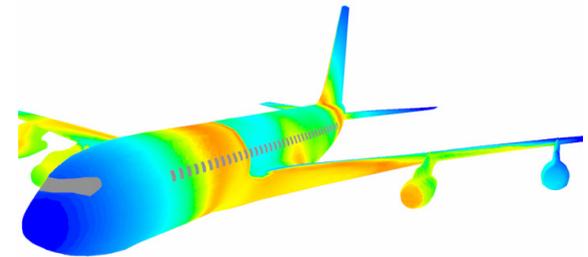


Computational Flame Characterization of New Large Aircraft Immersed in Accidental Hydrocarbon Pool Fires

20 April 2010



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Materials & Manufacturing Directorate
Air Force Research Laboratory

Christopher P. Menchini
Senior Engineer (Contractor)
Applied Research Associates, Inc.



Introduction



- **Goal**

- Develop an efficient computational strategy to predict the flame characteristics and thermal response of aircraft structures immersed in hydrocarbon pool fires
- Apply strategy to crash fire scenarios of interest to the FAA and AFRL (e.g. past accidental fire case studies, novel commercial / military aircraft platforms)
- Integrate into an aircraft-crash-fire simulation framework

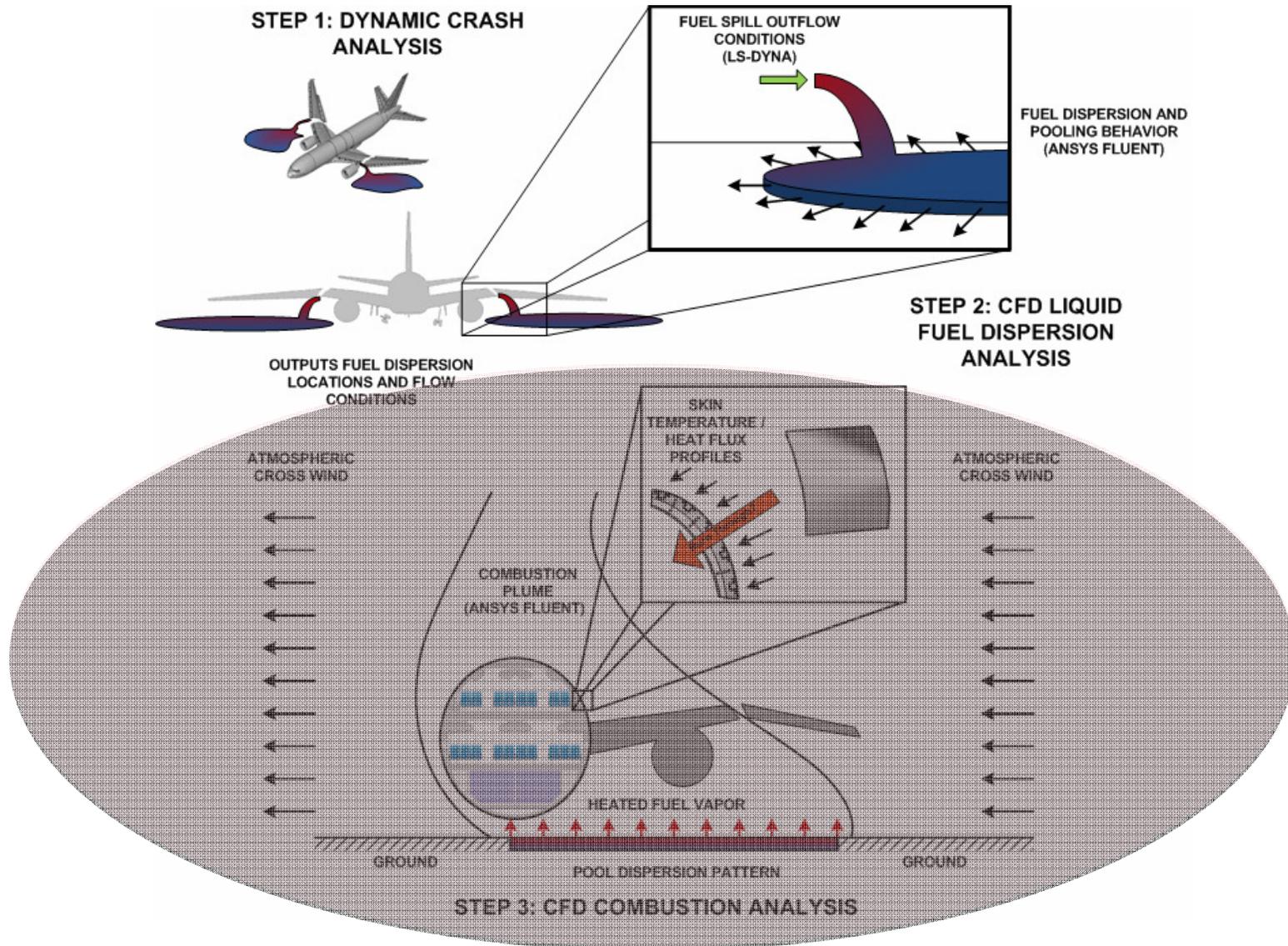
- **Motivation**

- Full-scale aircraft hydrocarbon pool fire testing is expensive and arduous
- The FAA is concerned with unique fire protection challenges New Large Aircraft (NLA) pose due to unusually great dimensions, fuel quantities, and novel (composite) materials





Aircraft-Crash-Fire Simulation





Technical Challenges



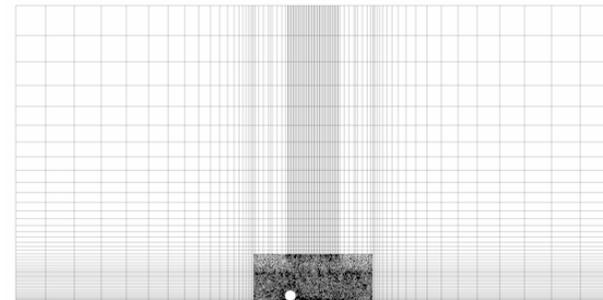
- **Computational efficiency**
 - Accuracy vs. Predictability
- **Experimental validation data**
 - Confidence Levels / Repeatability / Expense
- **Multiple non-linear PDEs governing complex flow physics**
 - Combustion / Heat Transfer / Turbulence / Multiphase Flow
- **Wide range of spatial and temporal scales**
 - Airbus A380 ϑ (100's m) vs. Turbulent dissipative length scales ϑ (mm)



HARDWARE RESOURCES



**MULTI-SCALE
TURBULENT FIRE PLUME**



**MESH TOPOLOGY
OPTIMIZATION**



Progress Path



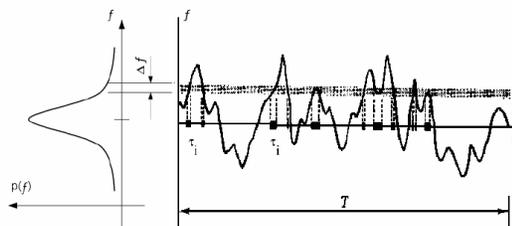
- **CFD Model Development**
 - Computational Resources / Physics / Boundary Conditions / Domain Development
- **Model Validation**
 - J.M. Suo-Antilla and L.A. Gritzo. “Thermal Measurements from a Series of Tests with Large Cylinder Calorimeter on the Leeward Edge of a JP-8 Pool Fire in Cross-Flow.” SAND 2001-1986.
 - Low / Medium / High cross wind cases
- **Application to Full-Scale Aircraft**
 - Boeing 707
 - NLA (Airbus A380, Boeing 707, Tyndall AFB Mock-Up, etc.)
 - Future Aircraft
- **Integration into a Dynamic Crash Aircraft-Crash-Fire Analysis**



CFD Model Development: Physics

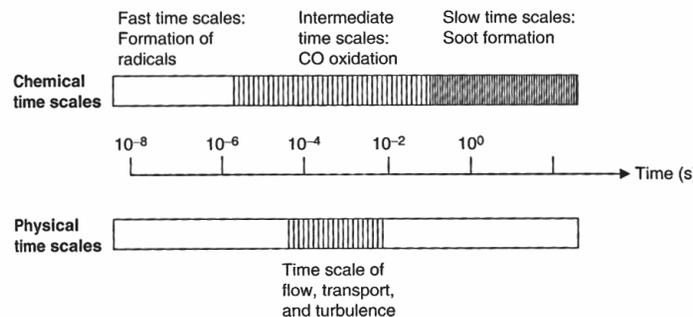


- **ANSYS Fluent 12.1: 11 Equation Model**
 - 3-D Navier-Stokes (5)
 - Non-Premixed Combustion (Mixture Fraction PDF) Approach (2)
 - Realizable $k-\epsilon$ (RANS) Turbulence (2)
 - Discrete Ordinates (DO) (1)
 - Single Step Khan and Greeves Soot Model (1)

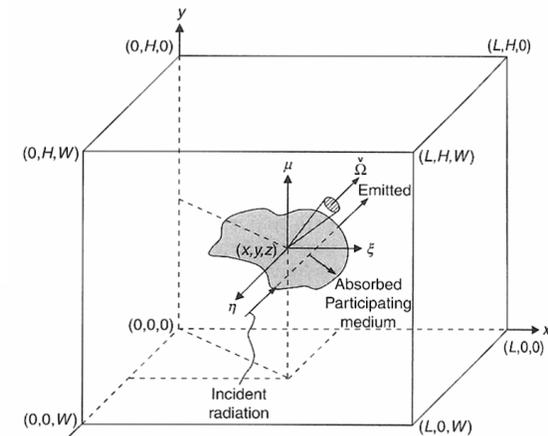


PROBABILITY DENSITY FUNCTION (PDF)

ANSYS Fluent Theory Guide (2009)



TURBULENT - CHEMISTRY INTERACTION



DO RADIATION DISCRETIZATION

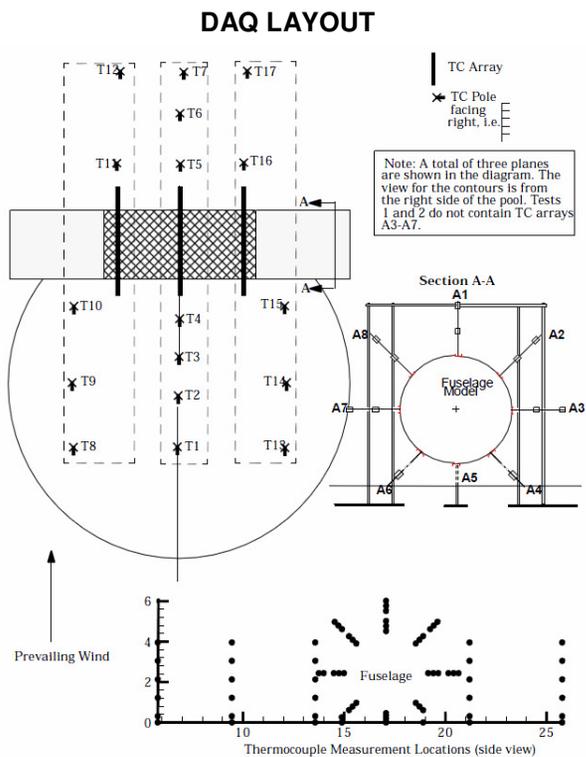
“CFD in Fire Engineering.” Yeoh and Yuen (2009)



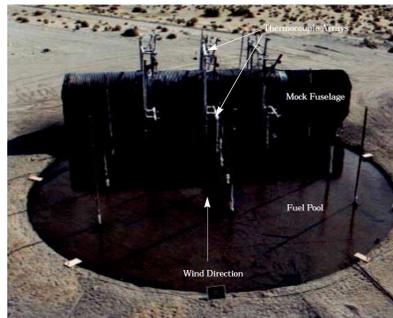
CFD Model Validation: Experiment



- Low / Med / High Cross Winds Over a Cylinder



EXPERIMENTAL SET-UP



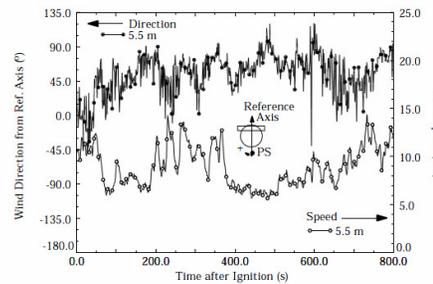
MEDIUM CROSS-WIND (INSTANTANEOUS)



MEDIUM CROSS-WIND (TIME-AVERAGED)



MEDIUM CROSS-WIND TIME HISTORY

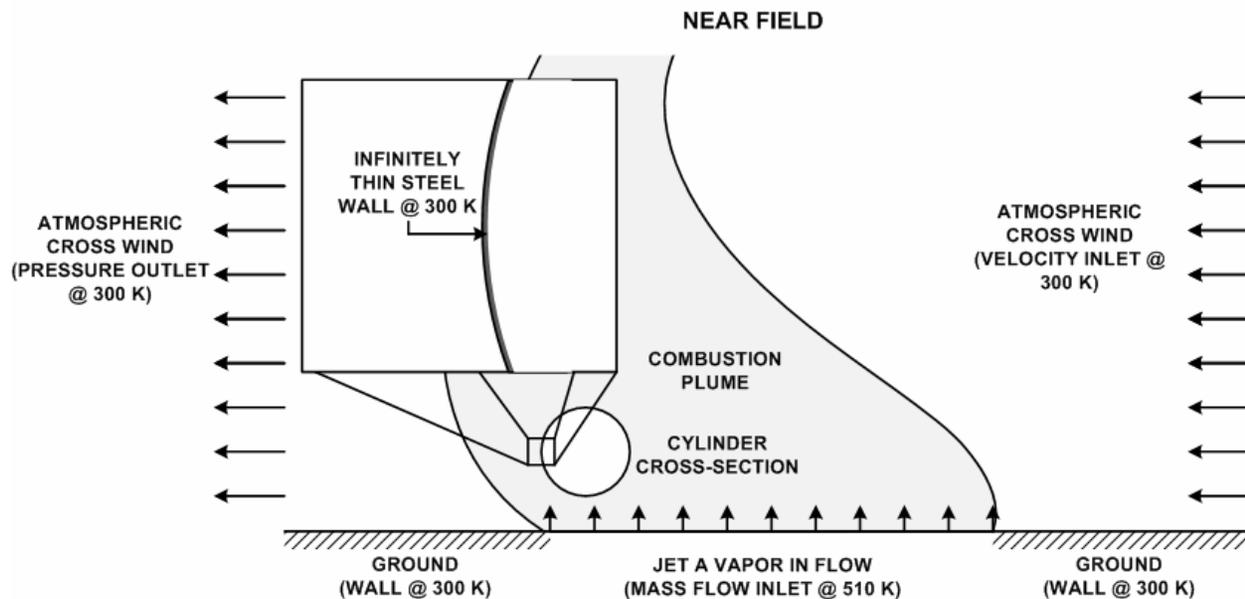
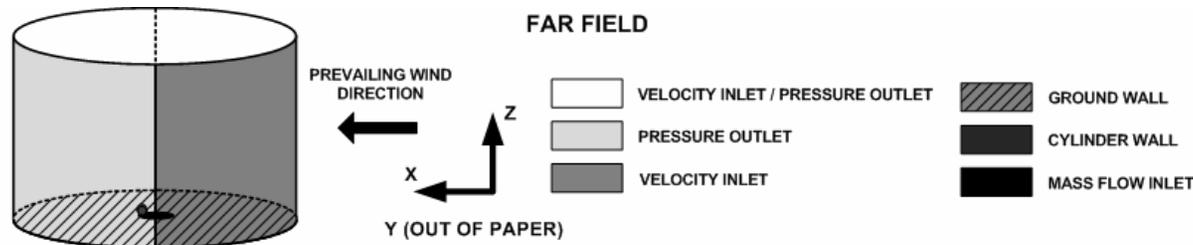


SUO-ANTILLA & GRITZO (2001)

Case Name	Time After Ignition (s)	Wind Velocity (m·s ⁻¹)	Wind Direction (°)
Low	225 – 350	1.9 ± 0.2	-36.9 ± 5.7°
Medium	400 – 575	5.4 ± 1.2	-11.4 ± 12.5°
High	300 – 600	10.2 ± 1.7	-22.7 ± 8.3°



CFD Model Validation: Model Set-Up



Fire Inlet Condition	Value
Flow Rate ($\text{kg}\cdot\text{m}^{-2}\text{s}^{-1}$)	0.058
Temperature (K)	510

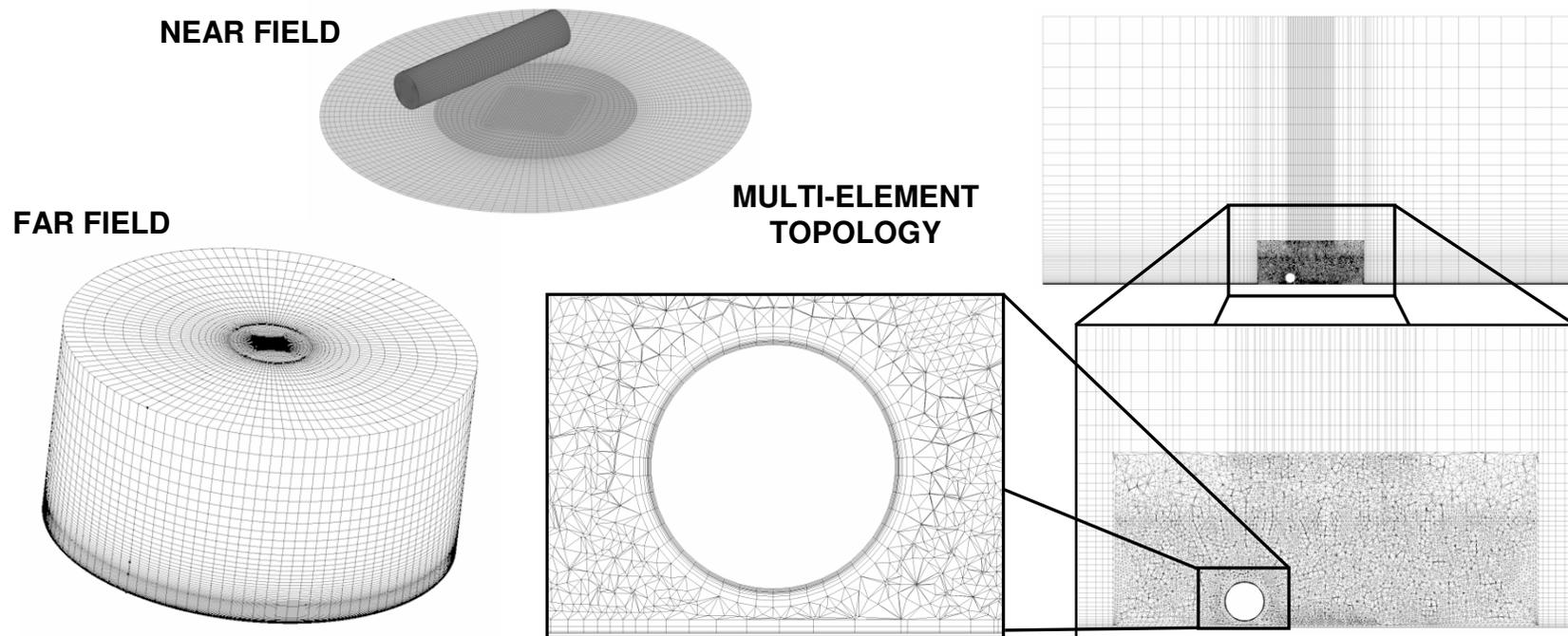
Case Name	Mean Wind Velocity (ms^{-1})	TI (%)	Reynolds Number (Re_{cyl})
Low	1.9	10.5	4.76×10^5
Medium	5.4	22.2	1.35×10^6
High	10.2	16.7	2.56×10^6



CFD Model Development: Domain



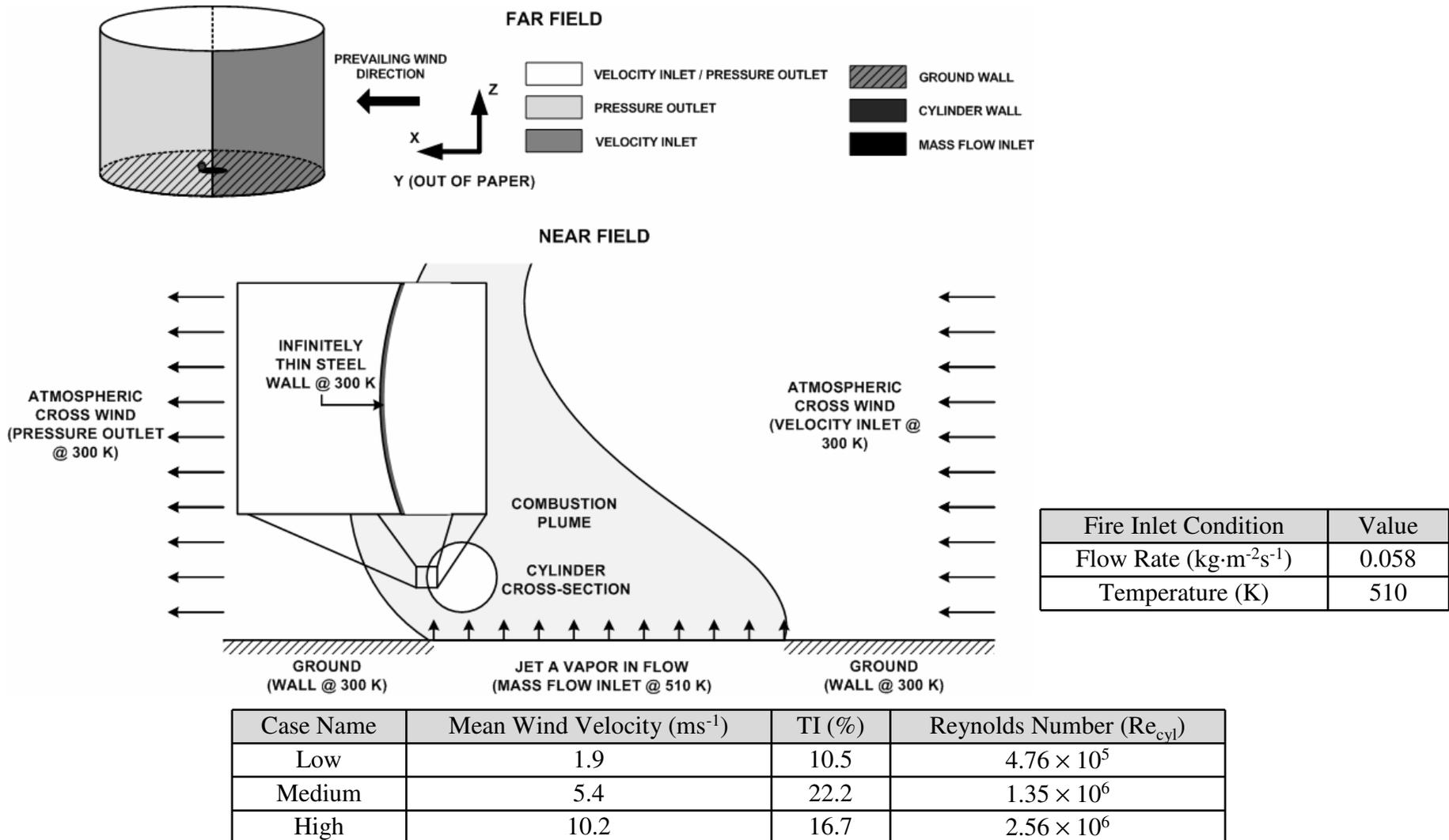
- **Pointwise Gridgen 15: Multi-Block Hybrid Topology**
 - Structured (hexahedral) high aspect ratio cells used for far field atmospheric boundary layer development and cylinder boundary layer growth
 - Unstructured (tetrahedral) cells used to link structured blocks



~ 400K NODES



CFD Model Validation: Model Set-Up

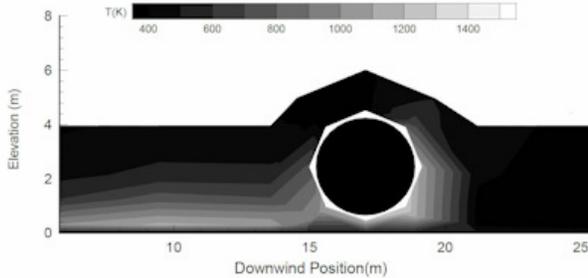
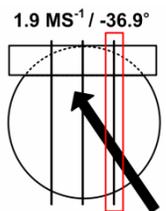
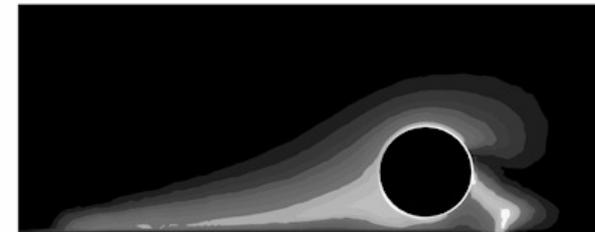
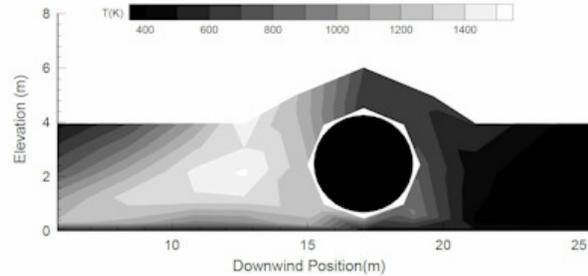
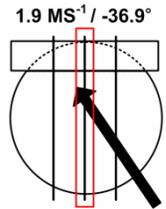
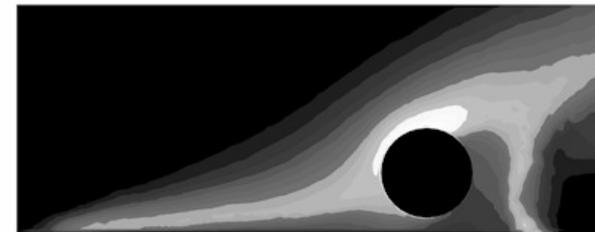
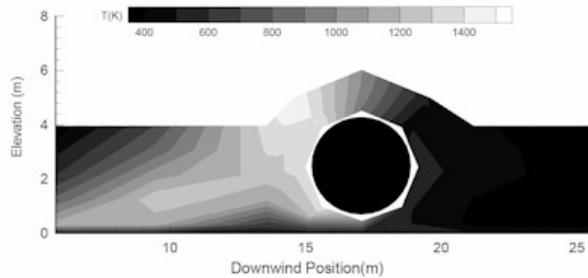
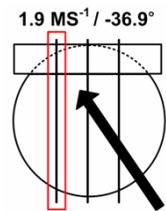




CFD Model Validation: Low Wind



- Flame Temperatures



SUO-ANTILLA & GRITZO (2001) - EXP

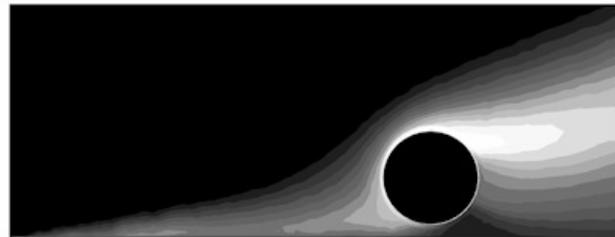
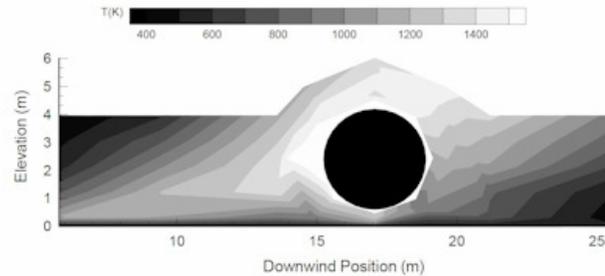
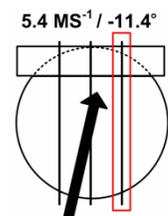
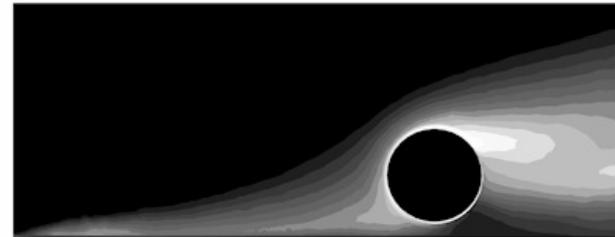
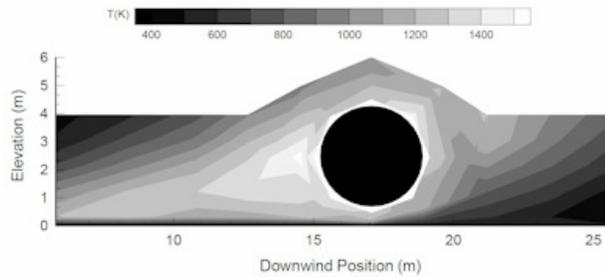
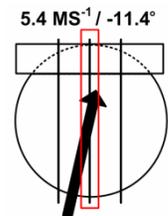
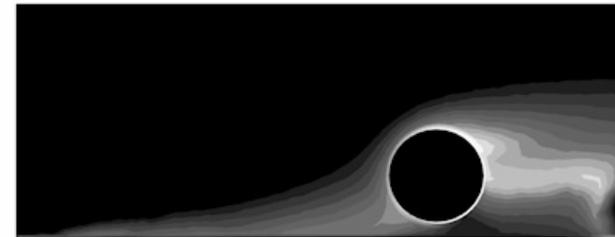
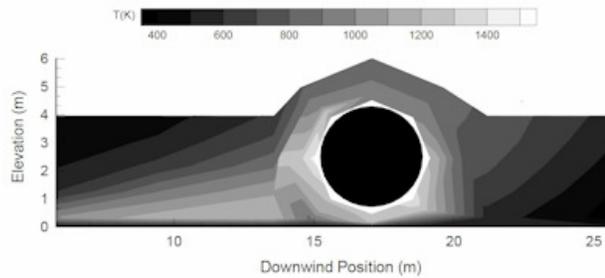
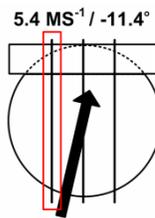
CFD



CFD Model Validation: Medium Wind



- Flame Temperatures



SUO-ANTILLA & GRITZO (2001) - EXP

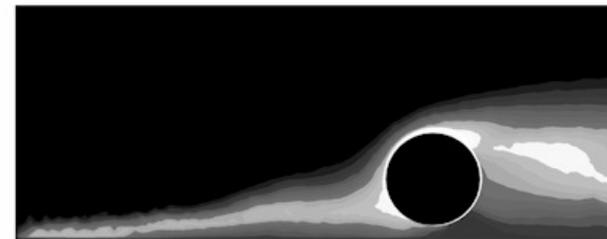
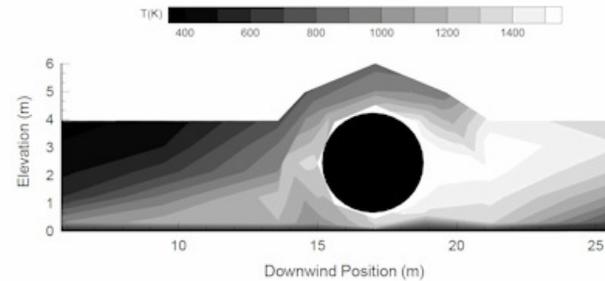
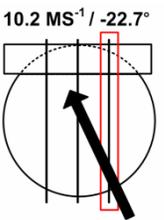
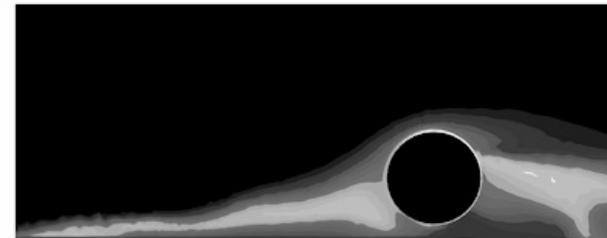
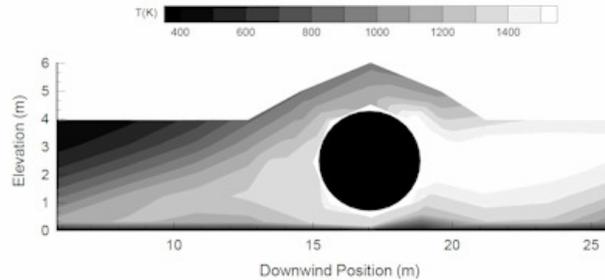
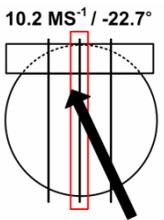
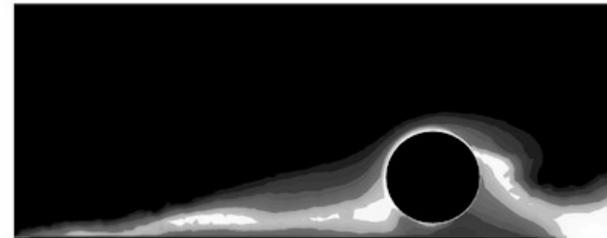
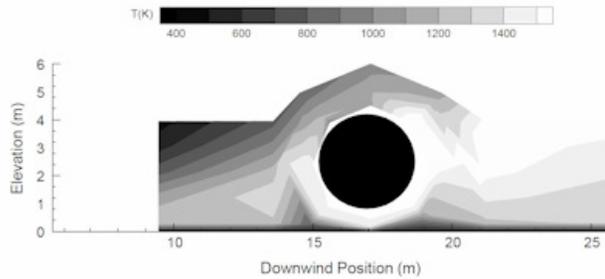
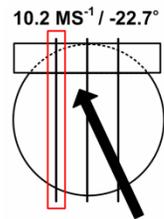
CFD



CFD Model Validation: High Wind



- Flame Temperatures



SUO-ANTILLA & GRITZO (2001) - EXP

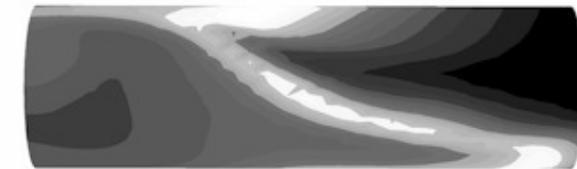
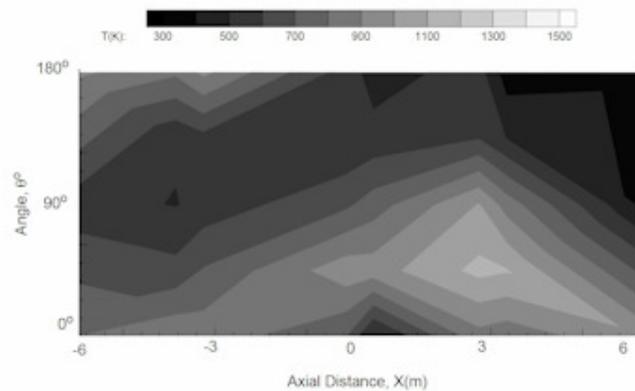
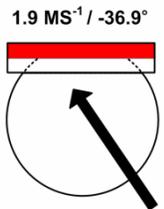
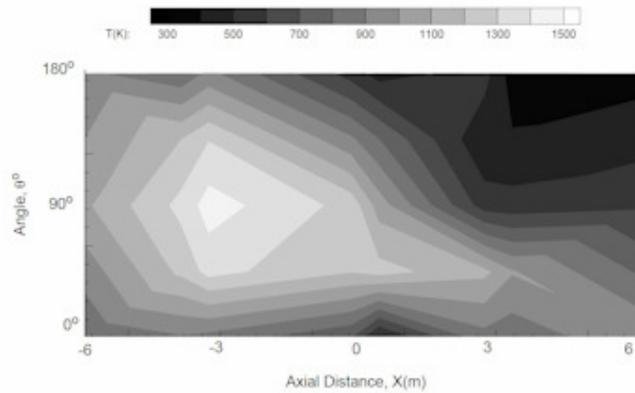
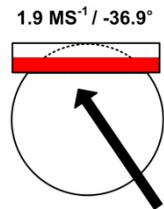
CFD



CFD Model Validation: Low Wind



- Skin Temperatures



SUO-ANTILLA & GRITZO (2001) - EXP

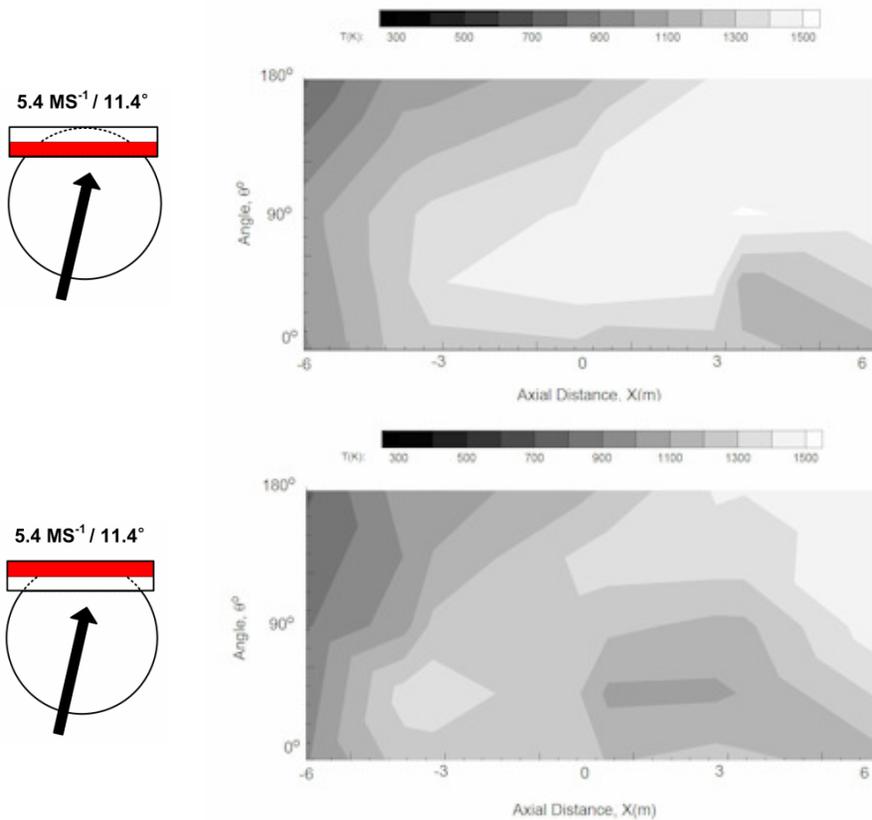
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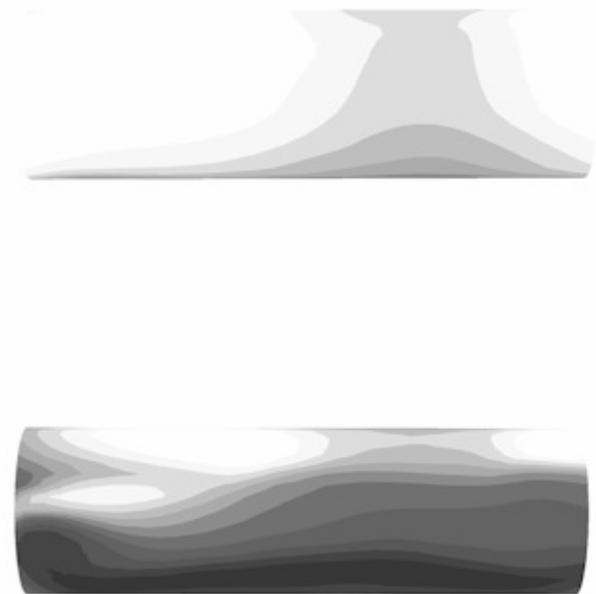
CFD Model Validation: Medium Wind



- Skin Temperatures



SUO-ANTILLA & GRITZO (2001) - EXP



CFD

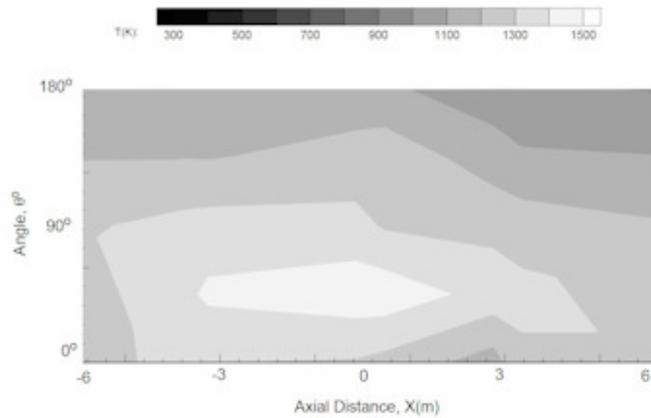
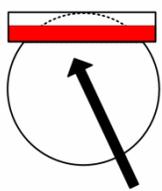


CFD Model Validation: High Wind

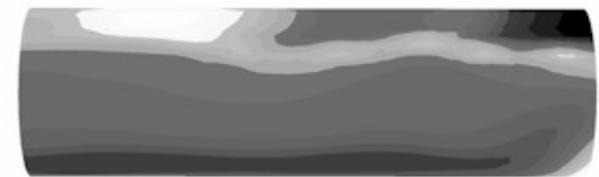
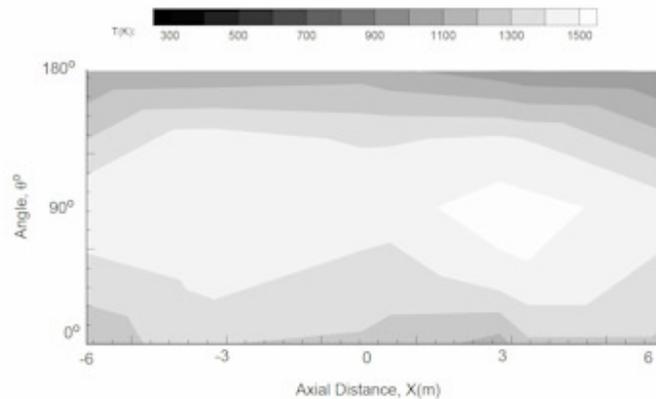
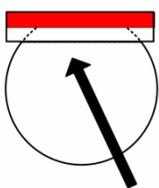


- Skin Temperatures

10.2 MS⁻¹ / -22.7°



10.2 MS⁻¹ / -22.7°



SUO-ANTILLA & GRITZO (2001) - EXP

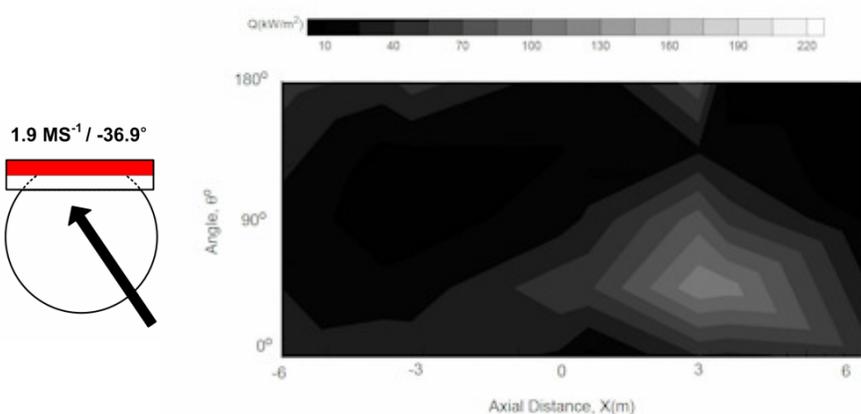
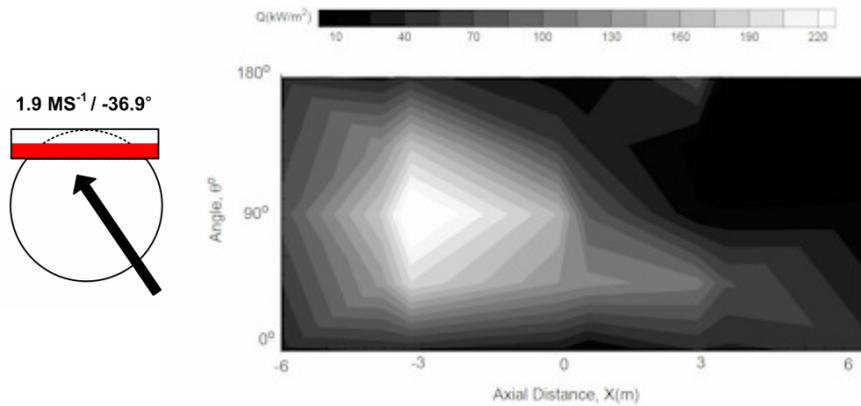
CFD



CFD Model Validation: Low Wind



- Skin Heat Fluxes



SUO-ANTILLA & GRITZO (2001) - EXP

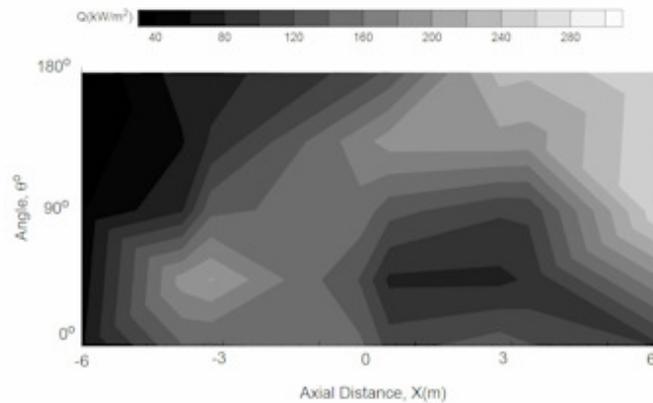
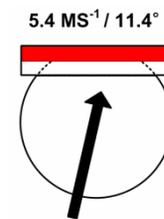
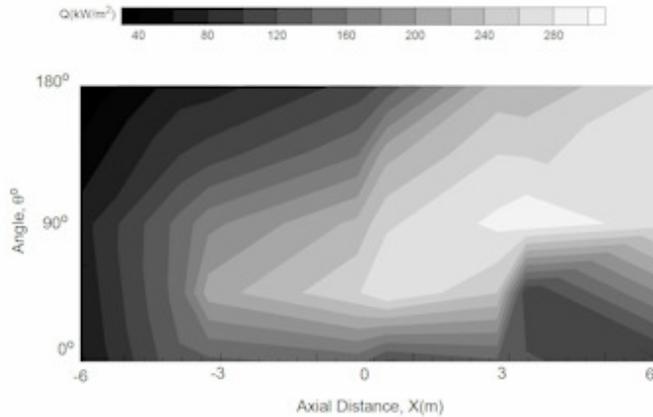
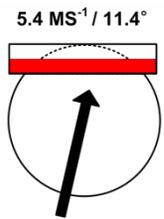
CFD



CFD Model Validation: Medium Wind



- Skin Heat Fluxes



SUO-ANTILLA & GRITZO (2001) - EXP

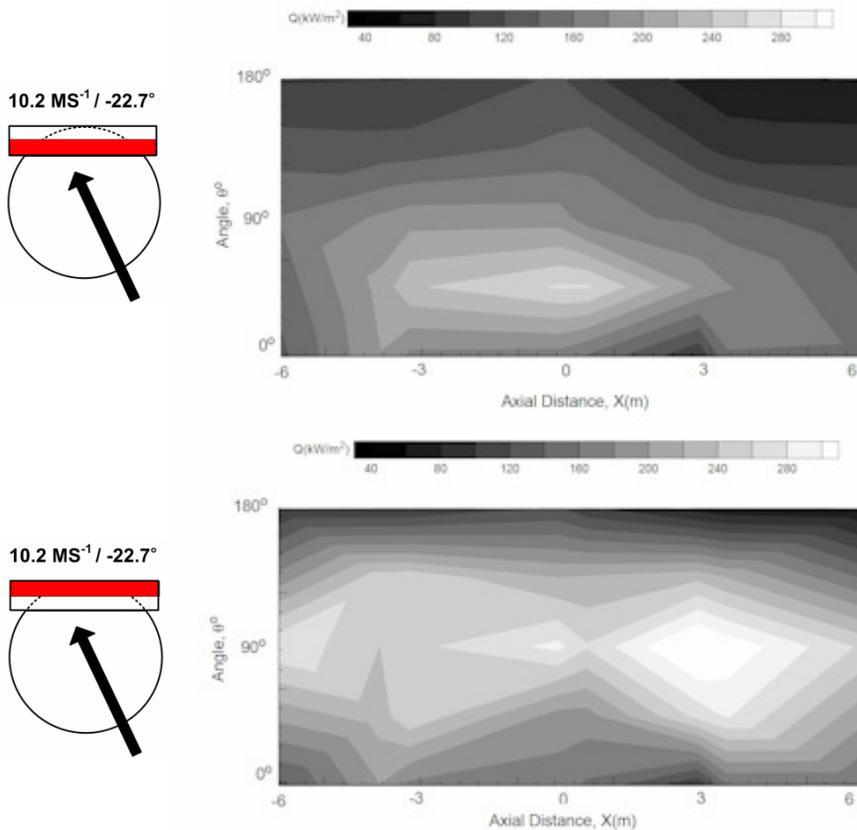
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CFD Model Validation: High Wind



- Skin Heat Fluxes

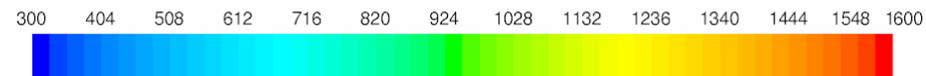
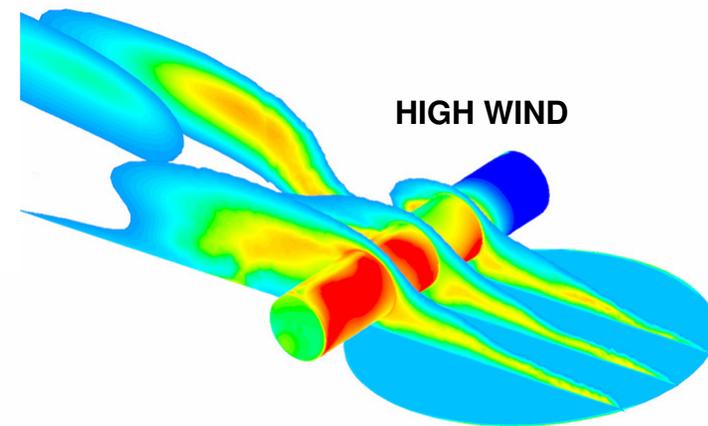
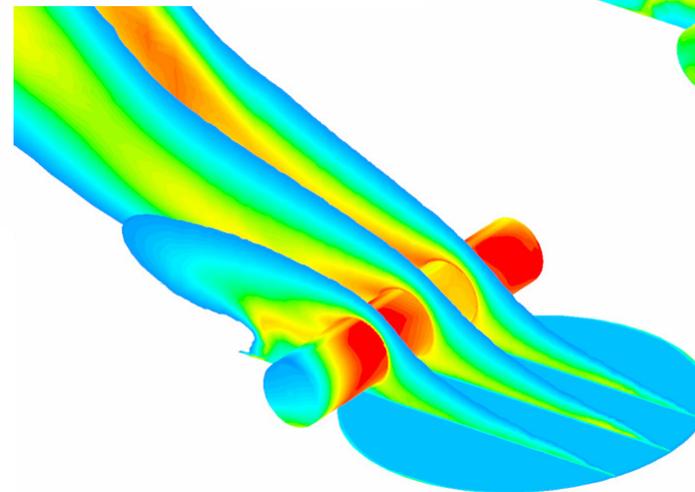
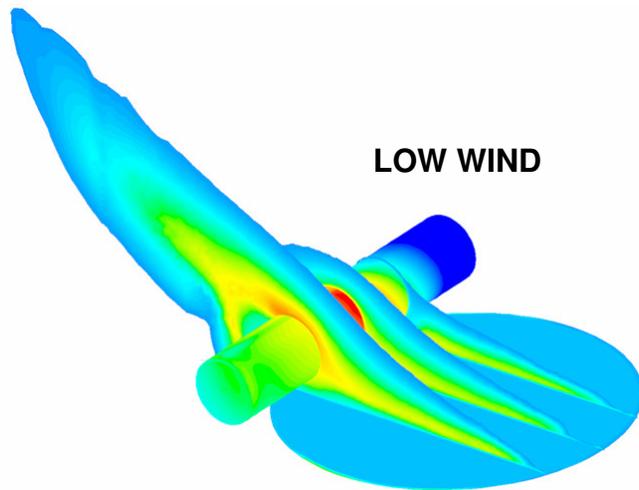


SUO-ANTILLA & GRITZO (2001) - EXP

CFD



CFD Model Validation: Flow Viz



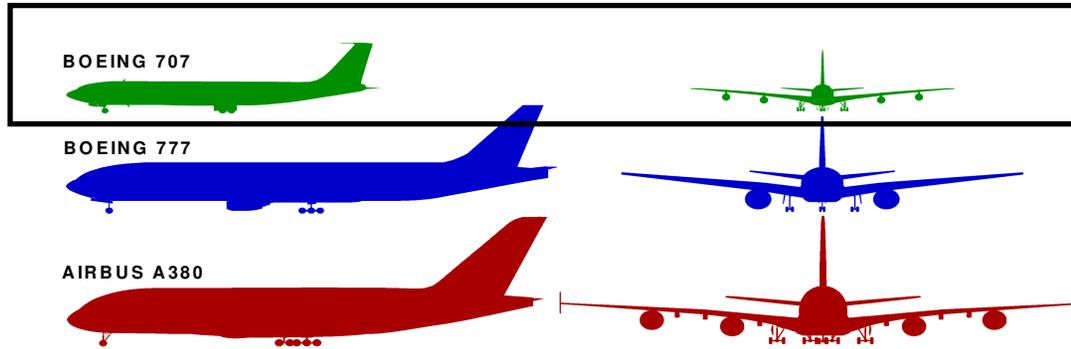


CFD Model Application: Aircraft

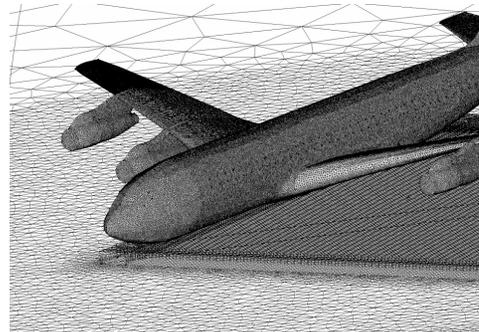
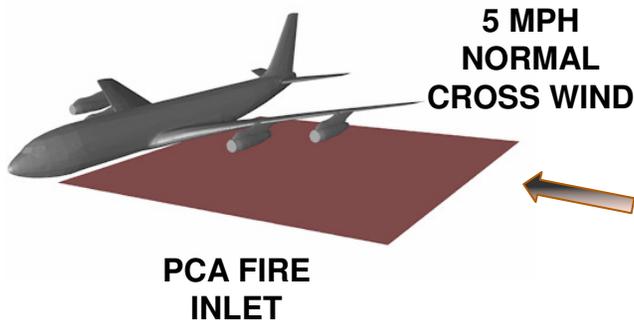
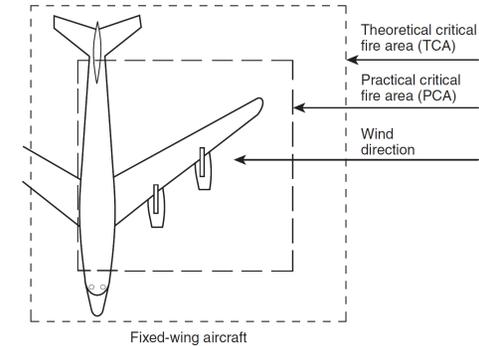


- Full-scale Boeing 707 selected as baseline aircraft
- NFPA 403 PCA fire condition under low speed wind conditions

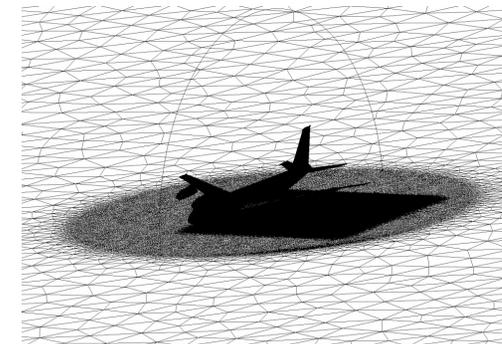
AIRCRAFT SHAPE/SIZE COMPARISON



NFPA 403 FIRE CONDITION



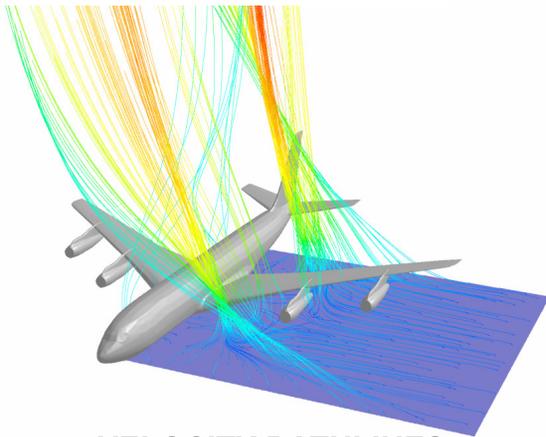
GEOMETRIC MESH



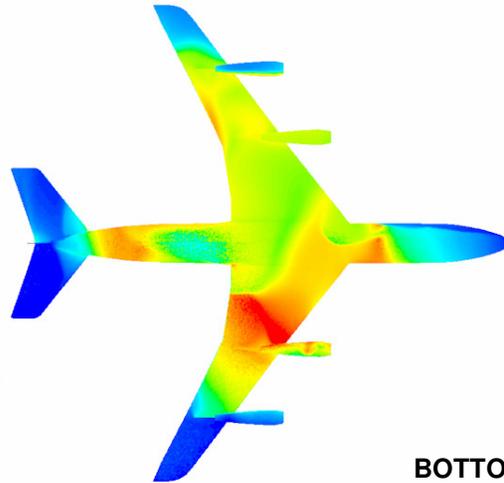
~ 1.4M NODES



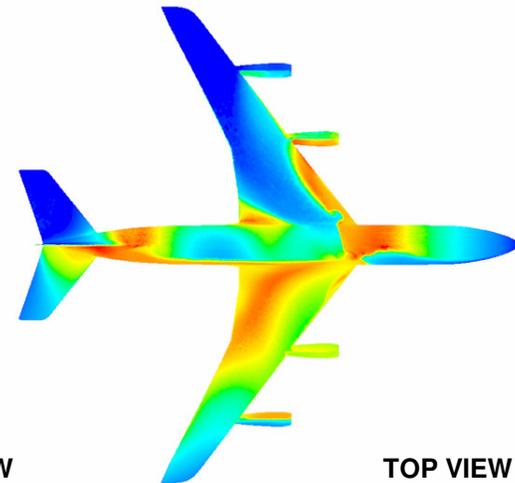
CFD Model Application: Aircraft



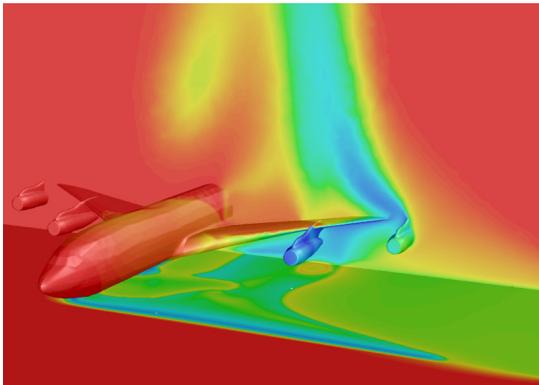
VELOCITY PATHLINES



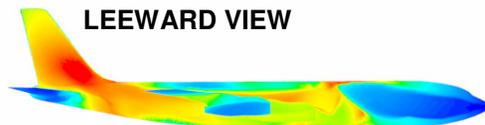
BOTTOM VIEW



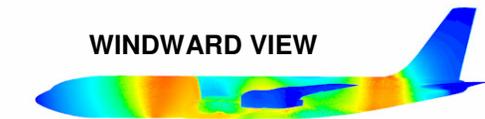
TOP VIEW



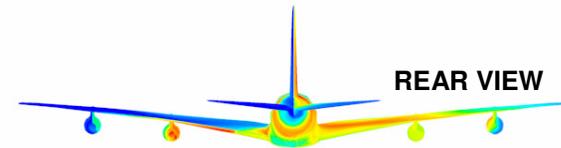
DENSITY CONTOURS



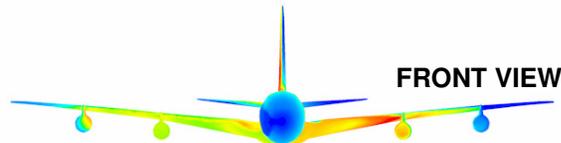
LEEWARD VIEW



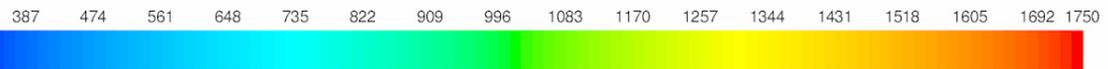
WINDWARD VIEW



REAR VIEW



FRONT VIEW



Contours of Total Temperature (k)

SURFACE TEMPERATURES



Conclusions



- Experimental flame and skin temperatures compare well profile trend and magnitude-wise to CFD at low to medium wind velocities, with the largest discrepancies in the high wind regime
- Cylinder flow separation appears to be a first order turbulent flow modeling effect leading to the divergence on the leeward cylinder surface thermal effects
- Sharp flamelet gradients are indicative of fast chemical kinetic time scales largely absent in the “mixed-is-burnt” model based upon slower fluid motion time scales
- Simple soot modeling provides sufficient radiant heat absorption to accurately meter total heat transfer magnitudes, but lacks in qualitative plume size and shape prediction
- Full-scale aircraft thermal and fluid structures trend similarly to the validation study, with resource needs increasing by about 4x.



Future Work



- Analyze alternative CFD sub-models (combustion / turbulence / soot) to increase accuracy
- Gather more validation / material property data
- Run unsteady cases to determine transient effects and examine material heat up times
- Complete Airbus A380 and Boeing 787 case studies (Possibly Tyndall AFB Airbus Mock-Up?)
- Apply to alternate aircraft / combustion scenarios of interest
- Ultimate integration into an aircraft-crash-fire simulation framework.