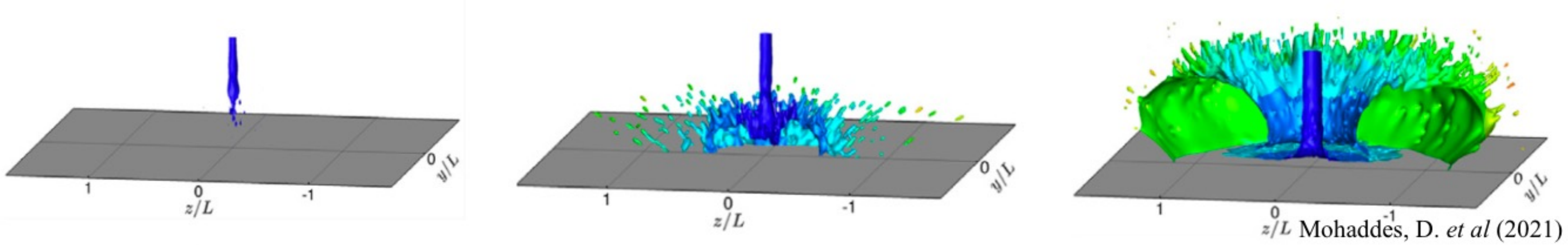
Hot-Surface Ignition of Fuel Sprays in Aircraft Compartment Fires

A COMPUTATIONAL & EXPERIMENTAL ANALYSIS

Lauren Simitz, Danyal Mohaddes, Jesus Cervantes,
Guillaume Vignat, Matthias Ihme



Mohaddes, D. *et al* (2021)

$t/\tau = 1.1$ $t/\tau = 3.3$ $t/\tau = 16.7$

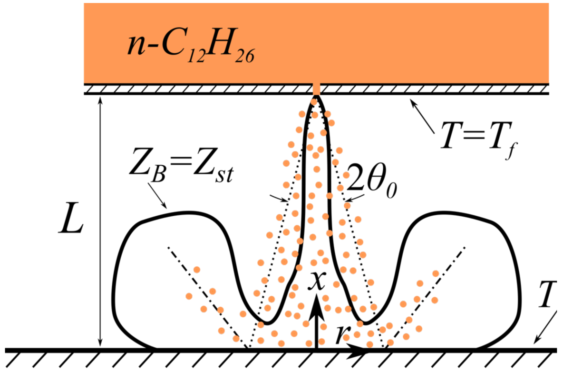
Acknowledgements: Philipp Boettcher, Brad Moravec, Jason Damazo

Stanford University

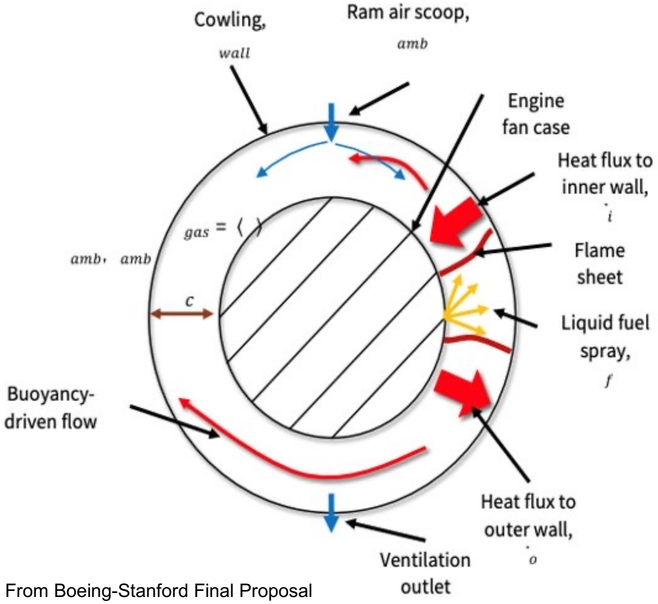
Outline

- **Introduction**
  - Motivation
  - Physics Overview
  - Research Challenges, Objectives
- **Geometric & Time Scale Analysis**
- **Simulations**
  - Detailed (3D) Modeling
  - Reduced-Dimension (1D) Modeling
- **Conclusion**
  - Key Findings
  - Future Work

General Electric GE90 [1]



Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.



From Boeing-Stanford Final Proposal

Introduction

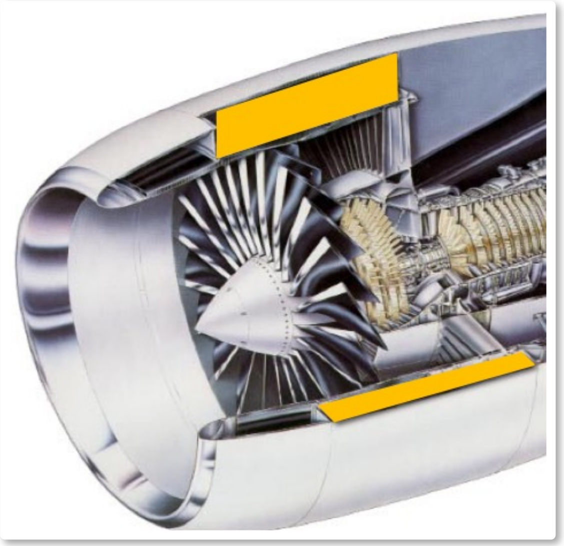


Image from “Towards an Automated Full-Turbofan Engine Numerical Simulation”, *NASA Report* (2003)

Motivation | Accidental Fires

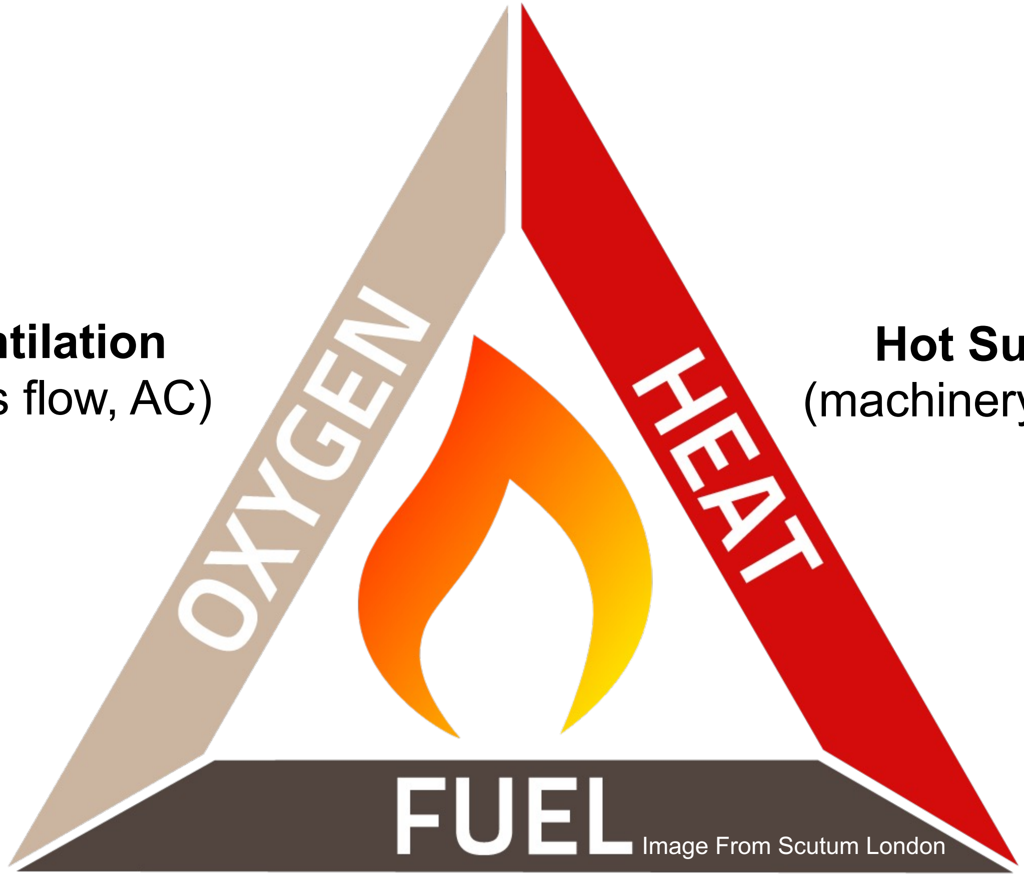
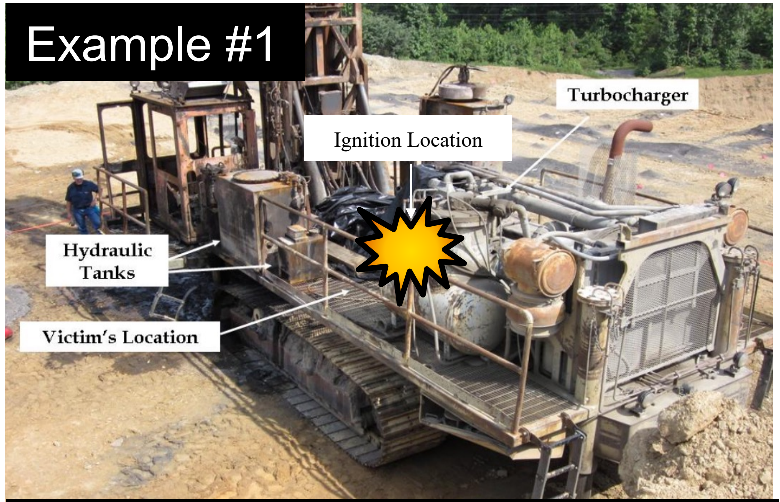


Image From Scutum London

Ventilation
(cross flow, AC)

Hot Surfaces
(machinery, casings)

Flammable Fluids
(fuel, hydraulics, oil)



Highwall Drill Rig involved in ignition accident, 2010

Fatal Ignition Investigation Report, Mining Safety & Health Agency

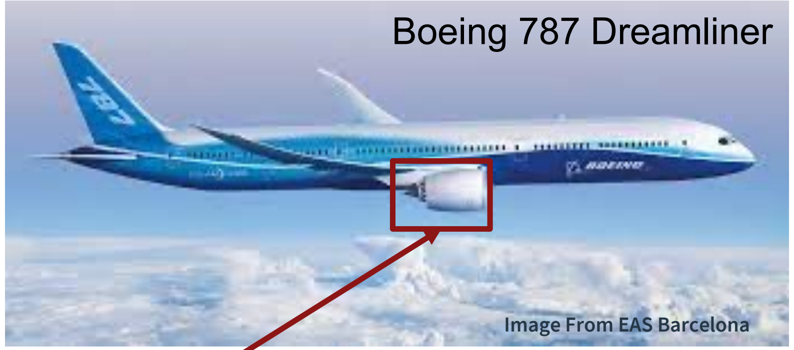
Rolls Royce Trent 700/Airbus A330, post-incident 2011

Final Report: Airbus A330 Engine Fire Event, AAIB Singapore

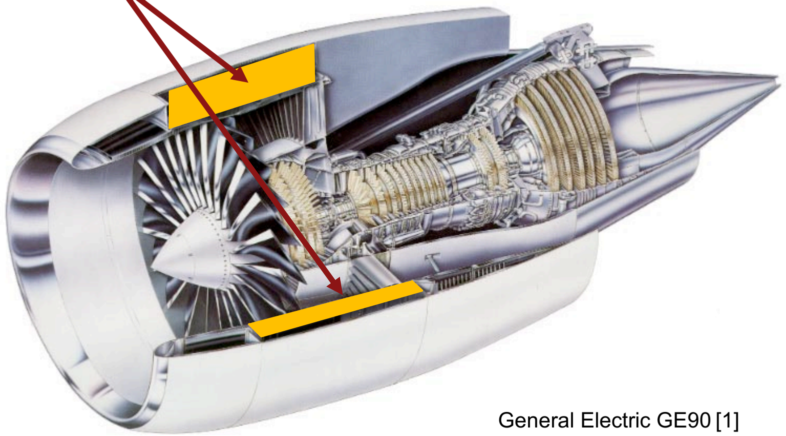
Motivation | Fire Safety Analysis in Engine Fan Case Compartment

- Small annular space between fan case and cowling
- Must be considered for aircraft fire safety analysis in event of a fuel line leak/breakage
- Fuel source:
  - Liquid Jet-A, $p_f \leq 8.3$ Mpa
  - Hydraulic fluid, lube oil (future work)

- Air sources: leakage through cowling from aerodynamic pressure, natural ventilation
  - 30 kPa $\leq p \leq 101$ kPa
  - 230 K $\leq T \leq 330$K
- Ignition sources: hot surfaces
  - Starter motor
  - Pumps, gearbox



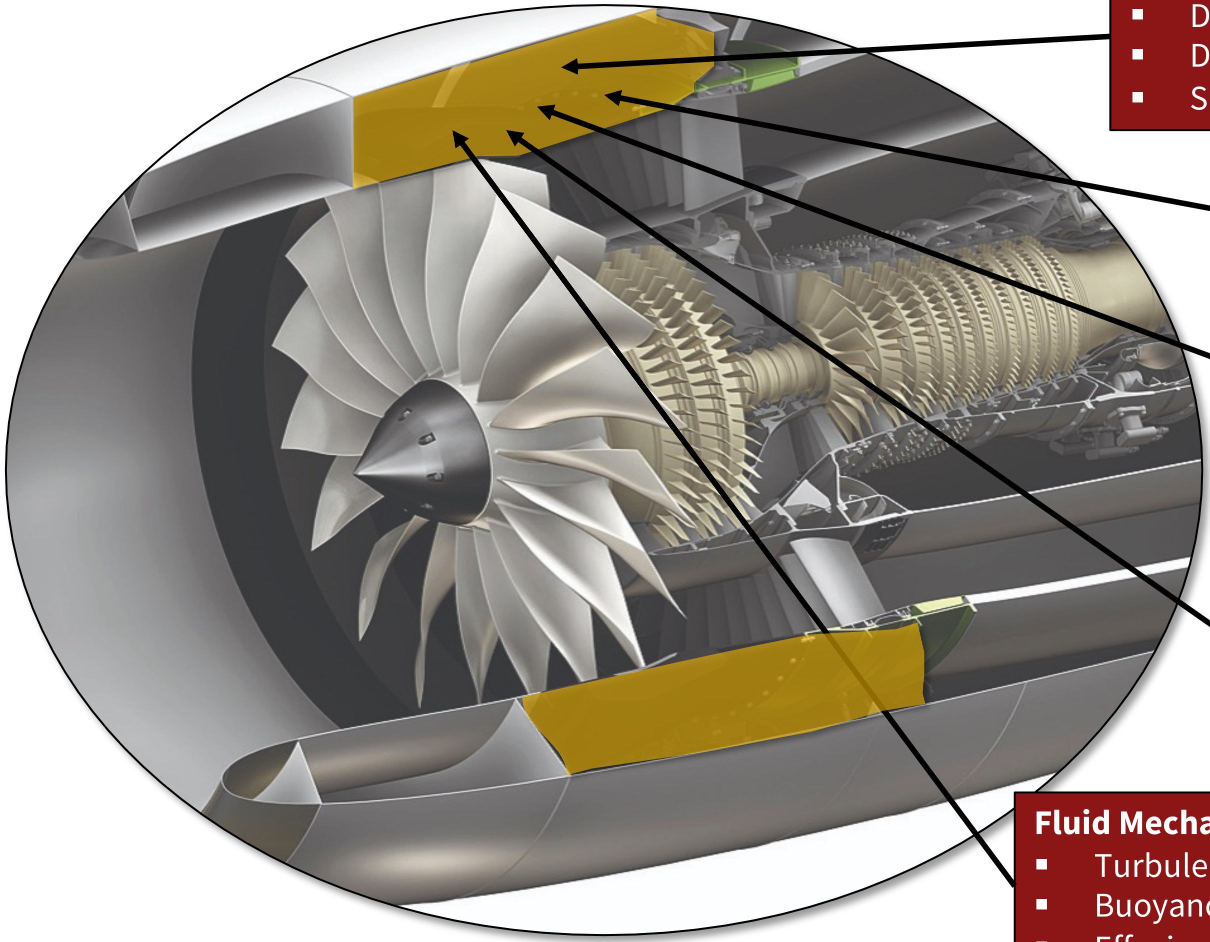
"Fan case compartment"



General Electric GE90 [1]

[1] Adapted from *Towards an Automated Full-Turbofan Engine Numerical Simulation,* NASA Report, 2003.
[2] *Final Report: Airbus A330 Engine Fire Event,* AAIB Singapore

Physics Overview



General Electric GE90 [1]

Fuel Leakage and Injection
- Droplet Breakup
- Droplet Distribution
- Spray/wall Interaction

Vaporization
- Multicomponent Fuel
- Fuel Description and Modeling
- Spray/Flow Interaction

Ignition
- Fuel Spray Spark Ignition
- Preferential Combustion
- Hot Surface Ignition

Combustion
- Chemistry
- Radiation
- Wall Heat Transfer

Fluid Mechanics
- Turbulent Mixing
- Buoyancy
- Effusive Flows

Research Challenges & Objectives

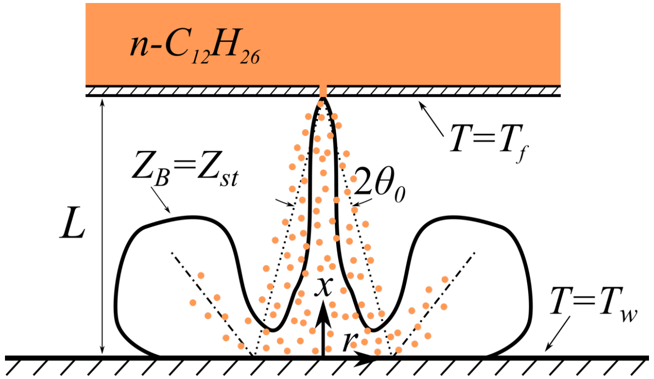
Research Challenges

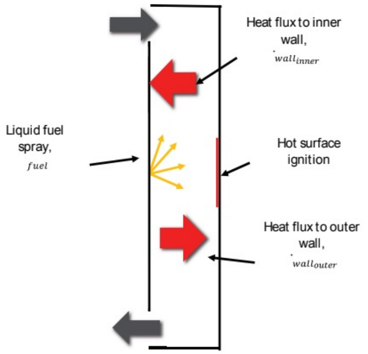
- Lack of fundamental understanding of multi-physics interaction in hot surface ignition (HSI)
- Lack of predictive models for HSI
- Need for simulation-informed fire safety certification for aircraft

Objectives

- Generate physics-based modeling tools to analyze and predict compartment fires
- Validate modeling tools with high realism, in-house experimental data


Aeon Brown (2021), FAA





Geometric & Time Scale Analysis

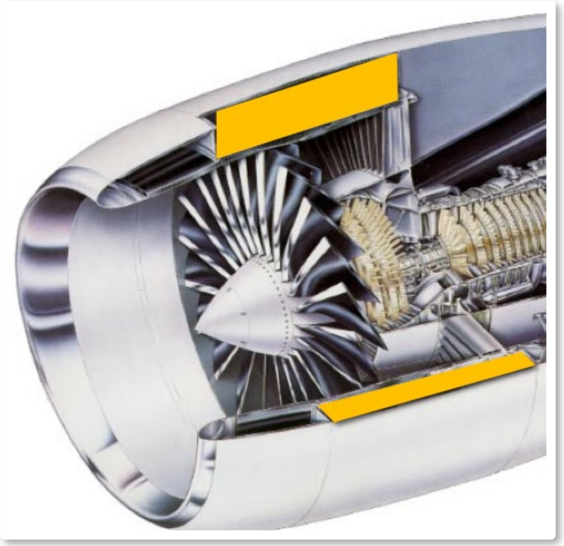
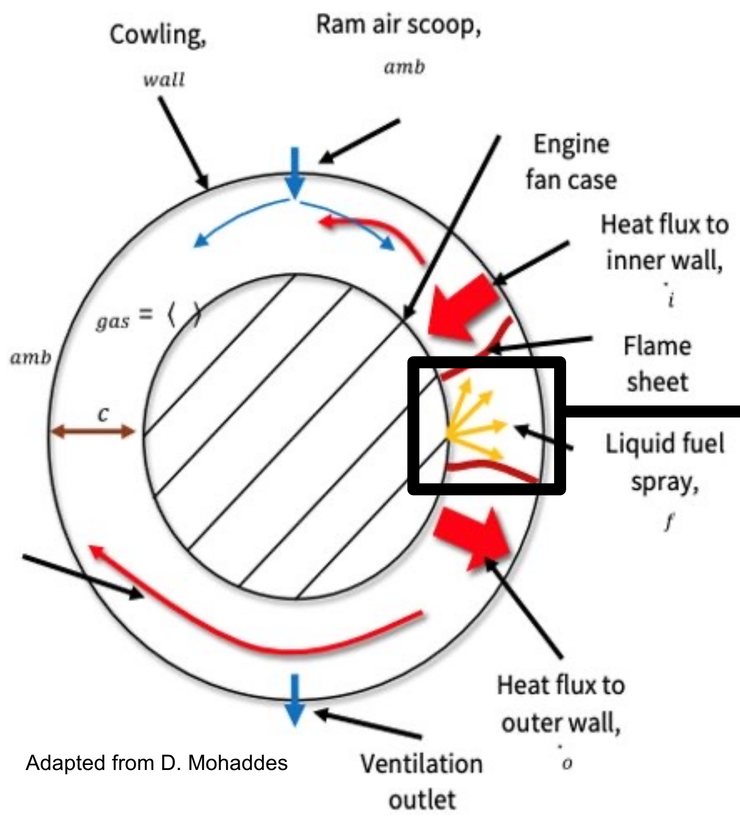


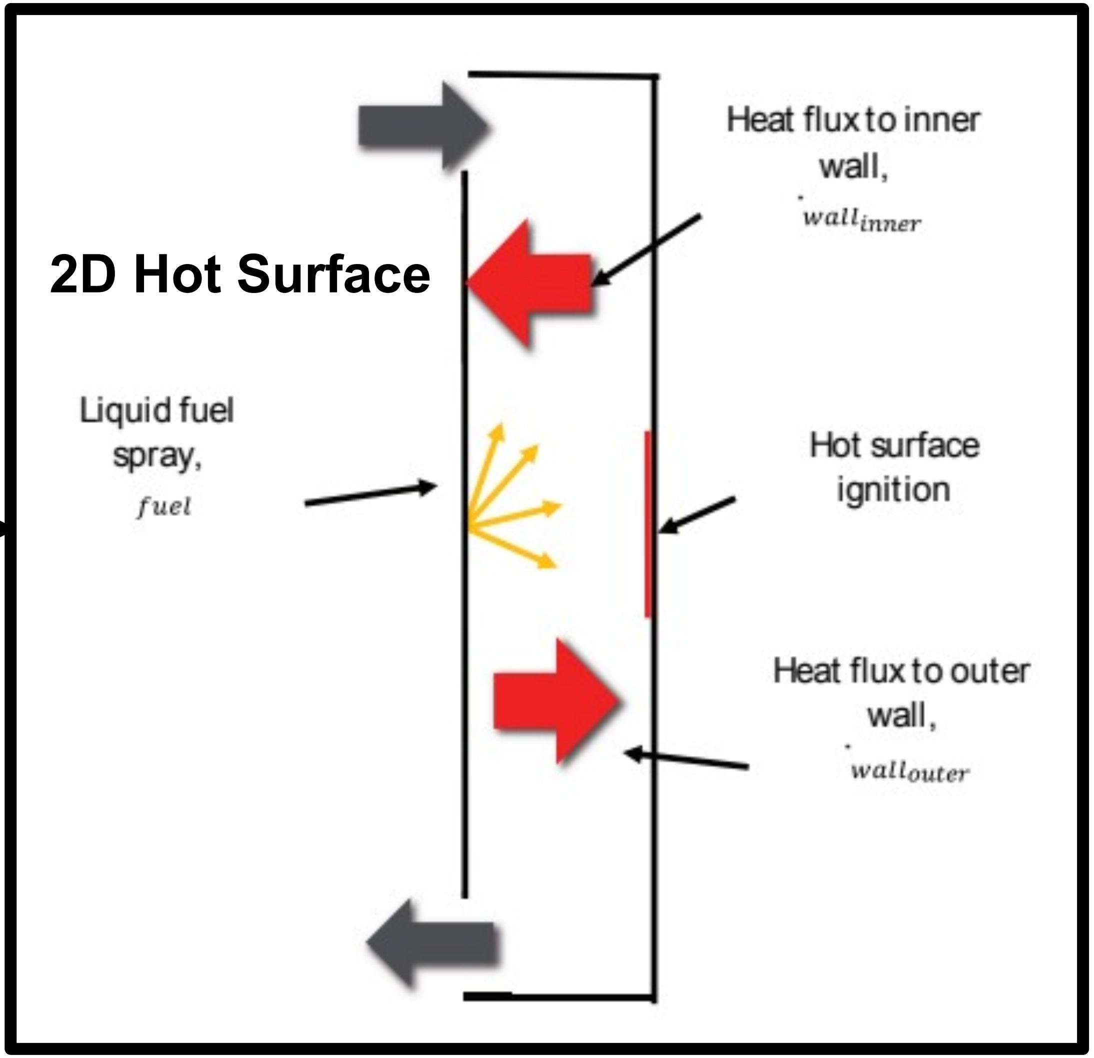
Image from “Towards an Automated Full-Turbofan Engine Numerical Simulation”, *NASA Report* (2003)

Geometric Representation



Adapted from D. Mohaddes

High-Realism Cylindrical Cowl

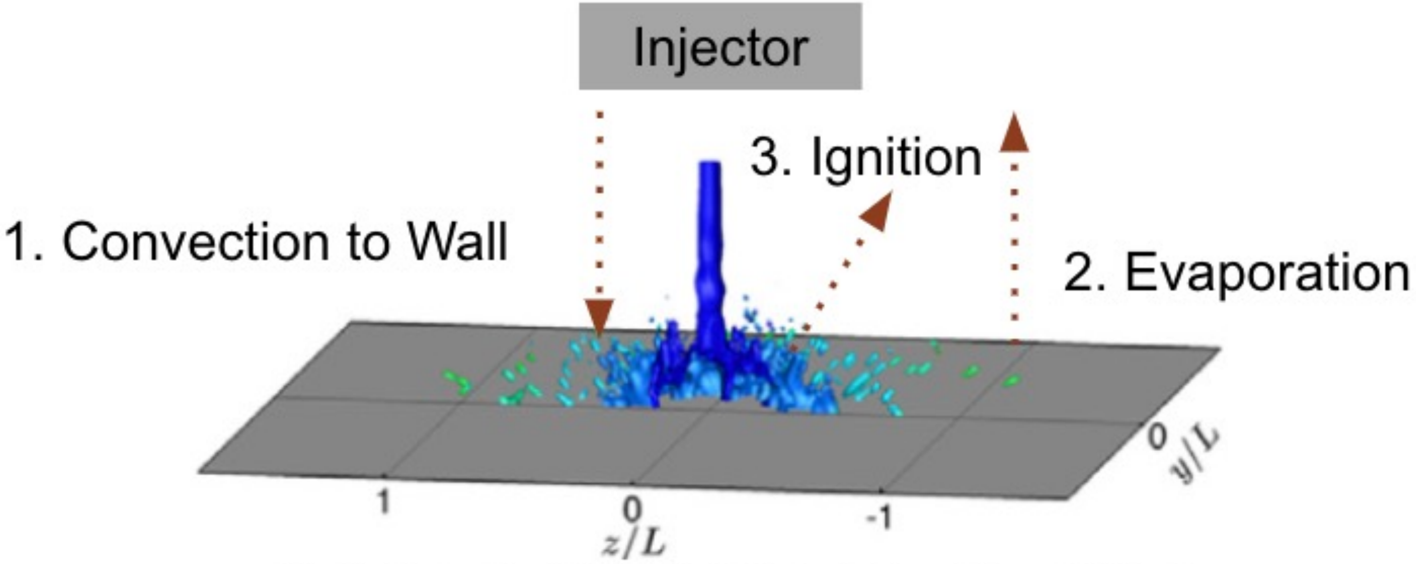


Time Scale Analysis

- We can consider the hot surface ignition of fuel spray impinging on a wall as an approximate three-step sequence:

T_{conv} → T_{evap} → T_{ign}

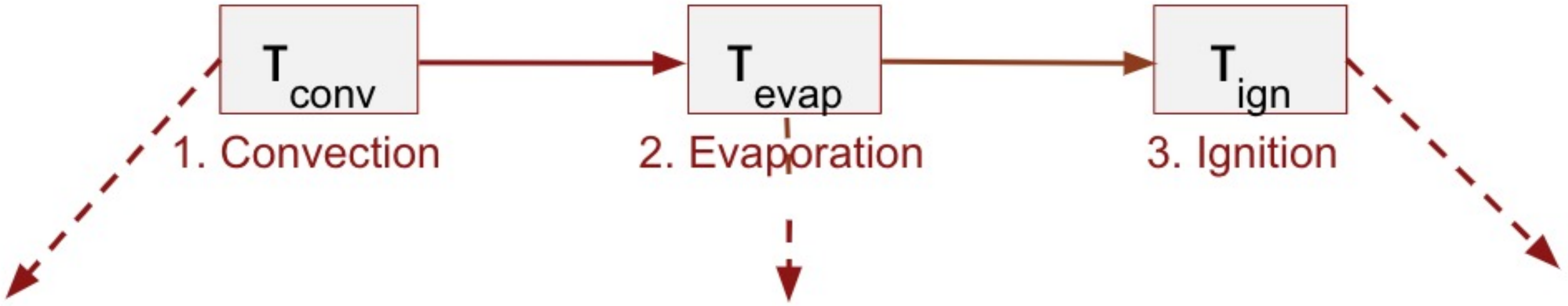
1. Convection 2. Evaporation 3. Ignition



Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.

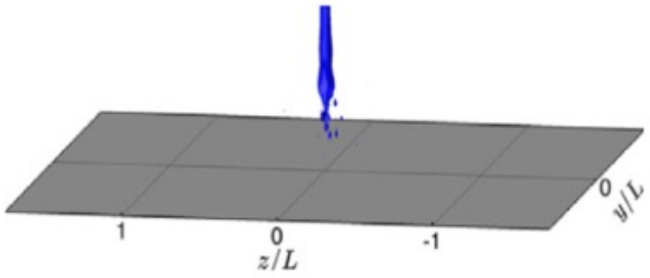
Time Scale Analysis | Methodology

- We can consider the hot surface ignition of fuel spray impinging on a wall as an approximate three-step sequence:



T_{conv} → T_{evap} → T_{ign}

1. Convection
2. Evaporation
3. Ignition



Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.

Convective Rate

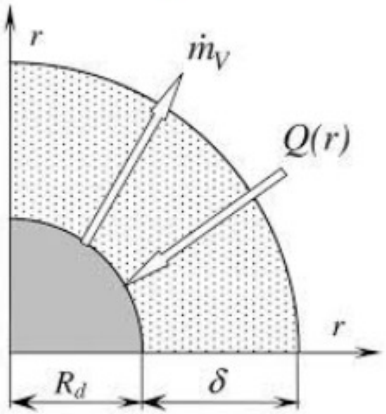


Image From Cambridge University Press

0D Droplet Evaporation Model

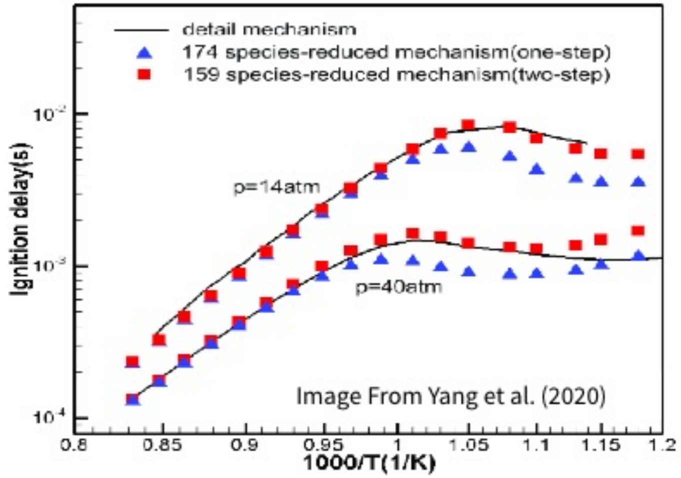
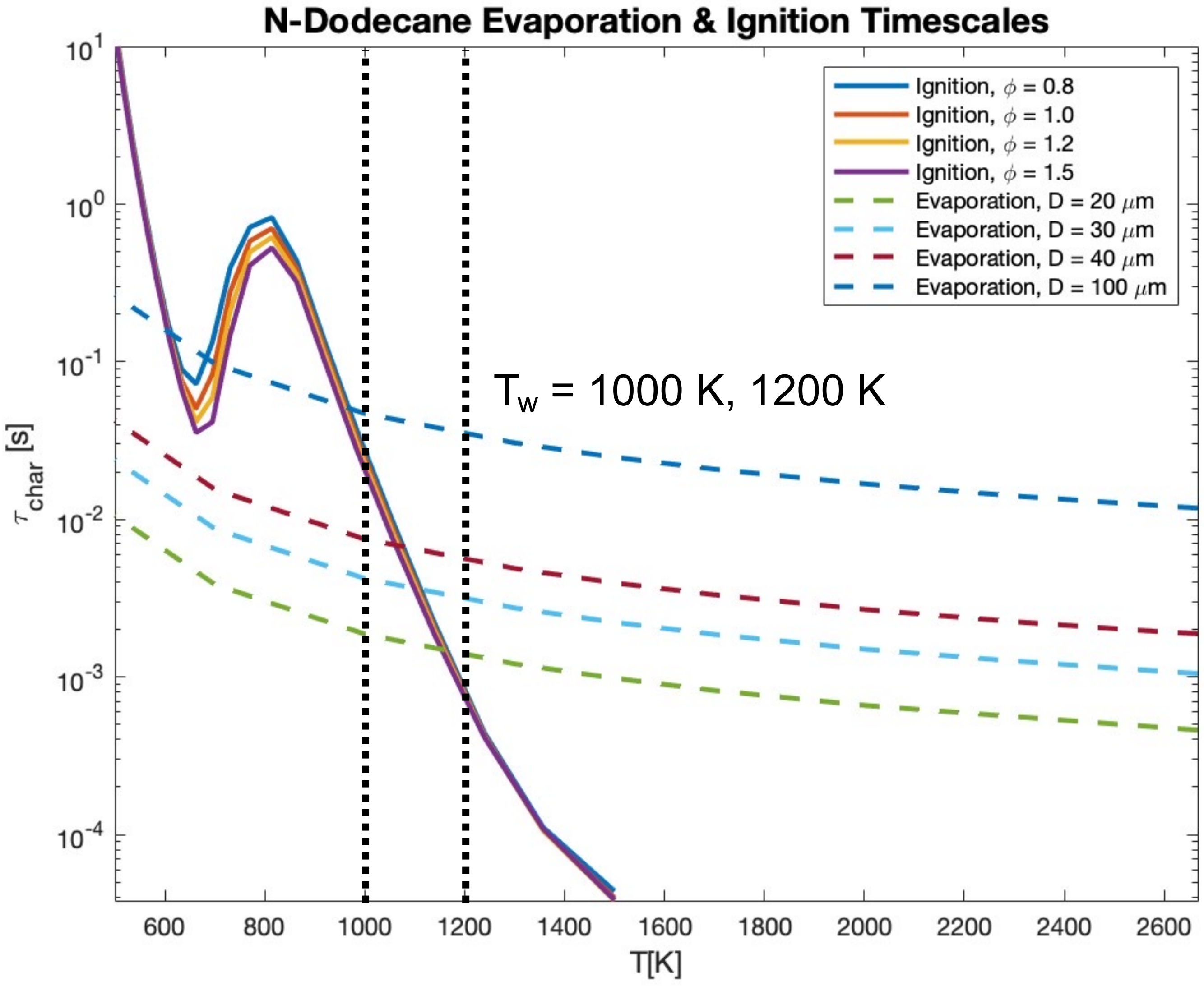


Image From Yang et al. (2020)

Ignition Delay Time

Time Scale Analysis | Results

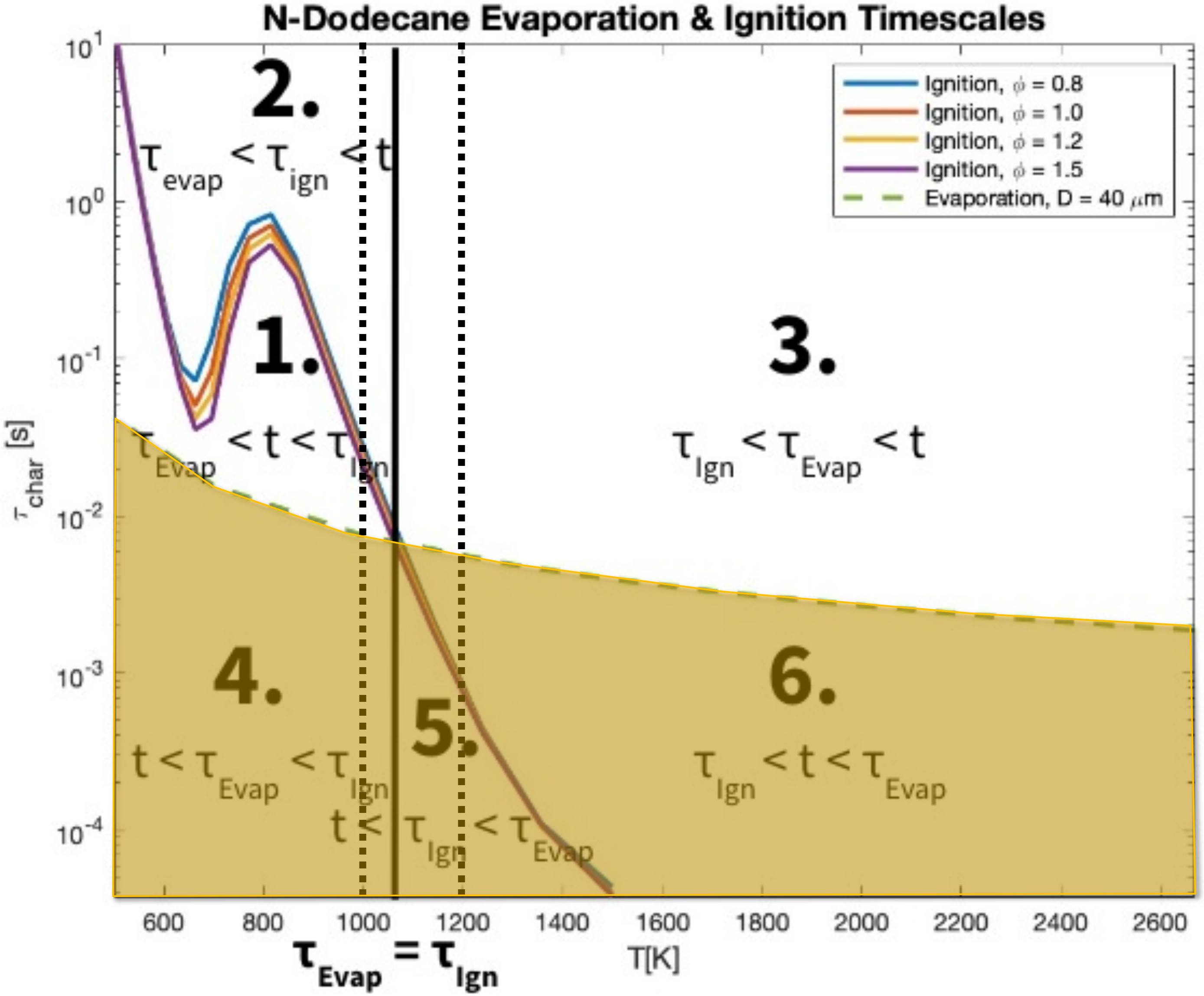


- **Ignition Time Scale**
  - 3×10^{-2} s (1000 K)
  - 8×10^{-4} s (1200 K)
- **Evaporation Time Scale**
  - 8×10^{-3} s (1000 K)
  - 6×10^{-3} s (1200 K)

- For experimental design, balance timescales for ignition and evaporation
  - Fast enough so not affected by environment
  - Slow enough for diagnostics

Time Scale Analysis | Results

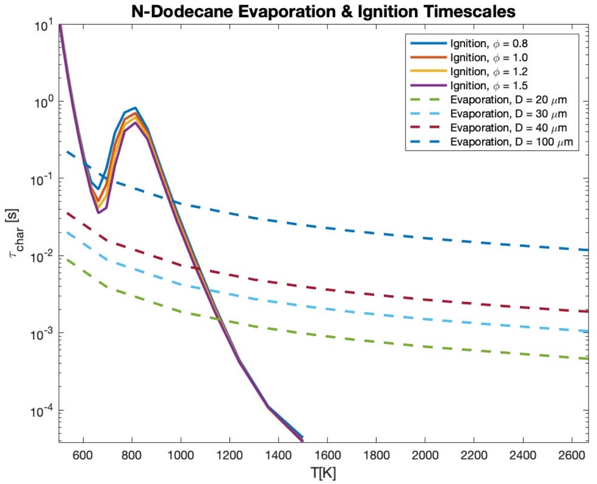
- Want droplets to convect and hit the wall as a liquid (*t* must < t_{evap}) → **Regions 4, 5, 6**
- Based on ignition timescale, can further separate into **ignition** and **flame-stabilized** regimes.



Time Scale Analysis | Bridge to Simulation Work

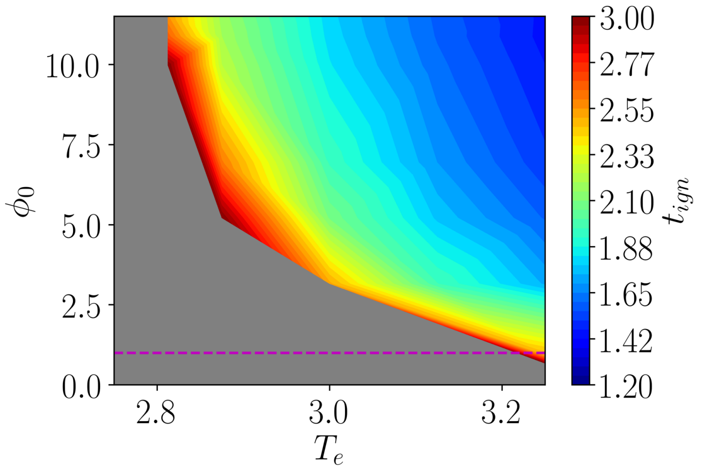
Outcomes

- Time scale analysis anticipates two regimes:
    - Ignition on short times
    - Stable, steady state combustion on long times
- Chronology of relevant processes important design consideration



Research Objectives

- Perform **detailed simulations** to examine unsteady ignition process at high spatial and temporal resolution
- Perform **low order modeling** to explore comprehensive parameter space and identify safety-critical ignition scenarios (ex. ignition limits)



Simulations

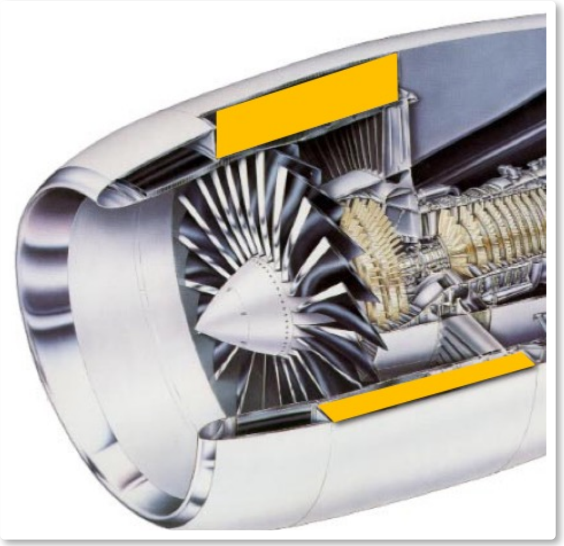
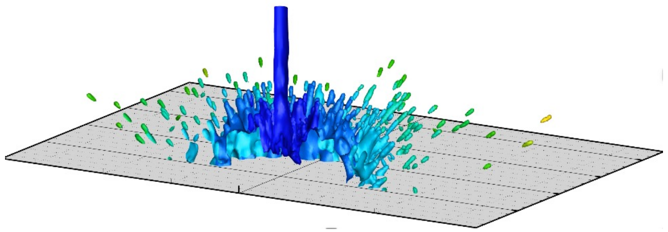


Image from “Towards an Automated Full-Turbofan Engine Numerical Simulation”, *NASA Report* (2003)

Approach | 3D vs. 1D Simulations

3D Large-Eddy Simulations



Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.

- Objectives
    - Resolve full flow field
    - Detailed combustion evolution
    - Estimates for surface temperature and heat flux
- Key Differences
    - Fully resolved flow-field simulation
    - Langrangian spray model

1D Eulerian-Eulerian Simulations

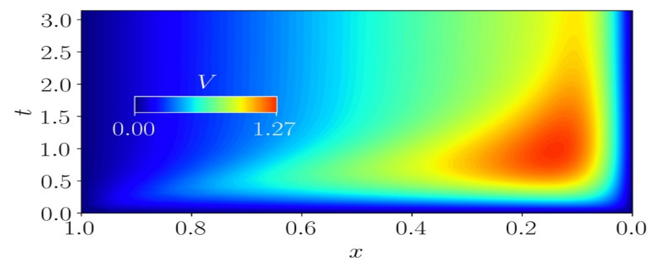


Image By Danyal Mohaddes

- Objectives
    - Describe phenomenology of spray-HSI
    - Analyze spray-HSI parametrically using non-dimensional variables
- Key Differences
    - Reduced dimensionality (1D)
    - Eulerian spray model (continuum)

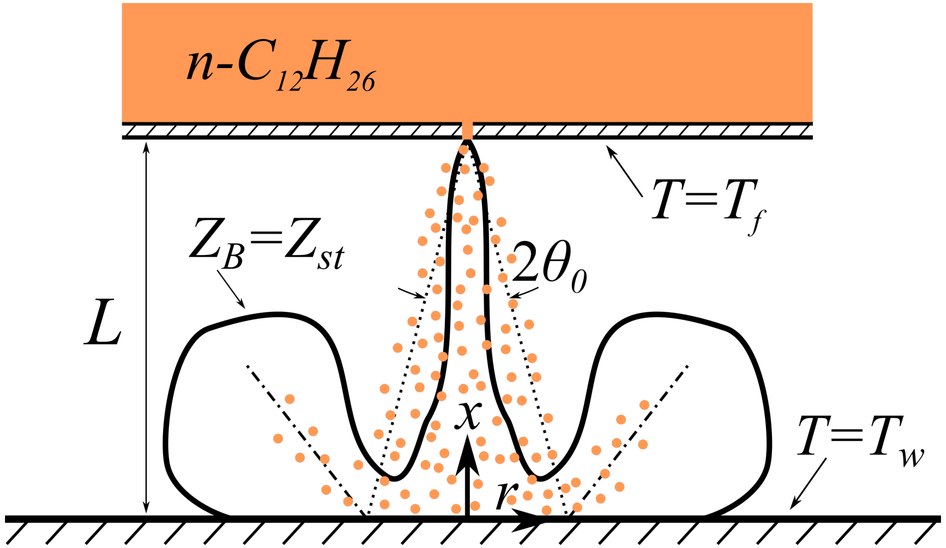
3D Simulations | Objectives, Set-up

Objective

- Performed detailed simulation to generate understanding of hot surface ignition of a wall-impinging fuel spray

Parameters

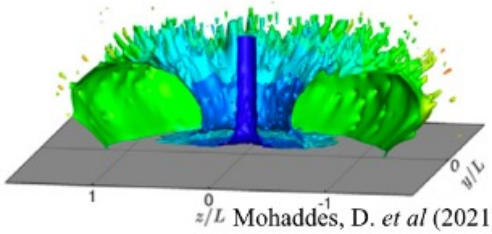
- Fuel: liquid *n*-dodecane at $T_f = 400\text{K}$
- Oxidizer: air at $p = 1\text{atm}$
- Gap size: $L = 2\text{cm}$
- Spray cone angle: $\theta_0 = 15°$
- Wall temperature: $T_w = [650\text{K}, \mathbf{1000K}, \mathbf{1200K}]$
- Spray-wall interaction: [Filming, **Leidenfrost**]



Schematic representation of spray-wall interaction during hot surface ignition [1]

[1] D. Mohaddes, P. Boettcher, M. Ihme, "Hot surface ignition of a wall-impinging fuel spray: Modeling and analysis using large-eddy simulation," Combustion and Flame, 228, 443–456.

3D Simulations | Methodology



Mohaddes, D. et al (2021)

Governing Equations

- Favre-filtered Navier-Stokes for large-eddy simulation of chemically reacting flows
- Lagrangian representation of spray

Chemistry Modeling

- 55-species chemical mechanism for *n*-dodecane/air combustion with low-temperature chemistry [1]
- Finite-rate chemistry with dynamic flame thickening

Numerical Method

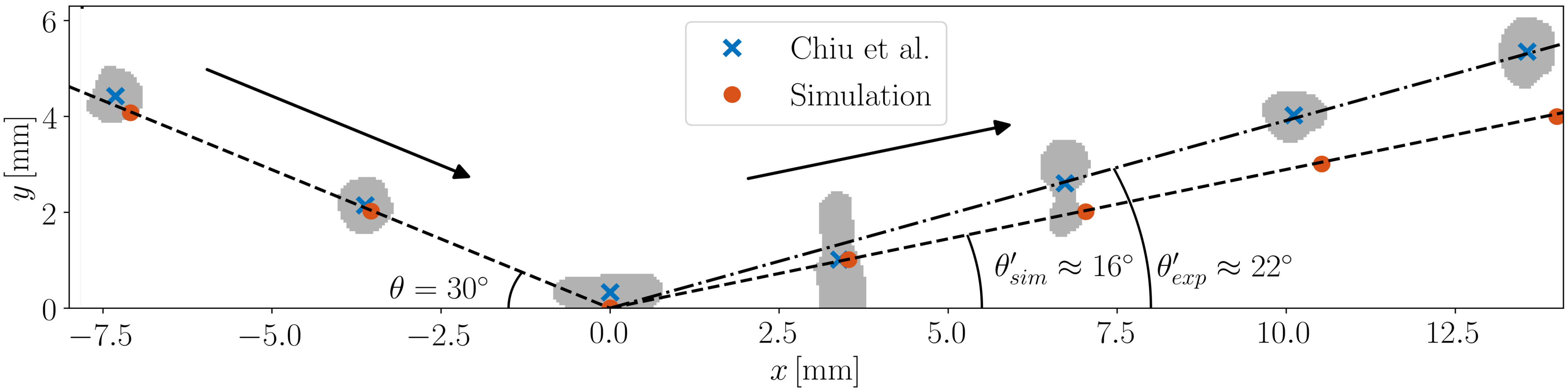
- In-house finite-volume solver, nominally 4th order
- Splitting scheme for explicit/semi-implicit treatment of transport/reaction terms, 2nd order [2]

Mesh

- Hexahedral; uniform isotropic with $\Delta = 0.2\text{mm}$ in region of interest
- 1.7 million elements per axial quarter sector (6.8 million for full mesh)

[1] P. Ma, H. Wu, T. Jaravel, M. Ihme, “Large-eddy simulations of transcritical injection and auto-ignition using diffuse-interface method and finite-rate chemistry,” PCI 2019
[2] H. Wu, P. Ma, M. Ihme, “Efficient time-stepping techniques for simulating turbulent reactive flows with stiff chemistry,” Comput. Phys. Comm. 2019

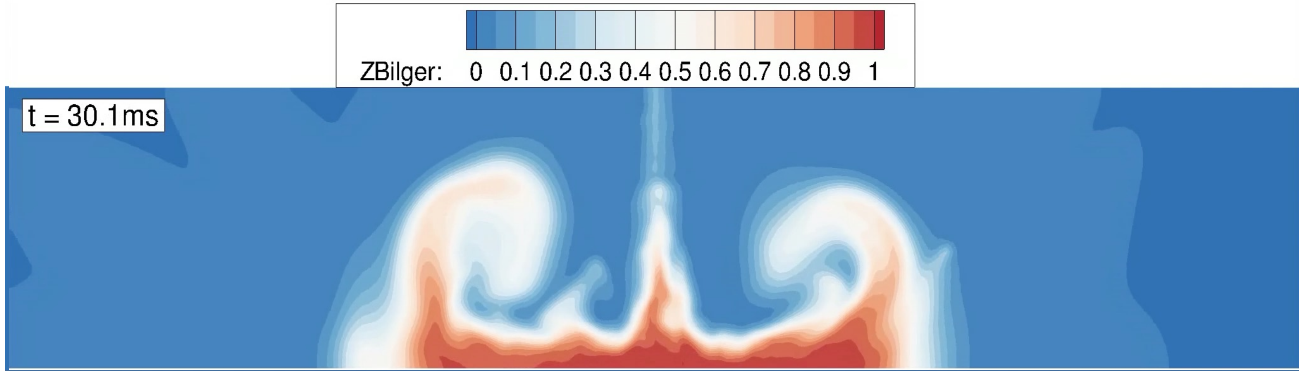
3D Simulation | Evaluation of Spray-Wall Interaction



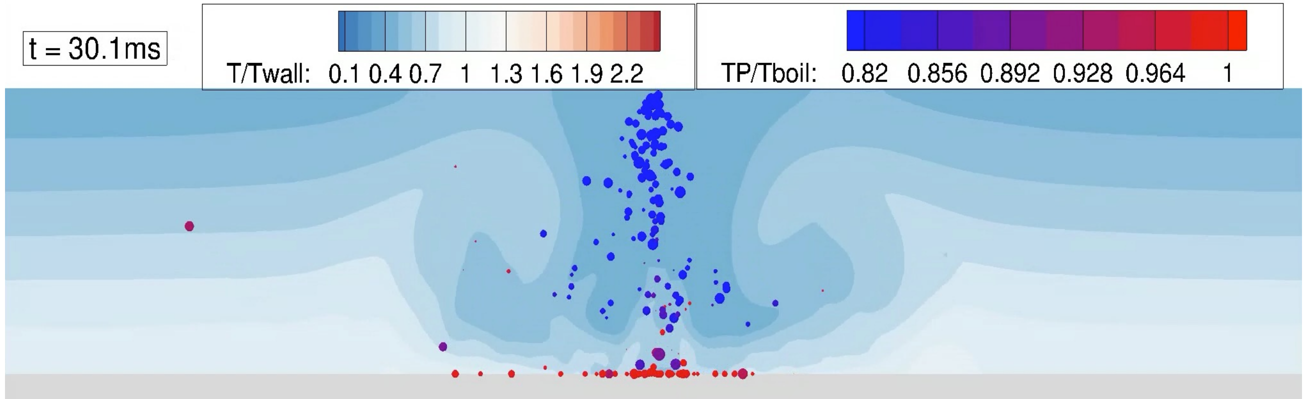
- For spray-wall interactions with $T_w > T_L$, droplets rebound inelastically
- Characterize coefficient of restitution L_n using impact Weber number We_n
  - $L_n = 0.263\mathrm{We}_n^{0.257}$ [1], where $\mathrm{We}_n = \frac{\rho_l u_{d,n}^2 D_d}{\sigma}$
- Simulated diesel spray-wall interaction experiment by Chiu et al. [2] to evaluate model performance
  - Acceptable accuracy, on order of spread in experimental data

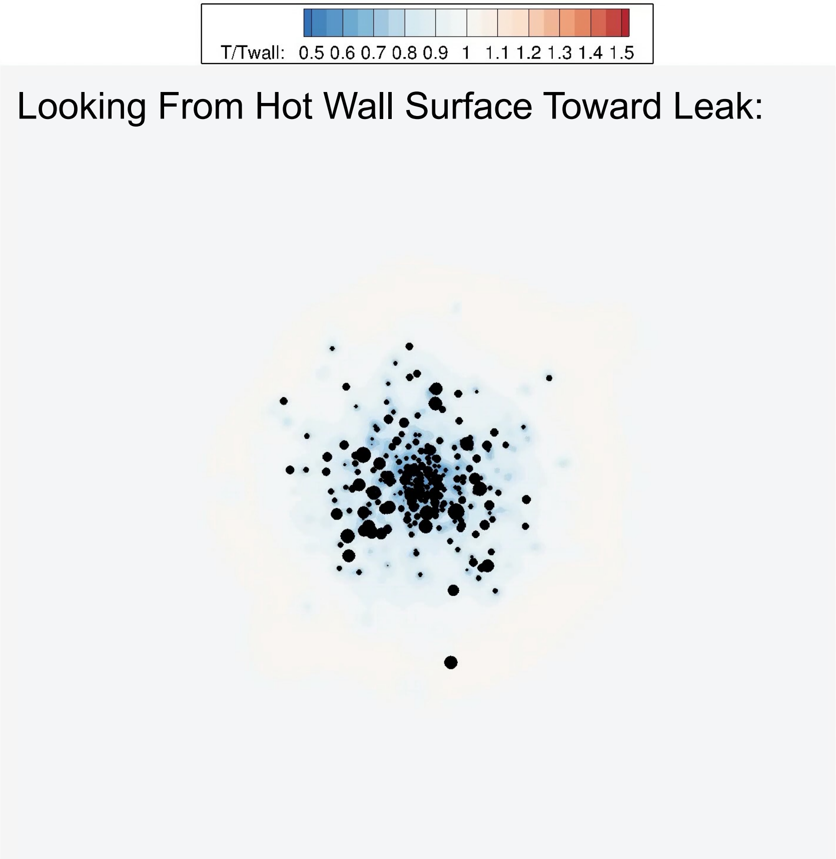
[1] Karl et al., "Experimental investigation of interaction processes between droplets and hot walls," Physics of Fluids, 2000.
[2] Chiu et al., "Experiment on the dynamics of a compound droplet impinging on a hot surface," Physics of Fluids, 2005.

3D Simulation | Evolution of Flow Structure



Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.





Looking From Hot Wall Surface Toward Leak:

Mohaddes, D., Boettcher, P., & Ihme, M. (2021). *Combustion and Flame*, *228*, 443–456.

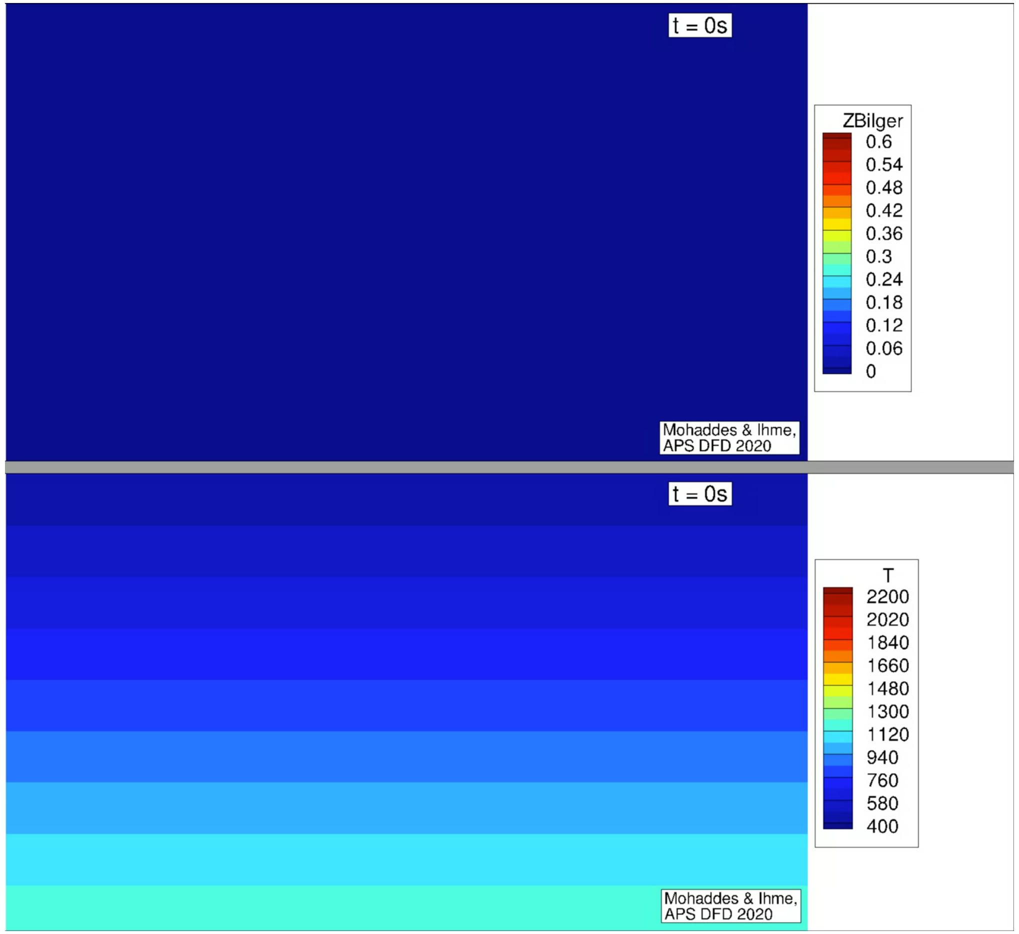
- Fuel film forms and evaporates rapidly
- Interaction of injected droplets with fuel vapor forms impinging jet-like core with rolling vortices
- Ignition occurs at edge of fuel vapor core at 34 ms

3D Simulations | Flow-field Temperature

$T_w = 1200\mathrm{K}$

Inlet

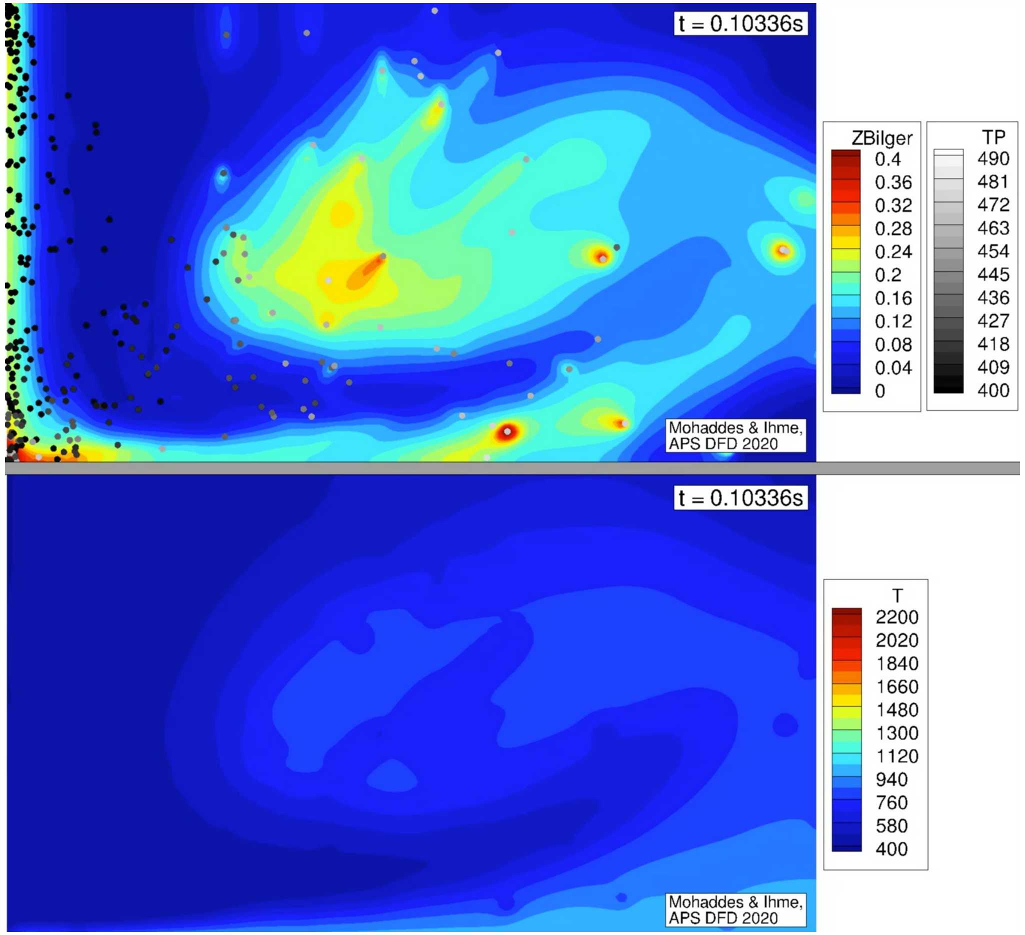
Wall



$T_w = 1000\mathrm{K}$

Inlet

Wall



- Higher wall temperature results in shorter ignition delay
- Less fuel vapor available for combustion at high wall temperature → rapid transition to compact flame

1D Simulation | Set-up, Methodology

Objective

- Develop low-order model to enable comprehensive parametric investigation of hot-surface ignition

Method

- Dimensionality reduction (1D model)
- Eulerian spray representation
- Coupled phases

Non-Dimensional Parameters

Parameter	Symbol
Normalized Solid External Temperature	T_e
Fuel/Air Equivalence Ratio	ϕ_0
Stokes Number (Droplet response)	St
Damköhler Number (Flow vs. Chemical time scale)	Da

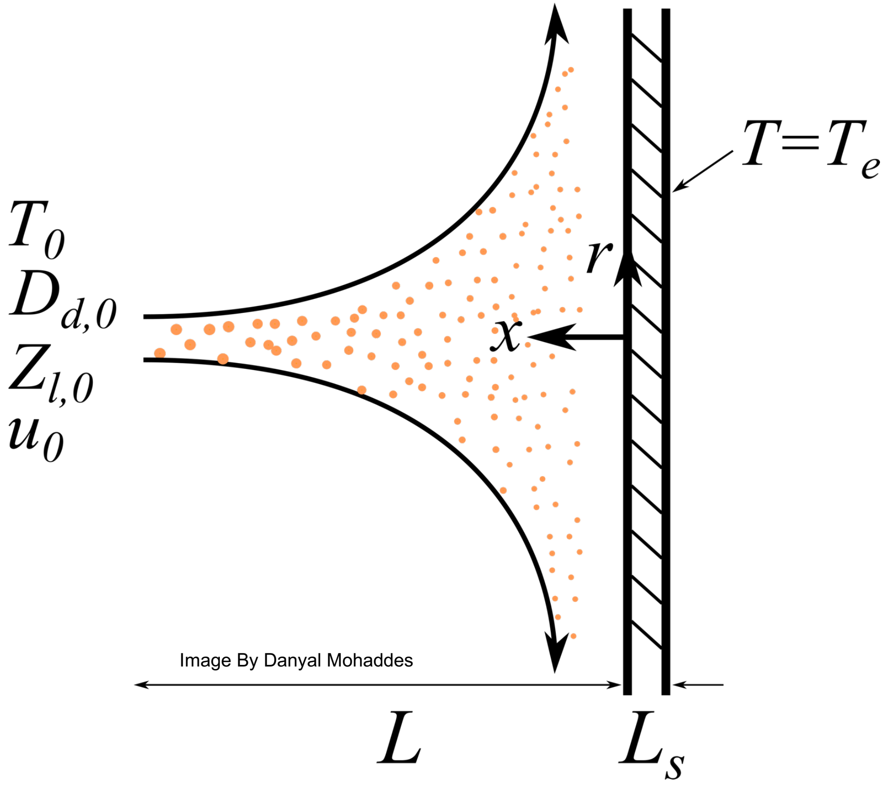
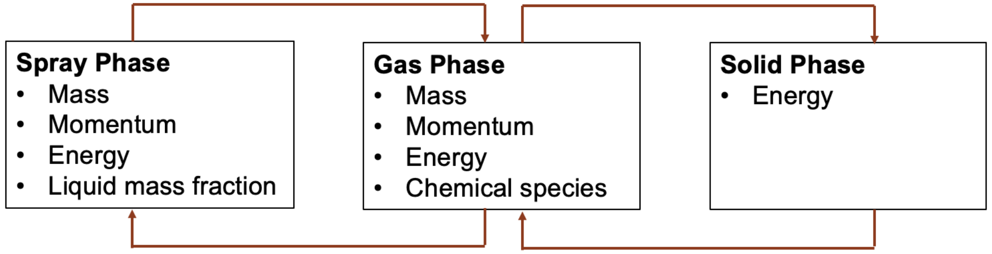


Image By Danyal Mohaddes

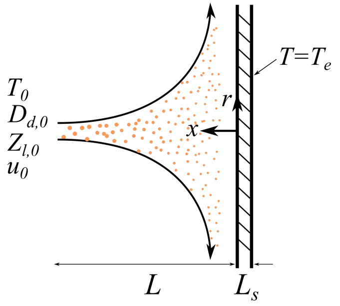


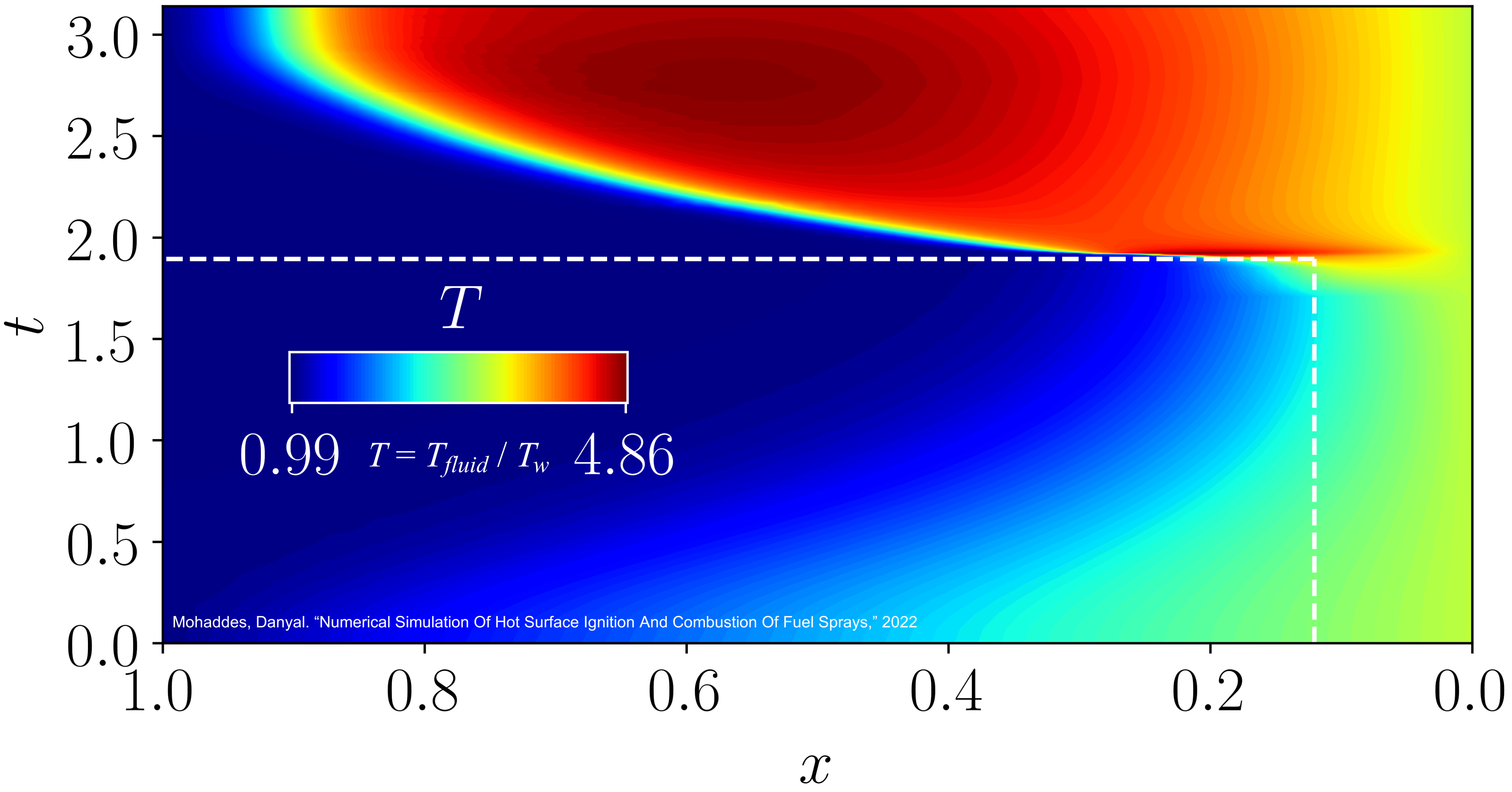
Spray Phase
- Mass
- Momentum
- Energy
- Liquid mass fraction

Gas Phase
- Mass
- Momentum
- Energy
- Chemical species

Solid Phase
- Energy

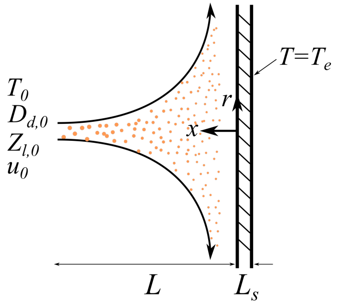
1D Simulation | Ignition Phenomenology





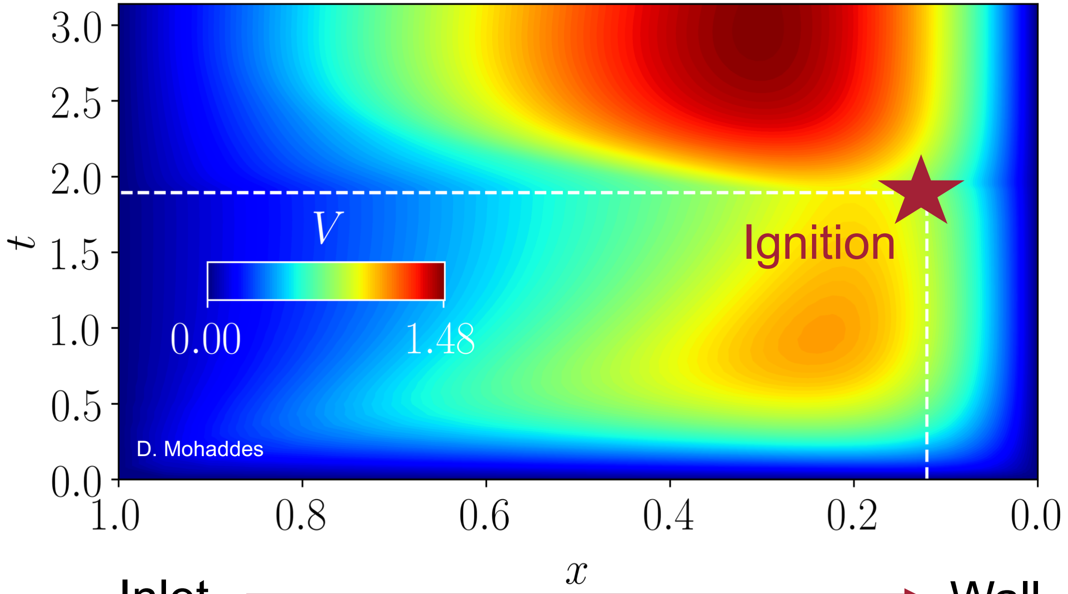
Mohaddes, Danyal. “Numerical Simulation Of Hot Surface Ignition And Combustion Of Fuel Sprays,” 2022

1D Simulation | Ignition Phenomenology



Fluid Dynamics

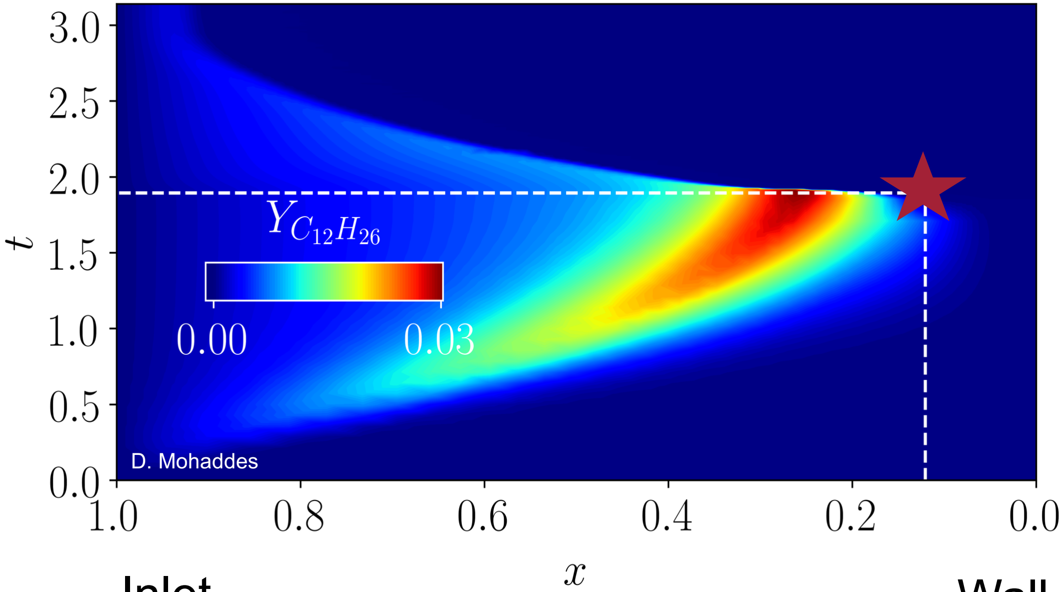
$$V \equiv \frac{v}{r}$$



Inlet → Wall

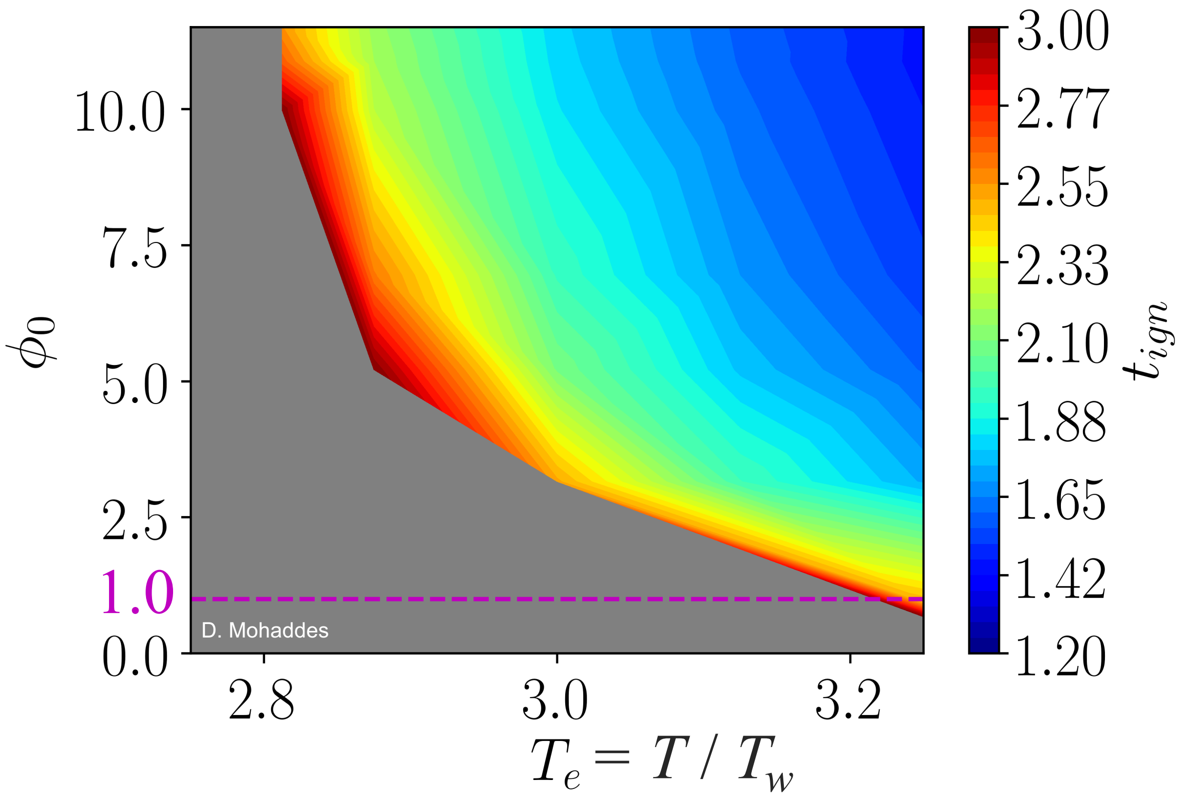
Thermochemistry

$\phi_0 = 1.0$



Inlet → Wall

1D Simulation | Parametric Study



Ignition Limits:

- Da largely determines igniting region
  - Lean and near-stoich ϕ_0 non-igniting
- Large gradient in T_e

Ignition Delay Time:

- Reaches maximum at ignition limit
- Minimum at high T_e, ϕ_0
- Modest variation relative to purely chemical ignition delay

Conclusion

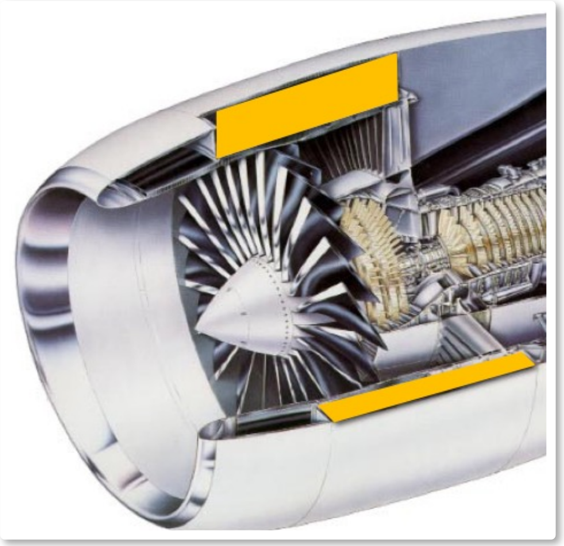
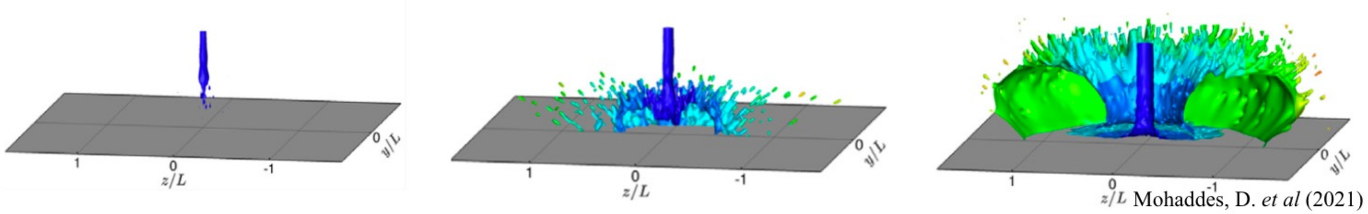


Image from “Towards an Automated Full-Turbofan Engine Numerical Simulation”, *NASA Report* (2003)

Key Findings



Mohaddes, D. *et al* (2021)

$t/\tau = 1.1$ $t/\tau = 3.3$ $t/\tau = 16.7$

Developed **predictive modeling tools for exploration and analysis of hot surface ignition** scenarios at quantitative level.

3D Simulations

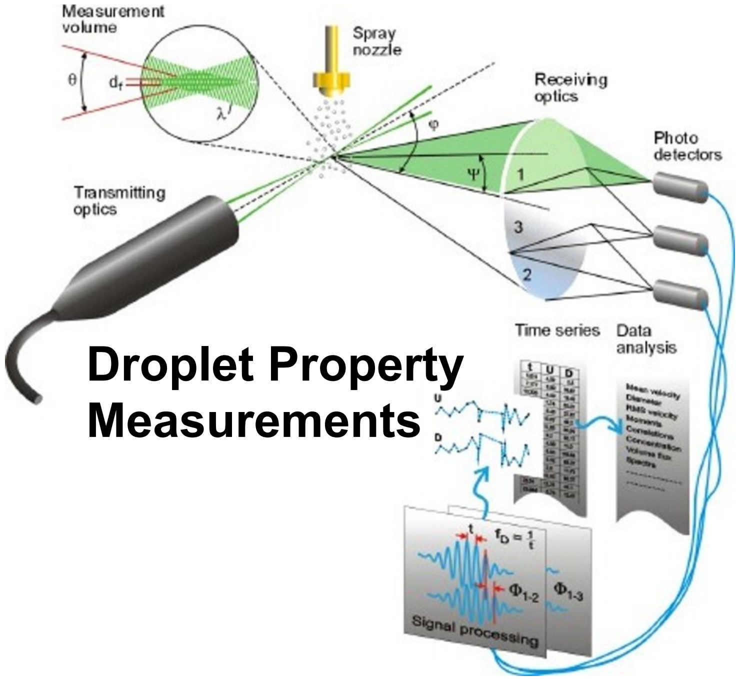
- Higher surface temperature reduces ignition delay, resulting in ignition occurring before gaseous flow field is fully developed
  - Higher wall temperature = lower maximum wall heat flux

1D Simulations

- Spray interaction with thermal boundary layer causes fuel deposition in vapor phase
- Ignition phenomenology
  - Flame stabilization near surface ➔ enhanced wall-heat flux
  - Injector-stabilized flame ➔ reduced heat-flux and early droplet combustion
- Parametric study
  - Ignition limit at richer ϕ_0 and higher T_e, depends on Da
  - Formation of ignition kernels in premixed region near the wall

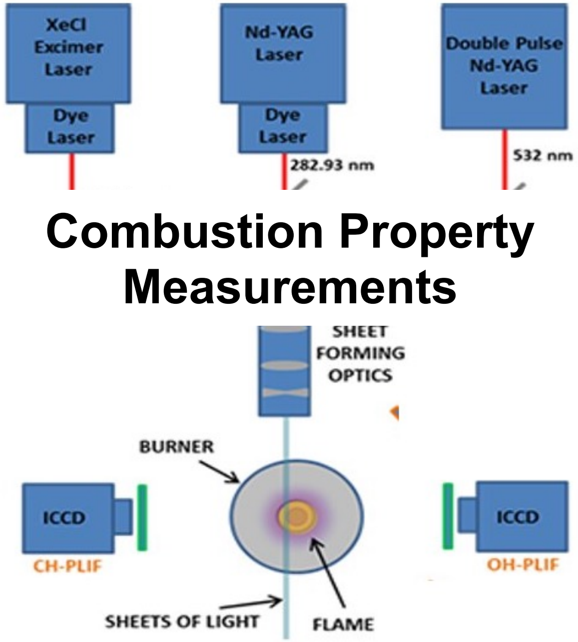
Future Work | Research Issue

- **Research Issue: Lack of high-quality experimental thermo-fluid data** to validate model
- **Research Objective: Develop and perform experiments** to experimental study hot-surface ignition phenomena using advanced diagnostics and target quantities
  - High speed imagery
  - Droplet properties
  - Combustion properties
  - Heat transfer at wall



Droplet Property Measurements

Image From Dantec Dynamics



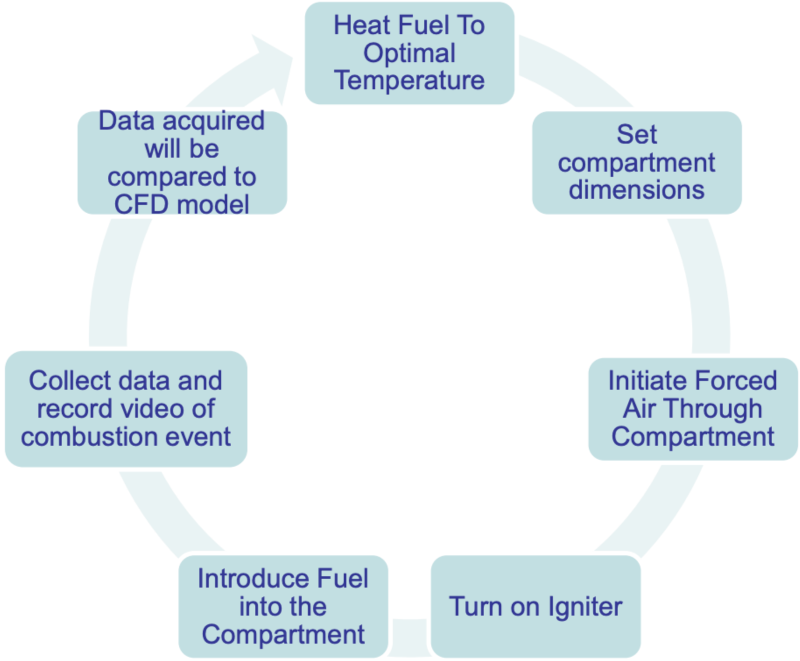
Combustion Property Measurements

Seitzman, J.M. and Hanson R.K. (1993), ISBN 0-12-683920-4.

Future Work | FAA Inspiration (Aeon Brown)

Goals

1. Study effect of jet fuel delivery, air flow delivery, and compartment dimensions on combustion
2. Use to validate fire CFD modeling



Heat Fuel To Optimal Temperature

Set compartment dimensions

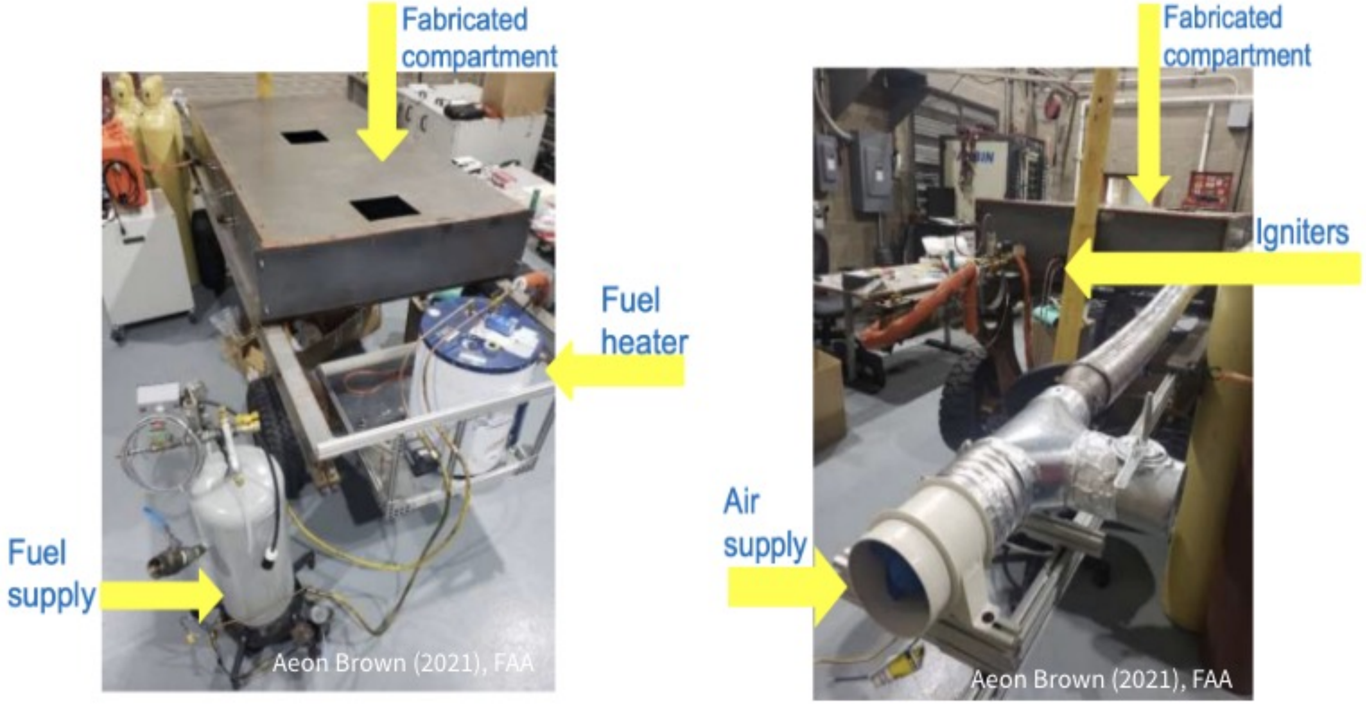
Initiate Forced Air Through Compartment

Turn on Igniter

Introduce Fuel into the Compartment

Collect data and record video of combustion event

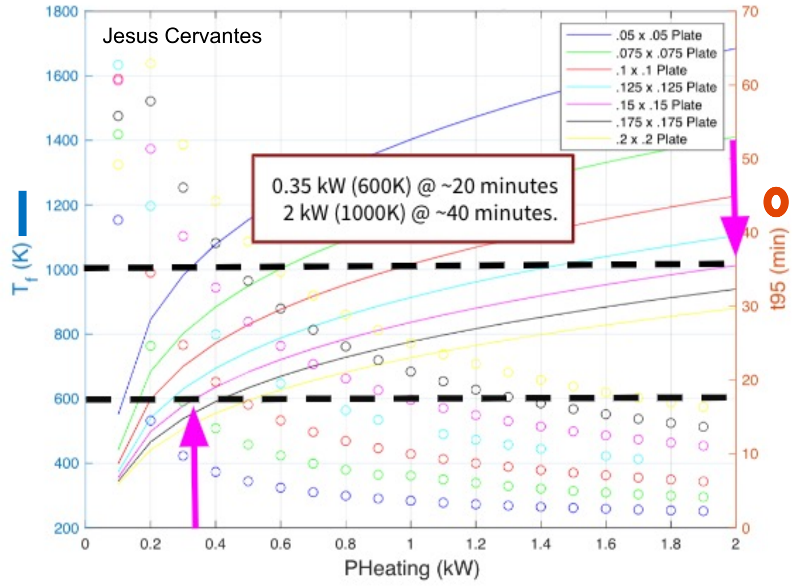
Data acquired will be compared to CFD model



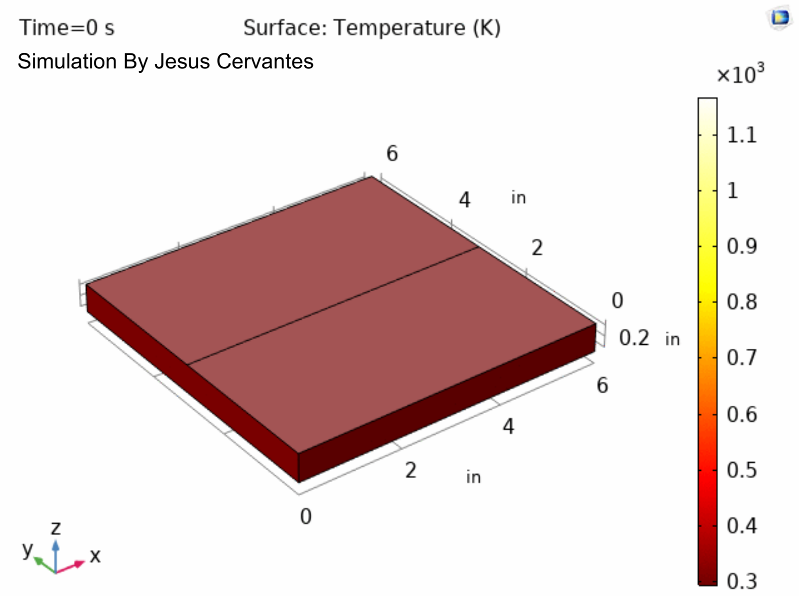
- **Aspects to Emulate:** Full-size compartment, modular dimensions, forced convection, use for CFD validation
- **Differences in Scope:** Fuel ignited via spark plug (cannot study hot surface ignition), minimal diagnostics

Future Work | Experimental Vision

- **Complement FAA set-up and work**, with a focus on:
  - Incorporate key elements in real aircraft, like cylindrical geometry and cross-flow.
  - Employ a suite of high fidelity diagnostics matching the physical and temporal resolution of the phenomena.
  - Establish a flexible and modular experimental platform that enables parametric dependency exploration
    - Different spray-angle, geometries, stream properties, etc.



0.15 x 0.15 m solid plate (~ 6” x 6”)



Up First: **Hot Surface Design**!

Acknowledgements

Ihme Group @ Stanford University
Specifically Danyal Mohaddes, Jesus Cervantes,
Dr. Guillaume Vignat, and Prof. Matthias Ihme

FX Lab | Stanford ENGINEERING | Laboratory of Fluids in Complex Environments

FAA

Boeing Company
under Grant No. 134708
[IC2017-2182]

U.S. Department of Energy Office of Science
National Energy Research Scientific Computing Center
under Contract No. DE-AC02-05CH11231.

Thank You!

QUESTIONS?

Matthias Ihme
mihme@stanford.edu

Lauren Simitz
lvsimitz@stanford.edu

Back-up

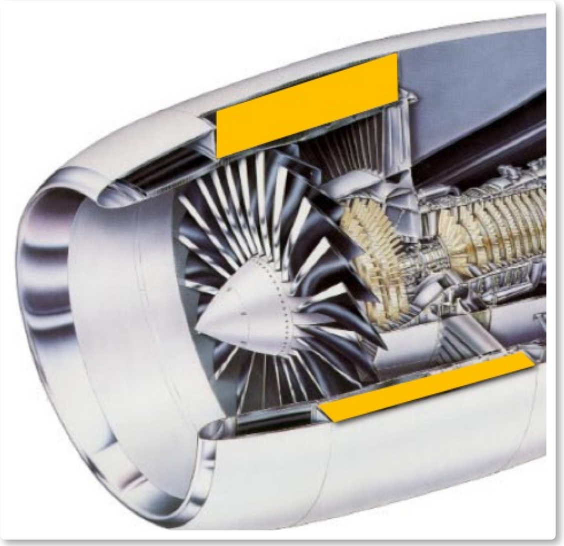
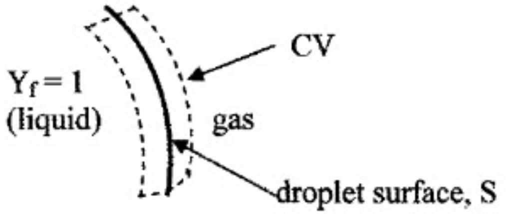


Image from “Towards an Automated Full-Turbofan Engine Numerical Simulation”, *NASA Report* (2003)

Time Scale Analysis | 0D Droplet Model



Bowman, C.T. ME 372 Course Reader.

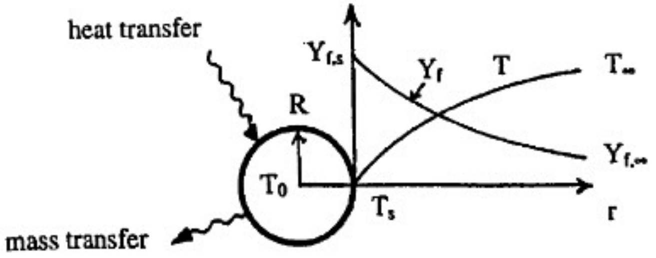
Inputs: T_{liq}, T_{gas}, Droplet Diameter, Liquid Properties CSV

Antoine Parameters (Vapor P = f(T))

name	rho	cp	Lv	prs_A	prs_B	prs_C	prs_D	Tb	unit
C6H14	653.17	2280.3	3.65E+05	4.00266	1171.53	-48.784		342.1	bar
NC12H26	669.43	2593.9	2.56E+05	4.10549	1625.928	-92.839		489.3	bar
N-C12H26	669.43	2593.9	2.56E+05	4.10549	1625.928	-92.839		489.3	bar

Operating Principles:

- 0D Droplet Evaporation Model
- Heat conduction from surroundings supplies energy for evaporation
    - Evaporation Rate = f(fuel properties, environment properties)
- Vaporized mass diffuses away from surface



Bowman, C.T. ME 372 Course Reader.

From Mass Conservation

$$\dot m''(4\pi r^2) = \dot m_s''(4\pi R^2) = \text{constant}$$

mass flux/area @ r

mass evaporation rate/droplet surface area (@ r = R)

$$B = B_T = -\eta_{T,s} = \frac{c_{P,g}(T_\infty - T_S)}{Q}$$

$$B = B_f = -\eta_{f,s} = \frac{(Y_{f,s} - Y_{f,\infty})}{(1 - Y_{f,s})}$$

Common to rewrite equations in terms of transport number B (driving force for heat/mass transfer)

From Energy Conservation

$$\underbrace{\dot m_s''[h_{fg} + c_L(T_s - T_0)]}_{Q} = \lambda_g\left(\frac{dT}{dr}\right)_{S,g} = \dot q_s''$$

h_{fg} = latent heat of vaporization of the liquid at pressure, P
c_L = specific heat of the liquid
T_s = droplet surface temperature = constant
T_0 = initial liquid temperature
Q = total energy required to increase the droplet temperature from $T_0 \to T_s$ and to evaporate the liquid.

From Species Conservation

$$\dot m_s'' = \dot m_s'' Y_{f,s} - \rho_g D_g\left(\frac{dY_f}{dr}\right)_{s,g}$$

Sum of gas-phase convection (Stefan flow) and gas-phase Fickian diffusion
Y = gas phase mass fraction
D_g = diffusion coefficient through gas

Primary Output: Droplet Diameter as f(Time)

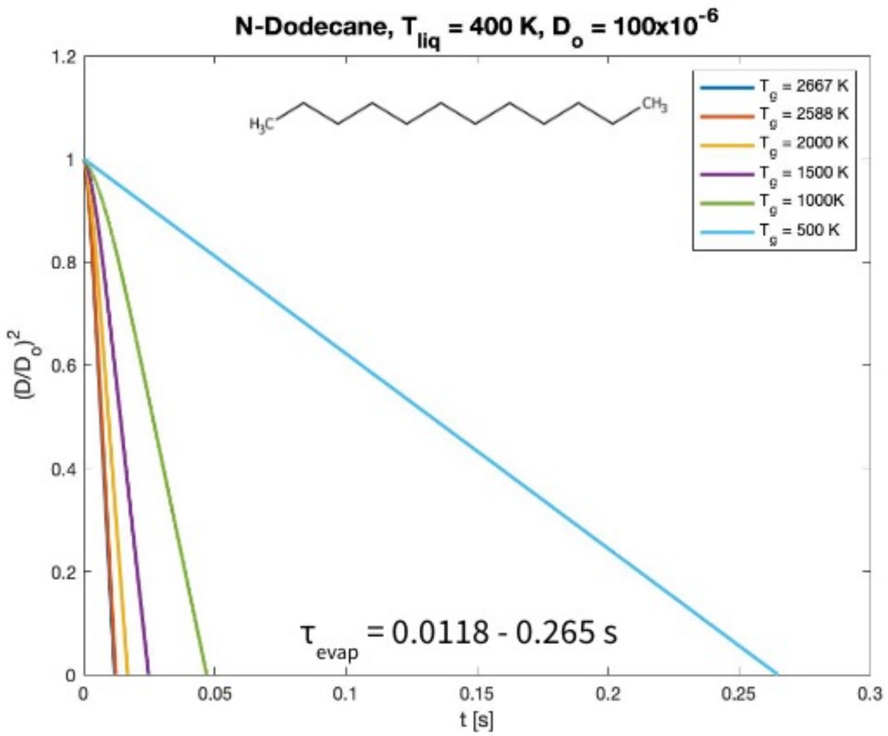
Time Scale Analysis | Evaporation as f(Temp)

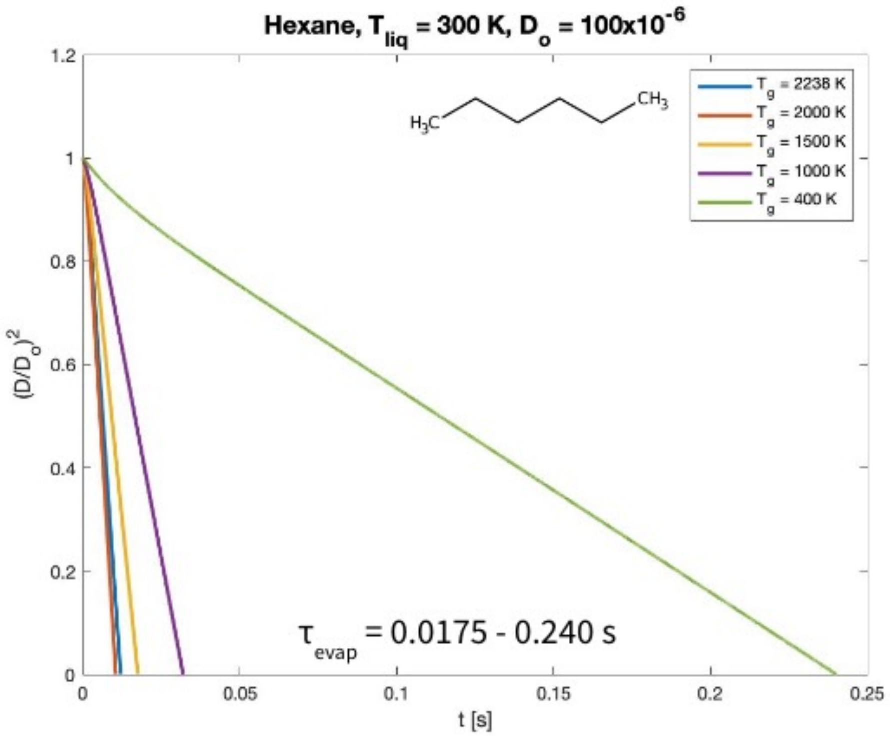
$$\frac{d(d^2)}{dt} = -\left(\frac{8\rho_g D_g}{\rho_L}\right)\ln(1+B) \equiv -k_{evap} \quad \text{(the evaporation constant)}$$

$$\underbrace{[h_{fg} + c_L(T_s - T_0)]}_{Q} =$$

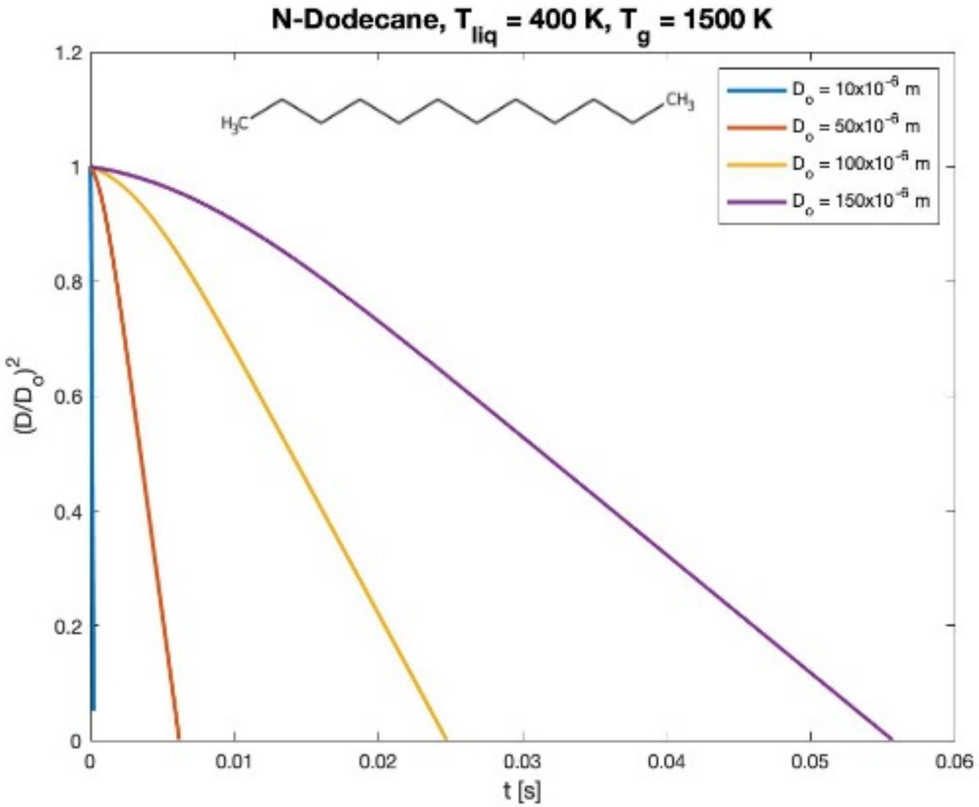
Assuming k_{evap} = constant $\Rightarrow$

$$d^2 = d_0^2 - k_{evap}t \Rightarrow t_{evap} = d_0^2/k_{evap}.$$



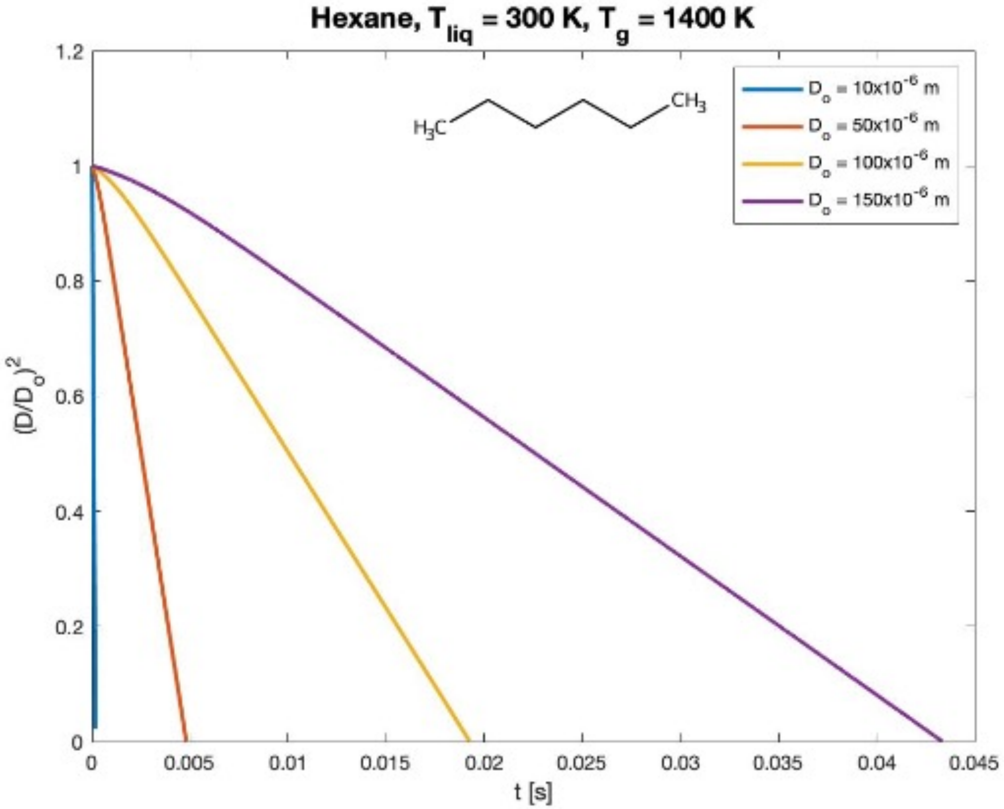


Time Scale Analysis | Evaporation as f(Droplet D)



N-Dodecane, T_{liq} = 400 K, T_g = 1500 K

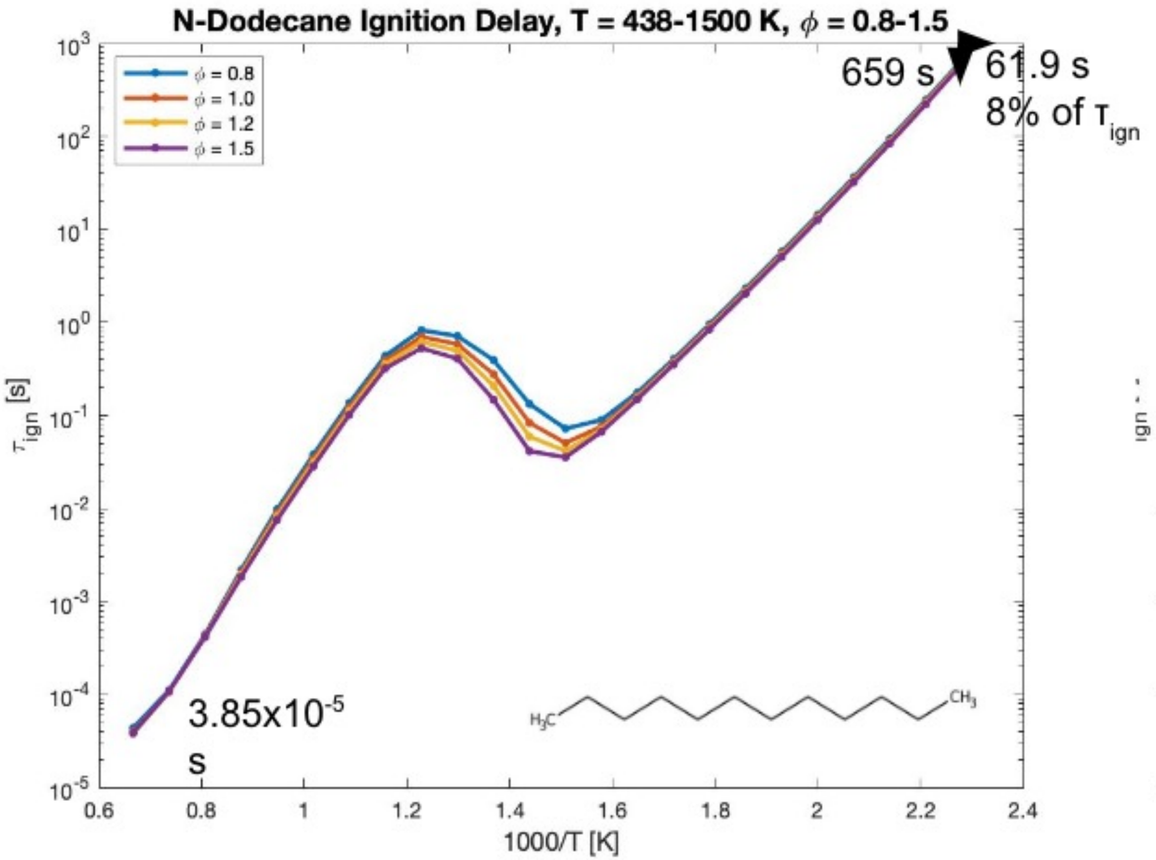
τ_{evap} = 0.00024 - 0.056 s



Hexane, T_{liq} = 300 K, T_g = 1400 K

τ_{evap} = 0.00015 - 0.043 s

Time Scale Analysis | Fuel Ignition



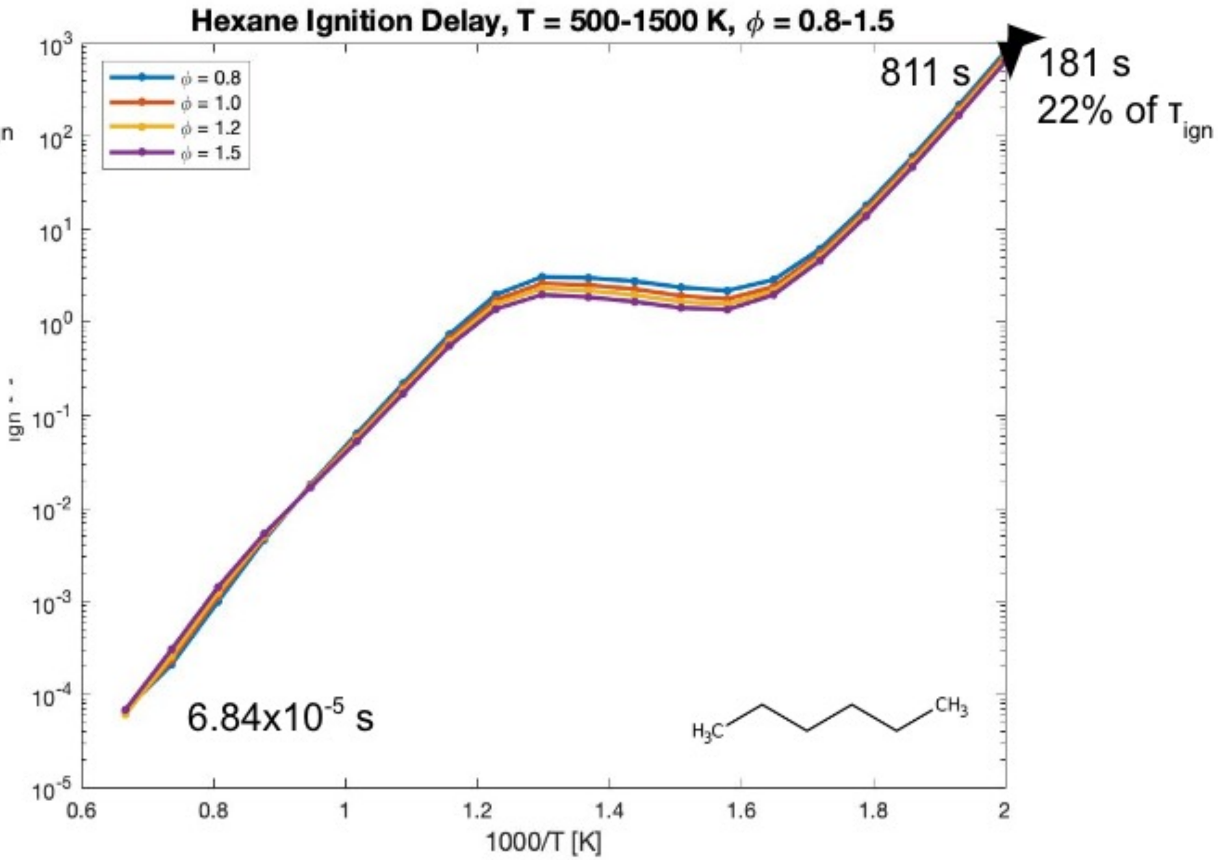
659 s

61.9 s

8% of τ_{ign}

3.85x10^{-5} s

From Cantera, SK54 compact skeletal mechanism with optimized low-temperature chemistry (Yao *et al.*)



811 s

181 s

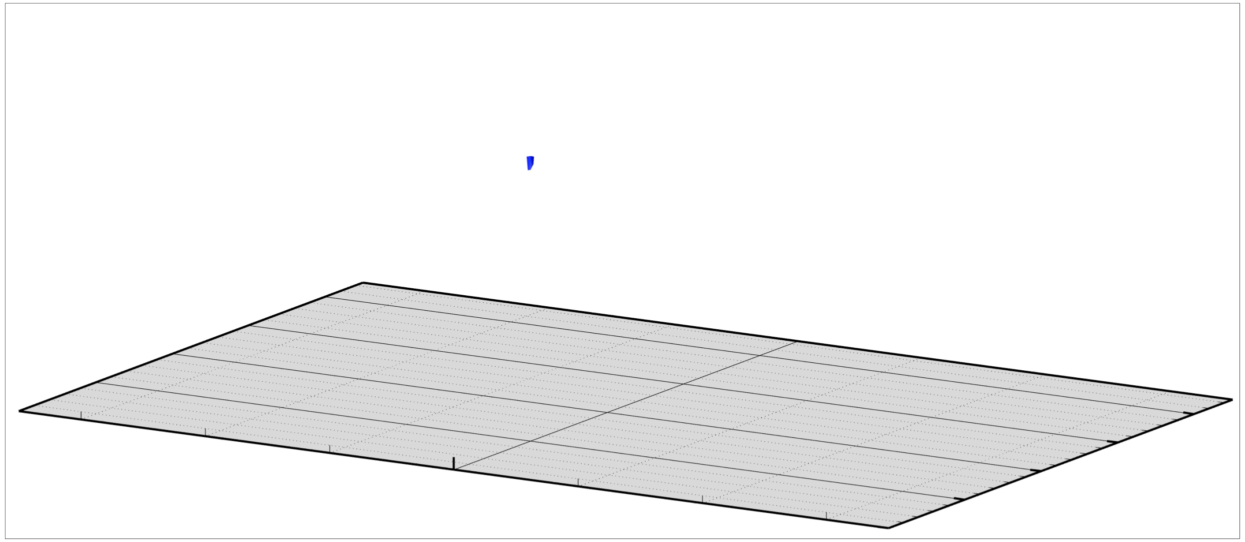
22% of τ_{ign}

6.84x10^{-5} s

From Cantera, Hexane (C6H14)-air full mechanism optimized for thermal ignition experiments (Mével *et al.*)

Results: Flow structure

$\boldsymbol{T_w = 1000\mathrm{K}}$, Z_{st} iso-surface, half-plane

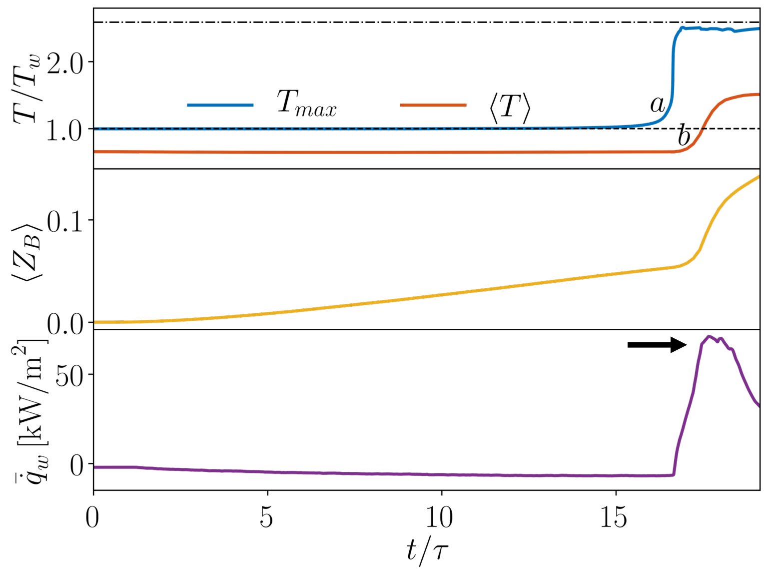


- Liquid injected stochastically in a conical spray, impinges on surface
  - Inelastic reflection due to Leidenfrost effect
- Spray drives gas-phase secondary flow due to momentum exchange
  - Droplet drag
- Spray evaporates due to interaction with hot air, mixes
  - Forms toroidal vortex, identifiable by stoichiometric (Z_{st}) iso-surface

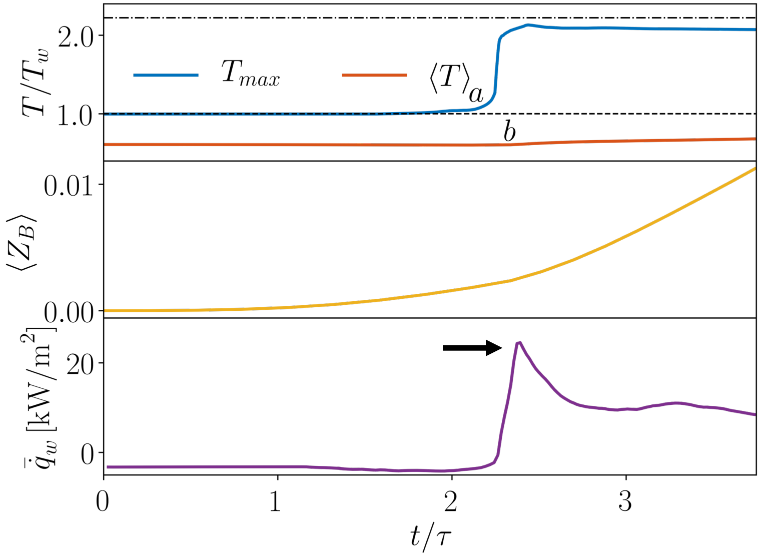
Analysis: Volume-averaged

- Consider results averaged on entire simulated domain
  - Mass-weighted volume averaging
- In both cases, lag time between ignition (a) and increase in compartment mean temperature (b)
  - Kernel development and flame propagation
  - Mixture fraction increases more rapidly due to increased evaporation
- Increased wall temperature results in reduced ignition delay
  - Shorter evaporation time, so lower $< Z_B >$
  - Less fuel in compartment, less mixing results in ~3x lower wall heat flux

$T_w = 1000\text{K}$



$T_w = 1200\text{K}$



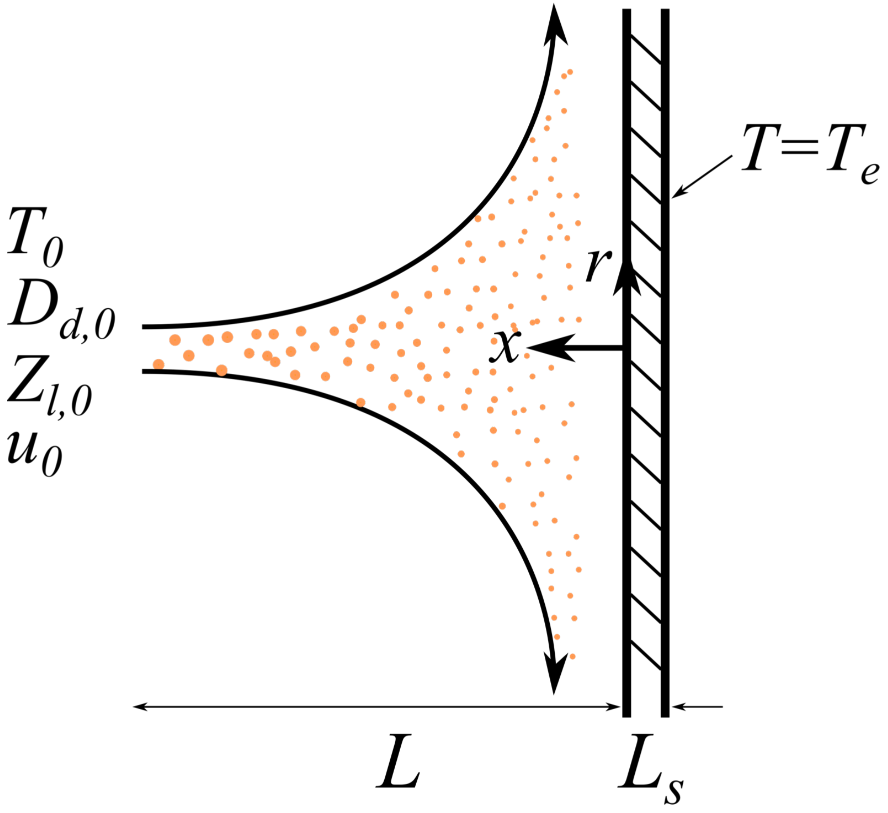
Problem definition and parametrization

Fixed parameters

- Fuel: liquid *n*-dodecane at $T_0^* = 400\mathrm{K}$
- Oxidizer: air at $p^* = 1\mathrm{atm}$, linear temperature between T_0^* and T_w^*
- Fluid gap size: $L = 2\mathrm{cm}$
- Wall: solid steel, linear temperature between T_w^* and T_e^*
- Wall thickness: $L_s = 3\mathrm{mm}$

Open parameters

- External wall temperature: $T_e^* = [1100\mathrm{K}, 1300\mathrm{K}]$
- Inlet liquid mass fraction: $Z_{l,0} = [0.03, 0.77]$
- Inlet droplet diameter: $D_{d,0}^* = [8\mu\mathrm{m}, 346\mu\mathrm{m}]$
- Global strain rate: $a^* = [1\mathrm{s}^{-1}, 100\mathrm{s}^{-1}]$



Governing equations

From 3D to 1D

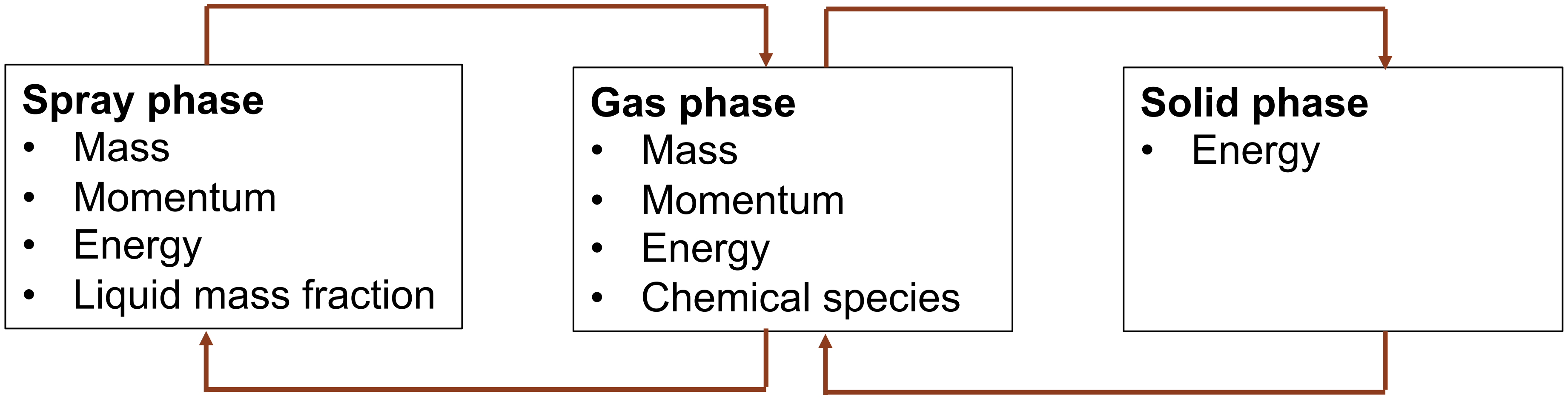
- Perpendicular impingement, thus assume axi-symmetry (3 → 2)
- Consider solution only on centerline $r = 0$ (2 → 1)

From Lagrangian to Eulerian

- Assume that on a length scale larger than the droplets, but smaller than the problem, droplets behave identically
- $[\boldsymbol{x}, \boldsymbol{u}, T_d, m_d]_i \ \forall \ i < N_d$ → $[Z_l, \boldsymbol{u}, T_d, m_d](\boldsymbol{x})$

Three coupled phases

- Spray-gas and gas-spray exchange conserved quantities through source terms
- Gas-solid and solid-gas exchange through boundary conditions



Spray phase
- Mass
- Momentum
- Energy
- Liquid mass fraction

Gas phase
- Mass
- Momentum
- Energy
- Chemical species

Solid phase
- Energy

Non-dimensional parameters

From non-dimensionalization of governing equations and boundary conditions, we obtain:

Parameter	Symbol	Definition	Range Considered
Normalized solid ext. temp.	T_e	$T_e = \frac{T_e^*}{T_0^*}$	$[2.75, 3.25]$
Total equivalence ratio	ϕ_0	$\phi_0 = \frac{Z_{l,0}}{f_{st}}$	$[0.5, 11.5]$
Stokes number	St	$St = \frac{\rho_l^* {D_{d,0}^*}^2}{18\mu_0^*} a^*$	$[0.001, 0.3]$
Damköhler number	Da	$Da = \frac{\dot{\omega}_C^*}{\rho_0^* a^*}$	$[10^1, 10^3]$

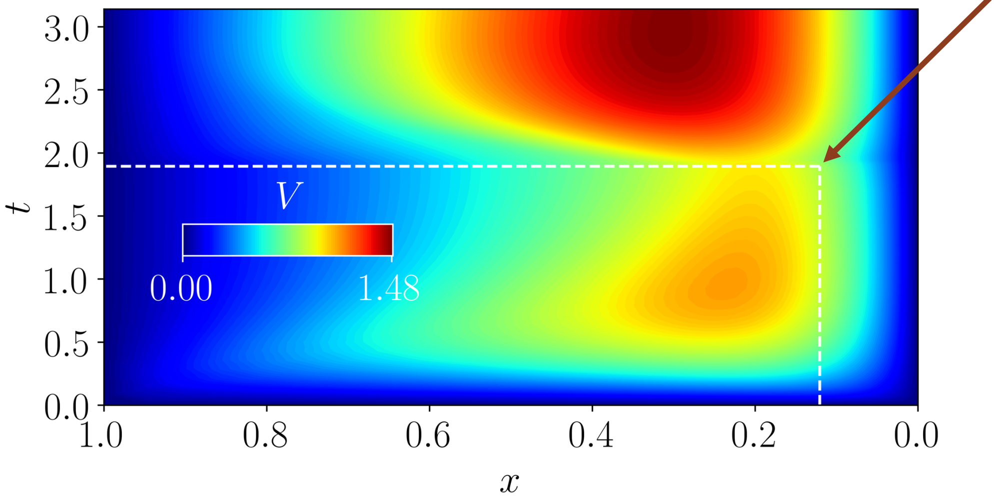
(*) indicates dimensional value

Results: Ignition phenomenology

$$T_e = 3.25, \quad \phi_0 = 1.0, \quad St = 0.1$$

$$t = \frac{t^*}{t_0^*}, \qquad t_0^* \equiv \frac{1}{a^*}$$

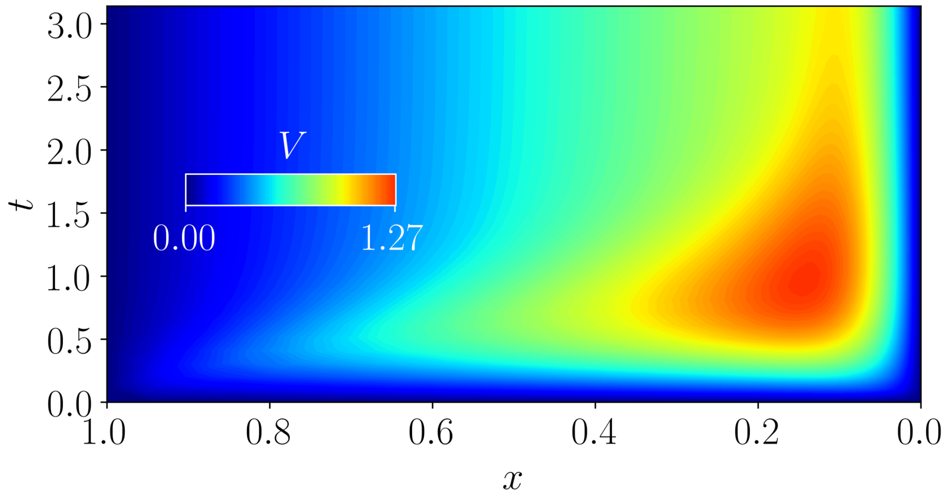
Fluid dynamics $V \equiv \frac{v}{r}$



Ignition

Inlet → Wall

Igniting (Da=120)



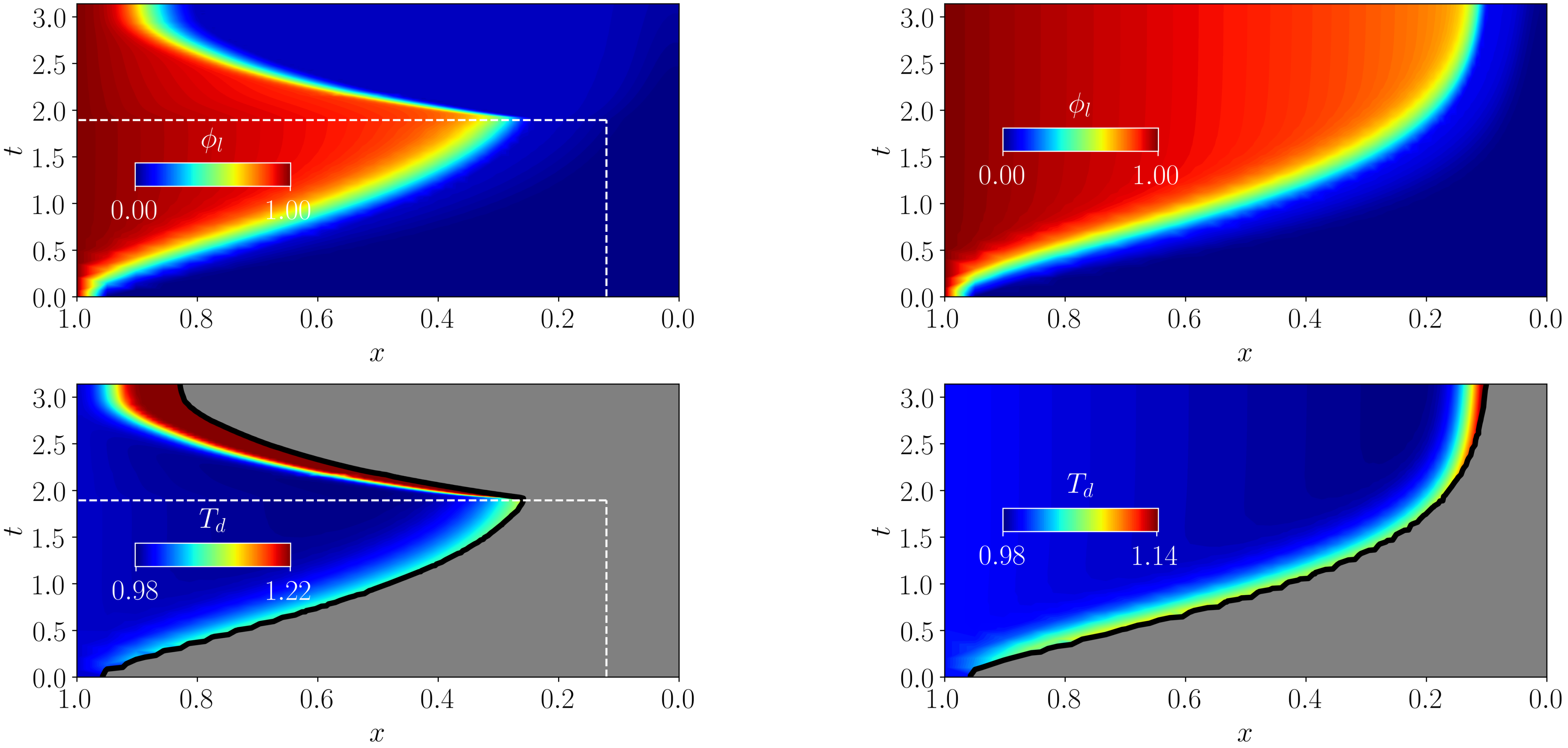
Non-igniting (Da = 30)

Results: Ignition phenomenology

$$T_e = 3.25,$$
$$\phi_0 = 1.0,$$
$$St = 0.1$$

$$t = \frac{t^*}{t_0^*}, \qquad t_0^* \equiv \frac{1}{a^*}$$

Spray dynamics $\phi_l \equiv Z_l/f_{st}$



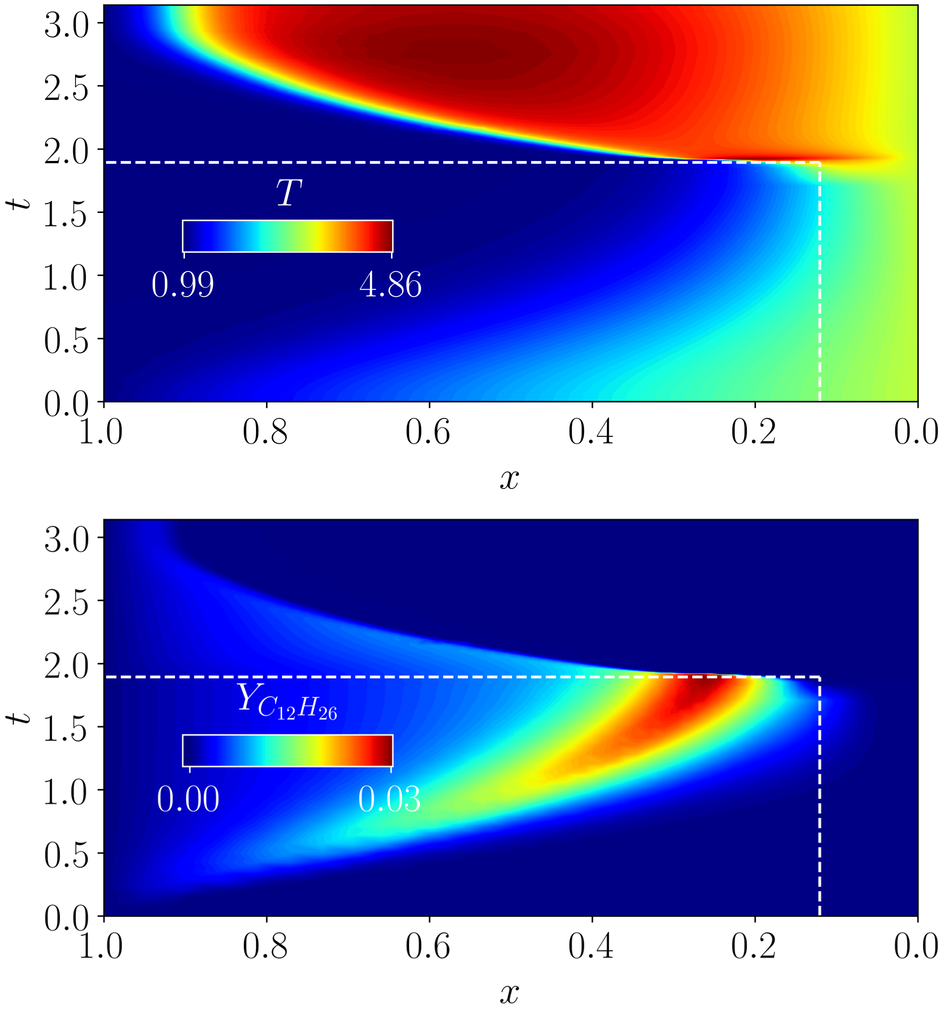
Igniting (Da=120)

Non-igniting (Da = 30)

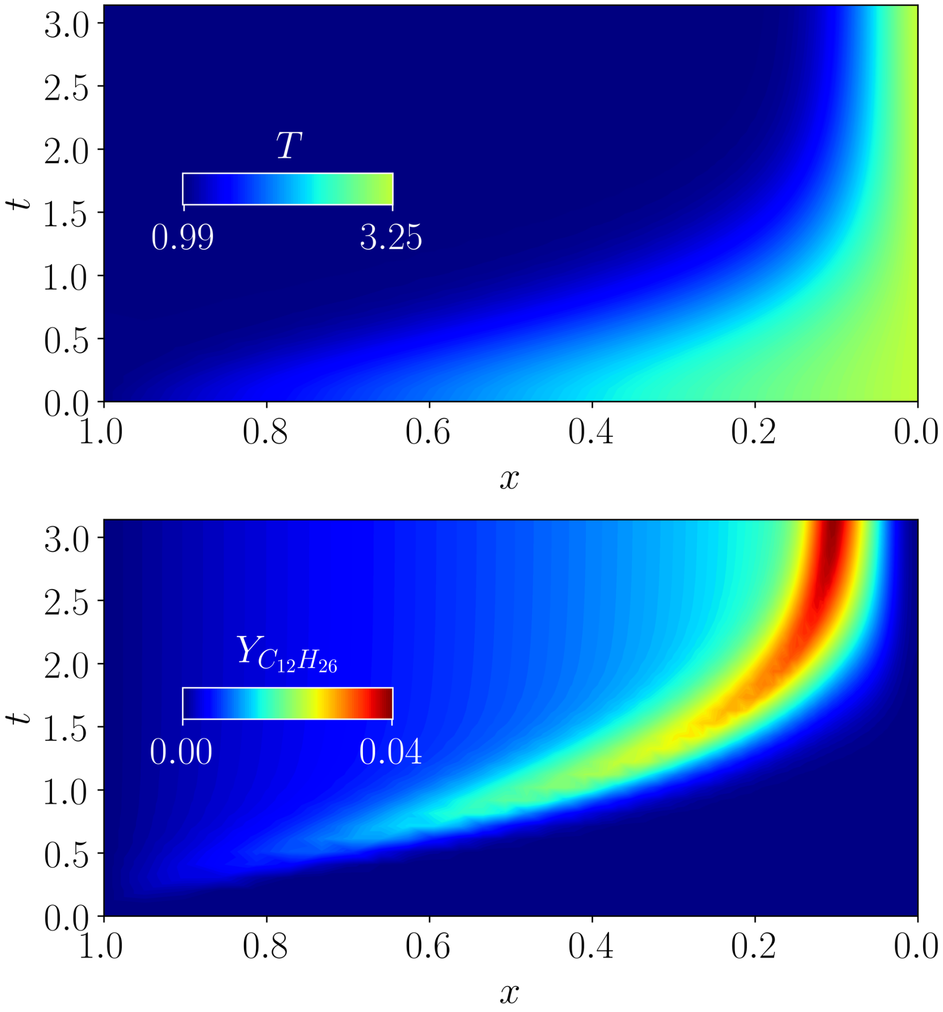
Results: Ignition phenomenology

$$T_e = 3.25,\quad \phi_0 = 1.0,\quad St = 0.1 \qquad t = \frac{t^*}{t_0^*}, \qquad t_0^* \equiv \frac{1}{a^*}$$

Thermochemistry



Igniting (Da=120)

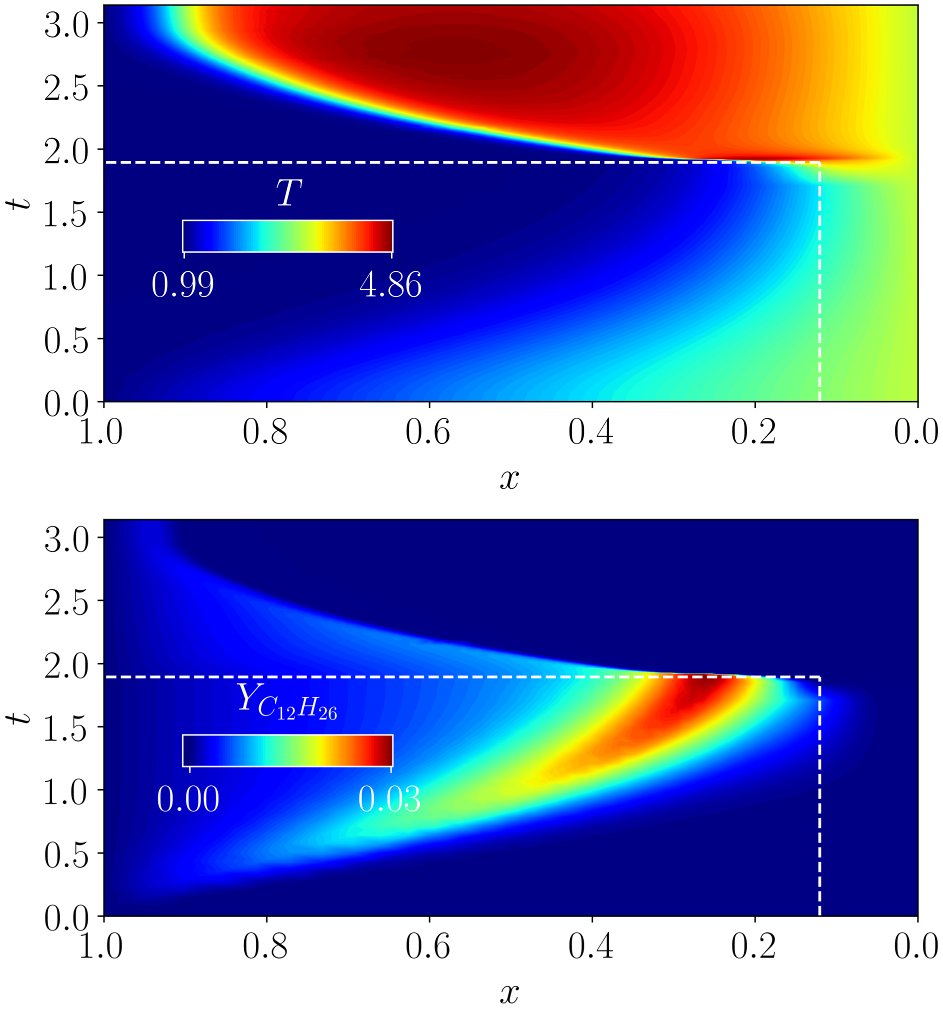


Non-igniting (Da = 30)

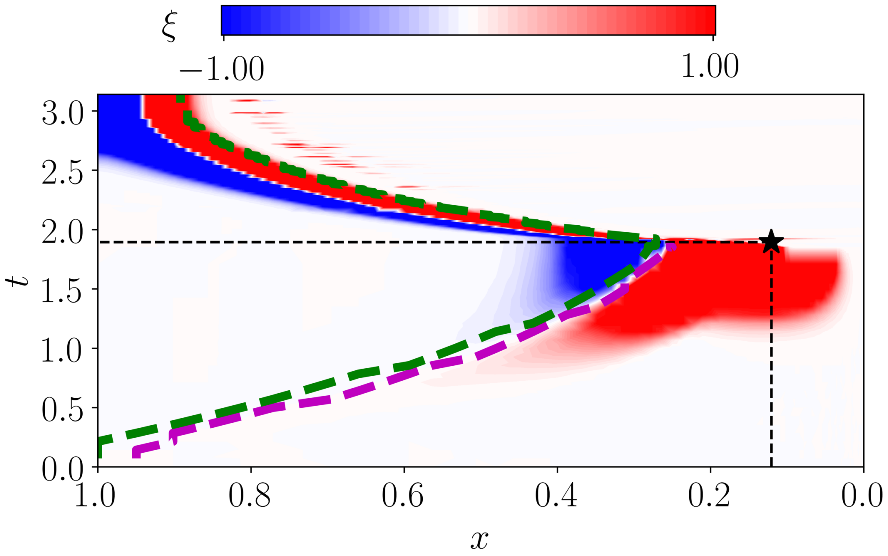
Results: Ignition phenomenology

$$T_e = 3.25, \quad \phi_0 = 1.0, \quad St = 0.1 \qquad t = \frac{t^*}{t_0^*}, \qquad t_0^* \equiv \frac{1}{a^*}$$

Thermochemistry



Igniting (Da=120)



ξ: Takeno flame index
- $\xi > 0$: premixed flame
- $\xi < 0$: non-premixed flame

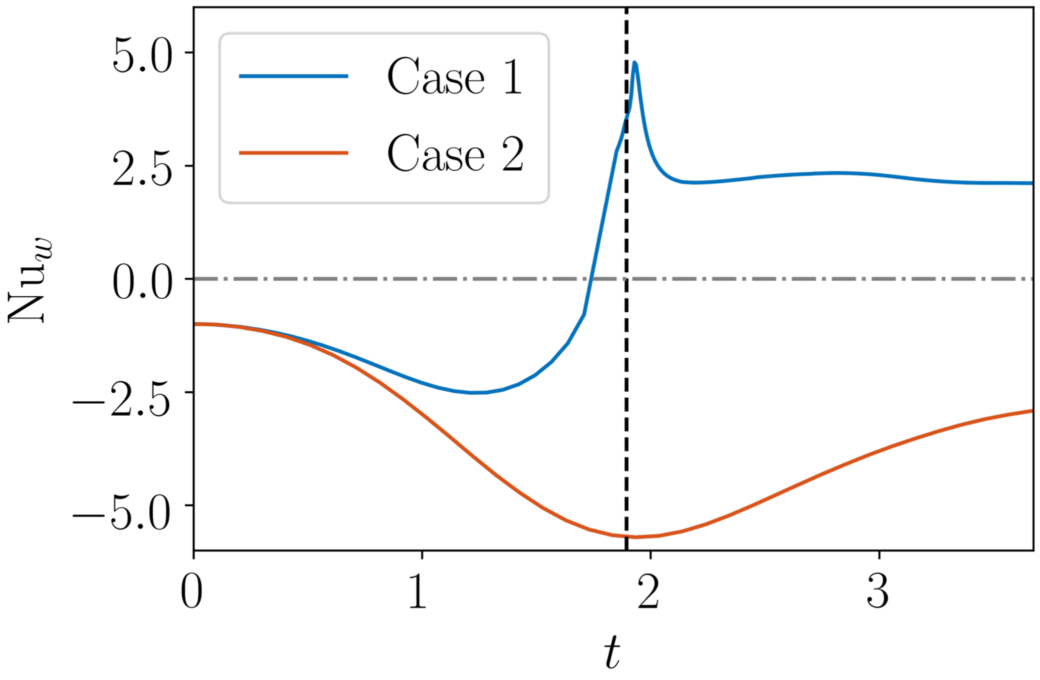
Igniting (Da=120)

Results: Ignition phenomenology

Wall heat transfer

- Case 1: igniting
  - $t_{ign} \approx 1.9$
  - $\max(\mathrm{Nu}_w) \approx 4.9$
- Case 2: non-igniting
  - Steady-state at $t \approx 5$ of $\mathrm{Nu}_w \approx -3$

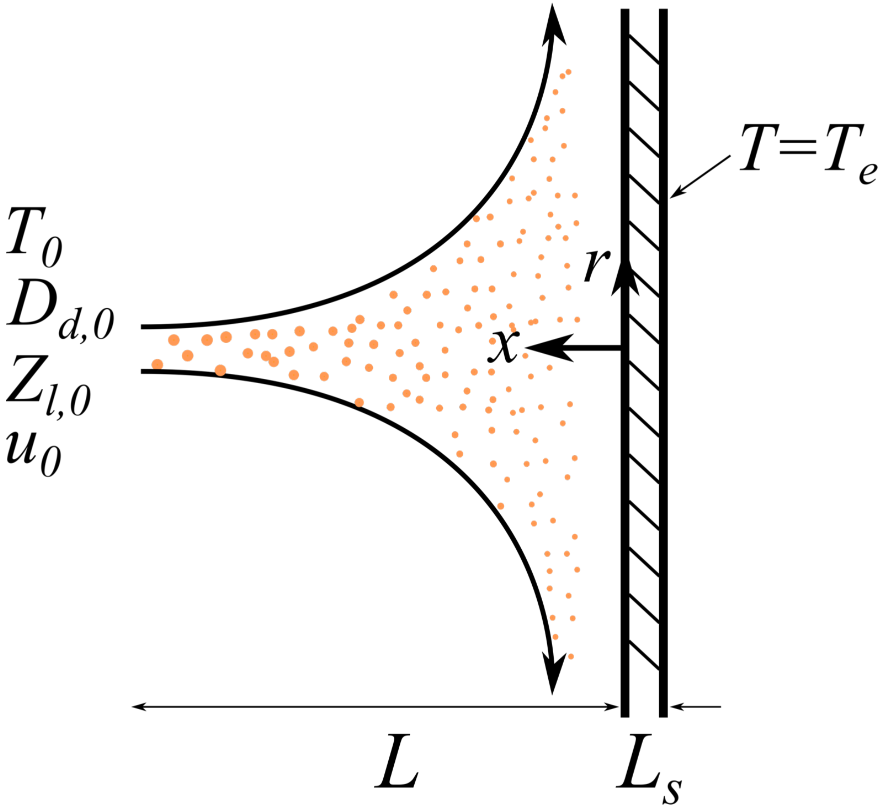
- Conjugate effects small on ignition time scale, wall is nearly isothermal
  - $1/\mathrm{Fo} \sim 10$



Parametric study

- For each simulation, consider a set of parameters
  - T_e, ϕ_0, St, Da
- Each simulation gives a set of quantitative results
  - Igniting (yes/no), $t_{ign}, \phi_{ign}, x_{ign}$
- Consider ~1000 simulations
  - Identify parametric sensitivities and system behavior

Parameter	**Range**
T_e	$[2.75, 3.25]$
ϕ_0	$[0.5, 11.5]$
St	$[0.001, 0.3]$
Da	$[10^1, 10^3]$



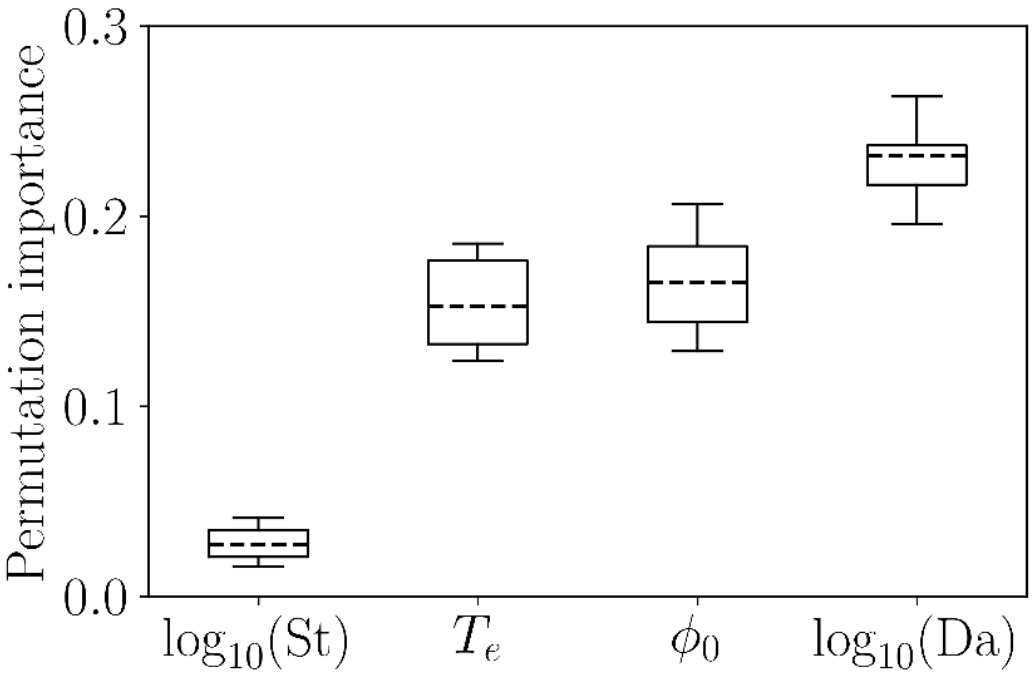
Parametric study

- To quantify importance of various parametric dependencies of ignition quantities, apply data analysis technique from machine learning

- Non-dimensional parameters → features
  - T_e, Da, St, ϕ_0
- Solution information → outputs
  - Ignited (yes/no), $t_{ign}, x_{ign}, \phi_{ign}$

- Trained data-driven model: random forest (RF)
  - Ignited (yes/no) → RF classifier
  - $t_{ign}, x_{ign}, \phi_{ign}$ → RF regressor

- Considered "permutation importances" for each output



Permutation importances for ignition classifier

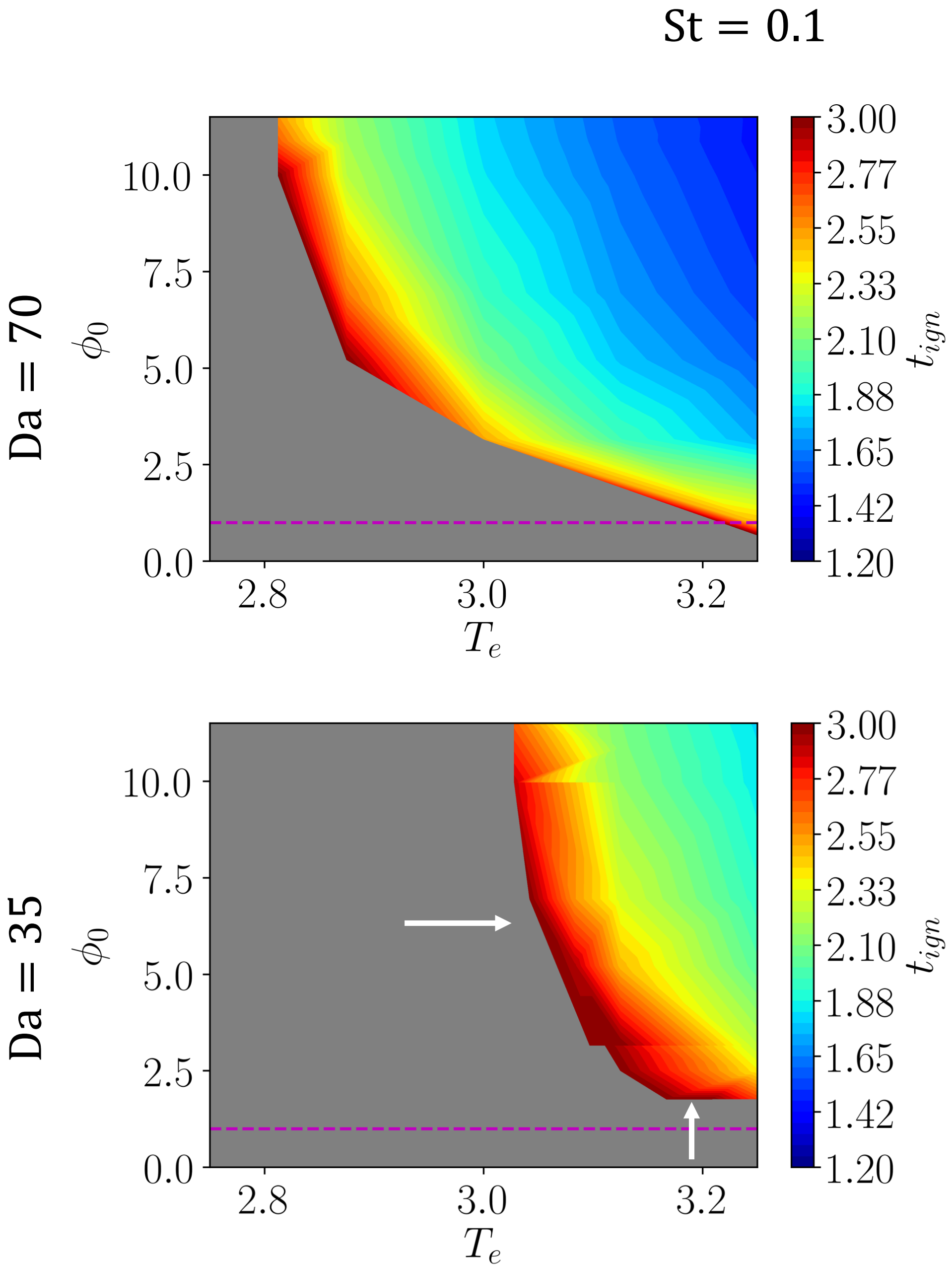
Results: Parametric study

Ignition limits:

- Reduced Da makes lean and near-stoich ϕ_0 non-igniting
- Large contraction in T_e

Ignition delay time:

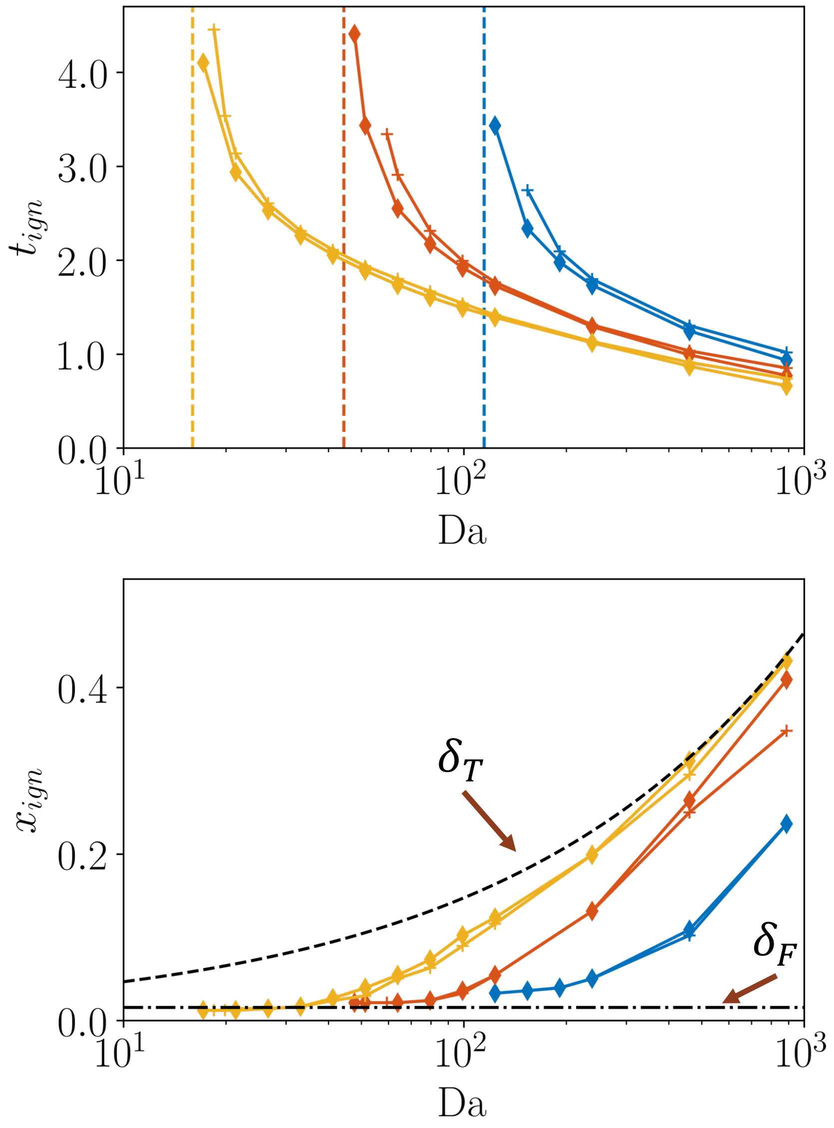
- Reaches maximum at ignition limit
- Minimum at high T_e, ϕ_0
- Modest variation relative to purely chemical ignition delay



Results: Parametric study

- Reduced Da results in increased t_{ign} as ignition limit is approached
- Increased St causes small contraction of ignition limit

- At high Da, ignition location x_{ign} varies proportionally to thermal boundary-layer thickness δ_T
- At low Da and up to the ignition limit, ignition kernels do not form closer to the wall than the laminar premixed flame thickness δ_F
  - $Pe_{\delta_F} = x/\delta_F \sim 1$, as in flame quenching literature



$\boldsymbol{\phi_0 = 3.0}$ $T_e = 2.75,$
$St = 0.01$ (◆) $T_e = 3.00,$
$St = 0.1$ (+) $T_e = 3.25$

Summary

Hot surface ignition of wall-impinging fuel sprays

- Important phenomenon in analysis of industrial and aero-engine safety
- Can occur due to fuel leakage near surfaces at elevated temperatures

Detailed modeling of spray hot-surface ignition

- Demonstrated and analyzed ignition kernel formation, propagation
- Shorter ignition delay from higher wall temperatures can result in reduced transient wall heat flux

Lower-order modeling of spray hot-surface ignition

- Allowed direct comparison of igniting vs. non-igniting phenomenology
- Damköhler number, wall temperature, total equivalence ratio and Stokes number determine ignition limits

Further research needs

Lack of validation data

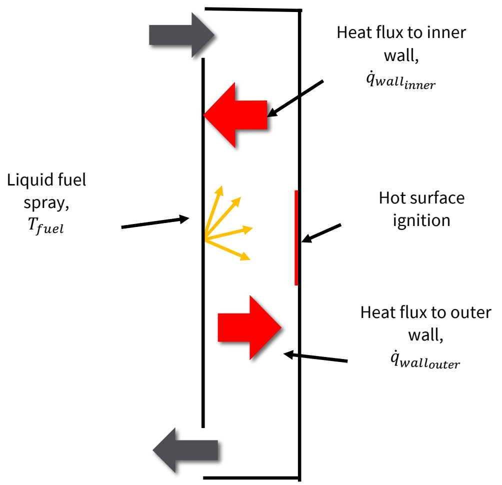
- Critical need to complement computational investigation with experimental measure to validate simulations
- Canonical experimental to enable parametric studies and support certification
- Knowledge transfer to FAA for certification

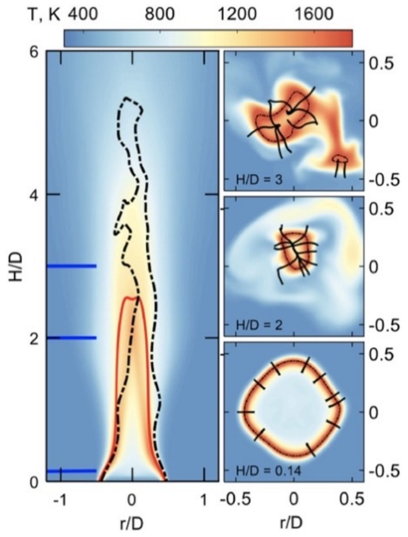
Computational modeling

- Extend modeling effort to account for equally important physical processes of
  - Heat-transfer and structural degradation
  - Leakage and pool fire formations

Innovative data analytics

- Integrate data-analytic models to support
  - Development of low-order models
  - Discovery of physical relations and evaluate stability limits
  - Inform certification processes





Heat Transfer Analysis for Hot Plate Design

Consider the hot surface design heater needs as an energy balance problem:

Some efficiency of heat transferred from heaters to material

$f(m, C_p, \Delta T)$

Convection Losses to Fluid

Conductive Losses to Insulation

$$\text{Heat Needed From Heaters} = \frac{\text{Heat Needed to Raise Mass to } T_{\text{Hot Surface}}}{\text{Heating Time Scale (Specified)}} + \text{Heat Lost to Environment}$$

Convection Losses to Air

Radiative Losses

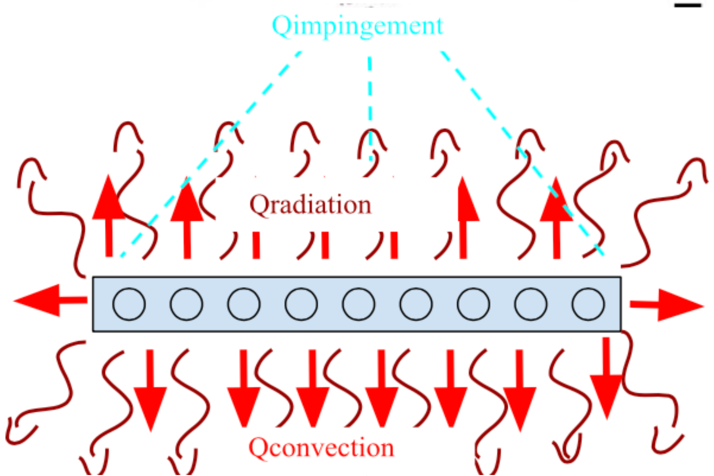


Image By Jesus Cervantes

Heat Transfer Analysis | Methodology

$Nu = 0.59Ra^{0.25}$ **for** $10^4 < Ra < 10^9$
for a vertical, isothermal plate
(M. Bahrami, SFU)

Total Heating Needs [J]

$$Q = mC_p\Delta T$$

**Integral of C_p over T if $C_p(T)$*

Q = **Total Heat [J],** m = **Hot Surface Mass [kg]**

C_p = **Specific Heat Capacity [J/kg-K]**

ΔT = **Change in Temperature [K]**

Natural Convection Loss [kW]

$$Ra = GrPr = g\beta(T_w - T_\infty)\frac{H^3}{v}\alpha$$

$\beta = \frac{1}{T_{film}}$ for ideal gases where $T_{film} = \frac{T_\infty + T_w}{2}$ [K], T_w= Wall Temp [K], T_∞= Ambient Temp [K], H = Hot Surface Height [m], v = Kinematic Viscosity [m²/s], α = Thermal Diffusivity [m²/s]

Used to find Nu, which is used to find heat transfer coefficient, h

Fluid Impingement Loss [kW]

$$Q = Q_{vap}$$

Conservative Estimate: Assume all fluid contacting plate evaporates, so the heat loss is associated with the heat necessary for the phase change. **Lack of good models to estimate these impacts.**

Radiation Loss [kW]

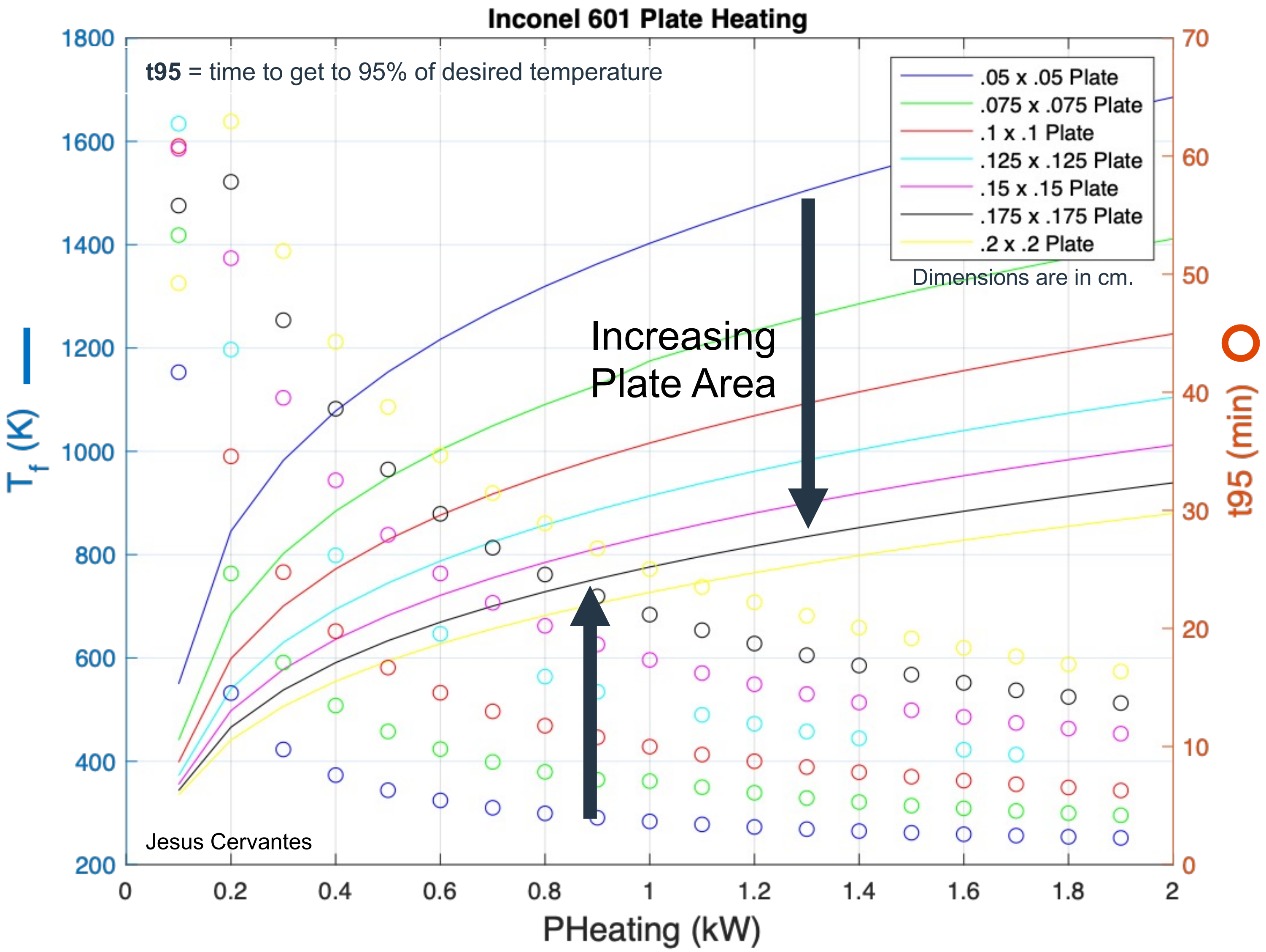
$$Q = \varepsilon\sigma A\left(T_{surface}^4 - T_{surroundings}^4\right)$$

***Emissivity varies with temperature**

Q = **Heat Flux [W],** ε = **Emissivity,**

σ = **Stefan-Boltzmann constant,** T_{surf} = **Surface Temp [K],** $T_{surroundings}$ = **Environment Temp [K]**

Heat Transfer Analysis | Plate Dimensions Impact



A

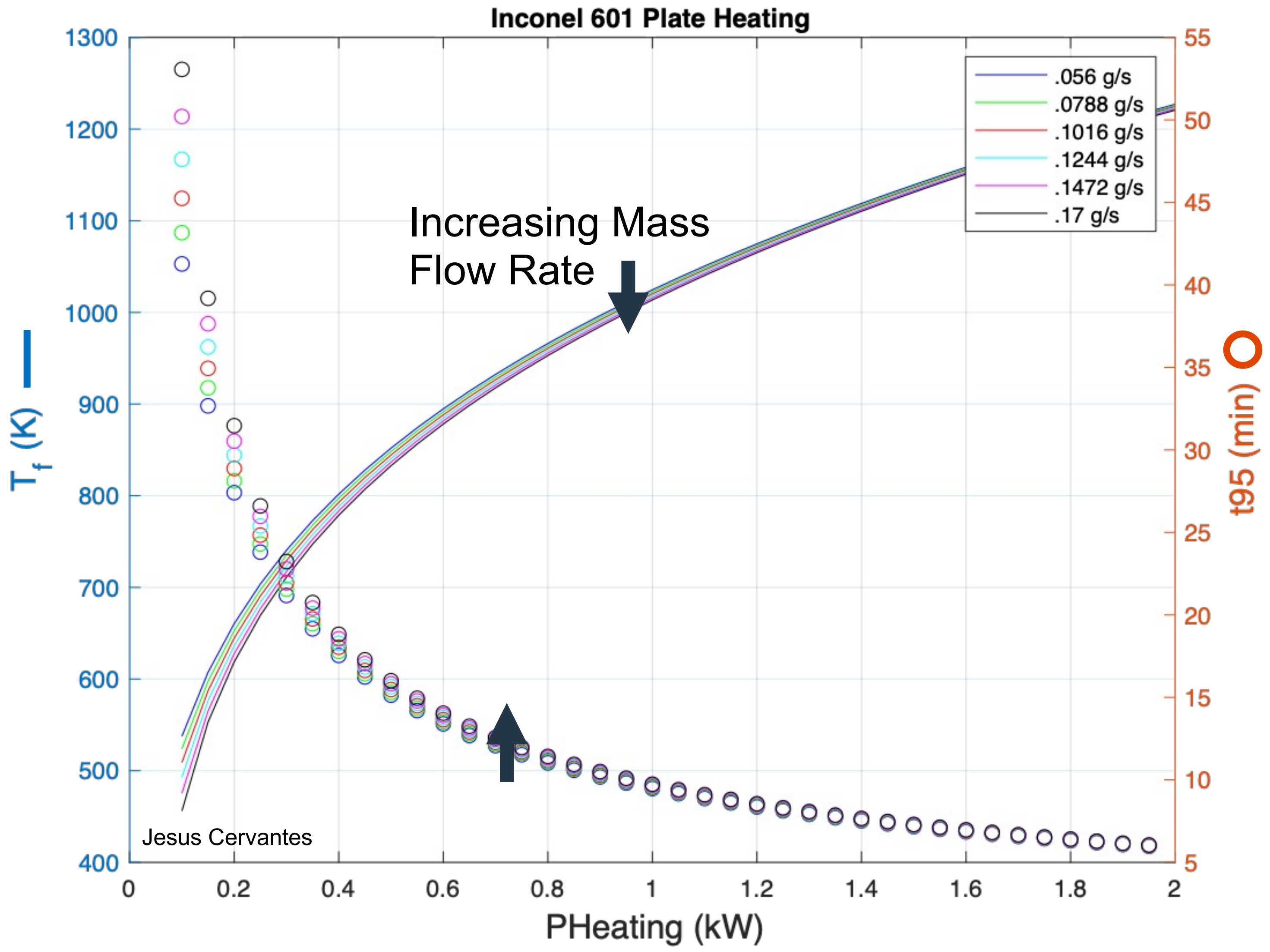
- Increased plate area **substantially** decreases temp and increases t95
  - 30 to 65 min t95 range
  - 900 to 1700 K range
- **Δ 35 minutes @ 2 kW between min and max area**
- **Δ 800 K @ 2 kW between min and max area**

Heat Transfer Analysis | Mass Flow Impact

m

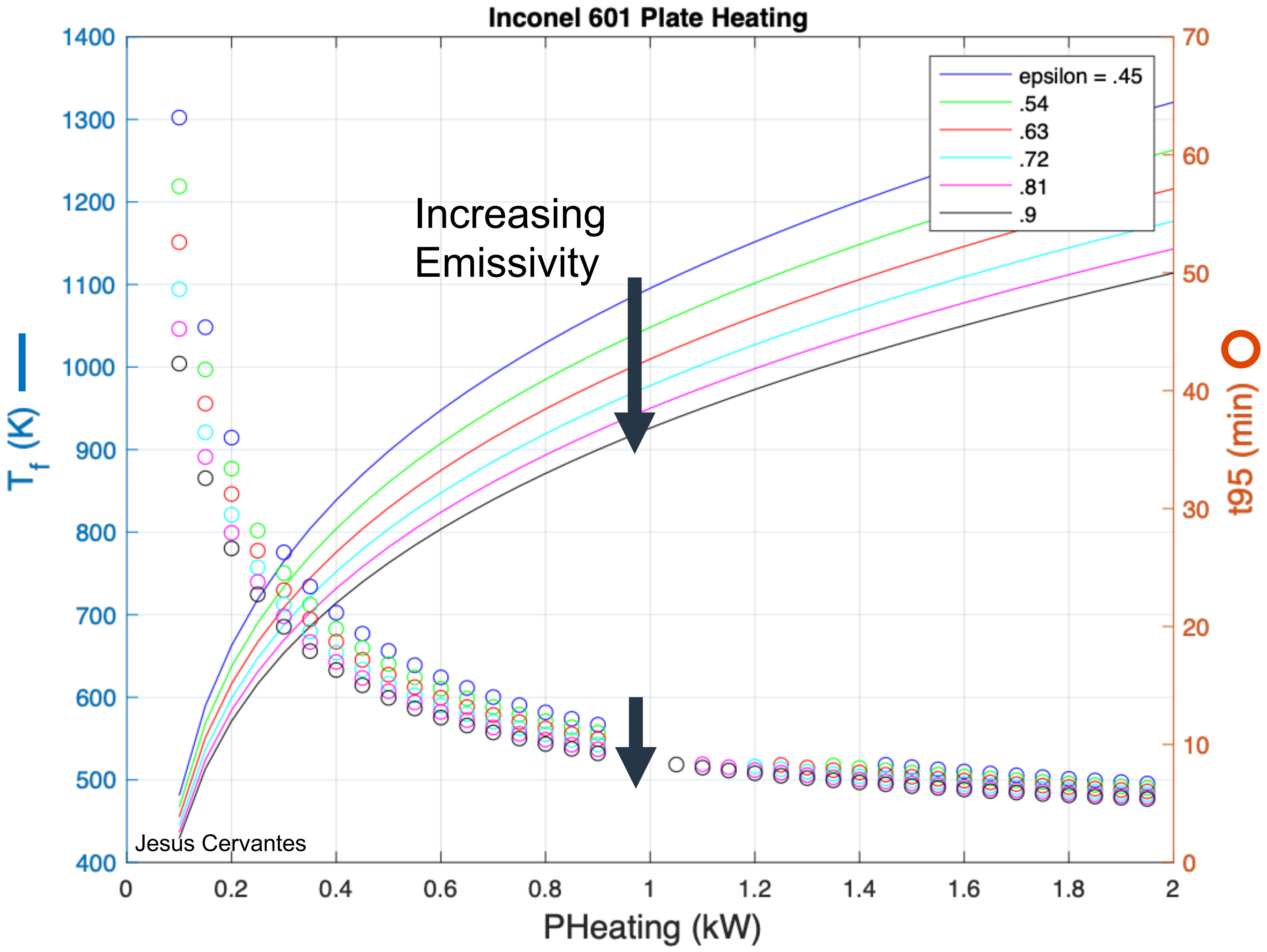
- **Increased mass flow rate minimally decreases temp and increases t95**
  - **50.5 to 51 min t95 range**
  - **Asymptotes to ~420 K**

- **Δ 30 s @ 2 kW between min and max mass flow**
- **Δ < 10 K @ 2 kW between min and max mass flow**



Jesus Cervantes

Heat Transfer Analysis | Emissivity Impact



Increasing Emissivity

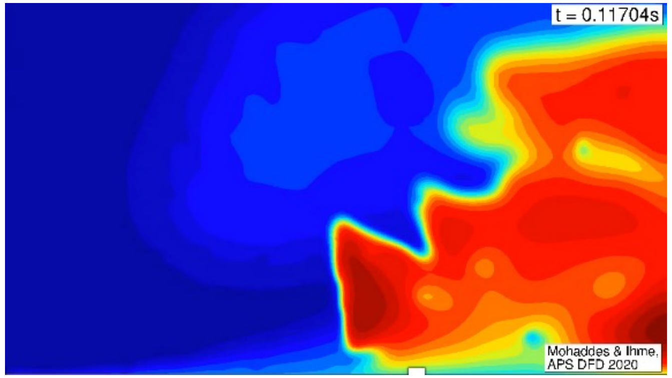
Jesus Cervantes

$\mathcal{E}$

- Increased emissivity notably decreases temp and t95
    - 50 – 65 min t95 range
    - Asymptotes to ~480 K

- Δ 15 min @ 2 kW between min and max area
- Δ 5 K @ 2 kW between min and max area

Conclusions



Mohaddes & Ihme, APS DFD 2020

Aeon Brown (2021), FAA

Hot surface ignition of wall-impinging fuel sprays important phenomenon in analysis of industrial and aero-engine safety

Can occur due to fuel leakage near surfaces at elevated temperatures

Through detailed simulation and low-order modeling, we identified key parameters that control hot surface ignition: L, T_e, ϕ_0, St, Da

Identified low-surface temperature conditions (< 1000K) to be more critical

- Enhanced wall heat flux
- Longer ignition delay
  - → more vaporized fuel available
  - → more air entrainment

Experimental testing imperative for certification