Analysis of Fire Suppression Jet Accumulation Characteristics: Effect of Varying Nozzle Pressure, Flow Rate, and AFFF Concentration

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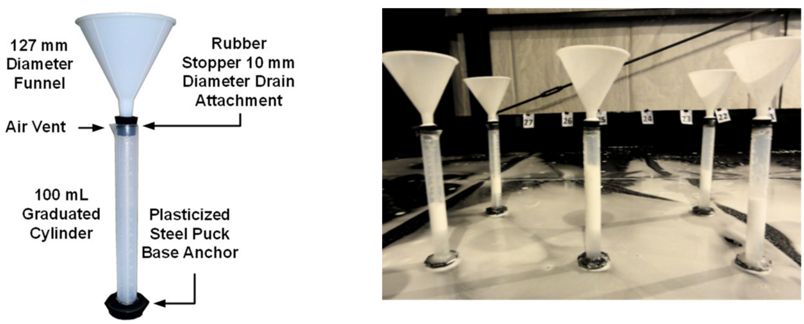
Abstract

Modern firefighting agent application methods use a range of delivery techniques to optimize the extinguishment process for various firefighting scenarios. Experiments were conducted to quantify how firefighting jet agent accumulation is affected by variation of nozzle pressure, flow rate, and aqueous film-forming foam (AFFF) concentration. Agent coverage area, reach, span, and foam expansion ratio were measured responses. Optimal values of these parameters are application specific and driven by fire type, dimension, and length scale. For full-scale aircraft rescue firefighting (ARFF) applications, a foam expansion ratio between 3:1 and 15:1 is typically sought. Sub-scale data were collected on jets ranging from 1 to 11 MPa (150 to 1,550 $lb \cdot in^{-2}$) and 4 to 25 $L \cdot min^{-1}$ (1 to 6.4 $gal \cdot min^{-1}$) at AFFF concentrations ranging from 0 (water) to 12 percent by volume using three-percent MIL-SPEC AFFF. Agent coverage area, reach, and span exhibited a descending degree of dependence on nozzle pressure, flow rate, and AFFF concentration, respectively. Foam expansion ratio, conversely, demonstrated an ascending degree of dependence on those same respective parameters. Full-scale data were collected on jets with the same range as tested sub-scale pressures, but at a constant flow rate of 76 $L \cdot min^{-1}$ (20 $gal \cdot min^{-1}$) with zero (water) and six percent by volume AFFF concentrations. Full-scale data supported the same trends observed at sub-scale. However, measured response sensitivity varied significantly by comparison. Further study at full-scale is recommended to better understand the impact of these parameters on delivery performance. Changes in nozzle type and aspiration method should also be investigated.

Keywords: firefighting agent, fire suppression, AFFF, ground pattern, foam expansion ratio, firefighting jet performance

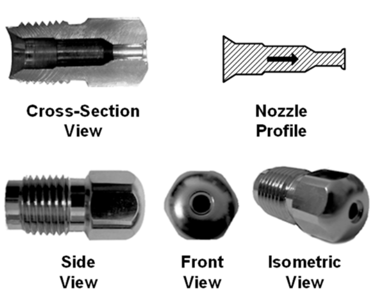
Test set-up

Sub-scale experiments were conducted in a 13.7×3.7×0.3-m (45×12×1-ft) fire suppression jet containment bed marked with dots orthogonally spaced 30.5 cm (1 ft) apart to serve as a location reference for agent collection devices. Modified 100-mL graduated cylinders outfitted with 127-mm (5-in) diameter funnels were placed to encompass the two-dimensional (2-D) jet footprint and measure agent accumulation. A self-similar family of non-air-aspirated 6.4-mm (0.25-in) Stoneage Waterblast Tools® AP4™ nozzles was used for all experiments. This nozzle was used because of its simple geometric profile and ability to span the delivery range of the sub- and full-scale fire suppression systems employed in this study. Fig. 1a shows the design of an agent collection device, and Fig. 1b shows a sub-scale foam expansion ratio measurement in progress. Fig. 2a shows the AP4 nozzle geometry, and Fig. 2b shows an overview of the jet containment bed. Full-scale experiments were conducted in an alternate 24.3-×24.3-×9.8-m (80-×80-×32-ft) facility using the same approach, but with scaled up 1000-mL collection devices. Full-scale measurements were collected along the jet centerline only.



(a) (b)

Fig. 1. (a) The agent collection device; (b) 6 % AFFF agent capture.



(a) (b)

Fig. 2. (a) The AP4 test nozzle; (b) Jet containment bed.

Test procedure

A flow deflector was used to initially divert agent away from the agent collection devices to avoid measuring underdeveloped jet flow. Once quasi-steady flow was achieved, the deflector was removed and the agent collection devices were allowed to fill. Water jet accumulation was determined by recording the collected water volume observed in each graduated cylinder. Foam expansion ratio was determined using a similar method presented in NFPA 412 by dividing the observed foam volume by the foam mass collected [1]. Three-percent MIL-SPEC AFFF proportioned at six-percent by volume with water was used to represent baseline AFFF jet conditions. This AFFF setting was chosen because modern high pressure fire supression jets often deliver AFFF at that proportion, with some citing the production of a more stable foam blanket [2]. Because different delivery conditions affected flow trajectory, accumulation times were optimized for each case to maximize the measurement accuracy for each configuration. Sub-scale cases involving jets of combined medium pressure and flow rate or greater used a staggered measurement pattern everywhere but the centerline. Skipped measurement locations were linearly interpolated from surrounding measurement locations. Experiments were replicated three times and averaged for each measurement location.

Sub-scale results

Sub-scale accumulation results comparing water and six-percent AFFF jets are summarized in Figs. 3a through 3c. Table 1 summarizes the delivery conditions presented in those respective plots.

Table 1. Sub-scale agent delivery parameters.

Case Reference	**Flow Rate**	**Nozzle Pressure**
Low Pressure-Flow Rate	4.20 $L{\cdot}min^{-1}$ (1.11 $gal{\cdot}min^{-1}$)	1.20 MPa (174 $lb{\cdot}in^{-2}$)
Medium Pressure-Flow Rate	12.9 $L{\cdot}min^{-1}$ (3.41 $gal{\cdot}min^{-1}$)	5.85 MPa (849 $lb{\cdot}in^{-2}$)
High Pressure-Flow Rate	19.8 $L{\cdot}min^{-1}$ (5.23 $gal{\cdot}min^{-1}$)	10.6 MPa (1540 $lb{\cdot}in^{-2}$)

Water jet coverage area, maximum reach, and maximum span increased an average of 449, 128, and 592 percent, respectively, from low to high nozzle pressures at constant flow rate. Those parameters increased an average of 152, 121, and 150 percent, respectively, between low and high flow rates at constant nozzle pressure. AFFF concentration negligibly affected coverage area and reach. However, span increased at low nozzle pressures and contracted at high nozzle pressures. Fig. 3d illustrates the relationship between foam expansion ratio and AFFF concentration at sub-scale, indicating a monotonic rise in foam expansion ratio as AFFF concentration increased. Figs. 4 through 9 show sub-scale contour plots comparing water jet agent accumulation and six-percent AFFF jet foam expansion ratio at the same nozzle pressure and flow rate conditions. These patterns indicate the local foam expansion ratio increases as agent accumulation increases. Figs. 4 through 9 also illustrates that increased nozzle pressure also increased agent distribution uniformity.

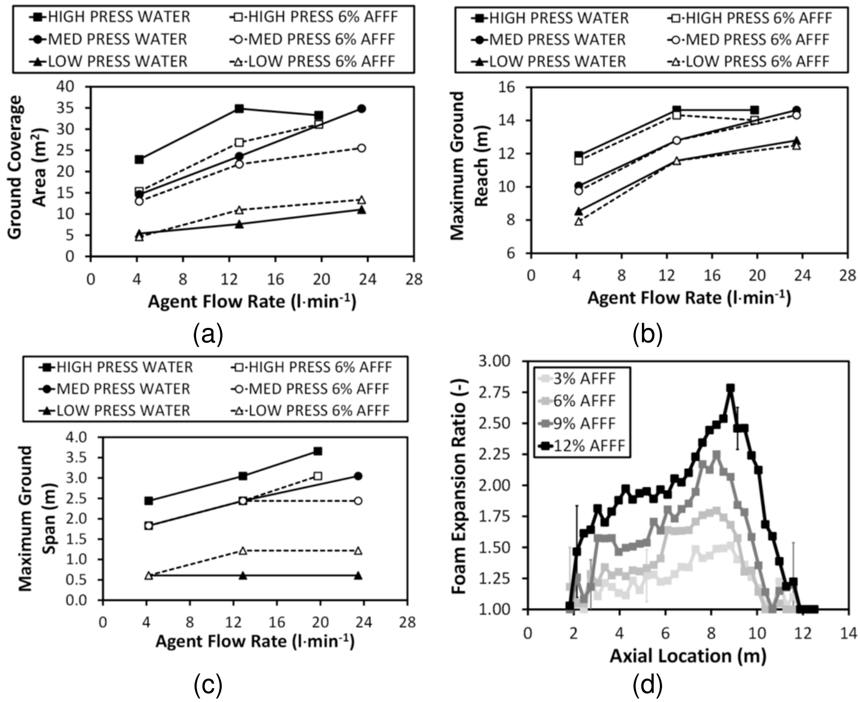


Fig. 3. Sub-scale test summary:
(a) ground coverage area, (b) max. reach,
(c) max. span vs. agent flow rate,
(d) foam expansion ratio vs. axial location for medium pressure-flow rate AFFF jets.

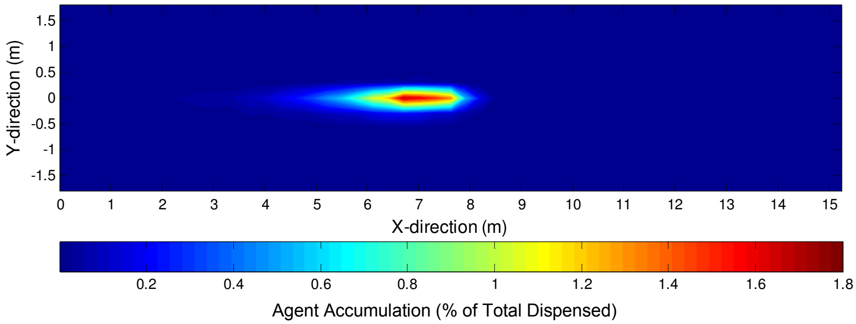


Fig. 4. Low pressure-flow rate water jet agent accumulation plot.

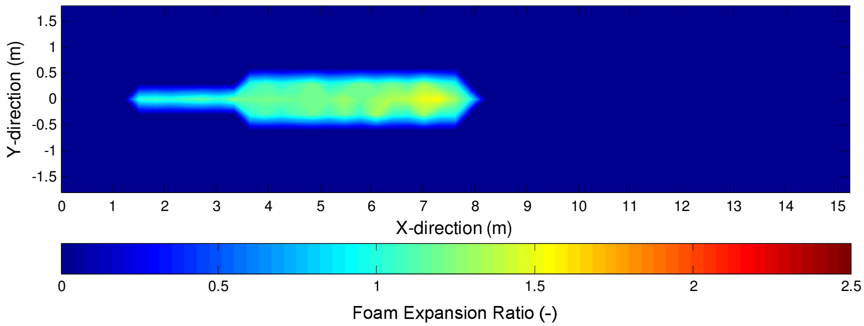


Fig. 5. Low pressure-flow rate 6% jet foam expansion ratio plot.

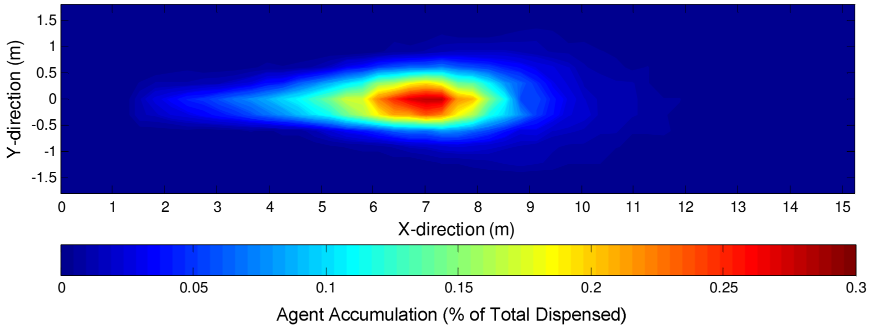


Fig. 6. Medium pressure-flow rate water jet agent accumulation plot.

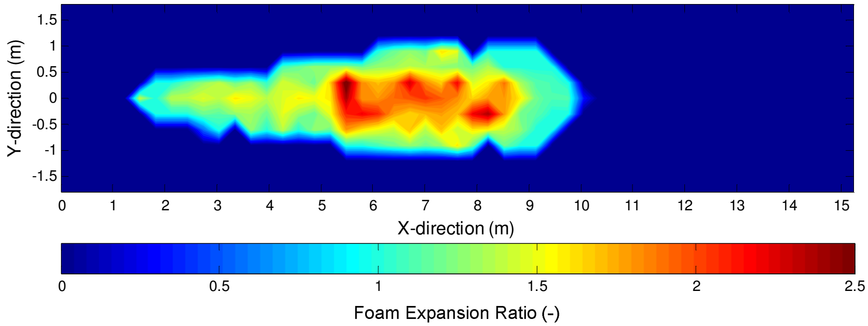


Fig. 7. Medium pressure-flow rate 6% jet foam expansion ratio plot.

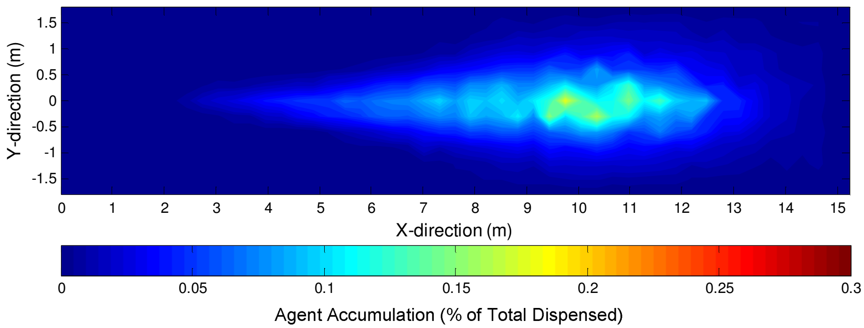


Fig. 8. High pressure-flow rate water jet agent accumulation plot.

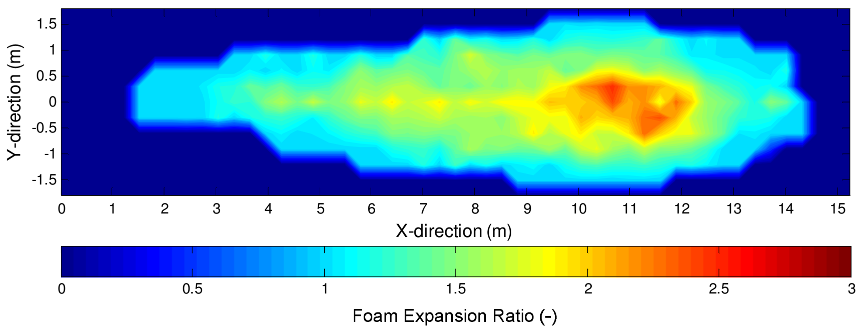


Fig. 9. High pressure-flow rate 6% jet foam expansion ratio plot.

Full-scale results

Full-scale centerline results of water jet accumulation and foam expansion ratio of six-percent AFFF jets are shown in Fig. 10. Table 2 summarizes the delivery conditions presented in those respective plots. Full-scale results supported sub-scale trends. However, full-scale foam expansion ratio increased over 200 percent compared to sub-scale results.

Full-scale foam expansion ratio measurement also exhibited greater sensitivity to nozzle pressure, significantly decreasing while nozzle pressure increased.

Table 2. Full-scale agent delivery parameters.

Case Reference	Flow Rate	Nozzle Pressure
Low Press	75.7 $L \cdot min^{-1}$ (20 $gal \cdot min^{-1}$)	1.06 MPa (154 $lb \cdot in^{-2}$)
Med Press	75.7 $L \cdot min^{-1}$ (20 $gal \cdot min^{-1}$)	5.89 MPa (855 $lb \cdot in^{-2}$)
High Press	75.7 $L \cdot min^{-1}$ (20 $gal \cdot min^{-1}$)	10.5 MPa (1530 $lb \cdot in^{-2}$)

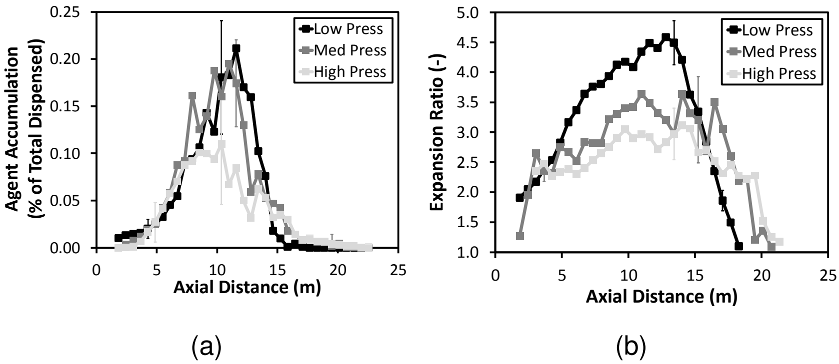


Fig. 10. Full-scale test summary: (a) water jet accumulation vs. axial location (b) foam expansion ratio vs. axial location.

Conclusions and recommendations

Fire suppression jet accumulation characteristics exhibited a strong dependence on nozzle pressure, flow rate, and AFFF concentration for the jet flow conditions investigated. Nozzle pressure most significantly impacted jet coverage area and span, and flow rate most significantly impacted jet reach and foam expansion ratio. The presence of AFFF had a negligible effect on coverage area and reach, and a minor effect on span.

Foam expansion ratio significantly increased as the amount of local agent accumulation increased, which was mostly governed by flow rate and somewhat less by nozzle pressure due to its effect on agent distribution uniformity. Foam expansion ratio of AFFF jets was also strongly affected by change in AFFF concentration. Because AFFF had minor impact on coverage area and overall ground dimensions, it is speculated that foam expansion ratio is also influenced by agent droplet-surface interactions that occur during ground accumulation as AFFF jet droplets coalesce to form a foam blanket. Further experiments are recommended to characterize the near-field agent accumulation process.

NFPA 412 requires non-air-aspirated fire suppression systems to reach a 3:1 minimum foam expansion ratio [1]. This was easily achieved by the AP4 nozzle at full-scale, but fell slightly short at sub-scale. Additional nozzle types, aspiration methods, and fire suppression systems should be analyzed to collect data on a wider range of jet flow conditions. Data should be collected particularly at greater flow rates to analyze the agent delivery performance of fire suppression systems mostly in use. In addition, fire suppression jet agent accumulation characteristics should be evaluated in tandem with fire extinguishment effectiveness to determine optimal agent application guidelines for fire environments of interest.

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References

[1] NFPA 412: Standard for Evaluating Aircraft Rescue and Fire Fighting Foam Equipment. National Fire Protection Association (NFPA). 2014 Edition.

[2] G. Noll, Ultra High Pressure Firefighting Technology, Fire Engineering, Vol. 165, Issue 11, p. 83, November 2012.