

Design of Dry Pipe Sprinkler Systems to Meet the Water Delivery Time Restriction in Industrial Freezers

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ABSTRACT

Dry-pipe sprinkler systems are commonly used when the ambient temperature of a protected space is below freezing temperature of water. Because the degree of fire spread prior to sprinkler actuation is greater than that of the wet system in comparable circumstances, a greater coverage area is often required in a dry-system than that of a wet system. In addition, the dry system also requires the water delivery time to the most remote sprinkler be within a certain time limit. Dry-pipe ceiling-sprinkler restriction imposed by NFPA 13 for the protection of Class 2 materials in rack-storage higher than 7.6-m under 12-m ceiling is a maximum 30-seconds water delivery time with a 4-heads-open assumption. An in-house computer program developed to estimate water delay times in dry-pipe systems has been extensively used at FM Global for the last 15 years to address the water delivery time requirement mentioned above for industrial freezers. This paper describes how the program was developed and how the 30-seconds water-delivery time requirement could be met by choosing proper operating conditions through numerous real design cases. The examples showed that by adjusting many operating control parameters, most of the system could meet the 30-seconds water delivery time restriction without making substantial alteration in system configurations. The case study also shows that the air trip time linearly increases with the system volumes as anticipated. The water transit time also increases with the system volume in general, however, the dependence was more complex, which indicates that the system configuration plays an important role in the transit time in dry-pipe systems. Overall, the case study shows that the program had enabled the system design to be much more flexible and cost effective.

KEYWORDS: dry-pipe sprinkler system, sprinkler at freezer, water delivery time; air trip time

NOMENCLATURE LISTING

A cross-sectional area

c specific heat

g gravitational acceleration

h water head

i water front location

P pressure

R specific gas constant

T temperature

t time

V volume

v velocity

X stream line length at a branch pipe

Y total length of stream line

Greek

γ specific heat ratio

ρ density

Subscript

a air

e exit; lumped volume equivalent

p pressure

v volume

T total

∞ ambient

INTRODUCTION

An automatic sprinkler system, one of the most reliable fire protection schemes, can be divided by two groups; wet- and dry-pipe systems. The wet-pipe system, in which sprinkler branch pipes are filled with water so that water can be discharged through the open orifices as soon as sprinkler heads are open, is more common. The dry-pipe system is used where the wet system is inoperable, e.g., where the ambient temperature is below freezing temperature---industrial freezer, large-scale food storage area, unheated warehouse, or outside loading dock, for example. In the dry-pipe system, water is filled only up to the dry-pipe valve and all the pipes from there to sprinklers are filled with either pressurized air or pressurized nitrogen. When sprinklers actuate, the pipes start to discharge air or nitrogen through the open sprinklers,

and when the dry-pipe valve opens due to the loss of air pressure, water starts to flow. Thus, there are always delays in water delivery to the open sprinklers in contrast to the wet system where the water delivery is instantaneous. Because of this, the degree of fire spread prior to sprinkler actuation is greater than that of the wet system in comparable circumstances. Thus, NFPA 13 [1] requires a 30 percent greater coverage area than that in a comparable wet system in the sprinkler design. The dry pipe system is subject to additional restrictions in order not to allow too long a water delivery time to the open sprinklers. For instance, NFPA 13 limits water delivery time to the most remote sprinkler from 40 to 60 seconds depending on hazards in non-residential environments. Until recently NFPA 13 restricted the maximum size of a dry-pipe system be less than 750 gallons (2.84 m³) unless an inspection connection attached to the system shows that the water delivery time is less than 60 seconds. Starting 2002, however, NFPA 13 allows the use of a computer program for the system design [2], which allows a system without installing the inspection test connection, if the program shows the system meets all the requirements in the water delivery time.

Another dry-pipe ceiling-sprinkler restriction for the protection of materials in rack-storage higher than 7.6-m under 12-m ceiling is a maximum 30-seconds water delivery time with a 4-heads-open assumption (see NFPA 13, Table 16.3.2.1(a)). This particular restriction stemmed from a fire test conducted at FM Global, which will be described later. Many industrial freezers store frozen food in open racks over 7.6 m high. An in-house computer program estimating a water delivery time in a dry-pipe system has been used to evaluate dry-pipe system designs in industrial freezers for FM Global's clients for over the last 15 years. Although the program was developed for general purposes, it has been used very extensively to check the 30-s delivery time requirement for the industrial freezers. This paper will describe how the program was developed and how it has been utilized to evaluate a dry-pipe system to determine whether the system meets the 30-second water-delivery time requirement through a number of real design cases.

The dry-pipe water delivery time consists of two periods; the valve-trip time and the water-transit time. As the system is filled with pressurized air or nitrogen, it takes time for the valve to open after sprinklers actuated. The pressure inside the system has to be low enough to meet a dry-pipe valve ratio or a pre-set pressure to open a dry-pipe valve so that water can flow. The time duration from the first sprinkler opening to the dry-pipe valve opening is the valve-trip time or, more commonly referred to as, the air-trip time. The water transit time is the duration from the opening of the dry-pipe valve to water appearing at any open sprinkler.

COMPUTATION OF THE VALVE-TRIP TIME (THE AIR-TRIP TIME)

When sprinklers in a dry-pipe system open, air in the system evacuates resulting in lowering the system pressure. When the system pressure reaches a trip pressure, the dry-pipe valve trips and water starts to flow into the system toward open sprinklers. The trip pressure is determined by the initial water pressure and the dry-pipe valve differential, or more commonly these days, by a quick-opening device. The air mass discharge rate through open sprinklers, \dot{m}_a , can be computed by the following equations [3] depending on either the flows at the exit are choked, i.e., sonic, or not, i.e., subsonic.

$$\dot{m}_a = \left[\left(\frac{\gamma}{R} \right) \left(\frac{2}{\gamma + 1} \right)^{\frac{(\gamma+1)}{(\gamma-1)}} \right]^{1/2} \left(A_e P_a / T_a^{1/2} \right) \text{ for } P_\infty / P_a < 0.528 \text{ (the discharge velocity is sonic)} \quad (1a)$$

$$\dot{m}_a = A_e \left\{ \frac{2\gamma P_a^2}{RT_a(\gamma-1)} \left[\left(\frac{P_\infty}{P_a} \right)^{2/\gamma} - \left(\frac{P_\infty}{P_a} \right)^{\gamma+1/\gamma} \right] \right\}^{1/2} \text{ for } P_\infty / P_a \geq 0.528 \text{ (the discharge velocity is sub-sonic)} \quad (1b)$$

here P_a and P_∞ are, respectively, the air pressure inside the system and that at ambient. T_a is the air temperature inside the system, A_e is the total discharge area of open sprinklers, γ is the ratio of constant pressure specific heat, i.e., c_p , to the constant volume specific heat, i.e., c_v , of air, and R is the specific gas constant of air. The decrease of air pressure inside the system corresponding to the air discharge can be expressed as

$$\frac{d}{dt} \left(\frac{P_a V_T}{RT_a} \right) = -\dot{m}_a \quad (2)$$

where V_T is the total volume occupied by air in the dry-pipe system, which would vary once the dry-pipe valve opens. Assuming that the air temperature inside the system, T_a , does not vary during the expansion in the system, Eq (2) can be written as

$$\frac{dP_a}{dt} = \frac{P_a}{V_T} \left\{ - \left[\gamma RT_a \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} A_e \right\} \text{ for } \frac{P_\infty}{P_a} < 0.528 \quad (3a)$$

$$\frac{dP_a}{dt} = \frac{P_a}{V_T} \left\{ - \left(\frac{2\gamma RT_a}{\gamma-1} \right)^{\frac{1}{2}} \left[\left(\frac{P_\infty}{P_a} \right)^{\frac{2}{\gamma}} - \left(\frac{P_\infty}{P_a} \right)^{\frac{\gamma+1}{\gamma}} \right]^{\frac{1}{2}} A_e \right\} \text{ for } \frac{P_\infty}{P_a} \geq 0.528 \quad (3b)$$

Eq. (3) was numerically integrated using a fourth-order Runge-Kutta scheme to obtain a time dependent function of the air pressure. The time for the dry-pipe valve actuation corresponds to the instant when the air pressure inside the system equals to the preset trip pressure of the valve.

COMPUTATION OF THE WATER TRANSIT TIME

The theoretical model developed by Heskestad and Kung [4] for prediction of water transit time in a non-gridded and non-looped system was utilized in the program. In the model, a dry-pipe sprinkler system was reduced to an equivalent simple system, and the water transit time of the equivalent system was then computed as shown in the following example.

Reduction of an Actual System to a Simplified Equivalent System

As the water front moves toward open sprinklers from the dry-pipe valve after the trip event, the front encounters a number of closed branch lines and other sub-volumes of the system as schematically illustrated in Fig 1. The pipe A-B represents the pipe line between the water supply and a riser B-D, and C is the Dry Pipe Valve located in the riser. The pipe B-D-E is the feed main, E-J is the cross main, and the pipes E through J are the branch pipes, while K through R are the sprinklers. The two circles V_A and V_B are the total volume of the minor systems prior to E, which are not shown in the figure, and that after J, respectively.

Water flows from Water Supply (tank or pump) through A-B-C-D-E-J-K-R, assuming R is the most remote sprinkler. As the water front travels past the closed sub-volumes, V_A , and the closed branch lines (F to J), air is trapped within these volumes. Water flows in and out response to the pressure changes at the junction with the main conduit leading toward the open sprinklers. A system such as the one depicted in Fig 1 is too cumbersome to be handled by theory; thus, a series of approximations was applied [4]. In the first approximation, the closed pipe branches seen by the water front while it progresses are treated as Volume V_2 through V_5 , each volume being that of the closed branch F through I. For systems with more branch lines, the number of sub-volumes will increase accordingly. Volume V_6 combines the left running branch at J and the sub-volume V_B attached to J via Section J-J₁ of the cross main. Volume V_1 represents the sub-volume V_A attached to E via Section E-E₁ of the cross main, and it is fed by a pipe having the diameter of Section E-E₁. The pipes upstream of Point E remain identical to those of the actual system.

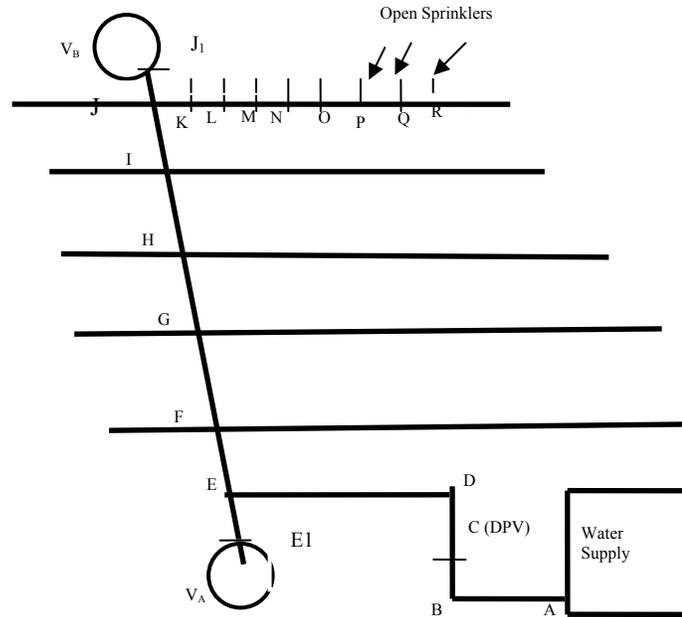


Fig. 1. Schematic of the system used in this study as an example.

In the second approximation (see Fig 2), the six closed branch volumes of the first approximation have been reduced to two approximately equivalent volumes, V_{e1} and V_{e2} . The pipes feeding the equivalent volumes have flow areas equal to the sum of the flow areas of the feed pipes [4].

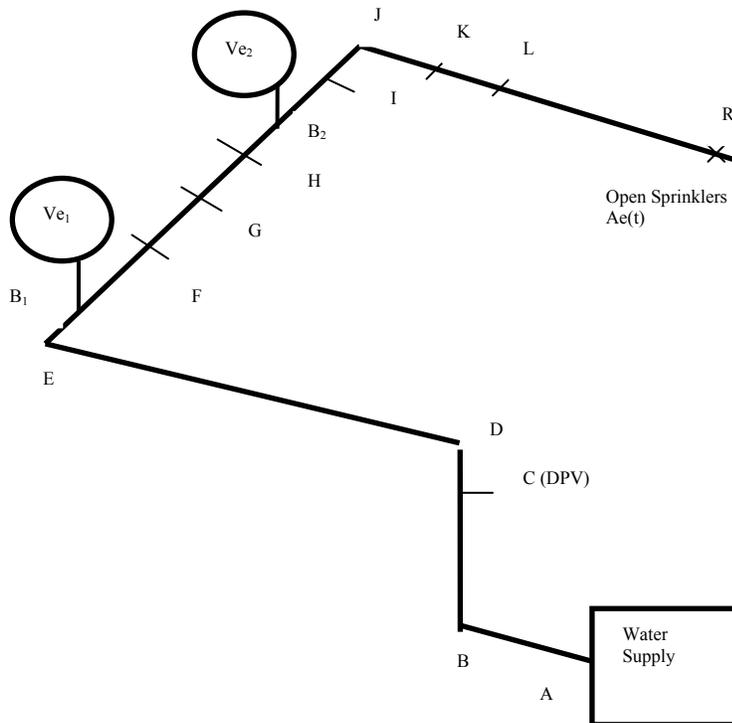


Fig. 2. Lumped-Volume equivalent of the example dry-pipe system.

The proper location for each of the equivalent volumes along E-J has to be determined. An appropriate location is the point at which the mass of water accumulated in the equivalent volume, while the water front traverses the pipe section reaching from the first to the last volume being lumped, is equal to the total mass of water accumulated in the individual volumes, V_1 through V_6 [4]. The mass accumulation of water in each volume is approximately proportional to the product of: (1) the size of each volume, and (2) the time interval elapsed since the front passed by the volume in question. The mass of water accumulated in the equivalent volume at some, yet unknown, location along E-J is required to be equal to the total mass of water accumulated in the lumped volumes fixes the location of each equivalent volume [4].

The sequential opening of sprinklers is represented by a prescribed time dependent function $A_e(t)$ for the total discharge orifice area which corresponds to that of the open sprinklers at a given instant. The program provides several options on determining sprinkler opening sequences for an end-user to choose, which will be explained shortly with more details. If the sprinklers on several adjacent branch lines have opened before water reaches the open heads, then these branch lines are replaced by a single equivalent branch. The equivalent branch has a cross section area equals to the sum of the cross-section areas of the individual branches in order to preserve the effects of the inertia [4].

Flow in Equivalent Systems

The lumped-volume equivalent system in Fig 2 includes compound pipe sections between (1) the water supply and the dry-pipe valve, (2) the dry-pipe valve and the first equivalent volume, (3) the first and the second equivalent volumes, and (4) the second equivalent volume and the sprinkler opening. Flow along the equivalent systems was treated as follows.

It is assumed that: the air temperature is constant during the expansion or compression of air trapped in the system (see Eq 3); the dry-pipe valve opens instantly; and the water front is normal to the pipe axis. The momentum equation for the water column which extends from the water supply of known hydraulic characteristics (pressure versus flow rate) to the water front is obtained by using unsteady Bernoulli equations including friction loss terms. The pressure differential between the water supply and the water front is balanced by: the acceleration of the water column; the wall friction; pressure drops along the column due to elbows, tees, and other restrictions; and water heads due to gravity. The pressure in the air phase is assumed to be uniform throughout. The unsteady mass conservation equation for the air phase leading to open sprinklers provides a connection between the air pressure at the water front and the air discharge rate at the open sprinklers (see Eq 3).

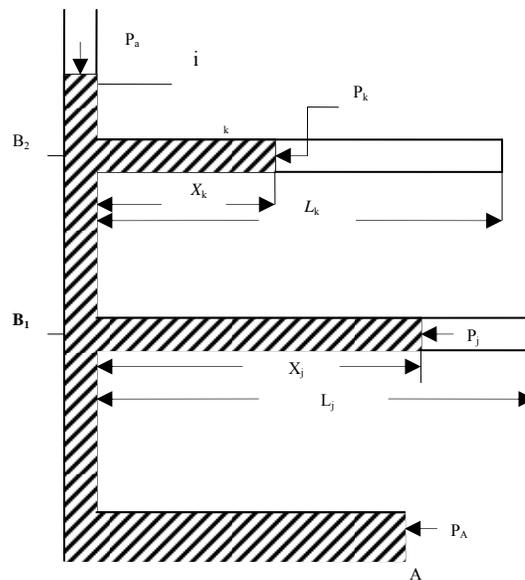


Fig. 3. Schematic drawing of water flow after the front passed the second branching point B_2 .

Figure 3 shows the current position of water front, i . Starting from A, the water passed the riser, dry pipe valve (DPV), first branch point B_1 , which is the point that the first Equivalent Volume Ve_1 (see Figure 2) meets the cross main, and passed the second branch point B_2 , where Ve_2 (see Figure 2) meets the cross main. Here the equivalent volumes Ve_1 and Ve_2 are represented by branch pipes having the same cross-sectional area as the sum of the cross sectional area of each lumped volume (V_1 through V_6) belongs to either Ve_1 or Ve_2 . The length of each branch pipe, L_j and L_k , is given as $A_j L_j = Ve_1$ and $A_k L_k = Ve_2$, where A_j and A_k , are, respectively, the cross sectional area of the branch pipe j and k . As the water front passes B_1 and B_2 , water started to flow into the equivalent volumes Ve_1 and Ve_2 . The location of water front in each branch pipe, X_j and X_k , would be determined by the force balance between the trapped air pressure and the water pressure. Here P_A is the initial static pressure at the water supply, P_j is the pressure of squeezed air inside the air pocket in the first branch, P_k is the pressure of the squeezed air inside the second branch pipe, P_a is the system air pressure at i exerted to the moving water front.

Eqs (4) to (8) below are extended unsteady Bernoulli equations for: (1) the water column from location A to location B_1 , (2) the water column from location B_1 to location B_2 , (3) the water column in the second equivalent volume Ve_2 , (4) the water column in the first equivalent volume Ve_1 , and (5) the water column

from location B_2 to the water front i . Here $\int \frac{\partial v}{\partial t} ds$ is the unsteady momentum term of the water flow, v is

the water flow velocity, t is time, s is the length of a stream line, v_{B_1} and v_{B_2} are the water flow velocity immediately upstream of B_1 and B_2 , respectively. v_A is the water flow velocity at the pipe section A;

however, as the pipe cross-sectional area from the source of water supply to the intersection B_1 can vary in general, Eq (4) can be divided into as many sub-equations as the number of different pipe areas from A to B_1 . P_{B_1} , P_A , and P_{B_2} are the water pressure at B_1 , A, and B_2 , respectively; P_k , P_j , and P_a are the air pressure at the branch pipe k and j , and that at the water front i , respectively. ρ and g are the water density and the gravitational acceleration, respectively; h_{B_1} is the elevation water head between A to B_1 gained by

the riser, and ${}_a(h_f)_b$ in the equations is the friction head loss term between the points a and b. Eqs (9) and

(10) show how the pressures P_k and P_j can be obtained. Here $P_k(0)$ is the air pressure inside the branch pipe k just prior to the water front passes the intersection B_2 and $P_j(0)$ is the air pressure inside the pipe j

just before the water front passes B_1 . In other words, $P_k(0)$ and $P_j(0)$ are, respectively, P_a at $i=B_2$ and P_a at $i=B_1$, which are continuously calculated by Eq (3) as the water front i travels. In addition, there are two mass continuity equations, Eqs (11) and (12) at the branching points B_1 and B_2 , where A_i , A_{B_2} , and A_{B_1} are,

respectively, the cross-sectional area of the pipe at i , B_2 , and B_1 . Also v_k , v_j , and v_i are the water flow velocities at X_k , X_j and i , respectively, which are calculated by the Eqs (13a), (13b), and (13c). Here Y_i is the total length of the stream line from i to the beginning of the water flow at A. Y_i grows from zero at the starting point to whatever distance the water front advances. The number of governing equations and the contents of the equations would vary depending on where the i point is. However, as the theory in this study only deals with two equivalent volumes, the number of equations and the number of the variables would not be greater than those in the equations from (4) to (13).

$$\int_A^{B_1} \frac{\partial v}{\partial t} ds + \frac{v_{B_1}^2}{2} + \frac{P_{B_1}}{\rho} + gh_{B_1} = \frac{v_A^2}{2} + \frac{P_A}{\rho} + gh_A - g[{}_{B_1}(h_f)_A] \quad (4)$$

$$\int_{B_1}^{B_2} \frac{\partial v}{\partial t} ds + \frac{v_{B_2}^2}{2} + \frac{P_{B_2}}{\rho} = \frac{v_{B_1}^2}{2} + \frac{P_{B_1}}{\rho} - g[{}_{B_2}(h_f)_{B_1}] \quad (5)$$

$$\int_{B_2}^k \frac{\partial v}{\partial t} ds + \frac{v_k^2}{2} + \frac{P_k}{\rho} = \frac{v_{B_2}^2}{2} + \frac{P_{B_2}}{\rho} - g \left[(h_f)_{B_2} \right] \quad (6)$$

$$\int_{B_1}^j \frac{\partial v}{\partial t} ds + \frac{v_j^2}{2} + \frac{P_j}{\rho} = \frac{v_{B_1}^2}{2} + \frac{P_{B_1}}{\rho} - g \left[(h_f)_{B_1} \right] \quad (7)$$

$$\int_{B_2}^i \frac{\partial v}{\partial t} ds + \frac{v_i^2}{2} + \frac{P_a}{\rho} = \frac{v_{B_2}^2}{2} + \frac{P_{B_2}}{\rho} - g \left[(h_f)_{B_2} \right] \quad (8)$$

$$P_j = P_j(0) \left[\frac{L_j}{(L_j - X_j)} \right] \quad (9)$$

$$P_k = P_k(0) \left[\frac{L_k}{(L_k - X_k)} \right] \quad (10)$$

$$A_{B_2} v_{B_2} + A_j v_j = A_{B_1} v_{B_1} \quad (11)$$

$$A_k v_k + A_i v_i = A_{B_2} v_{B_2} \quad (12)$$

$$\frac{dX_k}{dt} = v_k; \quad \frac{dX_j}{dt} = v_j; \quad \frac{dY_i}{dt} = v_i \quad (13a, 13b, 13c)$$

These are mathematically well posed problems. Numerical integrations and iterations were performed to obtain the values that would satisfy the above equations.

SYNOPSIS OF COMPUTER PROGRAM STRUCTURE

The program performs four main tasks. The first task is reading a data file created by the end user about the location of sprinklers, pipe size, main and branch pipe configurations, riser information, pump performance, air pressure, trip pressure, etc. The second task is converting the real system into a theoretical system of the two equivalent volumes, Ve_1 and Ve_2 , and placing them at B_1 and B_2 in the system, respectively.

The third task is calculating the air trip time using the supervisory and the trip air pressures provided by the end user. To perform the third task, a sprinkler opening sequence has to be provided. Two sets of options are given. One option is using sprinkler opening sequence scenarios based on fire histories. Once the burning materials and storage configuration are known, one can construct opening scenarios using fire plume correlations and ceiling jet flow correlations [5, 6] assuming that the fire is in a quasi-steady state. The other option is using real fire test data. Two fire tests were conducted in 1995 [7] to evaluate fire protection schemes by dry-pipe sprinkler systems in a 12-m (40-ft) high ceiling industrial freezer with large-drop sprinklers installed on the ceiling. The stored food on open racks was simulated by 7-tier (10.3-m high) FM Global Class II Commodity material, and the design density from the sprinklers was 56 mm/s (0.83 gpm/ft²). To simulate water delays in dry-pipe systems, water flow was held up by a valve for 60 seconds in the first test and for 30 seconds in the second test after the first sprinkler actuated. The first test opened 71 sprinklers, most of them within 1 min 10 seconds from the first sprinkler opening. The second test opened 24 sprinklers. The test data was delivered to NFPA 13, which help the 30-seconds water delivery time be part of the NFPA 13 standards. The sprinkler opening times in Test 2 [7] are given in Table 1. The program was designed to follow the opening sequence in Table 1 and the $A_e(t)$ was computed as the number of open sprinkler at a given time multiplied by the cross-sectional area of each sprinkler orifice.

The last task was solving the governing equations similar to those in Eqs. (4) through (13) following the movement of water front from Location A to the most remote sprinkler. As previously mentioned, depending on the location of the water front, i , the number of the equations and formats would change. The

equations would become gradually more complicated as i marches further away from A closer to the most remote sprinkler. In the computation, the values from previous times would provide reasonable first guesses for the values that would meet the governing equations at the given time through iterations. When i reaches the pre-assigned sprinkler, the program ends and yields the time for the water transit (from A to the final i destination), air trip time, and the number of open sprinklers that is obtained either by the above mentioned fire test or by the opening sequence scenario based on fire plume correlations.

Table 1. The sprinkler opening times in Fire Test 2.

| Opening Sequence | Actuation Time (m:s) |
|------------------|----------------------|------------------|----------------------|------------------|----------------------|------------------|----------------------|
| 1 | 2:13 | 7 | 2:32 | 13 | 2:44 | 19 | 2:55 |
| 2 | 2:17 | 8 | 2:32 | 14 | 2:46 | 20 | 2:57 |
| 3 | 2:23 | 9 | 2:34 | 15 | 2:48 | 21 | 10:00 |
| 4 | 2:30 | 10 | 2:34 | 16 | 2:49 | 22 | 17:28 |
| 5 | 2:30 | 11 | 2:35 | 17 | 2:51 | 23 | 19:28 |
| 6 | 2:31 | 12 | 2:43 | 18 | 2:51 | 24 | 19:31 |

The program was tested to the system shown in Fig 1. As there was only one open sprinkler in the test, the sprinkler opening sequence was not required. The computation showed the water transit time as 14.6 seconds, while the experiment showed that as 15.0 seconds. Another test was conducted with a 4.46 m³ (1180 gallons) real system having 14 branch pipes installed at an industrial freezer. As a real fire test could not be an option, the water delay time at an inspection connection was predicted by the program and compared with the measured one. The trip time predicted was 35 while the measured one was 38 seconds; the water transit time predicted was 27 while the measured one was 28 seconds. Thus, the comparison of the total water delay time between the prediction and the experiment was 63 vs. 66 seconds. These comparisons indicated that the evaluation of a system by this program would be reasonably reliable.

REVIEW OF SYSTEMS

Among the systems evaluated with the computer program mentioned above, the following 40 cases are listed in Table 2 as they have more complete data. In all the cases provided here, unless otherwise noted, large-drop sprinklers (Orifice diameter: 16 mm [0.64 inch]; Temperature rating: 141 °C; Response Time Index: 165 [m.s]^{1/2}) were installed on a 12-m (40-ft) high ceiling inside a freezer the ambient temperature of which was -7 °C (-20 °F). The sprinkler opening sequence was assumed to be identical to that in Table 1 described above.

The air trip time is mainly dependent upon the system volume and the difference between the supervisory pressure and the trip pressure, assuming that the sprinkler orifice size, opening sequence and ambient temperature are all fixed. However, the water transit time heavily depends on the system configuration in addition to the system volume and the static water pressure. Thus, the operating conditions given in Table 2 alone without full-system drawings are not sufficient to explain the differences in the final water delivery times among the systems. However, providing the full-system drawing of each system in a limited space would not be practical. When there are substantial differences in water delivery times among the systems in Table 2 that had comparable size and comparable operating conditions, one can assume that it was the system configuration that had made such difference in the water delivery time. In System 16, the riser location was altered to shorten the feed-main pipe; in System 23 and 26, the sprinkler orifice diameter was 24 mm (0.96 inch) and 19 mm (0.75 inch), respectively.

Several observations can be made as follows for the systems shown in Table 2:

1. All the systems up to 3.21-m³ (850-gallon) volume met the 30-seconds water delivery time restriction.
2. The largest system that met the 30-seconds time restriction was System 30, which had a 4.47 m³ (1182 gallons) volume; the air pressure difference of 69 kPa (10 psi); and the maximum static water pressure of 1034 kPa (150 psi). In contrast, System 31, which had a comparable size (4.47 vs. 4.73 m³) with comparable sets of operating conditions, yielded a water delivery time as twice longer as that of System 30 (29 vs. 58 seconds). A long feed-main and long cross-mains in System 31 made this difference.

3. The original design of System 16 was modified after first evaluation to reduce the length of the feed-main, which was accomplished by moving the location of the risers. That reduced the air trip time and

Table 2. System operating conditions for the cases evaluated since Yr. 2000.

| System Number | System Volume: m ³ (Gallon) | Super- visory Air Pressure: kPa (psi) | Trip Pressure: kPa (psi) | Static Water Pressure: kPa (psi) | Air Trip Time (s) | Water Transit Time (s) | Water Delivery Time (s) |
|---------------|-----------------------------------------|---------------------------------------|--------------------------|----------------------------------|-------------------|------------------------|-------------------------|
| 1 | 2.53 (670) | 69 (10) | 34 (5) | 1310 (190) | 11 | 12 | 23 |
| 2 | 2.56 (678) | 69 (10) | 34 (5) | 1097 (159) | 11 | 13 | 24 |
| 3 | 2.82 (747) | 207 (30) | 145 (21) | 1200 (174) | 10 | 18 | 28 |
| 4 | 2.88 (763) | 248 (36) | 152 (22) | 1207 (175) | 14 | 13 | 27 |
| 5 | 3.06 (810) | 69 (10) | 34 (5) | 1241 (180) | 12 | 12 | 24 |
| 6 | 3.21 (850) | 69 (10) | 34 (5) | 1241 (180) | 13 | 11 | 24 |
| 7 | 3.33 (881) | 248 (36) | 152 (22) | 1207 (175) | 15 | 16 | 31 |
| 8 | 3.33 (881) | 69 (10) | 34 (5) | 1103 (160) | 13 | 19 | 32 |
| 9 | 3.38 (895) | 89 (13) | 48 (7) | 1048 (152) | 13 | 12 | 25 |
| 10 | 3.41 (903) | 248 (36) | 152 (22) | 1207 (175) | 15 | 17 | 32 |
| 11 | 3.50 (925) | 248 (36) | 152 (22) | 1207 (175) | 16 | 17 | 33 |
| 12 | 3.52 (930) | 290 (42) | 241 (35) | 1152 (167) | 10 | 11 | 21 |
| 13 | 3.63 (960) | 69 (10) | 48 (7) | 1034 (150) | 10 | 15 | 25 |
| 14 | 3.64 (964) | 69 (10) | 34 (5) | 1034 (150) | 13 | 15 | 28 |
| 15 | 3.70 (978) | 69 (10) | 34 (5) | 1034 (150) | 13 | 12 | 25 |
| 16 | 3.72 (983) | 241 (35) | 172 (25) | 1317 (191) | 13 | 14 | 27 |
| 17 | 3.72 (983) | 344 (50) | 172 (25) | 1317 (191) | 19 | 15 | 34 |
| 18 | 3.84 (1014) | 228 (33) | 131 (19) | 800 (116) | 17 | 13 | 30 |
| 19 | 3.93 (1041) | 69 (10) | 34 (5) | 938 (136) | 14 | 12 | 26 |
| 20 | 4.03 (1067) | 69 (10) | 34 (5) | 1241 (180) | 14 | 13 | 27 |
| 21 | 4.18 (1107) | 138 (20) | 103 (15) | 1034 (150) | 11 | 15 | 26 |
| 22 | 4.18 (1107) | 138 (20) | 69 (10) | 966 (140) | 17 | 14 | 31 |
| 23 | 4.23 (1120) | 69 (10) | 34 (5) | 890 (129) | 9 | 16 | 25 |
| 24 | 4.23 (1120) | 69 (10) | 34 (5) | 1097 (159) | 14 | 14 | 28 |
| 25 | 4.25 (1125) | 55 (8) | 41 (6) | 1034 (150) | 9 | 17 | 26 |
| 26 | 4.35 (1150) | 69 (10) | 34 (5) | 1324 (192) | 12 | 15 | 27 |
| 27 | 4.35 (1152) | 69 (10) | 34 (5) | 1138 (165) | 15 | 14 | 29 |
| 28 | 4.39 (1161) | 103 (15) | 83 (12) | 1207 (175) | 10 | 14 | 24 |
| 29 | 4.43 (1171) | 69 (10) | 34 (5) | 1090 (158) | 15 | 13 | 28 |
| 30 | 4.47 (1182) | 276 (40) | 207 (30) | 1034 (150) | 14 | 15 | 29 |
| 31 | 4.73 (1250) | 145 (21) | 103 (15) | 966 (140) | 16 | 42 | 58 |
| 32 | 4.82 (1276) | 310 (45) | 172 (25) | 1000 (145) | 20 | 13 | 33 |
| 33 | 5.02 (1328) | 276 (40) | 172 (25) | 1131 (164) | 18 | 19 | 37 |
| 34 | 5.14 (1360) | 172 (25) | 103 (15) | 1131 (164) | 18 | 25 | 43 |
| 35 | 5.33 (1410) | 69 (10) | 28 (4) | 1262 (183) | 18 | 23 | 41 |
| 36 | 5.50 (1456) | 241 (35) | 138 (20) | 1103 (160) | 20 | 13 | 33 |
| 37 | 5.95 (1574) | 69 (10) | 34 (5) | 1090 (158) | 17 | 17 | 34 |
| 38 | 7.48 (1980) | 207 (30) | 186 (27) | 690 (100) | 12 | 42 | 54 |
| 39 | 7.56 (2000) | 345 (50) | 69 (10) | 1276 (185) | 59 | 56 | 115 |
| 40 | 8.98 (2375) | 172 (25) | 103 (15) | 1131 (164) | 22 | 38 | 60 |

the water transit time substantially and eventually met the 30-seconds restriction after a few operating conditions were adjusted.

4. Systems 23 and 26 had sprinklers orifice sizes of which were larger than the 16 mm ones used in all the other cases. The final water delivery times were comparable with those in systems of much smaller volumes, which illustrate the influence of sprinkler orifice size on the trip time. The cases suggest a means of reducing the water delivery time without significantly altering pipe configurations.
5. System 39, which had a 7.56 m³ (2000 gallons) system volume, yielded the longest water delivery time, 115 seconds, among the systems evaluated. The large volume and the large difference between the system and the trip pressures, 276 kPa (40 psi), were the main reasons for the long water delivery time. System 40, which was larger than System 39 (7.56 vs. 8.98 m³), however, yielded the water delivery time that is about a half of that of System 39. The comparison again illustrates the importance of system configuration and operating conditions in reducing the water delivery time. System 39 and 40 were divided into smaller systems eventually to meet the 30-seconds limitation.
6. In order to see the effect of a system volume to its air trip time, the trip time vs. system volume is plotted in Fig 4. For a fair comparison of the volume vs. trip time, the difference between the system pressure and the trip pressure should be the same for all the cases in the comparison. Cases 1, 2, 5, 6, 8, 14, 15, 19, 20, 21, 23, 24, 26, 27, 29, and 37 have the air pressure difference of 34 kPa (5 psi). As Systems 23 and 26 had larger sprinklers than those in the rest, they were eliminated from the comparison. As anticipated, the trip time almost linearly increases with the system volume. The one point that is substantially lower than the almost straight line composed by the others corresponds to System 21. The system pressure in System 21 was 138 kPa (20 psi) while that in all the other cases mentioned above was 69 kPa (10 psi). When System 21 discharges air, the air flow in most time would be a choked flow (see Eq. 3); Thus, the system discharges a larger air mass than the other systems do in the same period of time, which in turn would shorten the trip time compared with those in lower system pressure cases.
7. The relation between the water transit time and the system volume is shown in Fig 5. Although there is an unmistakable trend that larger volume systems require longer transit times, the correlation is not as straight forward as the trip time vs. the system volume, because the differences in system configurations could not be reflected in the figure. A high static water pressure was believed to contribute to reduce the water transit time, but the degree of the contribution was not substantial. Also it was feared that a high air pressure in the system would lengthen the water transit time; but this also showed very minimal effect. The most significant factor in reducing the water transit time was the system configuration. It is important to maintain the total water transit length, which was computed by the travel path of the water front *i* in the program, as short as practically possible when a system covers a large area. As mentioned earlier, the location of risers in System 16 was altered in order to reduce the length of feed-main pipe after the evaluation of the original system concluded that the system would not be able to meet the 30-second water-delivery time restriction. That substantially reduced air volume and the total length of water path as well. Systems close to a center-center feed system configuration yielded the shortest, systems close to a side-end feed system configuration yielded the longest, and systems close to center-end feed system configuration yielded somewhere in between water-transit times, while they cover comparable areas. The most common system configuration reviewed in the above 40 cases was the center-end feed system. As altering system configuration was not practical in many real cases where the geometry of a site very much dictates the feasible configuration, finding operating system conditions that would enable the system to meet the 30-seconds time limit was a more practical option.

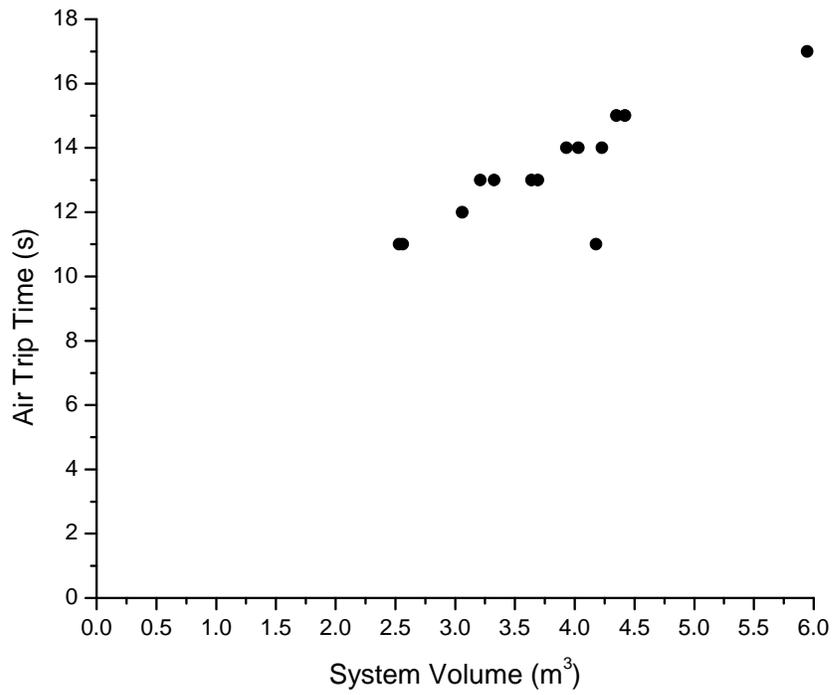


Fig. 4. Air trip time vs. system volume. The pressure difference to trip the valve was 34 kPa.

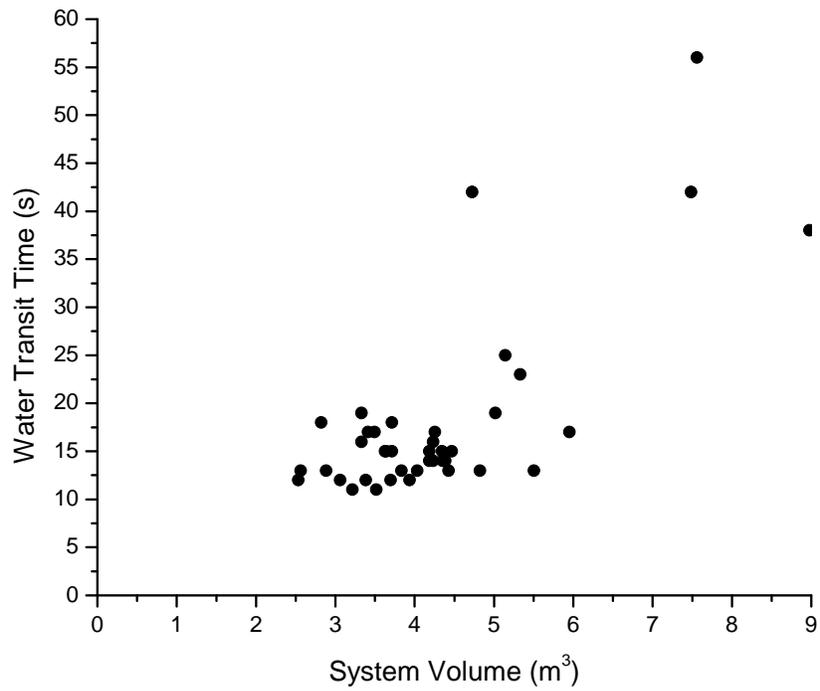


Fig. 5. Water transit time vs. system volume.

SUMMARY

When ambient conditions are not appropriate to employ a wet-sprinkler system, a dry-pipe system is commonly used. In order to mitigate potential fire losses associated with a water delay time in the dry systems, there are a few restrictions governing the maximum allowable water delay times in dry-pipe system design. One of them is the 30-seconds maximum water delivery time in Class 2 materials on open racks over 7.6 m high under 12-m high ceiling.

A computer program developed at FM Global had been used to evaluate dry-pipe systems installed on the 12-m high ceiling of industrial freezers for over the last 15 years. The program was successfully used to aid system designs so that the systems could satisfy the 30-seconds water-delay time limitation. Cases introduced in this paper show many ways that one can design to reduce the total water delivery times in real systems. The program also was used in determining performance-based heat detector spacing when a heat detector actuates a pre-action valve in a dry-pipe system. The water transit time in the given system must be compared with the actuation time of the pre-action valve with different heat detector spacing and thus the computational ability of a water transit time play a critical role in determining the maximum heat detector spacing [8].

The cases given in this paper show that the air trip time is linearly proportional to the system volume provided that other operating conditions are comparable. The water transit time also in general increases as the system volume increase. However, the dependency is not as straight forward as that in the air trip time as the system configurations play a dominant role in determining the water transit time. By adjusting many operating parameters, systems could have met the water delivery time restriction in very cost effective ways. The practice showed that having a tool similar to the program introduced in this paper would help design dry-pipe systems in a very efficient manner to meet fire safety standards.

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