Numerical Simulation of Turbulent Combustion

Using the Turbulent Flamelet Model

CNF, Atlanta 2019.

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INTRODUCTION

part1.1

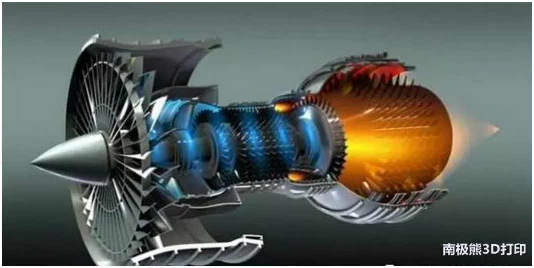
part1.2

part1.3

part1.4

Backgound

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



Meaningful to practical systems:

(a) Improve efficiency, meet demanding standards.
(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.

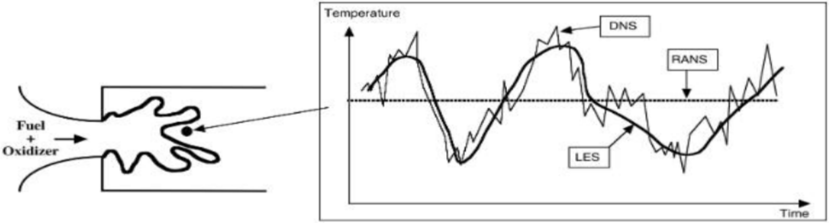
Numerical simulation of flowfield

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 mannually assumed.
- Parameter tuning may be unphysical.

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

- Designed especially for LES, with tfewer approximation.
- Relations are provided through scaling law, which is based on DNS database.

TURBULENT FLAMELET MODEL

Theory

Original G.E. in the context of LES:

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

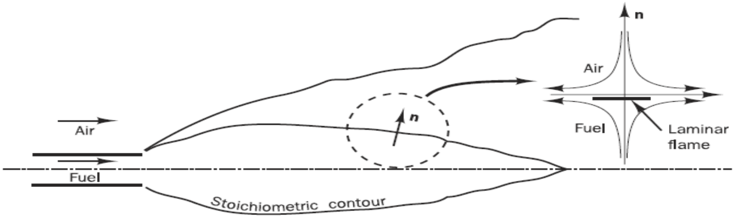
$$\frac{\partial \bar{\rho}\tilde{\mathrm{Y}}_\mathrm{i}}{\partial \mathrm{t}} + \nabla \cdot (\bar{\rho}\tilde{\mathrm{Y}}_\mathrm{i}\tilde{\vec{\mathrm{u}}}) = \nabla \cdot [\bar{\rho}(\mathrm{D} + \mathrm{D_T})\nabla \tilde{\mathrm{Y}}_\mathrm{i}] + \overline{\omega_\mathrm{i}} \tag{2}$$

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

$$\begin{aligned} \bar{\rho}\frac{\partial \tilde{\mathrm{Y}}_\mathrm{i}}{\partial \tau} + \bar{\rho}\left(\tilde{\vec{\mathrm{u}}} \cdot \nabla_\perp \tilde{\mathrm{Y}}_\mathrm{i} + \frac{\partial \tilde{\mathrm{Y}}_\mathrm{i}}{\partial \mathrm{Z}_2}\frac{\partial \mathrm{Z}_2}{\partial \mathrm{t}} + \frac{\partial \tilde{\mathrm{Y}}_\mathrm{i}}{\partial \mathrm{Z}_3}\frac{\partial \mathrm{Z}_3}{\partial \mathrm{t}}\right) &= \frac{\bar{\rho}\chi}{2\mathrm{Le_T}}\frac{\partial^2 \tilde{\mathrm{Y}}_\mathrm{i}}{\partial^2 \tilde{\mathrm{Z}}} \\ + \frac{\partial \tilde{\mathrm{Y}}_\mathrm{i}}{\partial \tilde{\mathrm{Z}}}\nabla \cdot \left[\bar{\rho}(\mathcal{D}_{\mathrm{T,i}} - \mathcal{D}_\mathrm{T})\vec{\mathrm{n}} \cdot \frac{\partial \tilde{\mathrm{Z}}}{\partial \vec{\mathrm{n}}}\right] &+ \nabla \cdot (\bar{\rho}\mathcal{D}_{\mathrm{T,i}}\nabla_\perp \tilde{\mathrm{Y}}_\mathrm{i}) + \overline{\omega_\mathrm{i}} \end{aligned} \tag{3}$$

Laminar Flamelet assumption

Locally, the characteristic timescale of chemical reaction is much smaller that that of flow($t_c \ll t_f$).
Thus, local flame structure can be described by the difffusion flame under counterflow configuration.

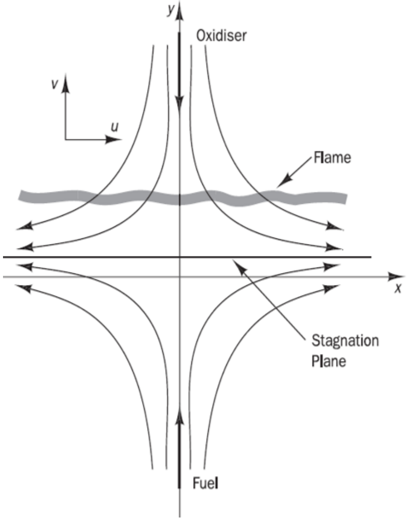


Each micro flamelet can be described by Z and χ:

- Z describes chemical reaction.
- χ 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 turbulet flamelet model from

$$\rho \frac{\mathrm{DY_i}}{\mathrm{Dt}} = \mathcal{D}_\mathrm{i} \frac{\partial^2 \mathrm{Y_i}}{\partial^2 \mathrm{x}} + \omega_\mathrm{i}(\mathrm{T}, \vec{\mathrm{Y}}) \tag{4}$$

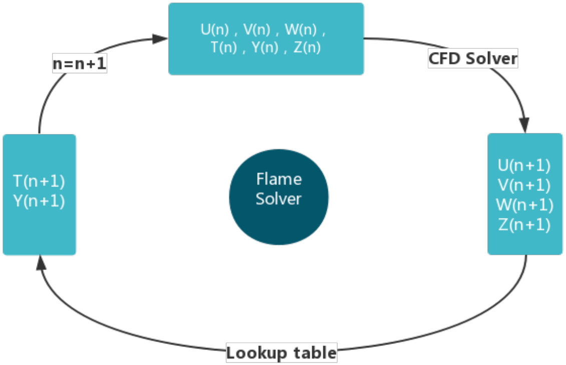
to

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

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

Solution procedure

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

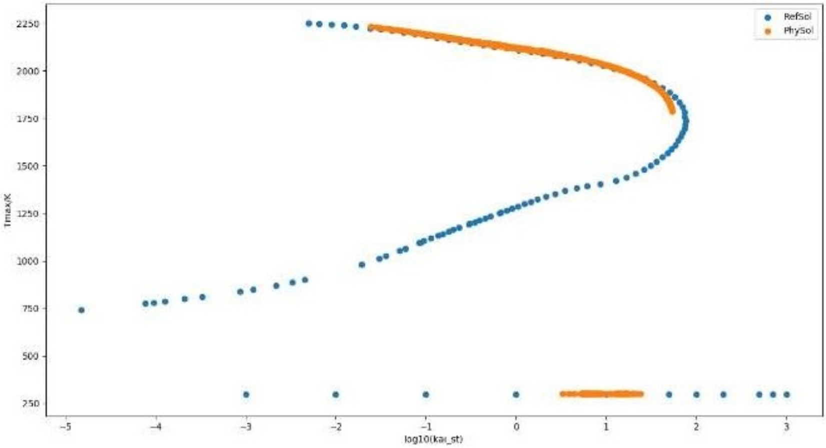


NUMERICAL RESULTS

Comparsion of “S” curve

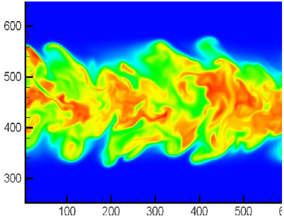
The T_{max} plot:

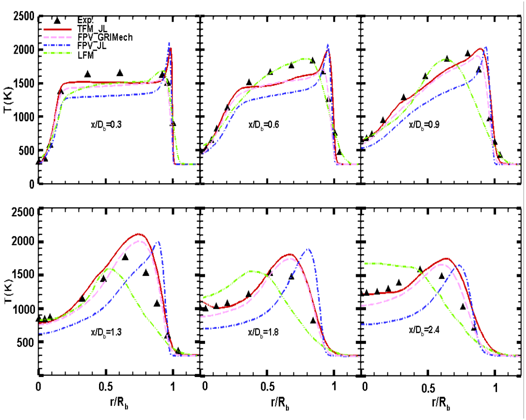
- One of the most convincing testing cases.
- Difference and transition position are clearly revealed!



Standard case

Comparsion between experimental data, which is widely used as benchmark[1].





Reference

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).