Spray-Wall Interaction at High-Pressure and High-Temperature Conditions

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Project ID # ACS108

2017 DOE Vehicle Technologies Office
Annual Merit Review and Peer Evaluation Meeting
June 8, 2017 – Washington, DC

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Overview

Timeline

- Project start date: Jan. 2016
- Project end date: Dec. 2018
- Percent complete: 40%

Budget

- Total project funding
  - DOE share: $570K (+ANL $180K)
  - Cost share: $85K
- Funding received in FY 2016: $185K
- Funding for FY 2017: $190K

Barriers

- Insufficient understanding of spray physics and spray-wall interactions (SWI)
- Absence of extensive data for development and validation of spray-wall impingement models
- Lack of measurement method of post-impingement vaporization and film dynamics

Project Partners

- Michigan Technological University - Lead
- Argonne National Laboratory
- University of Massachusetts Dartmouth

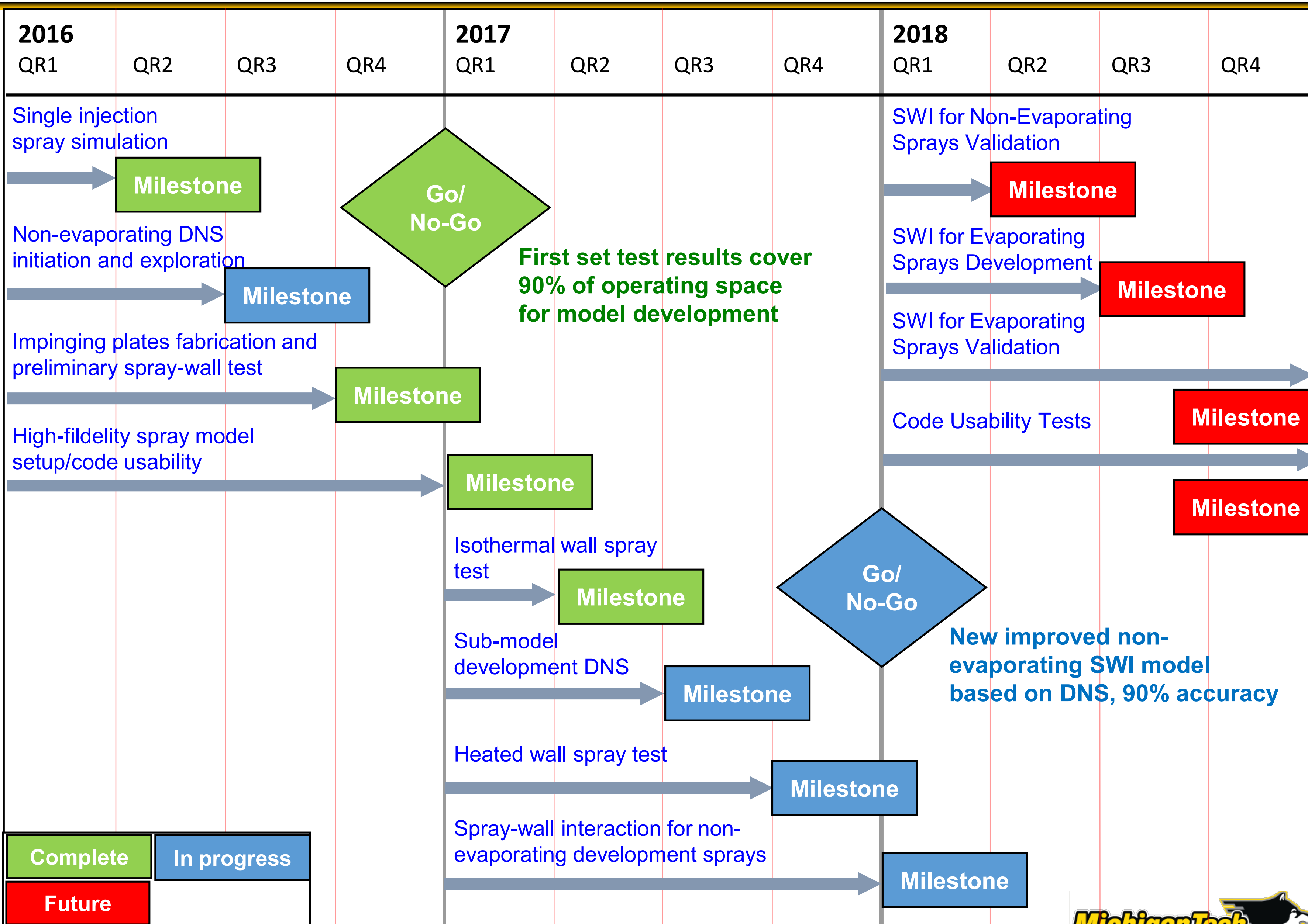
Relevance/Objectives

- Relevance
  - Improvement of existing spray-wall interaction models that are 20 years old and are validated for water only
- Overall Objectives
  - High pressure vaporizing drop-wall impingement and film formation supported by laboratory experiment
  - Physics-based predictive CFD sub-models of spray-wall interaction
- Objectives this period
  - Impingement experimentation for rebound spray dynamics characterization
  - Experimentally validated a high fidelity Lagrangian-Eulerian (LE) Reynolds-Averaged Navier-Stokes (RANS) model for spray-wall interaction
  - DNS frame of droplets impinging on dry/wet walls supported by LE model
- Impact
  - Improve the high-density ratio vaporizing processes on spray-wall wetting

Milestones – FY 16 & 17

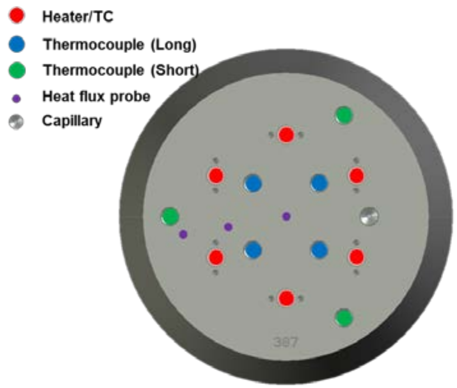
Date	Milestones	Status
April 2016	**Milestone** Transparent and metal plates design and fabrication	Complete
September 2016	**Milestone** Validate spray models in CONVERGE framework	Complete
March 2017	**Milestone** Impinging characterizations in high-pressure chamber	Complete
April 2017	Develop capabilities to extract required pre-impingement droplet characteristics from LE CFD simulations	Complete
June 2017	**Milestone** Implementation of basic DNS model of droplet-wall impingement with multiple droplets	On track
December 2017	**Milestone** Model of film formation dynamics and interactions between multiple droplets on splashing supported by heated wall test	On track
December 2017	**GO/NO-GO** New improved non-evaporating SWI model based on DNS, 90% accuracy	

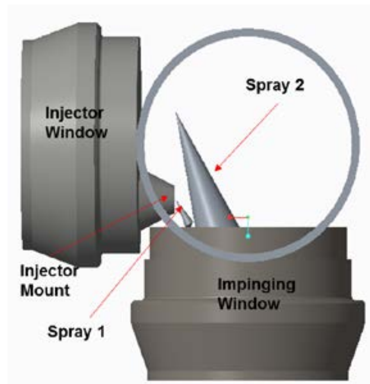
Approach/Strategy – Plan



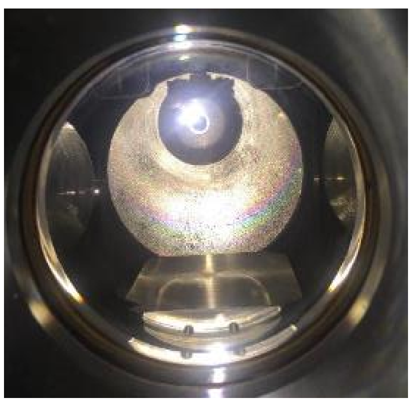
Technical Accomplishments

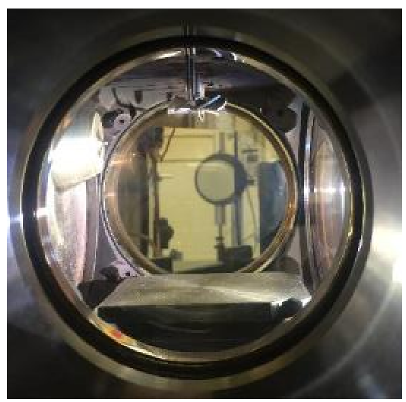
Experimental Approaches

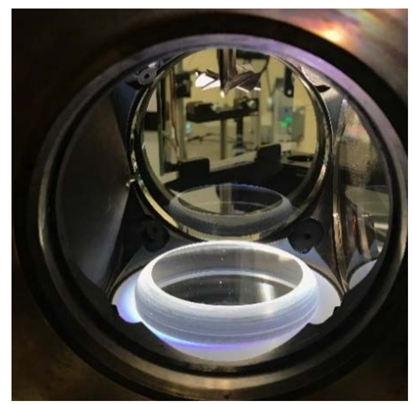


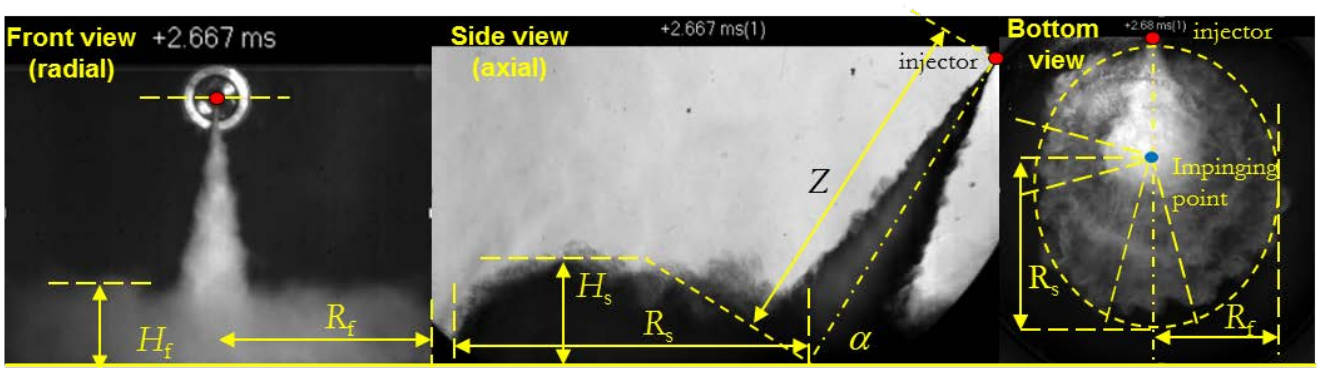


- Two **metal** / one **transparent** plates and off-axis **injector** window
- Temperature-controlled impingement window: six heaters, seven thermocouples, and three heat flux probes







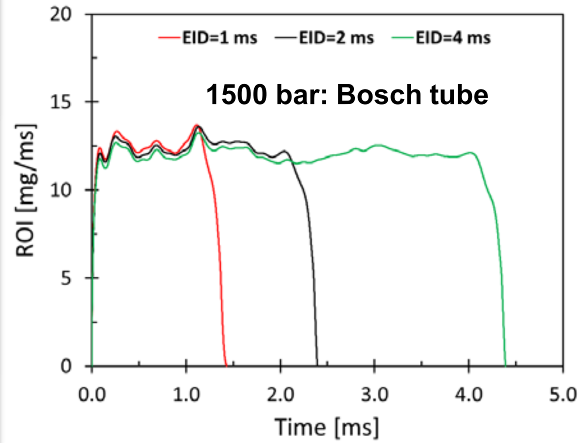


- Visualization: **simultaneous** front, side, and bottom spray views
- Optical methods:
  - **Schlieren**: vapor spray
  - **Mie**: liquid spray
  - **RIM** (refractive index method): film thickness
  - **LIF** (laser-induced fluorescence: film thickness
- Injector: 7-hole and single-hole nozzle

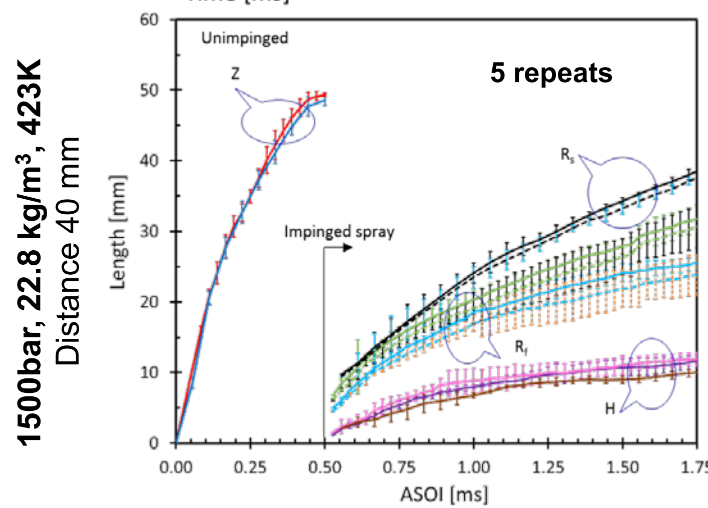
Test/Simulation Conditions and Experimental Results

	7-hole	Single-hole
Ambient gas temperature	423K / 900K	423, 500, 600, 700, 800, 900K
Ambient gas density	0.8 - 30 kg/m^3	
Ambient gas oxygen	N2 (non-vapor)/ 0% O_2 (non-reacting)	
Nozzle outlet diameter	~ 0.139 mm	0.200 mm
Nozzle K factor	1.5	0.0
Orifice orientation relative to injector axis	ψ = 74° (inclined angle: 148°)	ψ = 60° (inclined angle: 120°)
Fuel injection pressure	1500 bar	1200, 1500, 1800 bar
Fuel	Diesel	
Fuel temperature at nozzle	150°C	90°C
Wall temperature	150°C	150°C, 200°C, 250°C
Injection duration	2.0 ms	
Distance between injector tip to impinging surface	64 mm	Metal: 40 mm Transparent: 52 mm

Plate temperature determination: GDI engine piston surface temperature range- 125°C to 150°C; Diesel engine piston surface temperature range- 125°C to 200°C



- Single-hole: Injected mass is 28.4 mg in 2ms injection duration
- Cd:~0.793 at steady state

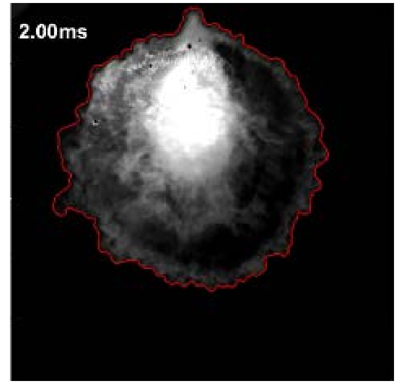


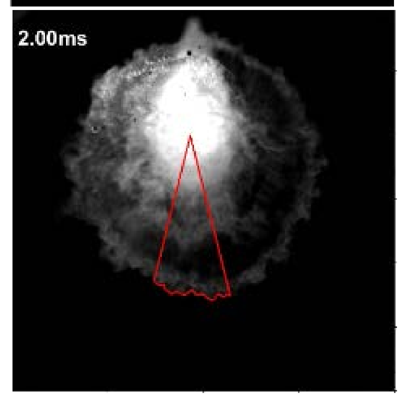
- Rebound radii have larger penetrations than rebound spray on wall. This phenomenon occurs for both axial and radial directions
- Axial rebound radius is slightly higher than that in radial direction and rebound height in axial direction is slightly lower than one in radial direction

Rebound Spray Characterizations

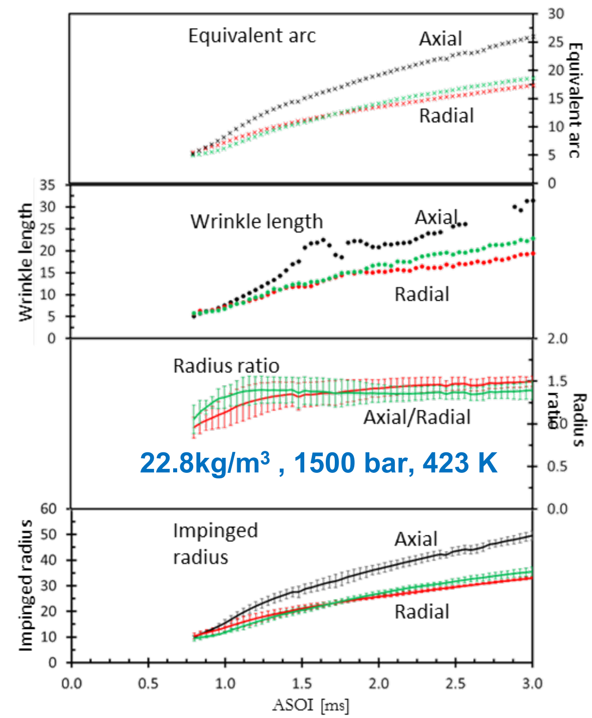
Wall-impinged expanding spray (WIES)

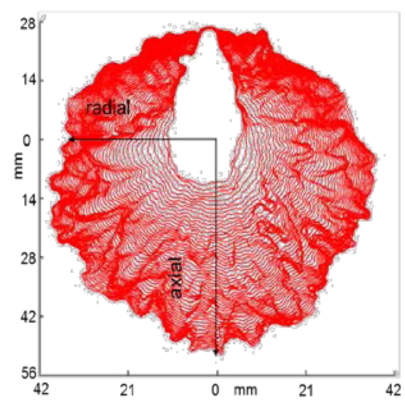
- Sector-averaged radius over the arc sector is estimated because the WIES front is highly **wrinkled** as it propagates on the wall surface
- Final **arc angle** (30°) is determined by varying angle for the **least sensitivity** for the radius variation
- A number of **spikes** (time interval of 40 μs) are formed randomly due to combined effect of **injected flow rate fluctuation and turbulence** between WIES front and surrounding gas
- WIES expansion process is divided into **four stages**: rapidly decelerated stage, slowly decreasing stage, relatively constant stage, and expanding termination stage



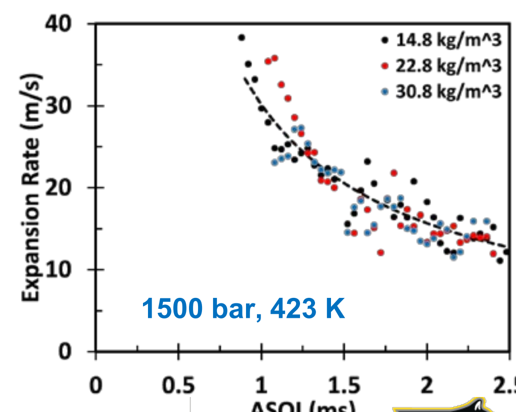


WIES properties





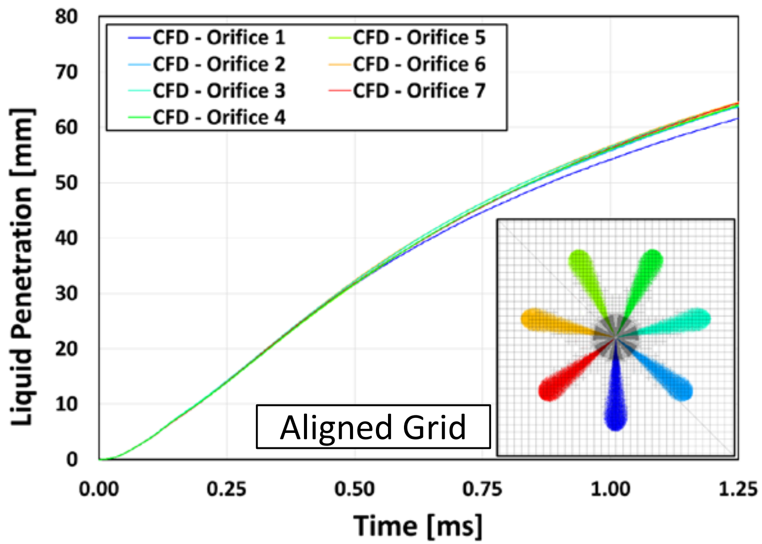
1500 bar, 22.8kg/m³, 423 K

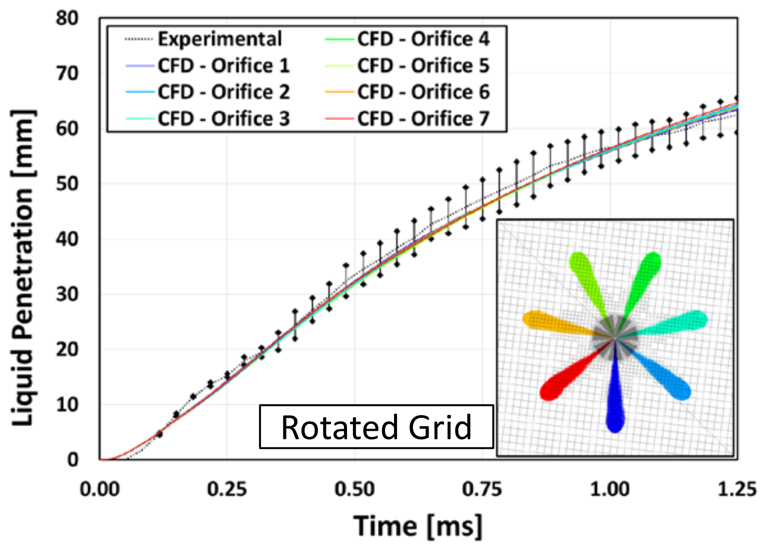


MichiganTech

Mesh Strategies for Grid-Dependency Reduction

A **best practice** was developed for **reduced grid-dependency** with **multi-hole injectors**





- Plumes **aligned** with the grid (e.g., Orifice 1) are affected by a different **momentum exchange**
- **Maximizing the misalignment** between the grid and the plumes guarantees that the **influence of the grid is minimized** with respect to the **free-spray penetration**
- The results were validated against MTU's experiments on the 7-hole injector

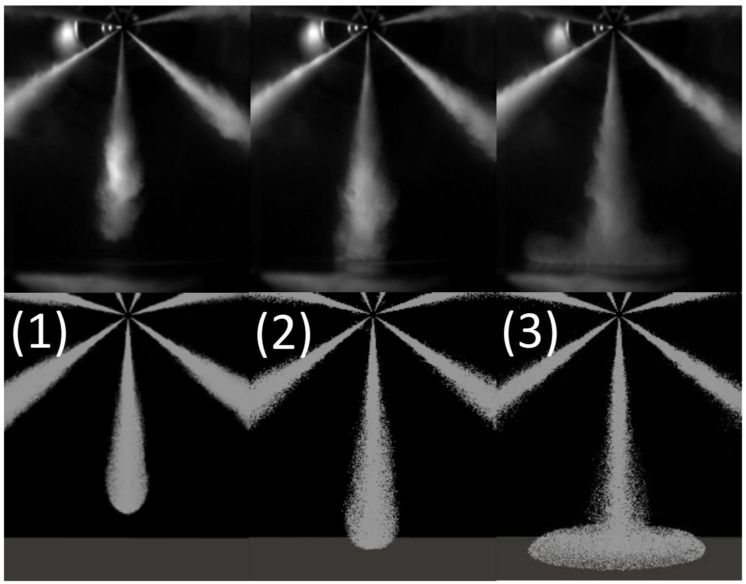
Validation of CFD Setup

The **CFD setup was validated** against data obtained from several injectors and for multiple operating conditions, including **ECN Spray A** and **MTU's 7-hole injector**

1.000 ms 1.334 ms 2.334 ms

Experimental

CFD



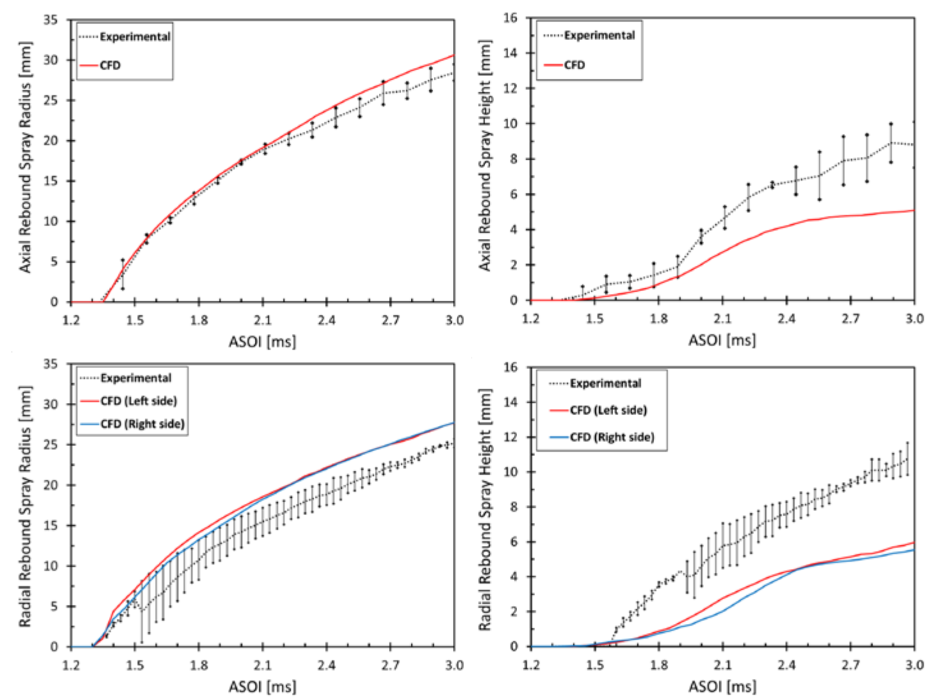
1.000 ms 1.350 ms 2.350 ms

The **free-spray behavior** (1) was **well predicted** as well as the **time of impingement** (2).

Some **discrepancies arose** in the description of the **spray-wall interaction** with the **available models** (spray recirculation at the edges is not captured (3))

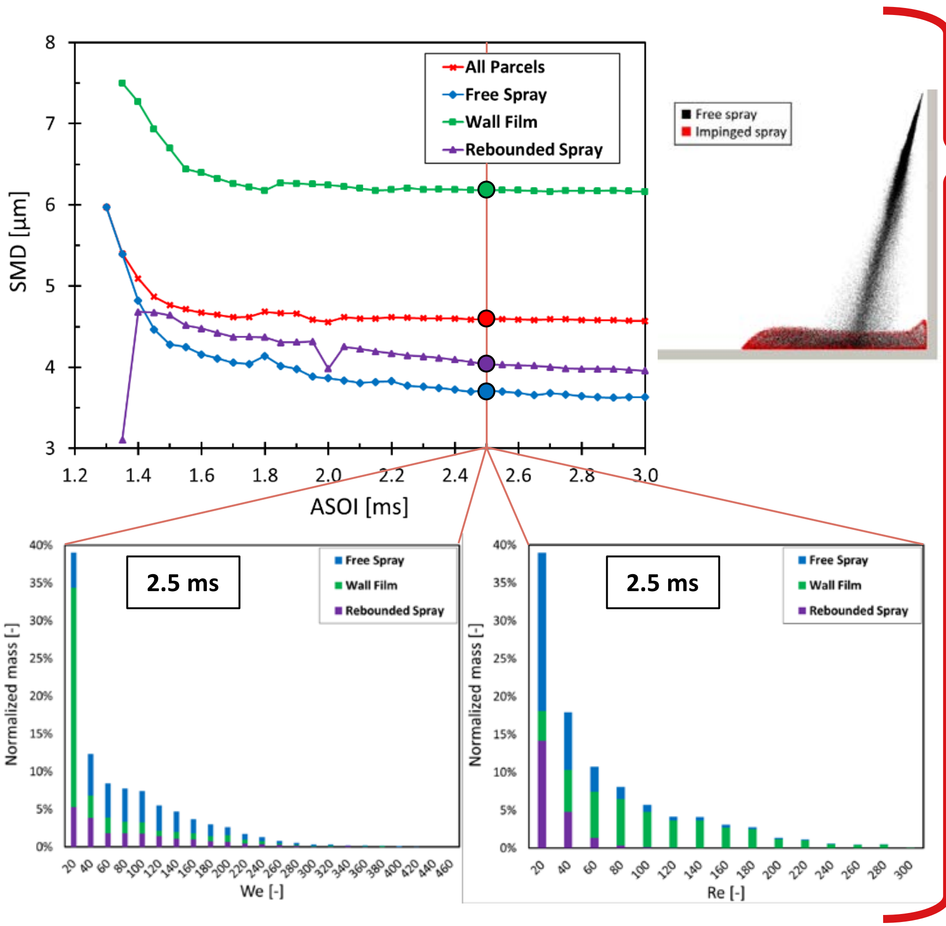
Post-processing tools were developed to **compare** the **CFD results** with the experimental measurements:

- **Good** agreement for **axial spreading** of the spray
- **Model improvement** is **necessary** for correct predictions of radial rebound and spray height: **splashing** dynamics **are not well reproduced** by the available models



Generated Inputs for DNS

Newly developed post-processing tools include also extraction of spray morphology related data



Data can be extracted at any point and time to initialize **DNS** of **droplet impingement**

Data include, but are not limited to, **global** (SMD, *We* and *Re* distributions) and **local quantities** (droplet size, temperature, gas pressure, velocities)

From ANL to UMassD

DNS calculations can capture important **details of droplet impact dynamics** onto **wet** or **dry** surfaces, under **non-evaporating** and **evaporating** conditions

Back to ANL

The feedback from DNS runs will be used to **improve** the **spray-wall interaction models** with **more detailed** and **accurate correlations**

Spray Film Interaction (O'Rourke & Amsden)- Validation

The splashing model:

The secondary drop information input to:
film momentum[1] & film energy[2] equation

Mundo, Sommerfeld and Tropea[3]

- Experiment: Single impinging drop on dry solid surface
- A splash parameter for occurrence of splash
- Secondary drop size / velocity measured

Yarin and Weiss[4] Multiple drop interaction

- Experiment: train of drop impinging on wet wall
- Secondary drop size / total mass measured
- Splash criterion independent of drop diameter

All experiments considered drop sizes 60 µm – 200 µm

O'Rourke and Amsden[1] Validation lacking

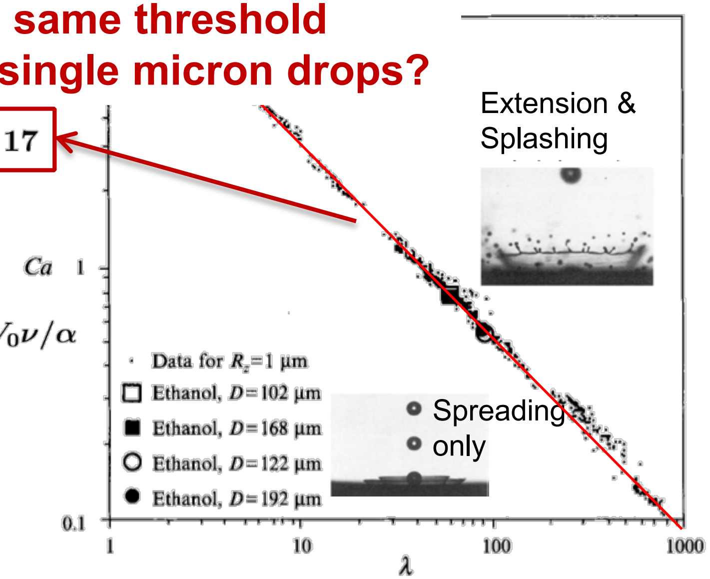
- Single drop impinging on a film
- Above experiments used to formulate: splash criterion and secondary droplet distribution

Splashing criterion (Yarin & Weiss):

Does the same threshold apply to single micron drops?

$Ca\lambda^{-3/4} = 17$

$Ca = \rho V_0 \nu / \alpha$



$\lambda = (\nu/f)^{1/2}\alpha/(\rho\nu^2)$

$$u = \frac{V_0}{(\alpha/\rho)^{1/4}\nu^{1/8}f^{3/8}} = 17 \text{ (Exp.[4])}$$

$$\frac{V_0}{(\alpha/\rho)^{1/4}\nu^{1/8}f^{3/8}} \gg 1 \text{ (Theory[4])}$$

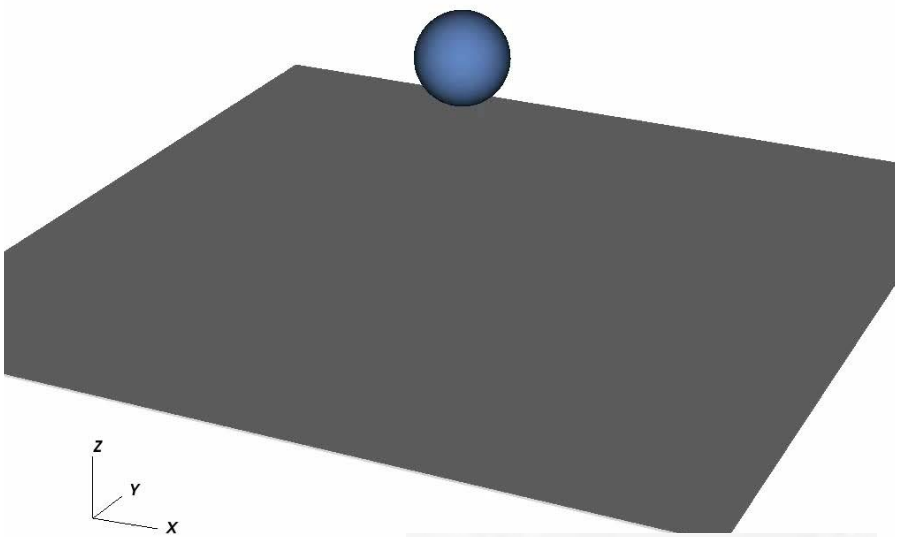
Splashing threshold of 17 independent of drop diameter

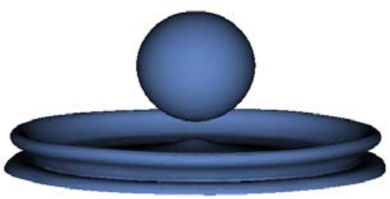
Length scale: distance b/w droplets (not diameter)

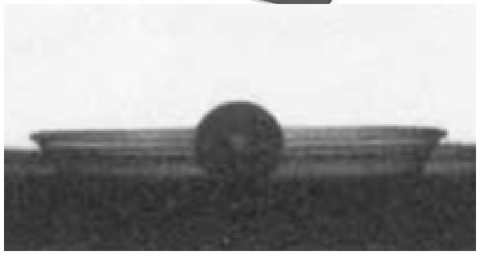
1. O'Rourke and Amsden, SAE, 2000
2. O'Rourke and Amsden, SAE, 1996
3. Mundo et al., Intl J Multiphase flows, 1999
4. Yarin and Weiss, J. Fluid Mech., 1995

Droplet Impact Simulation Results

Ethanol droplets
- 109 µm diameter
- u=15 (non-splashing)
- 31.77 kHz impact frequency

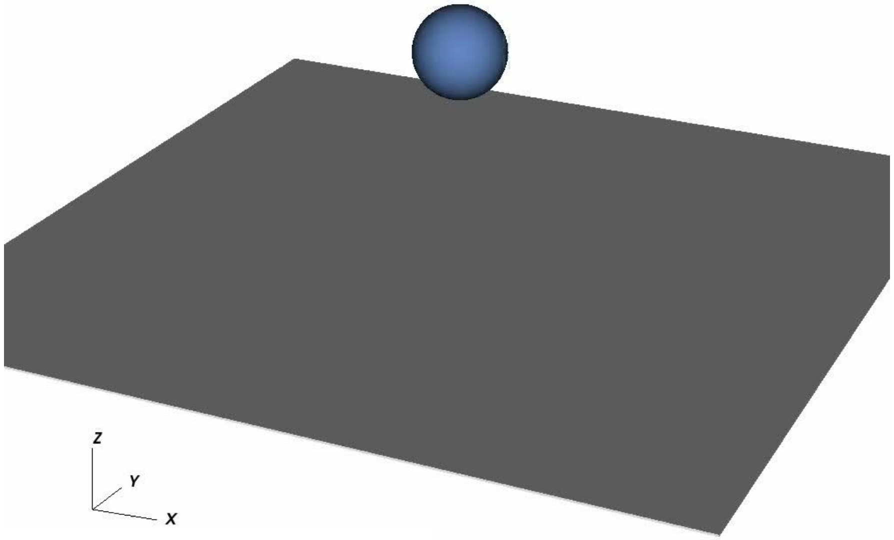


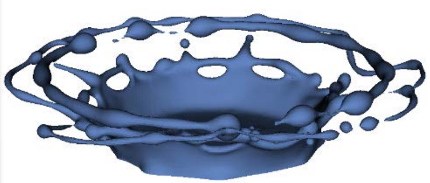


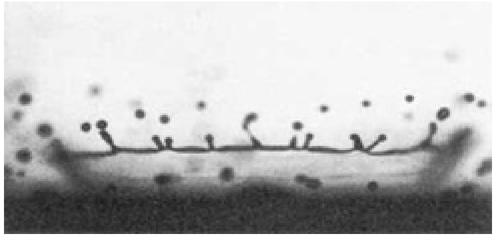


Simulation Results Experiment Results[1]

Ethanol droplets
- 109 µm diameter
- u=19 (splashing)
- 16.92 kHz impact frequency







Simulation Results Experiment Results[1]

1. Yarin and Weiss, J. Fluid Mech., 1995

Partners/Collaborations

MTU: Experiment
- Spray-wall interaction experimentation
- Rebound spray dynamics characterization
- Film dynamics, heat flux

Convergent Science
- Silence partner
- Sub-model code implementation

Rebound spray data

Feedback test

Code usability

ANL: HPC LE
- High fidelity Lagrangian-Eulerian model for spray-wall interaction
- Input generation for DNS wall interaction zone

Interaction zone data

Impinging sub-model

UMassD: DNS-eVOF
- DNS-VOF for droplet evaporation
- DNS-eVOF for spray-wall interaction

UMass | Dartmouth

CONVERGE CFD SOFTWARE

Remaining Challenges and Barriers

- To extract the details and physics-base information using the DNS model to quantify the model associated with **vaporization on the hot surface** and explore the post-impingement droplet dynamics and secondary **fuel vapor mixing process** with ambient gas
- To formulate a VOF-based **mathematical evaporation sub-model** of spray-wall impingement and film formation processes
- To **accurately measure**, firstly, the vaporization before the impingement and, secondly, the vapor portion and film after impingement
- To systematically analyze **uncertainties** in experimental and modeling results and parameters
- To address challenges associated with the **full implementation** of the proposed sub-models (eVOF and drop-wall interaction) in various relevant CFD frameworks

Future Work- We will continue to develop and validate of evaporation VOF and spray-wall interaction models

Ongoing Support validated LE model frame for DNS	FY16 – [Q1 Milestone] ECN single injection spray simulation FY16 – [Q3 Milestone] Isothermal spray-wall test for post impinging spray FY16 – [Q4 Milestone] High-fidelity spray model setup
Proposed Extend DNS model to handle evaporation spray-wall supported by heated wall test	FY17 – Spray-wall test • Continue isothermal non-isothermal/heated wall test • Film formation and surface heat flux FY17 – Sub-model development DNS • Non-evaporating spray-wall interaction • Impinging evaporating spray droplets FY17 – Spray-wall interaction for non-evaporating development sprays • Lagrangian-Eulerian (LE) model and VOF based on DNS
Planned Future solvers for CFD package	FY18 – Feedback test for heat flux and film characteristics FY18 – DNS for spray-wall interaction and evaporation • Impinging evaporating spray droplets • Validation of film dynamics and heat flux FY18 – Spray-Wall Interaction Validation at Vaporizing Conditions • Implement eVOF model into spray modeling approach • Make data to Public FY18 – Code Usability Test

Any proposed future work is subject to change based on funding levels.

Summary

Objective

- ❑ Develop, implement and validate an evaporation VOF sub-model of spray-wall interaction without extensive need of parameters tuning

Approach

- ❑ Impinging plates
  Temperature-controlled metal and transparent impinging plates
- ❑ Spray-wall impingement test
  - Develop simultaneous Mie/schlieren to extract post-impact spray properties
  - Develop RIM and LIF for film formation dynamics
- ❑ Lagrangian-Eulerian (LE) impinged spray model
  - Develop experimentally-validated LE model for post-impact sprays
  - Generate DNS input data and implement LES drop-wall model
- ❑ DNS of evaporating droplets impinging on surface
  - Develop DNS model of film formation dynamics, droplet splashing and rebound
  - Model film formation on an heated wall

Accomplishment

- ❑ Impinging plates
  Complete fabrication and functional (~ up to 550K)
- ❑ Spray-wall impingement test
  Complete first-round impinging characterization test and data used for LE model development
- ❑ Lagrangian-Eulerian (LE) impinged spray model
  Capture experimental trends but need to improve the rebound spray height match.
  Generate interaction zone data for DNS input
- ❑ Initiation of DNS model
  Match well with published data and progress on impinging test simulation

Future work

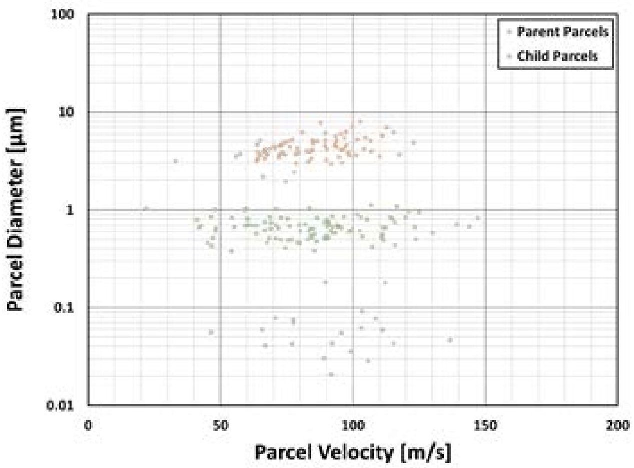
- ❑ Heat flux and film thickness measurement
- ❑ Local spray characteristics at the interaction zone in DNS and LE frameworks

Technical Backup Slides

Further DNS Work: we are trying to improve splashing threshold, film formation and wall-film interaction

- Verify splashing threshold $u = \frac{V_0}{(\alpha/\rho)^{1/4}\nu^{1/8}f^{3/8}} = 17$ for single micron diameter droplets

ANL Droplet Data



Representative Droplet Condition(s):

$$D = \overline{d}$$
$$U = \overline{u}$$

Fuel Spray Reconstruction:

$$D = \{d_1, d_2, d_3 ... d_n\}$$
$$U = \{u_1, u_2, u_3 ... u_n\}$$

- Use multiple median size droplets to represent the spray conditions
  - Representative droplet will be used to verify and revise the splashing threshold
- Use a distribution of droplets contained in the spray to study film formation dynamics and the interactions between multiple droplets on splashing
- Develop a VOF-based evaporation model to study how wall-film interaction changes due to evaporation