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Powerplant & Propulsion Fire Protection Fire Modeling Guidelines

The Tenth Triennial International Aircraft Fire and Cabin Safety Research Conference

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Abstract

Computational modeling is an effective way of analyzing aircraft powerplant and propulsion fires. While testing based on the FAA AC 20-135 guidelines has traditionally been used to demonstrate safe operation, reactive flow computational fluid dynamics (CFD) of fires can better assess the thermal threat to the airplane structures during a fire scenario if the analysis is appropriately validated. This presentation will discuss requirements on validation and propose best practices in performing fire CFD analyses.

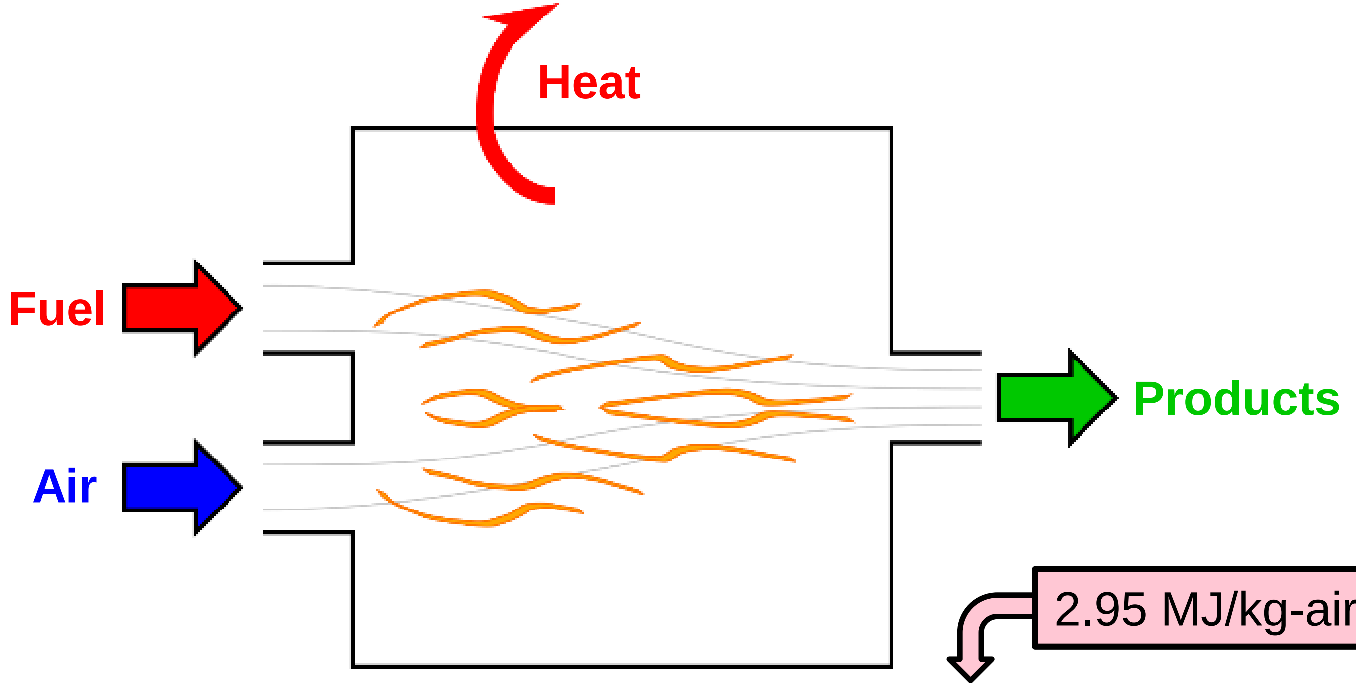
Reactive flow CFD models and results must be rigorously validated using test data. Some validation data is available from industry studies, but validation is challenging in situations where there is little or no direct test data at the conditions required for certification, such as an inflight engine nacelle fire. Of particular interest are regions that are oxygen limited, like under ventilated fire zones, and realistic modeling of fuel spray fires, including ignition of the fuel spray and the steady state thermal loads.

A thorough methodology for model validation requires that the following aspects are covered: theoretical basis and assumptions, environmental conditions and fire scenario, mathematical and numerical robustness, model uncertainty and accuracy, and model limitations. Finally, the full validation to satisfy regulatory authorities requires: general discussion of the industry guidelines for fire modeling, compartment benchmark tests, subscale tests, model sensitivity, and in-service experience.

An Introduction to Compartment Fires

An Introduction to Compartment Fires

In a compartment fire, heat release may be limited by ventilation (i.e., oxygen availability)



2.95 MJ/kg-air

Psuedo Jet-A Combustion Eqn: $C_{12}H_{23} + 17.75\,(O_2 + 3.76N_2) \rightarrow 43.0\ \text{MJ/kg-fuel} + 12\,CO_2 + 11.5\,H_2O + 66.74\,N_2$

Insufficient oxygen ➔ limited heat production

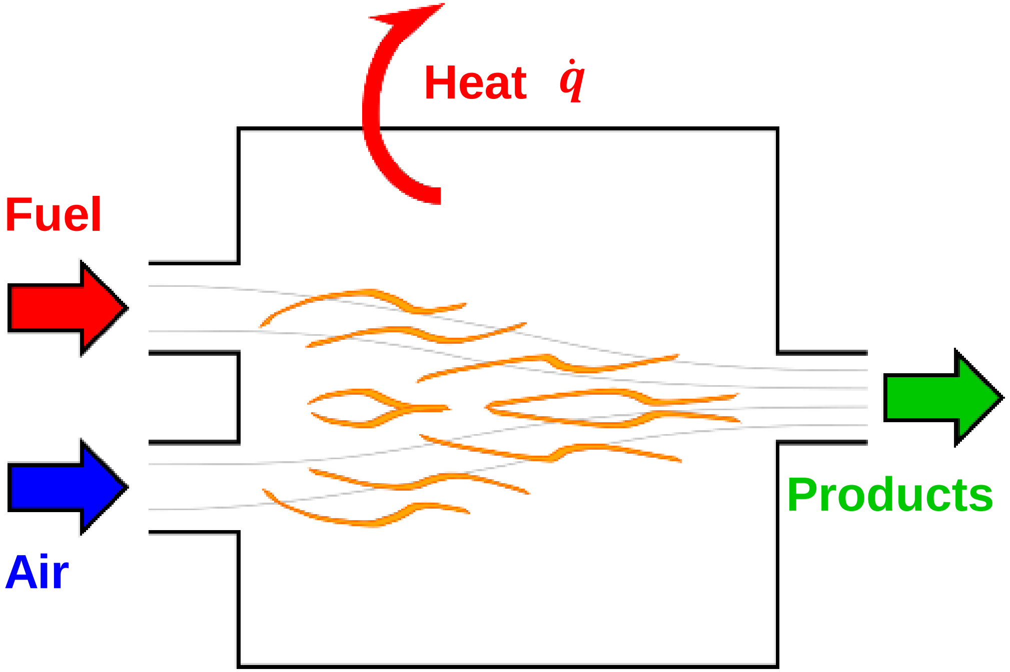
Edwards (2017): POSF 10289 ΔH_c = 43.0 MJ/kg-fuel

An Introduction to Compartment Fires

- Compartment fires have been modeled using engineering fits
  - E.g., Kawagoe (1958) (variable definitions to right)

$$\dot{q} = k_v \underline{A_W H^{\frac{1}{2}}} \Delta H_c$$

Increased ventilation → increased heat release



Kawagoe Model
$\dot{q}$: Heat release rate
k_v: Engineering constant
A_W: Ventilation Opening
H: Ventilation Height
ΔH_c: Heat of combustion

- For aircraft, compartment fires are relevant in closed volumes with the possibility for an abundance of fuel.

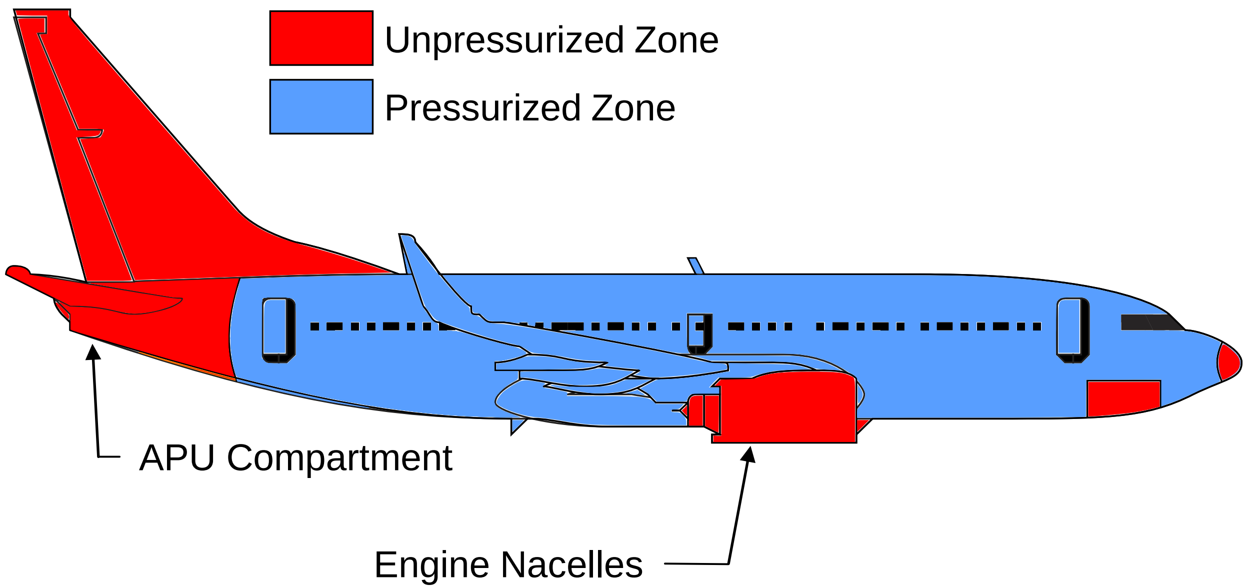
Source for equation for heat release from a pre-flashover compartment fire: Kawagoe (1958)

Environment of Interest

- Unpressurized compartments
  - Auxiliary Power Unit (APU) compartment
  - Engine nacelle compartment

- Today's presentation does not cover engine core compartment fires
  - In these scenarios the fire size is more limited by mixing and residence time of the combustion
  - There are opportunities for future collaborations between aircraft and engine OEMs & FAA

Airplane Fire Zones



Ventilation-Controlled Compartments on Aircraft

Consider an intact engine fan compartment:

- Plenty of available fuel (e.g., high pressure spray of Jet-A)
- Insufficient air to combust all fuel
  - Air supply is restricted by the opening sizes
  - Note: Loss of fan cowl or other extreme damage would change the scenario
- Therefore, the quantity of available oxygen is the key limiting factor that restricts the fire size
  - “Available oxygen” is oxygen that is usable by the fire

The compartments surrounding some engines are Flammable Leakage Zones; today we’re specifically considering engines in which the fan case is a Fire Zone.

Modeling Compartment Fires – Qualitative

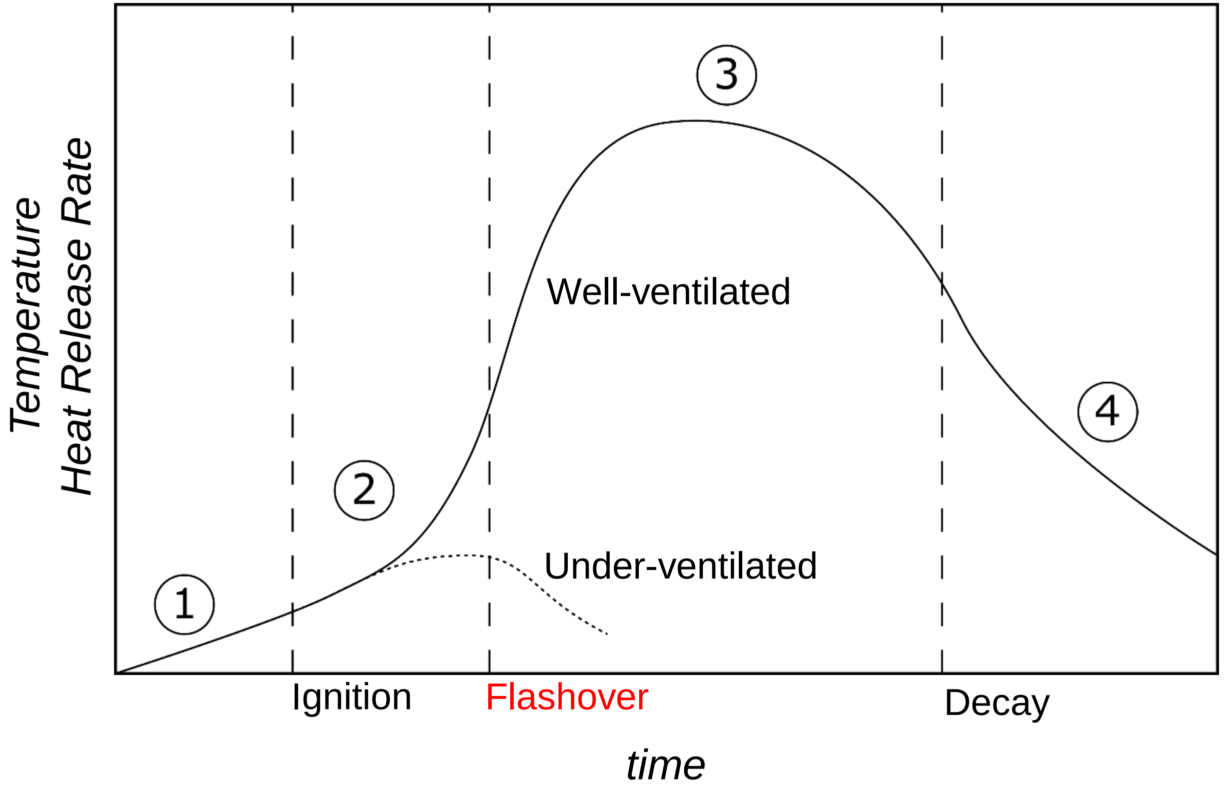
The qualitative development of a compartment fire included four phases:

1. Smoldering
   – Limited heat release
   – If fuel is readily volatized, this will be quick
2. Developing Fire
   – Consumes oxygen that is present in the compartment at the onset of the fire

Flashover: Transition from a fuel-controlled fire to a ventilation-controlled fire

3. Fully Developed Fire
   – Heat release reaches a maximum
   – Limited by availability of fuel or oxygen
4. Decay

Compartment Fire Phases



More information in Alarifi, Phylaktou and Andrews (2016), and many other sources.

Tiered Model Approach

1. Engineering/Analytical Fits
   - Quick/low cost
   - Limited accuracy
   - Provides basis for higher fidelity solutions
2. Detailed FEM/CFD simulation
   - Higher cost
   - Increased accuracy
   - Complicated models require extensive validation

Greater Scenario Detail
Higher Fidelity Results

How to Model Compartment Fires

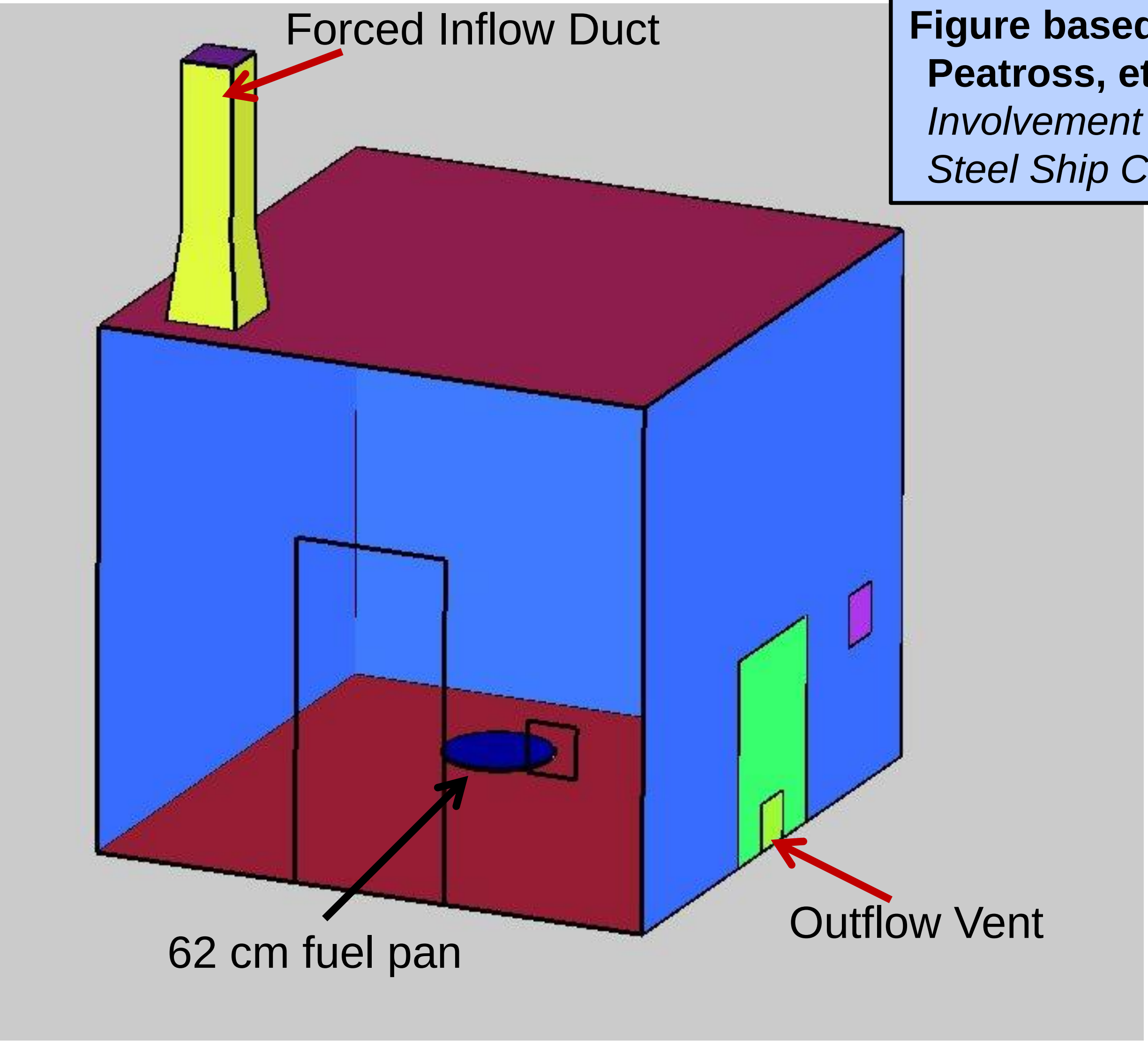


Figure based on the S207 case described in:
Peatross, et al. *Validation of Full Room Involvement Time Correlation Applicable to Steel Ship Compartments*. **1993.**

Model Validation Steps

Big Picture: How to Validate Compartment Fire Models

Guiding Principles

- **Benchmark:** The accuracy of all models must be assessed with experimental data
- **Subsystem Validation:** Testing all scenarios which are desired to be modeled is not possible → Validate sub-models to create a tiered validation process
- **Model Accuracy Assessment:** No model is perfect → Determine if model accuracy is adequate
- **Use of Modeling Best Practices:** Use of industry standards and publically validated techniques
  - ASTM E1355 – Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models
  - Sandia Report – On the Integration of Technology Readiness Levels at Sandia National Laboratories

Compartment Fire Analysis

Model Validation: Substantiation that a computerized model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model.

CFD Fire Model Validation			
Complete System	**In-Service Fire Events**		
Subsystem	**½-Scale Rig Test**	**Building Compartment Fire Data**	
Benchmark Component Models	**Turbulence**	**Radiative Heat Transfer**	**Finite-Rate Combustion**

Input Sensitivity Analysis

Grid-Studies

Comparison to Other CFD Models

Time-Accurate Studies

Note: Benchmark Models and Validation Sub-Systems are examples only

Oberkampf and Roy, Verification and Validation in Scientific Computing. (2010)

Benchmark Component Models

Model Component Validation

1. Identify physical phenomena of interest and modeling tools
2. Determine relevant input conditions for worst-case fire
3. Perform benchmark validation of component models

Requires engineering judgement to know which phenomena will affect the results. Example physical phenomena discussed on next slide

Good understanding of the complete failure scenario is essential in evaluating the worst-case condition

Validating individual component models gives confidence that the assembled component model will be accurate

After individual component models are implemented and validated, we proceed to validating the complete model

Model Component Validation: (1) Identify Physical Phenomena

- For each phenomena, multiple modeling methods are available
- Which modeling tools are used is less important than validating the model accuracy by benchmarking against empirical data

Phenomena to Model
Fluid Flow
Flow Turbulence
Chemistry Reaction and Species Transport
Radiation
Buoyancy Effect
Fuel Spray
Flame Extinction

Note: List is not meant to be exhaustive for all possible compartment fires

Model Component Validation: (2) Determine Input Conditions

- Conditions selected correspond to the fire scenario to be modeled
  - E.g., a worst-case fire
- Understanding the failure conditions is essential in determining the appropriate fire scenario

Input data	Purpose
Flow field geometry	Digitized compartment geometry data for defining the CFD solution domain and for mesh generation
Computational mesh	Boundary-fitted unstructured computational cells for the three-dimensional fan compartment flow field
Thermodynamic properties	Fluids Mixtures - air, liquid fuel, gaseous fuel species
Material Properties	Surface materials, internal parts, insulation
Heat transfer properties	Wall surfaces, reacting gas mixture for convective, conductive, and radiative heat transfer
Flight conditions	Flight speed, altitude, and ambient temperature
Flow boundary conditions	Mass flow rates of incoming fuel and air, temperatures and pressures, concentrations of gaseous species, flow turbulence quantities
Ignition conditions	Location and intensity of thermal energy source to ignite fuel/air mixture

Example Input Conditions

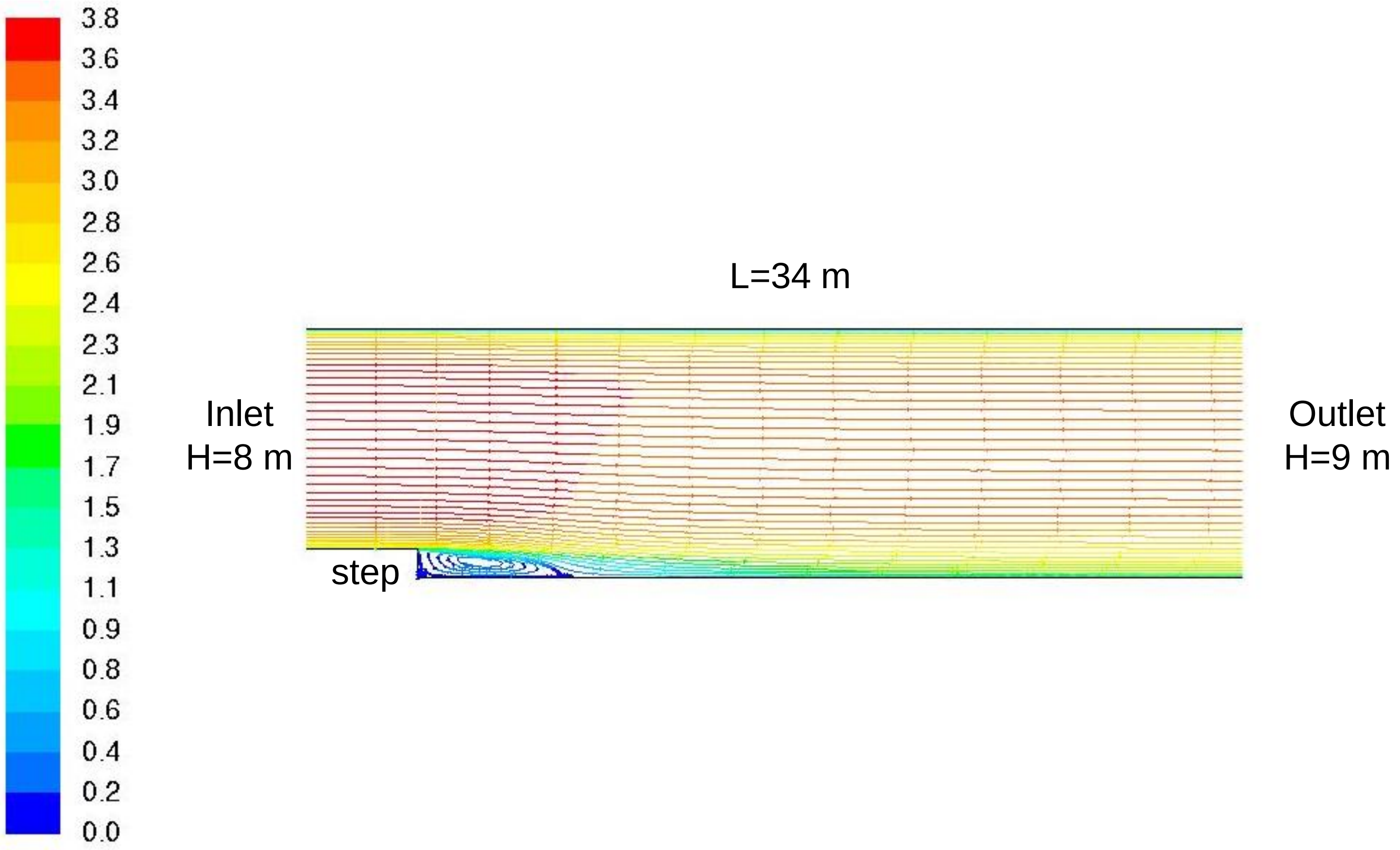
Model Items	Data and Conditions	
Flight Phase	Takeoff	Wind-Milling
Flight Mach Number and Altitude	M = 0.388 and h = 1,500 ft	
Air Flow Rate (lbm/sec)	“medium”	“low”
Fuel Flow Rate (gph)	“high”	“medium”
Crew Response Time	Delayed // Immediate	
Fire Type	Spray Droplet Fire	Evaporating Fuel Vapor Fire on Wetted Surface
Fire Location	Worst Case Fire Size	Fire Near ignition Source
Fire Extent	Local // Wide-Spread	

Crew Response must be considered in addition to physical effects in modeling fire damage

Model Component Validation (3)
Benchmark Example #1 – Subsonic Flow

Modeled Process: Two-equation realizable k-ε turbulence model using a subsonic pipe flow through sudden area expansion.

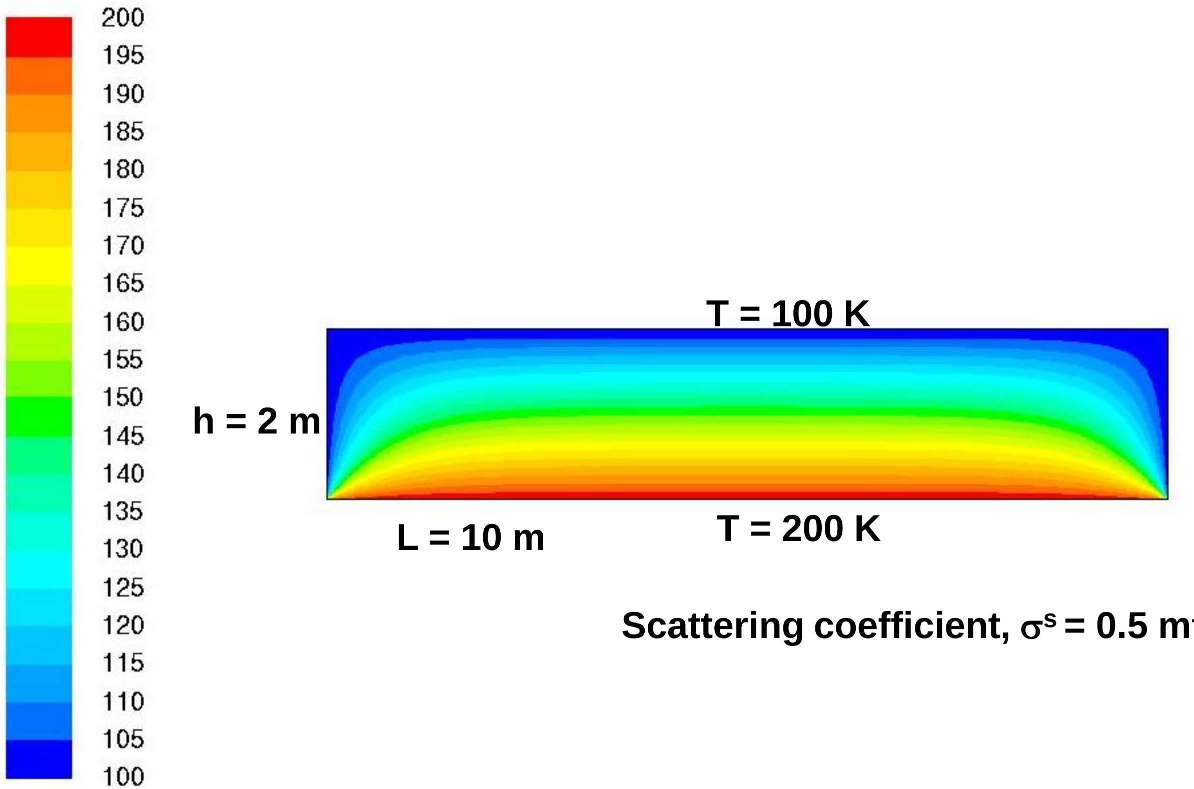
Empirical Data Contained In: Driver and Seegmiller. Features of a Reattaching Turbulent Shear Layer in Divergent Channel Flow. AIAA Journal, 23 (2). (1985)



Model Component Validation (3)
Benchmark Example #2 – Discrete Ordinate Radiation Heat Transfer

Modeled Process: Discrete ordinate radiation heat transfer model for the wall heat transfer with and without internal radiation heat transfer.

Empirical Data Contained In: Raithby and Chiu. A Finite-Volume Method for Predicting Radiant Heat Transfer in Enclosures with Participating Media. Transactions of the ASME, Vol. 112. (1990)

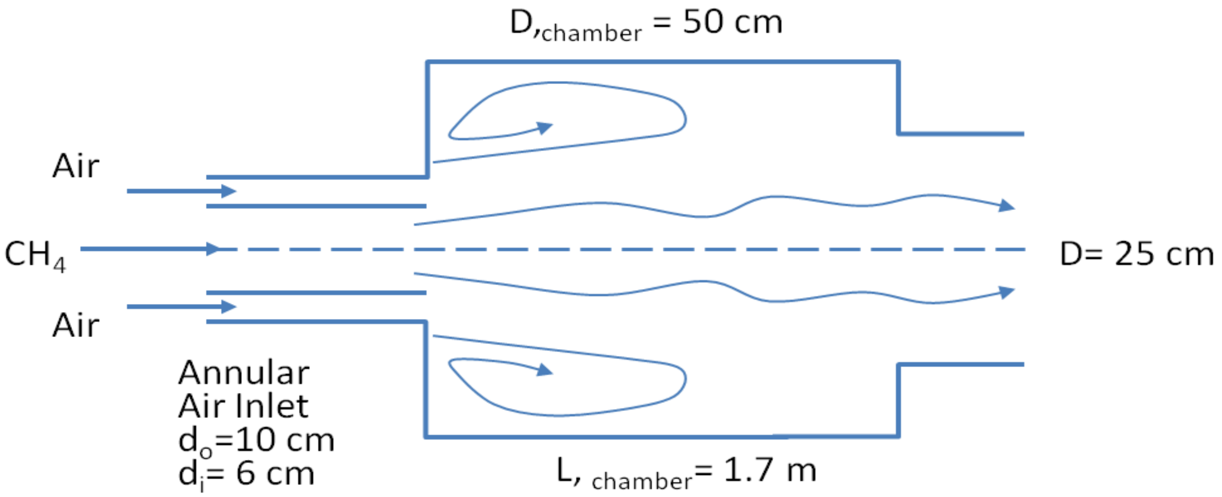


Scattering coefficient, $\sigma^s = 0.5\ m^{-1}$

Model Component Validation (3)
Benchmark Example #3 – Non-Premixed Combustion

Modeled Process: Species transport model with volumetric reaction based on the finite-rate/eddy-dissipation reaction mechanism for the non-premixed gas combustion of hydrocarbon fuel.

Empirical Data Contained In: Bechtel, et al. *Atmospheric Pressure Premixed Hydrocarbon-Air Flames: Theory and Experiment*. Combustion and Flame, 42: 197-213. (1981)

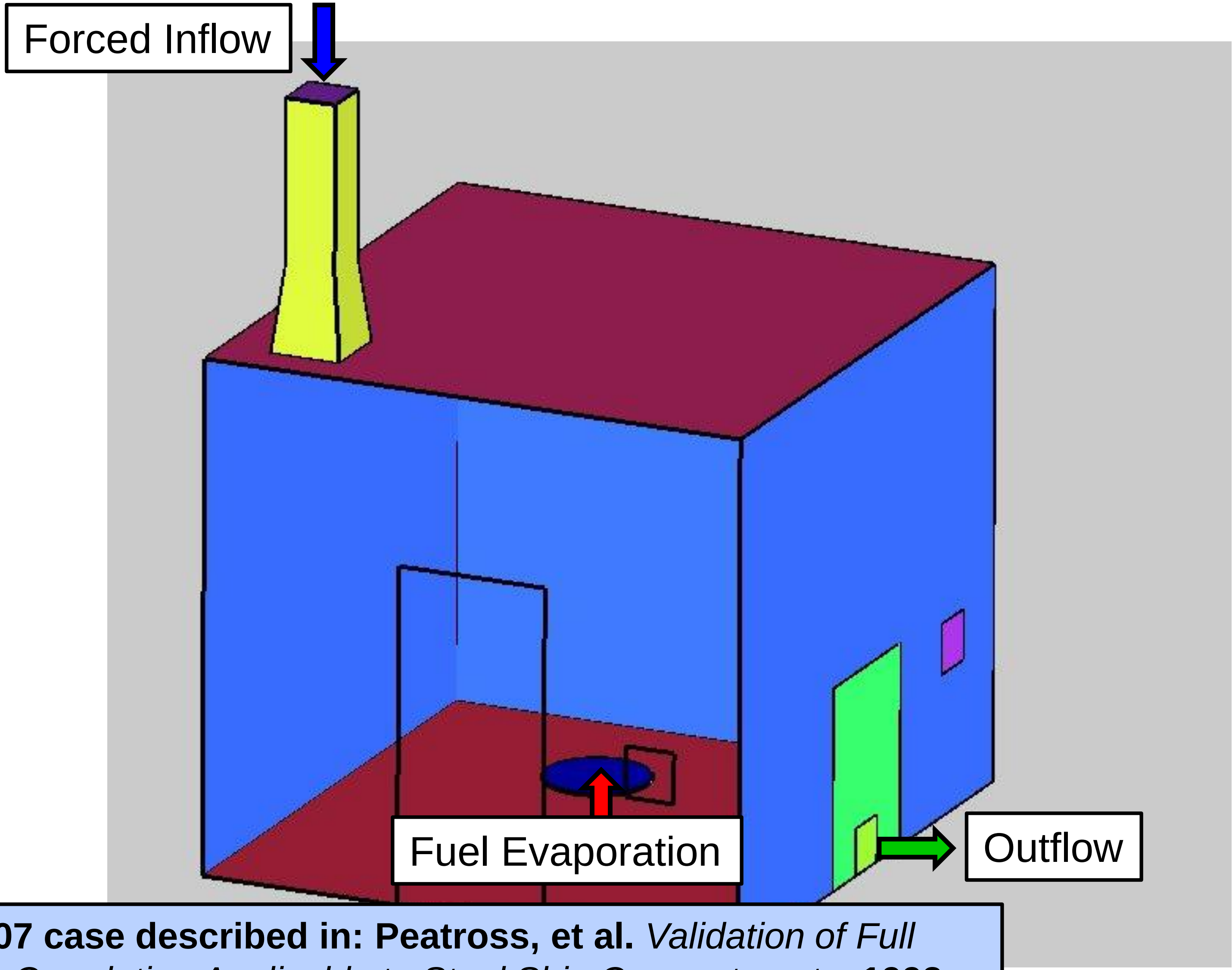


Models Used:

- Standard k-ε Turbulence Model
- Discrete Ordinates Radiation Model
- Single-Step Finite Rate/Eddy Dissipation Reaction Model
- NIST Flame Extinction Model

Subsystem Validation

Subsystem Validation Example: Case S207 of Peatross et al. – Oxygen controlled fire with outflow vent low in the compartment)



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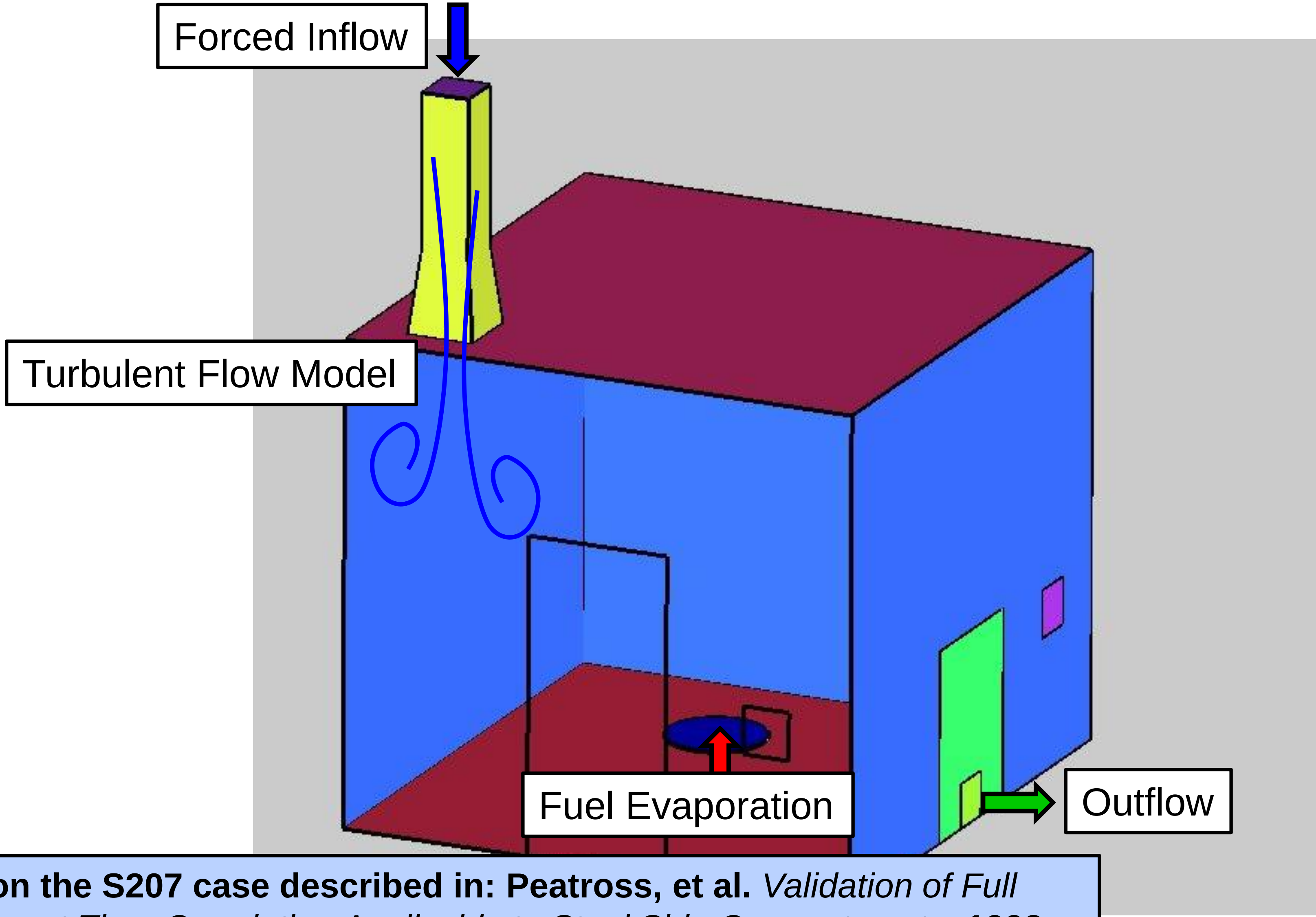

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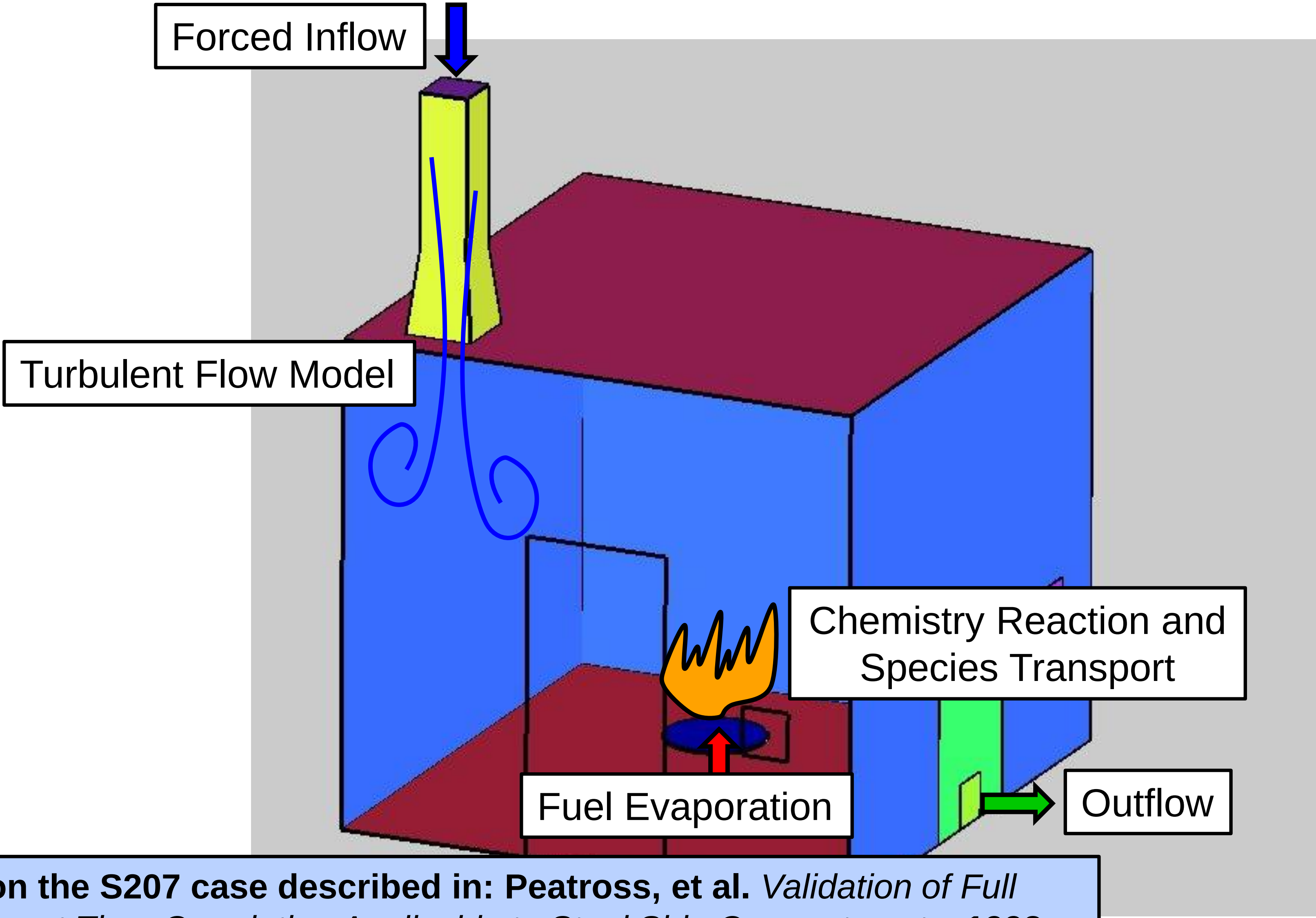

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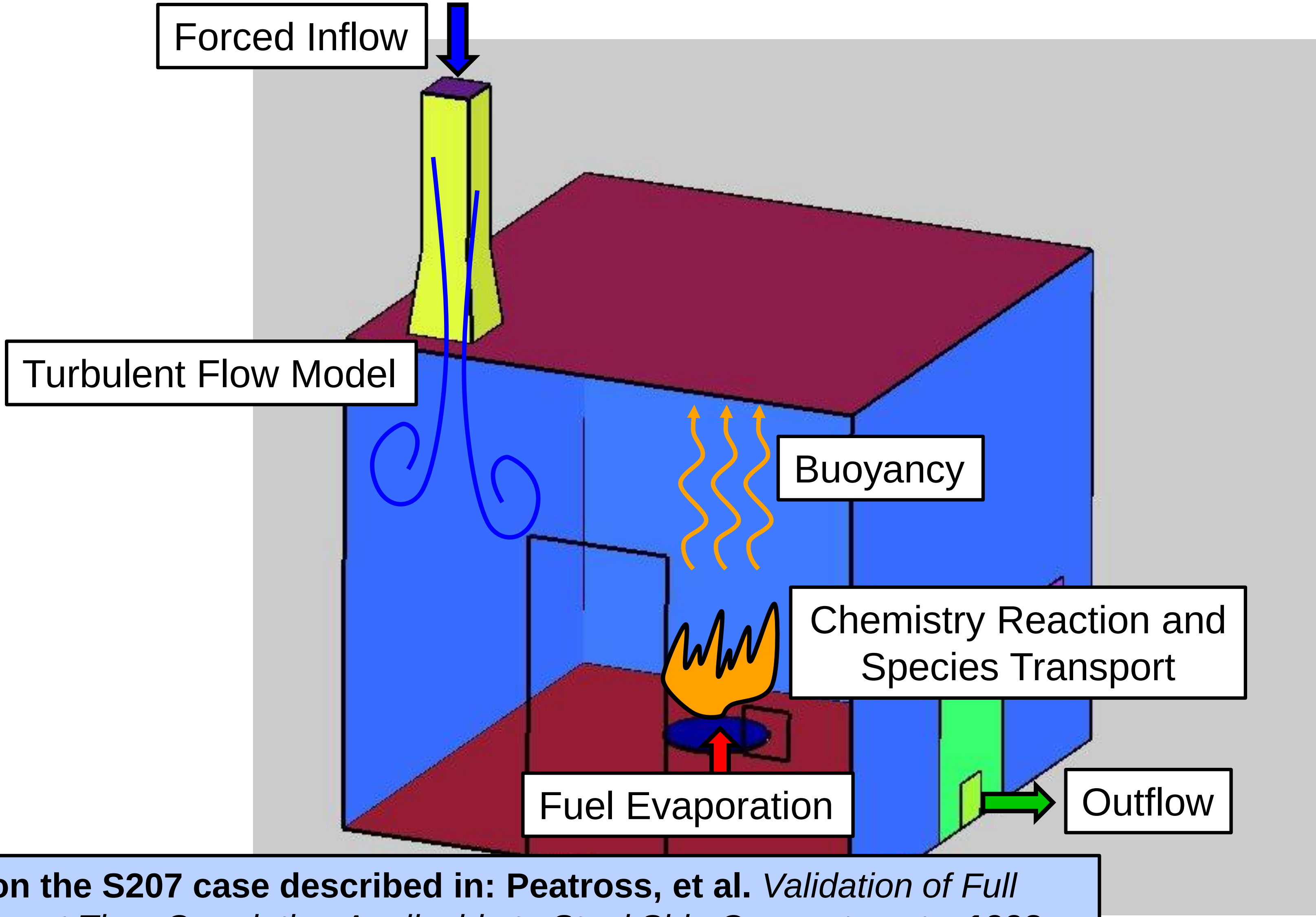

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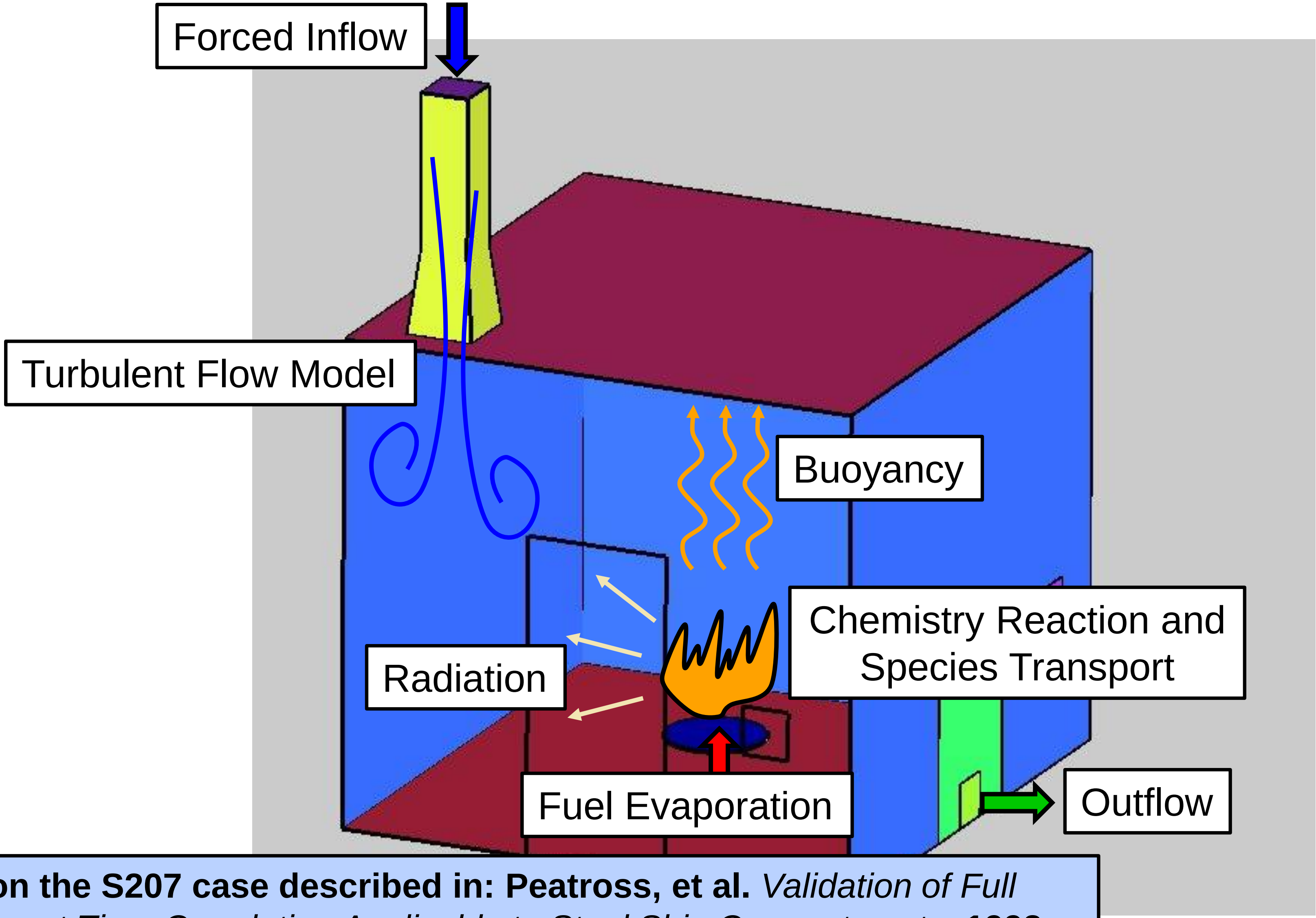

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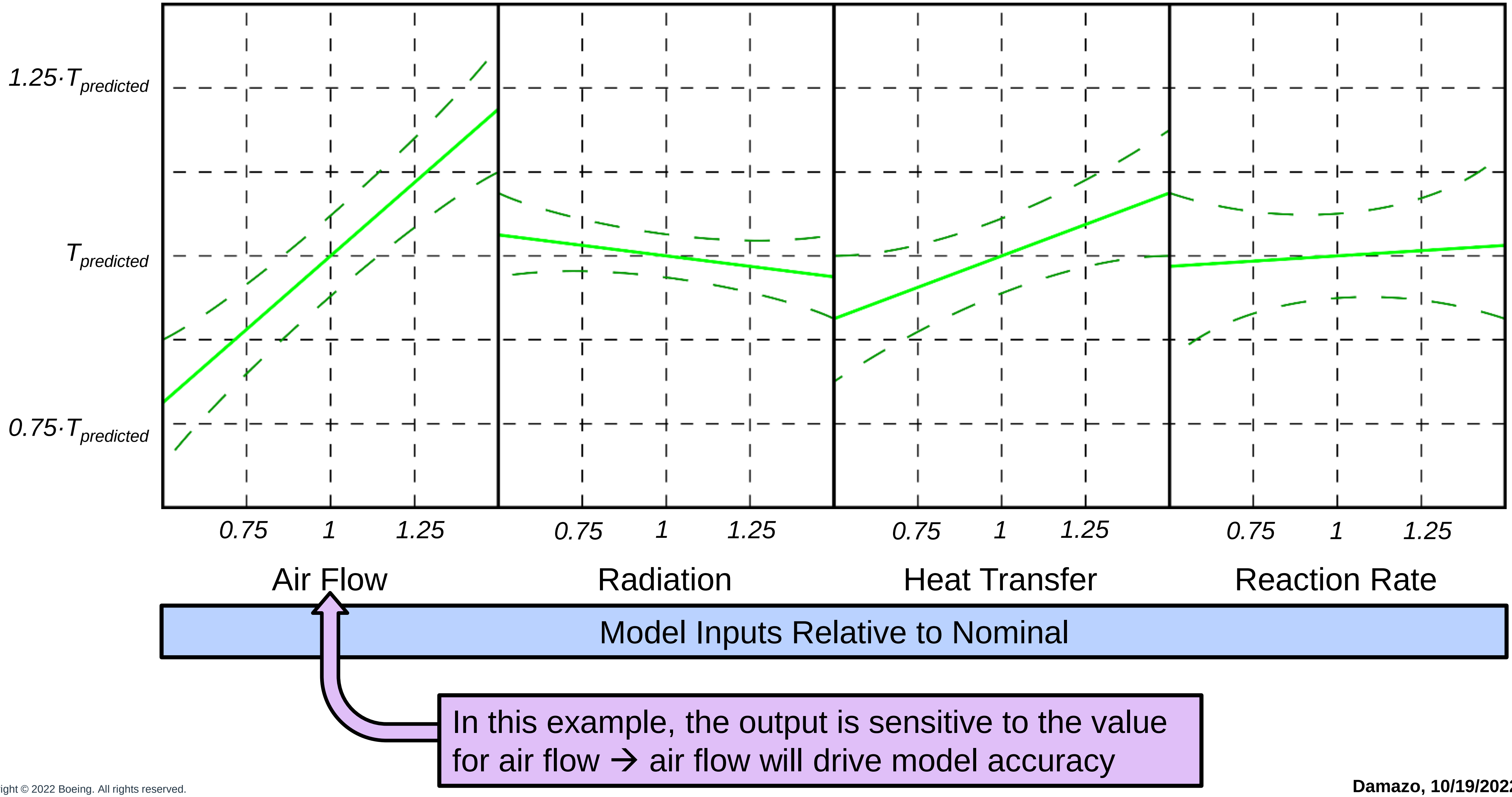
Complete System

Full System Sensitivity Analysis
Average Compartment Temperature



Closing Thoughts

Key Takeaways

- Compartment fires that are large and diffused may make conventional fire testing, via use of the standard burner flame, inappropriate.
- Instead, analytically predicting a “foreseeable” fire using computational fluid dynamics (CFD) is an appropriate choice provided the CFD model can be adequately validated.
- A hierarchy of tests from benchmark to the full-scale system can be used to validate the CFD fire model for its intended application.
- Once the fire model has been validated, structural damage can be determined through the used of thermal and finite element models.

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Effect of Hydrogen on Fires

- Simplified chemistry (easier to model)
- Higher Explosion Risk
  - Detonation risk
  - MIE ~ 0.02 mJ
  - High flame temperature
- Wide Flammability Range 4-75% (Jet-A: 0.7-5%)
- Different (maybe lower) Fire Risk
  - No pool fire
  - Low volumetric density
  - Radiative heating – localized heat transfer (welding torch)

Battery Fires

- Battery vent gases
  - Hydrogen, CO, CO_2
- Thermal Runaway