Hot Surface Ignition Temperature of Aviation Fluids

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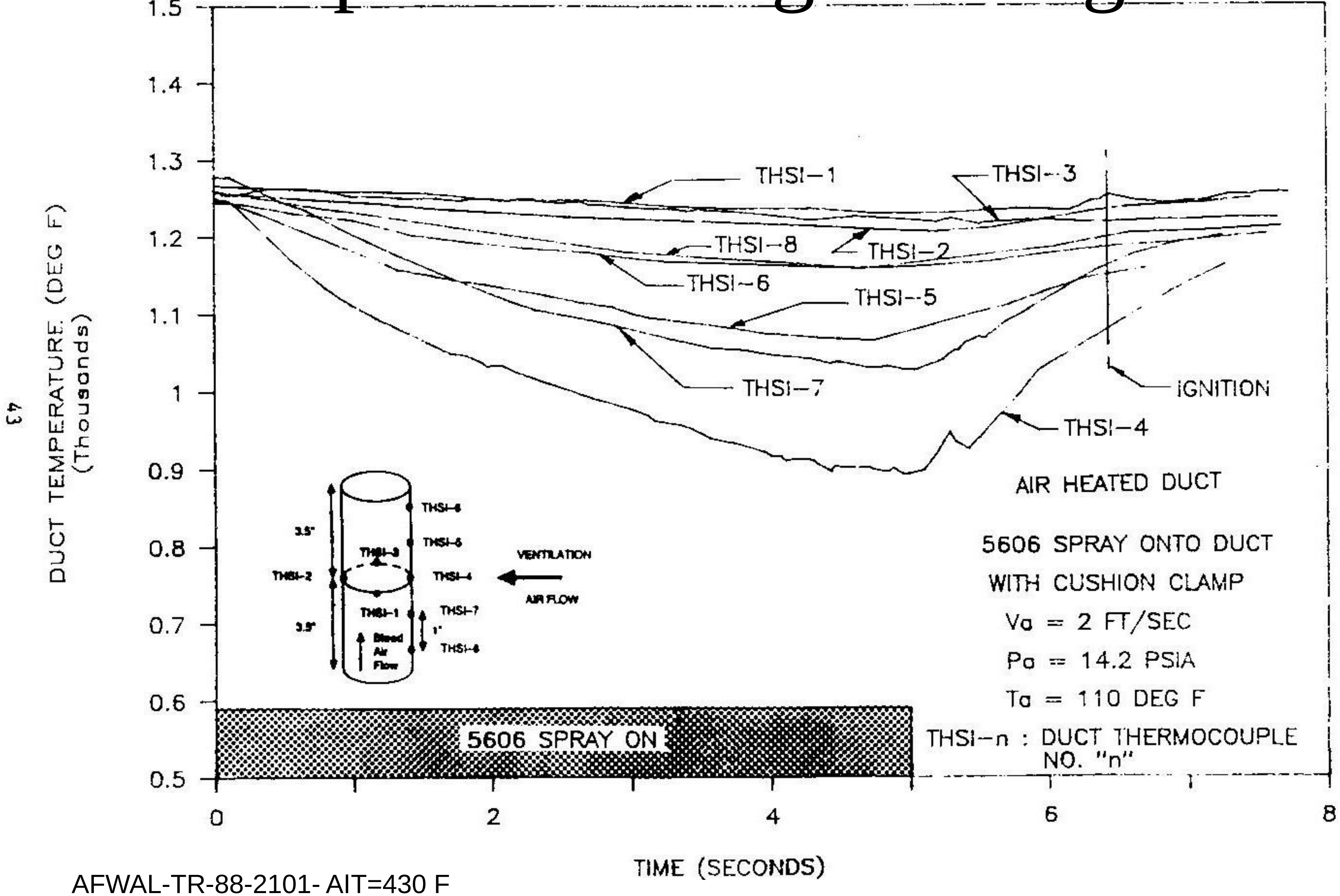
Background

- Context: Ignition assessment of fuel leaks near a hot surface
- What ignition temperature to use?
  - Auto-Ignition Temp. (AIT) is not representative of the dynamic conditions of a leak
  - Hot Surface Ignition temperature (HSIT) is more representative and depend on their local conditions
- Values reported for HSIT vary significantly (about 400 F for same fuel)
- The purpose of this talk is reliable measurements of HSIT
- This work was performed under Air Force sponsorship

Outline

- Challenge in measuring HSIT
- BlazeTech approach
- Experimental setup
- Test results for a hot cylindrical duct
- Comparison of hot duct with flat plate results
    - Computational Fluid Dynamics (CFD) to interpret test results
- Engineering model to predict HSIT

Challenge in Measuring HSIT is Surface Temp. Can Change During Test



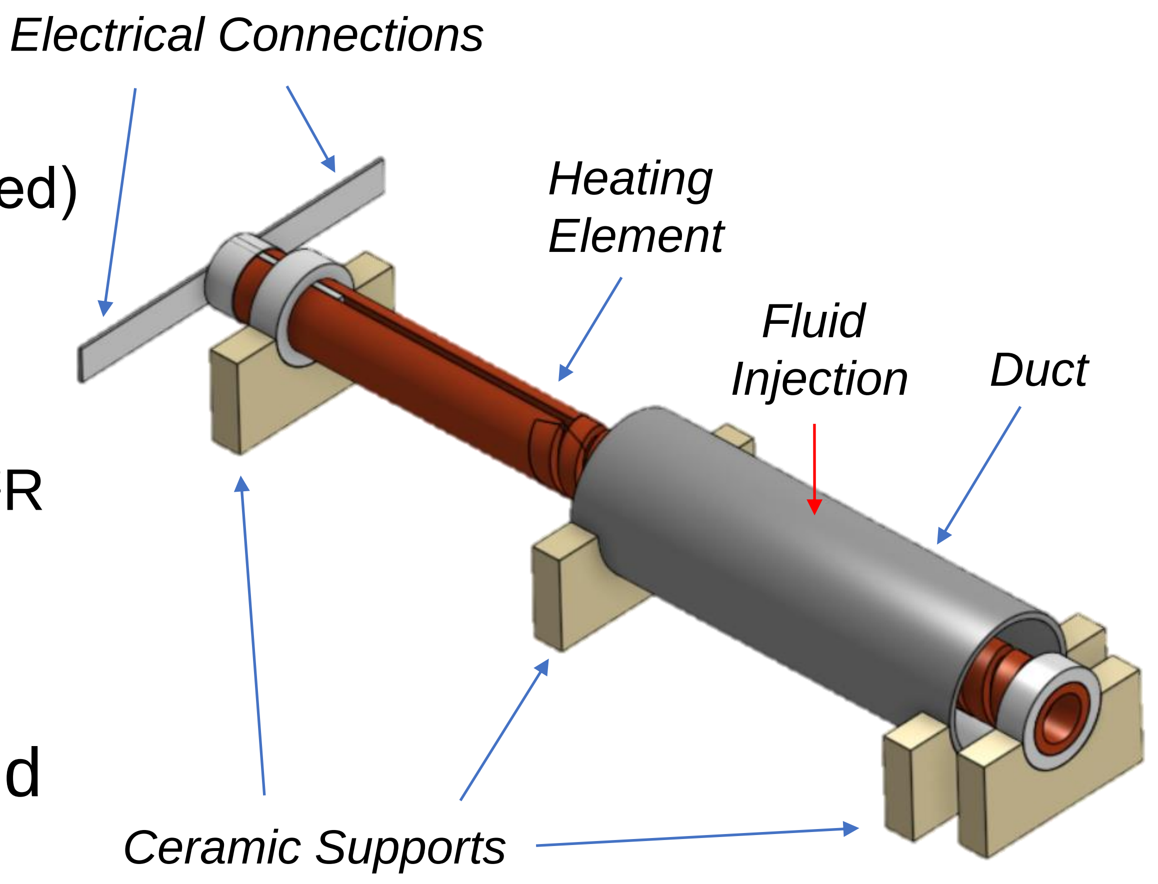
AFWAL-TR-88-2101- AIT=430 F

Approach:
Maintain Constant HSIT during Ignition

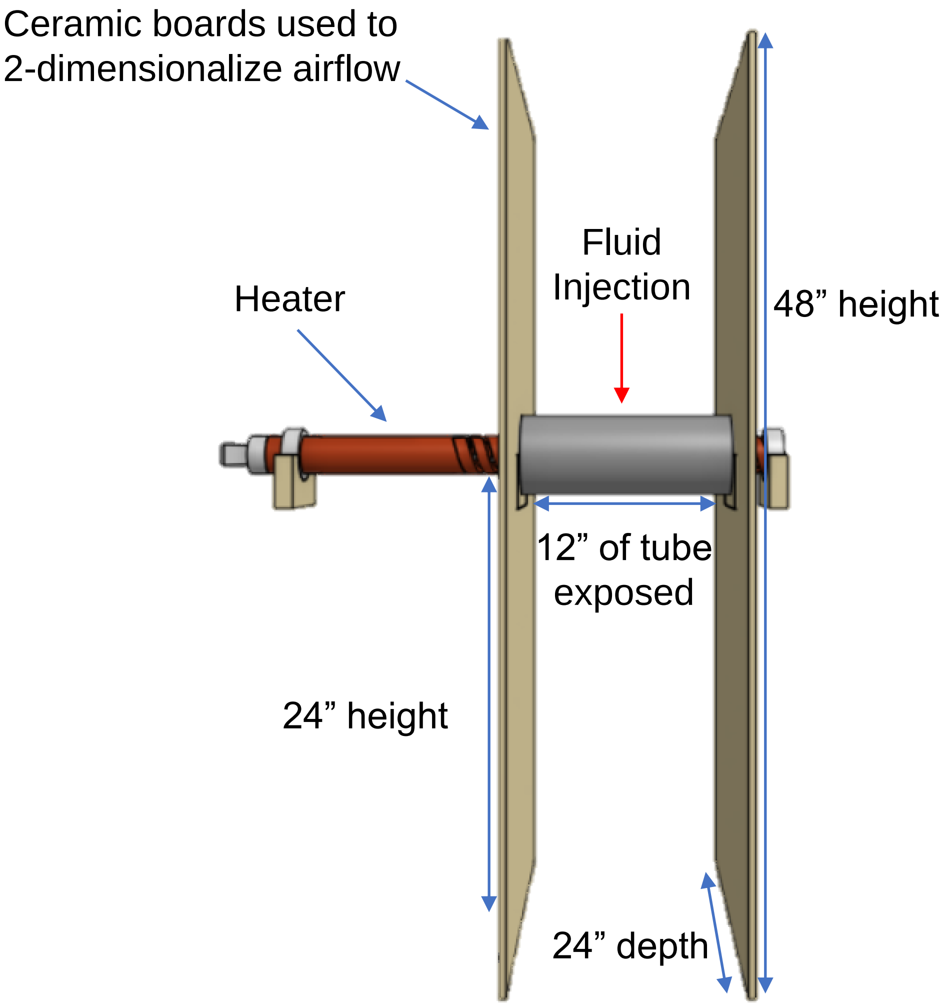
- Use test surface with high thermal diffusivity and high thermal mass
- Inject small volumes (50 to 300 µL)
  - Using accurate micropump
- Result: minimal surface quenching during test
  - $T_{Surface}$ (before liquid injection) ~ $T_{Surface}$ (at ignition)
  - Confirmed by measurements on flat SiC plate
  - Constant temp. enables us to get kinetics data →modeling
- Use simple geometries: flat plate and cylindrical duct

Hot Duct Design

- Testing Surface
  - 4.5” OD Tube
  - 14” overall length (12” of tube is exposed)
  - 0.2” tube thickness
  - Inconel 625
- Heating Element
  - 11 kW Silicon Carbide “Starbar” from I^{2}R Elements
  - 2.125” OD, 29” overall length
  - 16” of the 29” is the “hot zone”
- Injection achieved by micropump and removable injection arm



Hot Duct Experimental Setup



Sample Video

617 °C – 300 μL

Inconel Duct – Jet A – Inj. Height 20 cm – Nozzle ID: 0.6 mm
240 FPS

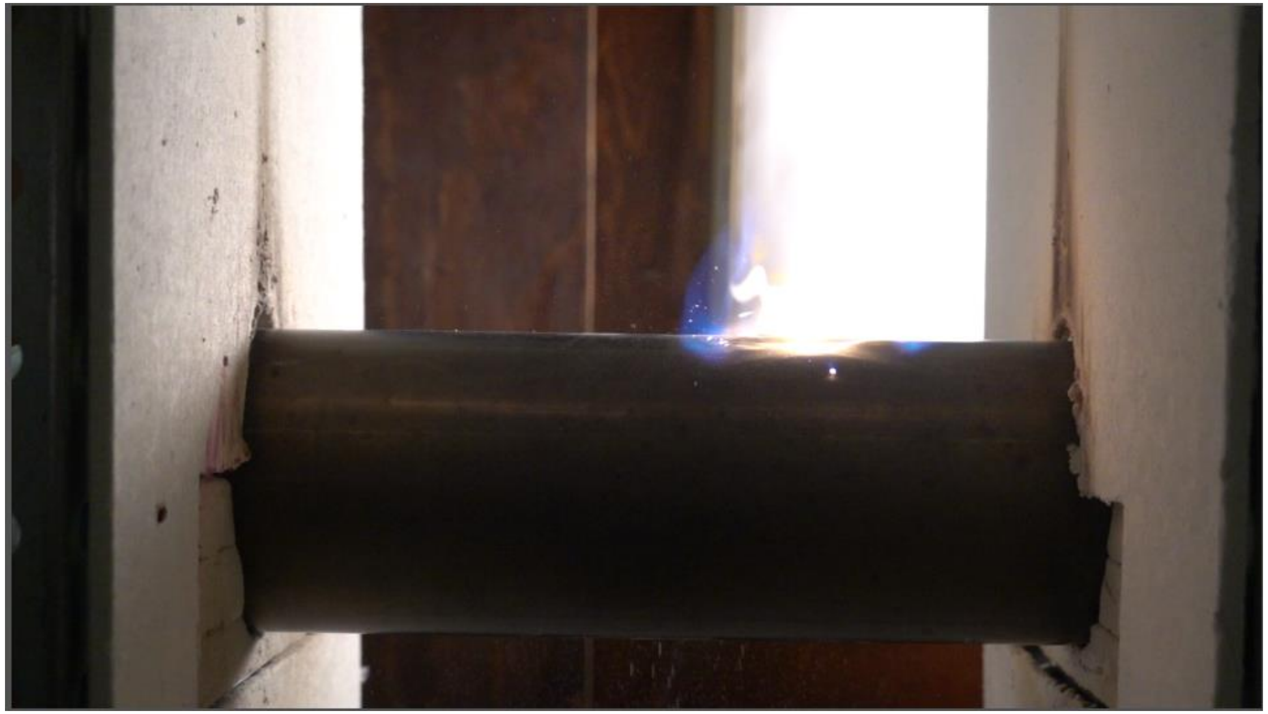
Sample Video – 16x slow

617 °C – 300 µL

Inconel Duct – Jet A – Inj. Height 20 cm – Nozzle ID: 0.6 mm

Sample Experiment

617 °C – 300 μL



t = 33 ms

t = 659 ms

Inconel Duct – Jet A – Inj. Height 20 cm – Nozzle ID: 0.6 mm
Ignition temperature corresponds to 3 Ignition out of 5 runs (60%)

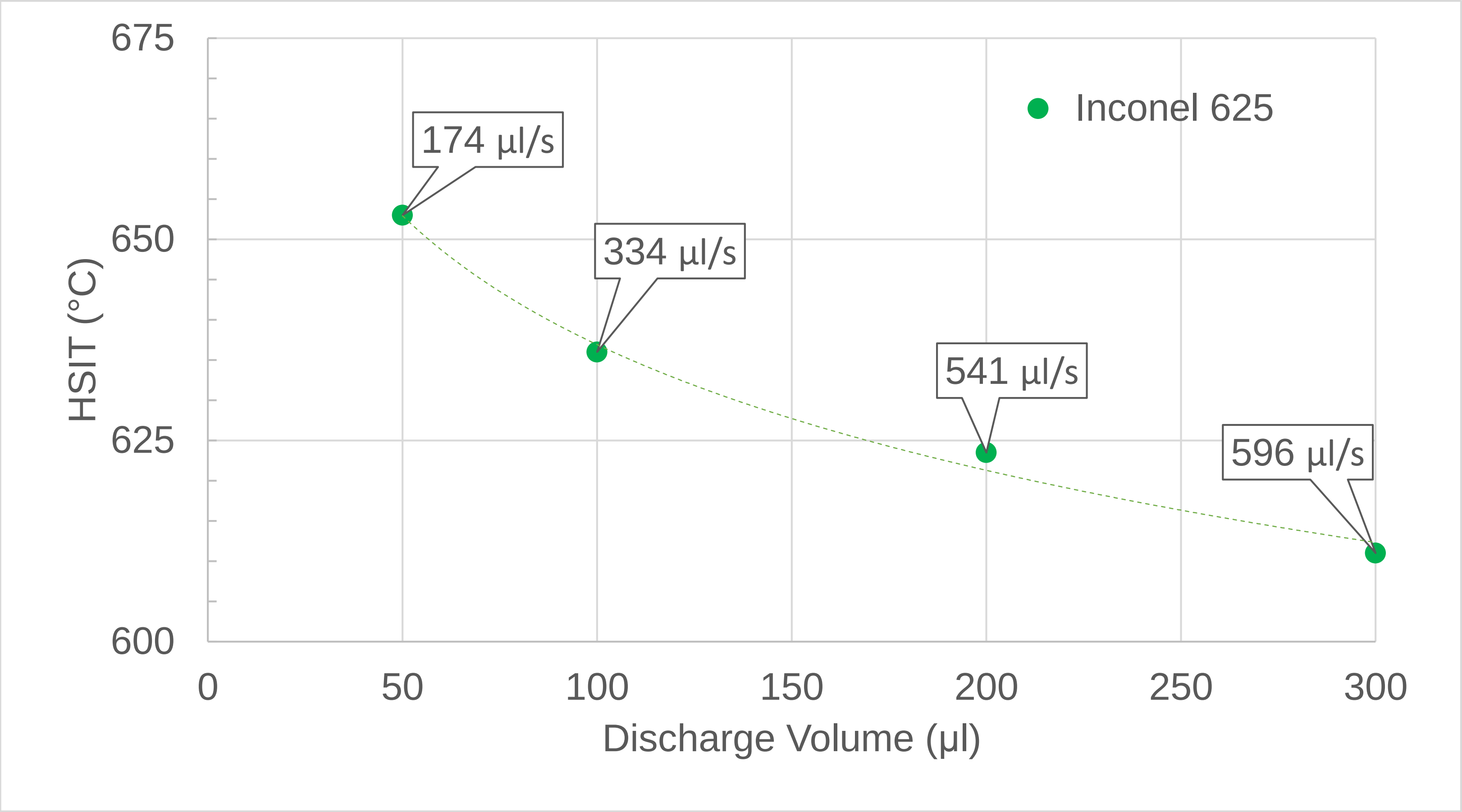
Selected Test Parameters# for Hot Duct

- Fluids
  - Jet A (most test data), n-Decane (some tests and model), hydraulic fluid 83282
- Dosage Volume*
  - 50 – 300 µL
- Injection Height*
  - 10 cm – 50 cm relative to hot surface
- Injection Nozzle Inner Diameter (ID)
  - 0.6 mm – 0.8 mm
- Effect of Confinement*

Effects of altitude and ventilation air velocity will be accounted for by modeling

*Not usually varied by other investigators

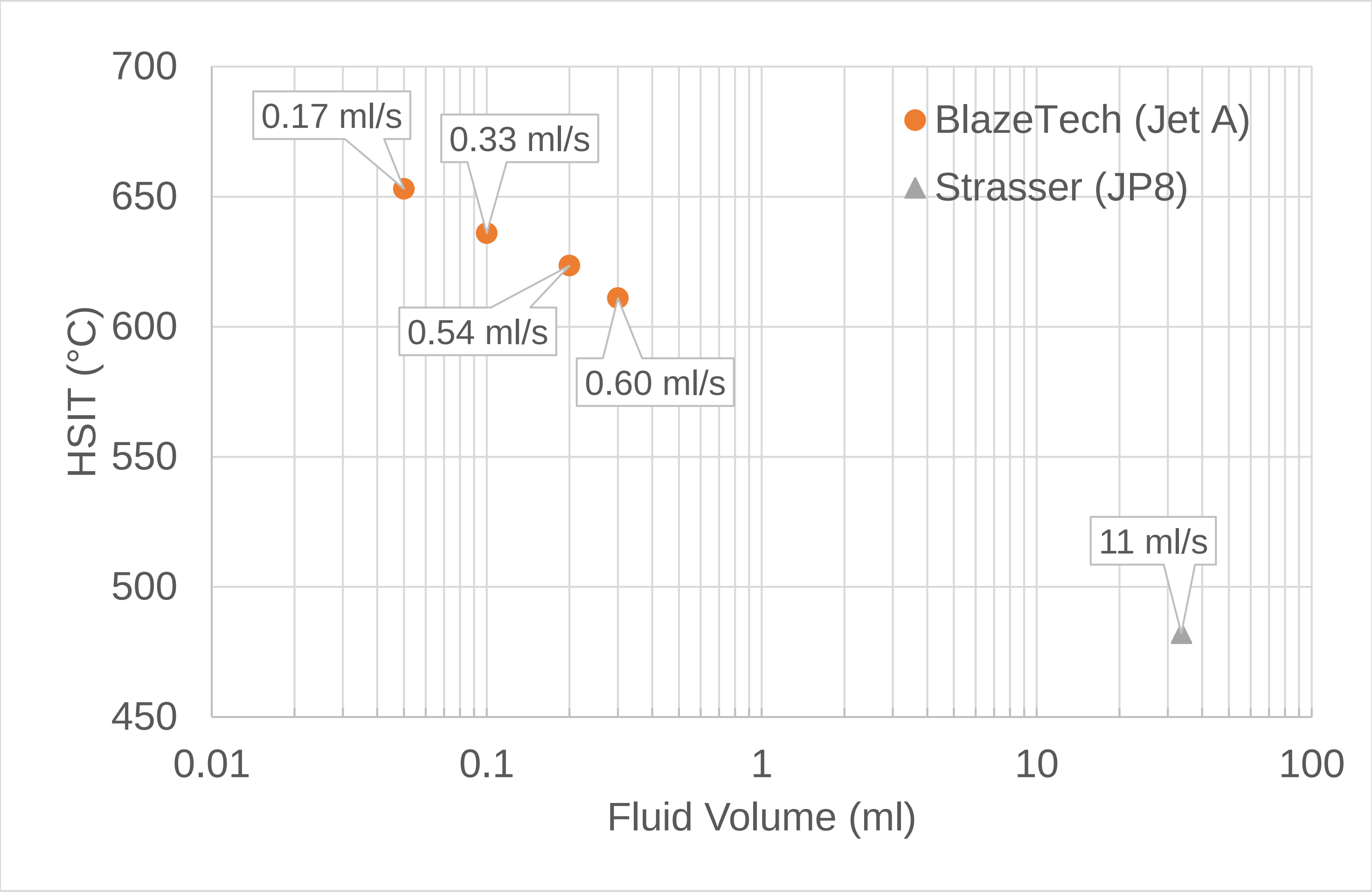
Effect of Injection Volume and Flow Rate



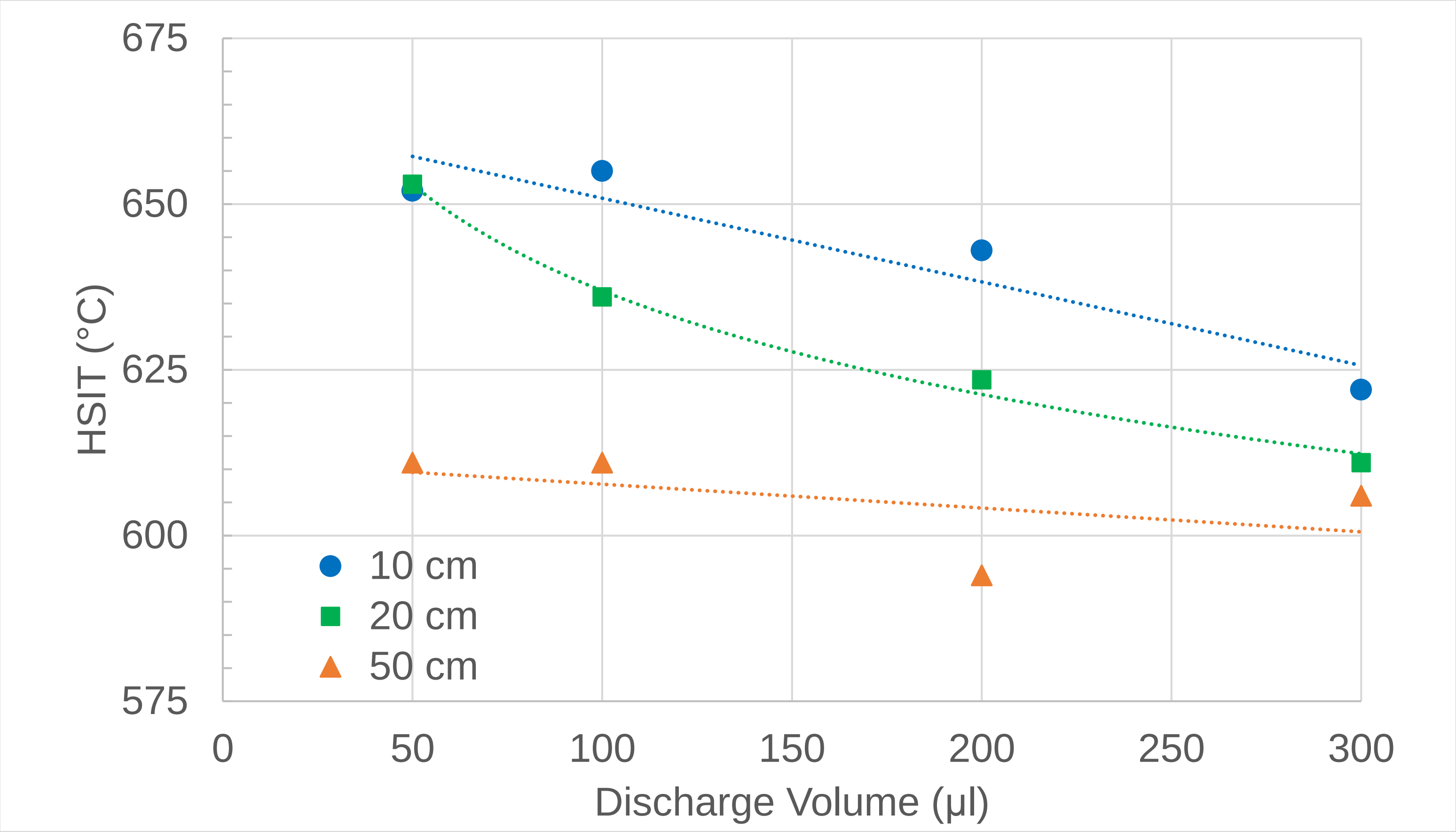
Inconel Duct – Jet A – Injection Height: 20 cm – Nozzle ID: 0.6 mm; AIT=238 C

HSIT Comparison with Literature

Study	Fuel	Relevant Cylinder Dimensions	Thickness	Material
BlazeTech	Jet A	4.5" OD, 12" length	0.2"	Inconel 625
Strasser, Waters, Kuchta	JP8	4" OD, 12" length	0.010”	SS

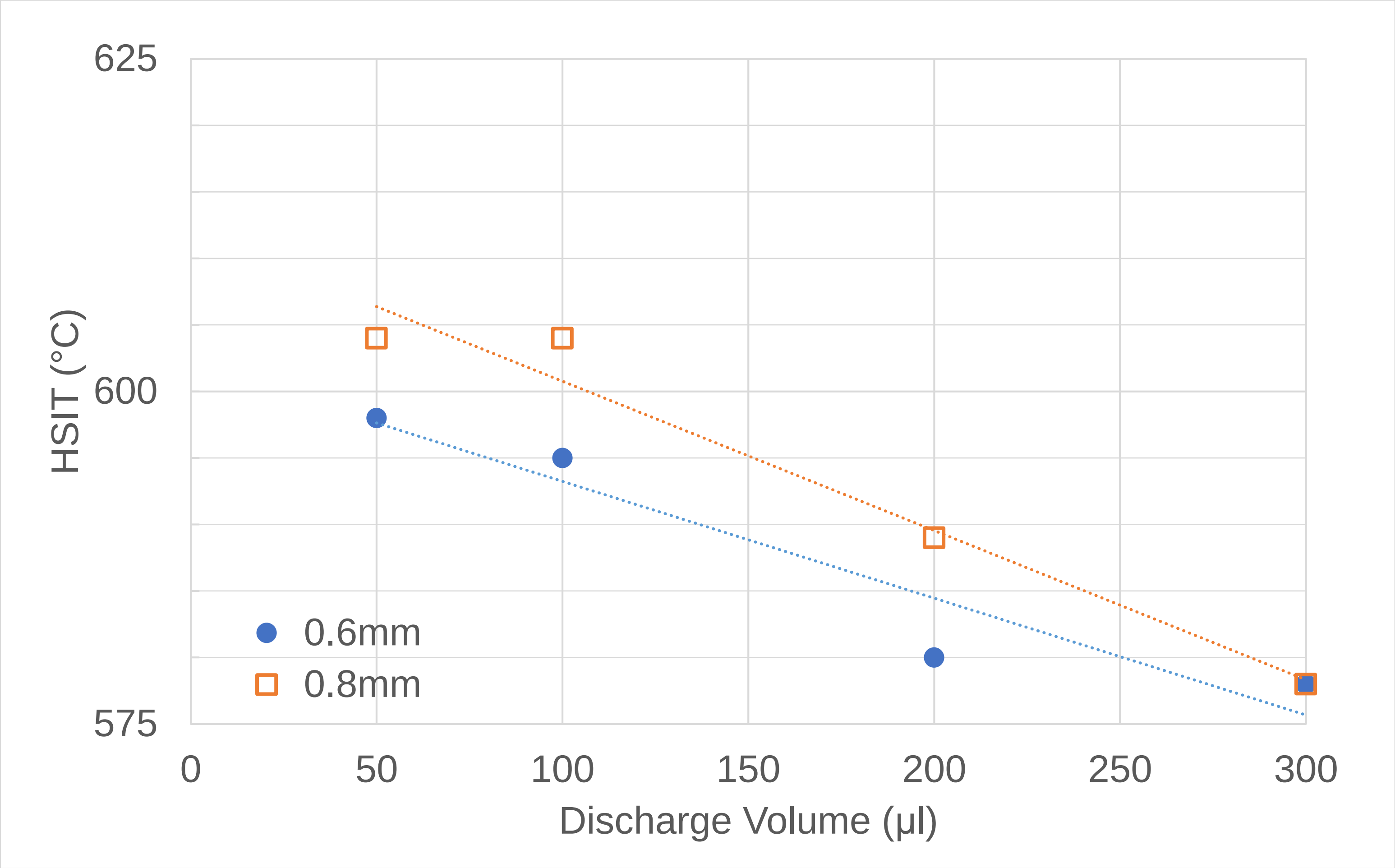


Effect of Injection Height



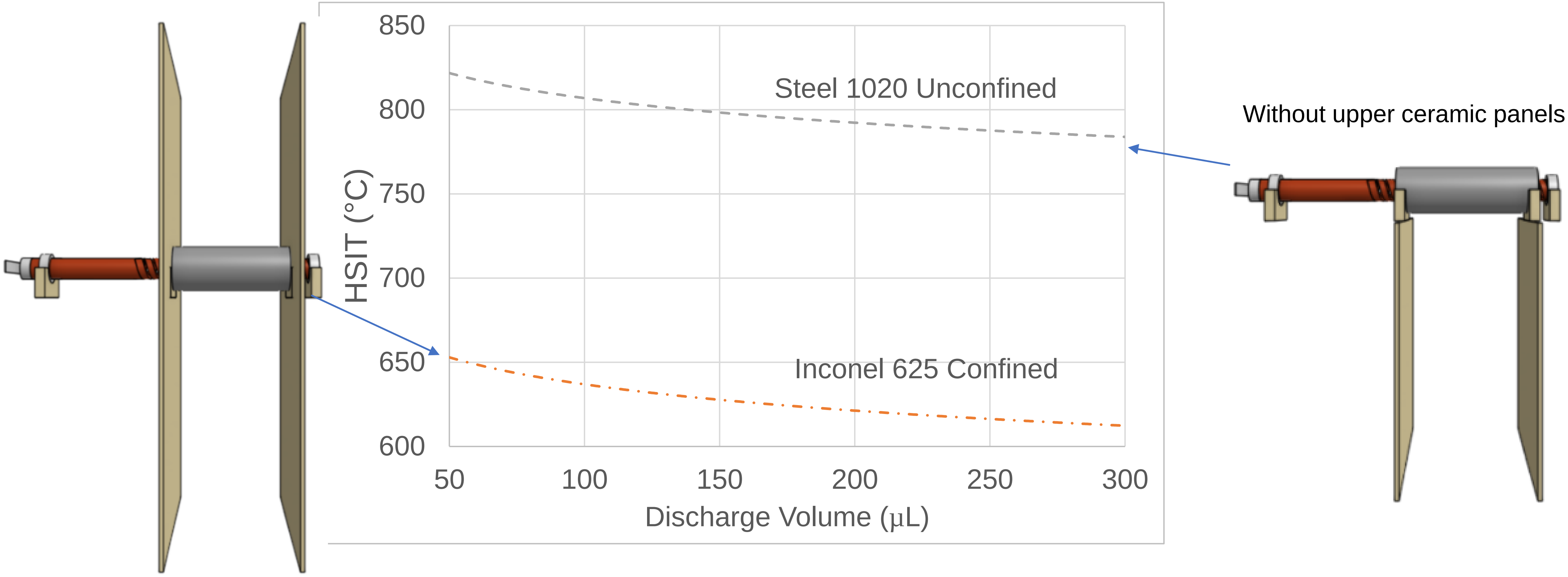
Inconel Duct – Jet A – Nozzle ID: 0.6 mm

Effect of Injection Nozzle ID



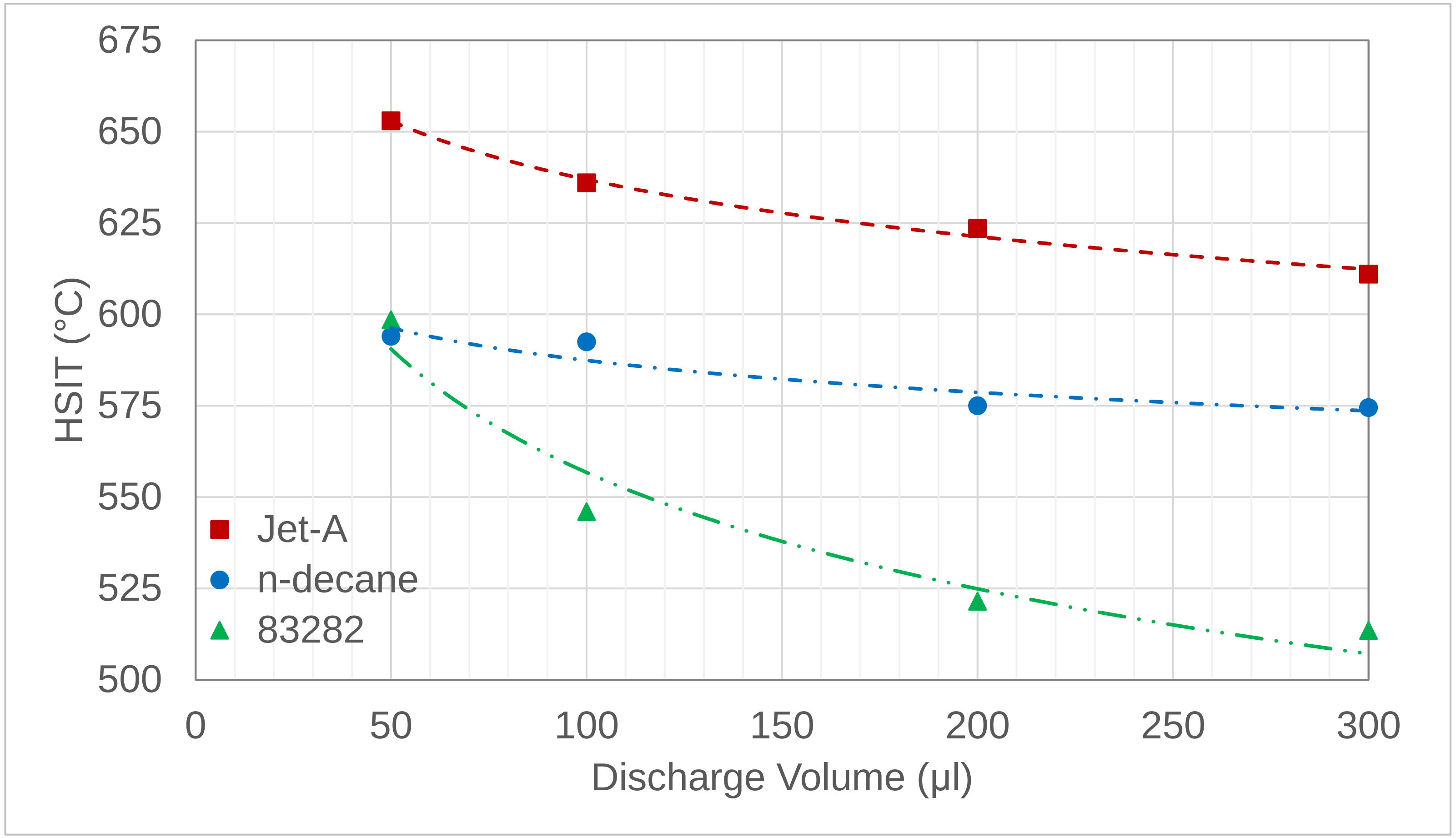
Inconel Duct – n-Decane – Inj. Height 20 cm

Effect of Confinement



Jet A - Inj. Height 20 cm - Nozzle ID: 0.6 mm

HSIT for Various Injected Fluid



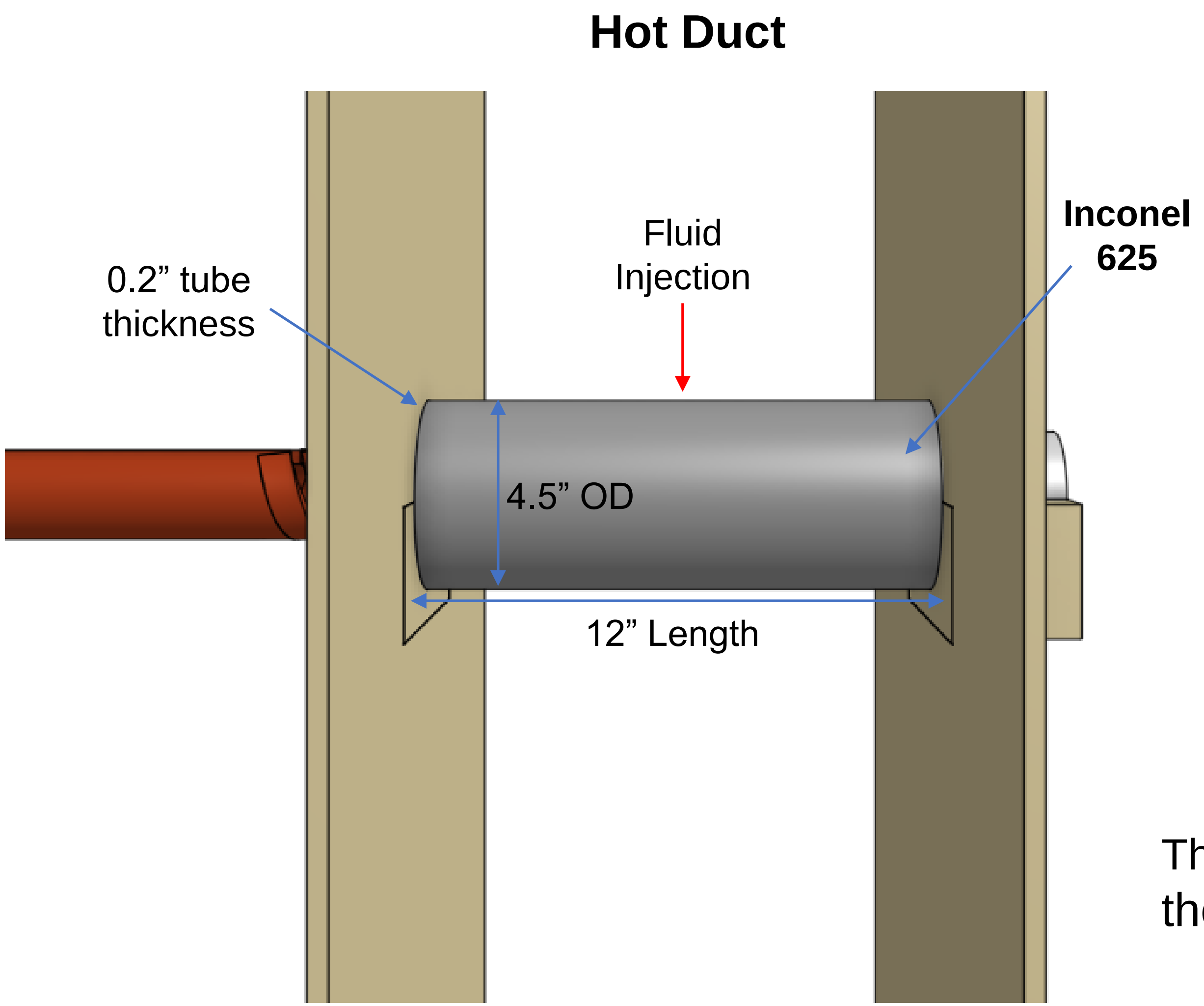
Inconel Duct - Inj. Height 20 cm - Nozzle ID: 0.6 mm

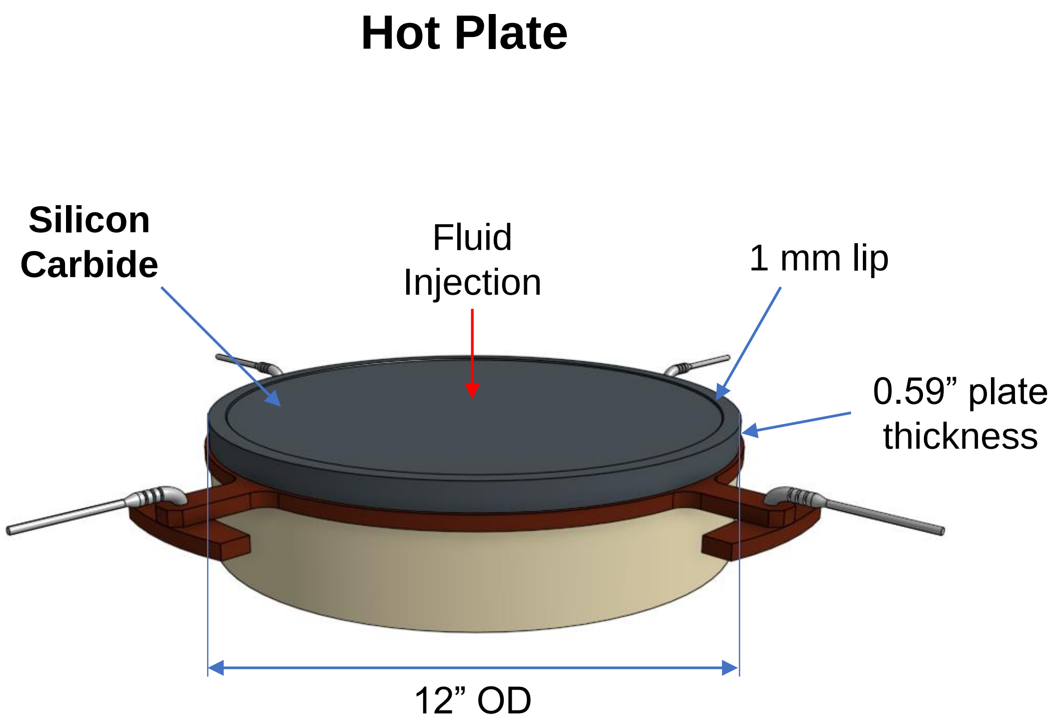
AITs: jet A 238 C; n-decane 210 C; 83282 > 345 C

Summary of Results for Duct Configuration

- For jet A, HSIT decreased with:
  - Increasing discharge volume
  - Increasing injection height
  - Increasing injection nozzle tip diameter
  - Increasing confinement
- For all test parameters, HSIT decreased from:
  - Jet A → n-decane → hydraulic fluid (83282)

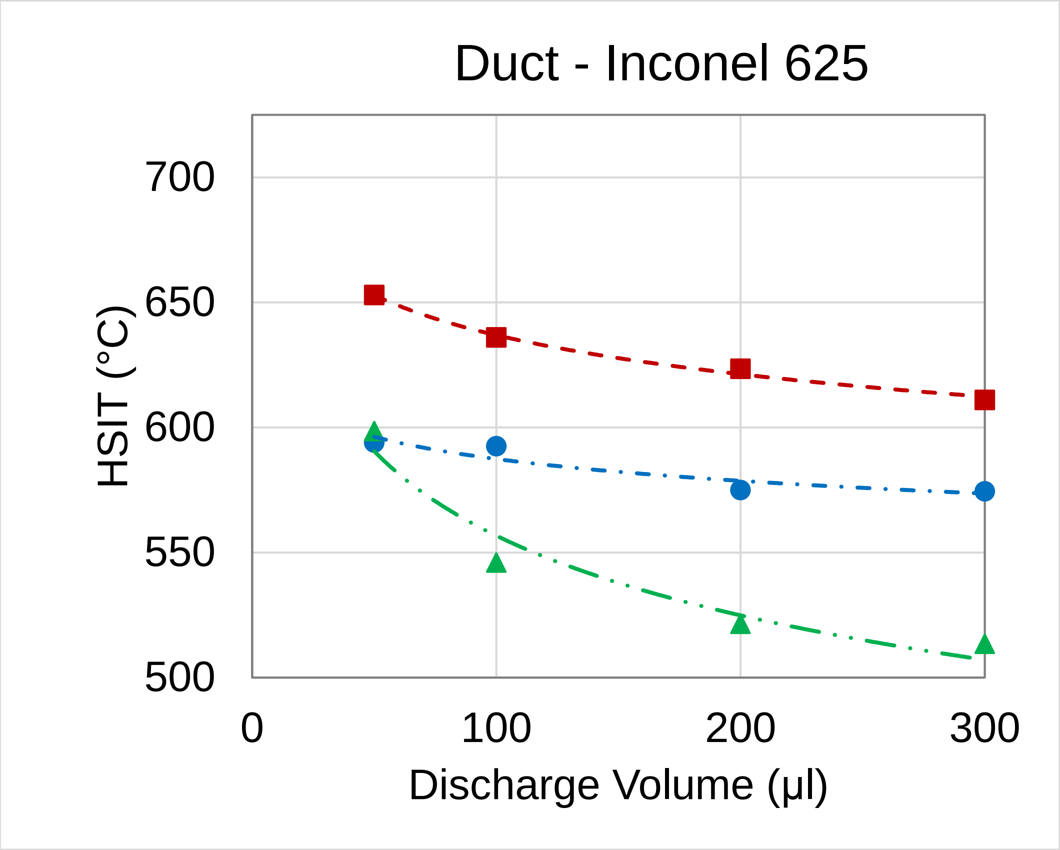
Hot Duct vs. Hot Plate Setups

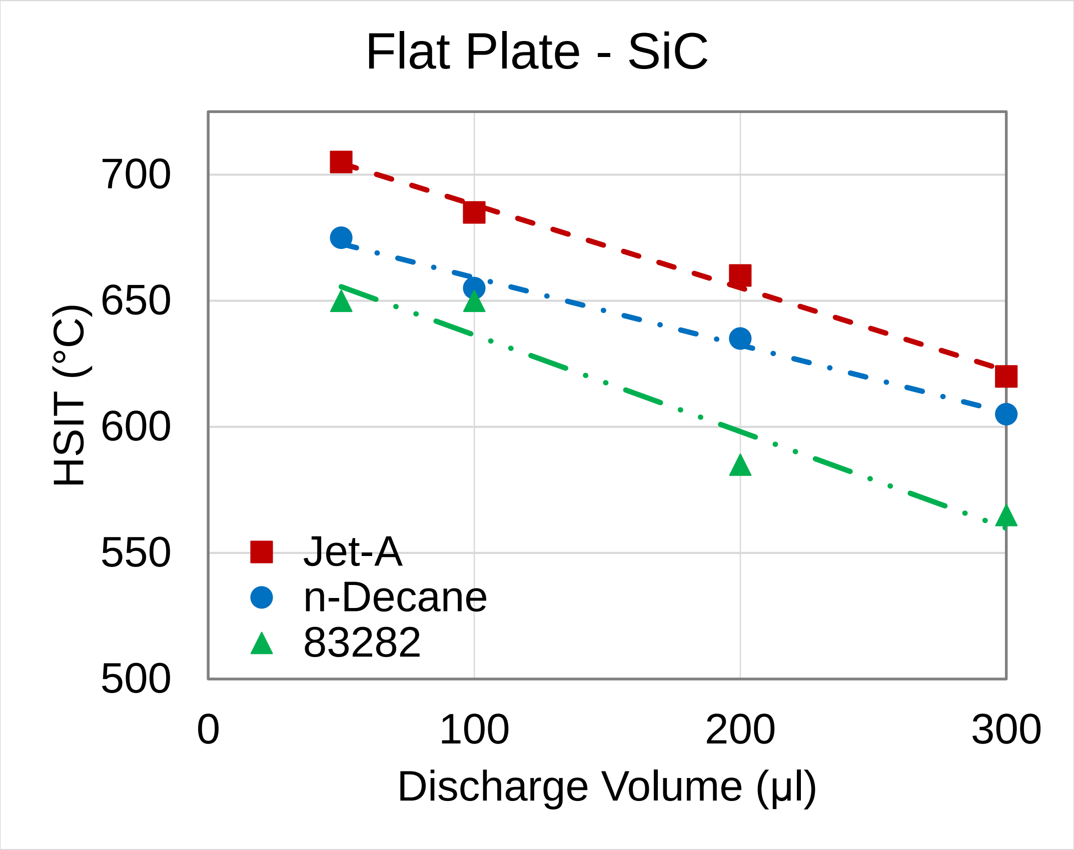




The 2 surfaces differ in materials, thickness and thermal inertias but same temperatures and lengths

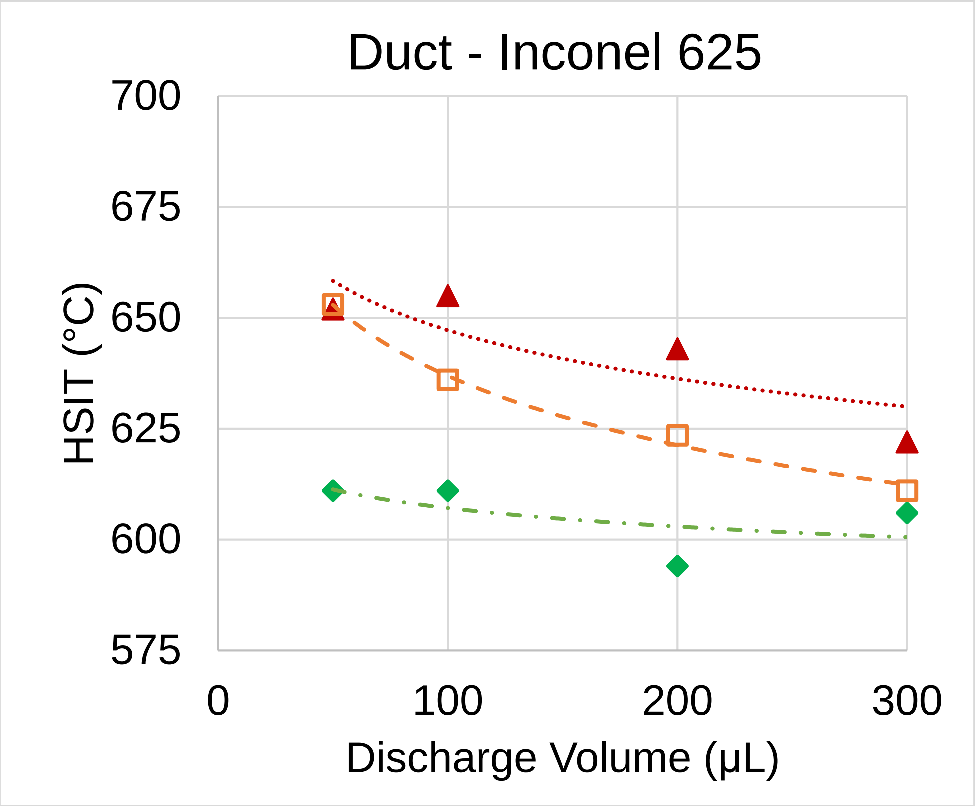
Duct vs. Flat Plate for Various Fluids

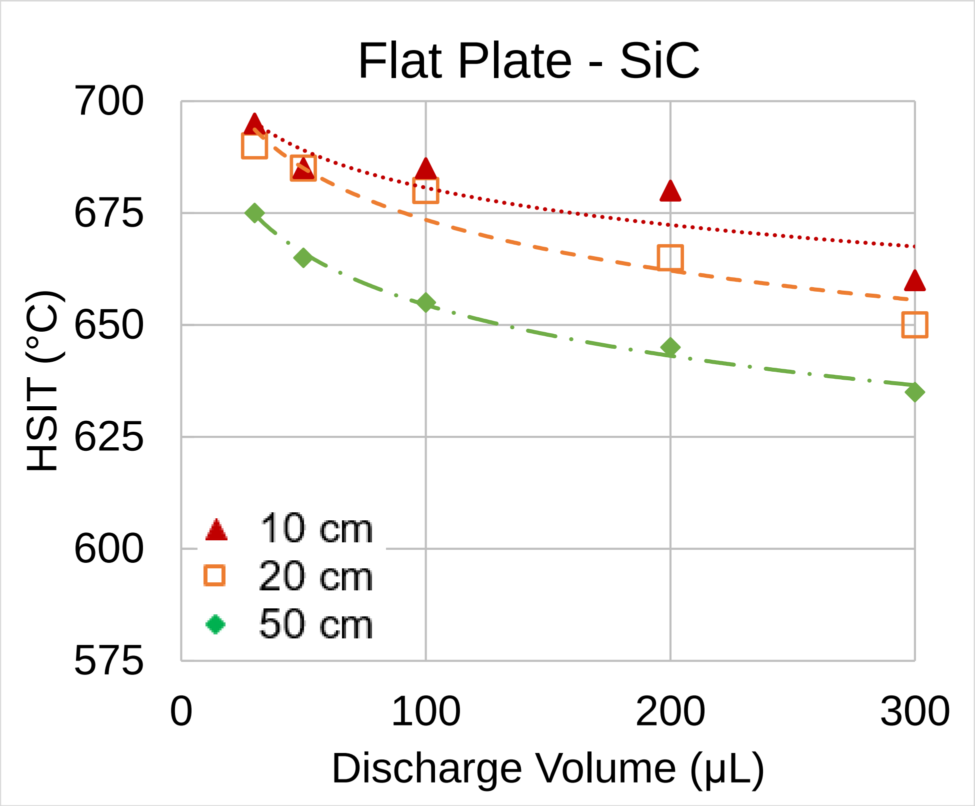




Inj. Height 20 cm - Nozzle ID: 0.6 mm

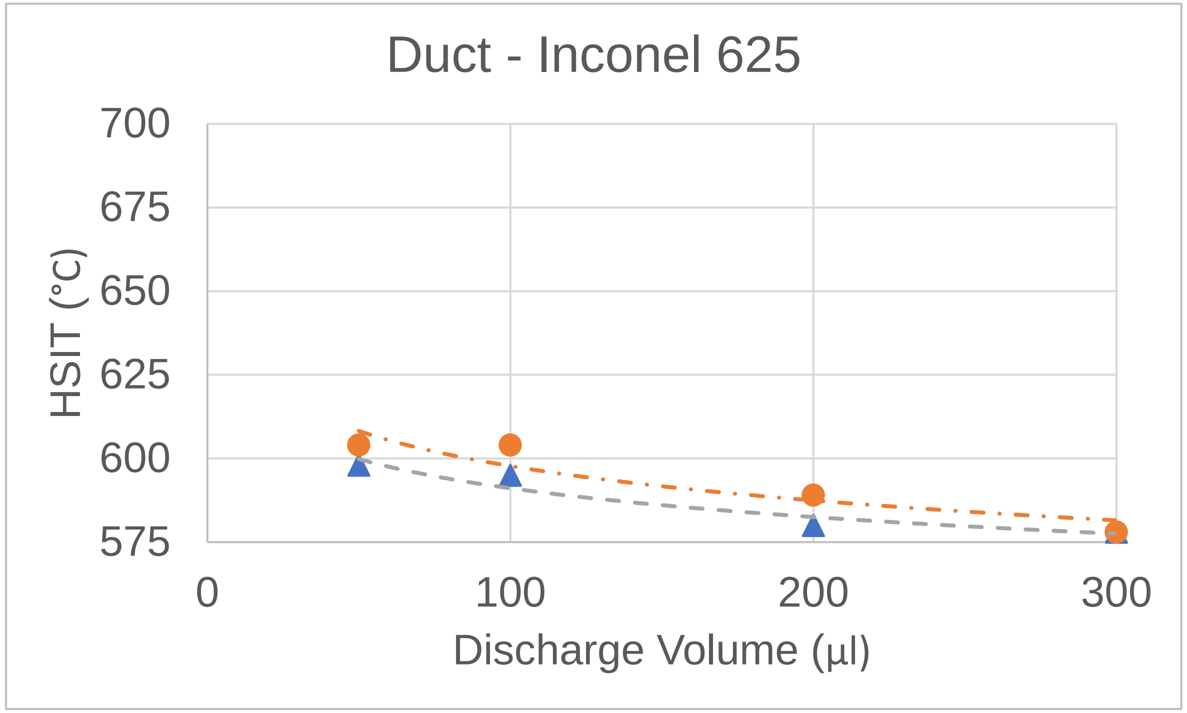
Hot Duct vs. Hot Plate – Injection Height

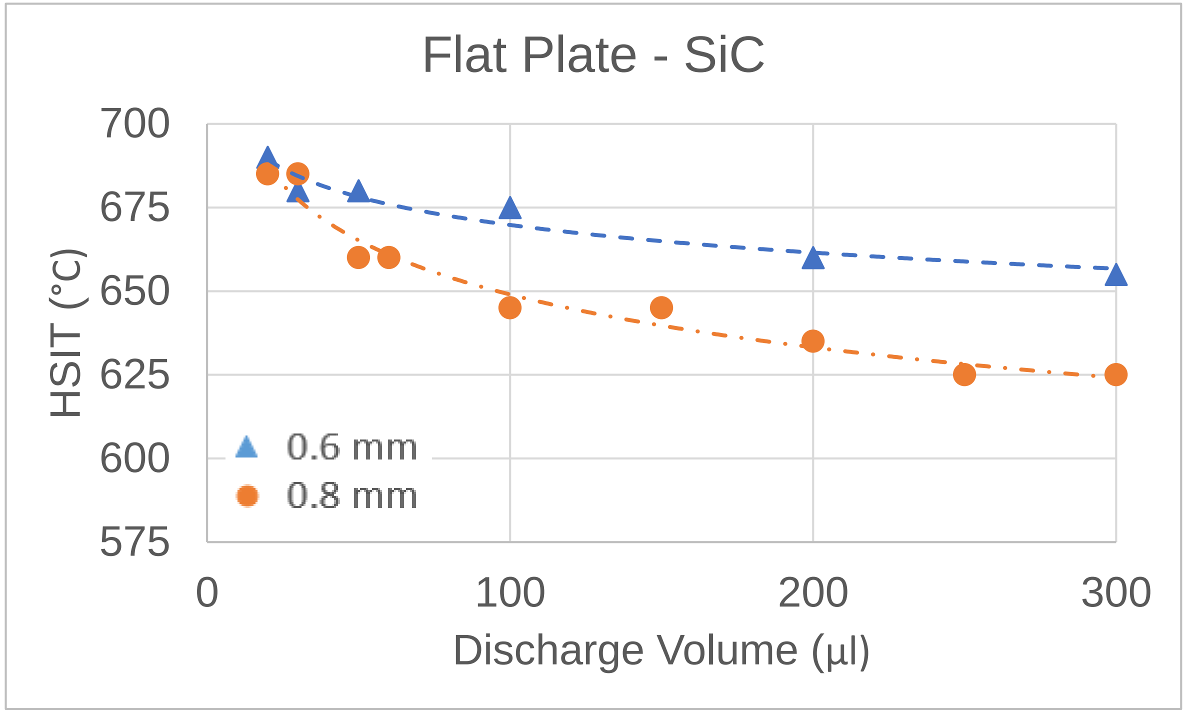




Jet A – Nozzle ID: 0.6 mm

Hot Duct vs. Hot Plate – Nozzle Tip ID

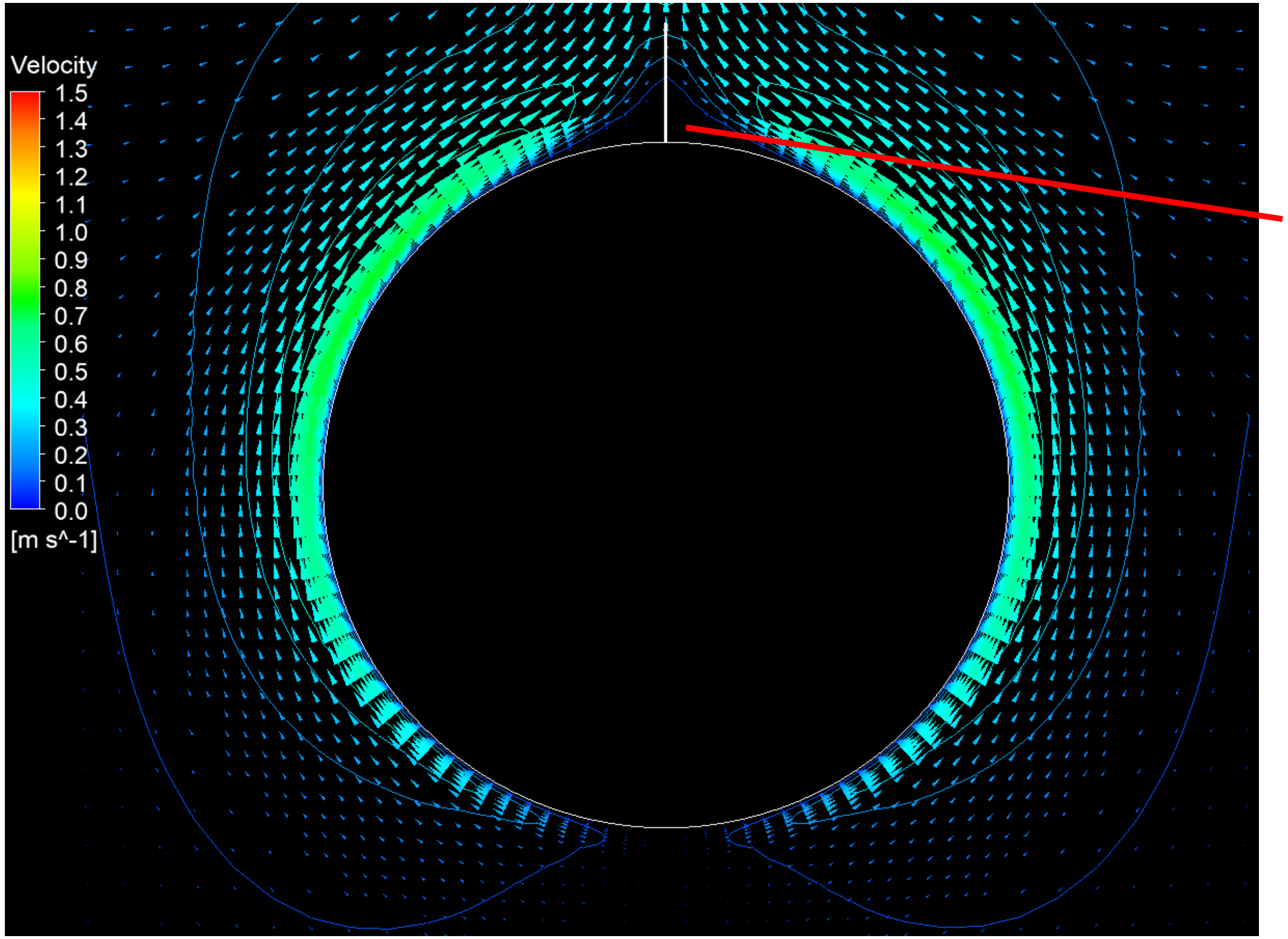




n-Decane – Inj. Height 20 cm

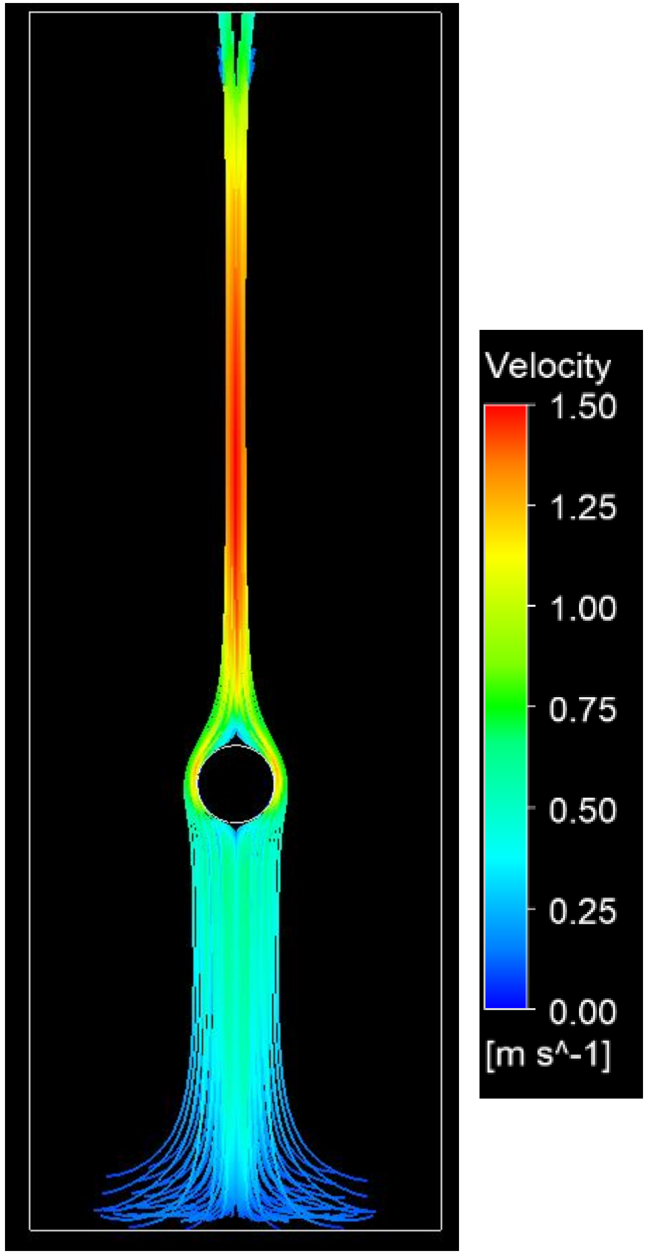
Hot Duct Side View

Velocity Vectors and Contours



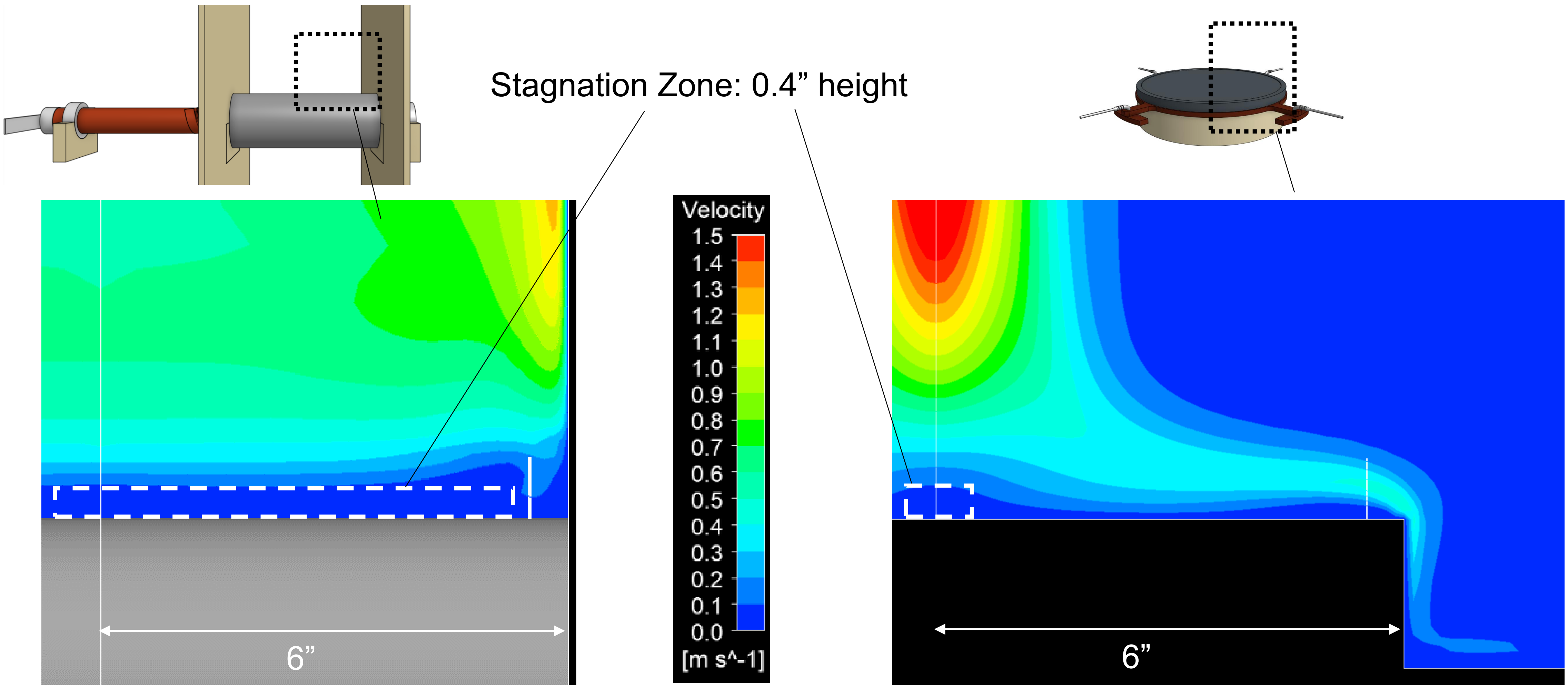
Stagnation Zone:

Streamlines



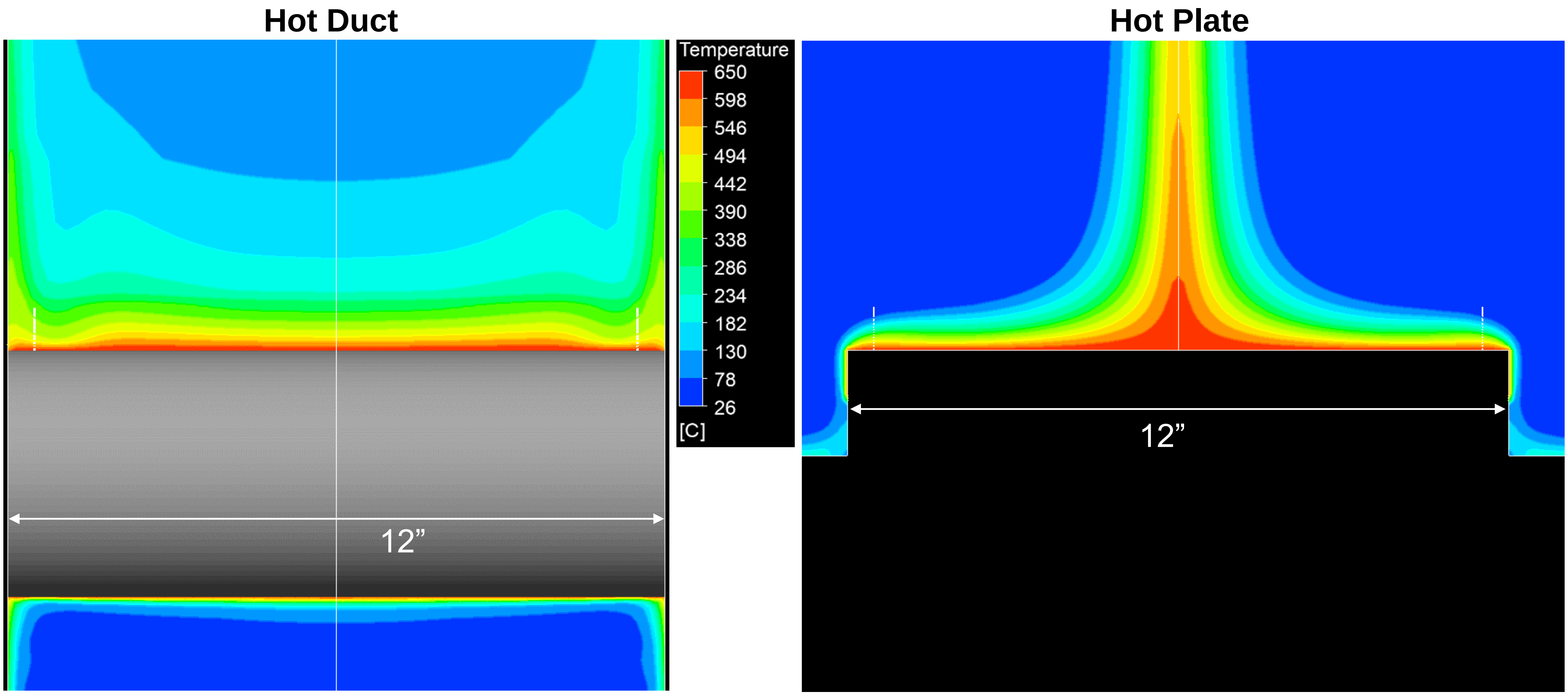
Duct vs. Flat Plate - Velocity Contours from CFD

Hot Duct **Hot Plate**



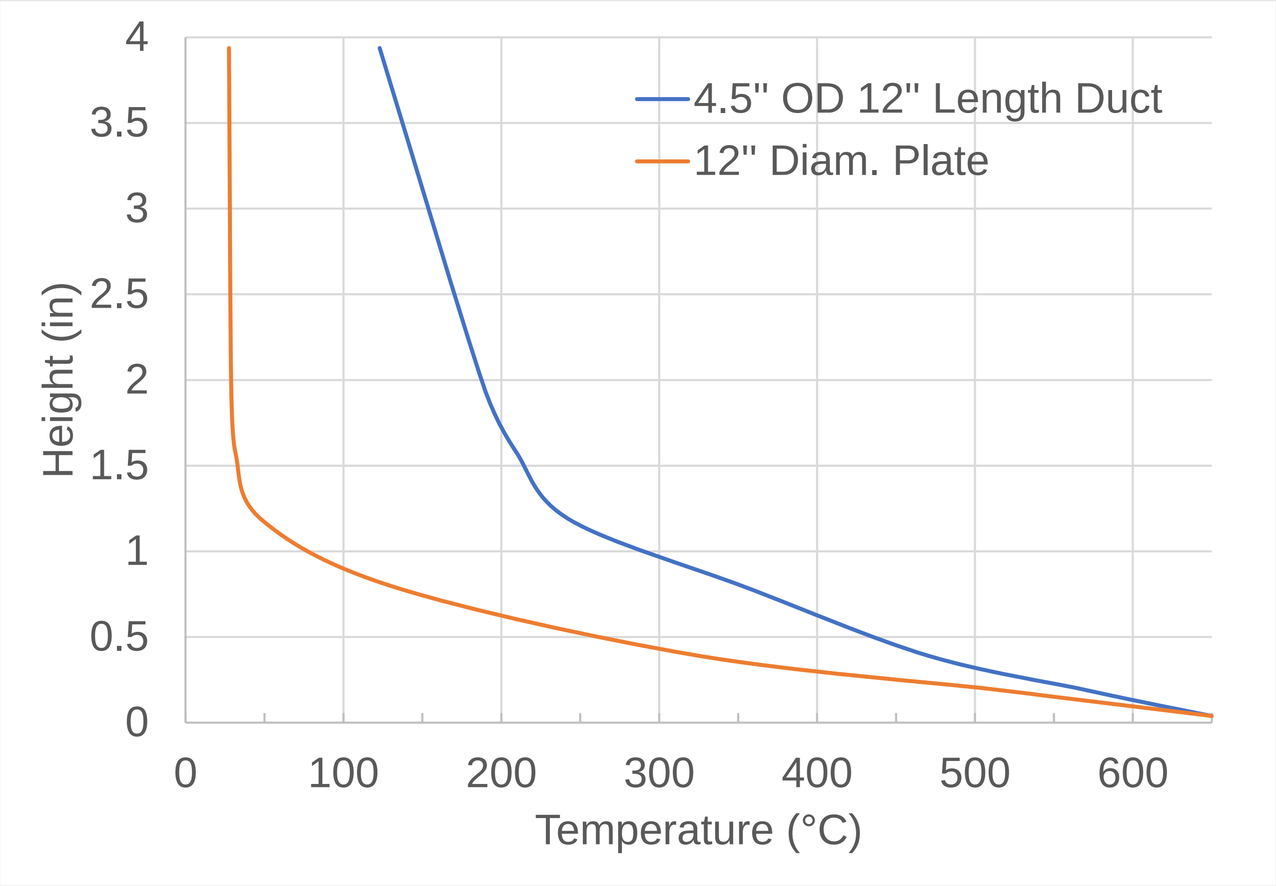
Longer duct stagnation zone promotes ignition; also higher temperature there

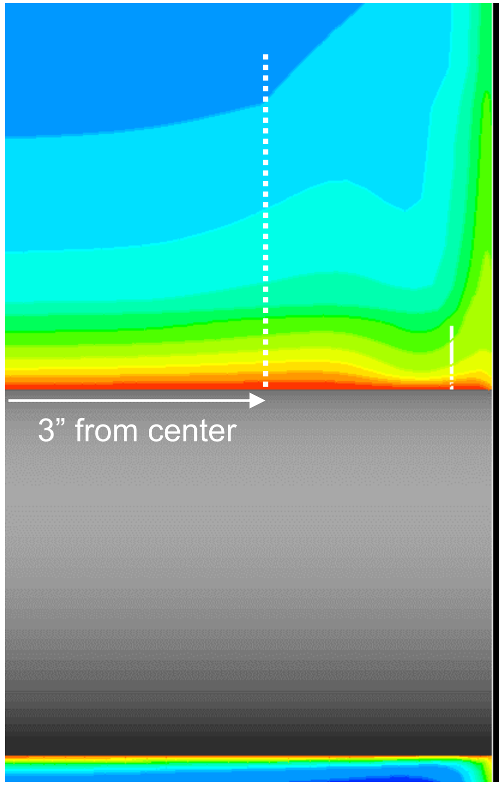
Duct vs. Flat Plate – Air Temp. Contours from CFD

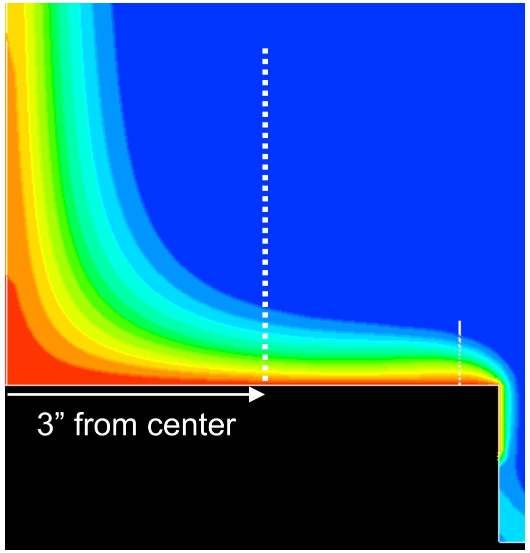


FLUENT, $T_{Duct} = T_{plate} = 650\ °C$

Temperature as a function of height at 3” from center, $T_{Duct} = T_{plate} = 650$ °C

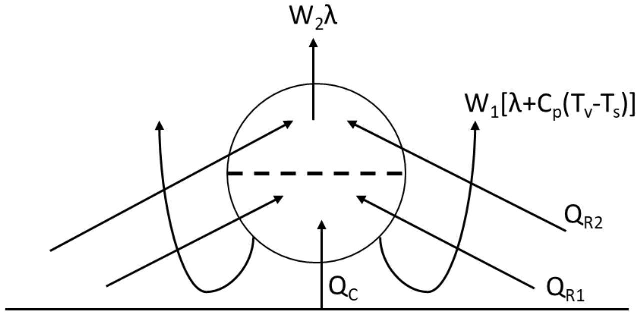


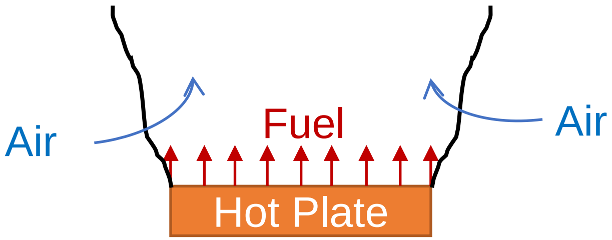




Higher B.L. temperature and longer duct stagnation zone promote ignition at lower HSIT

Engineering Model – Individual Modules





I. Fuel injection and impact velocity
II. Droplet breakup[1] and dynamics
III. Droplet evaporation rate[2]
IV. Integration of vapor from each droplets
V. Hot air plume correlation from Fu[3]
VI. Vapor-air mixing in plume
VII. Ignition criteria –
    Heat Generation Rate > Rate of external heat input from plume

1. A. S. Moita and A. L. N. Moreira, "Development of empirical correlations to predict the secondary droplet size of impacting droplets onto heated surfaces," *Experiments in Fluids,* vol. 47, no. 4-5, pp. 755-768, 2009.
2. B. S. Gottfried, C. J. Lee and K. J. Bell, "The Leidenfrost phenomenon: film boiling of liquid droplets on a flat plate," Int. J. Heat Mass Transf., vol. 9, no. 11, pp. 1167-1188, 1966.
3. T. T. Fu, "The turbulent free convection flow above a heated horizontal circular plate," 1970.

Summing Vapor Contribution from Each Droplet

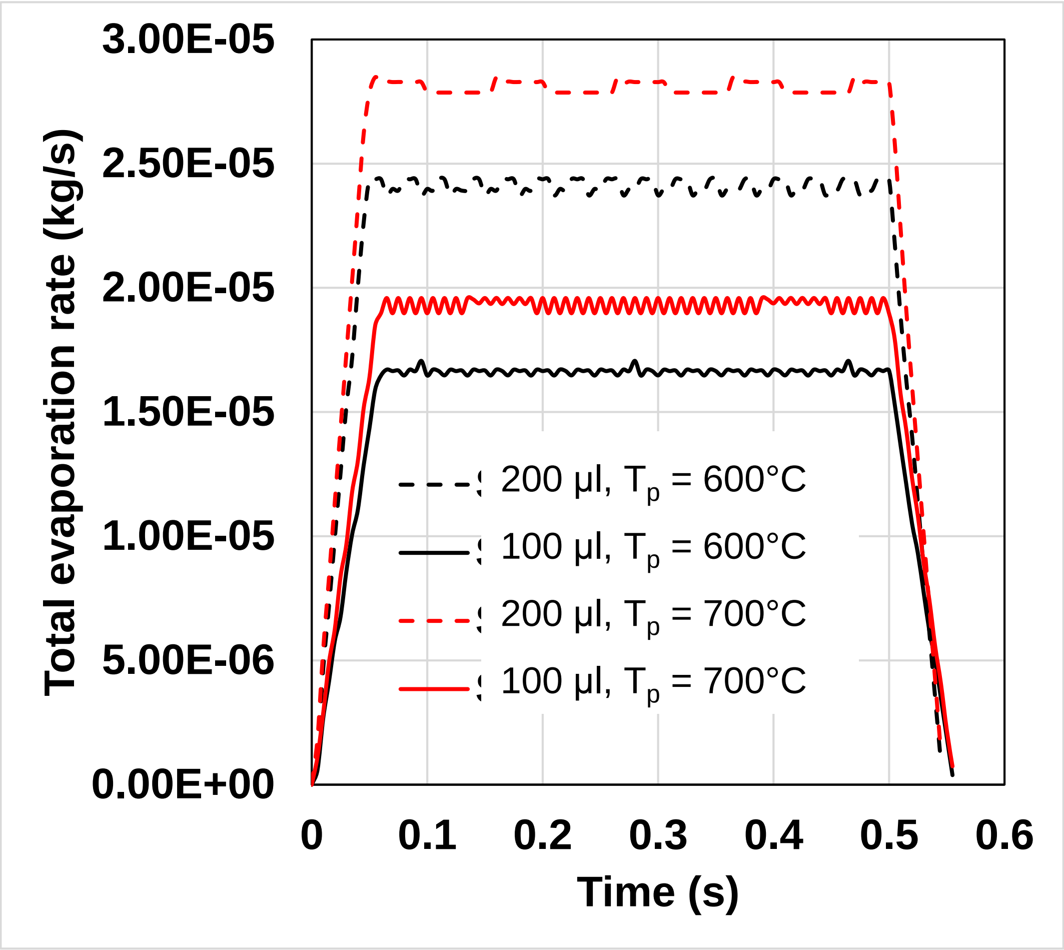
$$\dot{m}_f(t,n) = \begin{bmatrix} \dot{m}_f(1,1) & \cdots & \dot{m}_f(1,t_{exit}) & 0 & & \cdots & 0 \\ 0 & \dot{m}_f(2,1) & \cdots & \dot{m}_f(2,t_{exit}) & & \cdots & 0 \\ 0 & \cdots & \dot{m}_f(n,t) & \cdots & & \dot{m}_f(n,t+t_{exit}) & 0 \\ 0 & \cdots & \cdots & \ddots & & & \\ 0 & \cdots & & & & & \\ 0 & \cdots & 0 & \dot{m}_f\left(t_{discharge},N\right) & & \cdots & \dot{m}_f(t_{end},N) \end{bmatrix}$$

$$\sum \dot{m}_f\,(t) = \left[\sum \dot{m}_f(1,1{:}N), \sum \dot{m}_f(2,1{:}N), \ldots, \sum \dot{m}_f(t_{end},1{:}N)\right]$$

Where,

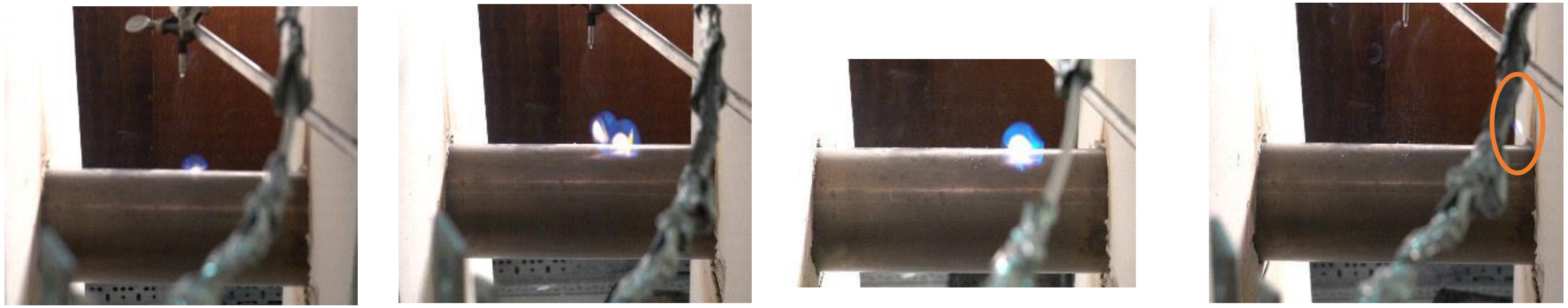
- t_{exit} = time for 1 droplet to travel from center of the plate to the edge (s)
- $t_{discharge}$ = total time of fluid discharge (s)
- t_{end} = total time from the start of the first droplet formation to the last droplet left the hot surface $= t_{exit\ of\ 1st\ droplet} + t_{discharge} + t_{exit\ of\ the\ last\ droplet} = 2t_{exit} + t_{discharge}$ (s)
- N = total number of droplets formed

Summing Vapor Contribution from Each Droplet



12" Flat Plate – n-Decane - Inj. Height 20 cm - Nozzle ID: 0.6 mm - Discharge time: 0.5 s

Approach for Duct Model

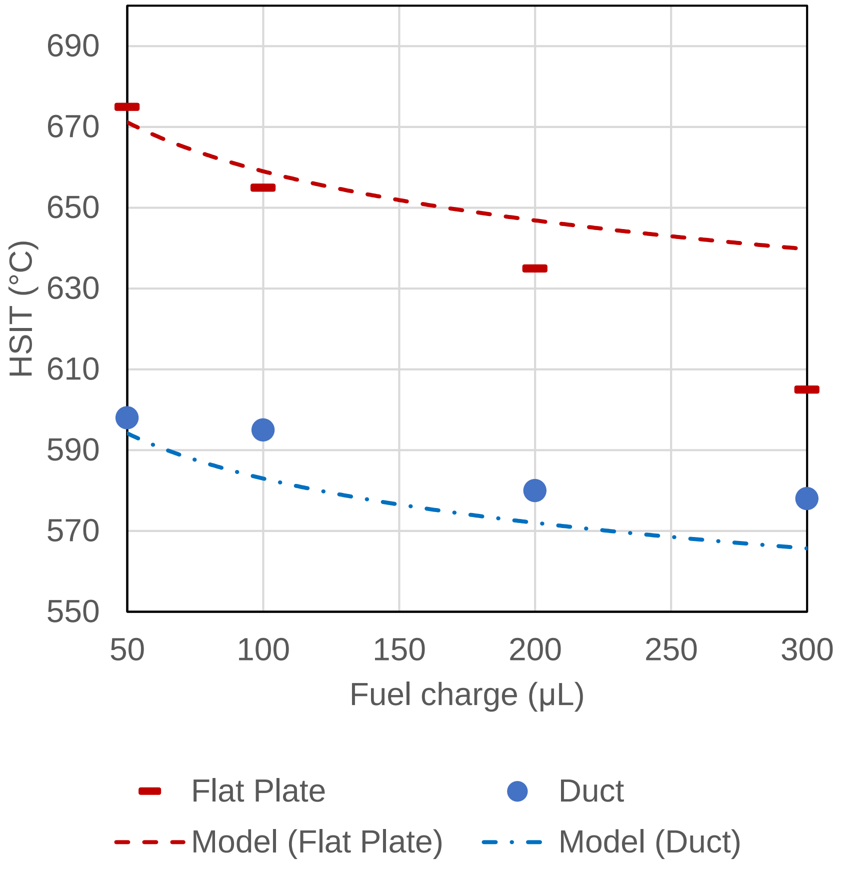


50µL 100µL 200µL 300 µL

- Ignition occurs at the top of the duct, therefore only the droplets traveling on the top of the surface are accounted for in the model.
  - $N_{duct} = K \times N_{plate}$
  - Where *K* ~ 0.1
- Temperature gradient close to the duct are considered negligible in the stagnation zone
  - $T_{gas} \approx T_{surface}$

4.5" Dia. Inc 625 Duct – Jet A - Inj. Height 10 cm - Nozzle ID: 0.6 mm

Comparison of Engineering Model Results for Duct vs. Flat Plate



n-Decane - Inj. Height 20 cm - Nozzle ID: 0.6 mm

Closure: Duct vs. Flat Plate

- They same temp. and length
  - But different materials, thickness and thermal inertia
- For all liquids tested, lower HSIT for duct than flat plate
  - Ducts more realistic on aircraft than flat surfaces
- From CFD, this was attributed to:
  - Longer stagnation zone created above the duct longer time in hot zone
  - Temp. drops slower for duct than flat surface as one moves away from surface
- Engineering model yields reasonable trends, but further work is needed for closer agreement with test data
  - Runs faster and easier to use than CFD
  - Can be adapted to individual cases