10th Triennial International Aircraft Fire and Cabin Safety Research Conference

Transported probability density function modeling of fire extinction

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PURDUE UNIVERSITY

Conclusion

Pool Fires

Introduction

Introduction

Turbulent diffusion combustion

- Buoyancy controlled
- Low strain
- Low velocity fuel

* Video is from https://www.youtube.com/watch?v=vDqBnjpKh1A and https://www.youtube.com/watch?v=OkzOMY31HlU

Objectives of this work

- Has larger size of the flame region
- Used highly simplified chemical mechanisms
- Used reduced order turbulence and combustion models

Models' accuracy

Highly simplified or reduced-order models cannot capture detailed physics

Pool Fires

Use high order model to get accurate prediction of fire extinction limit

Transported PDF modeling of pool fires

Fire Dynamics Simulator (FDS)

FDS (Fire Dynamics Simulator) is a free and open-source software tool provided by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce.

FDS is a large-eddy simulation (LES) code for low-speed flows, emphasizing smoke and heat transport from fires.

Videos is from https://www.youtube.com/watch?v=gq2Xhcsoh-w

Transported PDF model

- PDF represents **Probability Density Function**
- Transported PDF model represents the turbulent reacting flow by using Joint PDFs of fluid properties
- Advantages:
  - Does not assume a particular mode of combustion
  - Chemical reaction terms are in a closed form
  - Turbulent fluctuations of all species can be represented
  - Applicable to RANS and LES

Transported PDF model

A joint pdf transport equation for the velocity and the reactive scalars can be derived *

$$\frac{\partial \bar{\rho} f}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{\rho} u_j f\right) + \frac{\partial}{\partial \psi_\alpha}\left[\bar{\rho} f S_\alpha(\psi)\right] - \frac{\partial}{\partial x_j}\left(\bar{\rho}\Gamma \frac{\partial f}{\partial x_j}\right) = -\frac{\partial}{\partial x_j}\left(\bar{\rho} f u''_j|\psi\right) - \frac{\partial^2}{\partial \psi_\alpha \psi_\beta}\left[f\left(\overline{\rho\Gamma \frac{\partial \phi_\alpha}{\partial x_j}\frac{\partial \phi_\beta}{\partial x_j}|\psi}\right)\right]$$

local change and convection of the probability density function in physical space

source terms due to chemical reaction and it appears in the closed form

spatial flux of the PDF due to residual velocity

molecular mixing in the composition space due to the conditional scalar dissipation

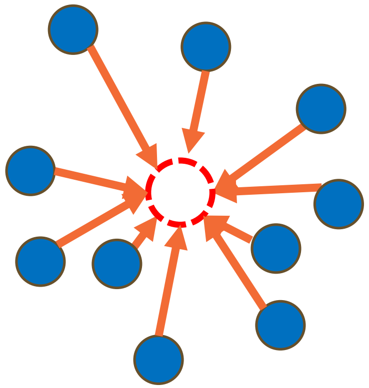
* Pope, S. B. (1985). PDF methods for turbulent reactive flows. Progress in energy and combustion science, 11(2), 119-192.

Mixing models implemented in PDF

Popular models used in this work

- Interaction by Exchange with the Mean (IEM) model
- Modified Curl (MCurl) model
- Euclidean Minimum Spanning Tree (EMST) model

IEM

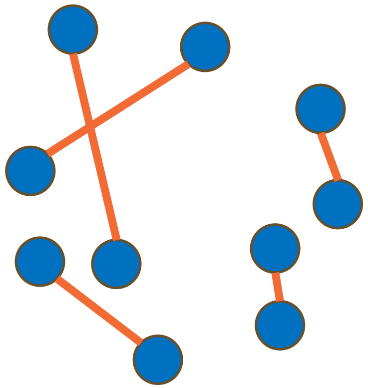


Interaction with the mean

$$\frac{d\phi^{(i)}}{dt} = -\frac{1}{2}\frac{C_\phi}{\tau}\left(\phi^{(i)} - \tilde{\phi}\right)$$

* Villermaux and Devillon, 1972

MCurl



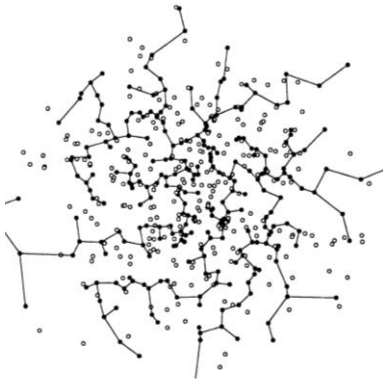
Randomly pairwise mixing

$$\phi^{(i),t+1} = \phi^{(i),t} + h\left(\frac{w^{(i)}\phi^{(i),t} + w^{(j)}\phi^{(j),t}}{w^{(i)} + w^{(j)}} - \phi^{(i),t}\right)$$

$$\phi^{(j),t+1} = \phi^{(j),t} + h\left(\frac{w^{(i)}\phi^{(i),t} + w^{(j)}\phi^{(j),t}}{w^{(i)} + w^{(j)}} - \phi^{(j),t}\right)$$

* Janicka et al., 1979

EMST



Interaction with neighboring particle in composition space

$$\frac{d\phi_\alpha^{(i)}}{dt} = -\frac{1}{w^{(i)}} M_{ij}\phi_\alpha^{(j)}, \quad i = 1, \ldots, N'_p \left(N'_p \le N_p\right),$$

* Subramaniam and Pope, 1998

Mixing parameters implemented in PDF

$$\frac{\partial \bar{\rho} f}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{\rho} u_j f\right) + \frac{\partial}{\partial \psi_\alpha}\left[\bar{\rho} f S_\alpha(\psi)\right] - \frac{\partial}{\partial x_j}\left(\bar{\rho}\Gamma \frac{\partial f}{\partial x_j}\right) =$$

$$-\frac{\partial}{\partial x_j}\left(\bar{\rho} f \overline{u_j''|\psi}\right) - \frac{\partial^2}{\partial \psi_\alpha \psi_\beta}\left[f\left(\overline{\rho\Gamma \frac{\partial \phi_\alpha}{\partial x_j}\frac{\partial \phi_\beta}{\partial x_j}|\psi}\right)\right]$$

With all the unclosed terms modelled, the transport equation for the PDF is solved numerically by using the Monte Carlo particle method.

$$\Omega = \frac{C_\phi\left(\Gamma + \Gamma_t\right)}{2\Delta^2}$$

The effects of the mixing parameter C_ϕ and three different mixing models will be examined.

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* Pope, S. B. (1985). PDF methods for turbulent reactive flows. Progress in energy and combustion science, 11(2), 119-192.

HPDF 01

Suitable to solve problems need to consider detailed chemical reactions

FDS 02

Different molecular diffusivities for different species can be considered

HPDF 02

Has better capability to deal with flame local extinction problems and the study of flame instabilities

Coupled

Take advantages from these two models

FDS 01

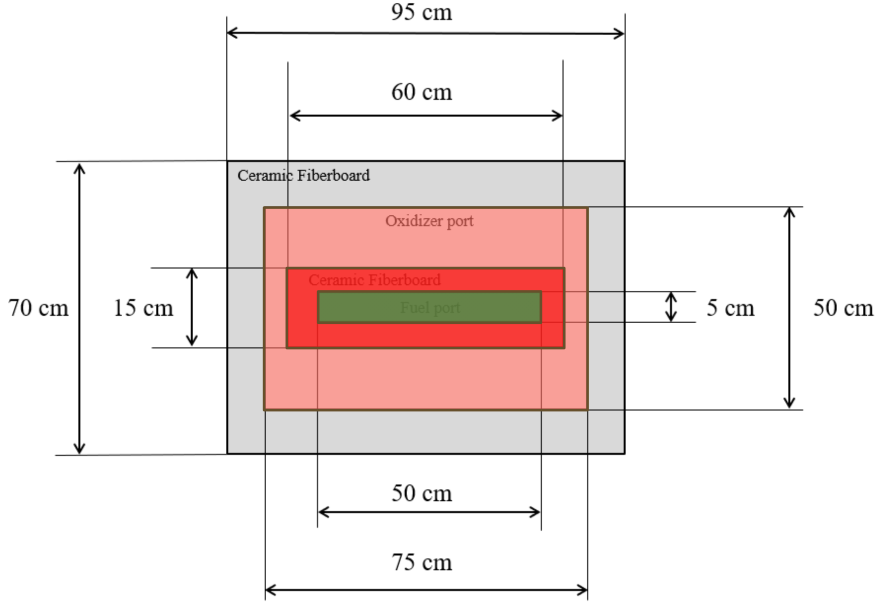
Can provide information about mesh grids, velocity fields, and transport properties for transported PDF model

HPDF 03

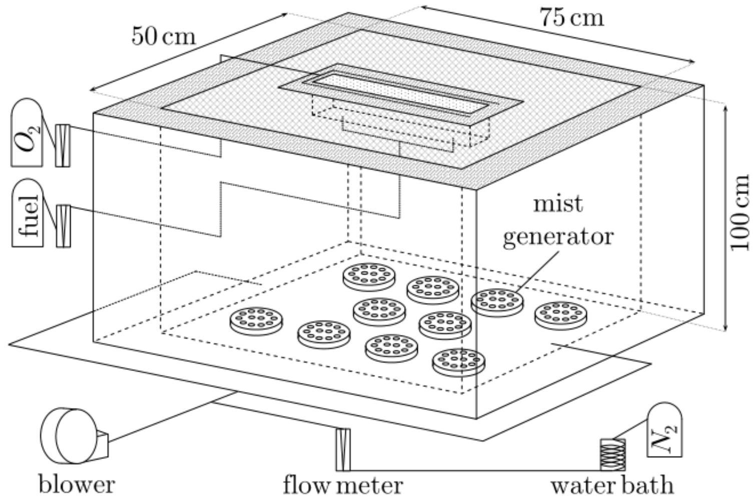
Only equal diffusivity is assumed

UMD line burner

* J.P. White, Measurement and simulation of suppression effects in a buoyant turbulent line fire, Ph.D. thesis, University of Maryland, College Park, 2016.

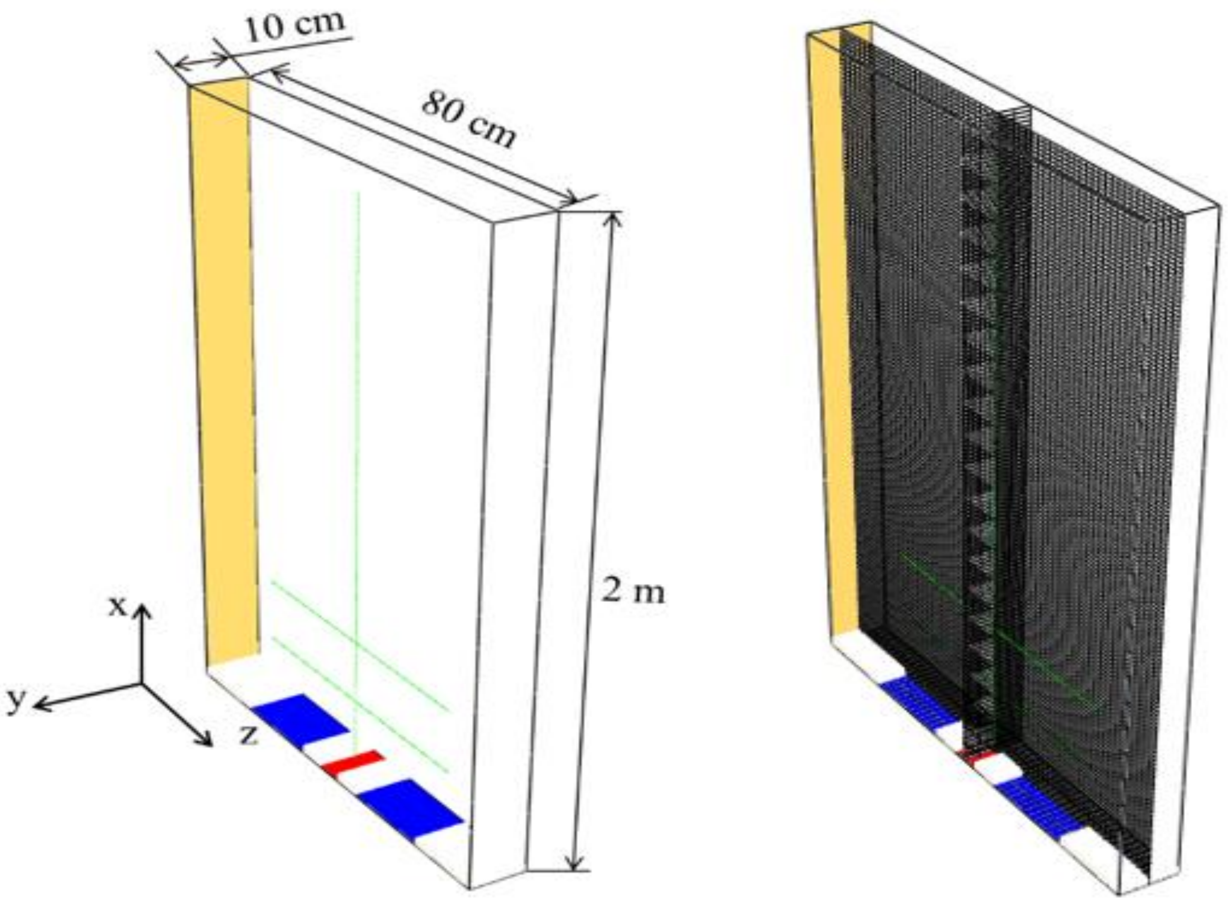


Plane view



Experimental setup

Coupled model simulation setup



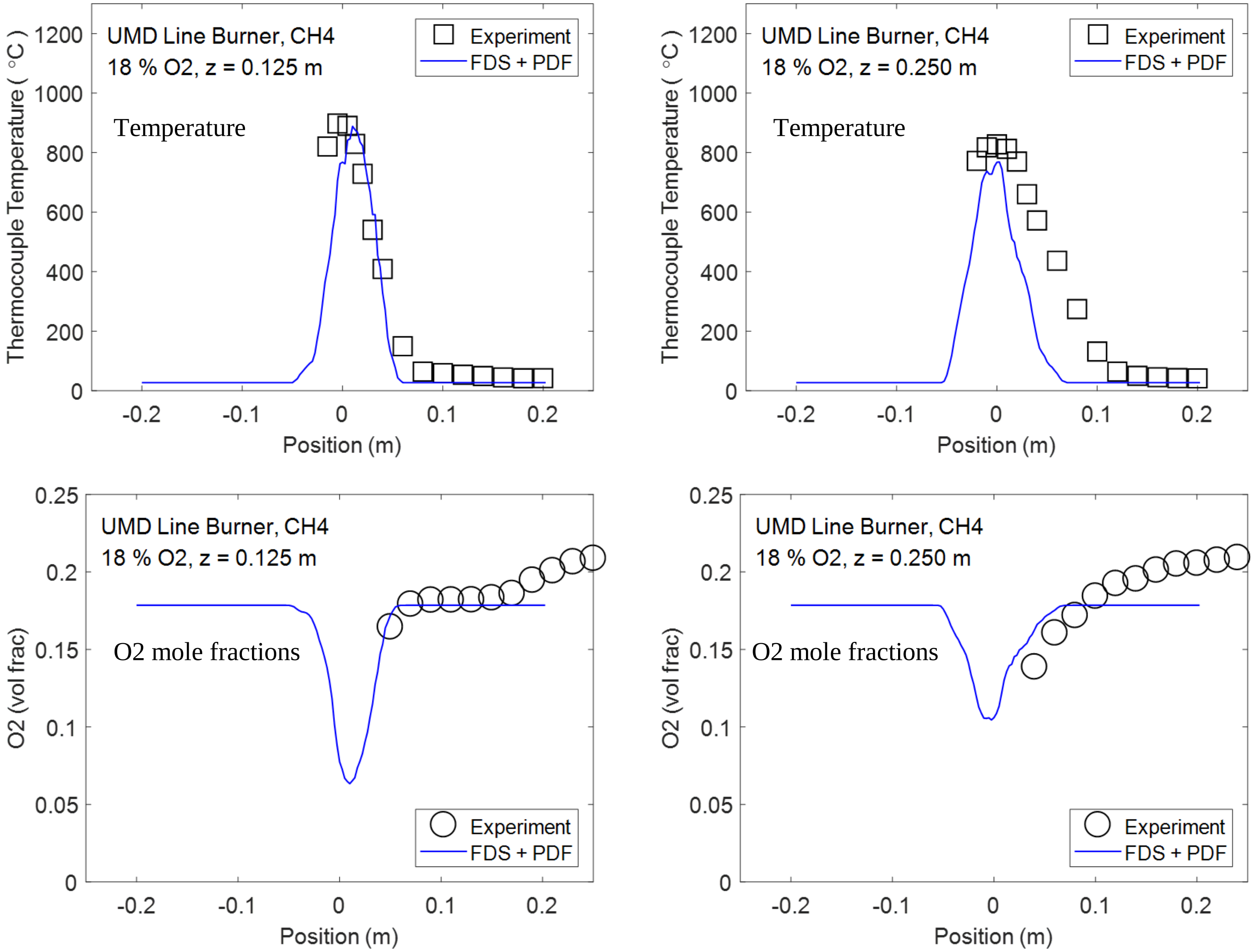
Conclusion

Pool Fires

Introduction

Coupled model simulation results

$C_\phi = 3.0$ with EMST model



* Experimental data get from J. P. White, E. D. Link, A. C. Trouve, P. B. Sunderland, A. W. Marshall, J. A. Sheffel, M. L. Corn, M. B. Colket, M. Chaos, H. Z. Yu, Radiative emissions measurements from a buoyant, turbulent line flame under oxidizer-dilution quenching conditions, Fire Safety Journal 76 (2015) pp. 74-84.

Coupled model simulation results

- White, J. P. (2016). Measurement and simulation of suppression effects in a buoyant turbulent line fire (Doctoral dissertation).

Conclusion

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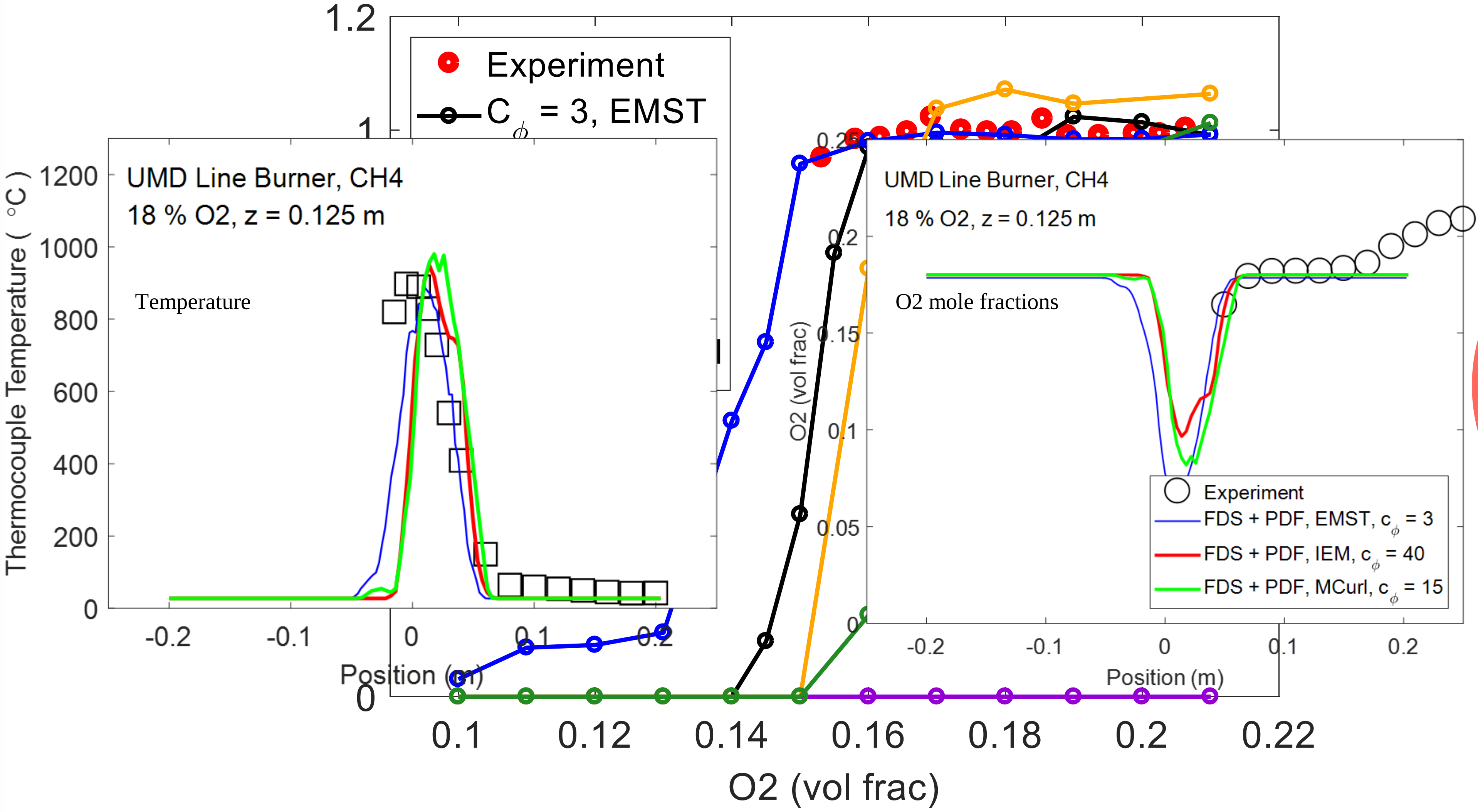
Investigation of fire extinction limits prediction

Investigation of fire extinction limits prediction



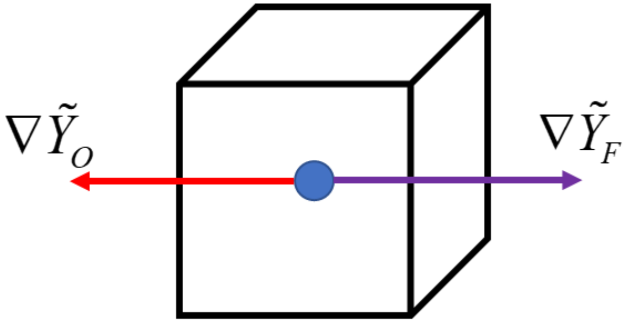
Conclusion

Pool Fires

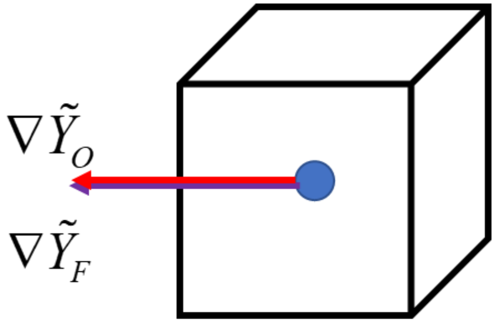
Introduction

C_ϕ

Flame regime identification by using flame index



FI = -1
Non-premixed mixing



FI = +1
Premixed mixing

Mixing Model	C_ϕ can yield burning flames
EMST	3
IEM	40
Modified Curl	15

Partially premixed mixing

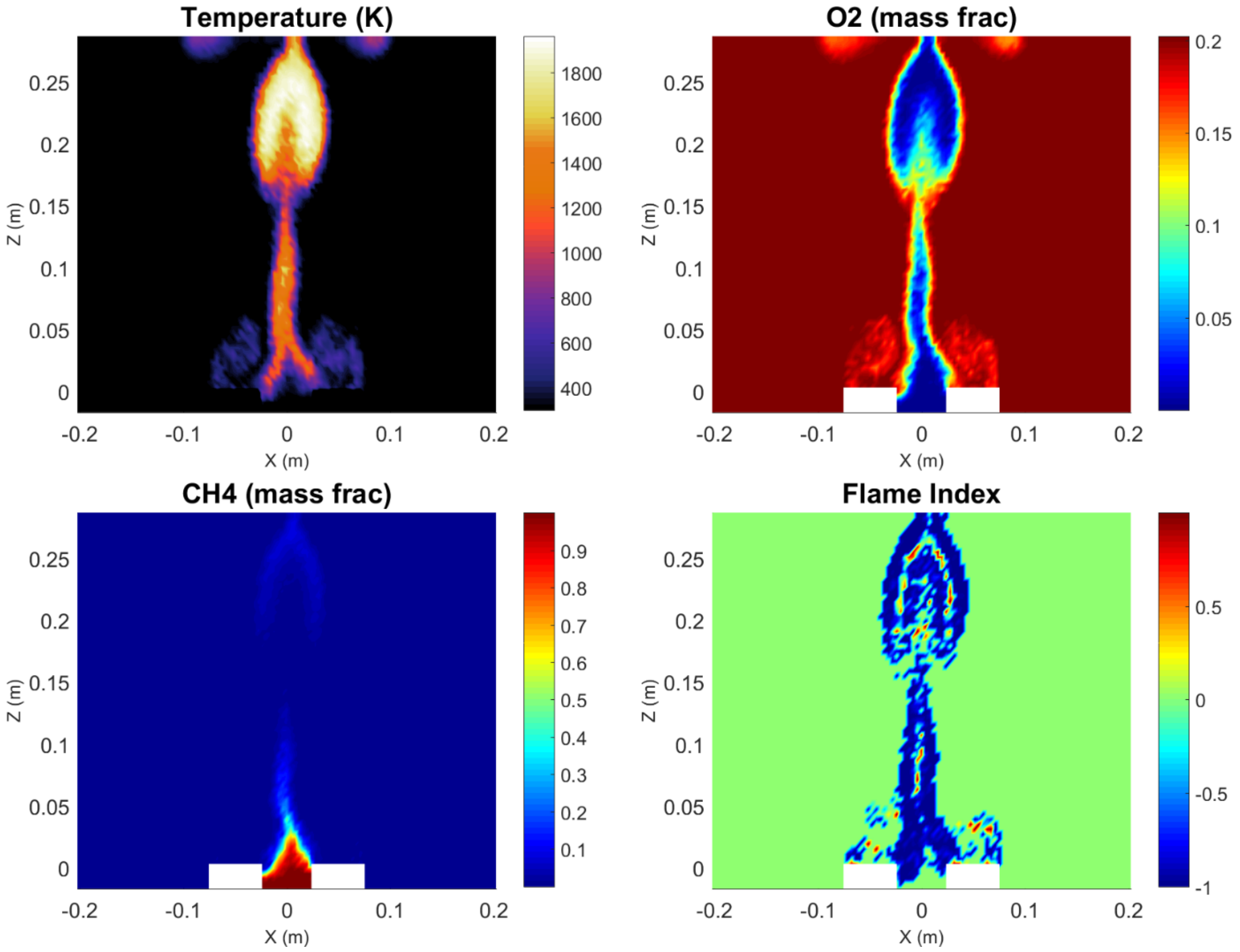
$$FI = \begin{cases} 0 & \left(\left|\tilde{Y}_O\right| < \beta\%(\max\left|\tilde{Y}_O\right|), \left|\tilde{Y}_F\right| < \beta\%(\max\left|\tilde{Y}_F\right|)\right) \\ \dfrac{\nabla \tilde{Y}_O \cdot \tilde{Y}_F}{\left|\tilde{Y}_O\right|\left|\tilde{Y}_F\right|} & \end{cases}$$

Conclusion

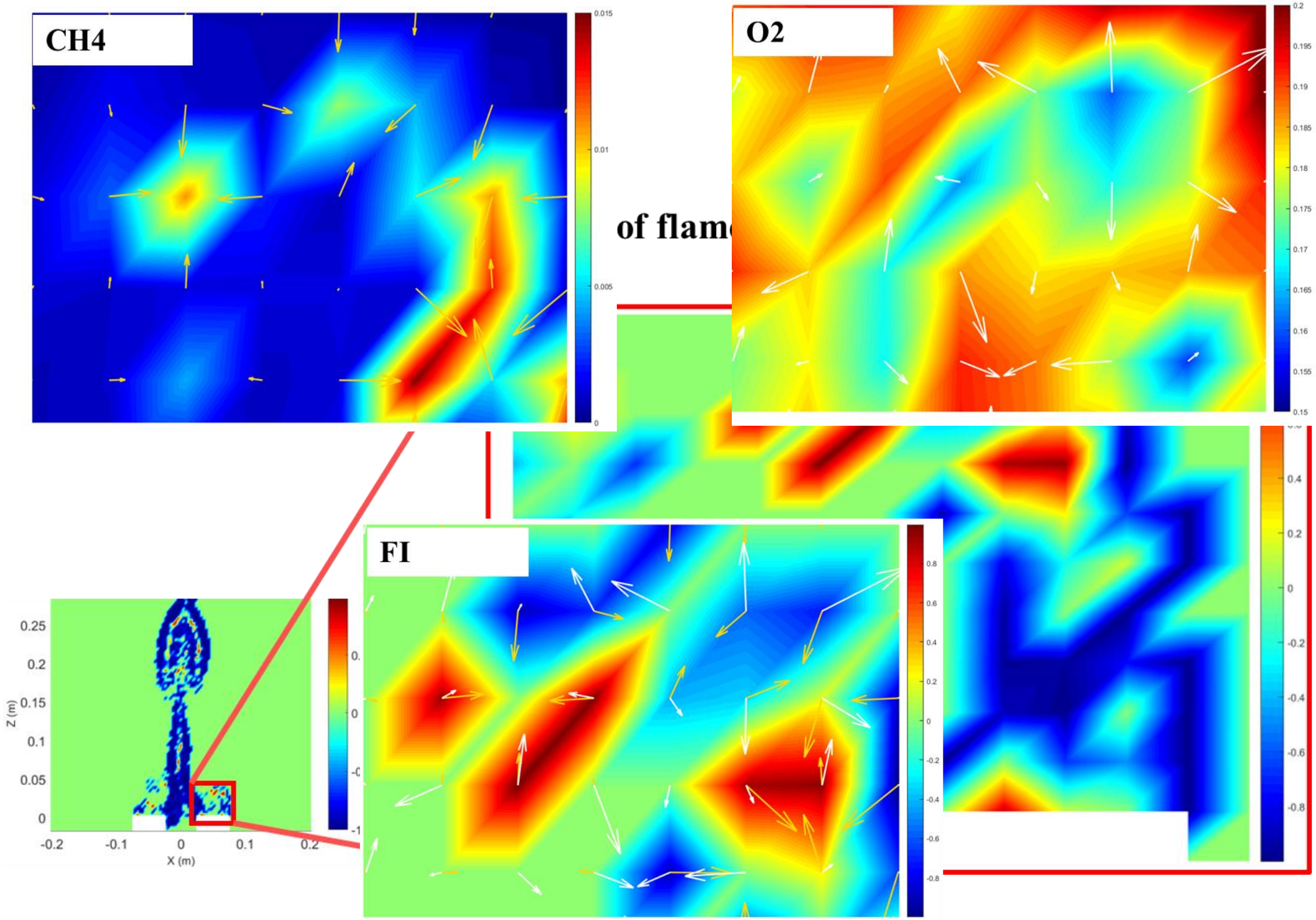
Pool Fires

Introduction

Flame regime identification by using flame index



Flame regime identification by using flame index



Conclusion

Pool Fires

Introduction

Conclusions

Conclusions

Buoyancy-controlled pool fires

- Discovered the method that combines the NIST Fire Dynamics Simulator (FDS) code of LES and our in-house PDF code, HPDF
- The EMST model can yield burning flames without difficulty and perfectly match the measured combustion efficiency
- The IEM model and Modified Curl model need a high value of C_ϕ to yield burning and constantly underpredict the combustion efficiency
- The premixed combustion regimes are enriched in the pool fire's root, which could be the main reason behind the mixing models' performance differences
- Fire extinction limit is very sensitive to the different mixing models and mixing parameters. That suggests the importance of mixing modeling in fire simulations.

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