Studio sperimentale e simulazioni numeriche di sistemi water mist

Paolo Tartarini*, André Marshall°

*DIMEC - Università di Modena e Reggio Emilia
° Dept. of Fire Protection Engineering - University of Maryland, USA

Milano, February 12, 2008
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Objective:

TO CREATE A MODEL AND A COMPUTER CODE WHICH PROVIDE THE DESIGN INFORMATION TO OPTIMIZE A HIGH-PRESSURE WATER MIST SYSTEM

A bit of luck:
Programma Regionale per la Ricerca Industriale, l’Innovazione e il Trasferimento Tecnologico (PRRIITT),
Misura 1. Azioni per lo sviluppo del sistema produttivo regionale verso la ricerca industriale e strategica.
Azione A. Progetti di ricerca industriale e sviluppo precompetitivo.

The grant:
Modello matematico per la simulazione del comportamento della nebbia d’acqua per diversi scenari di incendio.
Fundings by: Regione Emilia Romagna
Partners: Bettati Antincendio – DIMeC (Unimore)
DIMeC partner: Dept. of Fire Protection Eng. (Univ. of MD.)
Motivation

‘Cut and Try’

‘Characterization’
Motivation

Gain New Knowledge

• Physical models characterizing the break-up process and the associated initial spray in fire suppression devices have yet to be developed.

Develop Injector Technology

• The absence of this analytical capability impedes the development of suppression injectors and systems.

Understanding the relationship between atomization physics and injector control parameters would facilitate a transition away from ‘cut and try’ injector development.
Motivation

• CFD modeling tools of fire phenomena are becoming increasingly popular for fire protection analysis and performance based design.
• The absence of physical models describing atomization in sprinklers and water mist injectors results in profound uncertainties in CFD simulation of suppressed fires.
• Errors in the specification of the initial spray will be propagated and amplified during dispersion calculations.

The atomization model represents a critical missing link in the modeling of suppressed fires.
Approach

A Water Mist System from Tank to Fire

1) A simulation code has been written for the simulation of pipelines

2) The spray atomization process has been studied both theoretically and experimentally

3) The interaction between the characterized water mist and fire has been and is still being simulated by FDS
Pipeline Simulation Code

• A simulation code has been written for the simulation of pipelines

• The code was written in MATLAB for its easiness in getting graphical output

• It is provided with a Graphical User Interface
Pipeline Simulation Code Properties

• Both Darcy-Weisbach and Hazen-Williams formulas for pressure loss are implemented

\[ \Delta p = \lambda \frac{L}{D} \rho \frac{u^2}{2} \]

\[ \Delta p = \frac{10.64LQ^{1.85}}{C^{1.85}D^{4.85}} \]

• The Colebrook friction factor is used in the Darcy-Weisbach formula

\[ \frac{1}{\sqrt{\lambda}} = -2 \log_{10} \left( \frac{\varepsilon}{3.7D} + \frac{2.51}{\text{Re} \sqrt{\lambda}} \right) \]
Pipeline Simulation Code Properties

• Concentrated losses are calculated as $\rho \beta u^2/2$

• The solution is found firstly guessing the mass flows at the nozzles and updating them iteratively up to convergence

• So far the code only works for open pipelines
Screenshots
Fire Suppression Mechanisms

It is important to understand ‘how fire suppression injectors work’ to appreciate why the initial spray is important.
Background

Fire Suppression Systems and Injectors

(Grant, 2000)
Fire Suppression Systems and Nozzles

- **LP Nozzle**: 2 bar ~ 700 μm
- **MP Nozzle**: 15 bar ~ 225 μm
- **HP Nozzle**: 100 bar
FOCUS:

CHARACTERIZING THE ATOMIZATION PROCESS OF A WATER JET EXITING A HIGH-PRESSURE SINGLE INJECTOR
EXPERIMENTAL MEASUREMENTS

A laser-based device (Spraytec by Malvern Inc.) has been employed in order to gain a set of data related to dropsize vs. CVF (Cumulative Volume Fraction). Characteristic size ($d_{v50}$, SMD) has been automatically determined.
THEORETICAL APPROACH

Target: obtaining the three components (axial $u$, radial $v$, tangential $w$) of velocity at the outlet of the injector.

Procedure:
• applying a slightly modified Bernoulli expression between the proper inlet and the outlet of the injector in order to gain the modulus of total velocity;
• employing the flow number ($FN$) of the injector to come up with the discharge coefficient ($C_D$);
• expressing $u$ as a function of $C_D$. $v$ and $w$ are obtained as a consequence.

$$u = \frac{C_D}{(1-X)} \left( \frac{2p_{PG}}{\rho_L} \right)^{1/2}$$
Objectives

• Provide discharge characteristics based on injector geometry, suppressant properties, injection conditions, and ambient conditions (measurements and models).

• **Fundamental Discharge Characteristics**: drop size, velocity, and location distributions of the initial spray.

• **Rational Discharge Characteristics**: spray angle, velocity magnitude, distributions of mass flux, characteristic drop size.

• **Injector Parameters**: injection pressure, orifice diameter, nozzle configuration, and deflector configuration.

| Injectors: | LP | MP | HP |
Overall Approach: Atomization Physics

Injected Flow Section

Photograph (Top View)
Regional Similarity Analysis and Friction Modified Layer Height

Viscous interactions with deflector are important for initial thickness and velocity of unstable free liquid sheet.

Liquid Sheet

Transport equations for mass and momentum provide the sheet trajectory.
Pressure forces from accelerating and decelerating flow drive the wave growth.

The most unstable wave is determined, which breaks up the sheet at $r_{bu,sh}$ into a fragment having characteristic length $\lambda_{bu,sh}/2$.

Liquid Sheet Breakup

&

Ligament Breakup

The most unstable wave is determined, which breaks up the ligament at $r_{bu,lig}$ into a fragment having characteristic length $\lambda_{bu,lig}$. 

Dilatational Waves
Trajectory Measurements (PLIF)

- Rotating Mirror
- Nozzle
- Laser Source
- Pressure Transducer
- Flow Meter
- Camera
- FOV
  - $t_{exp} = 900 \, \mu s$

Water and Rhodamine Dye
- Water and Rhodamine Dye
- Cooke 16-bit cooled 2.0Mpixel High-Speed Digital Video Camera.
Sheet Breakup Measurements

- Reflector
- Nozzle
- Flash ($t_{\text{exp}} = 15 \, \mu\text{s}$)

Dimensions:
- 1.9 m
- 1.7 m

Equipment:
- Canon 12-bit 3.4 Mpixel Digital SLR Camera

Water
Mass Flux Measurements

Diagram showing measurements with angles 30°, 15°, 7.5°, 0°, and distances 1.0m, 2.0m, 3.0m, 4.0m, 5.0m, 7.2 m, 3.0 m, and 8.6 m.
Drop Size Measurements

Malvern Spraytec Analyzer
(Light Diffraction Technique)

Sampling Volume
(283 cm³)

Local Measurements

Beam Power Detector

Scattering Detector

Laser Beam

Lens

Diode

Laser

Particle

Scattered Light Beam

8.6 m

1.0 m 3.0 m 4.0 m 5.0 m

7.2 m

30°

15°

7.5°

0°
Results and Analysis

Scaling Laws - Sheet Breakup Parameter, $X$

\[ X = \frac{3 f_0}{\rho^* D_d^*} \sqrt{\frac{2 h_d^* \cos \theta}{We}} = \frac{3 f_0}{\rho^*} \sqrt{\frac{f(Re) \cos \theta}{2 We (D_d^*)^3}} \]

- Sheet Breakup Parameter
- Dimensionless Sheet Thickness
- Spray Cone Angle
- Dimensionless Deflector Diameter
- Density Ratio
- Weber Number
Experimental and Modeling Results
Drop Size Characterization

Experimental Methodology for Model Development:
- Malvern measurements using pressure washer pump to supply center injector.
- Comparisons with correlations to check measurements.
- Apply existing modeling concepts where applicable and develop predictive model.
Plain jets are used to establish a baseline reference case for model development and suppression performance evaluation.
Experimental and Modeling Results

FDS Integration

HP (80 bar)

MP (13 bar)

Floor Mass Flux (kg/s/m²)

Mass Flux (Kg/m²)

Mass Flux (Kg/m²)
PIV Measurements – Sketch of the system

View from above

View from side
(the camera is not shown in this sketch)
PIV measurements – Laser and spray

- This analysis is aimed to gain experimental data about initial velocity of the spray.
- The laser has been set up in order to fire its beam directly to the outlet of the injector.
- PIV tests run from above were meaningless because of the impossibility to track the motion of a single particle between the two laser shots.
- The nozzle has been covered with dark tape in order to avoid unsafe reflection of the laser beam.
PIV measurements - Processing

- 300 double-frame images have been taken for each operative pressure (60, 70, 80 bar).

- A mask (shown in the figure) has been applied to every image in order to reduce the computational cost.

- The velocity vectors are calculated averaging over the set of images the path of every particle (the droplets, as far as they are so tiny that no seeding is needed).

- Suitable correlations are applied to obtain the velocity map.

The figure is referred to the tests carried on at 80 bar.
PIV measurements - Output

• The figure represents a plot of the modulus of velocity.

• The vectors seem to be meaningful approximately 2 mm below the outlet of the injector, where the concentration of droplets is slightly lower.

• Higher velocity values are located in the centre, while in the peripheral area mist driven by buoyancy is recognizable.

• The spray cone angle can also be detected looking at the velocity map.

The figure is referred to the tests carried on at 80 bar.
PIV measurements – Output images

BETTATI

HP Nozzle
100 bar

~ 100 m/s max
First PIV frame of the 80 bar flux (low scattering).
PIV measurements – Output images

300th PIV frame of the 80 bar flux (low scattering).
PIV measurements – Output images

Velocity map at 80 bar

Velocity map at 80 bar, with superposition of the spray image
PIV measurements – Output images

Axial velocity map at 80 bar.  
Radial velocity map at 80 bar.
COMPUTATIONAL ANALYSIS

The Fire Dynamics Simulator (FDS) by NIST has been used to perform a numerical investigation of the mass flux distribution. Spray cone angle (detected by photographic measurements) and velocity (obtained by theoretical calculation) are the main input data for the model.
Current HP Action Plan (Experimental)

• Single Nozzle Characterization
  – Drop Size
  – Trajectory / Cone Angle
  – Patternation / Mass Flux

• Parameter Variation
  – Characterize impact of nozzle swirl slot dimensions on spray characteristics through previously described measurements.
Current HP Action Plan (Modeling)

- **FDS Analysis**
  - Run spray simulation with detailed specification of the spray based on measurements.

- **Model Development**
  - Evaluate slot dimension effects to develop a model for predicting the initial spray based on this effect for input into FDS.
Conclusions

• Measurements have been taken and models have been established for canonical suppression nozzle configurations at various stages in the atomization process.

• The measurements provide qualitative and quantitative information for atomization model development.

• Comparisons have been made between the predictions and experiments showing promising results and revealing focus areas for experimental and model refinement.
Future (upcoming) work

FDS Integration

• Code atomization model into FDS so that FDS will use nozzle geometric and injection quantities instead of spray specification.
THANKS FOR YOUR ATTENTION

Milano, February 12, 2008