as influencing the water distribution. In addition, many of these parameters were found to interact. Due to the complexity of these interactions and the large number of parameters involved, it would be difficult to devise simple guidelines for the design of water deluge systems providing an optimum water distribution on the tank surface. It was therefore decided that a model capable of predicting the water distribution on the tank surface for any given set of water deluge parameter settings/operating conditions should be developed, and that this model should be empirically based.

The principle of the model employed was that surface water flow rate data (measured by means of the standardised method described in section 3 above) were obtained for a matrix of combinations of water deluge parameter settings. In preliminary tests, surface water flow rates were found to vary in a steady manner for each parameter varied (with all other parameters held constant), such that the relationship between them could be satisfactorily represented by a simple polynomial equation. Three or four sets of measurements across the selected range was sufficient for the polynomial relationship to be determined, in each case. Thereafter, by interpolation of these polynomial equations, the surface water flow rate for any intermediate combination of water deluge parameter settings could be predicted.
Water deluge parameter settings and operating conditions varied (while surface water flow rates were measured) include:

(a) the tank size i.e. diameters of 1.2, 2.2 and 3.0 m.
(b) the number of rows of nozzles i.e. 3 , 4 and 5-row systems.
(c) the operating pressure i.e. pressures ranging from 1.4 to 3.5 barg.
(d) the nozzle discharge angle i.e. angles of 95°, 110° and 125°.
(e) the nozzle yoke arm orientation i.e. "in alignment" and "at 90°" to the axis of the tank.
(f) the stand-off distance of the nozzles from the tank surface i.e. distances ranging from 0.45 to 0.65 m.

In each case, surface water flow rate measurements were carried out for all of the 15 selected zones across the tank surface. These zones covered a region extending from the centre line at the top of the tank to just below the tank equator, and from directly in line (vertically) with one set of nozzles to half distance (horizontally) between adjacent nozzles. This provided a surface water flow rate distribution that was representative of the whole of the tank surface, above the tank equator. This was the main region of interest with respect to protection of the tank surface against fire, since it is only within this region that the development of hot spots/dry spots has been observed during jet fire impingement tests (Roberts *et al*, 1997). Details of the rationale for the designation of the 15 representative zones on the tank surface, have been provided previously (section 3.3).

One of the main advantages of the empirical modelling approach employed here is that individual empirical models for particular tanks and water deluge designs can be added together in a modular fashion to build an overall generic model. The generic model can then be used to predict surface water flow rate distributions for a wide variety of tanks and deluge designs.

# 5 Acquisition of Empirical Relationships for a 2.2 m Diameter Tank and Five-Row (Pentagonal) Water Deluge System

In order to acquire the empirical relationships for a five-row (pentagonal) water deluge system for incorporation into the generic model, a 2.2 m replica LPG tank, built in the laboratory and described previously (Davies & Nolan, 2002), was used. The water distribution on one side of the tank only was considered (since symmetry about the horizontal axis of the tank was assumed). It was therefore possible to use 3 rows of nozzles only to generate the same water distribution as with 5 rows of nozzles, for the single tank side surface used for measurements. The locations of the nozzle rows around the replica LPG tank were: (i) directly above the axial centre line at the top of the tank; (ii) at 72° to the first row of nozzles (in front of the tank); (iii) at 144° to the first row of nozzles (in front of the tank). The other two rows of nozzles (if used) would have been located on the far side of the tank, but would not have influenced the water distribution on the tank side considered.

As described above (section 4), the water deluge design settings and operating conditions were each varied within their designated range, and a matrix of surface water flow rate measurements acquired for the 15 selected zones across the tank surface. This data was then incorporated into the overall generic model. A photograph of the 2.2 m replica LPG tank and pentagonal water deluge system is shown below. The water collection hoppers used to measure the surface water flow rates for each zone are also shown.

*2.2 m replica LPG tank and pentagonal water deluge system. Photograph courtesy of London South Bank University*

The generic model was used to predict the optimum water distribution for the 2.2 m diameter tank and 5-row water deluge. The optimum water distribution has been defined previously (Davies & Nolan, 2003), as the distribution giving the highest value for the minimum zone i.e.

the distribution for which the highest value was attained for the zone (on the tank surface) receiving least water. The results for the 2.2 m diameter tank and 5-row water deluge system are shown in Figure 4 below. For comparison purposes, the optimum water distribution for the 2.2 m diameter tank, with a 4-row water deluge system is shown in Figure 5. In addition, the predicted water distribution for the 2.2 m tank and 5-row deluge system using the same water deluge parameter settings as those producing the optimum water distribution for the 2.2 m diameter tank and 4-row deluge system, is shown in Figure 6.

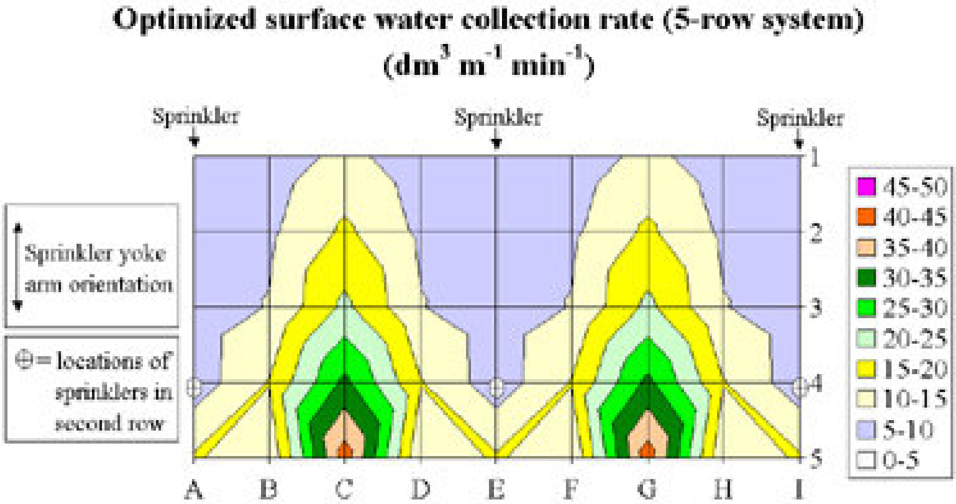



**Figure 4** Optimum water distribution predicted for 2.2 m diameter tank and 5-row deluge

For the predicted water distribution shown in Figure 4 above, the corresponding optimum water deluge parameter settings were: operating pressure 3.4 barg; nozzle discharge angle 125°; nozzle yoke arms "at 90° to the axis of the tank"; stand-off distance 0.45 m. The minimum zone value was predicted to be 6.8 $dm^3\ m^{-1}\ min^{-1}$ for zone locations A3, E3 and I3. The maximum zone value was predicted to be 42.7 $dm^3\ m^{-1}\ min^{-1}$ for zone locations C5 and G5.

In contrast, the optimum water distribution predicted for a 2.2 m diameter LPG tank with a 4-row water deluge system is shown in Figure 5 below.

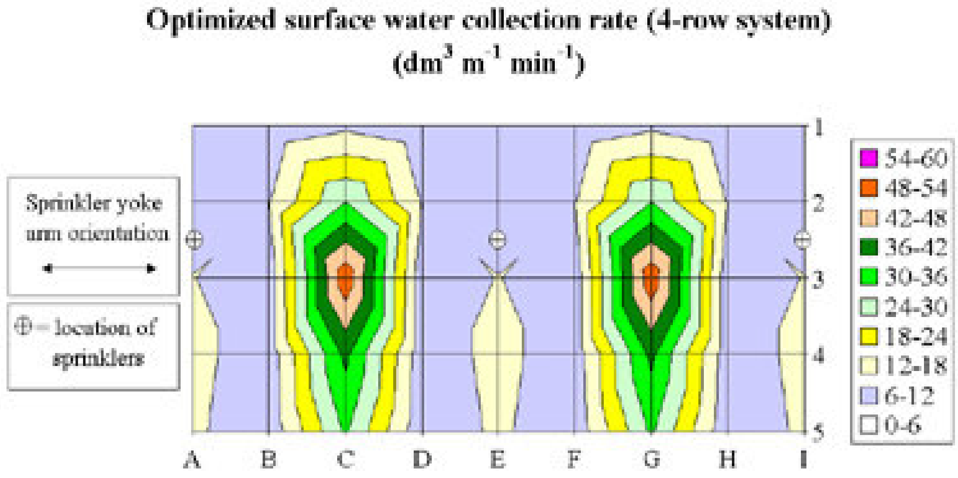



**Figure 5** Optimum water distribution predicted for 2.2 m diameter tank and 4-row deluge

For the predicted water distribution shown in Figure 5 above, the corresponding optimum water deluge parameter settings were: operating pressure 3.5 barg; nozzle discharge angle 125°; nozzle yoke arms "in alignment with axis of tank"; stand-off distance 0.65 m. The minimum zone value was predicted to be 6.7 $dm^3\ m^{-1}\ min^{-1}$ for zone locations B1, D1, F1 and H1. The maximum zone value was predicted to be 52.5 $dm^3\ m^{-1}\ min^{-1}$ for zones C3 and G3.

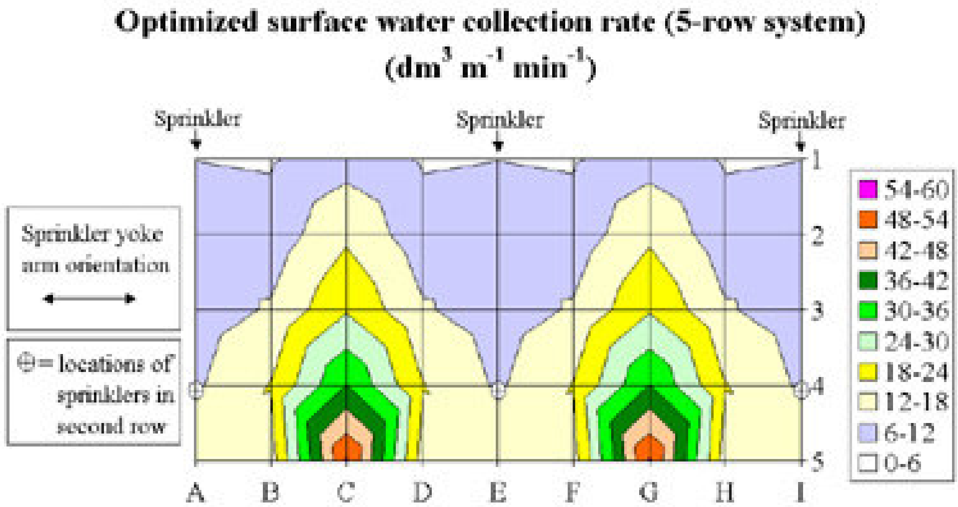



**Figure 6** Water distribution predicted for 2.2 m diameter tank and 5-row deluge using same water deluge settings as for optimum water distribution with 4-row deluge

In Figure 6, the water deluge parameter settings used were identical to those corresponding to the optimum water distribution for the 2.2 m diameter tank and 4-row water deluge system. The minimum zone value was predicted to be 5.4 $dm^3$ $m^{-1}$ $min^{-1}$ for zone locations B1, D1, F1 and H1. The maximum zone value was predicted to be 55.0 $dm^3$ $m^{-1}$ $min^{-1}$ for zones C5 and G5.

Comparing the results for the optimum water distributions for the 4 and 5-row water deluge systems for the 2.2 m diameter tank (i.e. Figures 4 and 5), it is seen that there was relatively little advantage in terms of the minimum zone value i.e. 6.8 $dm^3$ $m^{-1}$ $min^{-1}$ for the 5-row system, as compared with a value of 6.7 $dm^3$ $m^{-1}$ $min^{-1}$ for the 4-row system. The maximum value for the 5-row system i.e. 42.7 $dm^3$ $m^{-1}$ $min^{-1}$ was less than that for the 4-row system i.e. 52.5 $dm^3$ $m^{-1}$ $min^{-1}$, and less water overall was present on the tank surface for the 5-row system, than for the 4-row system. Since more water per unit area was being applied to the tank surface for the 5-row system, this indicates that much more water was being lost e.g. by spray droplets missing the tank; water running off the tank surface in streamlets; or due to droplets bouncing off the tank surface. In terms of the locations of the minimum value zones a significant difference was seen. The minimum zones were in the third row i.e. zones A3, E3 and I3 for the 5-row system, but in the first row i.e. zones B1, D1, F1 and H1 for the 4-row system. Therefore the row of nozzles directly above the centre axis at the top of the tank, for the 5-row system, was providing some additional protection for the top of the tank, as compared with the 4-row system. However, the location of the minimum value zones for the 5-row system (i.e. in the third row from the top of the tank) meant they were still within the region of the tank surface that was potentially vulnerable to the development of dry spots/hot spots in the event of an impinging jet fire. Therefore, using an optimized 5-row system rather than an optimized 4-row deluge system for a 2.2 m diameter tank did not appear to significantly increase the degree of protection afforded, and the 5-row system was much less efficient than the 4-row system, in terms of the quantity of water used for this tank size (i.e. 2.2 m diameter).

Comparing the water deluge parameter settings used to generate the optimum water distributions for the 5 and 4-row water deluge systems (i.e. Figures 4 and 5), the main differences found were in terms of the nozzle yoke arm orientation and the stand-off distance. For the 5-row system the yoke arm orientation was "at 90° to the axis of the tank", while for the 4-row system the yoke arms were "in alignment with the axis of the tank". An optimum stand-off distance of 0.45 m was determined for the 5-row system, as compared with a stand-off distance of 0.65 m for the 4-row system. The operating pressures i.e. 3.4 barg for the 5-row system and 3.5 barg for the 4-row system were virtually the same, and the nozzle discharge angles i.e. 125°, were identical.

To investigate further the effects of using a 5-row deluge system as compared with a 4-row system, on the predicted water distribution, the optimum water deluge settings predicted for the 4-row deluge (and 2.2 m diameter tank) were entered into the model, which was used in its "Evaluate or Optimize an Existing Water Deluge" mode. However, 5 nozzle rows were specified for this deluge system. The model was then used to predict a water distribution on the tank surface. This distribution is shown in Figure 6.

The overall pattern of the predicted water distribution for the 5-row system with the 4-row optimum deluge parameter settings (i.e. Figure 6) was similar to that for the optimum distribution for a 5-row system (i.e. Figure 4), but was less uniform. A higher maximum value of 55.0 $dm^3$ $m^{-1}$ $min^{-1}$ was predicted for the 5-row system using the 4-row optimised deluge parameters (i.e. Figure 6), as compared with a value of 42.7 $dm^3$ $m^{-1}$ $min^{-1}$ for the optimised 5-row system (i.e. Figure 4). In each case, water was concentrated towards the bottom of the region of the tank surface considered, with the maximum values at zones C5 and G5. In terms of the minimum zone, a lower value of 5.4 $dm^3$ $m^{-1}$ $min^{-1}$ was predicted for the 5-row system with 4-row optimized deluge parameters (i.e. Figure 6) as compared with a value of 6.8 $dm^3$ $m^{-1}$ $min^{-1}$ for the 5-row optimum distribution (i.e. Figure 4). The minimum value zone locations for the 5-row system with 4-row optimised deluge parameters (i.e. Figure 6) were at B1, D1, F1 and H1, which were at the same locations as for the 4-row optimum distribution (i.e. Figure 5), but was significantly different to the minimum zone locations of A3, E3 and I3 for the 5-row optimum distribution (i.e. Figure 4).

Overall, it was concluded that for the 2.2 m diameter tank with either a 4 or 5-row deluge system, the highest minimum zone values were achieved with a high degree of overlap between adjacent spray envelopes i.e. with a nozzle discharge angle of 125°, and a high operating pressure i.e. 3.4 or 3.5 barg. However, the effect of increasing the number of nozzle rows from 4 to 5, with all other water deluge parameters maintained constant (i.e. comparing Figures 5 and 6), was to significantly increase the degree of non-uniformity of the water distribution. This non-uniformity was reduced by rotating the nozzle yoke arms through 90° and reducing the stand-off distance from 0.65 m to 0.45 m (i.e. comparing Figures 6 and 4). Using a 5-row rather than a 4-row deluge system for the 2.2 m diameter tank did not significantly increase the degree of protection provided, and was certainly less efficient in terms of water usage. It is considered likely, however, that a 5-row system may provide better protection than a 4-row system for larger diameter tanks.

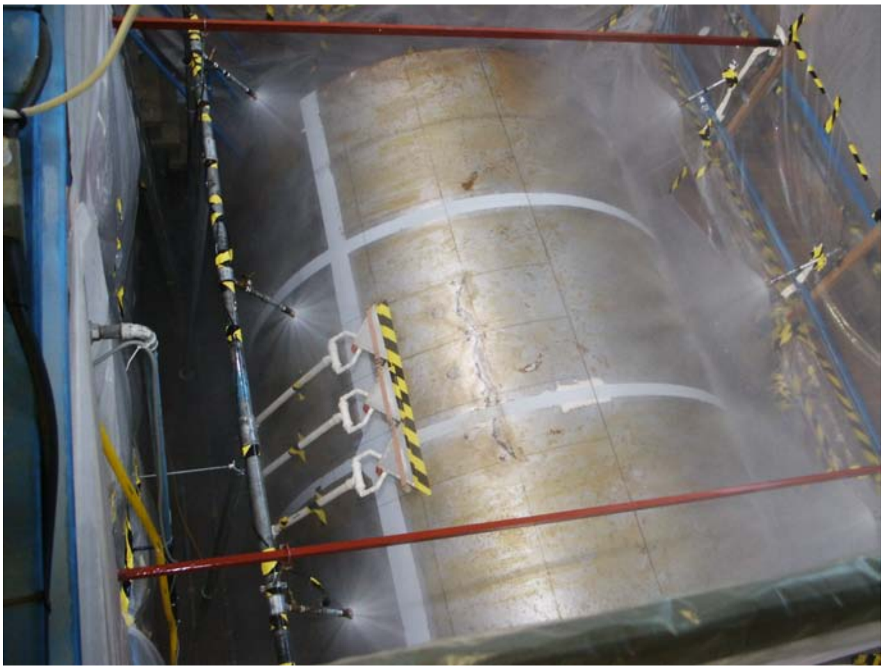
# 6 ACQUISITION OF EMPIRICAL RELATIONSHIPS FOR A 3.0 M DIAMETER TANK AND FOUR-ROW (SQUARE) WATER DELUGE SYSTEM

In order to extend the generic model to deal with 3.0 m diameter tanks, a replica tank of this diameter was built in the laboratory. In fact, the replica tank comprised two thirds of the circumference of a complete 3.0 m diameter tank, permitting realistic water flows and measurements of surface water flow rate on one side of the tank only. The length of the replica tank was 3.2 m, representing a section of the side of a horizontal cylindrical tank (i.e. without end caps) and was similar in design to the 1.2 and 2.2 m diameter replica tanks described previously (Davies & Nolan, 2002; 2004a). The 3.0 m diameter replica tank was surrounded by a 4-row water deluge system in a square pattern arrangement, similar to that used for the 2.2 m diameter replica tank (Davies & Nolan, 2002). As with the 2.2 m tank, it was only necessary to use 3 of the 4 rows of nozzles to generate a representative water flow over the single tank side surface for which measurements were carried out.

As described earlier (section 3), the tank surface for the 3.0 m diameter replica tank was divided into a series of zones of width 0.35 m, and zone height (i.e. distance between horizontal divisions around the circumference of the tank) 0.46 m. This was equivalent to an arc of 0.31 radians around the circumference of the tank, and was identical to that used for the 1.2 and 2.2 m replica tanks. The same designation (i.e. numbering system) as used for the earlier replica tanks was employed for the 3.0 m diameter replica tank, as indicated in Figure 2.

Empirical relationships between measured surface water flow rates and a matrix of combinations of water deluge parameter settings were obtained for each of the 15 selected zones on the tank surface. These relationships were incorporated into the generic model.

A photograph of the 3.0 m diameter replica tank and 4-row water deluge system, with the deluge in operation is shown below. The water collection hoppers are also shown.



*3.0 m diameter tank and 4-row water deluge system. Photograph courtesy of London South Bank University*

The generic model was used to predict the optimum water distribution for a 3.0 m diameter tank and 4-row water deluge system. The results are presented in Figure 7 below.

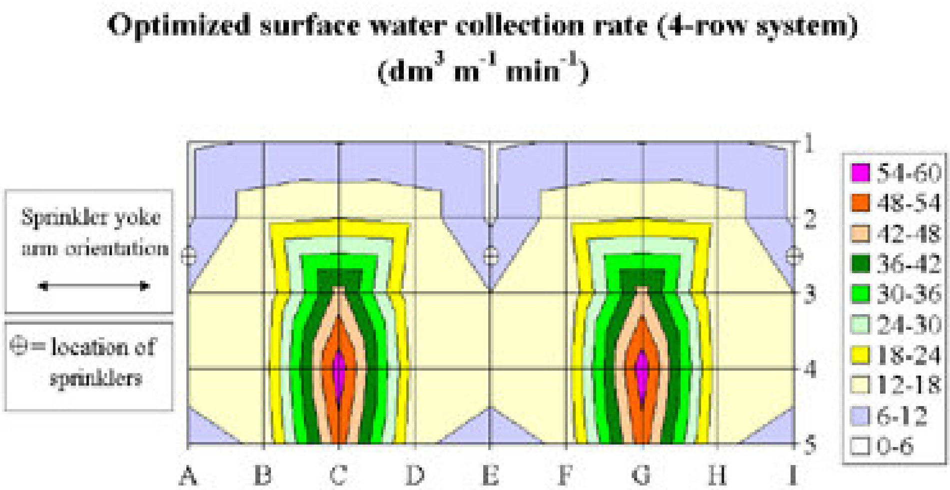



**Figure 7** Optimum water distribution predicted for a 3.0 m diameter tank and 4-row water deluge

The corresponding optimum water deluge parameter settings were: operating pressure 3.5 barg; nozzle discharge angle 125°; nozzle yoke arms "in alignment with axis of tank"; stand-off distance 0.55 m. The minimum zone value was predicted to be 5.0 $dm^3\ m^{-1}\ min^{-1}$ for zone

locations A1, E1 and I1. The maximum zone value was predicted to be 51.5 $dm^3$ $m^{-1}$ $min^{-1}$, at zone locations C4 and G4.
The predicted water distribution for the 3.0 m diameter tank, obtained using the water deluge parameter settings corresponding to the optimum water distribution for the 2.2 m diameter tank and 4-row deluge system, is shown in Figure 8.

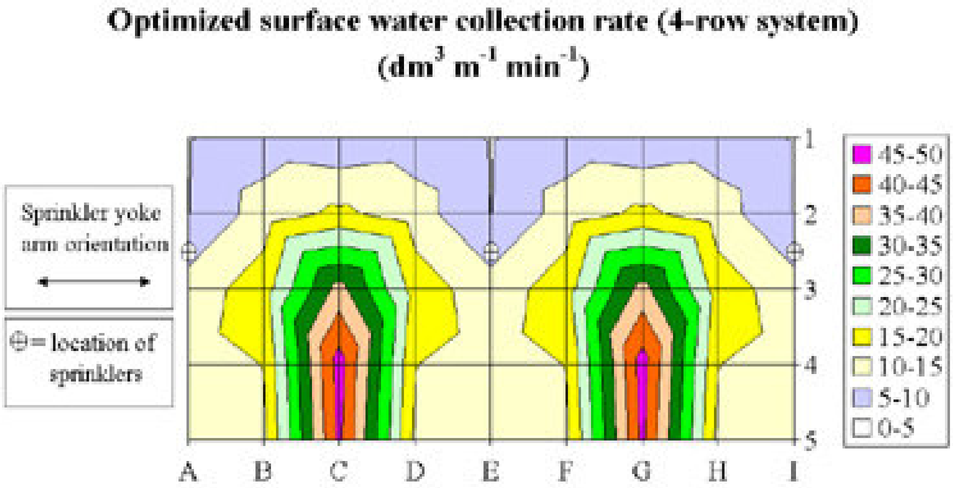



**Figure 8** Predicted water distribution for a 3.0 m diameter tank and 4-row deluge, using the optimum water deluge parameter settings determined for a 2.2 m diameter tank and 4-row deluge system

The water deluge parameter settings found to generate the optimum water distribution for the 2.2 m diameter tank and 4-row deluge system were used, namely: operating pressure 3.5 barg; nozzle discharge angle 125°; nozzle yoke arms "in alignment with axis of tank"; stand-off distance 0.65 m. The minimum zone value was predicted to be 4.7 $dm^3$ $m^{-1}$ $min^{-1}$ for zone locations A1, E1 and I1. The maximum zone value was predicted to be 46.2 $dm^3$ $m^{-1}$ $min^{-1}$, for zones C4 and G4.

Comparing the predicted optimum water distribution for the 3.0 m diameter tank and 4-row deluge (Figure 7) with the predicted water distribution for the 3.0 m tank obtained using the optimum water deluge parameter settings for the 2.2 m diameter tank and 4-row deluge (Figure 8), the distributions were seen to be similar. In the case of the optimum water distribution (Figure 7), the minimum zone value was 5.0 $dm^3$ $m^{-1}$ $min^{-1}$, while for the predicted distribution generated using the 2.2 m diameter tank optimum water deluge settings, a minimum value of 4.7 $dm^3$ $m^{-1}$ $min^{-1}$ was found. In both cases the minimum values were found at zones A1, E1 and I1. The regions of maximum water coverage were also similar, with water concentrated at the midway point between adjacent nozzles, and with the maximum value zone locations at C4 and G4 for both distributions. A maximum zone value of 51.5 $dm^3$ $m^{-1}$ $min^{-1}$ was predicted for the optimum distribution (i.e. Figure 7), and a value of 46.2 $dm^3$ $m^{-1}$ $min^{-1}$ for the predicted distribution generated using the optimum water deluge parameter settings for the 2.2 m diameter tank (i.e. Figure 8).

In fact, the optimum water deluge parameter settings for both the 3.0 m (i.e. Figure 7) and 2.2 m (i.e. Figure 5) diameter tanks with 4-row water deluge systems were very similar. The only difference between the water deluge parameter settings was in terms of the stand-off distance, with a value of 0.55 m for the 3.0 m tank, and a value of 0.65 m for the 2.2 m diameter tank. It was concluded that in the case of a 4-row water deluge system, the optimum water distribution was achieved using virtually the same water deluge parameter settings, for two markedly different sizes of tank i.e. 2.2 m and 3.0 m diameter.

When the optimum predicted water distribution for the 2.2 m diameter tank and 4-row water deluge system (i.e. Figure 5), reported in the previous section, was compared with the predicted water distribution for the 3.0 m diameter tank and 4-row deluge system, using the same water deluge parameter settings (i.e. Figure 8), some differences were seen. Water was concentrated at the midway point between adjacent nozzles i.e. zone columns C and G, in each case, however, the maximum value zones were at C3 and G3 for the 2.2 m diameter tank, but at C4 and G4 for the 3.0 m diameter tank. The maximum zone values were marginally higher for the 2.2 m diameter tank i.e. 52.5 $dm^3\ m^{-1}\ min^{-1}$, as compared with a maximum value of 46.2 $dm^3\ m^{-1}\ min^{-1}$ for the 3.0 m diameter tank. However, a more significant difference was seen in terms of the minimum zone value. A minimum value of 6.7 $dm^3\ m^{-1}\ min^{-1}$ was predicted for the 2.2 m diameter tank, while a minimum value of 4.7 $dm^3\ m^{-1}\ min^{-1}$ was predicted for the 3.0 m diameter tank, with the same water deluge parameter settings. The locations for the minimum value zones were in the top row (i.e. close to the top of the tank) for both tanks, with the minimum values at zones B1, D1, F1 and H1 for the 2.2 m diameter tank, and at zones A1, E1 and I1 for the 3.0 m diameter tank. The overall quantity of water on the tank surface was also significantly lower for the 3.0 m diameter tank, than for the 2.2 m diameter tank.

The reduction in the minimum and maximum zone values and in the overall quantity of water on the tank, was expected for the 3.0 m diameter tank, since by increasing the tank diameter (i.e. from 2.2 to 3.0 m diameter), while using the same number of nozzle rows (i.e. 4) and the same water deluge parameter settings, the water application rate per unit area of the tank surface would have been reduced. Conversely, it is considered likely that, although increasing the number of nozzle rows from 4 to 5 for the 2.2 m diameter tank had only a marginal effect (i.e. increase) on the minimum zone value, in the case of the 3.0 m diameter tank, increasing the number of rows from 4 to 5 would have a greater effect (i.e. increase) on the minimum zone value, since the water application rate per unit area would be increased.

These results suggest that the same water distribution pattern will be produced on the tank surface, for any tank size, for a given water deluge layout. Also the optimum water deluge distribution will be produced by the same water deluge parameter settings and operating conditions for the different tank sizes. The actual value for the minimum zone (i.e. reflecting the level of protection achieved) will decrease as the tank size increases, for a given water deluge design, as the rate of application of water per unit area of the tank surface is reduced. Therefore, to increase the level of protection i.e. increase the value for the minimum zone, for a large tank diameter, with optimised water deluge parameter settings, it would be necessary to increase the rate of water application e.g. by increasing the number of nozzle rows or increasing the nozzle bore size.

# 7 DEVELOPMENT OF A USER-FRIENDLY, FRONT-END INTERFACE FOR THE GENERIC MODEL

To facilitate use of the generic model, the whole of the model has been incorporated into a Visual Basic (VB) computer software code. The model is now accessed by means of a user-friendly, front-end interface, written in VB. The software comes in the form of a stand-alone executable (.exe) file, but makes use of the graphics/charting facilities within Microsoft Excel. It is therefore necessary for Microsoft Office/Excel to be installed on the computer used, in order for the model to run successfully.

On launching the model software (by clicking on the executable file), a title page is shown while the model data is loaded. A start button then appears and when clicked, presents the first interactive menu. This menu asks for initial details of the system to be modelled, first establishing the diameter of the LPG tank to be considered. The user is then asked to select whether a new optimised water deluge system is to be designed for the tank, or whether an existing water deluge system is to be evaluated and/or optimised. Figure 9 shows the first interactive menu screen displayed by the model.

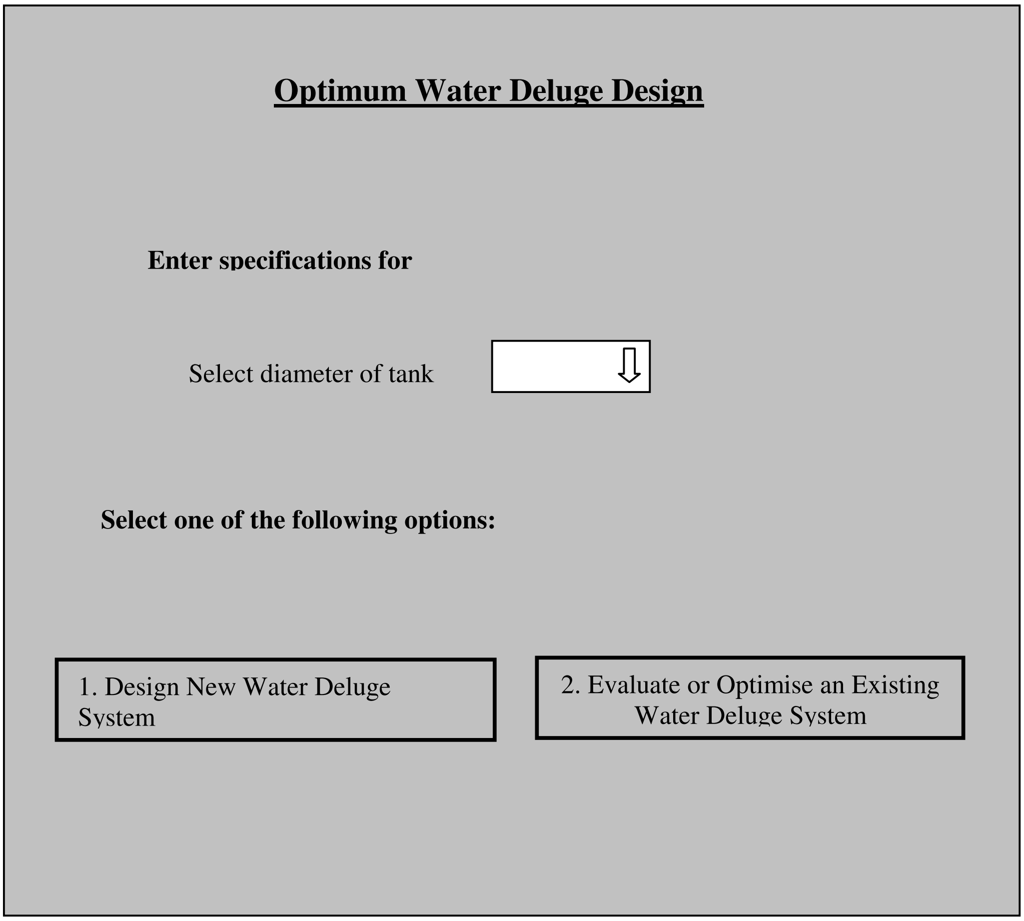



**Figure 9** First interactive screen displayed by model

N.B. The down arrow in the data entry box in Figure 9 indicates a “drop-down” menu giving a list of available options for selection.

If “Design New Water Deluge System” is selected, the model proceeds to compare all possible combinations of water deluge design parameters and operating conditions and determines the combination producing the optimum water coverage for the specified tank size. The results are presented in the form of a 2-D surface contour plot of the optimum surface water flow rate distribution across the tank surface. The corresponding optimum water deluge parameter settings and operating conditions are also reported. In fact, the 5 best water distributions and combinations of water deluge parameter settings are determined by the model. Initially, the very best predicted surface water flow rate distribution is displayed, but by clicking a button, the second, third, fourth and fifth best distributions can be displayed, in turn.

If “Evaluate or Optimise an Existing Water Deluge System” is selected from the first interactive screen (after entering the tank diameter), a second interactive menu appears. In this case, further details of the system are requested. For example, the number of rows of nozzles can be specified; the typical operating pressure; the nozzle discharge angle; the nozzle yoke arm orientation; the stand-off distance of the nozzles from the tank surface; the longitudinal spacing between nozzles; the offset distance (if other than zero) for nozzles in adjacent rows. Values can be entered for any or all of these parameters as desired. Any parameters for which values are not entered will be optimised for by the model. (If no values are entered for any of the parameters in the second interactive menu, the predicted optimised water distribution and water deluge settings will be identical to those that would be predicted for a new water deluge design for this tank.)

After entering parameter values using the second interactive menu screen, the button marked “optimise/evaluate” is clicked and this initiates calculation of the water distribution corresponding to the parameter values entered. When some of the parameters are optimised for (i.e. no value has been entered for this parameter), the 5 best (optimised) water distributions are reported, in turn, using the same results output screen as described earlier for new deluge designs.

Figure 10 shows the second interactive menu screen displayed by the model, when “Evaluate or Optimise an Existing Water Deluge System” is selected.

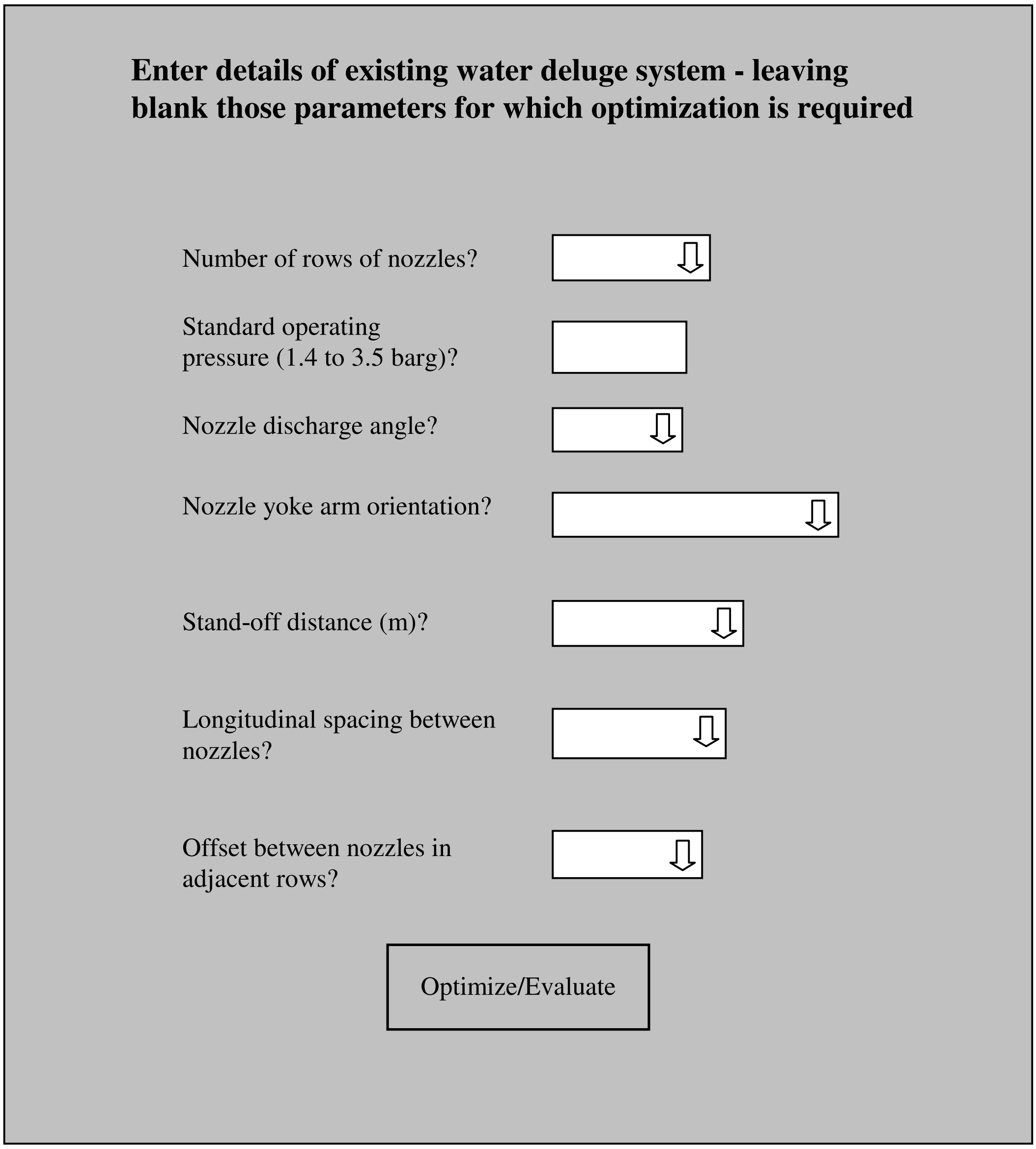



**Figure 10** Second interactive menu screen displayed by model

On clicking on the "Optimize/Evaluate" button, if any of the values entered are outside of the permitted range, or an unacceptable combination of parameter selections has been made (e.g. selecting a 5-row deluge system for a 1.2 m diameter tank), an error message appears. This informs the user of the problem and after automatically clearing the parameter value entered, the user is prompted to enter a new set of (permissible) values.

The same results screen is used for both new deluge designs and for optimisation/evaluation of existing deluge systems. A typical example of the output produced is shown in Figure 11. The results shown in this case are the optimum surface water flow rate distribution and the corresponding optimum water deluge parameter settings (i.e. deluge design and operating conditions) for a 1.2 m tank and 3-row water deluge system.

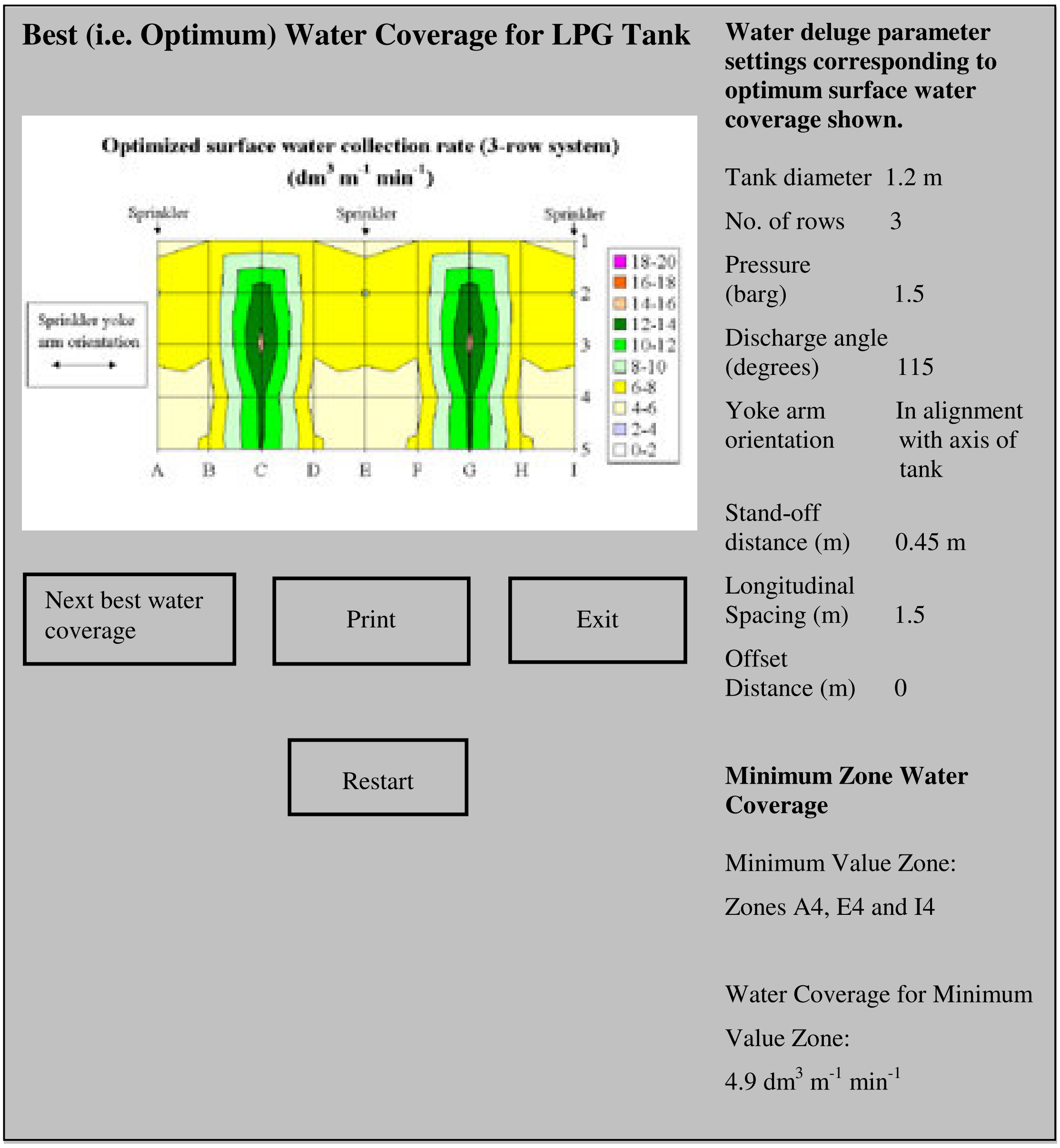



**Figure 11** Typical results output screen displayed by model

In the case of an existing tank, where values have been entered for all of the water deluge parameters listed in the second interactive menu, there will be only one predicted water distribution and therefore only a single results output screen. The "Next best water coverage" button will not be visible under these circumstances.

Apart from the 2-D surface contour plot of the predicted water distribution, and the corresponding water deluge parameter settings, the results output screen also reports the surface water flow rate for the minimum value zone, and indicates where these minimum values will occur on the tank surface. Also, in addition to the "Next best water coverage" button, a "Previous best water coverage" button becomes visible for the 2$^{nd}$, 3$^{rd}$, 4$^{th}$ and 5$^{th}$ best water coverage output screens. A "Print" button is also provided, enabling the entire results output screen, including the 2-D surface contour plot, to be printed. A "Restart" button returns the user to the first interactive screen, enabling a new set of parameter values to be entered and the model to be run again. The button marked “Exit” allows the user to quit the program.

It would be desirable for the predicted water distribution to be displayed as a 3-D surface contour plot, rather than as a 2-D surface contour plot, as above, since this would facilitate interpretation of the results for new users of the model. This could be achieved by using a commercial graph plotting software package such as TecPlot. This would significantly add to the cost of the model, so has not been incorporated into the current version (i.e. version 1.0) of the code. However, a 3-D surface contour plot version of the model could be developed in the future, if required.

In order to use the current version of the model for the design and evaluation of existing systems, it is suggested that the FOC Tentative Rules (1979) are followed when circumstances are encountered which are outside the present scope of the model. For example, in the case of the tank ends, the FOC Tentative Rules (1979) recommend that an extra set of nozzles is used, which extend beyond the end of the tank for each nozzle row, and are then directed back towards the tank ends. Although not mentioned in the FOC Tentative Rules (1979), in the case of a staggered nozzle arrangement, it is suggested that the spacing between nozzles be reduced at the end of rows, where appropriate, to bring the end nozzles in each row into alignment. The reduced spacing between adjacent nozzles in alternate rows is likely to be beneficial, since the results predicted using the model to date, indicate that the best water coverage is obtained when the overlap between adjacent nozzle spray envelopes is greatest.

# 8 VALIDATION OF THE MODEL

The model has been validated by comparing predicted surface water flow rate data against measured data obtained using a 3.0 m diameter, replica LPG tank and 4-row water deluge system. The model was used to predict surface water flow rates for 3 adjacent zones on the tank surface, namely zones E2, F2 and G2 (see Figure 3.3), in the second row from the top of the tank. The water deluge settings selected for the validation were:

(1) MV18-125 nozzles (i.e. a nozzle discharge angle of 125°); nozzle yoke arms in alignment with the axis of the tank; a stand-off distance of the nozzles from the tank surface of 0.50 m; and operating pressures of 1.8, 2.3 and 3.2 barg,
(2) MV18-95 nozzles (i.e. a nozzle discharge angle of 95°); nozzle yoke arms at 90° to the axis of the tank; a stand-off distance of the nozzles from the tank surface of 0.50 m; and operating pressures of 1.8, 2.3 and 3.2 barg.

The stand-off distance (i.e. 0.50 m) and operating pressures (i.e. 1.8, 2.3 and 3.2 barg) had not been previously used for measurements using the 3.0 m replica LPG tank and 4-row water deluge.

The water deluge parameter settings and operating conditions listed above were entered into the model using the VB interactive menus and then predictions for surface water flow rates (in $dm^3 m^{-1} min^{-1}$) were obtained for the three zones, at the three different pressures. The selected water deluge parameter settings were then adopted for the 3.0 m replica LPG tank and 4-row water deluge system, and surface water flow rates measured for these zones using the standardised measurement procedure described in section 3. The predicted and measured surface water flow rate data were then compared. The results obtained are shown in Table 2.

**Table 2** Validation of model by comparison of predicted and measured surface water flow rate data

| *Zone No.* | *Pressure (barg)* | *Discharge angle (degrees)* | *Stand-off distance (m)* | *Orientation of nozzle yoke arms* | *Predicted surface water flow rate (P) ($dm^3\ m^{-1}\ min^{-1}$)* | *Measured surface water flow rate (M) ($dm^3\ m^{-1}\ min^{-1}$)* | *Absolute difference (P –M) ($dm^3\ m^{-1}\ min^{-1}$)* | *Percentage difference (%)* |
|---|---|---|---|---|---|---|---|---|
| E2 | 1.8 | 95 | 0.50 | 90° | 4.22 | 4.83 | 0.61 | 12.6 |
| E2 | 12.3 | 95 | 0.50 | 90° | 3.96 | 4.66 | 0.70 | 15.0 |
| E2 | 3.2 | 95 | 0.50 | 90° | 3.85 | 4.60 | 0.75 | 16.3 |
| E2 | 1.8 | 125 | 0.50 | 0° | 5.35 | 5.37 | 0.02 | 0.4 |
| E2 | 2.3 | 125 | 0.50 | 0° | 4.99 | 4.89 | 0.10 | 2.0 |
| E2 | 3.2 | 125 | 0.50 | 0° | 4.59 | 4.37 | 0.22 | 5.0 |
| F2 | 1.8 | 95 | 0.50 | 90° | 4.45 | 4.23 | 0.22 | 5.2 |
| F2 | 2.3 | 95 | 0.50 | 90° | 4.51 | 4.71 | 0.20 | 4.2 |
| F2 | 3.2 | 95 | 0.50 | 90° | 3.57 | 4.89 | 1.32 | 27.0 |
| F2 | 1.8 | 125 | 0.50 | 0° | 9.48 | 9.86 | 0.38 | 2.6 |
| F2 | 2.3 | 125 | 0.50 | 0° | 11.63 | 11.65 | 0.02 | 0.2 |
| F2 | 3.2 | 125 | 0.50 | 0° | 14.87 | 13.63 | 1.25 | 9.1 |
| G2 | 1.8 | 95 | 0.50 | 90° | 24.56 | 25.97 | 1.41 | 5.4 |
| G2 | 2.3 | 95 | 0.50 | 90° | 31.01 | 33.03 | 2.02 | 6.1 |
| G2 | 3.2 | 95 | 0.50 | 90° | 40.18 | 43.31 | 3.13 | 7.2 |
| G2 | 1.8 | 125 | 0.50 | 0° | 7.56 | 7.23 | 0.33 | 4.6 |
| G2 | 2.3 | 125 | 0.50 | 0° | 10.05 | 10.00 | 0.05 | 0.5 |
| G2 | 3.2 | 125 | 0.50 | 0° | 15.79 | 16.25 | 0.46 | 2.8 |

In Table 2 above, in the "Orientation of nozzle yoke arms" column, 0° indicates that the nozzle yoke arms were in alignment with the axis of the tank, and 90° indicates that the nozzle yoke arms were at 90° to the axis of the tank.

It is seen from Table 2 that the predicted and measured surface water flow rates were generally in good agreement. The average percentage difference between predicted and measured values was 7.0%. This indicated an even closer agreement between predicted and measured values, than the 10.2% achieved by the model in earlier validation tests with the 2.2 m replica LPG tank and 4-row deluge system (Davies & Nolan, 2003).

For the results reported above (Table 2), the greatest percentage difference between predicted and measured surface water flow rates was a value of 27.0% for zone F2. This occurred at an operating pressure of 3.2 barg; a nozzle discharge angle of 95°; and with the nozzle yoke arms at 90° to the axis of the tank. These conditions were known from previous experience (e.g. Davies & Nolan, 1997) to generate a highly irregular water distribution across the tank surface, with water concentrated at the midway point between adjacent nozzles i.e. along the line of zone G2. This was also found in the present case, with the highest zone value measured during the current validation tests being 43.31 $dm^3\ m^{-1}\ min^{-1}$ at zone G2, for this set of operating conditions. As a result, the relatively low value measured for the adjacent zone on the tank surface i.e. F2, of 4.89 $dm^3\ m^{-1}\ min^{-1}$, is likely to be subject to marked fluctuations. These could occur as a consequence of small changes in the operating and environmental conditions causing the path of the water flowing across the tank surface to vary slightly. If a small percentage of the water normally flowing into zone G2 is diverted into zone F2, a large percentage change in the water collected at this zone may result. It is therefore to be expected that the measured value for zone F2, under these conditions, may be subject to a higher degree of variation on different measurement occasions, than for other zones on the tank surface.

# 9 CONCLUSIONS

1. The current guidelines for the design of water deluge systems are based on meeting a single, overall water application rate of 9.8 $dm^3\ m^{-2}\ min^{-1}$. This has been shown to be inadequate, since the water distribution on the tank surface is often highly irregular, with regions of very low water coverage, and consequently poor fire protection.

2. There is a need for improved guidance for the design of water deluge systems to protect LPG tanks against fire, taking into account the water distribution on the tank surface.

3. A standardised method for measuring the water flow across the surface of a LPG tank, protected by a water deluge, has been defined. The standardised method is based on measurements of the water collection rate per unit width of the collecting vessel (in $dm^3\ m^{-1}\ min^{-1}$), which has been termed the "surface water flow rate".

4. Experimental surface water flow rate data has been acquired for 1.2, 2.2 and 3.0 m diameter, horizontal, cylindrical LPG tanks, and for 3, 4 and 5-row water deluge systems. This data has been used to develop an empirically based generic computer model, to predict the water distribution on the tank surface for any given combination of water deluge parameter settings.

5. The optimum predicted water distributions for both 2.2 m and 3.0 m diameter tanks, with 4-row water deluges, were achieved with virtually identical water deluge parameter settings, although the minimum zone value was lower for the 3.0 m diameter tank. Increasing the number of nozzle rows from 4 to 5 produced only a marginal improvement in the optimum water coverage for a 2.2 m diameter tank.

6. The generic model has been incorporated into a Visual Basic (VB) software code, which provides a user-friendly front-end interface for the model, whereby details of the LPG tank and water deluge system to be modelled can be entered into the code via an interactive menu. The predicted water distribution generated by the model is currently displayed as a 2-D surface contour plot. A method for displaying the results in a 3-D format, using a commercial graph plotting program has been identified, but has not yet been implemented, although it could be included in a future version of the model.

7. The model has been validated for both 2.2 m and 3.0 m diameter experimental LPG tanks, with 4-row water deluge systems. Good agreement between predicted and measured values has been achieved, with an average percentage difference of 10.2% in the case of the 2.2 m diameter tank, and 7.0% for the 3.0 m diameter tank. Validation on industrial tanks will also be carried out, when appropriate systems have been identified by the HSE.

8. The model is ready to be applied to the design of experimental water deluge systems for use in full-scale fire trial experiments, when required.

# 10 FUTURE WORK

To complete the existing model for horizontal, cylindrical LPG tanks, the effects of nozzle bore sizes and nozzle separation distances (within rows) will also need to be taken into account. This will involve acquiring further empirical relationships between surface water flow rates and these water deluge parameters, for inclusion in the model. In addition, a study of the water flow over the surface of hemi-spherical/toroidal tank ends is needed, to obtain experimental input data for the model, to enable prediction of the water coverage on the ends of horizontal, cylindrical LPG tanks.

However, it is proposed that the main focus of future work should involve undertaking experiments to relate the surface water flow rate on spherical and vertical, cylindrical vessels to the design and operating parameters of these water deluge systems. The equations derived would also be incorporated into the existing code, extending its range of applicability.

Further modifications to the code will involve developing a 3-D results display option for the model, to facilitate interpretation of the model's predicted water distributions, for inexperienced users.

The model will also be validated by comparing predicted water distributions for new industrial water deluge installations, designed using the model, against measured values.

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