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TURBULENCE MODELS FOR GAS TURBINE COMBUSTORS

N95- 27888

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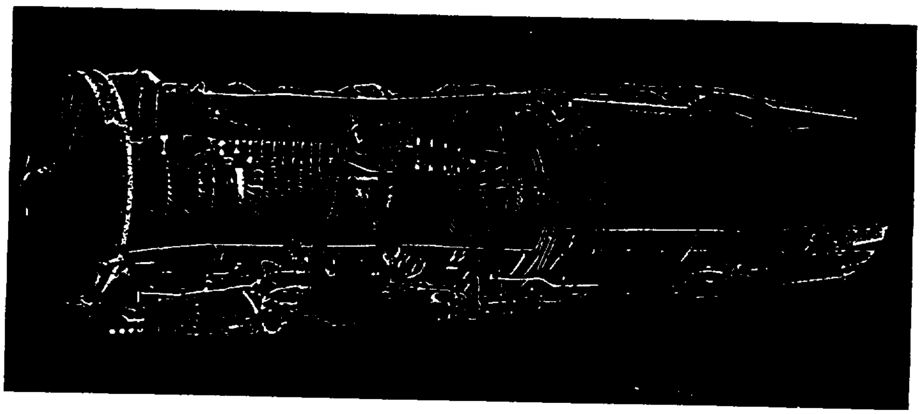
F100-PW-200 TURBOFAN ENGINE



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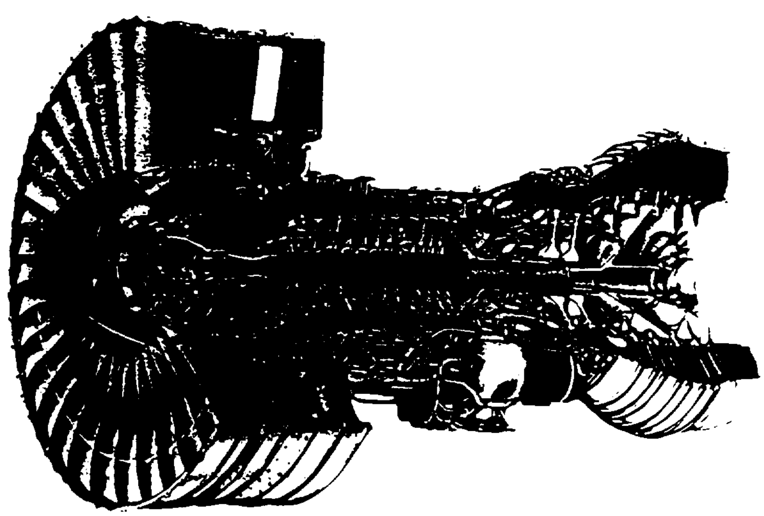

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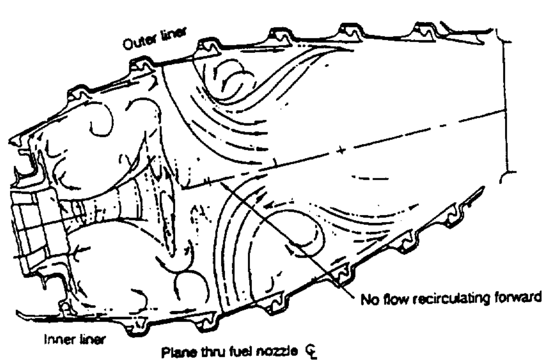
CONTENTS

- Gas Turbine Combustor Flow Physics
- Turbulence Model Investigations
- Turbulent Combustion Modeling
- Present Status and Future Needs

GT COMBUSTOR FLOW PHYSICS

- Key issue is flame stabilization by means of recirculating flow of hot gases and chemically-active species to ensure continuous ignition of fresh reactants.
- Three main mechanisms: 1) axial swirling air jet associated with each fuel introduction; 2) sudden expansion of axial swirling jets; 3) blockage due to radial air jets downstream of fuel sources.

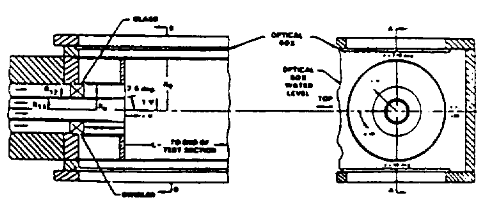


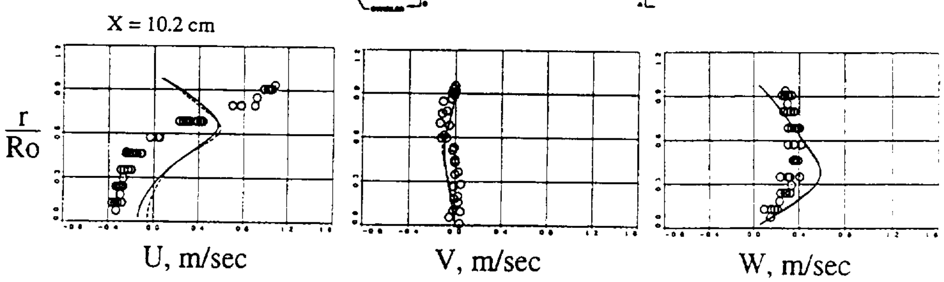
TURBULENCE MODELS SURVEYED

- Following models or modifications have been tested at P&W / UTRC using RANS solvers on building block flows:
  1. low-Re models (complex ducts);
  2. RSTM or SMC (complex ducts, swirling and non-swirling dump combustor);
  3. RNG (pipe, backstep, 180 deg duct);
  4. two-layer near-wall model (internal flows, heat transfer);
  5. realizable algebraic stress model (swirling dump combustor);
  6. compressible turbulence (shear layers, compression corner)
  7. steady vs. unsteady-state solver (bluff-body, compression corner)
- Major difficulty occurs with swirling flows, and failure to predict downstream velocity components.

SWIRLING FLOWS

- Benchmark-quality data set provided by Johnson-Roback co-annular combustor with swirl:

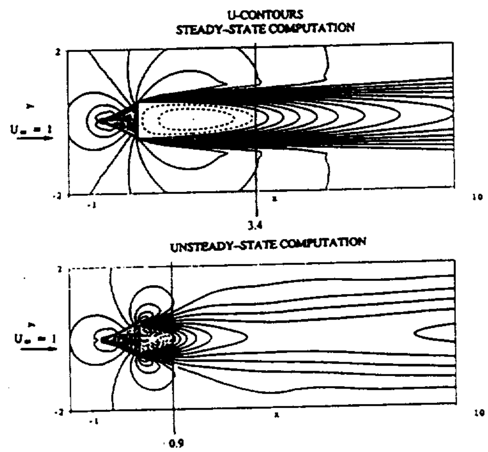




- Poor agreement of CFD and data highlights need for improved upstream BC specification (swirler geometry), 3-D, unsteady analysis. Even SMC models fail to reproduce downstream velocity profiles.

UNSTEADINESS AND FLOW FIELD RESOLUTION

- **RANS** solvers can predict flow coherence (vortex shedding) when run in an unsteady mode with small Δt.
- Same flow field computed in steady-state sense gives completely unusable results.
- Example: V-gutter flow, computed by Durbin (1994):

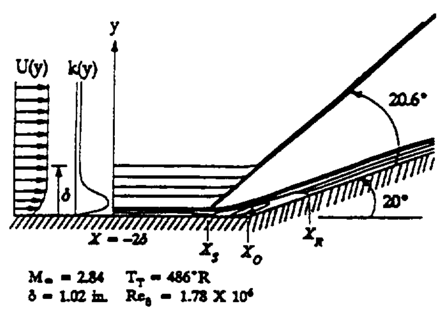


Ratio of characteristic frequences (estimated)

$$\frac{f_T}{f_o} \approx 225$$

UNSTEADINESS AND FLOW FIELD RESOLUTION

- **RANS** solvers cannot predict flow oscillations at frequencies near characteristic turbulence frequency.
- **Example:** Unsteady comp. corner flow of Dolling and Or (1983):



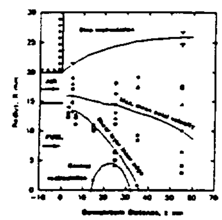
Frequency ratio:

$$\frac{f_T}{f_o} \approx 7.7$$

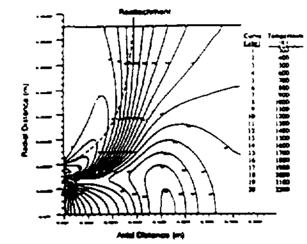
- Separation bubble oscillations (at resonant frequency) not resolved by RANS solver.
- Limitations of steady-state and unsteady-state RANS solvers set by flow characteristic time scales.
  True time-accurate solvers (LES, DNS) needed for prediction of all relevant phenomena

TURBULENT COMBUSTION MODELING

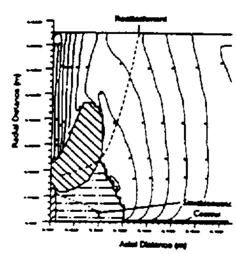
- Eddy Dissipation Concept Model, together with reaction exclusion regions, capable of prediction gross flow features at near LBO conditions (Sturgess et al., 94-GT-433)



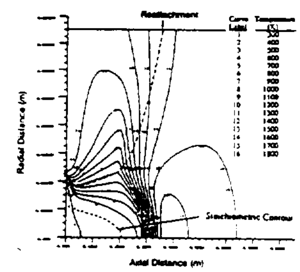
Near-field flow features



EBU-model Temperature field



Reaction exclusion regions



EDC-model Temperature field

- EDC model, however, fails to predict flame attachment at rich conditions

TURBULENT COMBUSTION MODELING

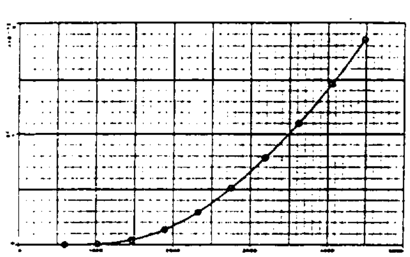
- Assumed-Pdf method of Girimaji (LaRC Workshop, 1991) used with non-equilibrium kinetics model.

$$\frac{K_{f\,\mathrm{turb}}}{K_{f\,\mathrm{Lam}}} = \frac{\int_a^b k_f(T)\ P(T)\ dT}{k_f\left(\tilde{T}\right)}$$

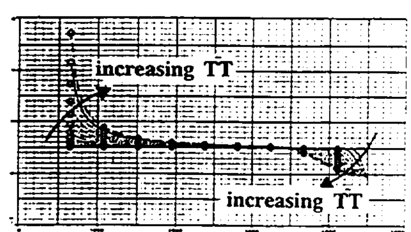
$$T_{min} = \max\left(\tilde{T} - \phi\ \sqrt{\widetilde{T''T''}}\ ,\ T_{low}\right)$$

$$T_{max} = \min\left(\tilde{T} + \phi\ \sqrt{\widetilde{T''T''}}\ ,\ T_{high}\right)$$

K_F



Temp, °R →

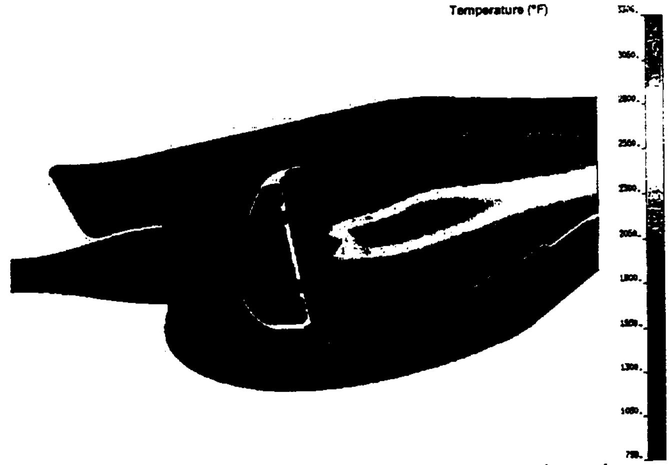


Temp, °R →

- **Example:** $N + O_2 \leftrightarrows NO + O$ in extended Zeldovich model
- Results dependent on T_{Low}, T_{High}, ϕ, modeling of $\widetilde{hh}$ transport equation, etc.
- More testing needed

PRESENT STATUS OF COMBUSTOR MODELING

- Corsair (Ryder, P&W) unstructured, unsteady flow solver

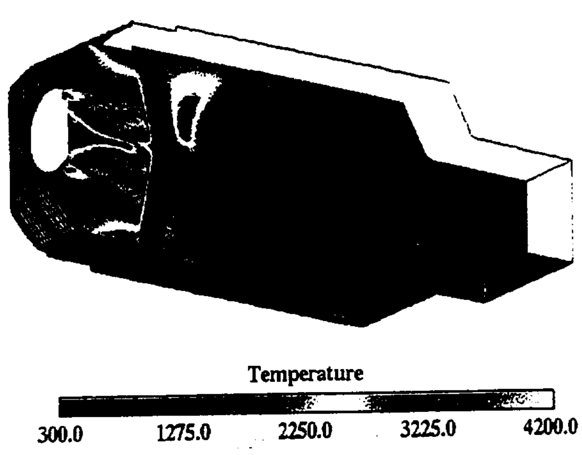


- **Example:** Time-dependent combustor flow using engineering boundary conditions, compressor exit to turbine inlet

- Code currently includes standard k-ε and EBU combustion model. Additional capabilities being added under "Subsonic Emissions and Combustor Design Code" program with NASA LeRC.

PRESENT STATUS OF COMBUSTOR MODELING

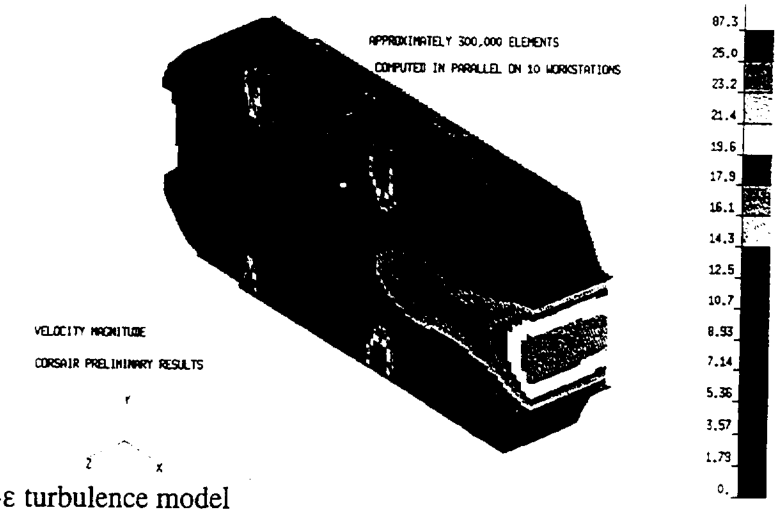
- **Example:** Structured flow solver solution of Task 200 LBO Research Combustor:



- k-ε turbulence model
- EBU combustion model for propane fuel
- 285,000 elements

PRESENT STATUS OF COMBUSTOR MODELING

- **Example:** Unstructured flow solver solution of Task 200 LBO Research Combustor:

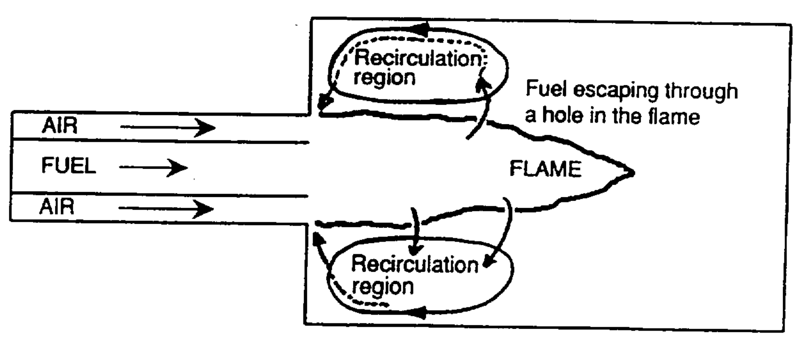


- k-ε turbulence model
- EBU combustion model for propane fuel
- Approx. 300,000 elements

TURBULENCE RESEARCH NEEDS

- **Modelling:** Applications / validations of currently available combustion models (β-pdf, Monte Carlo pdf, laminar flamelet) to complex combustor geometry with jet fuel kinetics.

- **Flow Physics:** Accurate numerical description of mechanisms responsible for flame holding, local extinction (LES, DNS); contrast cold flows with heat release flows.



Entrainment of unburned fuel
in the recirculation region