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Literature Survey on Drop Size Data, Measuring Equipment, and A Discussion of the Significance of Drop Size in Fire Extinguishment

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Revised Edition

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Gaithersburg, MD 20899

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LITERATURE SURVEY ON DROP SIZE DATA, MEASURING EQUIPMENT, AND A DISCUSSION OF THE SIGNIFICANCE OF DROP SIZE IN FIRE EXTINGUISHMENT

Abstract

The literature was searched for information on the size of water droplets from fire fighting equipment, on instrumentation and techniques for measuring droplet size in dense sprays, and on the significance of droplet size in water sprays used for fire extinguishment. From the information on drop size analyzers gathered, it is likely that analyzers using a shadowgraphic method to measure drop size are best suited for drop size measurements in water sprays from fire hose nozzles. The effects of droplet size in water sprays used for extinguishment in confined and unconfined spaces and with and without counterflowing air currents are discussed.

1. INTRODUCTION

This literature survey was conducted to obtain technical information related to fire suppression with water sprays. Technical publications dealing with water spray formation, water spray measurement, and fire extinguishment tests were sought. Special effort was made to find data on drop size distributions produced by 1-1/2 inch fire hose nozzles. This literature search was initiated with computer searches of the following indexes, the descriptions of which are in the appendix:

(1) INSPEC - Information Services in Physics, Electrotechnology, Computers and Control

(2) NTIS - National Technical Information Service

(3) BHRA - British Hydromechanics Research Association

(4) COMPENDEX - The Engineering Index

(5) TRIS - Transportation Research Information Service

(6) POLAB - Pollution Abstracts

The computer search was followed by manual searches of the Engineering Index for the years 1955 through 1969 to complement the computer search of COMPENDEX, The Building Research Establishment References to Scientific Literature on Fire for the years 1950 through 1980, and the NBS Fire Research Information Service subject file. Lastly, telephone discussions were held with the following: two staff people in college fire protection curriculum, three people on the NFPA fire hose committee, two technical people with companies manufacturing hose nozzles, two federal fire researchers outside of NBS, a fire researcher in the Building Research Establishment in England, two federal aerodynamic engineers, and several people in industry doing droplet analyses and droplet measuring research.

As a result of the index searches and telephone discussions, nine books, twenty-six reports, thirty-four articles, and two standards were identified and reviewed. Only those discussed are cited, but the remainder are included in the bibliography.

2. LITERATURE SEARCH

2.1 The Search for Existing Data

The search for existing data on droplet size of sprays from fire hose nozzles yielded only one document, the summary of which follows. Savage and Freeman [1] reported the results of their drop size measurements in sprays from nozzles used in the extinguishment of fully developed room fire tests of Hird [2]. The fog nozzles were of the impinging jet type. This means that the nozzle was designed to direct pairs of jets to collide exterior to the nozzle to form the spray. The aforementioned nozzles were operated at 552, 1551 and 3147 kPa (80,225 and 500 psi) pressure and with flow rates of 1.14, 3.41 and 5.68 m^3/s (5, 15 and 25 gpm). The orifice size was held constant at 1.59 mm (1/16 in), and therefore, the flow rate was varied by changing the number of pairs of jets. The technique for determining drop size was one of collecting samples at selected points in the spray pattern in shallow glass dishes containing a layer of castor oil, making contact photographs of the dishes filled with droplets, projecting the photographs for enlargement, and measuring the image sizes with a template.

The following table was extracted from their report. The values are weighted for volume distribution of the water within the overall spray pattern from the nozzle.

Mass-Median Drop Size (μm)

Flow (m^3/s)	Pressure (kPa)		
	552	1551	3147
1.14	550	390	320
3.41	850	620	610
5.68	540	590	540

Unfortunately, the nozzle here characterized is not of a type commonly used for fighting fires in the United States. Most of the fog nozzles used in this country generate droplets by impaction of the hose stream with a plate within the nozzle.

The technical people working for fire hose nozzle manufacturing companies who were contacted by telephone did not reveal any results of drop size distribution measurements they have taken on their own nozzles or others.

2.2 The Search for Measurement Apparatus

The search for information on droplet size measurement apparatus was much more fruitful. The recent interest in energy conservation has intensified resarch in the measurement of droplet size and velocity even more so than did spray drying in previous years. Spray drying is a process that has been found very useful for generating many powdered materials such as instant coffee from solutions. The interest in droplet size related to energy conservation is in the development of fuel spray nozzles for improved combustion efficiency. The interest in such spray characteristics is not just of recent times, but rather a revival prompted by more recent improvements in measurement technology. Jones [3] wrote a comprehensive review of the methods for measuring droplet size in dense fuel sprays, which he defined as droplet concentrations in excess of one drop per cubic millimeter. He described most of the known mechanical, electrical and optical methods. The mechanical methods include droplet capture on slides coated with powders, or in pools of immiscible liquids like that used by Savage and Freeman [1], cascade impactors, freezing, and sedimentation, the electrical methods include gapped electrodes, charged wires and hot wire anemometers and the optical methods include high speed photography, holography and laser defraction. Fifty references are cited.

Azzopardi [4] subsequently published a much more comprehensive review in which he divided the droplet size measurement methods into the following categories: photographic, impact, thermal, electrical, optical, time of residence, and indirect via velocity. He further tabulated the methods with regard to their characteristics which included whether they provided number or mass flux data, single particle or cloud average counting, size distribution or mean size, and temporal or spatial distribution. The size range, disadvantages, advantages and references for each method are given. One hundred and thirty-one references are cited.

Chigier [5] followed with an extremely comprehensive review of drop size and velocity instrumentation. The main focus of this review however, was on optical methods such as holography, laser doppler anemometry (LDA) and laser transit anemometry (LTA). It also discussed a phase discriminating sampling probe that withdraws samples isokinetically and even briefly mentioned still and motion photography, and high speed video. Forty-five references are cited.

Not mentioned in any of these reviews but worthy of note is the work of Semiat [6] who simplified the formation of a laser beam interference fringe pattern with use of a Ronchi grid. A Ronchi grid is a glass plate with equally wide alternating clear and opaque lines. When the grid is placed in a laser beam, the identical pattern is transmitted. An interesting feature of this technique is that crossed grids allow for the measurement of two-dimensional velocities.

It is evident from the number of fundamentally different methods of measuring droplet size here mentioned that there are numerous pieces of apparatus in existance. Improvements in signal acquisition and processing and miniaturization of computers have greatly simplified the process of obtaining droplet analyses of sprays. Even one of the oldest methods, photography, has attracted new interest because of the advent of image analyzers which digitize video images. Many of the pieces of apparatus were, however, not studied in detail by this author simply because they lacked provision for or because of the anticipated complexity of providing protection of the electronic and optical elements from the environment accompanying the production of sprays produced by some of the equipment of interest. The reader is reminded that fuel sprays for internal combustion engines are only a few hundred cubic centimeters in volume, and therefore very different from sprays that fill entire rooms for fire extinguishment. As one would expect, tradeoffs must be made.

Equipment that will measure drop size distributions of sprays from aerosol cans usually will not do so for sprays from fire hose nozzles and vice versa. Holographic equipment will capture action in very large volumes of space but obtaining a droplet size distribution analysis from the hologram is very laborious. The hologram like a 35 mm camera slide must be used to reconstruct (project) with use of a laser light source the captured image into space. The reconstructed object must then be manually analysed with use of a telescopic type lens system with a drop sizing reticule and this must be done plane by plane through the volume. Equipment that will analyse clouds of drops by use of Fourier transform lens focussing of diffraction patterns from each drop in the cloud onto a specially patterned detector is very good for quickly obtaining drop size averages from fairly large volumes of spray. This type of equipment does not, however, allow one to view the drops being measured or to obtain drop velocities. Shadowgraphic equipment that automatically will perform the laborious process of calculating the droplet size distributions usually will do so for only a small slice of the spray patterns at a time, and therefore, one must systematically take many samples of the whole pattern or part of the pattern for symetrical sprays. The size of the volume into which the sample can be placed also is important when one may want to include sources such as flames and hot surfaces that generate counterflows that would interact with extinguishment sprays.

Drop analyzers that use the shadowgraph technique, with a strobe light source and video monitoring and recording of individual drops are probably best suited for studying water sprays from fire fighting equipment. Images from individual drops ranging in size from 8 to 10,000 μm may be digitized and then sized and counted as directed by accompanying software which then can analyze the data and provide arithmetic, surface, volume, weight and Sauter mean diameters and size distributions. The addition of a multiple strobe feature can also provide the capability of obtaining droplet velocity data. Furthermore, it has been demonstrated to measure droplets immersed in propane flames.

3. BACKGROUND MATERIAL

3.1 Mechanisms of Extinguishment and the Effect of Firefighting Techniques

Water probably has been the primary fire extinguishant used by man since he learned to use fire. The delivery of water for the extinguishment of unwanted fires has changed over the years from hand transportation in buckets to flow through hoses supplied by pumps. The form of the water used has changed from bucketfuls to sprays. For many years between the use of bucketfuls and the use of sprays, solid hose streams were used. Thus the main topic related to extinguishment in the fire literature of this period was the transport of water from its source to the fire at a sufficient rate and in sufficient quantity. Nothing was said about the form of the water delivered. Sprays as opposed to solid streams were used but only in automatic sprinkler systems and only for the purpose of distributing the water throughout the space for which the protection was designed rather than for the benefit provided by the state of division of the water.

The earliest discussion advocating the use of sprays consisting of very small droplets of water for manual firefighting was by Lloyd Layman [7] who in 1954 originated the "indirect method of fire attack". The method was devised as a result of experiments in the extinguishment of fuel oil fires in merchant marine ship machinery spaces. Layman directed these experiments during World War II at which time he was Commandant of the U.S. Coast Guard Fire Fighting School. The method proposed that sprays consisting of very small water droplets be injected into confined spaces containing fires. The conclusion drawn from the test results was that the rapid generation of steam within a confined space created a violent atmospheric disturbance within the space. Put a little differently, the rate of evaporation is directly proportional to surface area of the water that is exposed to the heat and for a given volume of water is inversely proportional to the droplet diameters squared. Therefore, the smaller the droplets, the higher the rate of evaporation. The evaporation of water absorbs 2.26 x 10^3 MJ/m^3 (8100 Btu/gal) and is accompanied by a volume expansion of approximately 1700 times the original. The rate and magnitude of the expansion of the water to steam apparently creates great turbulence which contributes to the distribution of the remaining droplets of water to much of the remaining heat in a confined space. The steam displaces a large volume of the air required to sustain combustion in the space and consequently the fire is suppressed.

The National Board of Fire Underwriters [8] subsequently supported a more detailed investigation of the use of finely divided water at the Underwriters Laboratory. For this investigation a test chamber with an approximately one square meter base and approximately two meters in height was constructed of galvanized steel with a removeable top, adjustable vents and a spray port on the sides near the bottom. Nineteen spray nozzles were characterized for droplet size distribution at various water pressures and at various distances from the nozzle. Test fires using 237 mℓ of gasoline, kerosene, or ethyl alcohol were burned in sheet metal pans approximately 150 mm square by 50 or

150 mm deep or 300 mm square by 300 mm deep placed on the floor of the chamber. Fires of small wood piles also were included in the tests. Water sprays from each or some combination of the nineteen nozzles were directed toward the fires from approximately 3 m directly above or horizontally through the side port approximately 250 mm above the floor.

The conclusions were as follows: (1) That these flammable liquid fires were extinguished predominately by dilution of the air supply with water vapor. (2) Up to a point, reducing the droplet size of the water spray is beneficial. (3) Sprays directed down from directly above with droplet diameters less than 150 μm did not extinguish the fires because they were repelled by the fire plume. (4) The same sprays were effective when directed from the side. (5) There was a definite increase in the amount of water required when the droplets were larger than 300 μm. (6) Confining the fire to the burn compartment was a very important factor in the effectiveness of the water spray. (7) Wood fires had a strong tendency to rekindle after the spray was stopped.

Several investigators subsequently concluded that the mechanism of extinguishment of diffusion flames in other than the confined spaces used in the Layman and the National Board of Fire Underwriter Tests was by cooling of the fuel. Bryan's [9] tests of the extinguishment of wood cribs demonstrated that the resistance to extinguishment depended more on the heat content of the fuel than on the rate at which it was generating heat. Rasbash [10] concluded from his extinguishment experiments with pool and wood fires that the best way to extinguish a fire was to assure that the water reach and cool the fuel. He also stated that for most fires the droplet size of the spray was not usually an important factor. He did acknowledge that it was not clear whether room fires were more efficiently controlled by cooling of the fuel or by cooling of the flames. He believed that investigations up to that time had not been systematic enough to allow one to draw conclusions about how the extinguishment mechanisms operate during real room fires. Lacking were data on critical flow rate and quantity of water required.

It is obvious from the aforementioned works that different fire situations require different fire fighting tactics. Cooling of the fuel is the surest method for most situations, but smothering by the displacement of air with water vapor is very effective under certain conditions which have been characterized only as confined. Droplet size must be important because the droplet must have enough momentum to overcome the resistance over the path that it travels and because in many situations it must not evaporate before it reaches the fuel. The waterspray path is dependent upon the available access to the fire, the available equipment, and the firefighter's choice of attack position. The firefighter's preference for position of attack would be up-wind of the fire so that the smoke and heat would be blown away from him and so that the wind would help carry the water spray to the fire. Furthermore, the usual technique for applying water to a fire, excluding the situation of a fire in a confined space, would be to direct the spray at the base of the fire. As the base of the fire recede as the near part of the fuel is extinguished, the spray would be directed to follow it with due consideration of the burning characteristics of other fuel in the direction that the fire was being chased. The latter simply alludes to the fact that air entrained in the spray tends to blow the fire, persisting beyond the area of spray impaction, in the direction of the spray, and that the firefighter will not intentionally cause the fire to be blown toward highly flammable material if it can be avoided. The same consideration would apply to trapped occupants. For intense fires in confined spaces, the technique used initially might be to direct the spray to the upper part of the space from a low level opening. Since the hot gases from a fire tend to concentrate near the ceiling in a confined space, this tactic assures that the maximum amount of water is converted to vapor, a process which absorbs heat and displaces smoke and thereby provides better visability of and accessability to the base of the fire. This type of fire is frequently underventilated, lacking oxygen, when extinguishment is begun and has been known to flash when air currents created by air entrainment in the spray have ventilated the fire. In both of these situations, travel of the spray would probably be aided rather than impeded by currents of air. If however, the wind were to change, or simultaneous attack from other positions chase the fire toward the firefighter, or the firefighter be forced by inaccessibility of a better position to take a position requiring directing of the spray counter to the fire plume, the spray stream would have to be strong enough to overcome the counterflows. Dynamics of sprays are covered in the next section of this report.

3.2 Dynamics of Extinguishment

The relationship between spray momentum and gaseous counterflows has been discussed by several authors. The earliest discussions related to the process called spray drying, a technique for converting solutions or slurries into powders. Lapple and Sheppard [11] published a comprehensive theoretical, mathematical analysis of particle trajectories in a variety of air streams. The interest in this case was in suspending droplets in an air stream for the time required for them to crystallize or dry.

Kalelkar [12], Yao [13], Dundas [14], Liu [15] and Beyler [16] theorized about the interaction of spray droplets and fire plumes as related to automatic sprinklers. All of these authors based their discussions on a balance of forces relationship between a moving droplet and a moving air stream. For the simple case where the drop is falling straight down through an air stream moving straight up the balance of forces may be expressed as follows:

$$m \frac{dv_d}{dt} = mg - \frac{\rho_s C_D A_d v_{ds}^2}{2}$$

where m = mass of the drop (kg)

v_d = velocity of the drop (m/s)

t = time (s)

g = acceleration of gravity (m/s^2)

ρ_s = density of the air stream (kg/m^3)

C_D = drag coefficient of drop

$= f(N_{Re}) = f \dfrac{D_d v_{ds} \rho_s}{\mu_s} = 0.44$ [11]

for $500 < N_{Re} < 200{,}000$ where D_d = diameter of drop (m)

μ_s = viscosity of air stream (kg/m-s)

A_d = largest cross sectional area of drop normal to air stream (m^2)

v_{ds} = velocity of drop relative to air stream (m/s)

Solving for v_d in fire extinguishment sprays is difficult for the following reasons:

1) The motion of the droplets in fire extinguishment is a three-dimensional problem rather than the one-dimensional problem given as the simple case. The thrust of the fire driven air current varies three-dimensionally with location and conditions in the compartment fire even without the disturbing forces that accompany extinguishment. Furthermore, the conditions vary as the characteristics and location of the burning fuel involved change with the progression of the fire.

2) The approximation of the drag coefficient previously given was determined from experiments with single drops rather than the dense clouds of spray associated with extinguishment. One would expect that in a dense spray many drops would be in the wake of others and that the drag in such a situation would be different from that for a single drop, but such a determination apparently has not been made. Of course, evaporation from the many drops in the cloud would raise the water vapor level in the cloud which in turn would reduce the rate of evaporation from the drops which does have an effect on drag. Drag on drops has two components, friction drag and pressure drag. Yuen [17] found that evaporation from water drops always reduces the friction drag. The pressure drag is not affected by evaporation at Reynolds numbers below 20, but at that point it begins to

increase with Reynolds number. He determined that the increase in pressure drag will equal the decrease in friction drag when the Reynolds number reaches 1000 resulting thereafter in increasing total drag. Evaporation also reduces the size of the drop which reduces the cross section of the drop and thereby reduces the drag.

3) The cross section of the drop varies in flight because the shape of the drop oscillates between a teardrop and horizontal ellipsoid. This instability is worse for larger drops.

The spray from a sprinkler is probably the most extreme interaction of an extinguishant and a fire driven counterflow and, therefore, the most difficult to predict. The reason is that the active sprinkler usually is to the side of the vertical axis of the fire where the plume is the strongest.

Thomas and Rasbash have done studies on the characteristics of sprays from fire hose nozzles. Thomas [18] derived a formula for predicting the throw of spray from a fire hose nozzle in the absence of wind from data taken from a NFPA report [20]. The formula is as follows:

$$t = 2.32 + 0.85\, r + 2.15\, a + 0.36\, p + 1.03\, ra$$

where $t = \log_{10}$ throw (m)

$r = \log_{10}$ flow rate (m^3/s)

$a = \log_{10} \dfrac{\tan(\text{total spray cone angle})}{4}$

$$p = \log_{10} \frac{\text{pressure(KPa)}}{100}$$

Rasbash [19] discussed penetration of spray to the "seat of the fire" as affected by drop size, thrusts of the spray and of the fire plume, the wind, and gravity. For example, the critical spray "thrust" (i.e. its spray momentum per unit area at the flame) to just penetrate the flame from above was suggested by Rasbash [19] to be related to the flame height as follows:

$$T_c = 0.5\ \rho\ g\ x$$

where T_c = critical thrust (N/m^2)

ρ = density of air (Kg/m^3)

g = acceleration due to gravity (m/s^2)

x = height of flame prior to spray (m)

One can then use the following relationship between flame height and heat release rate as determined by McCaffrey [21] to determine this critical thrust in terms of heat release rate:

$$x = 0.2\ Q^{2/5}$$

where x = flame height (m)

Q = heat release rate (kW)

Rasbash [19] also determined that the spray thrust from a nozzle was related to reaction of the nozzle in the following manner.

$$\text{Spray thrust} = R/A = CP^{0.5}F/A$$

where R = nozzle reaction force

A = cross sectional area of the spray at the plane of interest

P = nozzle pressure

F = nozzle flow rate

C = a nozzle constant

He also made the very interesting statement that the spray thrust was entirely converted to momentum of the entrained air stream within about six feet of the spray nozzle. Purington [22] gives a relationship to estimate spray nozzle reaction in terms of flow rate. The above relationships give some sense of the factors influencing the dynamics of water sprays in fires.

4. CONCLUDING REMARKS

The extinguishment of room fires is a very complex phenomenon. The literature suggests that the strategy for the majority of fires should be to cool the fuel rather than smother the flame. This is in spite of the fact that most unwanted fires are already in a ventilation controlled stage when extinguishment is begun [23, 24]. Water must reach the fuel to cool it. Most of the theoretical and experimental work thus far has dealt with penetration of the fire plume by water spray. This itself is a very complex problem because of the variability encountered in the burning characteristics and arrangement of combustible furnishings, the ventilation characteristics of the space, the difficulty of dealing with the three-dimensional motion of both the droplets in the water spray and the fire driven counter air currents, and the reaction of the fire to the extinguishment process.

To apply existing knowledge of extinguishment dynamics to real life fire fighting requires more information on the drop size and velocity distributions from hose nozzles. This report identifies available techniques for the measurement of nozzle spray characteristics, and contains a literature bibliography on the subject, and on the research studies of the dynamics of water sprays on flames.

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APPENDIX

Computer Indexes

1. INSPEC (Information Services in Physics, Electrotechnology Computers and Control) corresponds to the three Science Abstracts printed publications. Electrical and Electronics Abstracts, Computer and Control Abstracts, and Physics Abstracts.

2. NTIS (Dialog Information Retrieval Service) The database consists of government sponsored research, development, and engineering reports as well as other analyses prepared by government agencies, their contractors or grantees.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The literature was searched for information on the size of water droplets from fire fighting equipment, on instrumentation and techniques for measuring droplet size in dense sprays, and on the significance of droplet size in water sprays used for fire extinguishment. From the information on drop size analyzers gathered, it is likely that analyzers using a shadowgraphic method to measure drop size are best suited for drop size measurments in water sprays from fire hose nozzles. The effects of droplet size in water sprays used for extinguishment is confined and unconfined spaces and with and without counterflowing air currents are discussed. This report supersedes the January 1985 edition (NBSIR 85-3100).

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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