UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

ADVANCEMENTS IN UNDERSTANDING WATER-MIST SYSTEMS: FROM SPRAY CHARACTERIZATION TO REAL-SCALE APPLICATIONS

Paolo E. Santangelo [a], Paolo Tartarini [b], Massimiliano Bettati [c]

[a] *Department of Fire Protection Engineering, University of Maryland, USA*
[b] *DIEF, Università degli Studi di Modena e Reggio Emilia, Italy*
[c] *Bettati Antincendio S.r.l., Italy*

Agenda and Problem Statement

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Task 1 – Spray Characterization

- What are the discharge characteristics of water-mist sprays issued by commercial nozzles?
- What physical parameters are to be investigated to quantitatively assess their performance?
- What spray-related mechanisms are of significant interest in determining suppression?

Task 2 – Suppression in Full-Scale Scenarios

- How does the spray actually perform against a real-scale severe fire case?
- What parameters are to be measured to quantitatively evaluate suppression performance?
- How is suppression performance influenced by the introduction of additives to water?

Task 1 – Motivation

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

TO PROVIDE A DETAILED CHARACTERIZATION OF WATER-MIST SPRAYS IN TERMS OF **DROP-SIZE DISTRIBUTION** AND **SPATIAL DISPERSION**

FIRE PROTECTION ENGINEERING

STANDARDS (NFPA, UL, etc.) and **DESIGN** (number/height of nozzles, etc.)

HEAT TRANSFER
(Suppressing agent with surroundings, solid walls, etc.)

SUPPRESSION MODELS
(Physical/analytical, CFD)

FLUID DYNAMICS
(Flow/flame interaction, jet penetration, etc.)

DISCHARGE CHARACTERISTICS OF THE SPRAY

Background and Recent Advancements

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Main References:

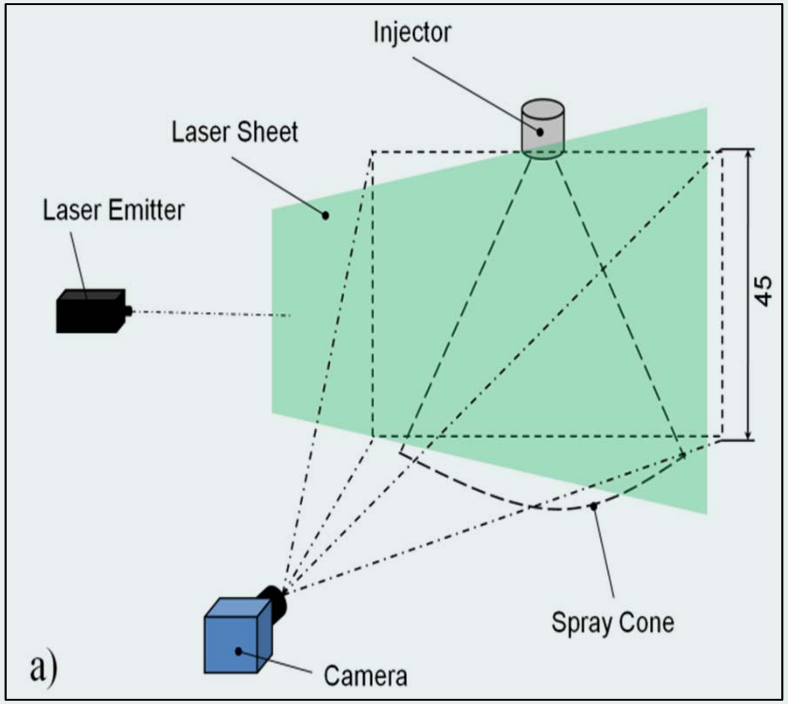
- **Wang et al.**, Exp. Fluids 33 (2002) 587-593. Low pressure (2-8 bar), PIV + Digital-Image Processing. Main results: drop size and velocity distribution at 1 m distance from the orifice. Other: breakup length.
- **Paulsen Husted et al.**, Fire Saf. J. 44 (2009) 1030-1045. High pressure (100 bar), hollow- and full-cone nozzles, PIV and PDA. Main results: comparison of these techniques, drop size and axial velocity in the initial region of the spray.
- **Santangelo**, Exp. Therm. Fluid Sci. 34 (2010) 1353-1366. High pressure (60-80 bar), full-cone nozzle, *Malvern Spraytec*, PIV, mechanical patternator. Main results: drop-size and flux distribution at 1 m distance from the orifice, velocity field and spray-cone angle in the initial region of the spray. Other: breakup length.
- **Santangelo et al.**, Proc. IMECE2011 6 (2011) 1167-1174. High pressure (80 bar), hollow-cone nozzle, *Malvern Spraytec*, PIV, mechanical patternator. Main results: drop-size axial trend from the orifice throughout 1-m distance, initial velocity, parametric analysis.

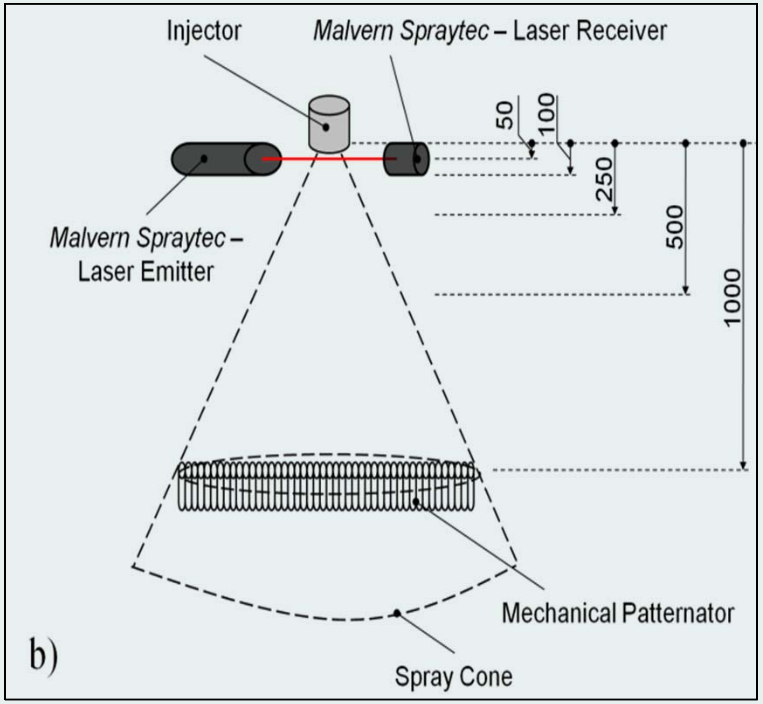
Recent Developments:

- Drop-size axial evolution: potential **coalescence** and **secondary atomization**.
- **Initial velocity** and **cone angle** for hollow-cone water-mist sprays.
- **Parametric analysis** comparing different orifices (flow number, outlet diameter).

Experimental Setup for Spray Analysis

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

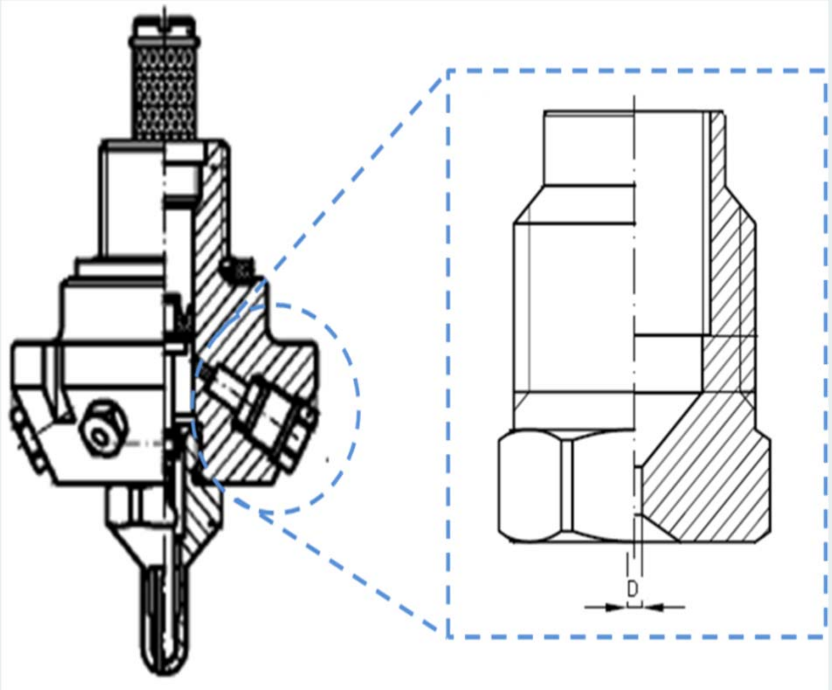




Sketch of the experimental apparatus:
a) PIV setup (velocity field and spray-cone angle);
b) *Malvern Spraytec* and mechanical patternator (droplet size).
All dimensions are in mm.

Employed Nozzles and Injectors

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)



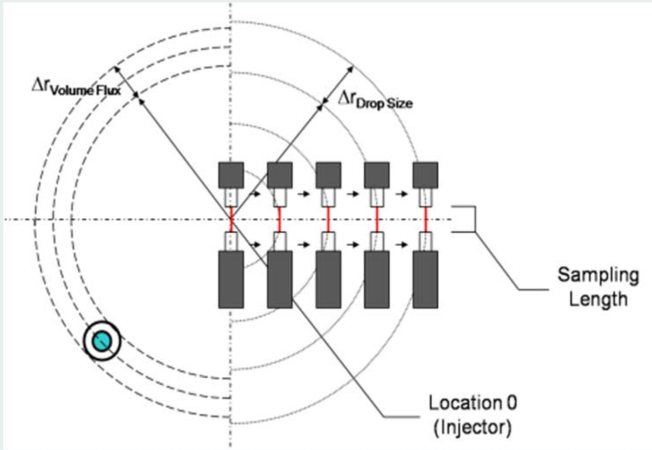
CJX series by *Bettati Antincendio S.r.l.* (pressure-swirl atomizers, hollow-cone sprays), here operated at 80 bar (pressure right upstream the injector)

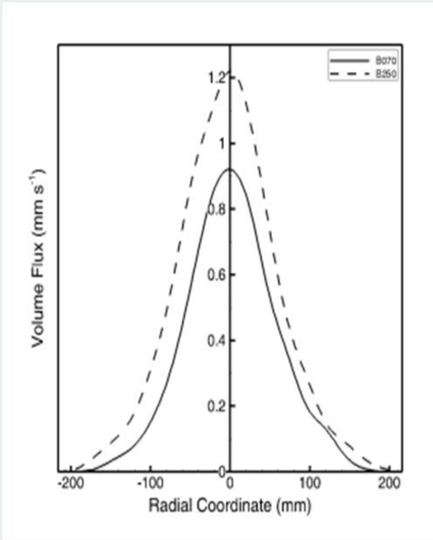
Injector	Orifice Diameter (mm)	Flow Number (lpm bar $^{-0.5}$)
B070	0.49	0.1167
B250	1.14	0.4167

Drop-Size Experimental Procedure

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

- Radial symmetry of the spray is assumed as a simplifying hypothesis.
- At 5, 10, 25 and 50 cm distance from the injector outlet, the drop-size distribution consists of the crude *Malvern Spraytec* results along a generic diameter.
- At 1 m distance from the injector outlet, a flux-based weighting procedure is employed to reconstruct the overall drop-size distribution, thus overtaking the biasing effect due to the mismatch between the geometric shape of *Malvern Spraytec* sampling volume and the spray cross section.
- Volume flux is yielded by patternation tests.



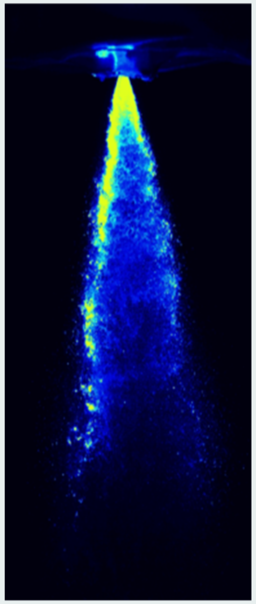


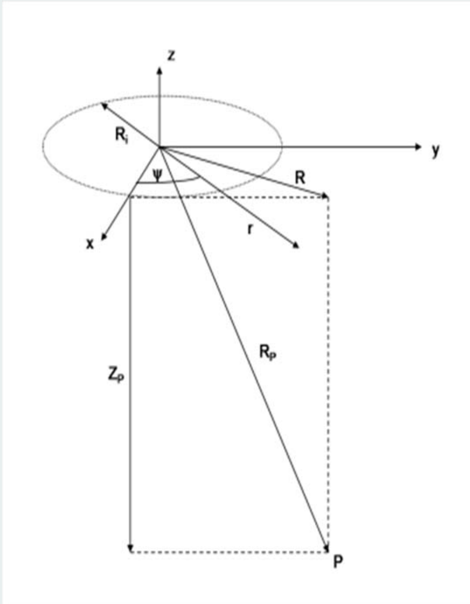
Equation to reconstruct the volume fraction pertaining to the *i*th drop size over all the *j* measurement locations:

$$V_i'' = \sum_{j=1}^{N} q_j'' \cdot \frac{1}{\rho_L} \cdot \frac{\Delta r}{R} \cdot VF_{i,j}$$

PIV Analysis: Parameters and Procedure

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)





- The PIV apparatus features a 30 mJ pulsed-Nd:YAG laser (by *Dantec Dynamics*), a thermo-electrically cooled CCD camera (14 bit, 4 Mpixels) and a post-processing software (by *LaVision*).
- Measurements have been taken at 4 Hz frequency, with a time interval of 5 μs between two exposures of the same pair.

➢ No seeding has been added: droplets constitute tracking particles themselves.

➢ Only axial and radial velocity components have been considered, because the tangential tends to collapse onto this latter within few millimeters downstream the outlet.

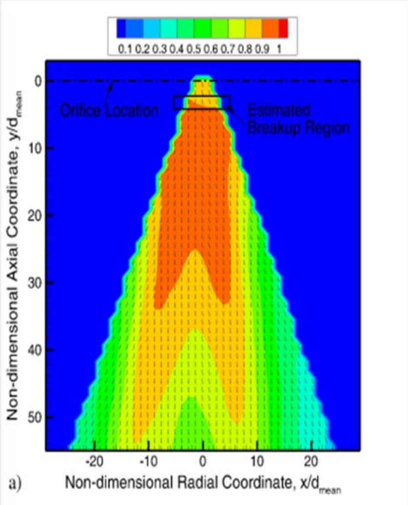
➢ LSV (Laser Speckle Velocimetry) has been employed to process images in the highly-saturated region (axially stretching over about 5 mm from the orifice).

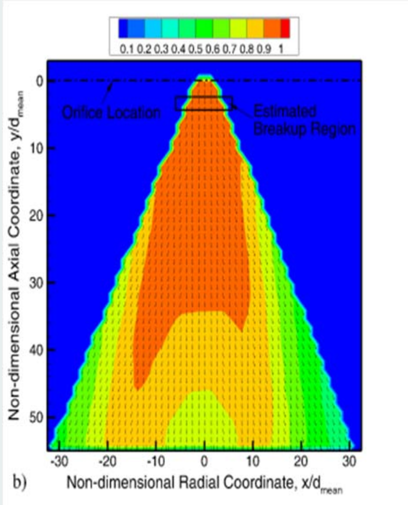
➢ Results upstream the breakup location are to be considered as unreliable (continuum flow).

➢ The velocity field has been reconstructed over a set of 300 images.

PIV Results: Velocity Maps and Profiles

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

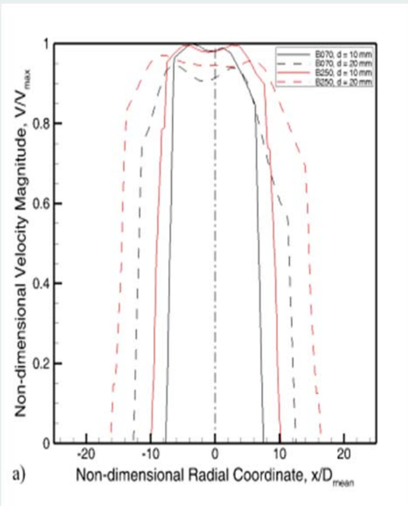


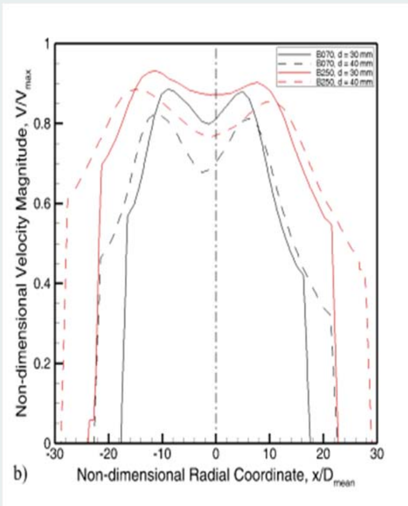


Map of velocity magnitude for

a) *B070* ($V_{max} \approx 101$ m s^{-1}) and

b) *B250* ($V_{max} \approx 85$ m s^{-1}) injectors





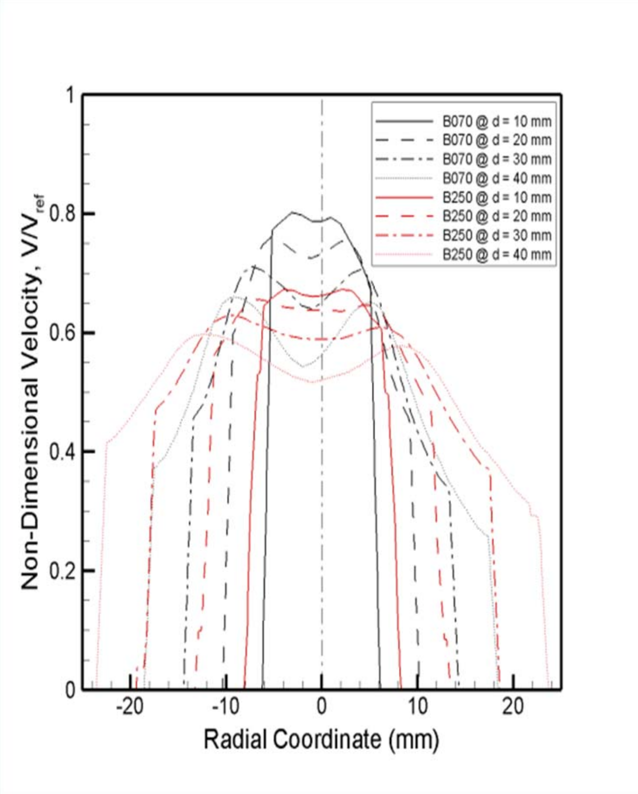
Radial velocity profiles in the region

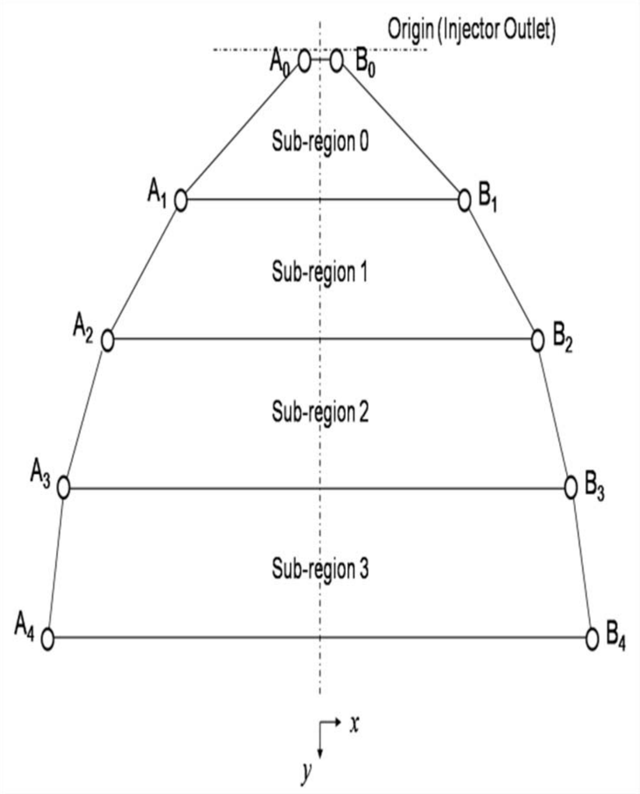
a) close to the orifice (10-20 mm) and

b) far from the orifice (30-40 mm).

PIV Results: Evaluation of Spray-Cone Angle

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)



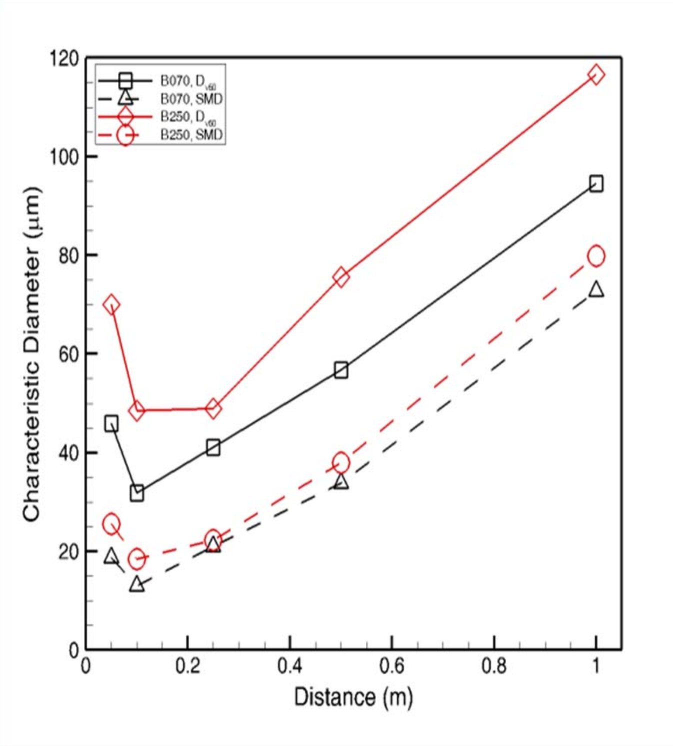


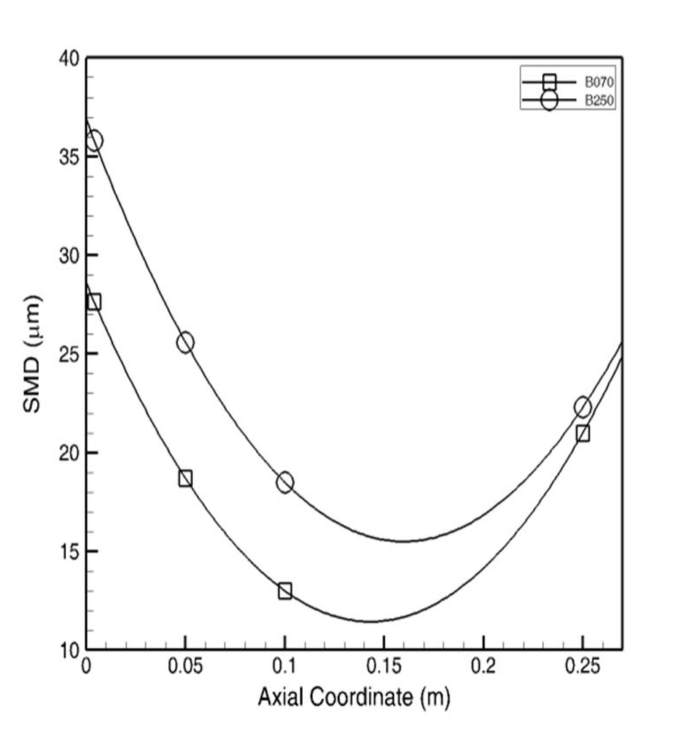
The cone boundary is identified by radial locations (x) where velocity magnitude turns into 0

$$\theta = arctan \frac{|x(A_{k+1}) - x(A_k)|}{|y(A_{k+1}) - y(A_k)|}, \quad k = 0,1,2,3$$

Drop-Size Experimental Results

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)





- Coalescence phenomena appear to govern droplet size after secondary atomization has occurred (about 15 cm downstream the outlet).
- The same qualitative drop-size trend is shown by both the injectors, even though larger diameters are generated by the bigger orifice.
- An attempt to extrapolate SMD at the supposed breakup location (4 mm downstream the outlet) has been made through a simple 3^{rd}-degree polynomial curve.

Physical Modeling for Initial Velocity

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

The classic inviscid model developed by Giffen and Muraszew (Atomization of Liquid Fuels, Chapman & Hall, London, UK, 1953) for pressure-swirl atomizers inspired some theoretical analysis to predict velocity and spray-cone angle.

$$sin\theta_{th} = \frac{(\pi/2)C_D}{K\left(1+X^{0.5}\right)}$$

$$K^2 = \frac{\pi^2(1-X)^3}{32X^2}$$

$$C_D = \left[\frac{(1-X)^3}{1+X}\right]^{0.5} \qquad C_D = \frac{FN}{A_o}\left(\frac{\rho_L}{2}\right)^{0.5}$$

$$V_{th} = \frac{Q}{X \cdot A_O}$$

Injector	Theoretical half cone angle, θ_{th} (°)	Experimental half cone angle, θ_{th} (°)	Cone-angle relative error	Theoretical velocity, V_{th} (m s^{-1})	Experimental velocity, V (m s^{-1})	Velocity relative error
B070	16.66	26.90	38.07%	108.63	101.40	7.13%
B250	30.61	35.40	13.52%	90.23	85.39	5.66%

Physical Modeling for Droplet Size

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

The very first physical parameter to be investigated is sheet thickness, which is

$$t = \frac{d_o \cdot \left(1 - X^{0.5}\right)}{2}$$

Rizk and Lefebvre (J. Propul. Power 1 (1985) 193-199) found that initial SMD is proportional to $t^{0.39}$ in pressure-swirl atomizers: this relation was mainly connected to fuel sprays, but results to be correct for water-mist too.

Lefebvre (Atom. Spray Technol. 3 (1987) 37-51) discusses the characteristic diameter as constituted by two contributions:

- **First stage:** disruptive hydro- and aerodynamic forces, $f((Re \cdot We^{0.5})^{-c})$;
- **Second stage:** velocity gradients, $f(We^{-g})$.

Wang and Lefebvre (J. Propul. Power 3 (1987) 11-18) provide an expression for SMD under certain ranges for dynamic viscosity and surface tension:

$$SMD = 4.52 \cdot \left(\frac{\sigma \mu_L^2}{\rho_A \Delta P_L^2}\right)^{0.25} \left(t \cdot \cos\theta\right)^{0.25} + 0.39 \cdot \left(\frac{\sigma \rho_L}{\rho_A \Delta P_L}\right)^{0.25} \left(t \cdot \cos\theta\right)^{0.75}$$

Injector	Theoretical sheet thickness, *t* (mm)	Extrapolated SMD (mm)	$SMD/t^{0.39}$	Modeled SMD	SMD relative error
B070	149.78	27.64	3.92	28.14	1.80%
B250	244.77	35.83	4.19	37.34	4.21%

Task 2 – Main References and Motivation

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

References:

- Experimental and numerical studies on flow-flame interaction of water-mist sprays in simple heptane pool fires (P.E. Santangelo et al., Proc. 14^{th} Int. Heat Transf. Conf. 5 (2010) 571-580);
- Experimental tests of water-mist discharge against high-rise-storage fires, within a highly equipped large-scale facility (P.E. Santangelo and P. Tartarini, Appl. Therm. Eng. 45-46 (2012) 99-107; P.E. Santangelo and P. Tartarini, Proc. 12^{th} Int. Conf. Multiph. Flow Ind. Plants (2011) paper V.4).

Objectives:

- ➢ Challenging water-mist fire-suppression performance in a large-scale and highly hazardous scenario;
- ➢ Comparing suppression capabilities with and without a commercially available additive.

Water-mist tests in a High-Hazard Storage facility (UNI EN 12845); additive F-500 by *Hazard Control Technologies Inc.*

Parameters of Suppression Performance

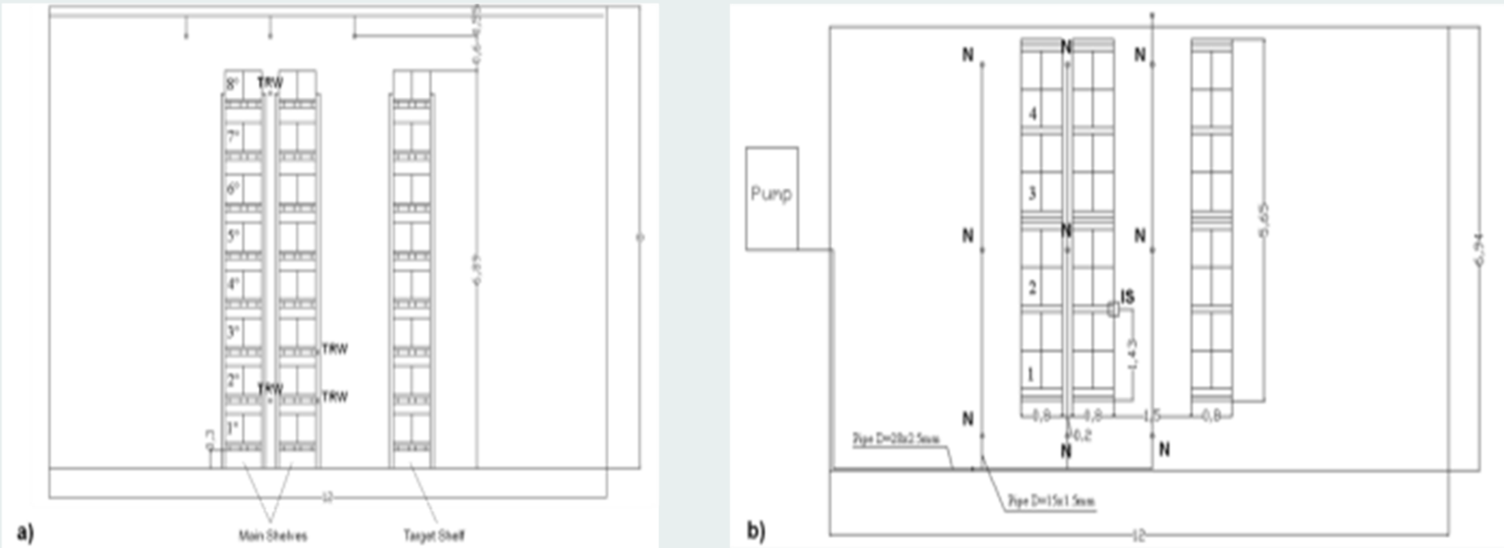
UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

- The fire should be **spatially controlled**, preventing the surrounding materials (i.e., the target shelf) from being burnt;
- The higher temperatures within the domain should be **limited under conservative values** to preserve the structural configuration of the building (i.e., the test chamber);
- The temperatures at eye level should be **kept as low as possible** to allow the best conditions for fire fighters;
- The fire spread within the involved commodities (i.e.: in the main shelves) should **be vertically and horizontally limited** as much as possible to optimize the rate of damages.

Experimental Setup

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

- **Test chamber:** Prefabricated iron box, base area ~ 83 m² (12 m × 6.94 m × 8 m);
- **Storage structure:** Iron beams, 3 shelves (5.65 m × 0.8 m × 6.89 m each), 8 storage levels;
- **Nozzle:** CJX 1140 B1SG by *Bettati Antincendio S.r.l.*, 7 injectors (total flow number = 1.4 l min^{-1} $bar^{-0.5}$); 9 nozzles located at the ceiling above the ignition-involved shelves;
- **Electric pump:** Maximum static head = 130 bar, operative pressure at the nozzle inlet = 100 bar.



Technical sketch of the experimental facility: a) view from side; b) view from above

Combustible Materials

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Commodities (*EUR Standard Plastic Commodities*):

- wooden pallets,
- cardboard boxes,
- plastic glasses.

	Wooden pallets	Cardboard boxes	Polystyrene glasses
Main shelves	64	256	30 720
Target shelf	32	128	15 360
Total amount	96	384	46 080
Total mass (kg)	2 400	691.20	138.24

Material	Lower Heat Value (MJ kg^{-1}), H	Combustion Efficacy, ϕ	Limiting Coefficient, ψ
Wood	19	0.8	1
Cardboard	17	0.8	1
Polystyrene	40	1	1

NOMINAL FIRE LOAD:

$$q_f = \frac{\sum_{i=1}^{N} m_i \cdot H_i \cdot \phi_i \cdot \psi_i}{A} = 617.33\, MJ m^{-2}$$

Experimental Facility – Photos

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Experimental Measurements and Procedure

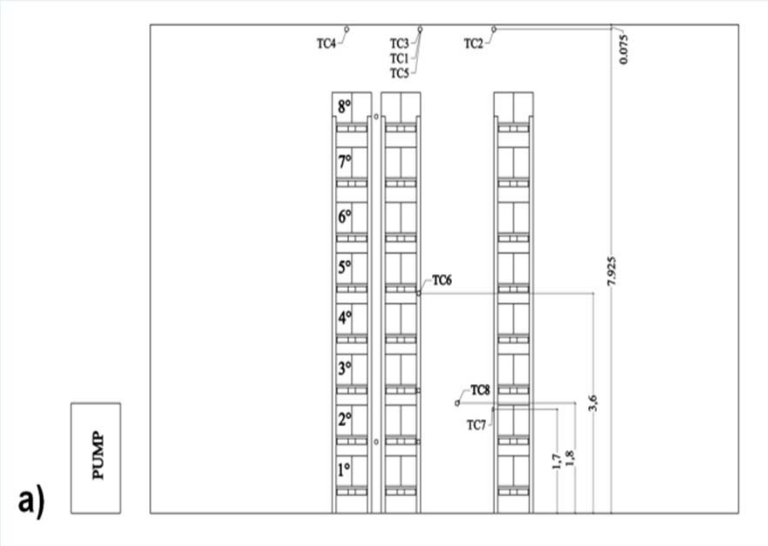
UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

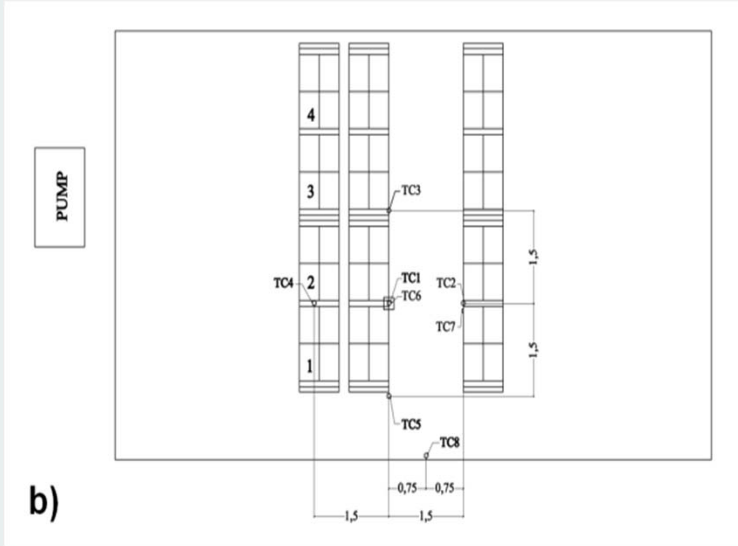
- **Thermocouples:** K type, diameter = 0.5 mm. 5 (TC1-TC5) placed between the ceiling and the nozzle height (hot gas temperature), 1 (TC6) placed at the flame axis 3.6 m distant from ignition source, 1 (TC7) placed at the target shelf, 1 (TC8) placed at eye-level height in between the shelves;
- **Thermal-response wires:** Activation temperature = 88 °C, all wires placed along the ignition-involved shelves at 1.1, 1.9 and 6.5 m from the floor;
- **Ignition source:** Heptane pool fire (120 ml), placed below the ignition-involved shelves;
- **Discharge:** 30 min; Test 1 - sole water, Test 2 - water/F-500 (2% volumetric concentration); if temperature at the ceiling = 350 °C, the test is interrupted (manual extinction for building preservation; failed suppression);
- **Water-mist activation:** both thermal-response-wire and temperature based.

Report From the Sensors	Discharge-Activation Time (s)
Alarm from 3 thermal-response wires within 60 s after ignition	60
Alarm from 2 thermal-response wires within 90 s after ignition	90
No/1 alarm from thermal-response wires within 120 s after ignition	120
Ceiling temperature = 300 °C	Immediate

Thermocouple Assembly

UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)



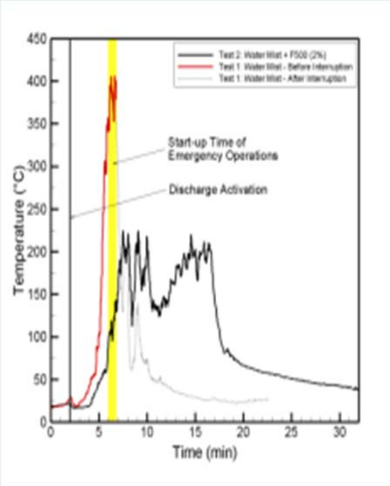


Locations

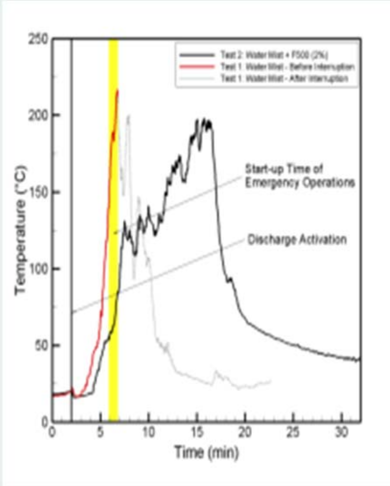
- **Ceiling Height:** 5 thermocouples (TC1-5) to measure hot-gas temperature;
- **Main Shelves:** 1 thermocouple (TC6) at the axis of the heptane pool fire to measure flame temperature;
- **Target Shelf:** 1 thermocouple (TC7) to measure the potential involvement of the target shelf;
- **Eye Level:** 1 thermocouple (TC8) to measure the environmental conditions for fire fighters.

Temperature Profiles (TC1-TC6)

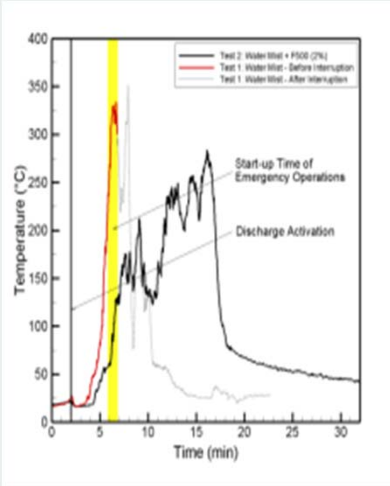
UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)



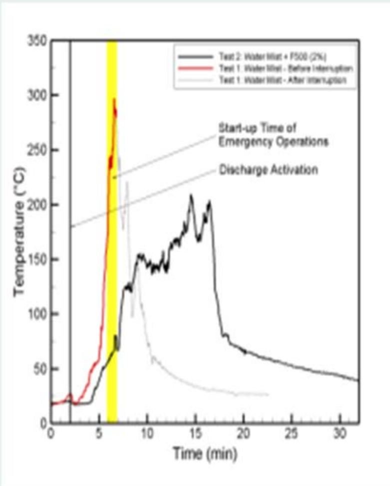
TC1 - Ceiling



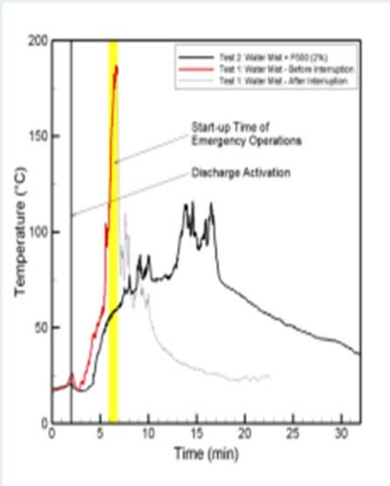
TC2 - Ceiling



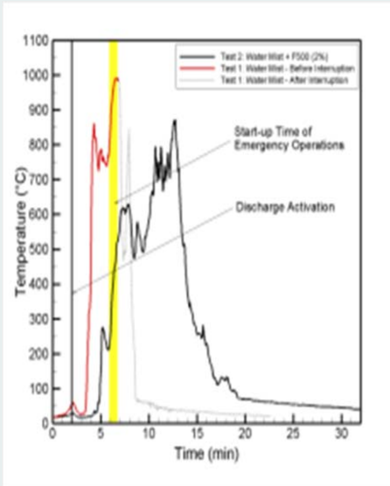
TC3 - Ceiling



TC4 - Ceiling



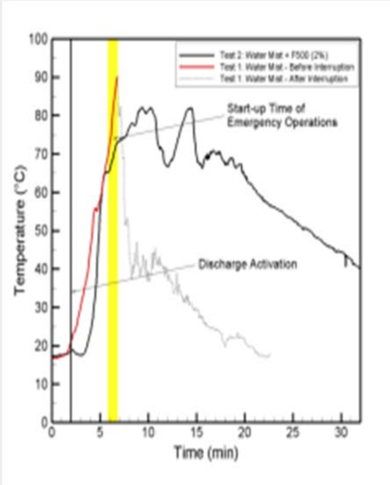
TC5 - Ceiling



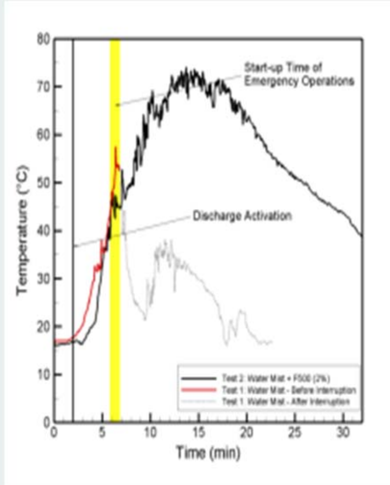
TC6 - Flame axis

Temperature Profiles (TC7, TC8 and details)

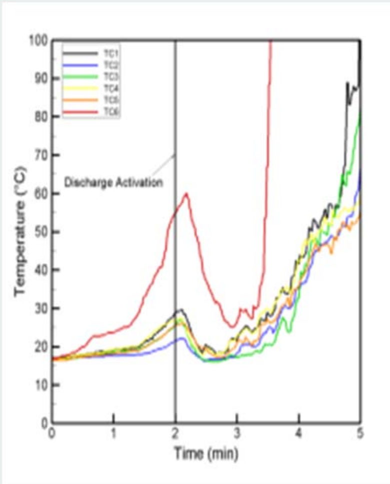
UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)



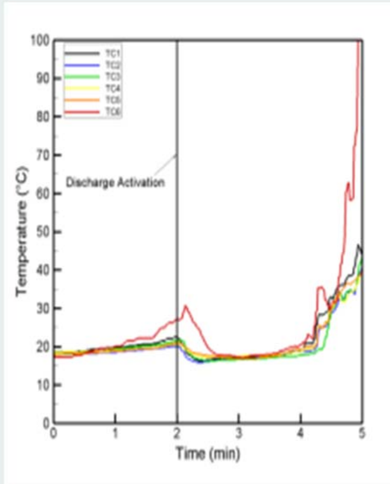
TC7 - Target shelf



TC8 - Eye-level height, hallway



TC1-TC6 after ignition (sole-water flow)



TC1-TC6 after ignition (water/F500 flow)

Additional Outcomes

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Mass-loss evaluation:

- No mass-loss actual measurement was carried out, since the main scope was to evaluate thermal control and because the size of the involved experiments;
- Following a post-fire damage evaluation, 4 pallets (base) and 6 storage levels (height) in the main shelves were involved in the fire spread for both the tests;
- As a conservative assumption, 25% and 37.5% of the combustible materials were burnt in Test 1 (sole water) and Test 2 (water/F-500) respectively;
- As an additional assumption, burning in Test 1 is assumed to stop at the end of emergency operations (0.16 $t_{Discharge}$), while burning in Test 2 is assumed to stop at the end of the discharge;
- Considering a free-burn time of 120 s (as in both tests), the **average burning rate** in **Test 1** is **3.15 higher** than in **Test 2**.

How does the presence of an additive affect drop size?

- Relative viscosity (to water) appears to be the main governing parameter in determining droplet size in water/surfactants (retardants) flows;
- According to F-500 declared components, its relative viscosity seems to be quite high (1.6-7.7);
- This case seems to be similar to agricultural water/drift retardant sprays;
- Drop size is assumed to **increase** by **35%** (D_{v50}) with respect to the sole-water flow.

Conclusions

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

- An experimental investigation was conducted to investigate velocity field, spray-cone angle drop-size axial evolution in water-mist sprays generated by two hollow-cone nozzles, employing laser-based diagnostics.
- The velocity field shows the same qualitative characteristics for both the injectors, while the cone angle is wider for larger orifices.
- Drop-size trends show that secondary atomization is the governing phenomenon until a minimum is reached; then, coalescence tends to increase droplet size.
- Drop-size trends are qualitatively very similar, but larger orifices tend to generate bigger droplet size on an average basis.
- Some predictive relations for pressure-swirl atomizers have been successfully validated for the water-mist case, as a result of non-viscous modeling.
- A water-mist system operating at high pressure was challenged in suppressing a fire within a high-hazard scenario; sole-water and water/additive flow were employed;
- Thermal transients was considered as the main parameter to determine suppression performance, together with post-fire damage evaluation and a temperature safety threshold;
- The sole water has been proved to provide ineffective action, even enhancing the temperature rise (turbulent effect on fire); on the other hand, the water/F500 flow yielded to successful thermal control and fire suppression;
- Fire spread was mainly vertical over both the tests (reduced temperature rise at the target shelf); eye-level temperature was lower than 80 °C over both the tests, thus allowing safe fire-fighters' operations.

Future Work

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

- Coupled velocity and drop-size measurements are to be pursued, employing shadowgraphy as one of the possible techniques.
- A more accurate patternation system should be designed to collect the smaller floating particles, thus implying an indirect evaluation of the evaporated share of the whole spray.
- Statistic analyses on turbulence can be conducted on PIV images, thus evaluating air entrainment within the spray.
- Modeling air entrainment in hollow-cone sprays still needs to be accomplished.
- Additional full-scale tests under downsized configurations should be performed to carry out a scaling approach on the involved physical phenomena;
- Numerical simulations of the fire scenario through CFD codes should be attempted to evaluate their predictability in terms of temperature profile and fire spread.

UNIVERSITÀ DEGLI STUDI
DI MODENA E REGGIO EMILIA
DIPARTIMENTO DI INGEGNERIA "ENZO FERRARI"
Via Vignolese, 905 – 41125 MODENA (Italy)

Thanks for your kind attention.

Questions?

Prof. Ing. Paolo Tartarini
Dipartimento di Ingegneria «Enzo Ferrari»
Università degli Studi di Modena e Reggio Emilia
Via Vignolese 905/b
41125 Modena (Italy)
Tel.: +39 059 205 6146
Fax: +39 059 205 6126
E-mail: paolo.tartarini@unimore.it