Advances in Turbulence and Plume Thermo-Chemistry on the Prediction of Missile Plume Structure

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Combustion Research and Flow Technology
(CRAFT Tech)

INTRODUCTION

CHARACTERISTICS OF MANY ROCKET PROPULSION SYSTEMS:

- **RUN FUEL RICH FOR PERFORMANCE REASONS**
- **EXHIBIT STRONG AFTERBURNING OF EXHAUST WITH THE ATMOSPHERE**
- **HIGH RADIATIVE EMISSIONS**
- **SIGNIFICANT BASE FLOW RECIRCULATION AND/OR BODY FLOW SEPARATION AT HIGH ALTITUDES**

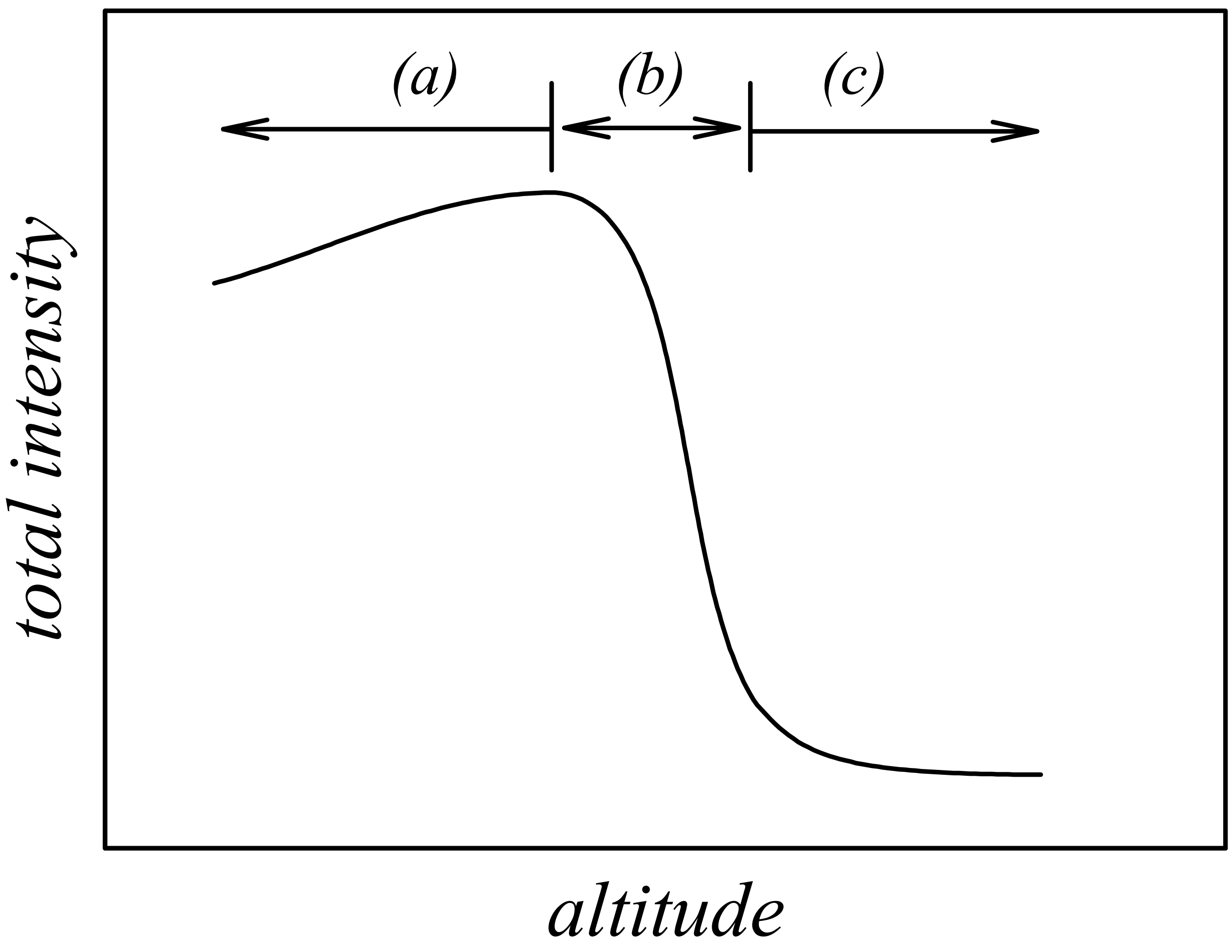
INTRODUCTION

PLUME AFTERBURNING CHARACTERISTICS IMPORTANT TO:

- **MISSILE BASE COMPONENT DESIGN**
  - **PLUME RADIANT HEAT TRANSFER**
  - **HEAT TRANSFER FROM BASE FLOW COMBUSTION**
- **MISSILE STABILITY AND CONTROL**
  - **PLUME INDUCED BODY FLOW SEPARATION**
- **MISSILE DEFENSE SYSTEM DEVELOPMENT**

INTRODUCTION

ILLUSTRATION OF PLUME TOTAL INTENSITY VARIATION WITH ALTITUDE



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INTRODUCTION

<u>COMPUTATIONAL CHALLENGES FOR THE ACCURATE PREDICTION OF MISSILE BODY AND PLUME FLOWS</u>:

- **TURBULENCE MODELING**
  - **HIGHLY COMPRESSIBLE TURBULENT FLOW**
  - **TURBULENT TRANSITION**
  - **STRONG FLOW CURVATURE – TURBULENT ANISOTROPY**
- **COMBUSTION MODELING**
  - **TURBULENCE-CHEMISTRY INTERACTIONS**
  - **TURBULENT FLAME EXTINCTION**
  - **BASE FLOW/SEPARATION ZONE FLAME HOLDING**

TURBULENCE MODELING

MODELING EFFORTS FOCUSED ON:

A. HIGH SPEED BOUNDARY LAYER TRANSITION MODELING

BODY FLOW SEPARATION COMBUSTION AND MISSILE HEATING

B. COMPRESSIBILITY AND AXISYMMETRIC CORRECTIONS FOR HIGH SPEED FLOWS

PLUME ENTRAINMENT RATE/COMBUSTION AND SIGNATURE

C. EXPLICIT ALGEBRAIC REYNOLDS STRESS MODELING

FLOW CURVATURE EFFECTS IN THE NEAR PLUME REGION

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COMPRESSIBILITY AND AXISYMMETRIC CORRECTION MODELING

PLUME MIXED SUBSONIC/SUPERSONIC FLOW:

- REQUIRES A UNIFIED TURBULENCE MODEL TO CAPTURE BOTH THE LOW AND HIGH SPEED FLOW REGIMES

MISSILE PLUME FLOW GEOMETRIC TRANSITION:

- HIGHLY 3-D BASE FLOW TO AXISYMMETRIC HIGH SPEED JET
- REQUIRES A COMPRESSIBLE AXISYMMETRIC CORRECTION

BASELINE TURBULENCE MODEL: STANDARD K-E

HIGH SPEED COMPRESSIBILITY CORRECTION

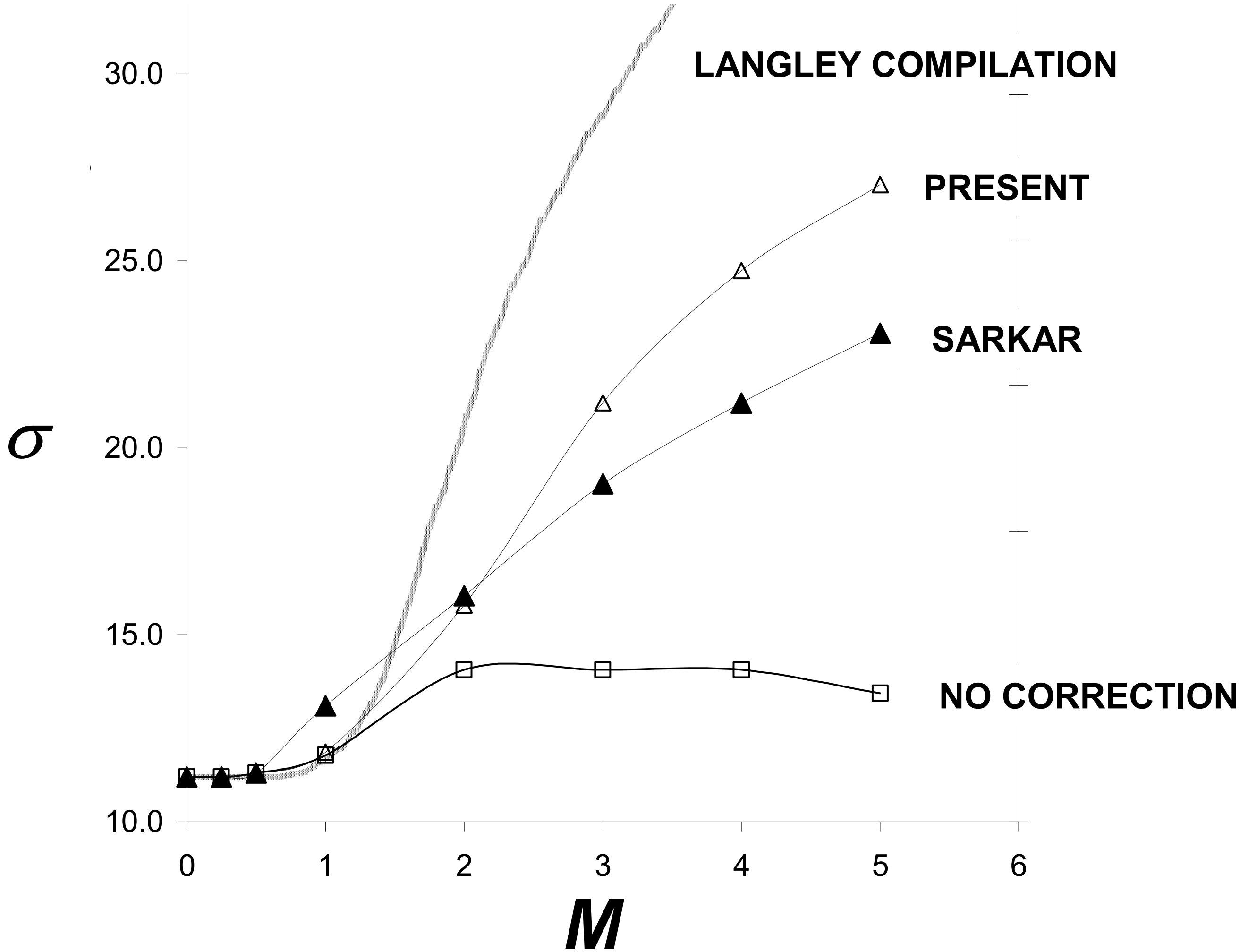
- EXTRA DISSIPATION EXHIBITED THROUGH PRESSURE AND VELOCITY FLUCTUATIONS
- TURBULENT MACH NUMBER, M_T, RELATING TURBULENT VELOCITY TO MEAN VELOCITY SCALE USED TO MODEL PRESSURE/VELOCITY FLUCTUATION
- IMPROVED MODEL USES ZEMAN TYPE LAG, λ, TO BRIDGE THE LOW AND HIGH SPEED REGIMES
- RECALIBRATION MODEL COEFFICIENTS FOR HIGH SPEED PLANAR JETS

$$SS_k = -\alpha_1 \widetilde{M}_T^2 P_k - \alpha_2 \widetilde{M}_T^2 \rho\varepsilon, \quad \widetilde{M}_T = max(M_T - \lambda, 0)$$

$$\alpha_1 = 2.5, \ \alpha_2 = 2.0, \ \lambda = 0.2$$

TURBULENT COMPRESSIBILITY CORRECTION

SHEAR LAYER GROWTH RATE PARAMETER AS A FUNCTION OF MACH NUMBER



TURBULENT COMPRESSIBILITY CORRECTION

- FOR AXISYMMETRIC FLOWS, VORTEX STRETCHING LEADS TO DECREASED TURBULENT SCALES AND INCREASED DISSIPATION

- POPE (1978) DEVELOPED INCOMPRESSIBLE MODEL BASED ON TURBULENT VORTEX STRETCHING INTERPRETATION:

$$SS_{\varepsilon} = C_{\varepsilon_3} \rho \varepsilon \left(\frac{k}{\varepsilon} \right)^2 \omega_{ij} \omega_{jk} \left(\frac{\partial u_k}{\partial x_i} + \frac{\partial u_i}{\partial x_k} \right)$$

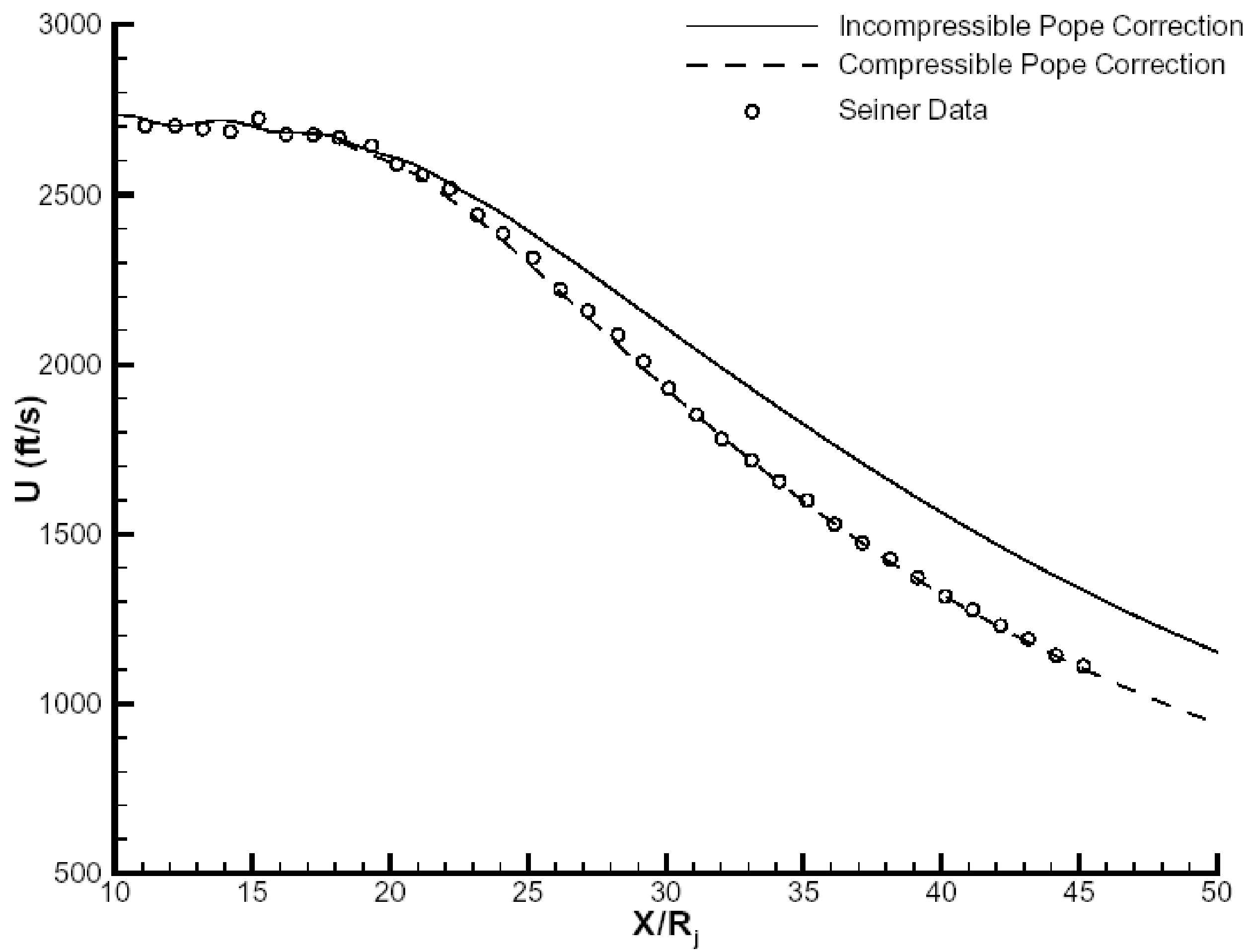
- COMPRESSIBLE EXTENSION:

$$SS_{\varepsilon} = C_{\varepsilon_3} \exp\left(- \beta \widetilde{M}_T^2 \right) \rho \varepsilon \left(\frac{k}{\varepsilon} \right)^2 \omega_{ij} \omega_{jk} \left(\frac{\partial \rho u_k}{\partial x_i} + \frac{\partial \rho u_i}{\partial x_k} \right)$$

$$\beta = 75.0, \; C_{\varepsilon_3} = 0.79$$

TURBULENT COMPRESSIBILITY CORRECTION

CENTERLINE VELOCITY DECAY FOR SEINER M_{JET} = 2.0 HOT JET EXPERIMENT



MISSILE PLUME COMBUSTION MODELING

MODELING EFFORTS FOCUSED ON:

A. HIGH SPEED TURBULENCE-CHEMISTRY INTERACTION MODELING

- **PLUME AFTERBURNING IGNITION AND SUSTAINMENT HIGHLY DEPENDENT ON TURBULENCE-CHEMISTRY INTERACTIONS**

B. TURBULENT FLAME EXTINCTION MODELING

- **PLUME AFTERBURNING SHUTDOWN MECHANISMS**
  - ***DAMKOHLER NUMBER REDUCTION – GRADUAL SHUTDOWN***
  - ***TURBULENT FLAME EXTINCTION – RAPID SHUTDOWN***

HIGH SPEED TURBULENT-CHEMISTRY INTERACTION MODELING

- **CLOSURE MODELING REQUIRED FOR:**
  - **MEAN REACTION RATE:** $\overline{w'_{k,dot}} = \int_0^\infty \int_0^\infty \int_0^1 \ldots \int_0^1 w'_{k,dot} P(\rho', T', Y_k') dY_1' \ldots dY_k' d\rho' dT'$
- $P(\rho, T, Y_k)$ **REPRESENTS THE COMBINED EFFECTS OF:**
  - **TURBULENT TRANSPORT (LARGE AND SMALL SCALE)**
  - **MOLECULAR DIFFUSION**
- $P(\rho, T, Y_k)$ **MODELED USING AN ASSUMED PDF FOR SPECIES AND TEMPERATURE:**
  - **REQUIRES TURBULENT TRANSPORT EQUATIONS FOR SPECIES AND TEMPERATURE FLUCTUATIONS**

HIGH SPEED TURBULENT-CHEMISTRY INTERACTION MODELING

- **MODELED TRANSPORTS EQUATIONS TO SPECIES AND TEMPERATURE FLUCTUATIONS:**

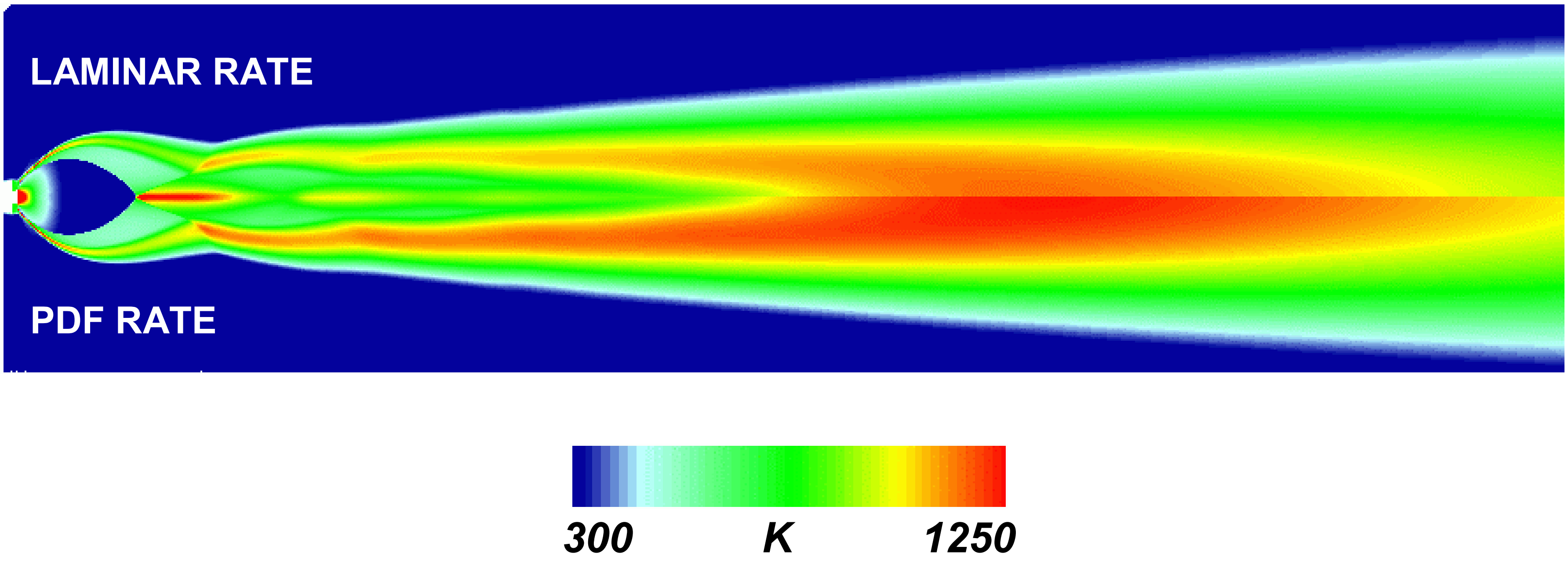
$$\frac{D\bar{\rho}Q}{Dt} = \frac{\partial}{\partial x_j}\left((\bar{D} + D_Y)\frac{\partial Q}{\partial x_j} \right) + 2D_Y \sum_{k=1}^{K} \left(\frac{\partial < Y_k >}{\partial x_j} \right)^2 - 2C_Q \bar{\rho} \frac{Q}{\tau} + 2\sum_{k=1}^{K} \overline{w'_{k,dot}\, Y''_k}$$

$$\frac{D\bar{\rho}g}{Dt} = \frac{\partial}{\partial x_j}\left(\bar{\gamma}(\bar{D}_T + D_{T,t})\frac{\partial g}{\partial x_j} \right) + 2\bar{\gamma} D_{T,t} \left(\frac{\partial < e >}{\partial x_j} \right)^2 - 2C_g \bar{\rho} \frac{g}{\tau} - 2(\bar{\gamma} - 1)\bar{\rho} g \frac{\partial < u_j >}{\partial x_j}$$

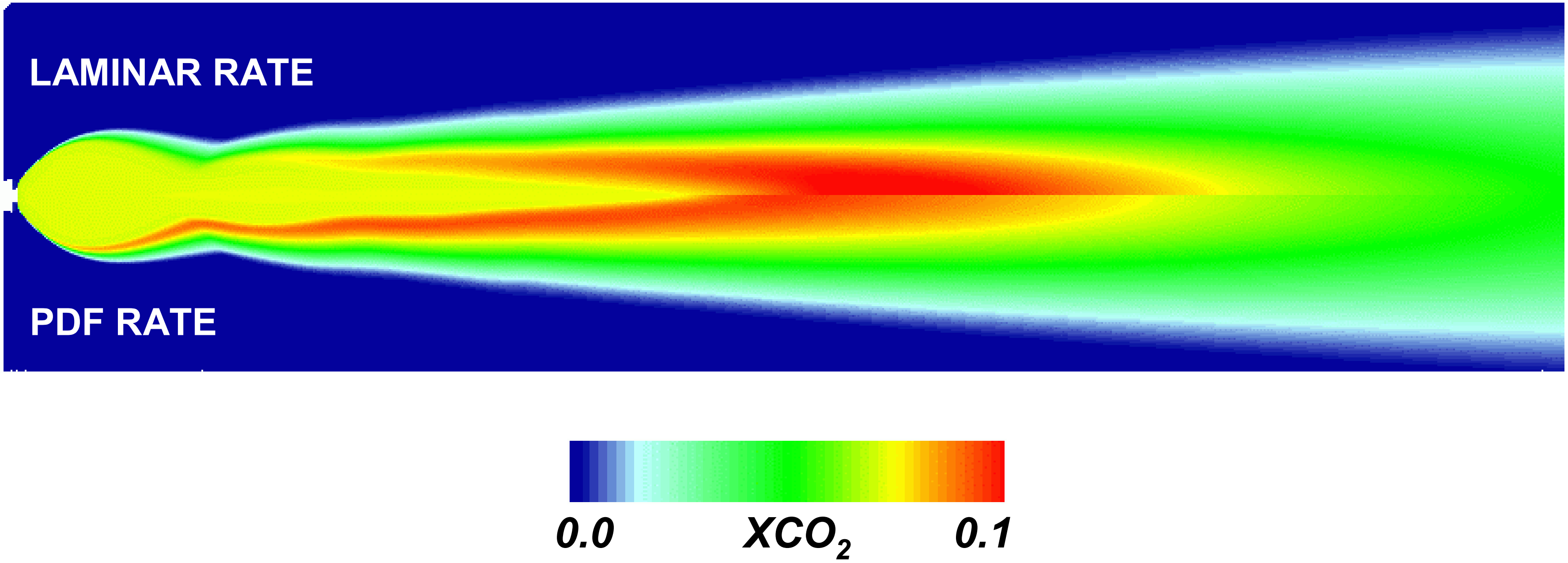
- **HIGH SPEED SCALAR FLUCTUATION DATA UNAVAILABLE**

- **MODEL COEFFICIENTS CALIBRATED USING AVAILABLE LOW SPEED DNS AND EXPERIMENTAL DATA**

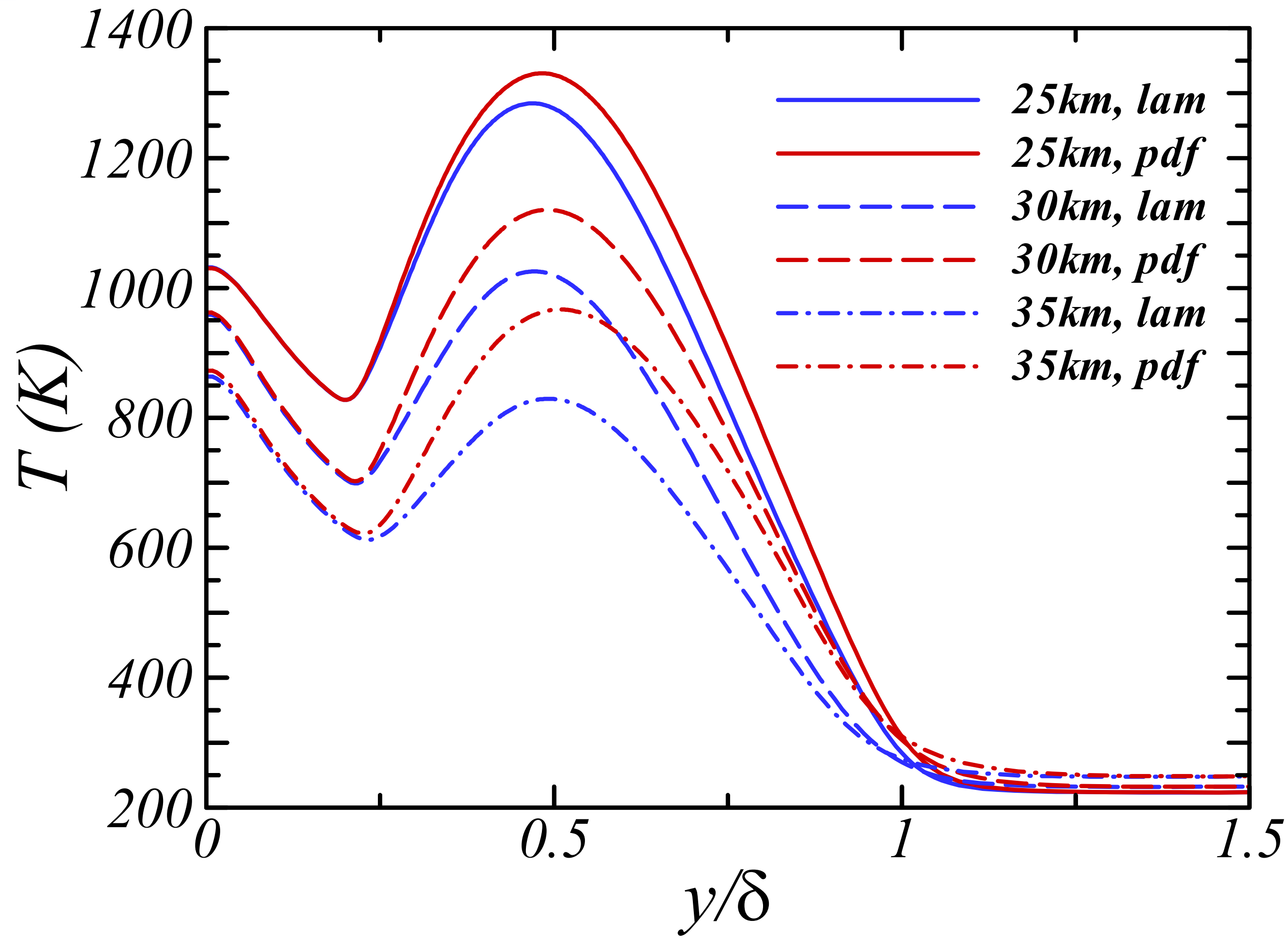
TEMPERATURE CONTOURS FOR LAMINAR AND PDF RATE MODELS AT 30 KM



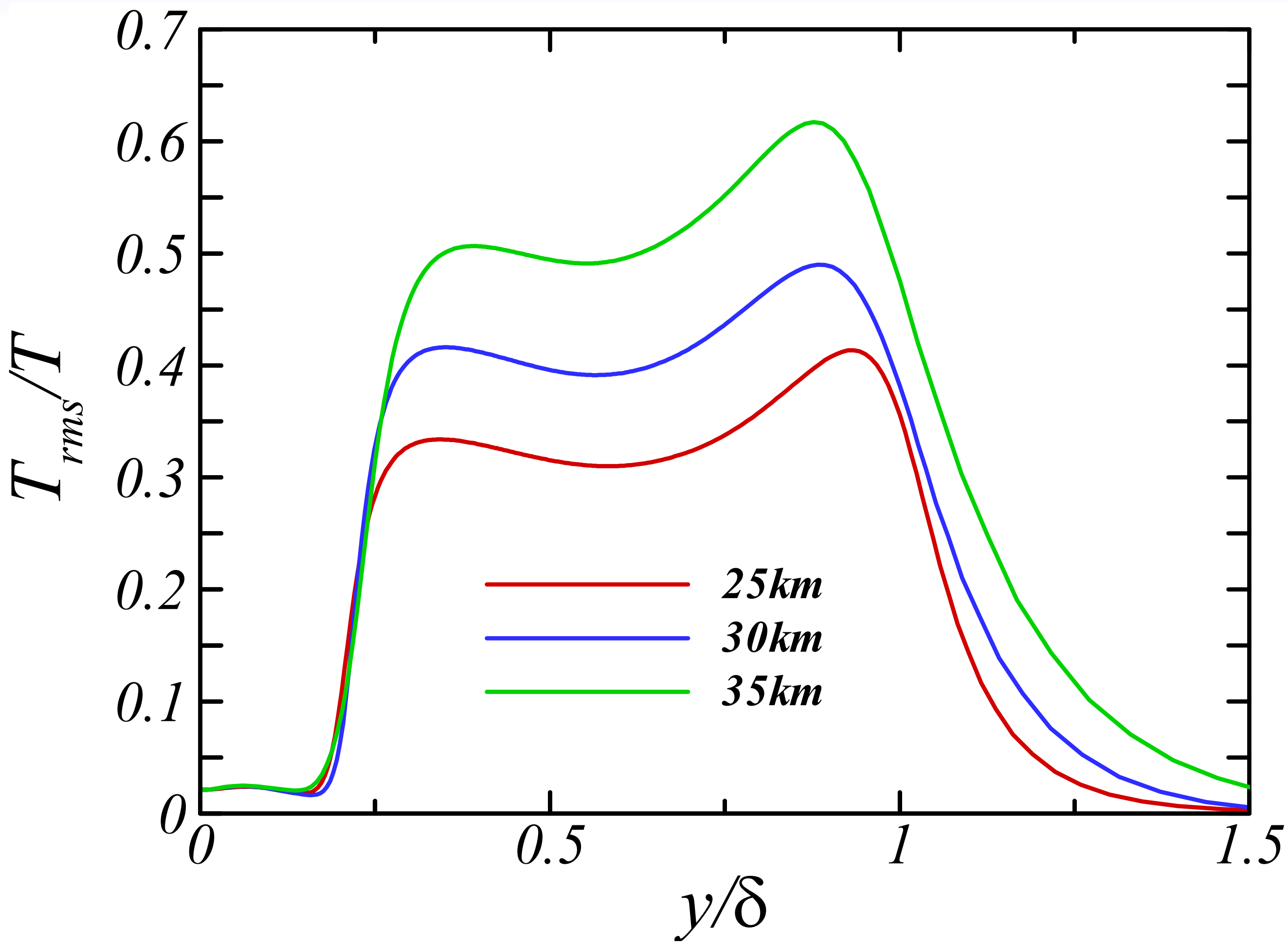
CO_2 MOLE FRACTION CONTOURS FOR LAMINAR AND PDF RATE MODELS AT 30 KM



COMPARISON OF LAMINAR AND PDF RATE MODELS FOR SHEAR LAYER TEMPERATURE, $x/x_{refl} = 3$



PREDICTED TEMPERATURE INTENSITY AT $x/x_{refl} = 3$



PDF MODEL SCALAR FLUCTUATIONS

- LOW SPEED CALIBRATION OVERPREDICTED SCALAR FLUCTUATION LEVELS BY ~ 40 %
- AD-HOC COEFFICIENT ADJUSTMENT REQUIRED TO REPRESENT FLIGHT DATA
- NO SCALAR FLUCTUATION DATA AVAILABLE FOR HIGH SPEED FLOWS
- LARGE-EDDY SIMULATION (LES) CAN PROVIDE DATA IN FLOW REGIMES UNSUPPORTED BY EXPERIMENTS
- SCALAR FLUCTUATION MODELING EFFORTS FOCUSED ON USING LES TO PROVIDE REQUIRED DATA AND PHYSICAL INSIGHT

LES PLANAR SHEAR LAYERS

<u>THREE FLOW REGIMES FOR PLANAR SHEAR LAYERS</u>:

- **LOW COMPRESSIBILITY: $M_C < 0.6$**
  - **DOMINATED BY 2-D MODAL INSTABILITIES**

- **MODERATE COMPRESSIBILITY: $0.6 < M_C < 1.0$**
  - **DOMINATED BY 2-D AND 3-D MODAL INSTABILITIES**

- **HIGH COMPRESSIBILITY: $M_C > 1.0$**
  - **DOMINATED BY 3-D MODAL INSTABILITIES**

LES PLANAR SHEAR LAYER CONDITIONS

ALL CASES USED:

- $U_1/U_2 = 6.1$
- $\rho_1/\rho_2 = 0.3$
- $T_1 = 1000$ K, $T_2 = 300$ K

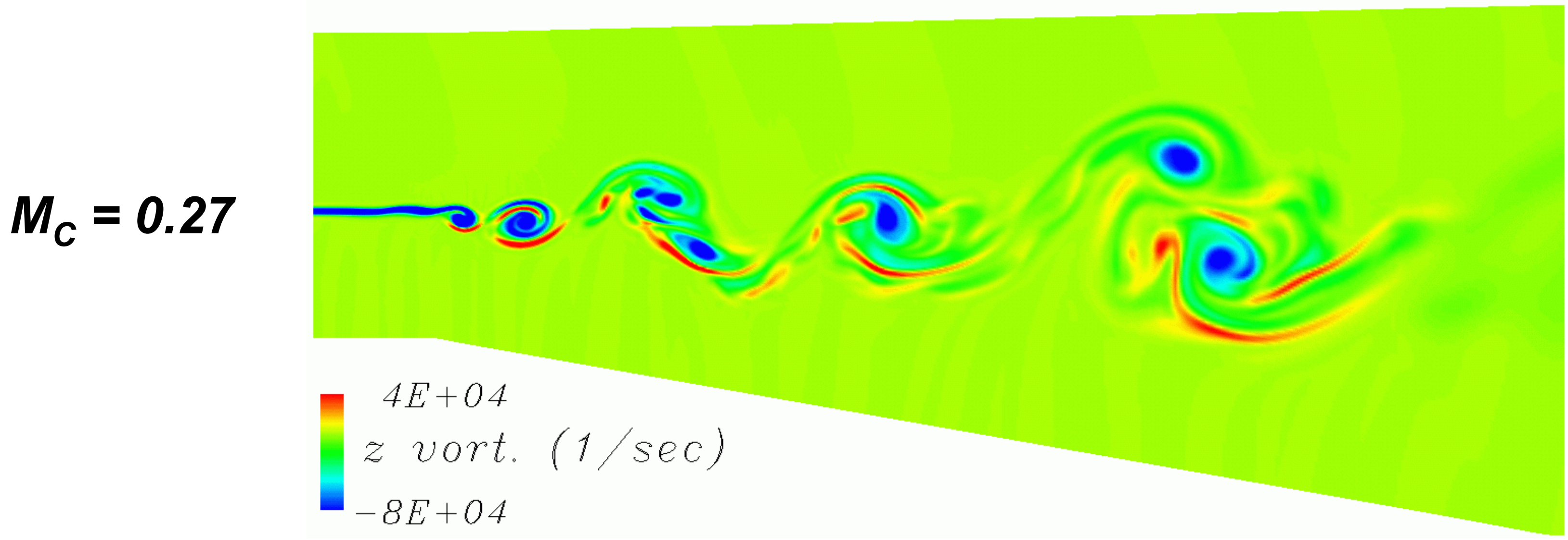
LOW COMPRESSIBILITY CASE:

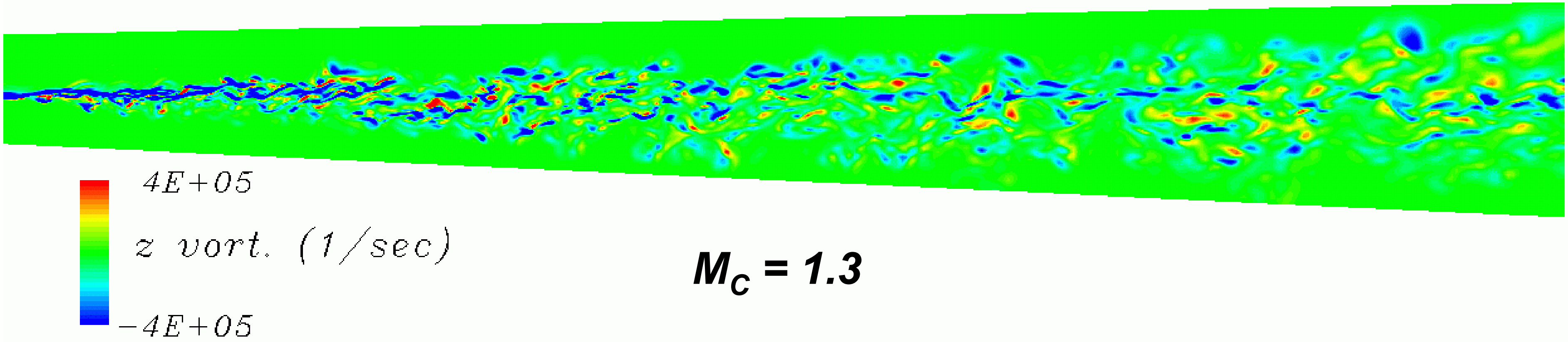
- $M_C = 0.27$
- $M_1 = 0.5$, $M_2 = .15$

HIGH COMPRESSIBILITY CASE:

- $M_C = 1.3$
- $M_1 = 2.41$, $M_2 = 0.72$

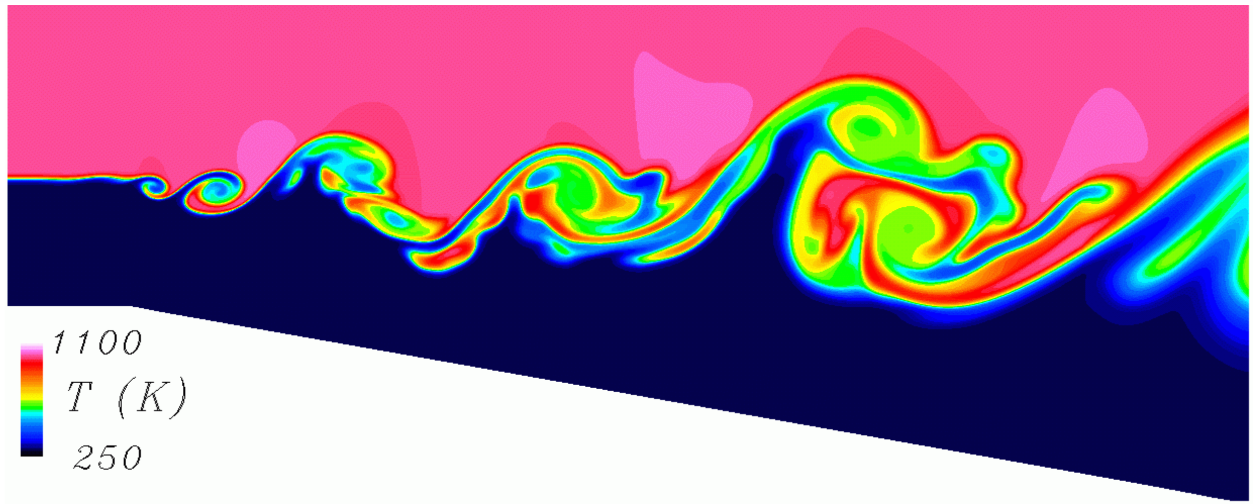
SPANWISE VORTICITY CONTOURS

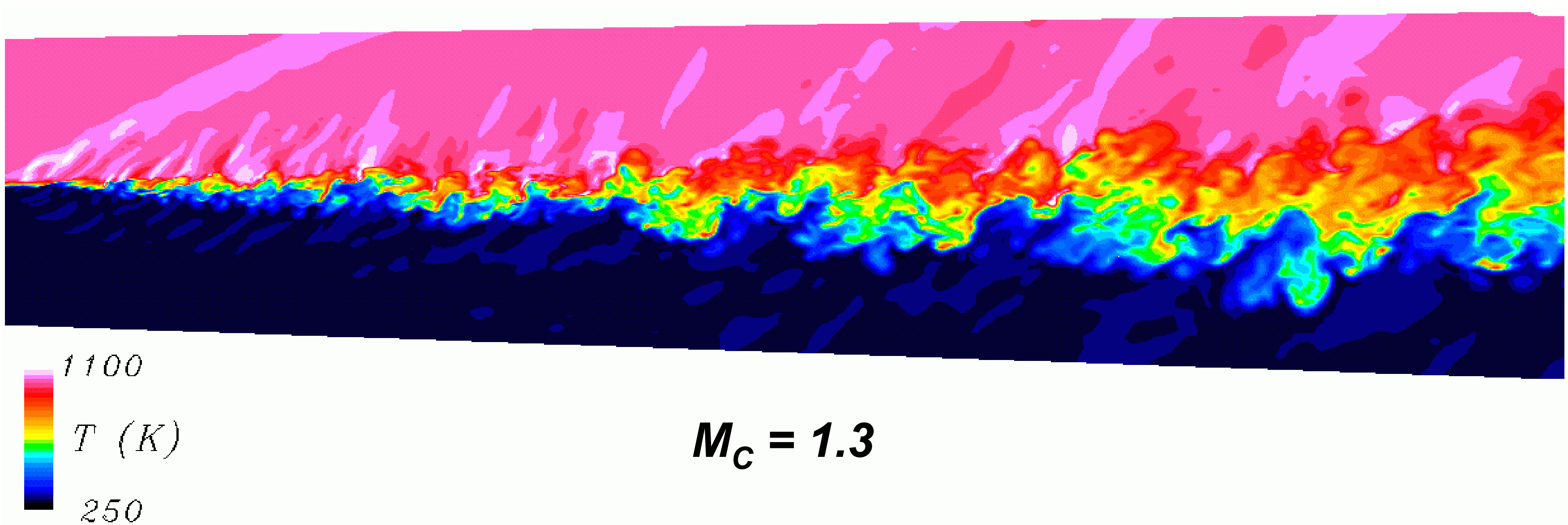




TEMPERATURE CONTOURS

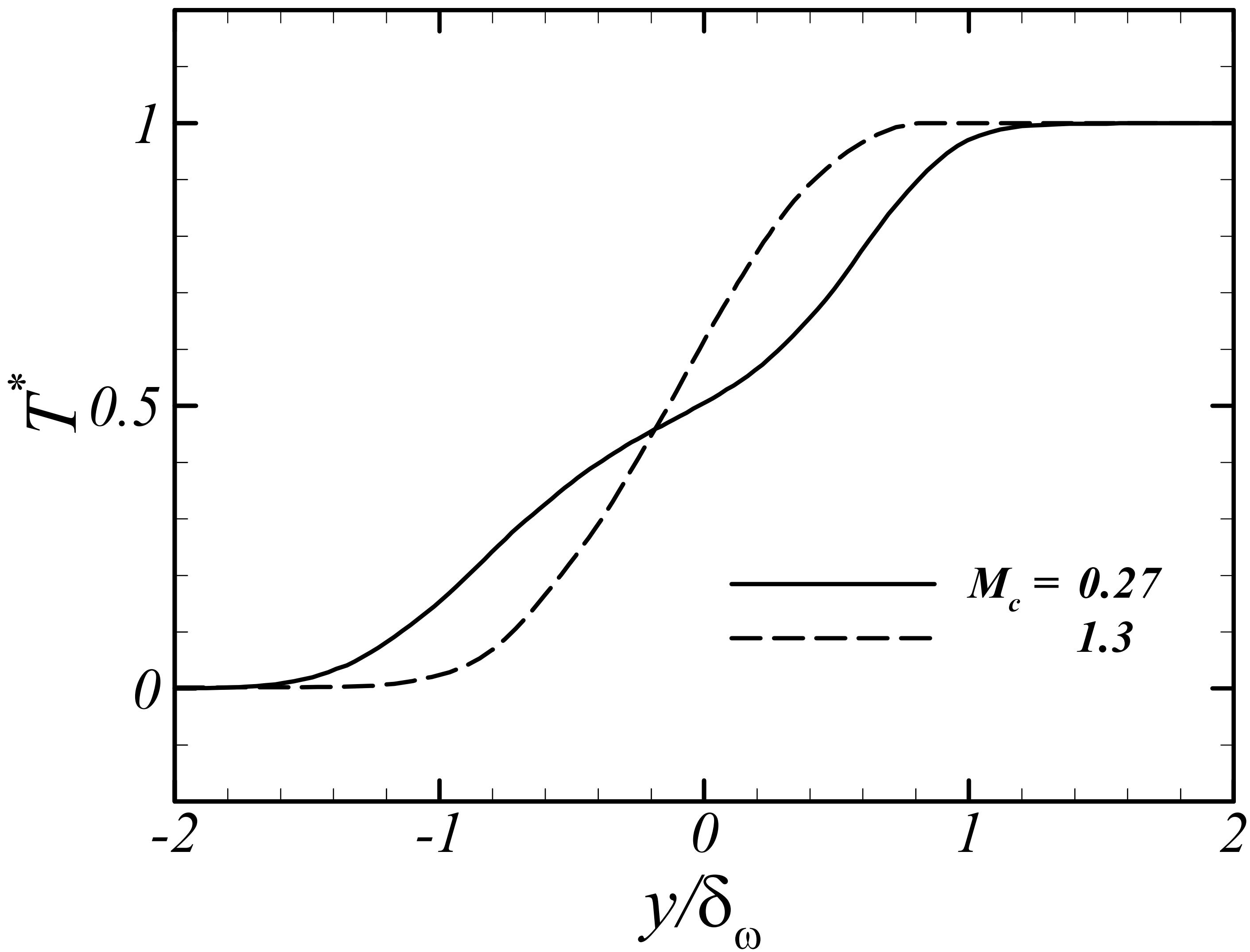
$M_C = 0.27$



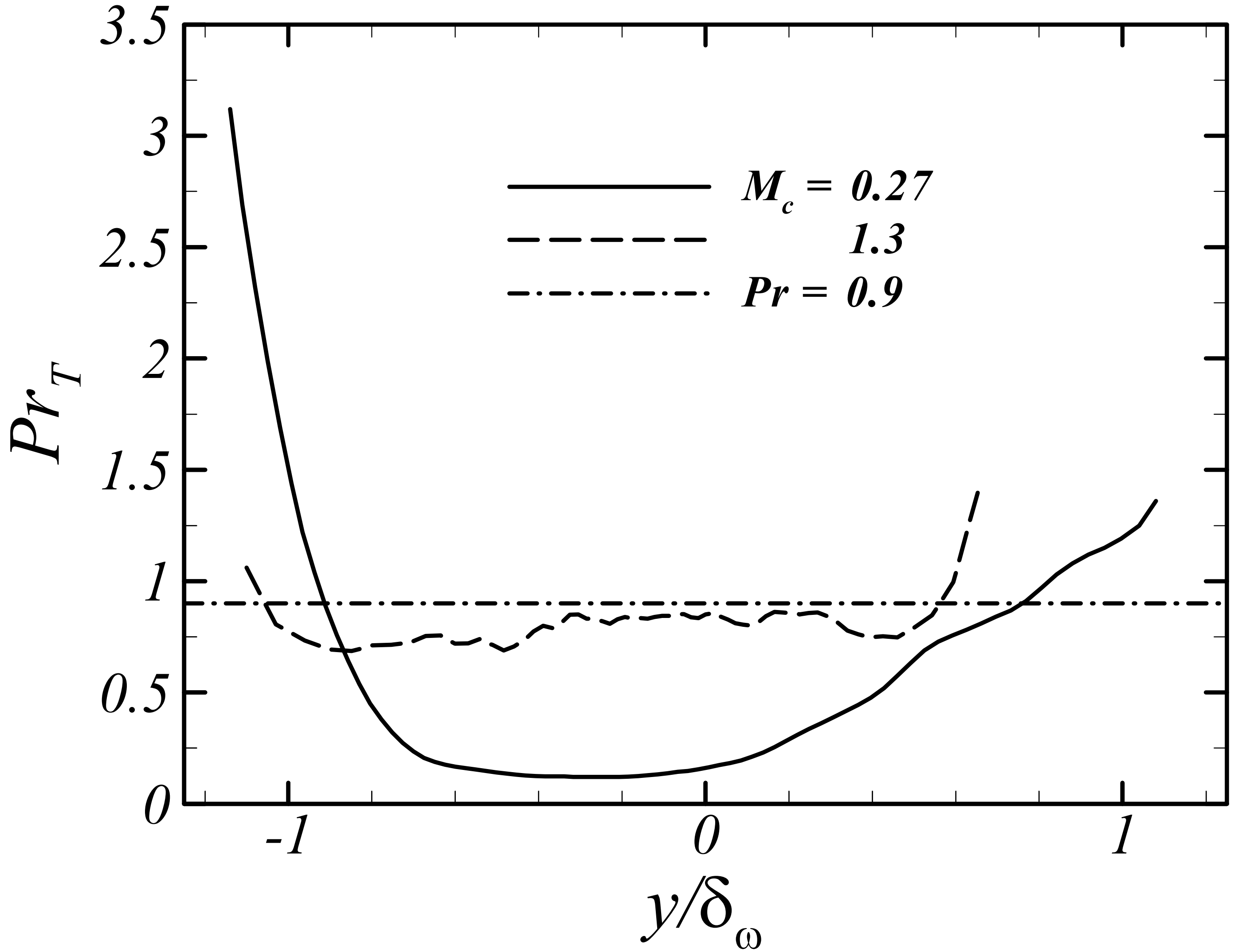


$M_C = 1.3$

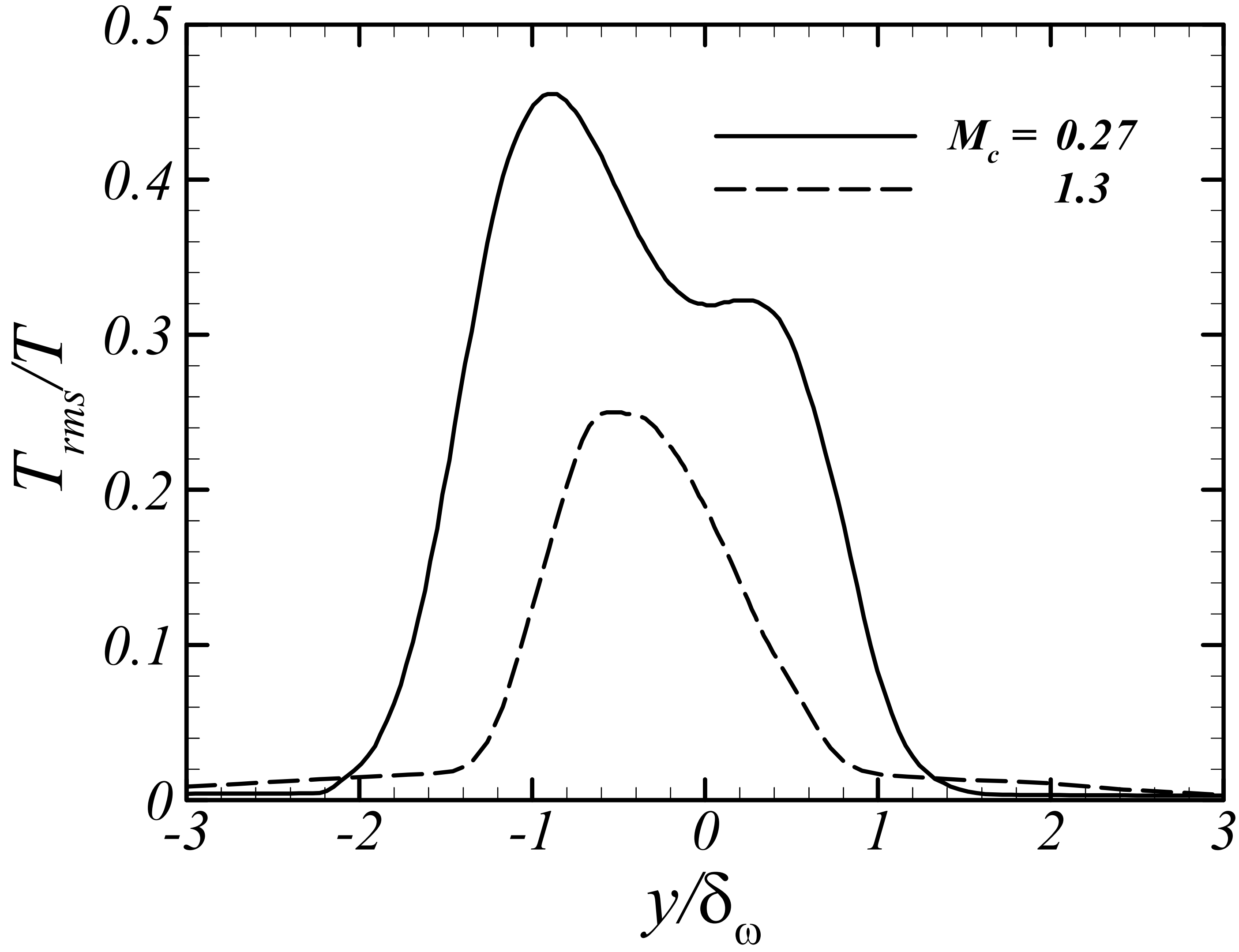
SELF-SIMILAR TEMPERATURE PROFILES



SELF-SIMILAR TURBULENT PRANDTL NUMBER PROFILES



SELF-SIMILAR TEMPERATURE INTENSITY PROFILES



CONCLUSIONS

- MISSILE EXHAUST PLUME FLOWFIELD AND SIGNATURE PREDICTION IS A VERY COMPLEX PROBLEM

- AN ADVANCED TURBULENCE AND COMBUSTION MODELING FRAMEWORK IS REQUIRED TO MAKE ACCURATE PREDICTIONS

- ONGOING RESEARCH AT CRAFT TECH FOCUSED ON IMPROVING PREDICTIVE CAPABILITIES FOR:
  - HIGH SPEED TURBULENT TRANSITION
  - ROTATING TURBULENCE AND ANISOTROPY
  - SCALAR FLUCTUATIONS
  - TURBULENT FLAME EXTINCTION
  - TURBULENT PARTICULATE DISPERSION