



# Numerical Simulation of Turbulent Combustion Using the Turbulent Flamelet Model

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# INTRODUCTION

part1.1

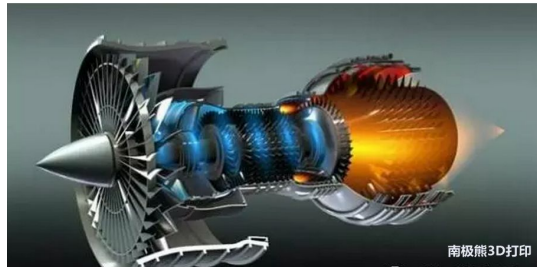
part1.2

part1.3

part1.4

# Background

Turbulent combustion is encountered in most practical combustion system such as rocket, ICE, and aircraft engine.



Meaningful to practical systems:

- (a) Improve efficiency, meet demanding standards[1].
- (b) Reduce pollution, environment friendly.

# Research aspects

Why is numerical simulation adopted?

- (a) Analytical techniques are difficult to handle.
- (b) Experiments are too expensive to be widely used.

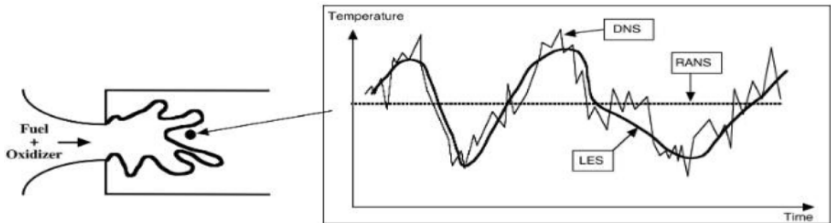
What are the key points in numerical practice?

- Interaction between turbulence and combustion.
- Proper flame model.

# Numerical simulation of flowfield

Based on CFD, there're 3 possible approaches:

- (a) Direct Numerical Simulation(DNS)
  - Precise, but costly(Tremendous memory and CPU).
- (b) Large Eddy Simulation(LES)
  - Compromise between accuracy and computational cost.
- (c) Reynolds Averaged Navier-Stokes(RANS)
  - Inaccurate for combustion phenomenon.



# Numerical simulation of flame

Although based on LES, traditional flame models are inadequate:

- Distribution of flame properties are manually assumed.
- Parameter tuning may be unphysical.

These drawbacks are overcome by the turbulent flamelet model to be introduced:

- Designed especially for LES, with fewer approximations.
- Relations are provided through scaling law, which is based on DNS database[2].

# TURBULENT FLAMELET MODEL

part2.1

part2.2

part2.3

part2.4

# Theory

Original G.E. in the context of LES:

$$\frac{\partial \bar{\rho} \tilde{Z}}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{Z} \tilde{\mathbf{u}}) = \nabla \cdot [\bar{\rho} (D + D_T) \nabla \tilde{Z}] \quad (1)$$

$$\frac{\partial \bar{\rho} \tilde{Y}_i}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{Y}_i \tilde{\mathbf{u}}) = \nabla \cdot [\bar{\rho} (D + D_T) \nabla \tilde{Y}_i] + \bar{\omega}_i \quad (2)$$

After coordinate transformation  $(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, t) \rightarrow (Z, Z_2, Z_3, \tau)$ :

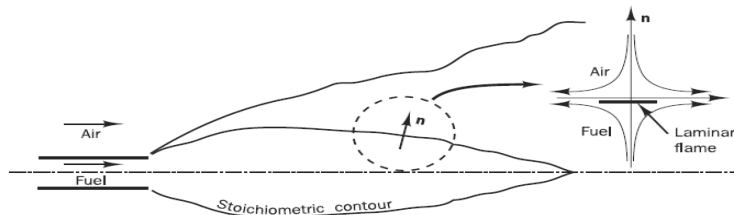
$$\begin{aligned} \bar{\rho} \frac{\partial \tilde{Y}_i}{\partial \tau} + \bar{\rho} \left( \tilde{\mathbf{u}} \cdot \nabla_{\perp} \tilde{Y}_i + \frac{\partial \tilde{Y}_i}{\partial Z_2} \frac{\partial Z_2}{\partial t} + \frac{\partial \tilde{Y}_i}{\partial Z_3} \frac{\partial Z_3}{\partial t} \right) &= \frac{\bar{\rho} \chi}{2Le_T} \frac{\partial^2 \tilde{Y}_i}{\partial^2 \tilde{Z}} \\ + \frac{\partial \tilde{Y}_i}{\partial \tilde{Z}} \nabla \cdot \left[ \bar{\rho} (\mathcal{D}_{T,i} - \mathcal{D}_T) \vec{n} \cdot \frac{\partial \tilde{Z}}{\partial \vec{n}} \right] &+ \nabla \cdot (\bar{\rho} \mathcal{D}_{T,i} \nabla_{\perp} \tilde{Y}_i) + \bar{\omega}_i \end{aligned} \quad (3)$$



# Laminar Flamelet assumption

Locally, the characteristic timescale of chemical reaction is much smaller than that of flow ( $t_c \ll t_f$ ).

Thus, local flame structure can be described by the diffusion flame under counterflow configuration.

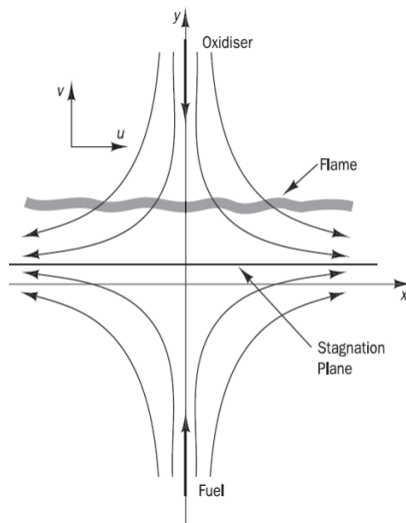


Each micro flamelet can be described by  $Z$  and  $\chi$ :

- $Z$  describes chemical reaction.
- $\chi$  indicates turbulence stretching effect.

Thus, a database can be pre-computed for later looking-up.

# Turbulent Flamelet



Unlike the laminar flamelet introduced above, G.E. of the counterflow flame is slightly modified by our turbulent flamelet model from

$$\rho \frac{DY_i}{Dt} = \mathcal{D}_i \frac{\partial^2 Y_i}{\partial^2 x} + \omega_i(T, \vec{Y}) \quad (4)$$

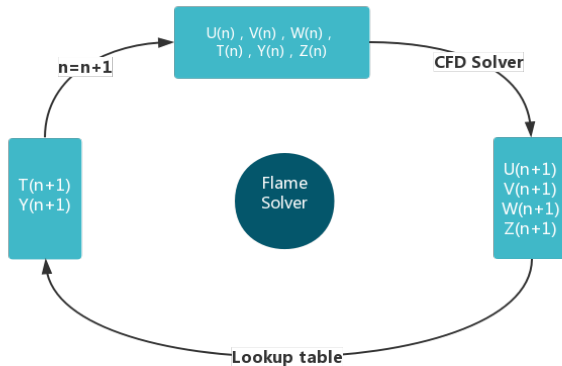
to

$$\bar{\rho} \frac{D\tilde{Y}_i}{Dt} = \mathcal{D}_i \frac{\partial^2 \tilde{Y}_i}{\partial^2 x} + \tilde{\omega}_i(\tilde{T}, \tilde{\vec{Y}}) \quad (5)$$

The two equations share similar form, but have totally different meanings.

# Solution procedure

Based on the filtered turbulent flamelet database generated in the way described above, the full solution procedure that incorporates a CFD solver can be described as follows:



# NUMERICAL RESULTS

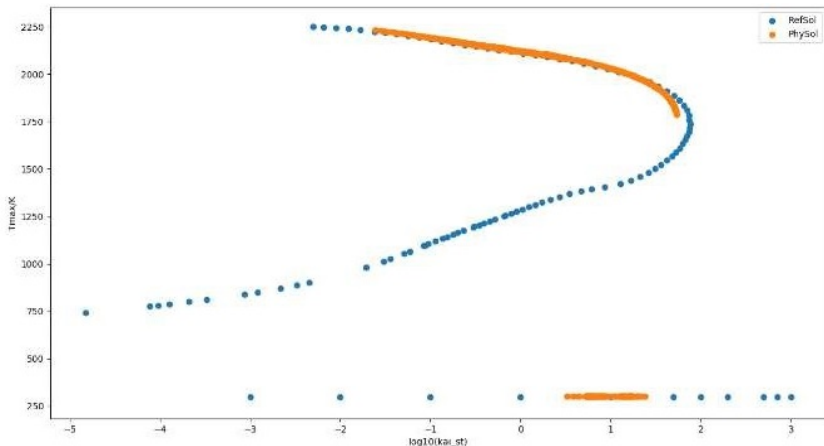
part3.1

part3.2

# Comparison of “S” curve

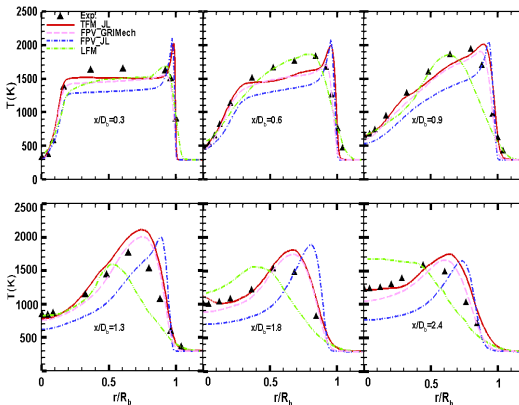
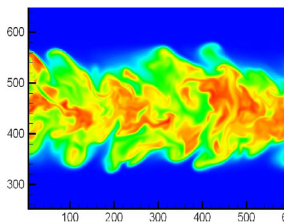
The  $T_{\max}$  plot:

- One of the most convincing testing cases.
- Difference and transition position are clearly revealed[3].



# Standard case

Comparison between experimental data, which is widely used as benchmark[4].



# Reference

- [1] Charles David Pierce and Parviz Moin. “Progress-variable approach for large-eddy simulation of turbulent combustion”. Thesis. 2001 (cit. on p. 3).
- [2] Wang Lipo. “Analysis of the filtered non-premixed turbulent flame”. In: Combustion and Flame 175 (2017), pp. 259–269 (cit. on p. 6).
- [3] Joseph F Grcar. “The Twopnt program for boundary value problems”. In: Sandia National Laboratories Report SAND91-8230 (1992) (cit. on p. 13).
- [4] P. E. Dimotakis. “The mixing transition in turbulent flows”. In: Journal of Fluid Mechanics 409 (2000), pp. 69–98. ISSN: 0022-1120. DOI: 10.1017/s0022112099007946 (cit. on p. 14).