Convective Heat Transfer from Impinging Flames

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"Behavior of Steel Beams under Localized Fire Exposure", NIST.

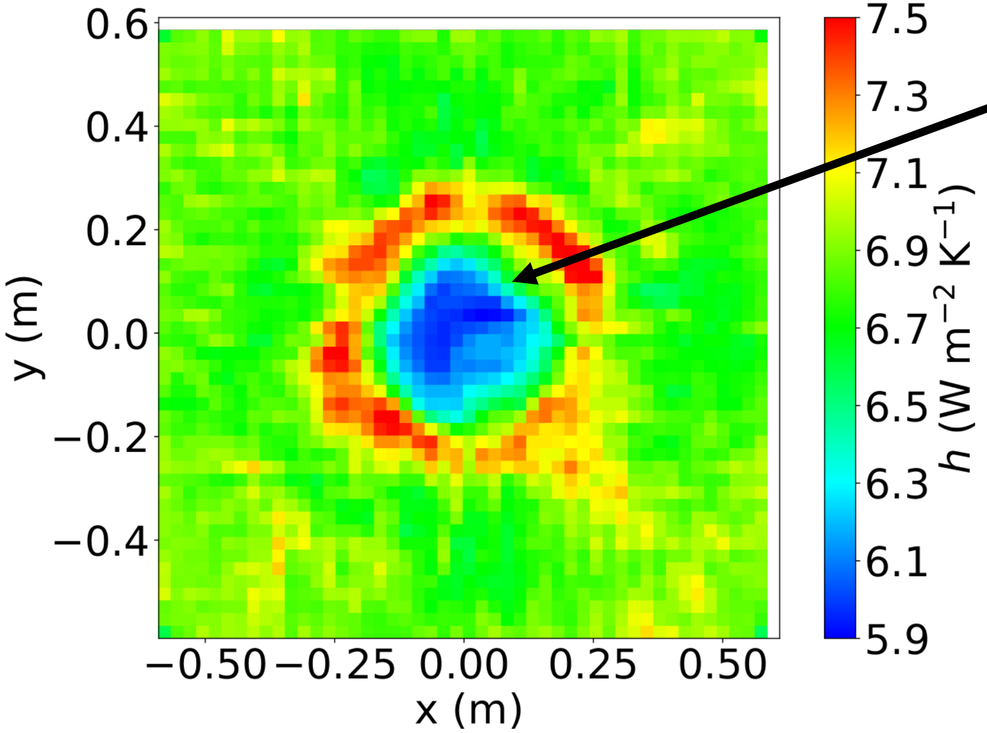
Outline

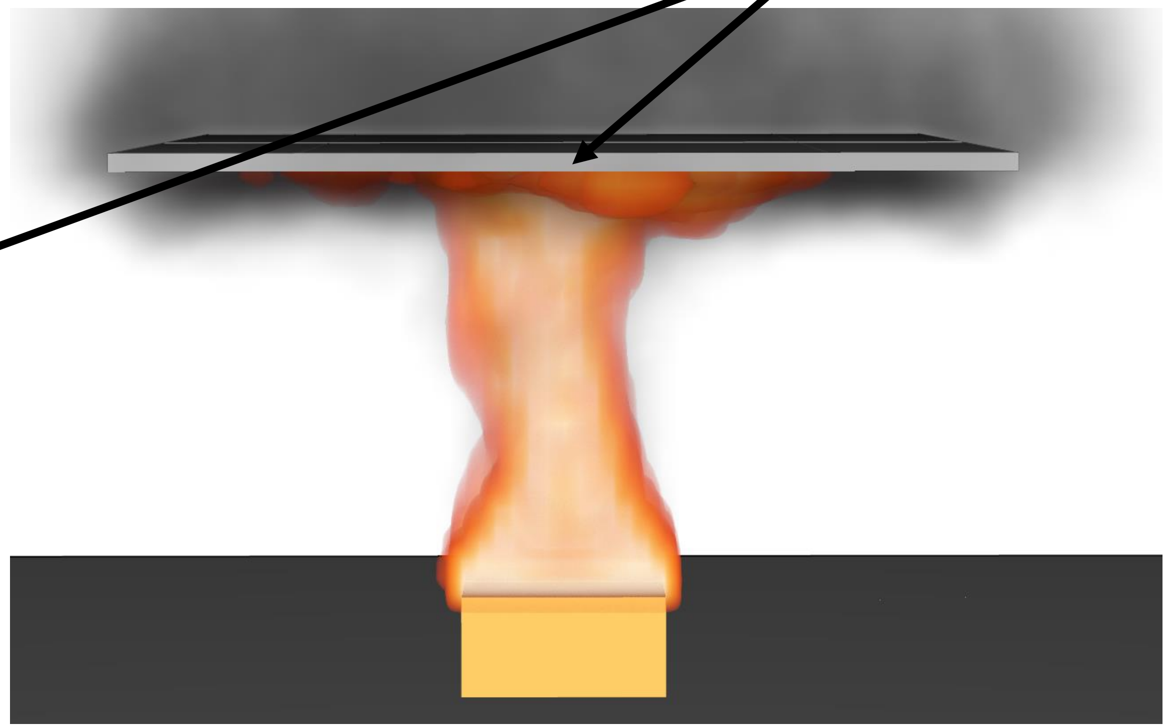
- Background on Convection
- FDS Defaults
- Impinging Jets
- Model Formulation
- Model Validation
- Example Performance-Based Design Application

“Behavior of Steel Beams under Localized Fire Exposure”, NIST.

Default FDS Configuration

- Local minima at stagnation point
  - Result of tangential velocities going to zero
  - Shift from forced convection regime to natural convection regime

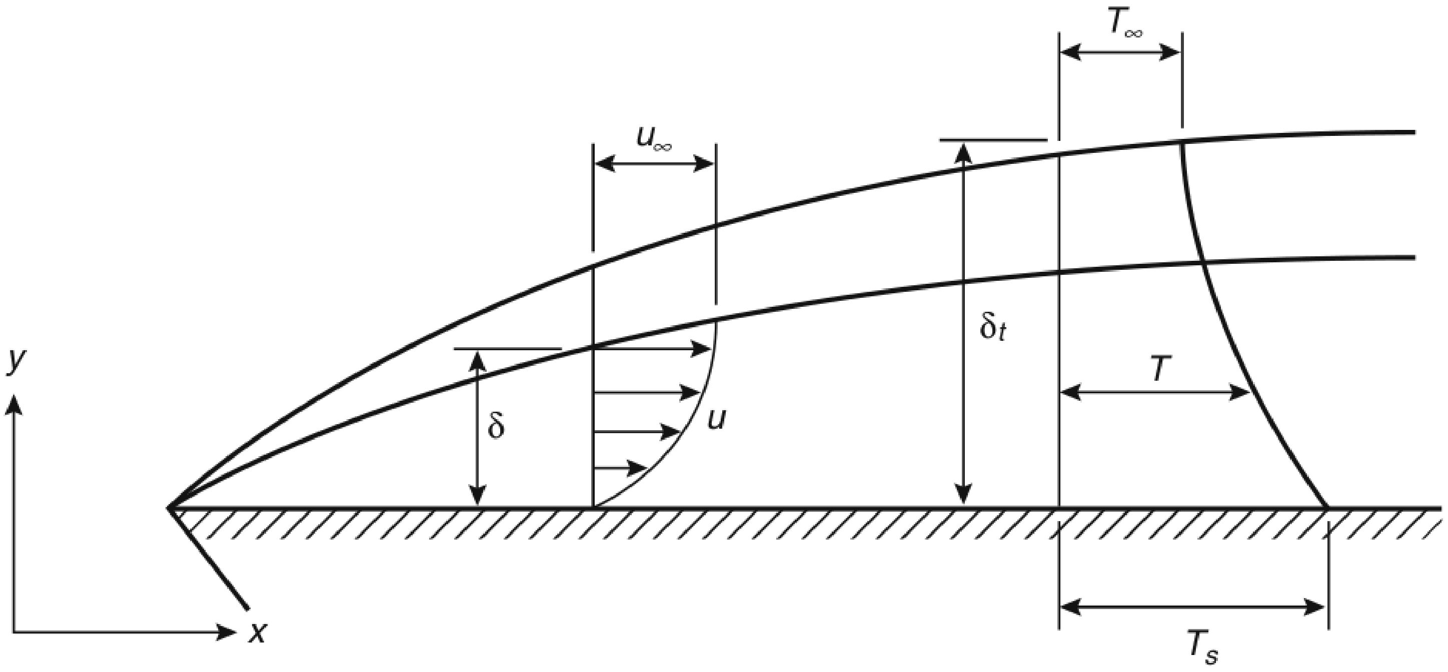




Stagnation Point

Convection

- Conduction between a moving fluid medium and a solid at different temperatures
- Physically related to the velocity and thermal boundary layers at the surface
  - Large Eddy Simulation (LES) models do not fully resolve the boundary layers
  - Correlations used to relate the free-stream to the sub-grid behavior within the boundary layer

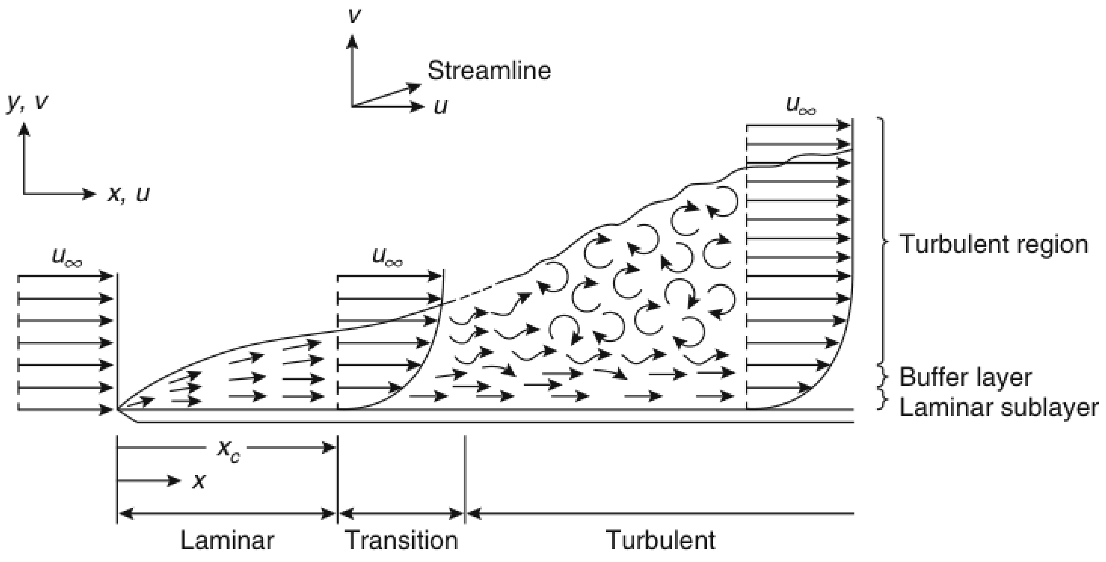


Atreya, A. “Convection Heat Transfer”, SFPE Handbook of Fire Protection Engineering, 2016.

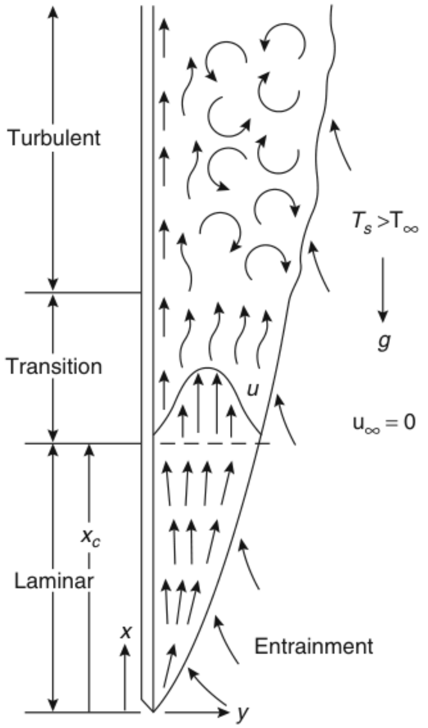
Newton’s Law of Cooling

$$\dot{q}''_{conv} = h(T_s - T_\infty)$$

- Complexity of boundary layer development embedded in the heat transfer coefficient, h



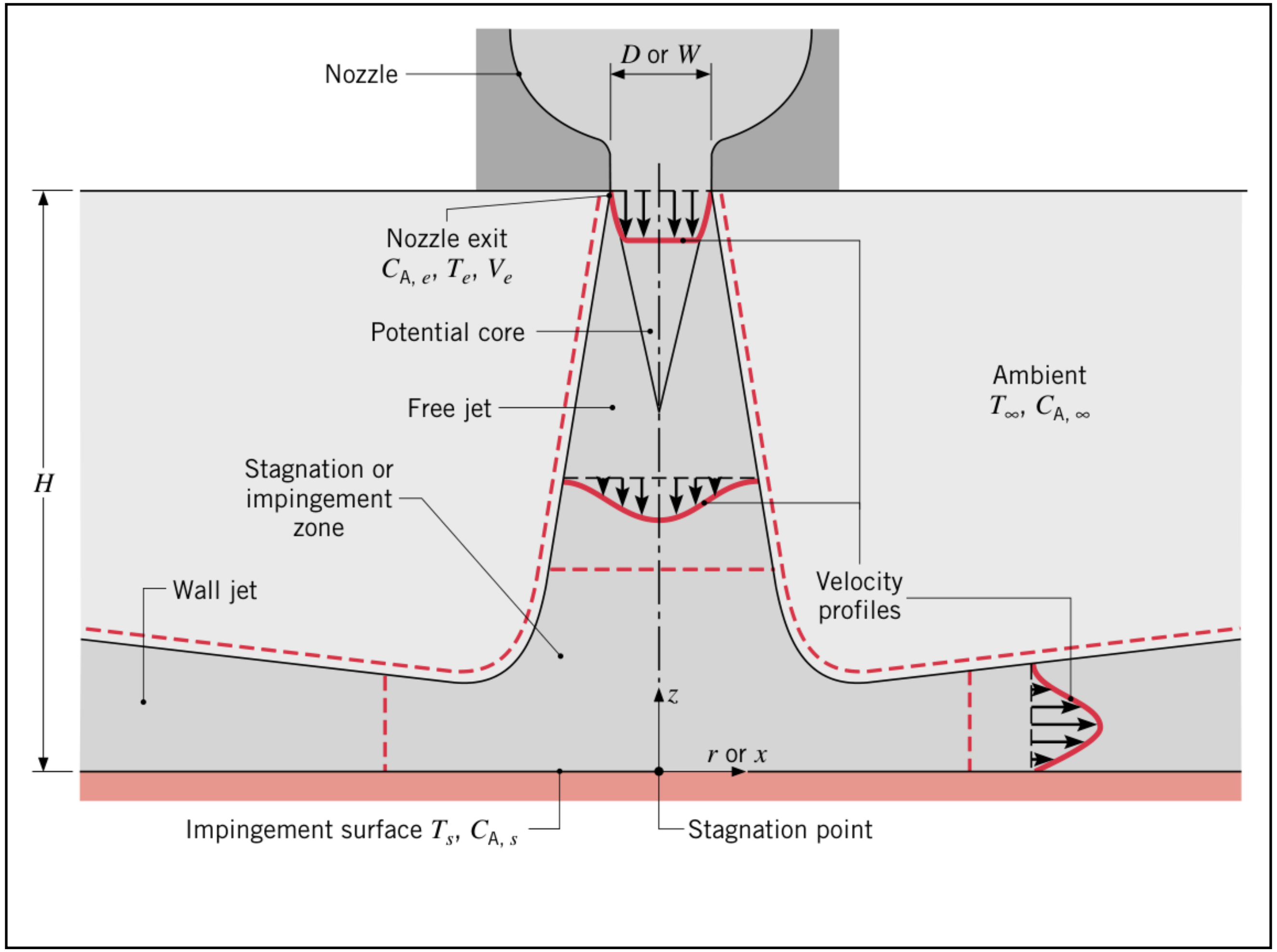
Forced convection over a horizontal plate



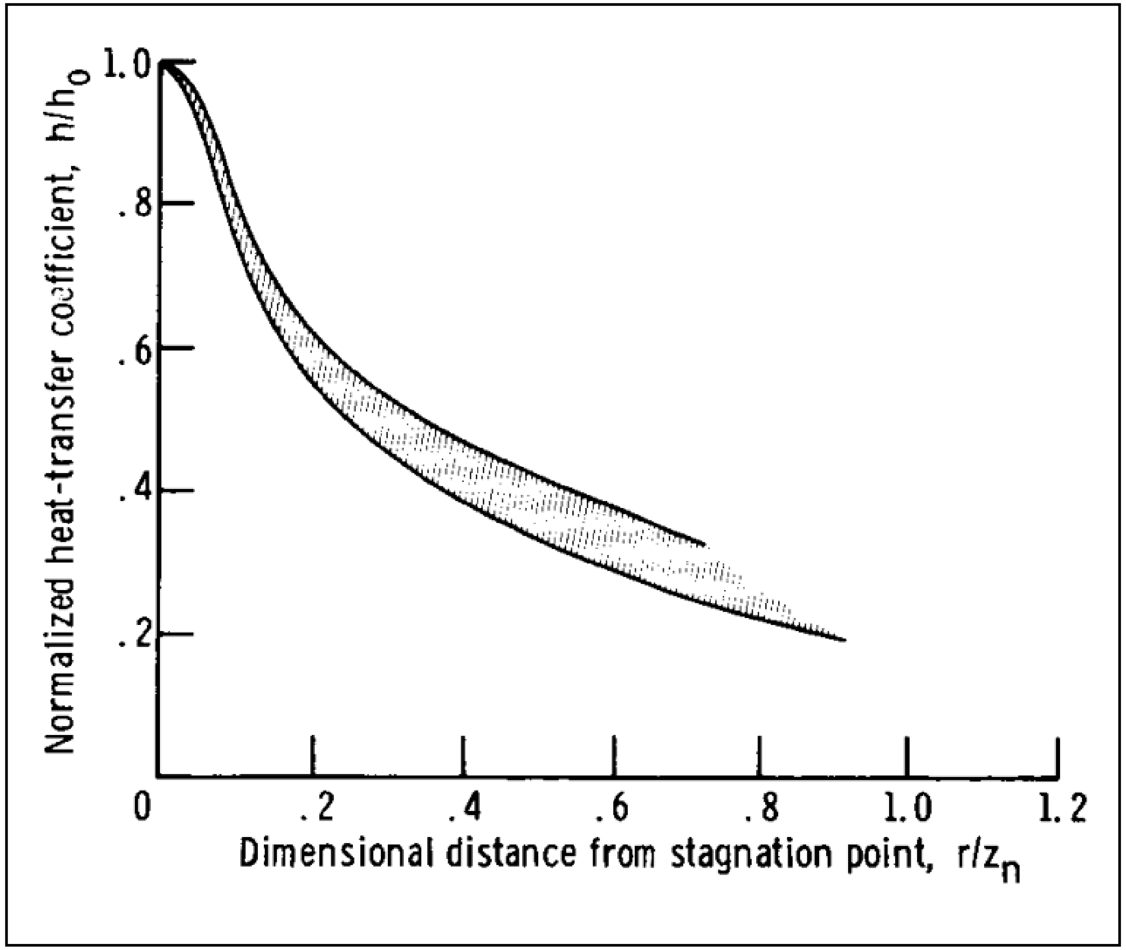
Natural convection on a vertical plate

Atreya, A. “Convection Heat Transfer”, SFPE Handbook of Fire Protection Engineering, 2016.

Impinging Jet Heat Transfer Literature



Incropera, F. P., Dewitt, D. P., Bergman, T. L., & Lavine, A. S. Fundamentals of Heat and Mass Transfer, 2006.



Livingood, J. B., & Hrycak, P. (1973). *Impingement Heat Transfer from Turbulent Air Jets to Flat Plates - A Literature Survey*.

Impinging Jet Heat Transfer Correlations

More difficult to adapt to diffusion flames

- Angle of impingement

(Perry) $\mathrm{Nu} = K \times \mathrm{Re}^{0.7}\mathrm{Pr}^{0.33}$ $K = \underset{15°}{\underline{0.1037}} - \underset{90°}{\underline{0.1810}}$

- Nozzle-to-plate spacing

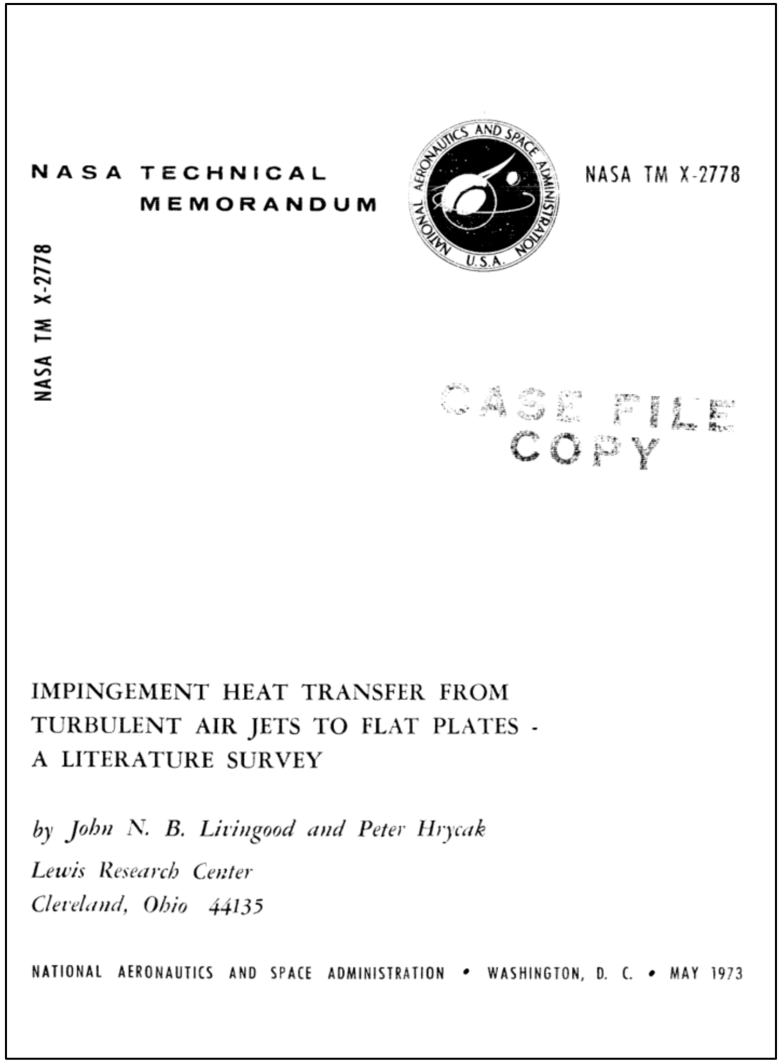
(Thurlow) $\mathrm{Nu} = C \times \mathrm{Re}^{1/3} \exp\left(-0.037 \frac{z_n}{D}\right)$ $C = \sim D^{3/2}$ D in inches

(Gardon, Walz, Brdlik) $\mathrm{Nu} = 13 \times \mathrm{Re}^{1/2} \frac{D}{z_n}$

- Stagnation pressure (Huang)

$\mathrm{Nu} = 0.0233 \times \mathrm{Re}^{0.87}\mathrm{Pr}^{0.33}$ $U_{\mathrm{imp}} = \sqrt{2(p_t - p_s)/\rho}$

Easier to adapt to diffusion flames



NASA TECHNICAL MEMORANDUM

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CASE FILE COPY

IMPINGEMENT HEAT TRANSFER FROM TURBULENT AIR JETS TO FLAT PLATES - A LITERATURE SURVEY

by John N. B. Livingood and Peter Hrycak

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1973

Livingood, J. B., & Hrycak, P. (1973). *Impingement Heat Transfer from Turbulent Air Jets to Flat Plates - A Literature Survey*.

Impinging Jet Heat Transfer Based on Impact Velocity

- Stagnation energy per unit mass, *H* $H \equiv |\boldsymbol{u}|^2/2 + \tilde{p}/\rho$
- Impact velocity – Equivalent velocity if all stagnation energy were kinetic energy $U_{\mathrm{imp}} = \sqrt{2H}$
- Length scale specified by the user (equivalent diameter in this work) $D = \sqrt{4A/\pi}$
- Nusselt relationship based on Martin $\mathrm{Nu} = 0.021 \times \mathrm{Re}^{4/5}\mathrm{Pr}^{1/3}$
- Properties for Re at the nozzle temperature (ambient in this work) $\mathrm{Re}_{\mathrm{imp}} = \dfrac{\rho_\infty U_{\mathrm{imp}} D}{\mu_\infty}$
- Properties for Nu at the film temperature $h = \dfrac{k_{\mathrm{film}}}{D}\,\mathrm{Nu}$

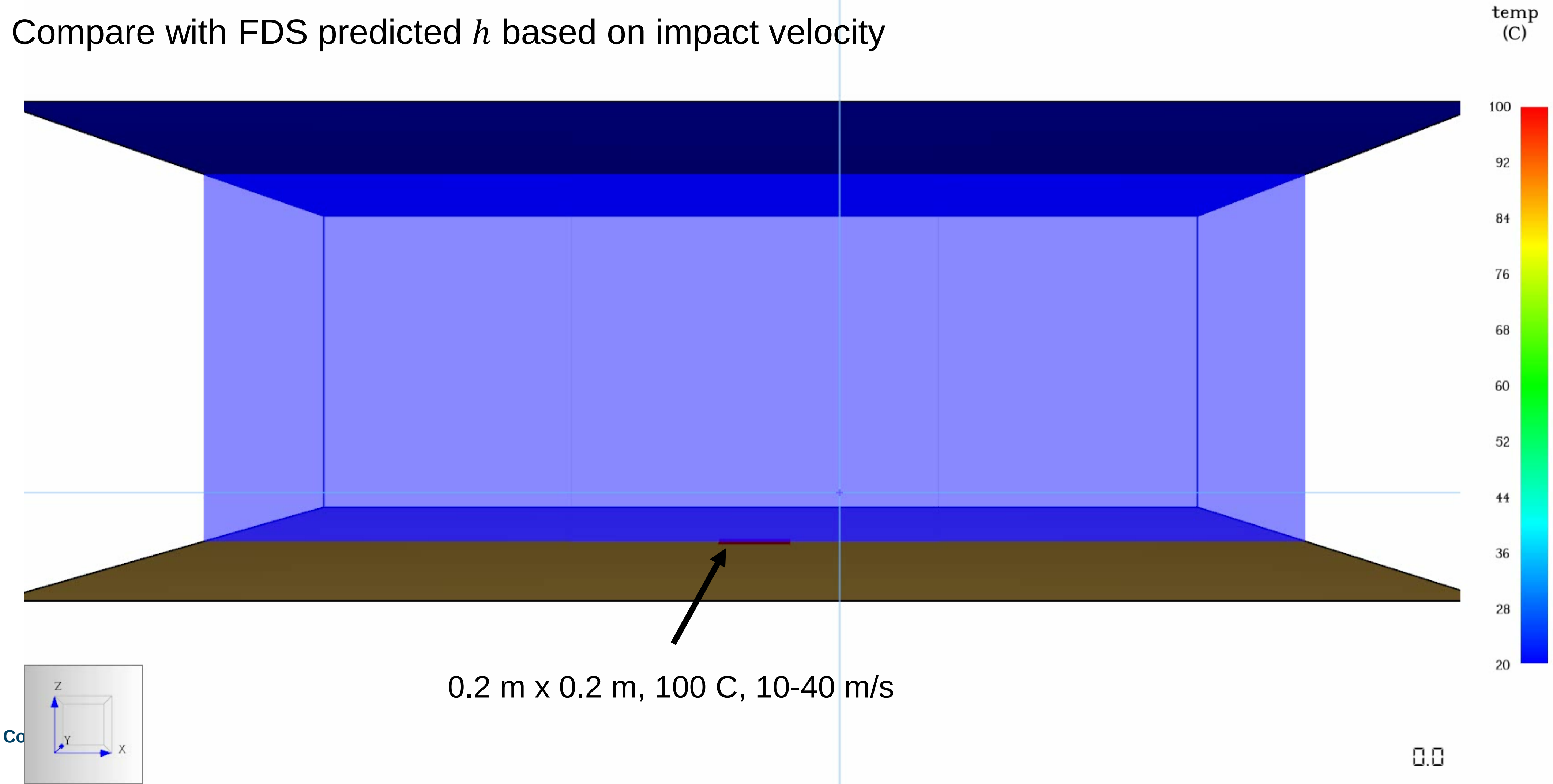
Model Validation

- Non-Reacting Hot Jet
- Fire Impinging on Unconfined Ceiling
- Fire Impinging on Corridor Ceiling

“Behavior of Steel Beams under Localized Fire Exposure”, NIST.

Non-Reacting Hot Jet (Martin)

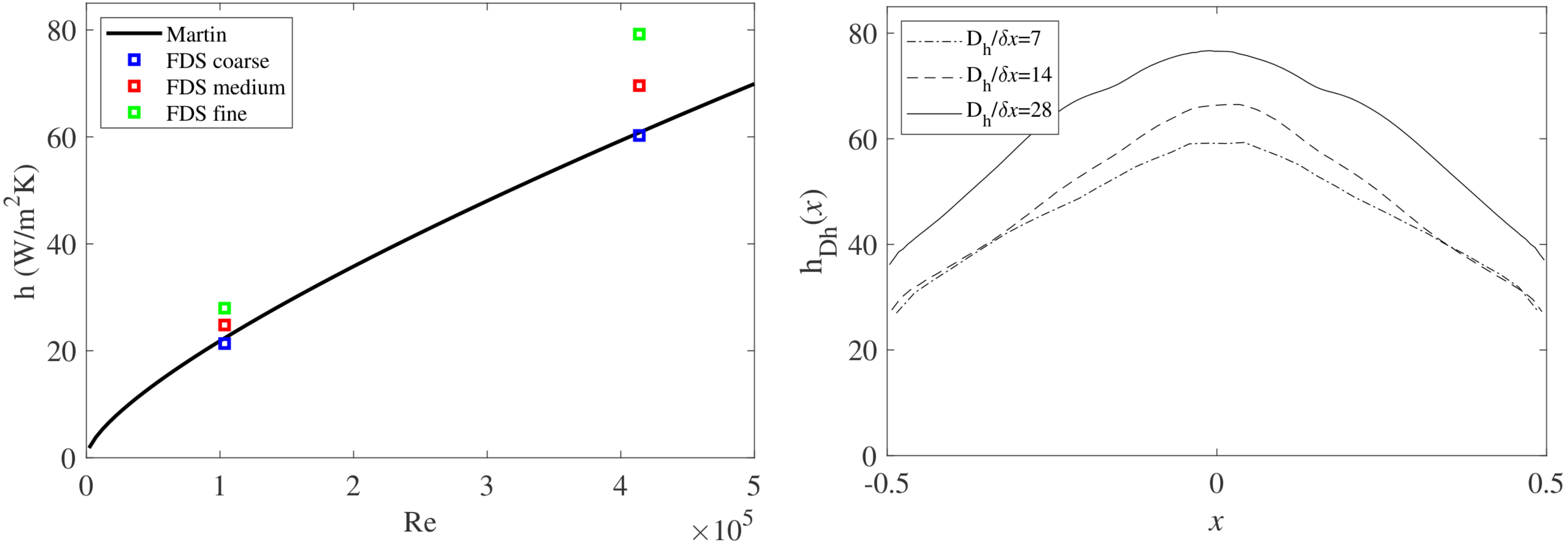
- 3 grid resolutions, $\Delta = 0.03, 0.015, 0.0075$ m
- Calculate h based on existing impinging jet correlations
- Compare with FDS predicted h based on impact velocity



0.2 m x 0.2 m, 100 C, 10-40 m/s

Non-Reacting Hot Jet (Martin)

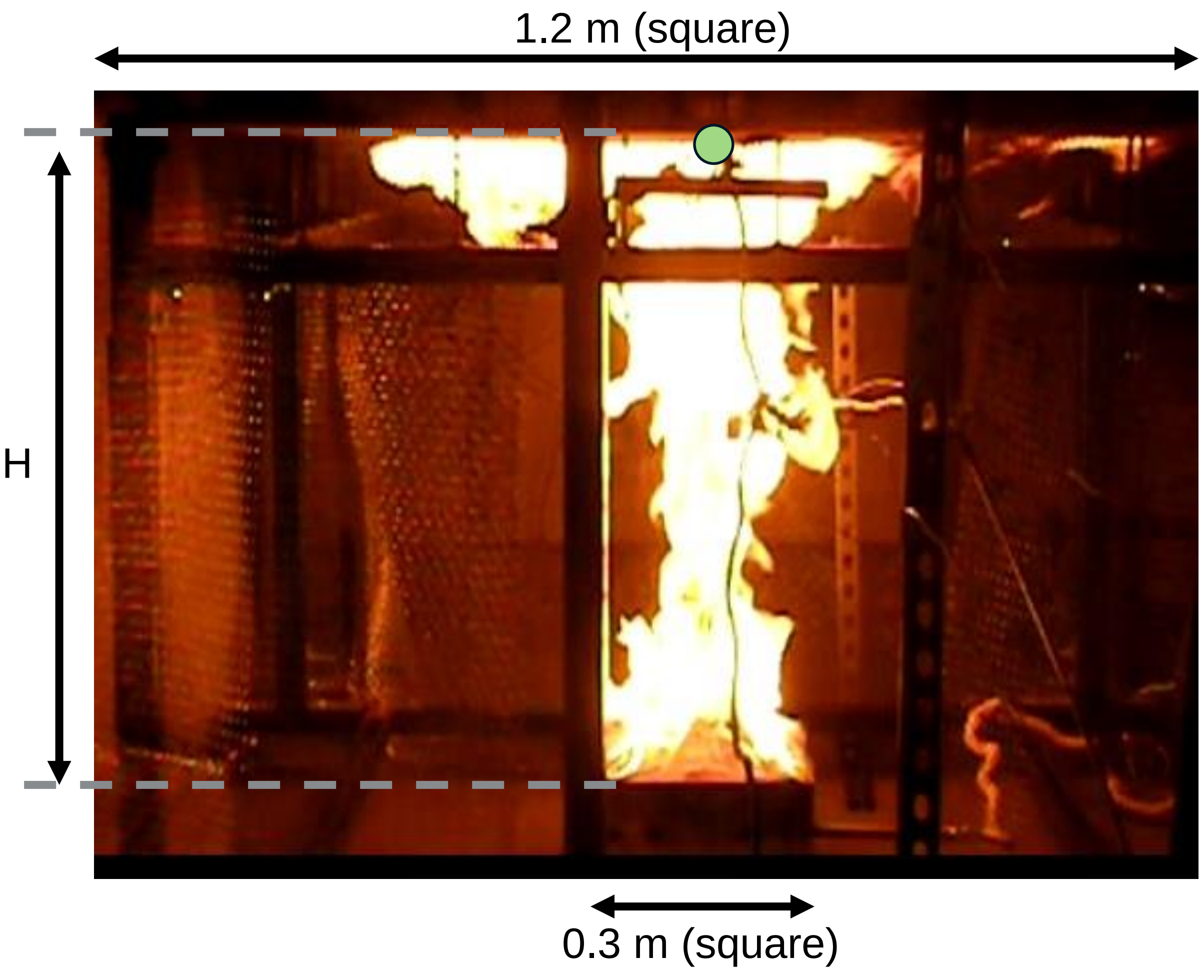
- Agrees well with existing correlations
- Some grid dependence, particularly at the higher Re number (40 m/s)



Fire Impinging on an Unconfined Ceiling Experiments (Wasson)

- Propane sand burner, 0.3 m square
- Adjustable ceiling height
- Measured total heat flux at impinging point
- Estimated split between convection and radiation

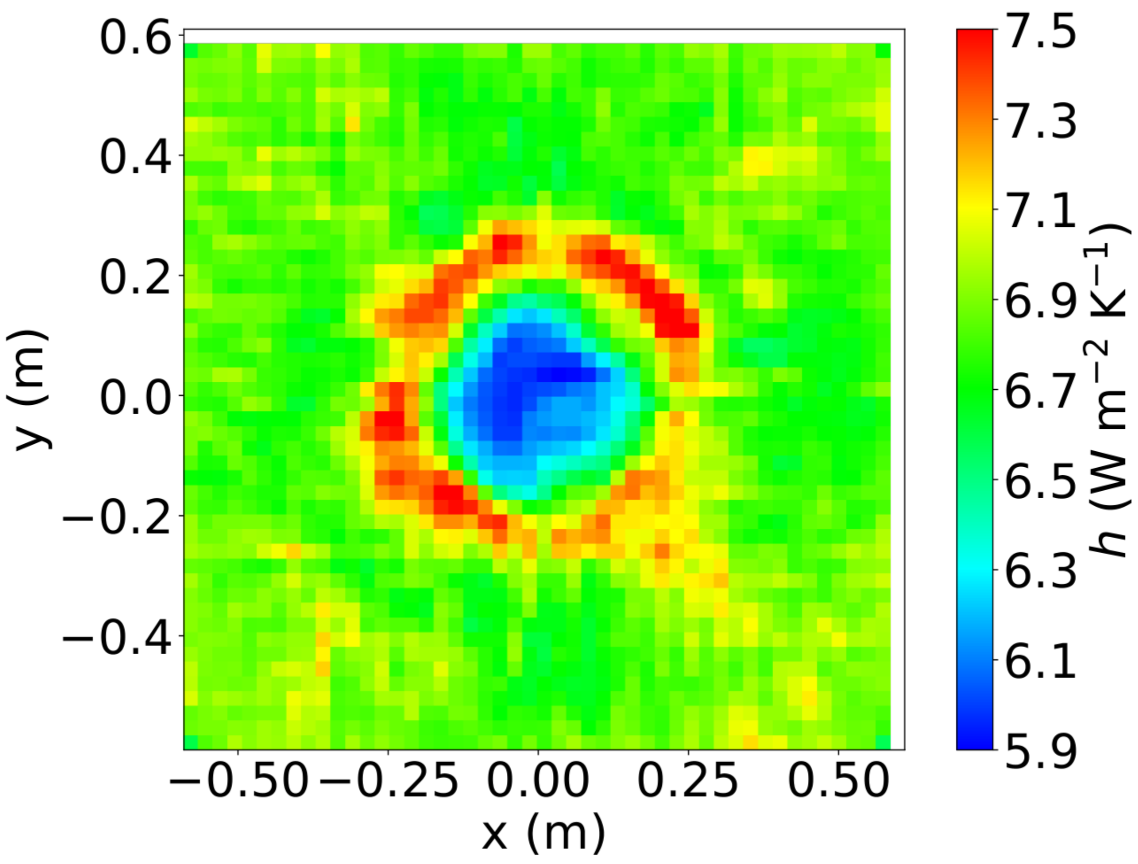
Test	HRR (kW)	H (m)	h (W/m^2K)	$\dot{q}''_{gauge}$ (kW/m^2)	T (°C)
1	50	0.97	34.8	13.9	296.8
2	50	0.64	36.1	35.7	550.6
3	50	0.49	50.5	56.9	676.5
4	90	1.28	42.0	23.1	396.3
5	90	0.85	60.8	56.3	682.5
6	90	0.64	57.5	75.8	839.4



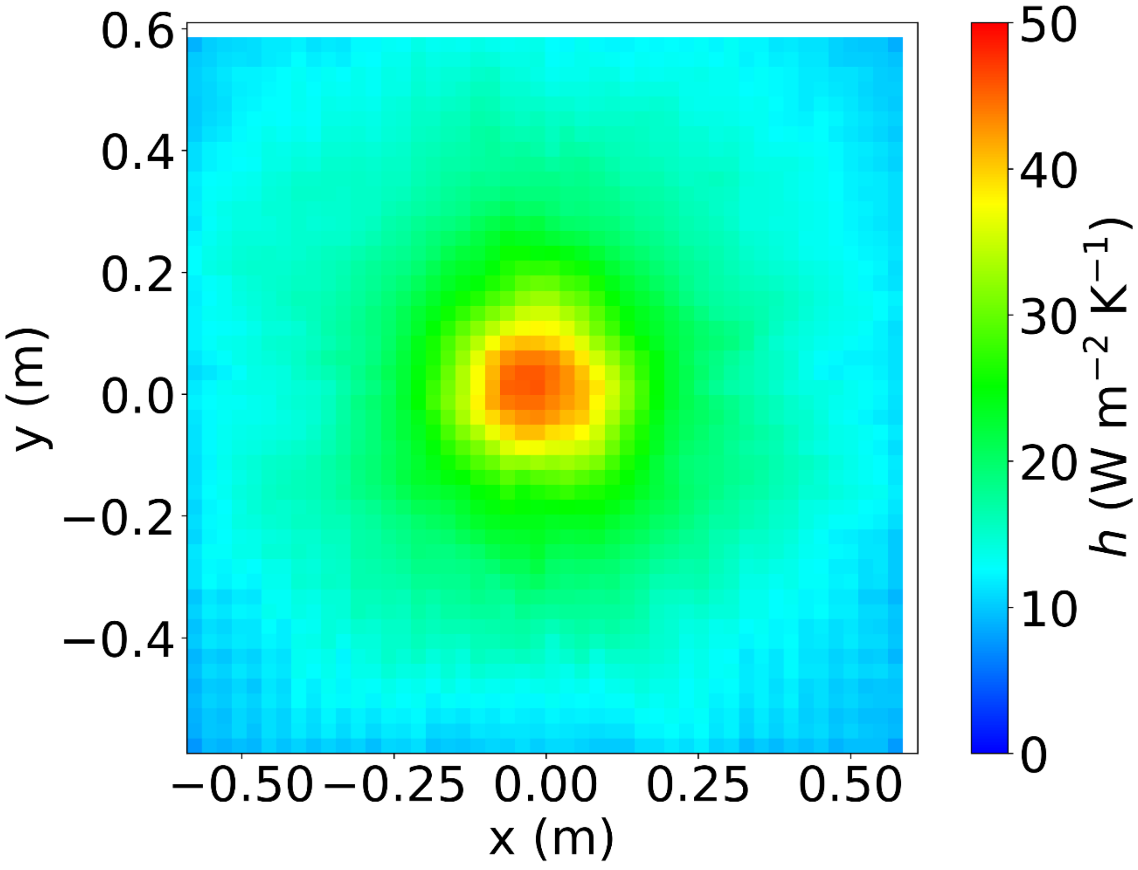
Wasson, R. (2014). Separation of the Heat Transfer Components from Diffusion Flames Impinging onto Ceilings. Virginia Tech.

Fire Impinging on an Unconfined Ceiling Experiments (Wasson)

- 90 kW fire impinging on ceiling 0.64 m above top of burner

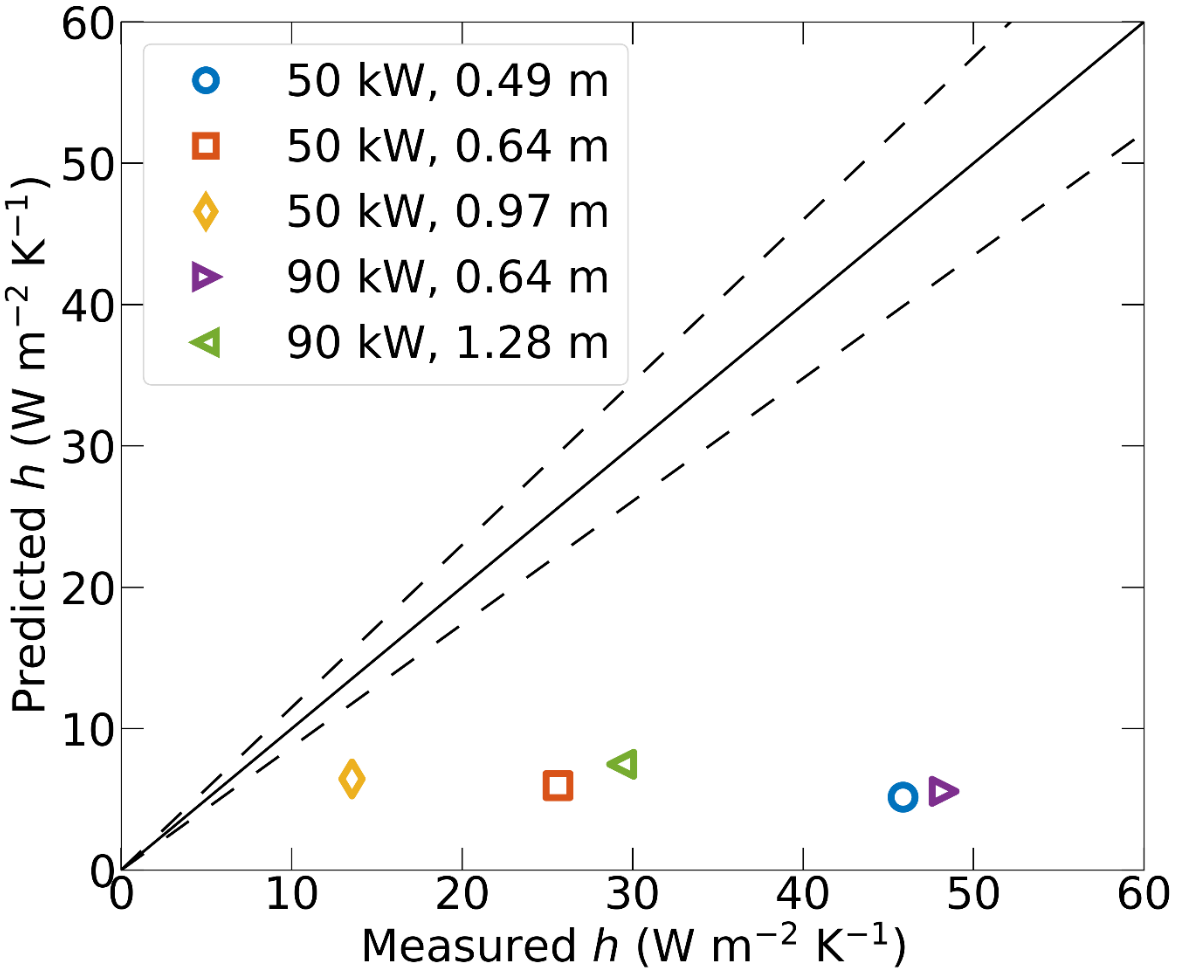


FDS Default

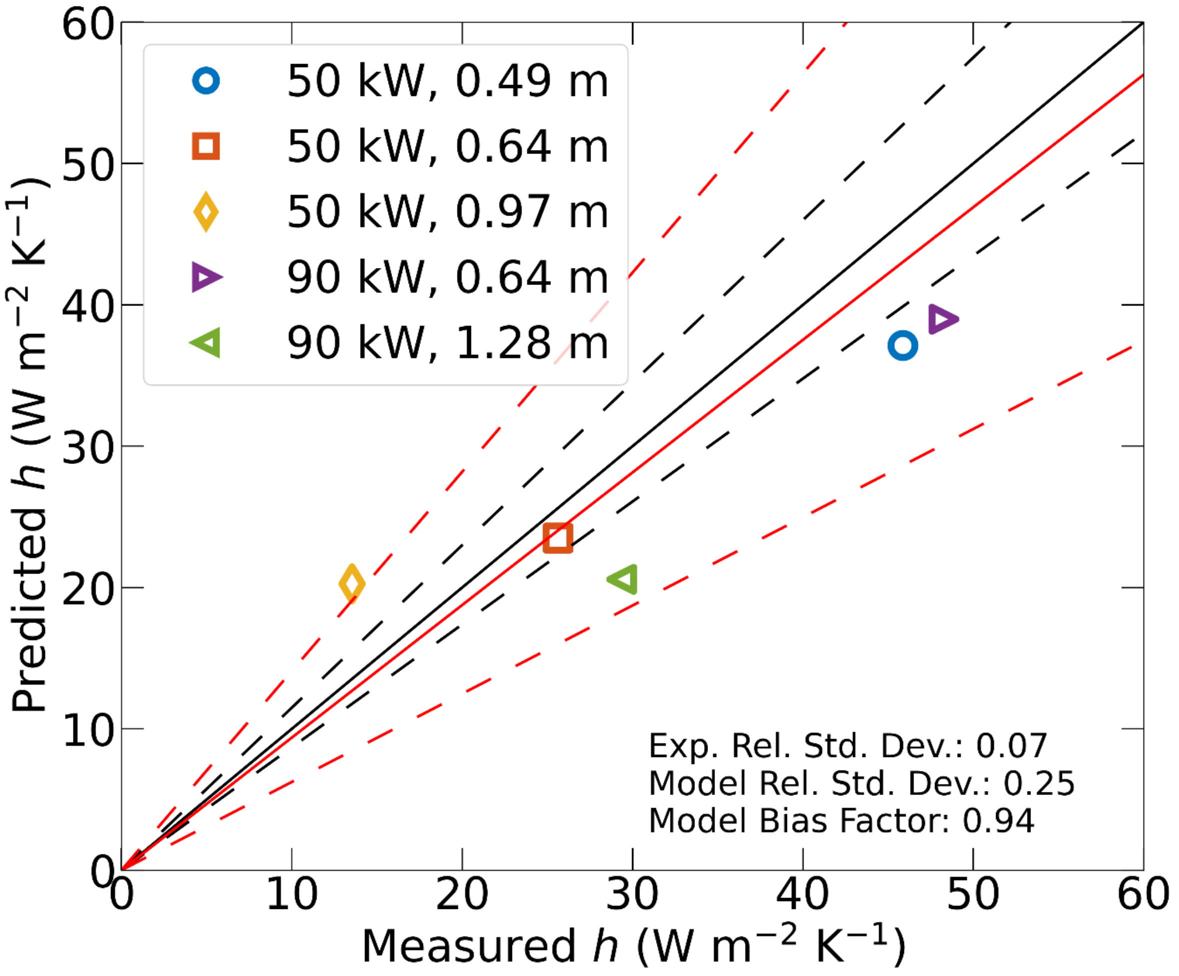


FDS with Impinging Jet Model

Fire Impinging on an Unconfined Ceiling Experiments (Wasson)



FDS Default

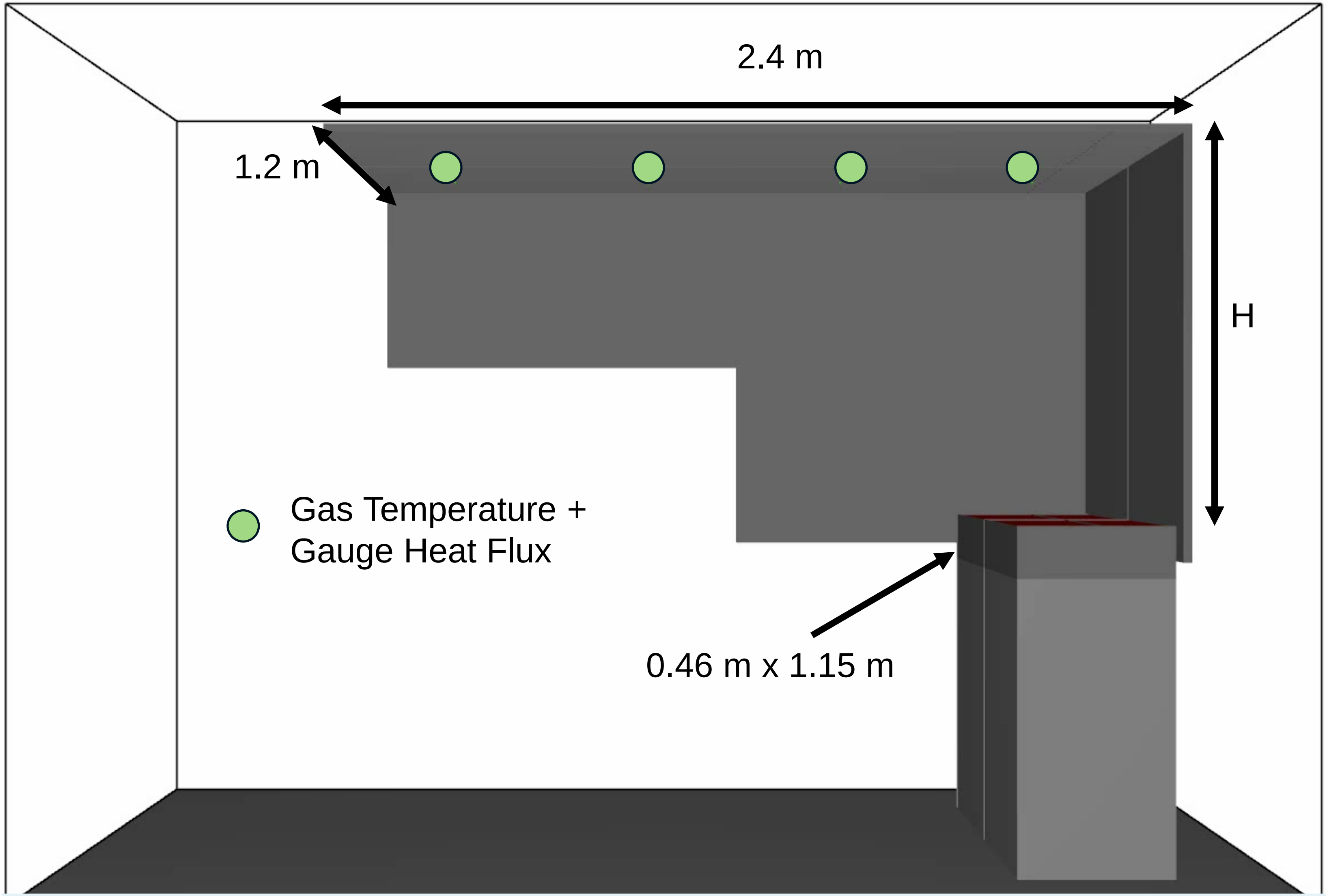


Exp. Rel. Std. Dev.: 0.07
Model Rel. Std. Dev.: 0.25
Model Bias Factor: 0.94

FDS with Impinging Jet Model

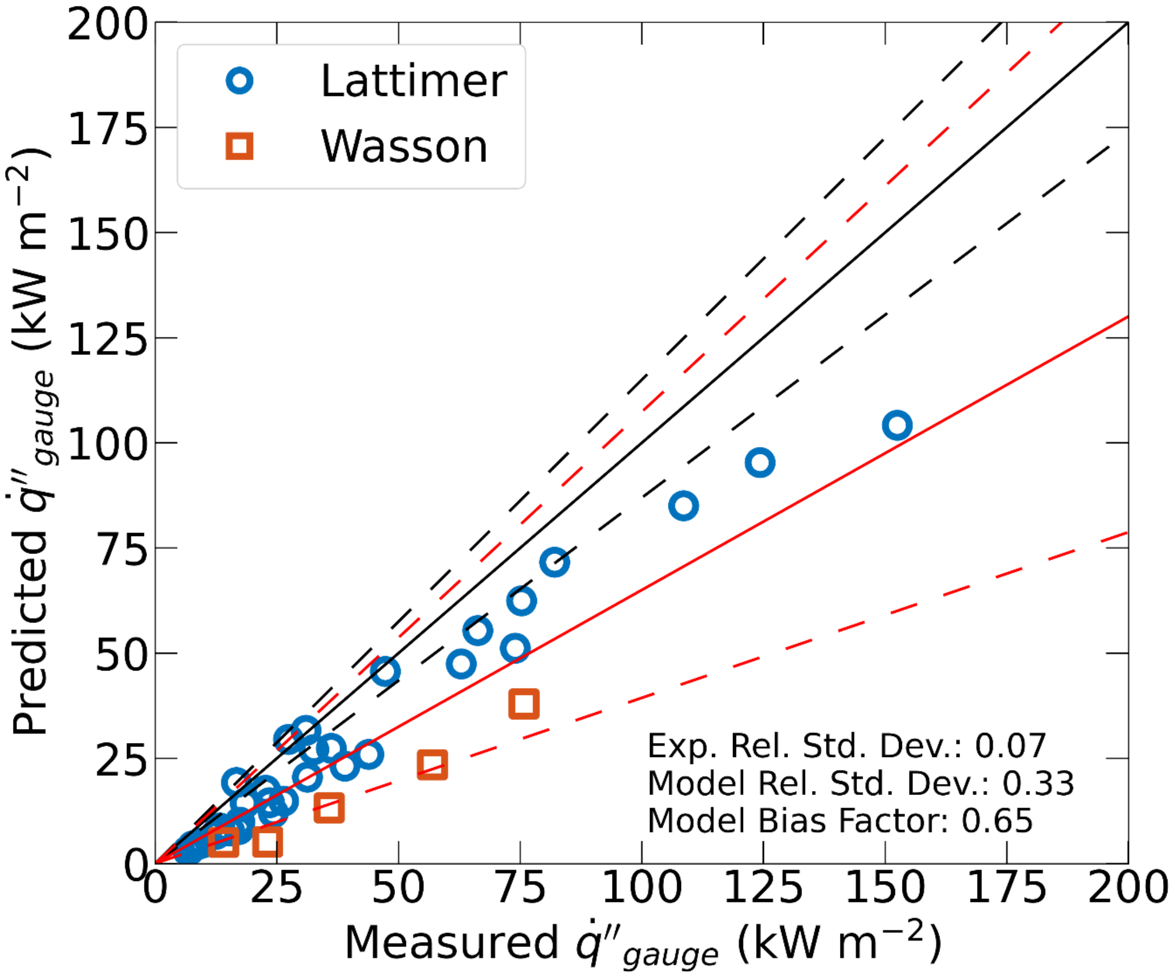
Fire Impinging on a Corridor Ceiling (Lattimer)

Test	HRR (kW)	H (m)	$\dot{q}''_{gauge}$ (kW/m^2)	T (°C)
1	150	1.1	26.4	400
2	200	1.1	39.0	507
3	300	1.1	74.0	736
4	400	1.1	108.6	887
5	100	0.6	31.3	494
6	200	0.6	75.3	800
7	300	0.6	124.3	1026
8	400	0.6	152.5	1144

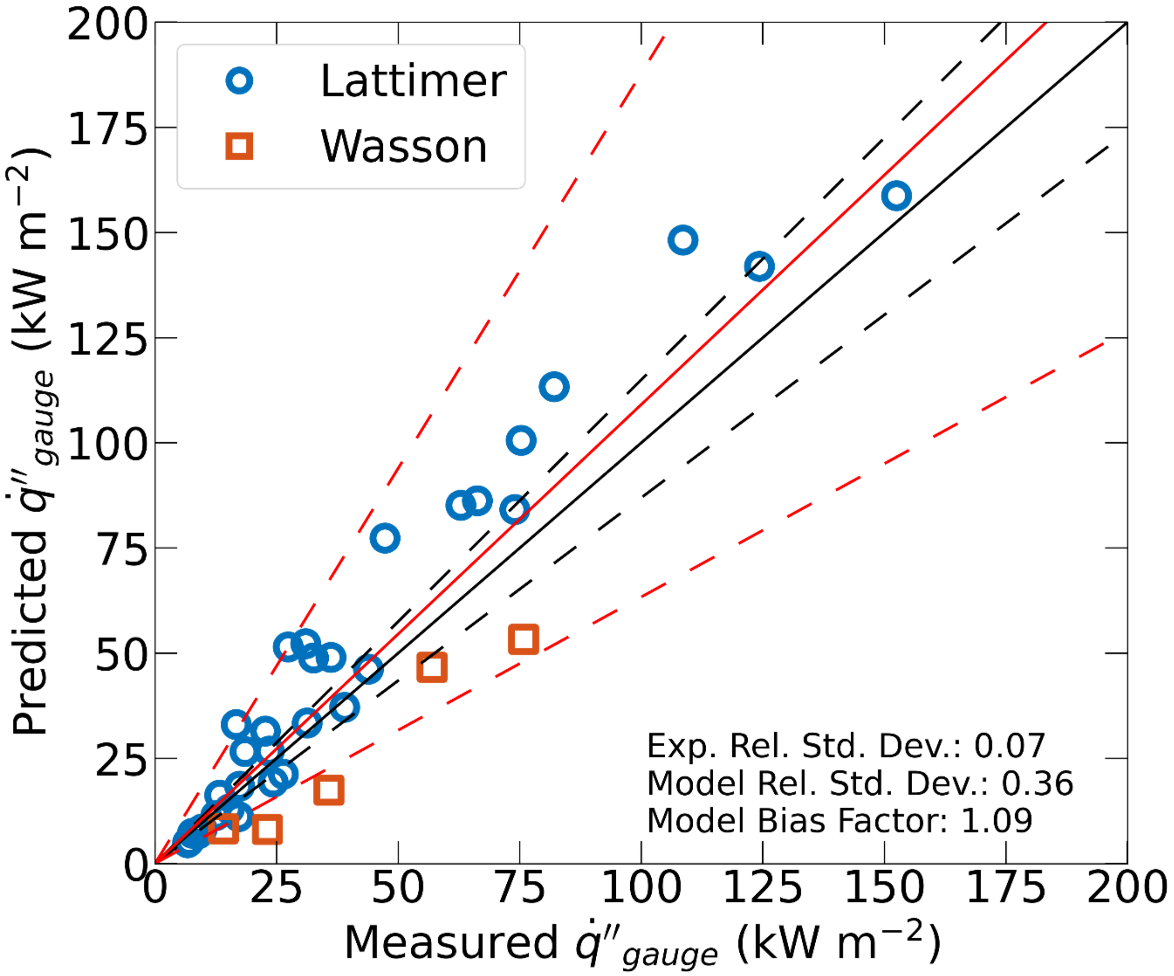


Lattimer, B. Y., Mealy, C., & Beitel, J. (2013). Heat Fluxes and Flame Lengths from Fires Under Ceilings. Fire Technology, 49(2), 269–291.

Fire Impinging Heat Fluxes



FDS Default

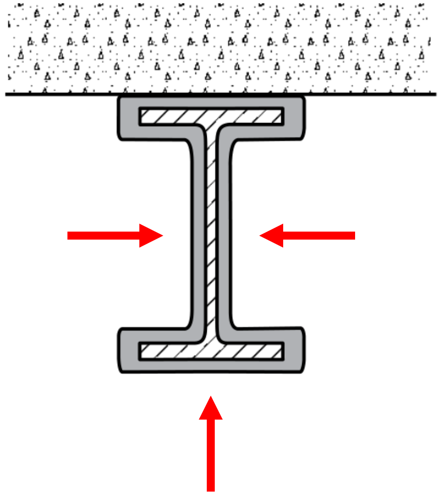


FDS with Impinging Jet Model

Example Performance-Based Design Application

- Model thermal response of an unprotected steel member using a lumped capacitance model (Eurocode Method)

$$\frac{dT_s}{dt} = \left(\frac{F}{V\rho_s c_{p,s}}\right) \cdot \left[h(T_{AST} - T_s) + \sigma\varepsilon_r\left(T_{AST}^4 - T_s^4\right)\right]$$



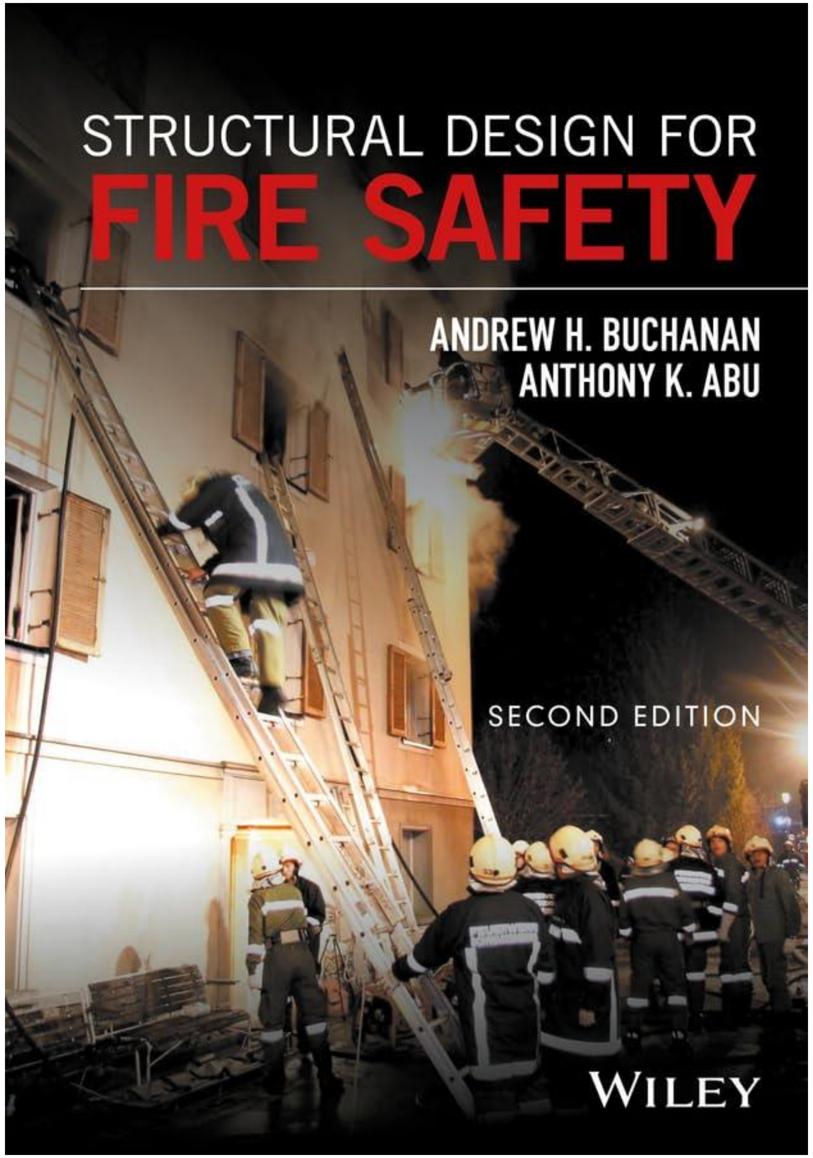
3-sided fire exposure

F: exposed surface area per unit length

V: volume of steel per unit length

T_{AST}: exposure temperature, adiabatic surface temperature in this work

ε_r: resultant emissivity, 0.7 for steel



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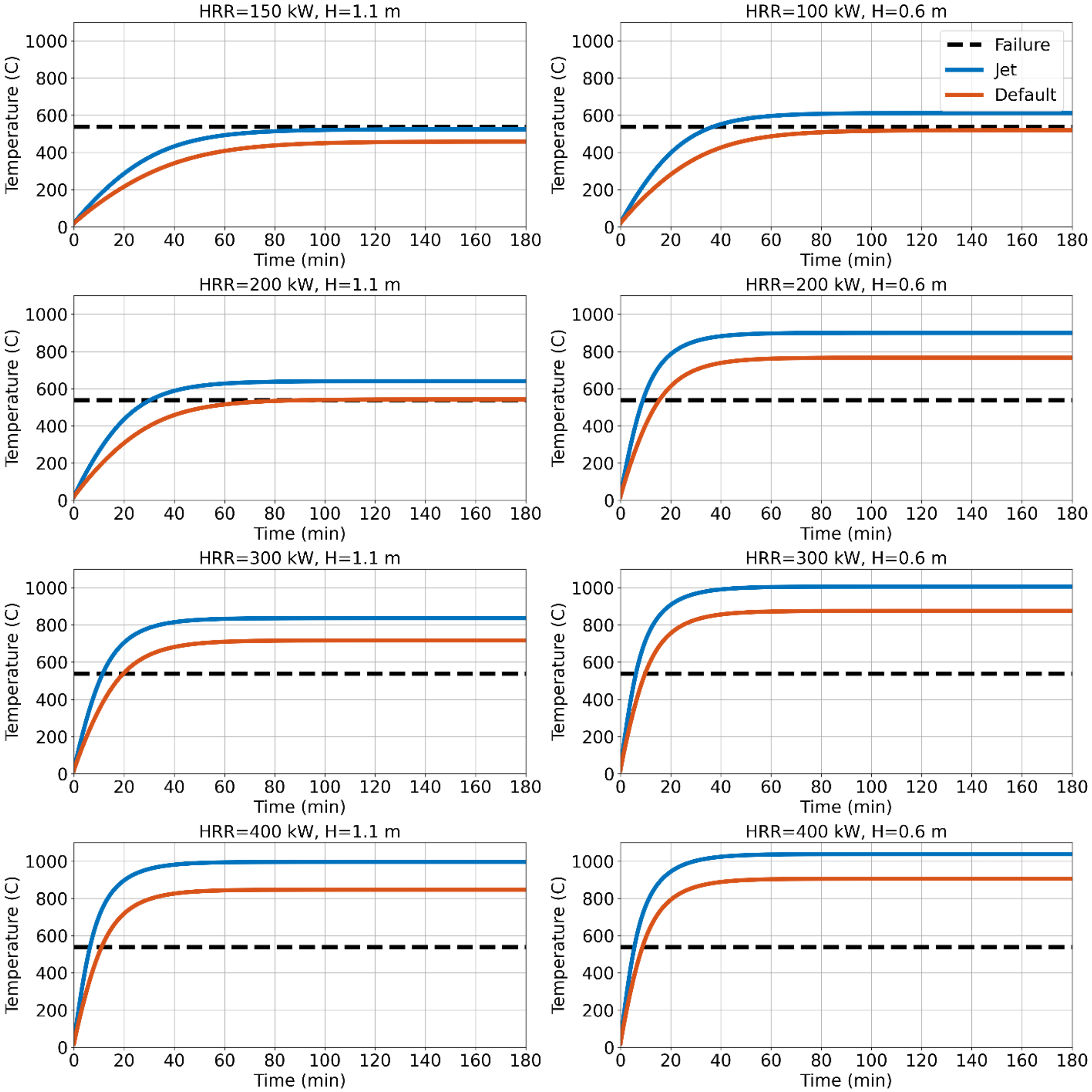
Example Performance-Based Design Application

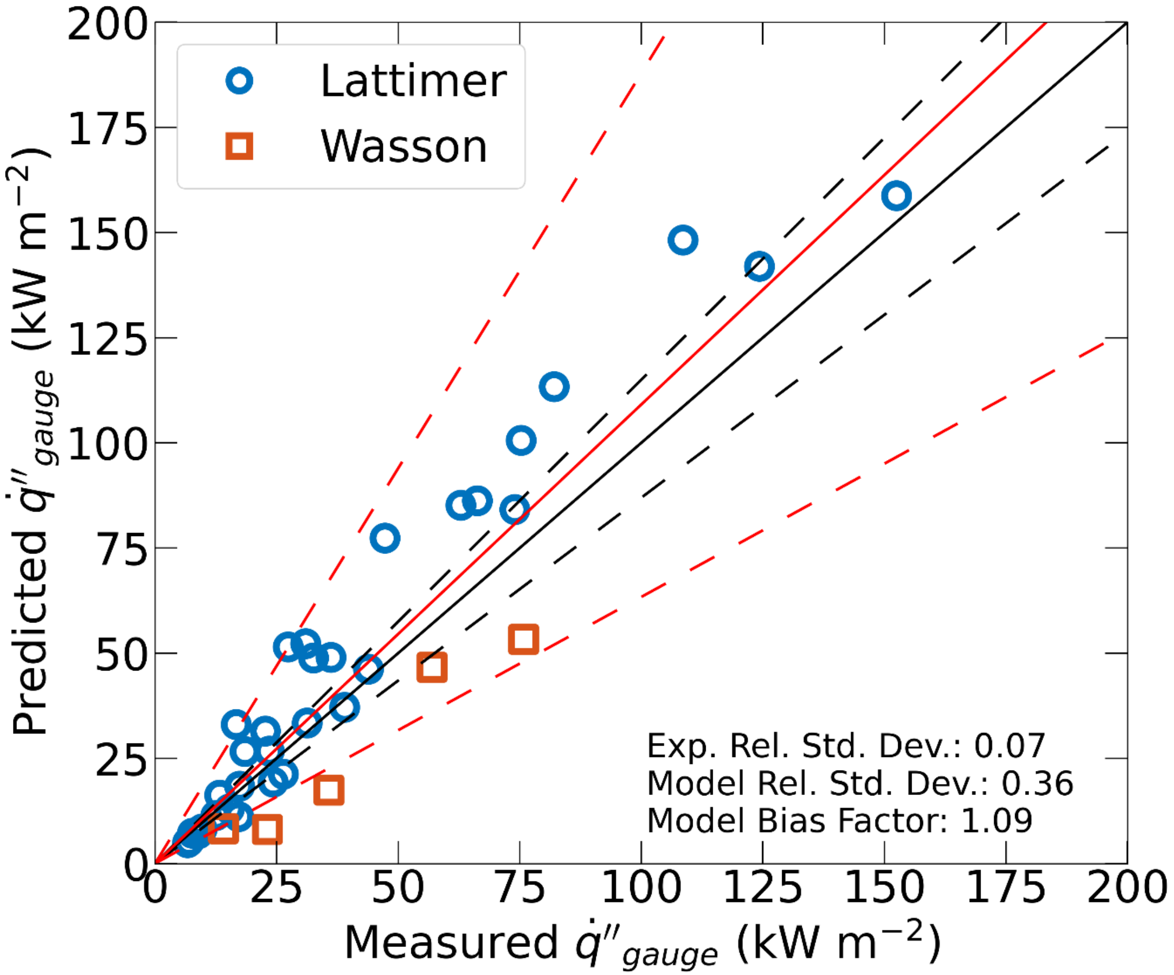
- Configuration
  - AISC W24x192 member
  - Exposed to 8 corridor ceiling cases for 3 hours
- Results
  - Section temperature 100-200°C using impinging jet model
  - Failure criteria exceeded in all exposures with impinging jet model

Design with default model potentially non-conservative.



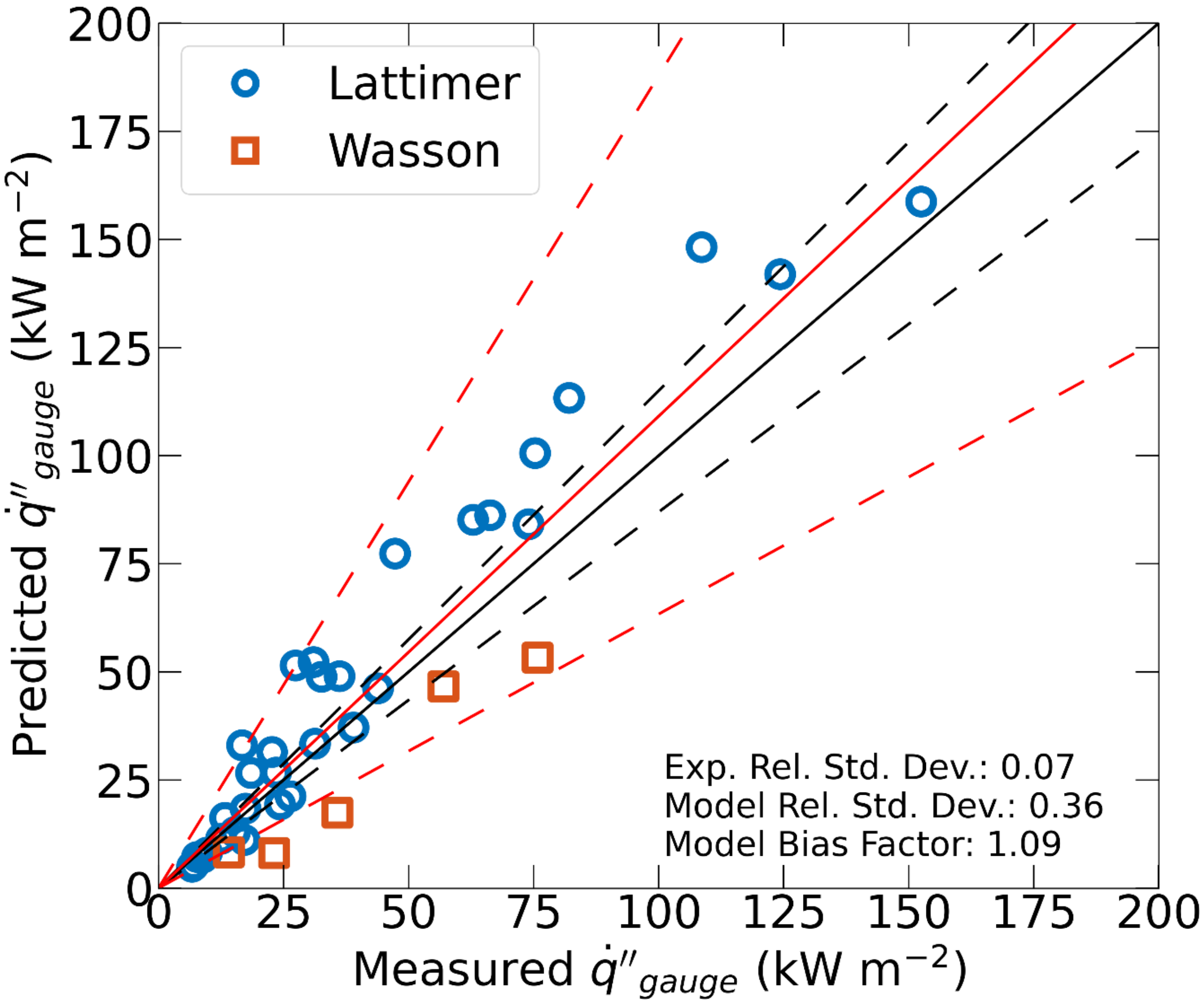
Conclusions

- Impinging jet model more accurate than default convection relationships on cases studied
- Some systematic differences between the two data sets, possibly due to experimental variability
- Additional work needed to expand the validation basis, evaluate different fire diameters, and explore realistic fuel packages
- FDS users may need to consider using the impinging jet model in evaluating structural fireproofing since default may be non-conservative



FDS with Impinging Jet Model

Q&A



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