Effects of fuel Lewis number on wall heat transfer during oblique flame-wall interaction of premixed flames within turbulent boundary layers

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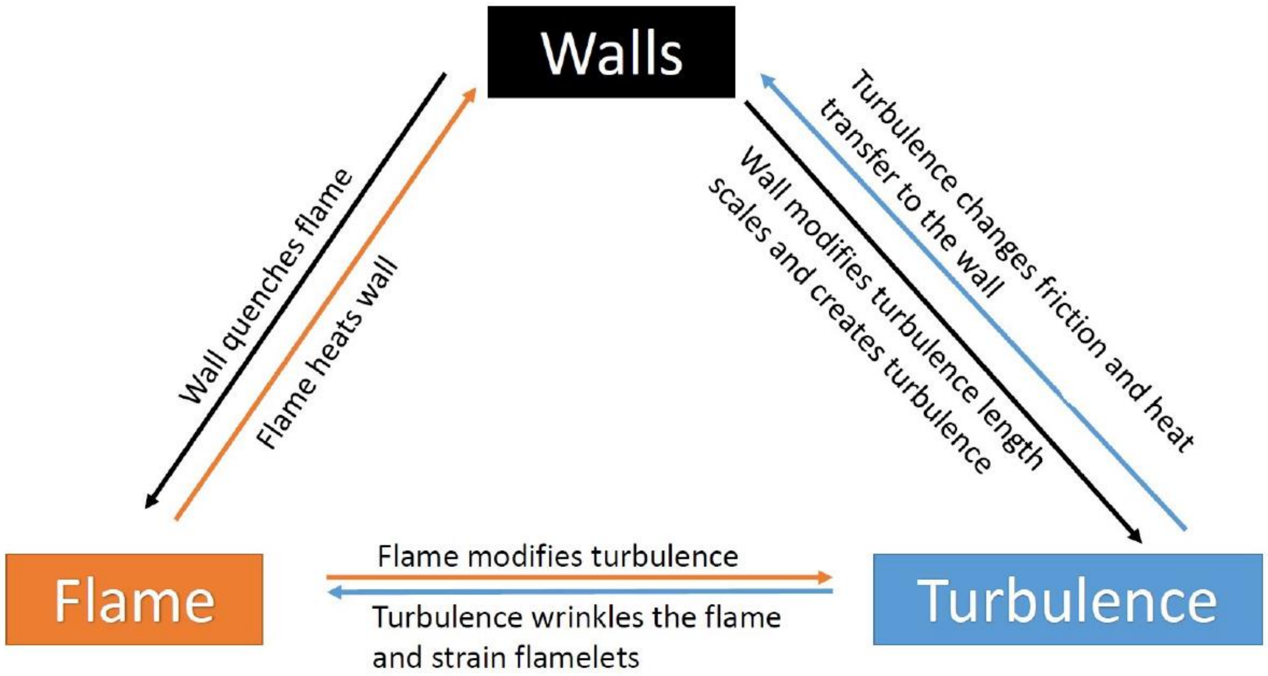
Sanjeev Kumar Ghai*, Umair Ahmed, Nilanjan Chakraborty

School of Engineering, Newcastle University,
Claremont Road, Newcastle Upon Tyne, NE1 7RU, UK
*Email : Sanjeev.Ghai@newcastle.ac.uk

Motivation



- **Flame-wall interaction** (FWI) occurs in many flows of engineering interest (e.g., Spark Ignition (SI) engines and gas turbines), and **modelling** of these events **remains challenging**.

- The **turbulence structure** is altered by the **walls**, and the interaction of flame elements with walls leads to **modifications** of the underlying combustion process.

- Spatial and temporal fluctuations of wall temperature **induce thermal stresses** and strongly affect **combustor lifetimes**.

- FWI is increasingly becoming important as **new combustors** are being made **smaller** to increase energy density and reduce weight (e.g. hybrid engines, micro-combustors).

Objectives

- **Wall heat flux** and **flame quenching** statistics have been analysed using 3D DNS data for the **oblique-wall quenching** of a V-shaped premixed flame in a turbulent channel flow

- To analyse **the thermo-diffusive effects** induced by **non-unity Lewis number** ($Le_F = \alpha_t/D \neq 1$), the simulations have been conducted for three different fuel Lewis numbers ranging from 0.6 to 1.4 (i.e. $\boldsymbol{Le_F = 0.6, 1.0}$ **and** $\boldsymbol{1.4}$)

- To analyse the effects of **near-wall coherent flow structures** and the **flame orientation** on the wall heat flux and flame quenching distance

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Direct Numerical Simulation

- A well-known **three-dimensional compressible** DNS code **SENGA+**[1] is used.
- The code solves conservation equations for mass, momentum, energy and chemical species using **finite difference method**.
- The spatial derivatives are evaluated via a **10th order central difference scheme** for internal points and gradually decreasing to **2nd order** at the non-periodic boundaries.
- A Runge-Kutta (**3rd order explicit**) scheme for time advancement.
- **Single step chemistry** representing the stoichiometric fuel-air mixture is considered for the computational economy.
- The **wall temperature** is set to that of the **non-reacting air-fuel mixture.**

[1]**K. Jenkins, R.S. Cant** *Recent Advances in DNS and LES: Proceedings of the 2nd AFOSR Conference (1999)*

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Wall heat flux and quenching distance

❖ The wall heat transfer and flame quenching in FWI are characterised in terms of **normalised wall heat flux $\boldsymbol{\Phi_w}$** and **Pectlet number *Pe***

$$\Phi_w = |q_w|/[\rho_0 c_{p0} S_L (T_{ad} - T_0)] \text{ and } Pe = y/\delta_Z$$

q_w	wall heat flux	δ_z	Zel'dovich flame thickness
ρ_0	unburned gas density	T_0	unburned gas temperature
c_{p0}	unburned gas specific heat	T_{ad}	adiabatic flame temperature
S_L	unstretched laminar burning velocity	y	wall normal distance

❖ The minimum value of the Peclet number provides the measure of the **flame quenching distance $\boldsymbol{\delta_Q}$** in the following manner

$$Pe_{min} = \delta_Q/\delta_z \mid \boldsymbol{\theta^* = 0.75}$$

Non-dimensional temperature $\theta = (T - T_0)/(T_{ad} - T_0)$

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Lewis Number and Flame Curvature

- The **Lewis number (Le)** is a dimensionless number defined as the **ratio of thermal diffusivity to mass diffusivity**

$$Le = \alpha_t / D = \lambda / \rho C_p D$$

where α_t is the thermal diffusivity and D is the mass diffusivity and λ is the thermal conductivity

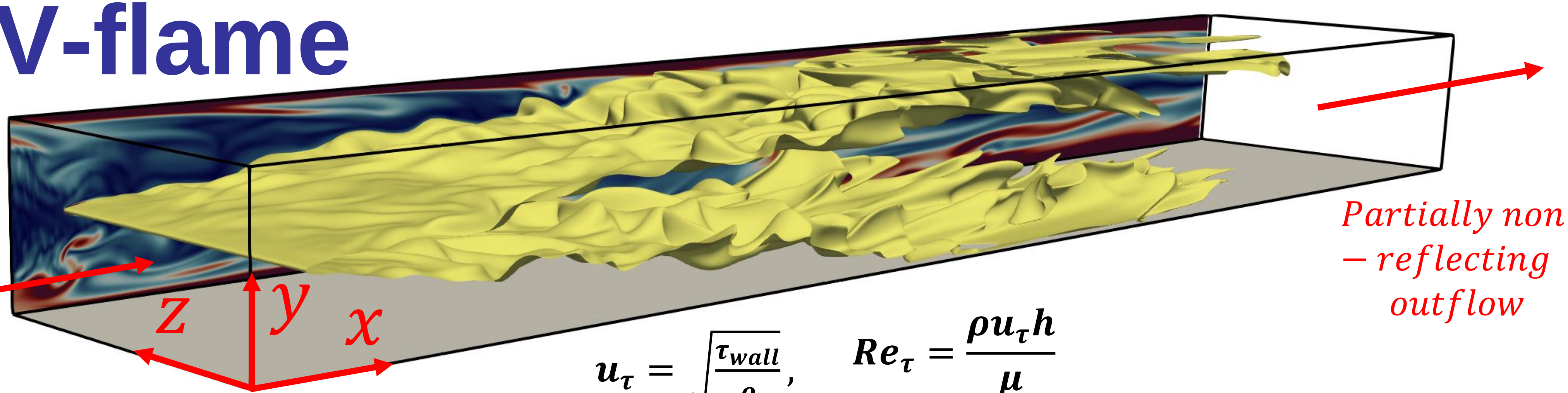
- The **flame curvature κ_m** can be defined as

$$\kappa_m = 0.5 \frac{\partial N_i}{\partial x_i}$$

where $N_i = -(\partial c / \partial x_i) / |\nabla c|$ is the **i^{th} component of flame normal**.

According to the convention used in this work, the **flame surface elements**, which are **convex (concave)** to the reactants, **have positive (negative)** curvature values.

OWI of V-flame



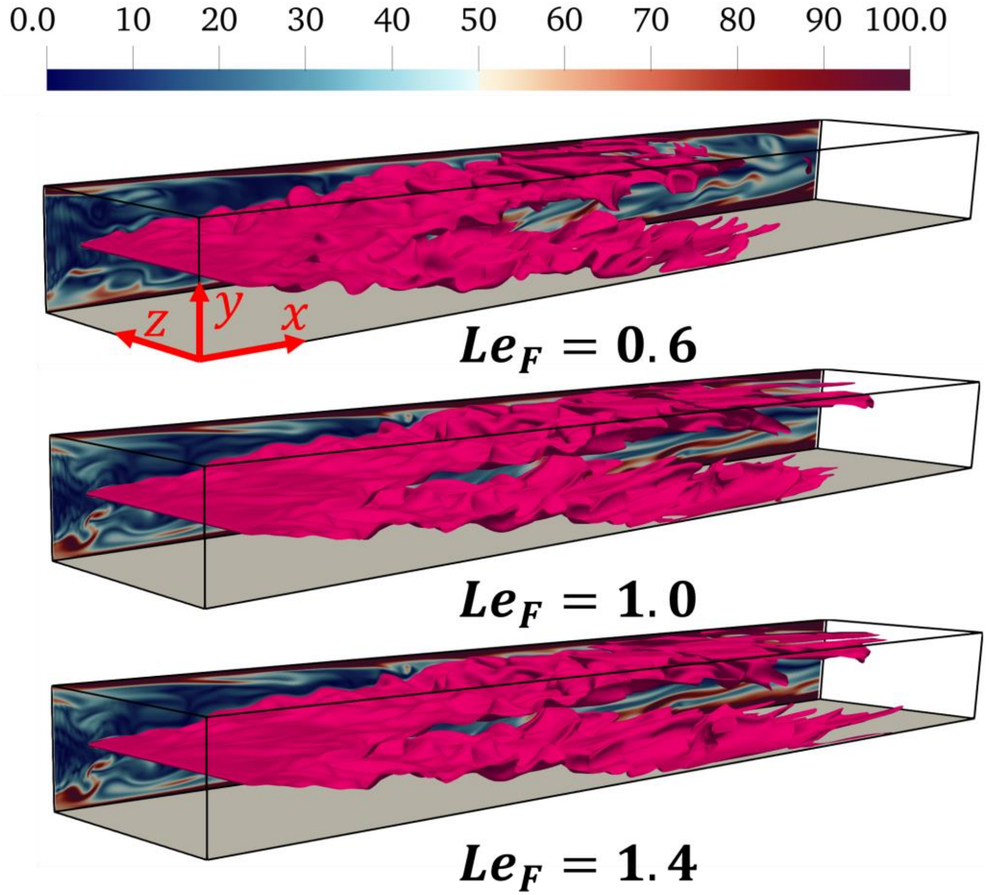
$$u_\tau = \sqrt{\frac{\tau_{wall}}{\rho}}, \quad Re_\tau = \frac{\rho u_\tau h}{\mu}$$

- V-flame is investigated in this work with **friction velocity based Reynolds number $Re_\tau = 110$** in channel flow configuration with inert walls for three different fuel Lewis numbers .
- Domain size of $22.22h \times 2h \times 4h$ discretised on $4000 \times 360 \times 720$ (**approx. 1.0 billion**) grid points.
- The simulation is run for **two flow through times** after the initial transients have decayed.
- **Progress variable** is defined in terms of the fuel mass fraction, $c = (Y_{Fu} - Y_F)/(Y_{Fu} - Y_{Fb})$.

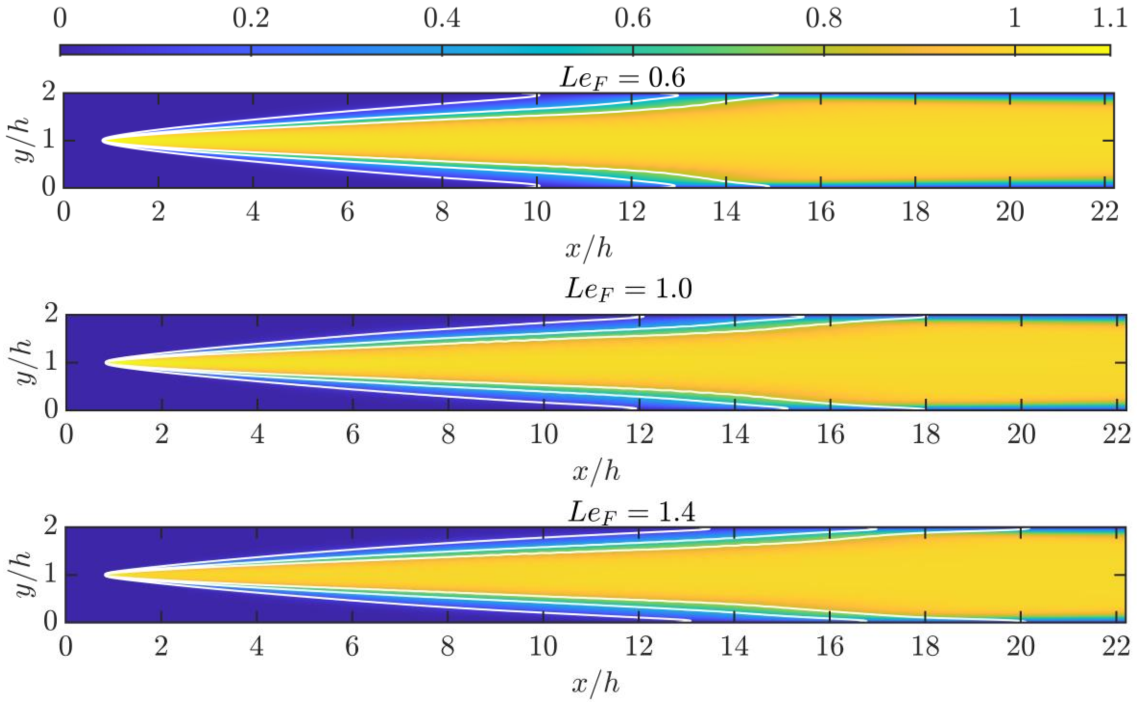
Cases	*Fuel Composition*
[1] $Le_F = 0.6$	$25\% H_2$ *and* $75\% CH_4$
[1] $Le_F = 1.0$	$100\% CH_4$
[1] $Le_F = 1.4$	$90\% C_2H_6$ *and* $10\% CH_4$

[1]**F. Dinkelacker, B. Manickam, S.P.R. Muppala**, Modelling and simulation of lean premixed turbulent CH4/h2/air flames with an effective Lewis number approach, Combust. Flame,158 (9), 2011, 1742-1749,

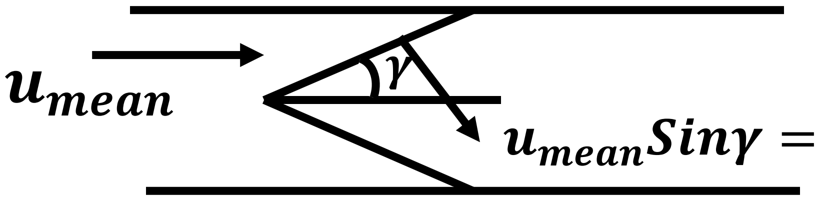
Instantaneous and Mean Scalar Field



Isosurfaces of $c = 0.5$ with distributions of normalised vorticity magnitude $\Omega = \sqrt{w_i w_i} \times h/u_{\tau,NR}$ in the central mid-plane

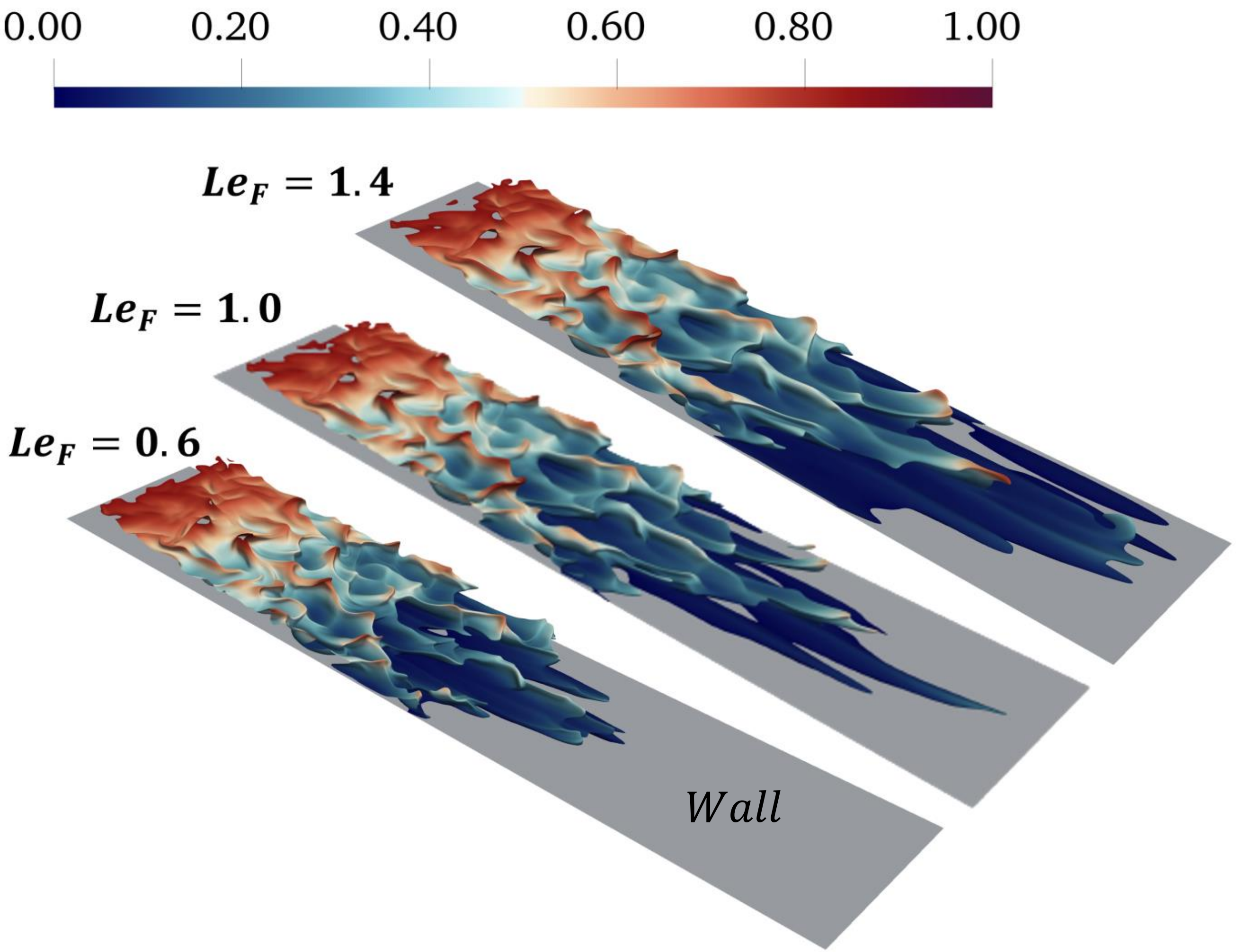


Fields of Favre-averaged temperature $\widetilde{\theta}$ along with mean reaction progress variable contour $\tilde{c} = 0.1, 0.5$ and 0.8.



$$u_{mean} Sin\gamma = S_T \propto \sum |\dot{\omega}_F| dV$$

Flame wall interaction



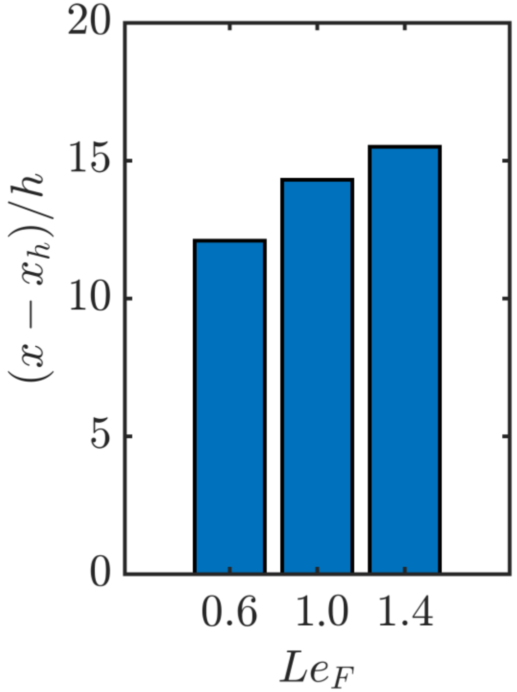
Isosurfaces of $c = 0.75$ coloured by wall normal distance y/h for bottom branches of turbulent V-flames

Normalised volume-integrated burning rate

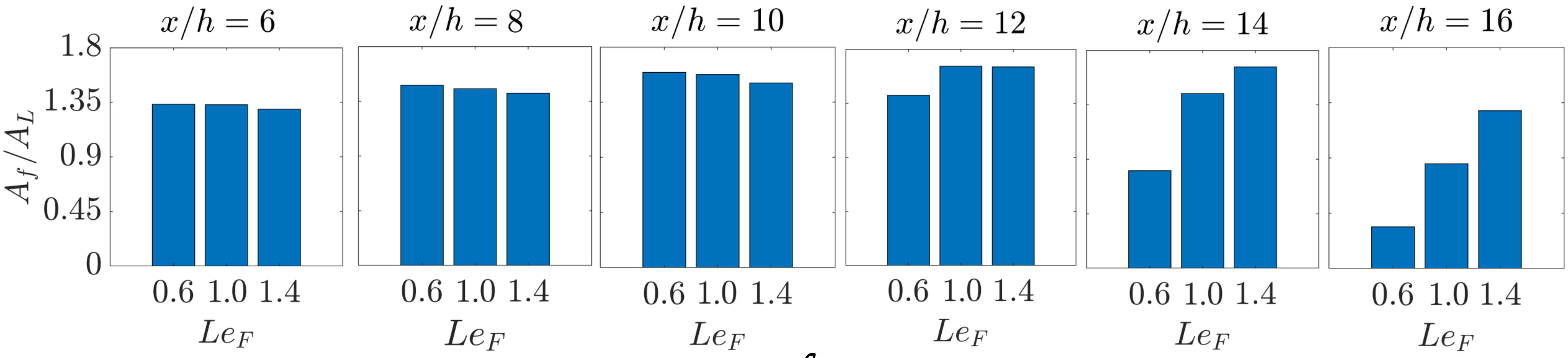
$$\Lambda = \int_V |\dot{\omega}_F| dV \,/ [\rho_0 S_L h^2 (Y_{F0} - Y_{F\infty})]$$

$Le_F = 0.6$	$Le_F = 1.0$	$Le_F = 1.4$
$\Lambda = 1.55$	$\Lambda = 1.33$	$\Lambda = 1.28$

Streamwise distance from the flame holder $(x - x_h)/h$ of the intersection point of $\tilde{c} = 0.5$ contour with the wall

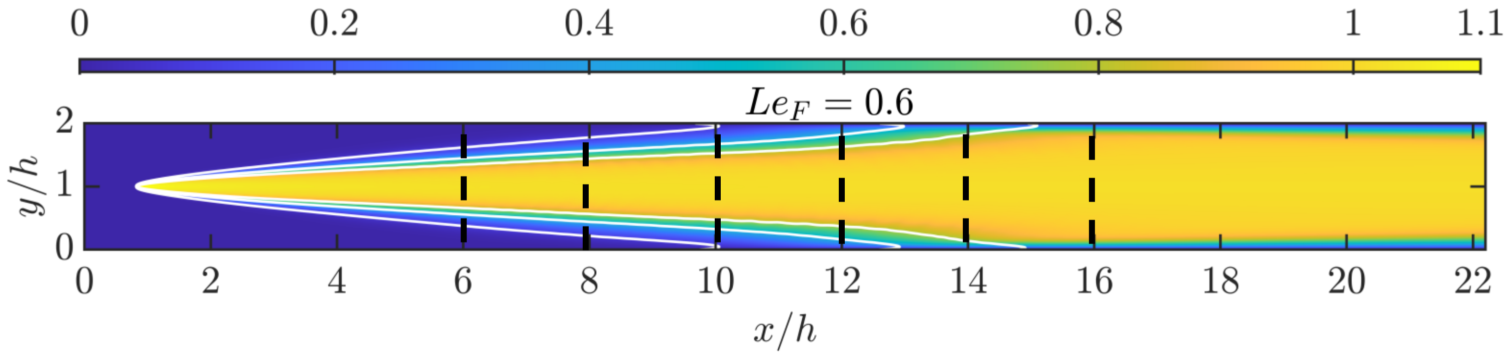


Variations of turbulent flame surface area A_f



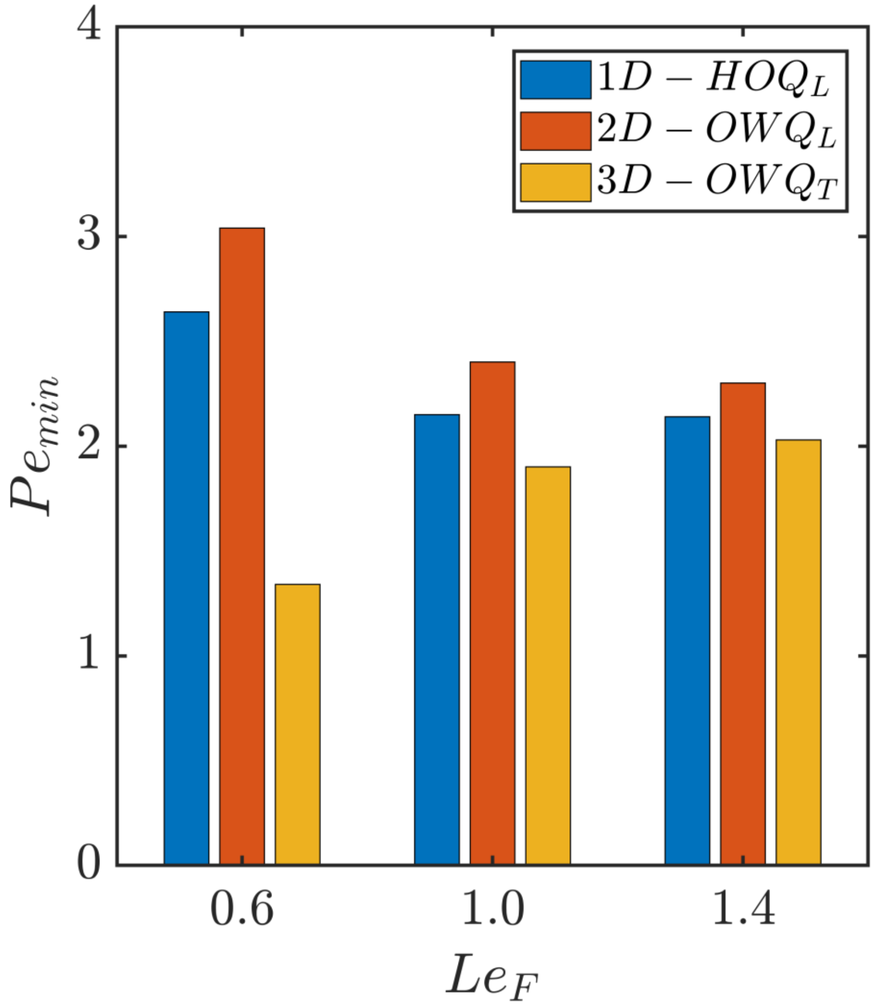
$$A_f = \int_V |\nabla c| dV$$

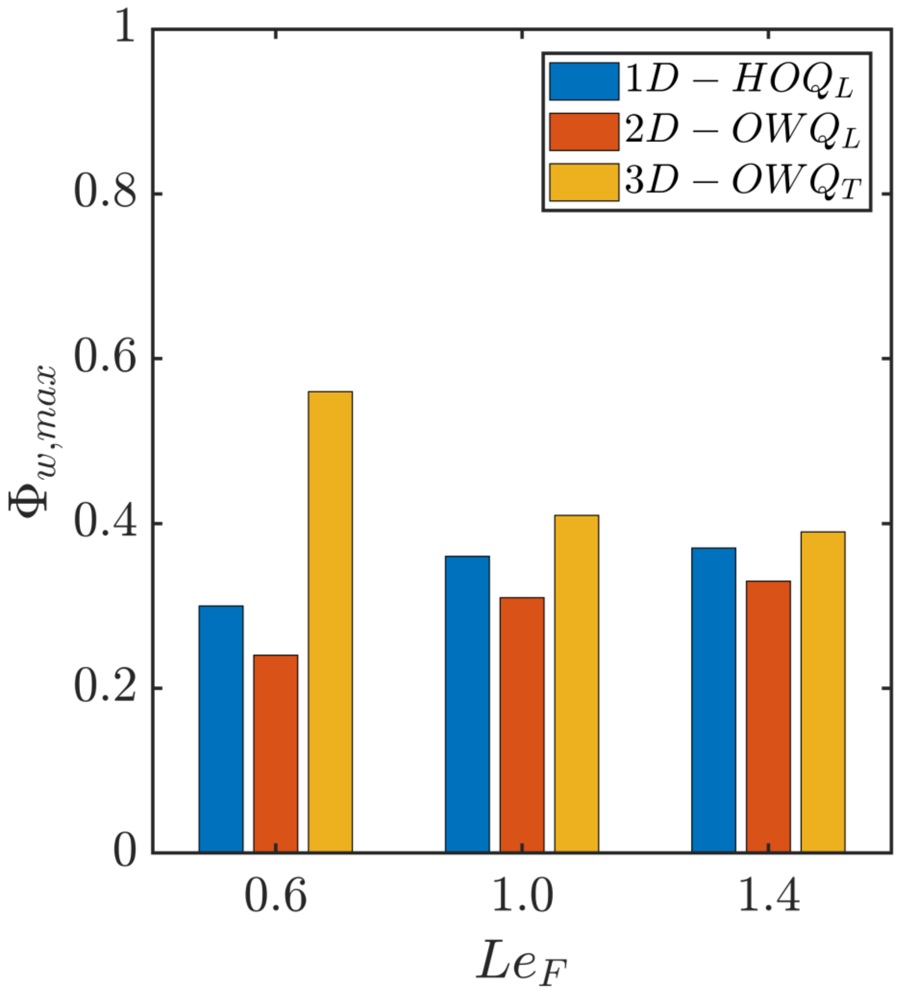
A_L is the flame surface area in the laminar V-shaped flames



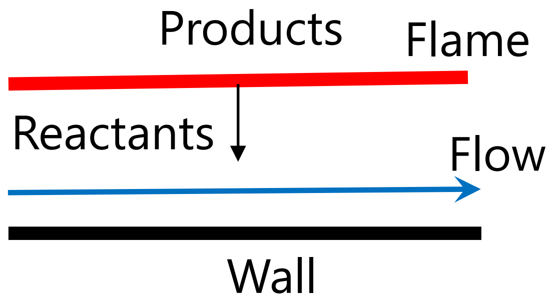
Variations of the minimum Peclet number Pe_{min} and the maximum magnitudes of wall heat flux $\Phi_{w,max}$

$$Pe_{min} \propto \frac{1}{\Phi_{w,max}}$$

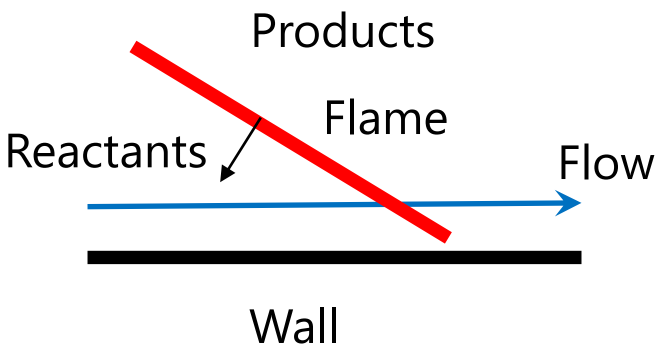




HOQ = Head on quenching



OWQ = Oblique wall quenching



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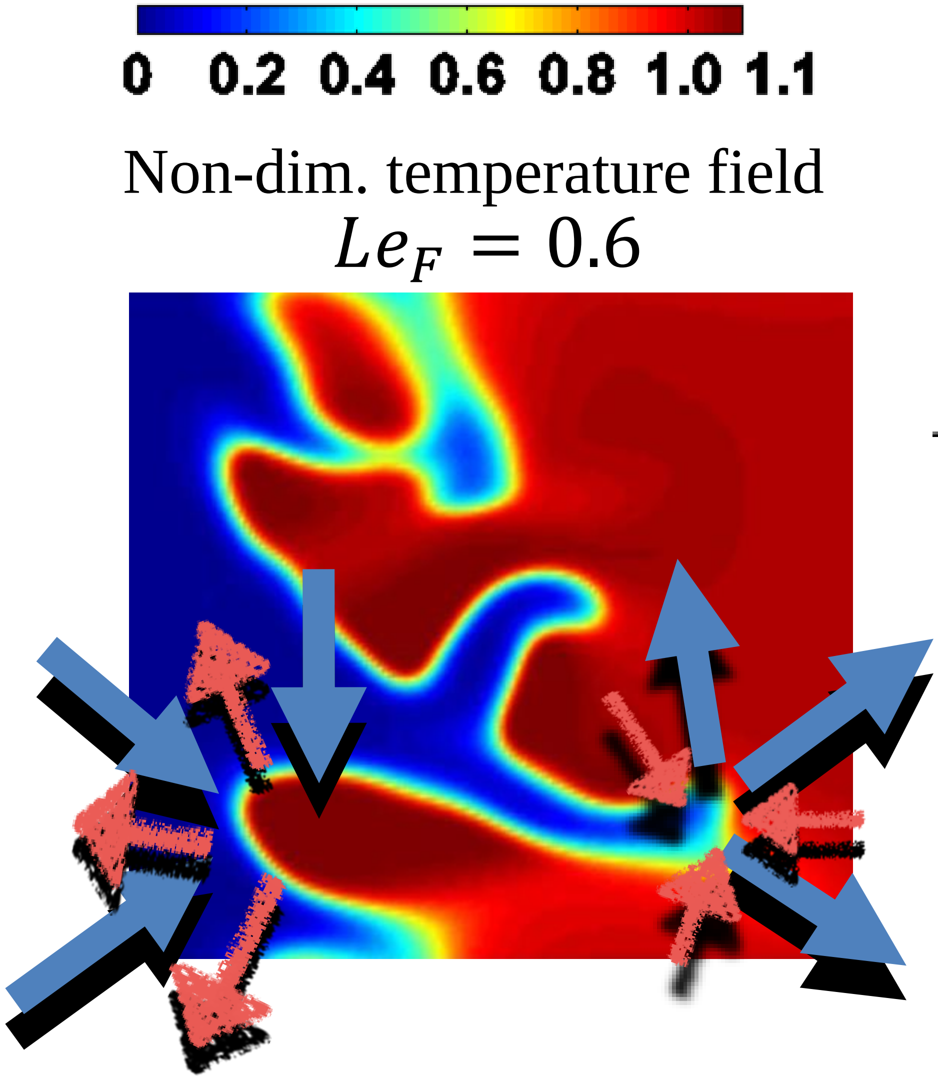
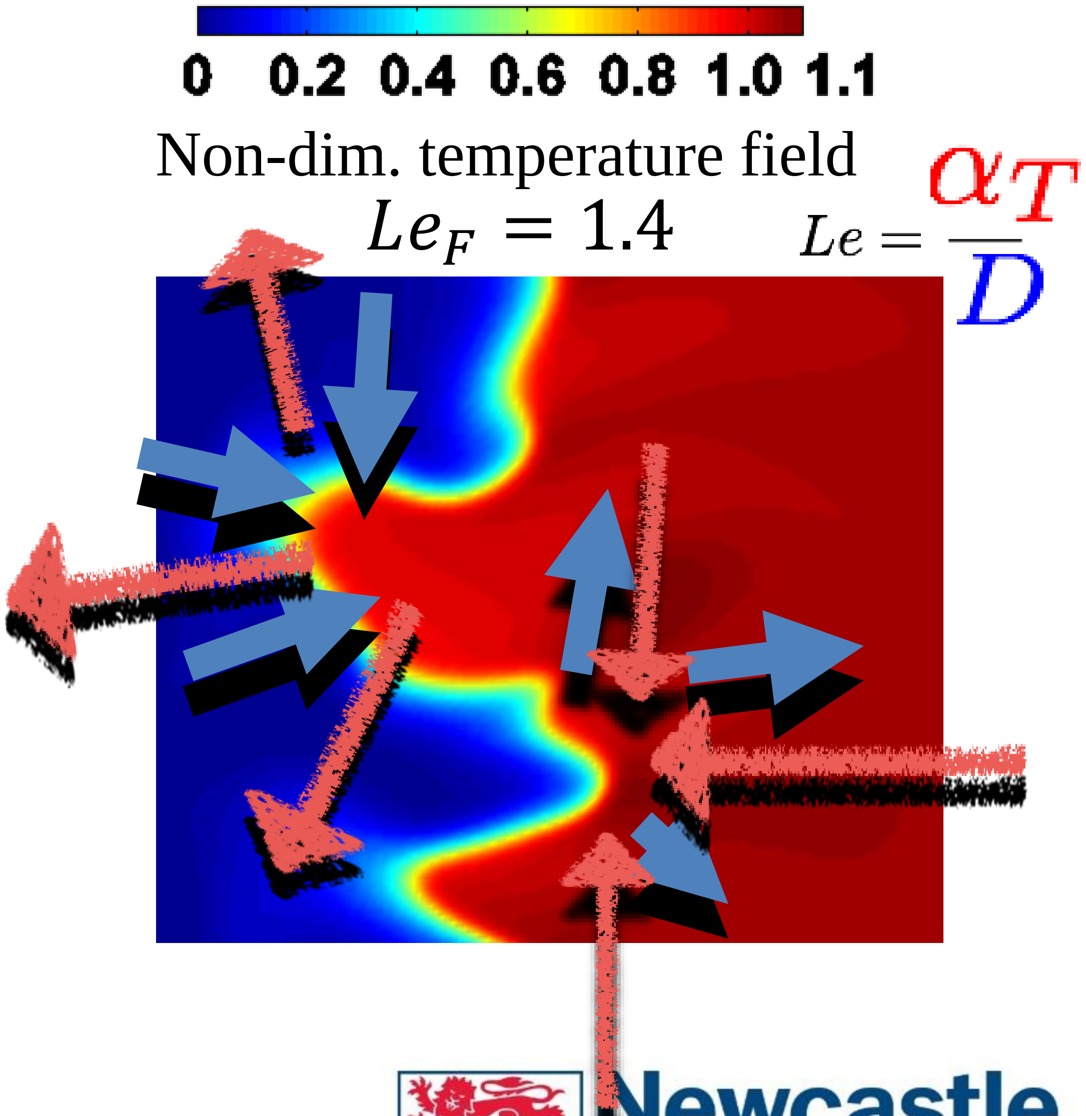
Lewis number effects



$$Le = \frac{\alpha_T}{D}$$



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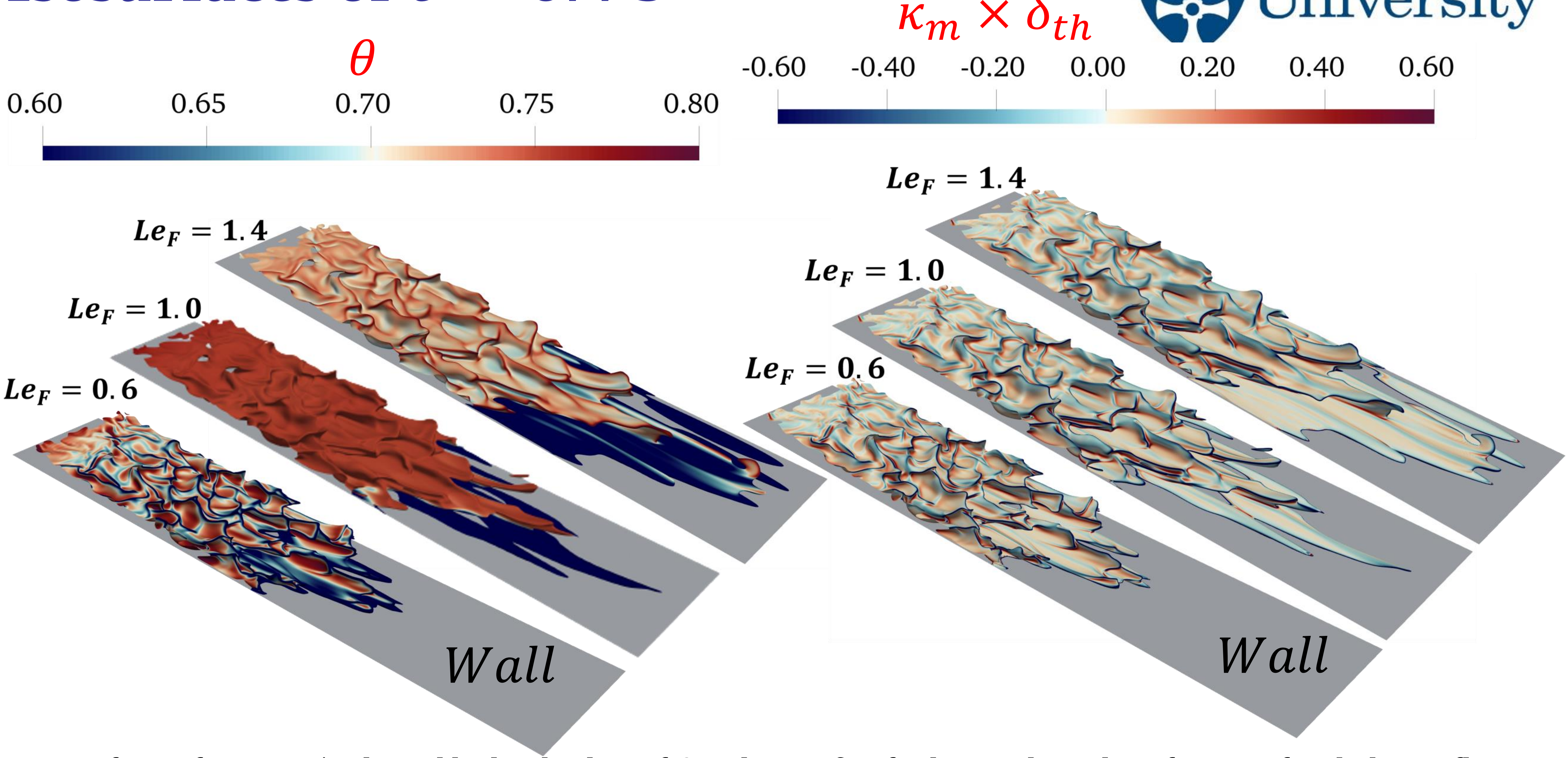
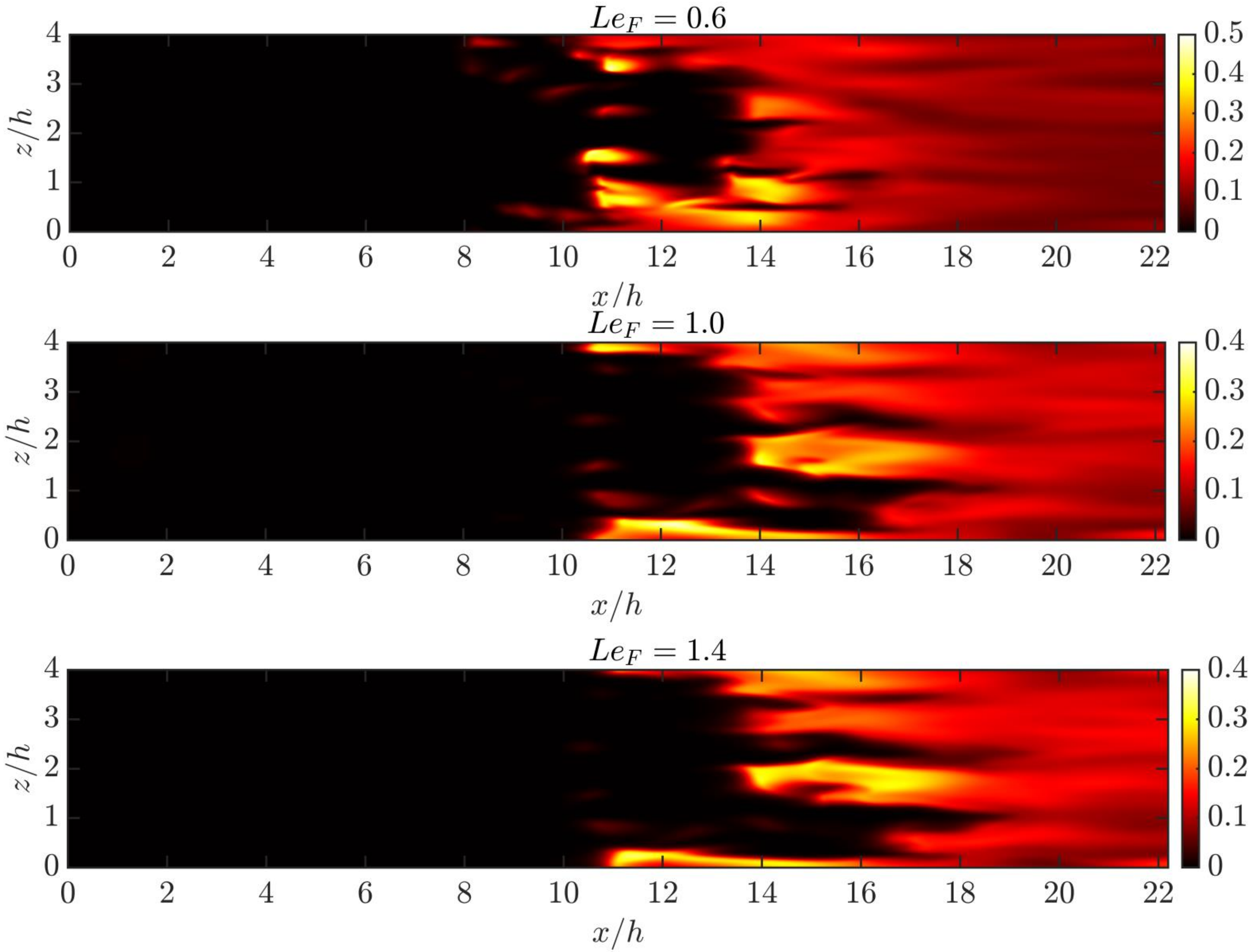
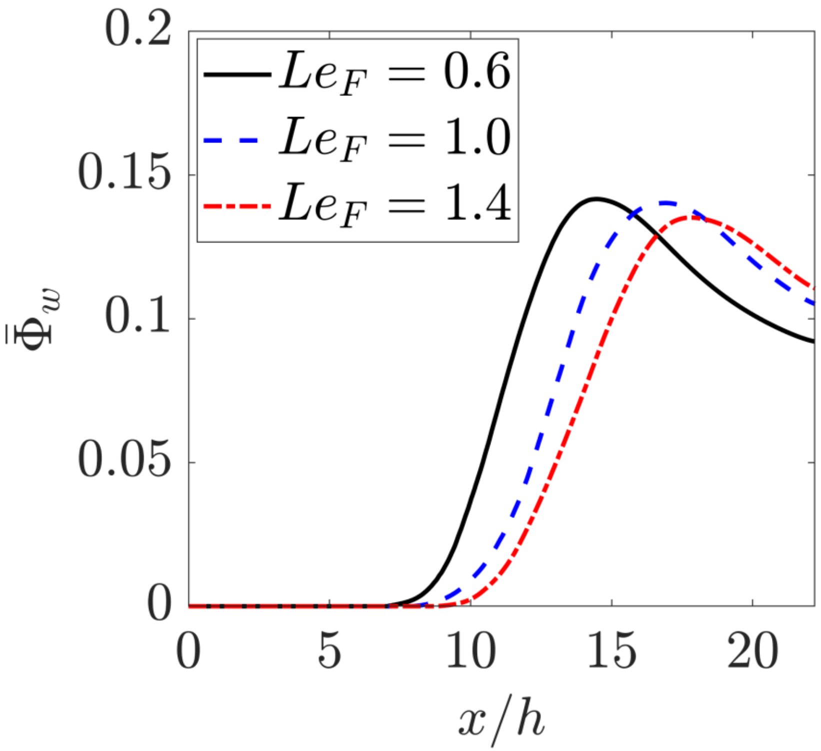
Isosurfaces of $c = 0.75$



Isosurfaces of $c = 0.75$ coloured by local values of θ and $\kappa_m \times \delta_{th}$ for bottom branches of OWQ of turbulent V-flames

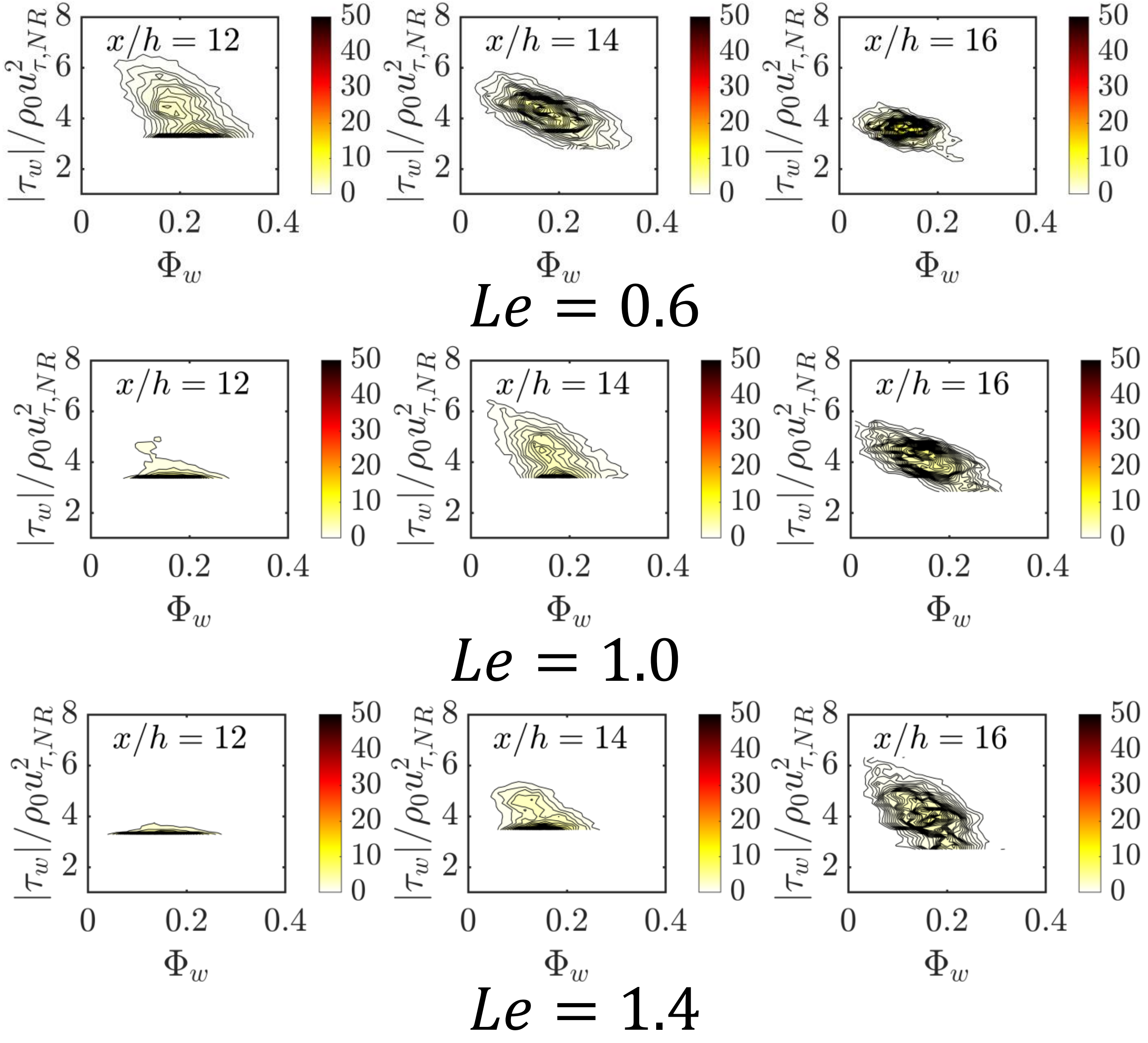
Instantaneous and mean distributions of normalised wall heat flux magnitude Φ_w





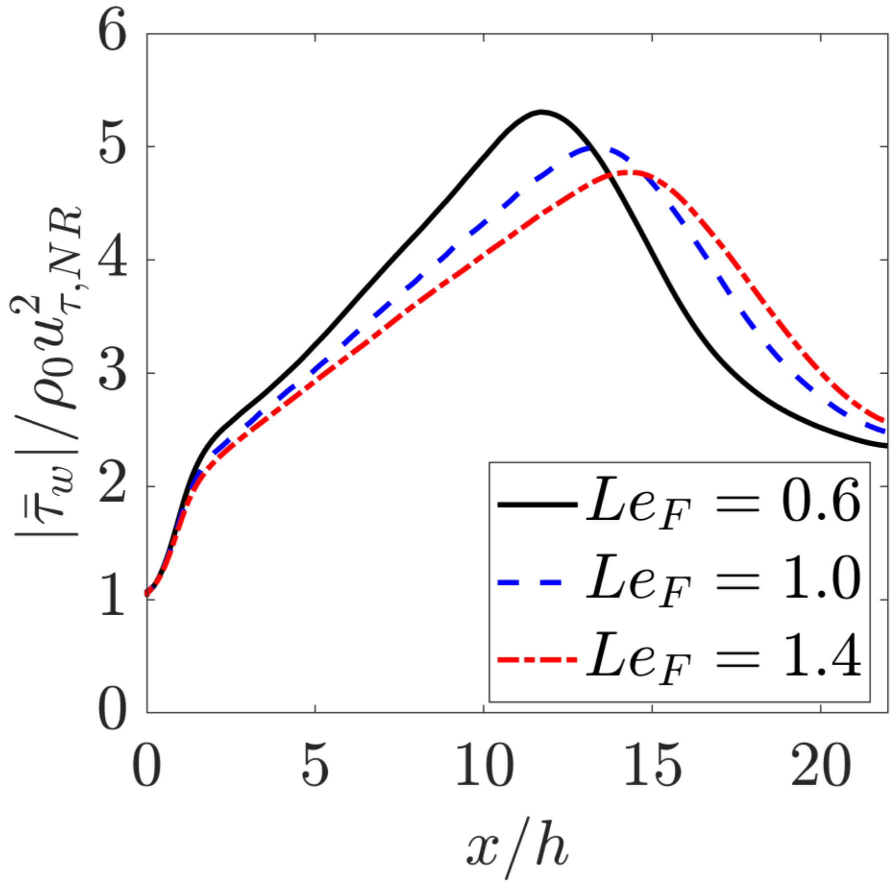
Mean wall heat flux magnitude $\bar{\Phi}_w$

Joint PDF distribution of Wall shear stress and wall heat flux

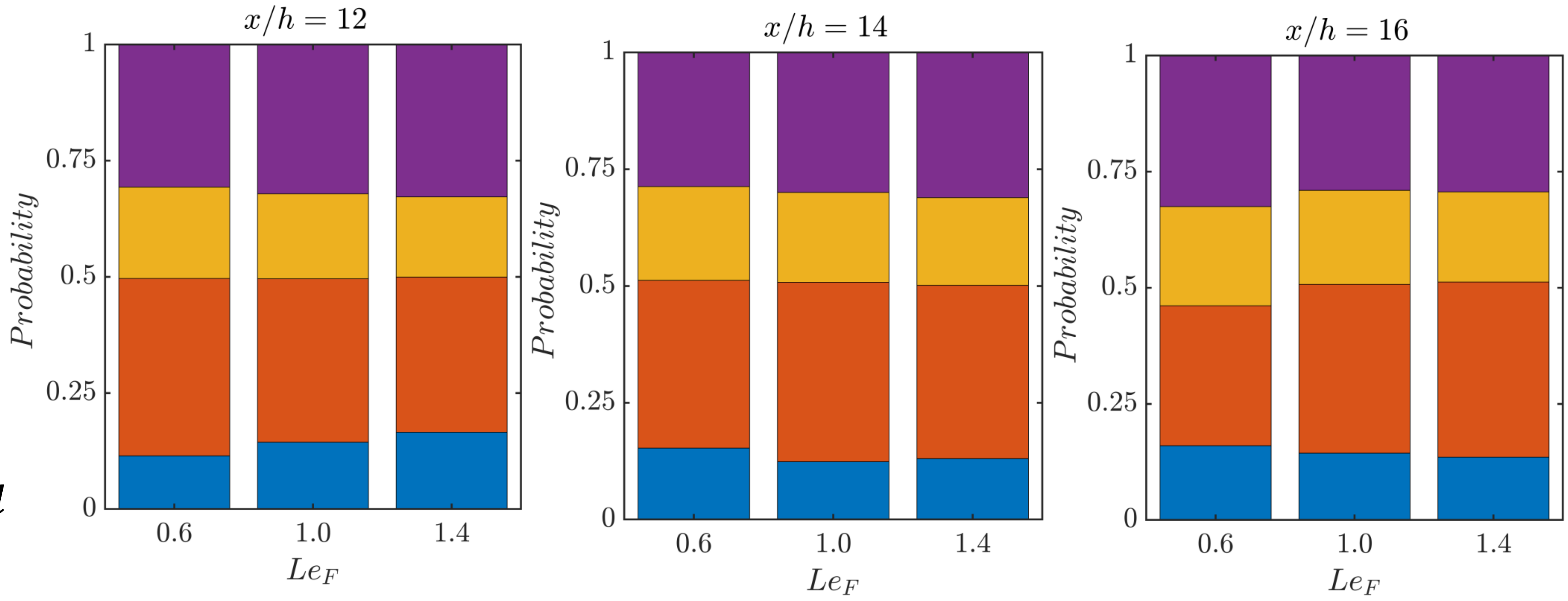


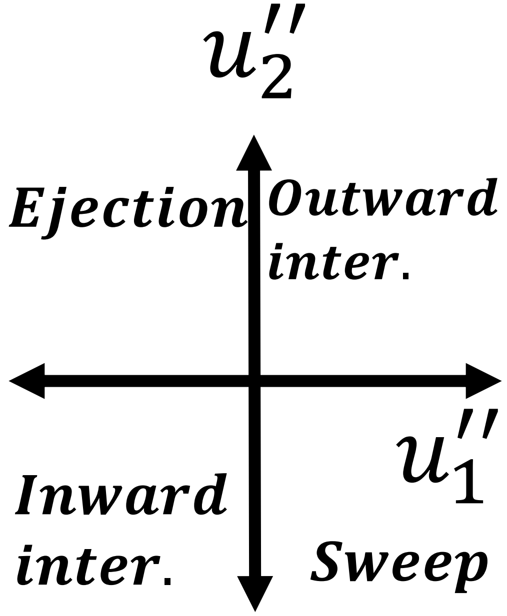
Joint PDF contours between Φ_w and $|\tau_w|/\rho_0 u^2_{\tau,NR}$

Variations of the normalised mean wall shear stress with the streamwise

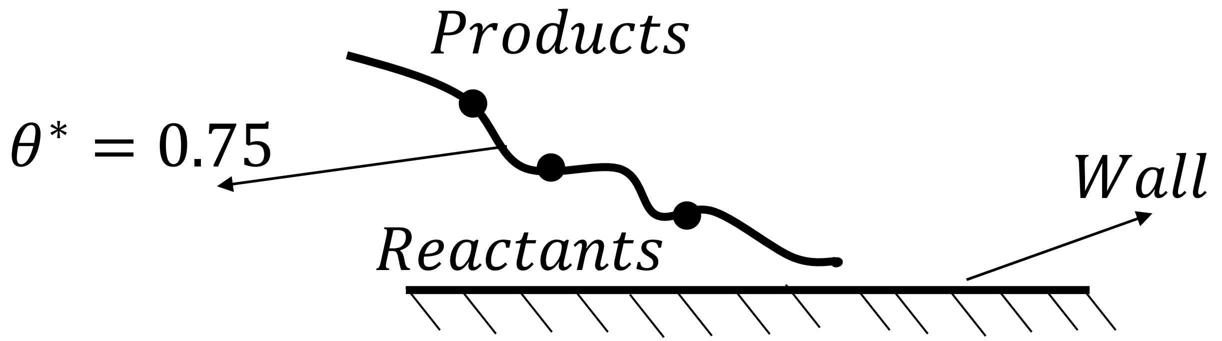


Probabilities of coherent structure

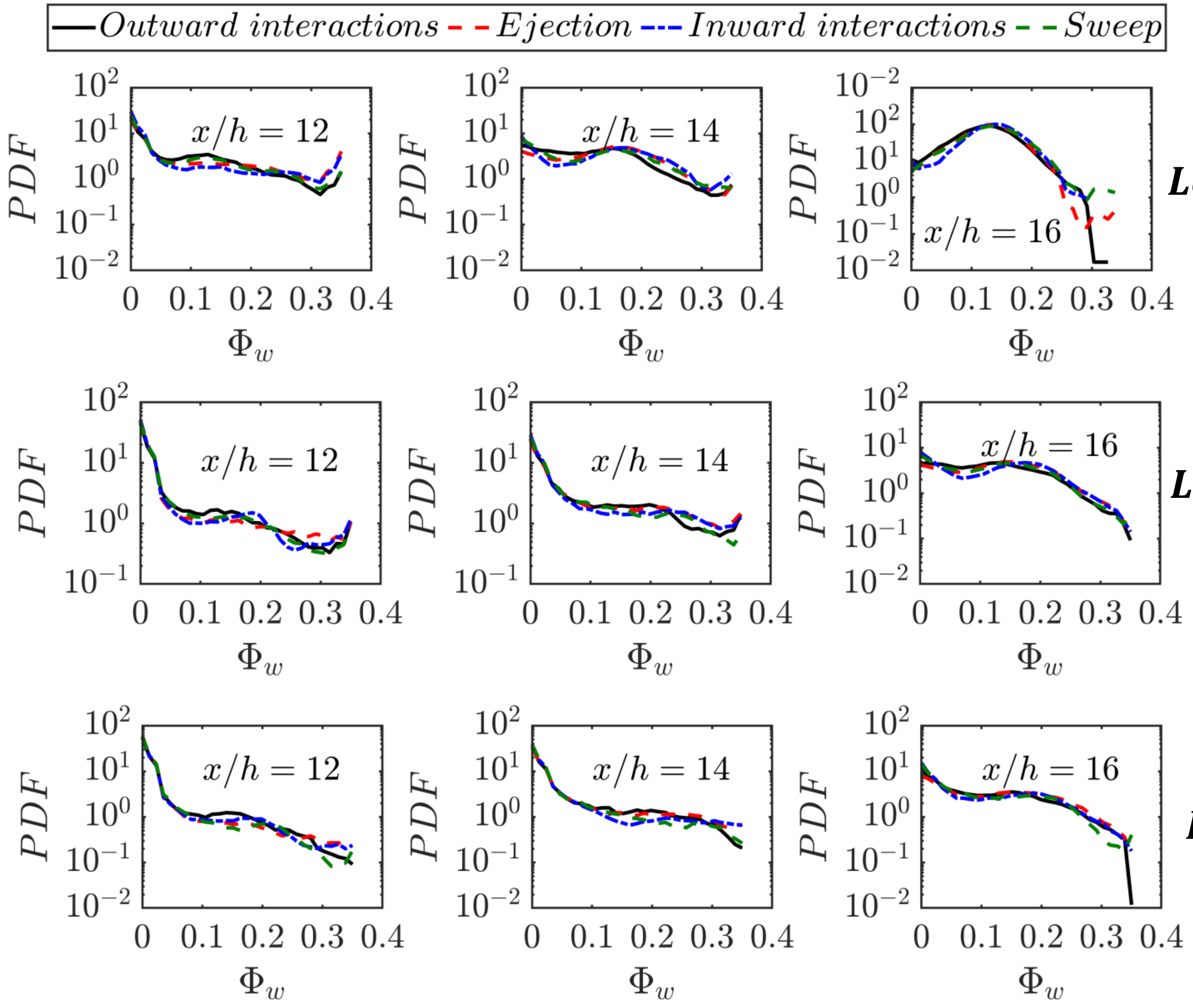




Probabilities of occurrences of different coherent structures at the normalised smallest wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface



Effect of coherent structure on Φ_w



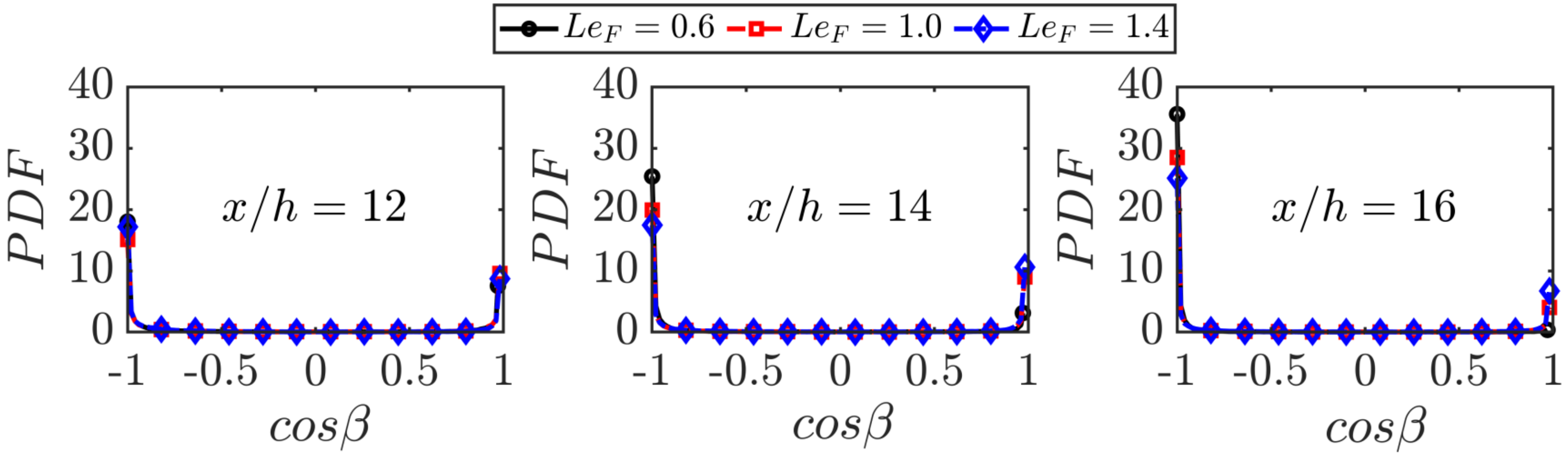
$Le_F = 0.6$

$Le_F = 1.0$

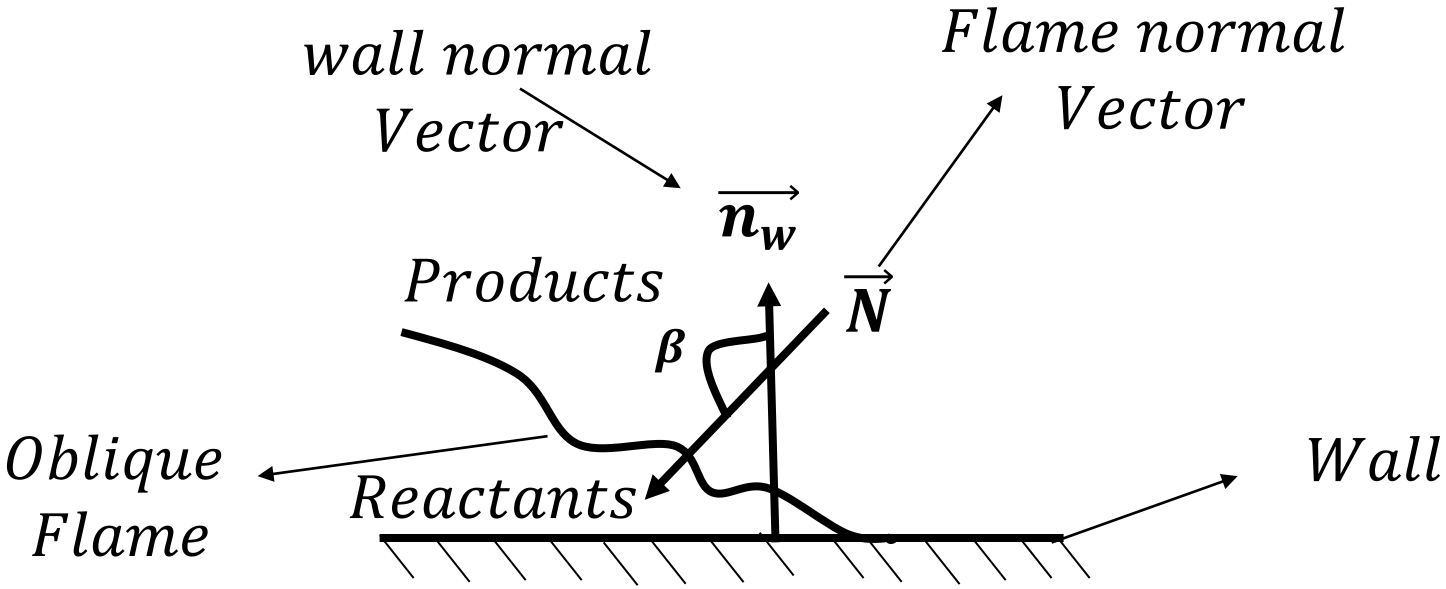
$Le_F = 1.4$

PDFs of Φ_w for different coherent events at the normalised wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface

Flame Orientation



PDFs of $cos\beta = \vec{N} \cdot \vec{n}_w$ at the normalised smallest wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface



$cos\beta = -1$	*Head on quenching*
$cos\beta = 0$	*Pure side wall quenching*
$cos\beta = 1$	*Entrained Flame*

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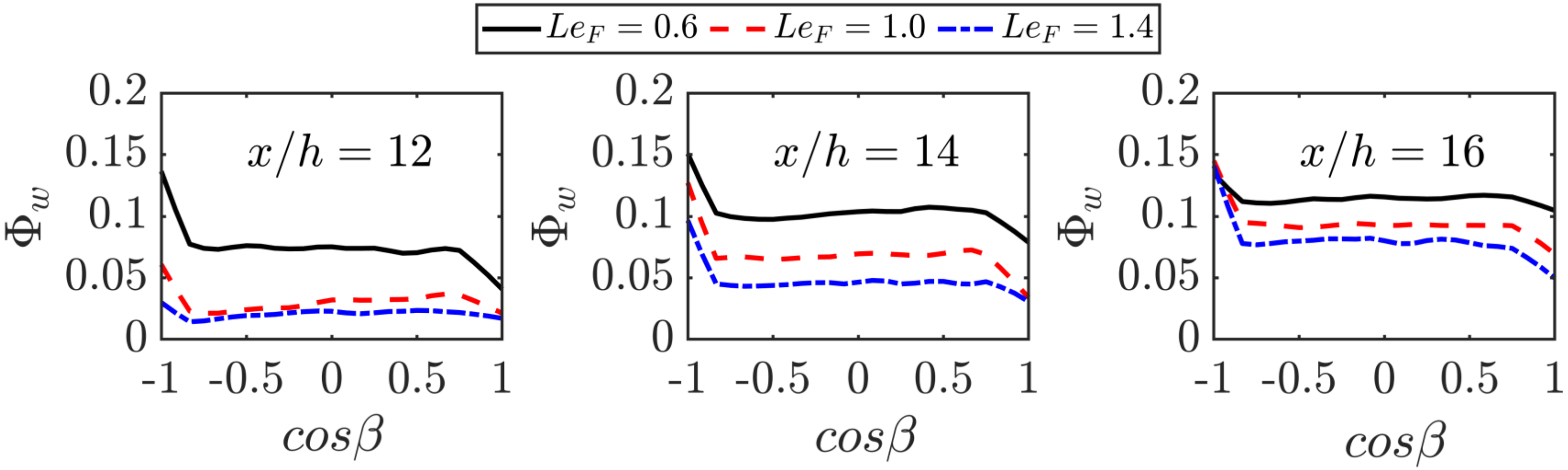
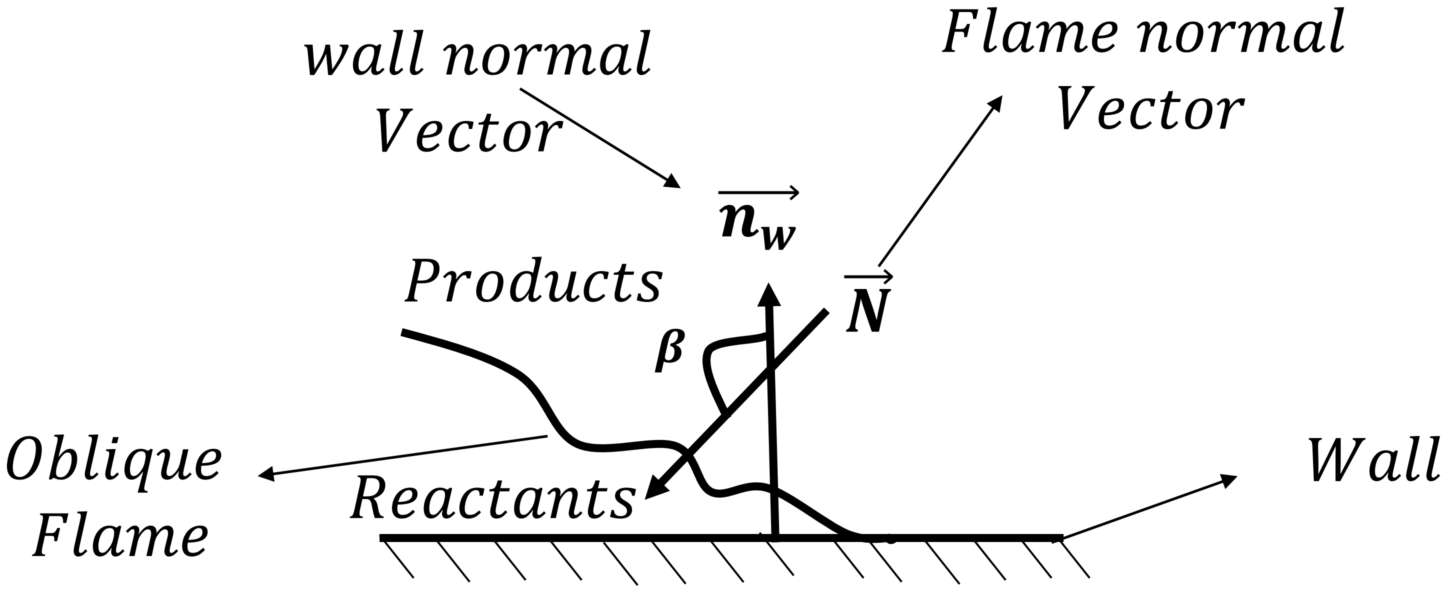
Effect of flame orientation on Φ_w



Mean values of Φ_w conditioned on the values of $cos\beta$ at the normalised smallest wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface



$cos\beta = -1$	*Head on quenching*
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Summary

- The **effects of fuel Lewis number Le_F** on the statistical behaviour of wall **heat flux and flame quenching distance** have been analysed for OWI of turbulent V-shaped flame with Le_F ranging from 0.6 to 1.4.

- **Maximum wall heat flux magnitude** increases with decreasing Le_F whereas the **flame quenching distance** decreases with decreasing Le_F in turbulent OWI case but just the **opposite trend** was observed for laminar OWI and HOI cases.

- **Greater extent of flame wrinkling** for smaller values of Le_F **alters the proportions** of flame surface area as well as local head-on and entrained flame quenching events.

- The effects of fuel Lewis number on **flame orientation** within turbulent boundary layers affect both wall heat transfer rate and flame quenching distance.

- Therefore, the **thermo-diffusive effects** arising from the non-unity Lewis number need to be accounted for **accurate modelling of wall heat transfer** during FWI in turbulent boundary layers.

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- HPC facility at Newcastle University (Rocket).

SKG, UA and NC are grateful to EPSRC (Project EP/V003534/1) for the financial support.

UK CTRF UK CONSORTIUM ON TURBULENT REACTING FLOWS

EPSRC Engineering and Physical Sciences Research Council

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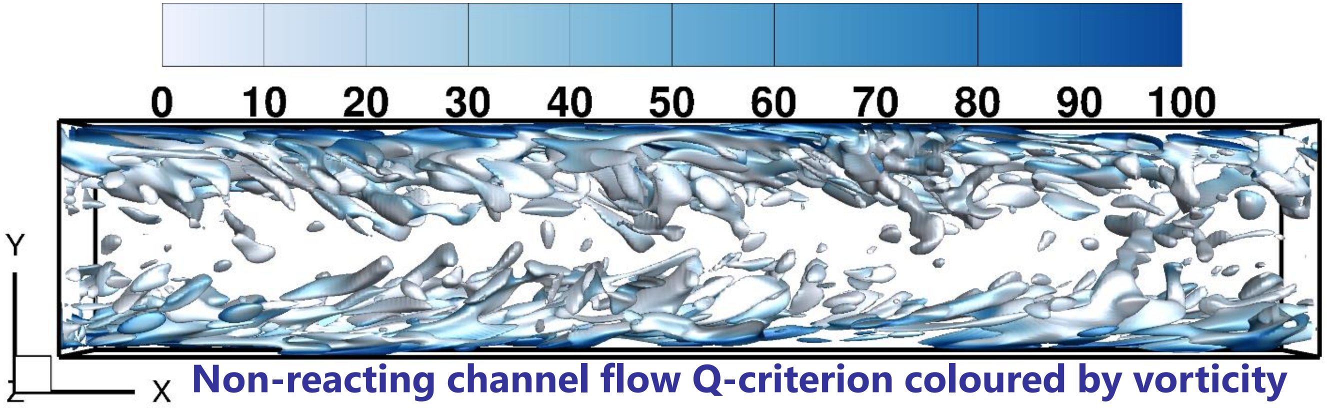
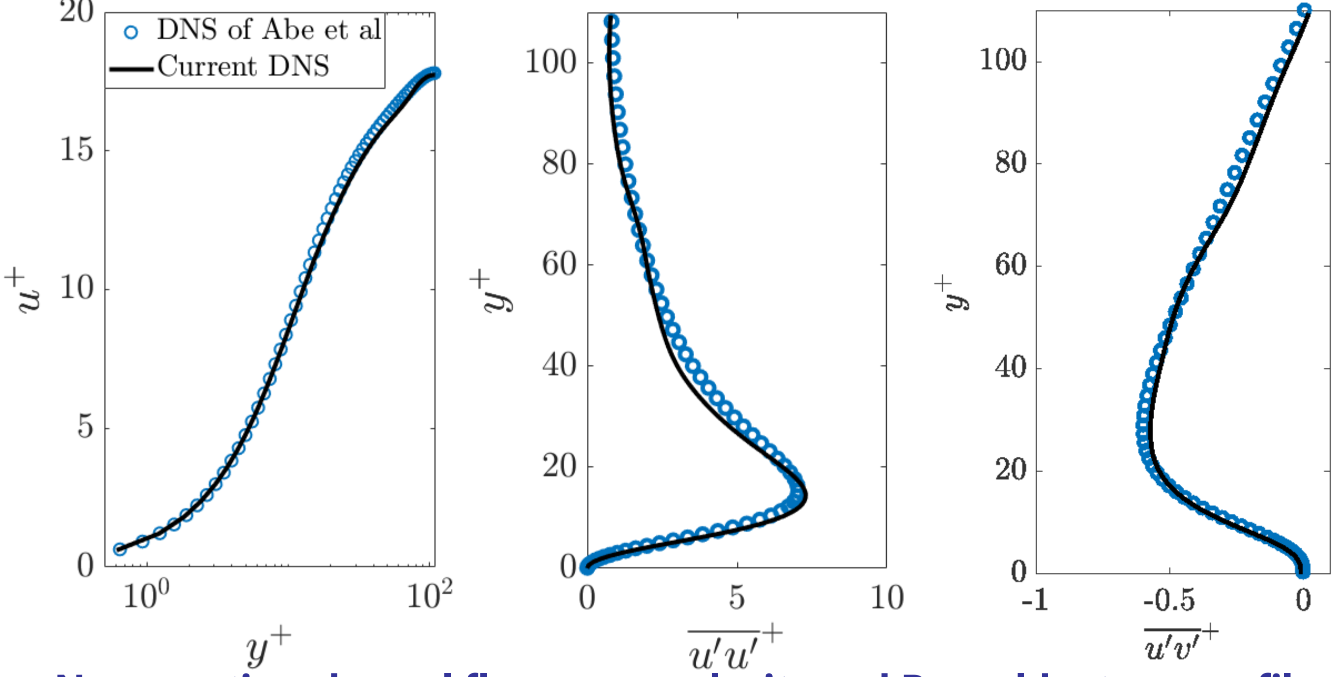
Non-reacting flow simulation



Non-reacting channel flow Q-criterion coloured by vorticity magnitude

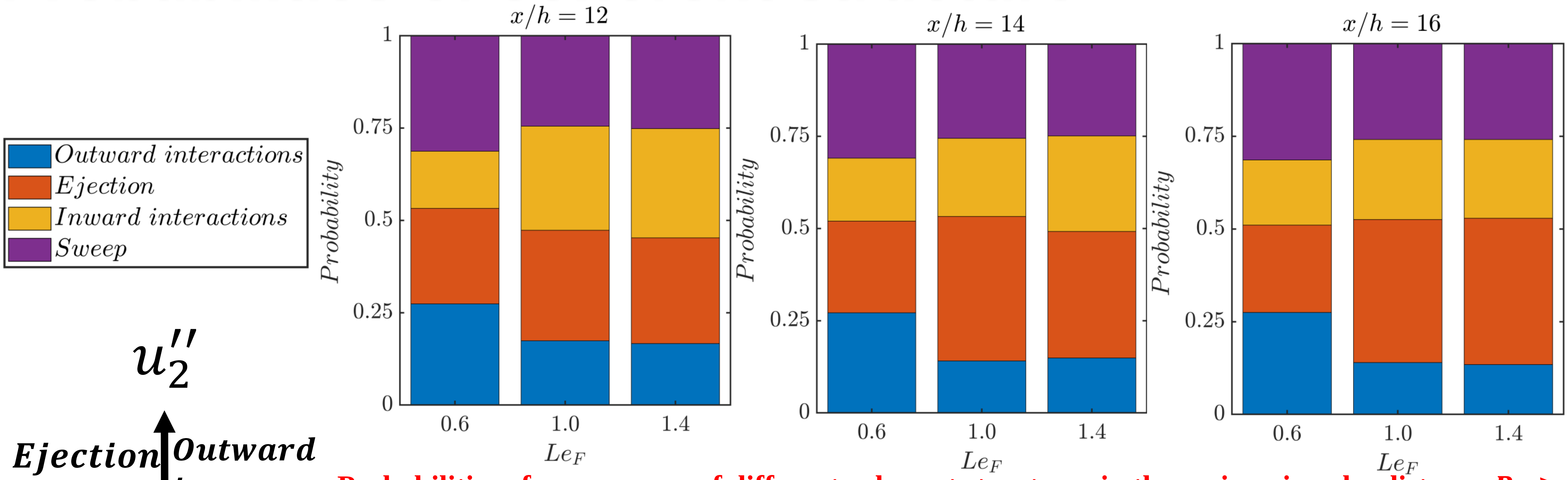


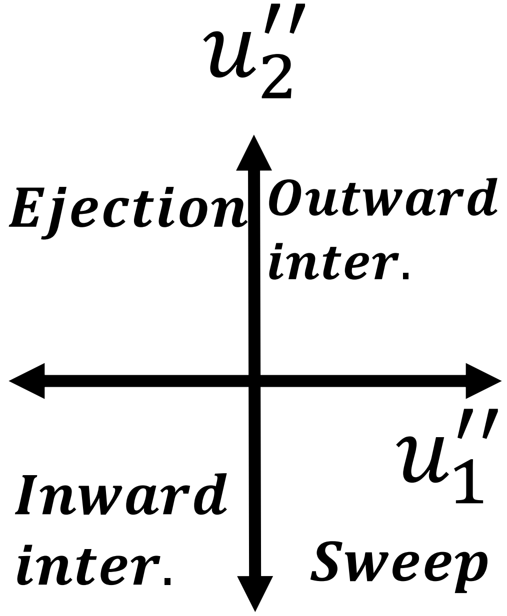
Non-reacting channel flow mean velocity and Reynolds stress profiles

- $Re_\tau = 110$ for the non-reacting channel.
- $y^+ = 0.6$ at the wall and at least two grid points are in $y^+ \leq 1.0$ region.
- Domain size $22.2h \times 2h \times 4h$.
- $4000 \times 360 \times 720$ (approx. 1.0 billion) grid points.
- Data validated against existing DNS.

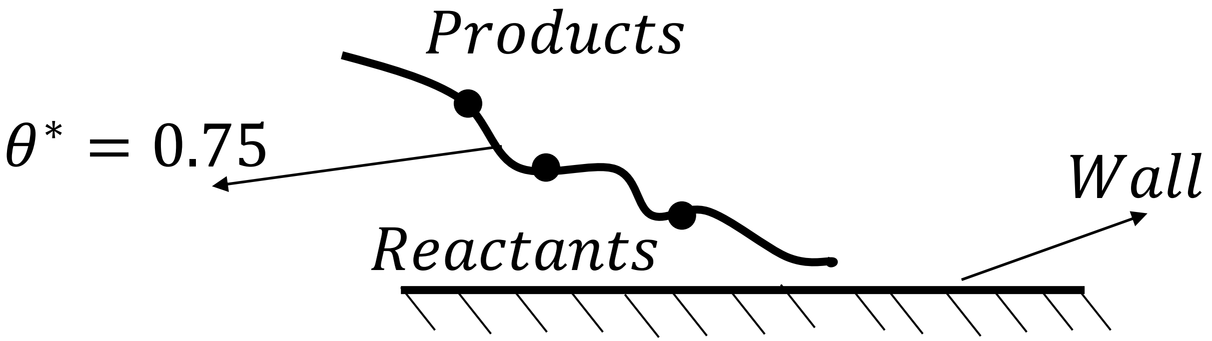
DNS data of Abe et al is available at **http://www.rs.tus.ac.jp/~t2lab/db/index.html**

Probabilities of coherent structure





Probabilities of occurrences of different coherent structures in the region given by distance $Pe \geq y/\delta_z \geq 0$ where Pe is the normalised wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface



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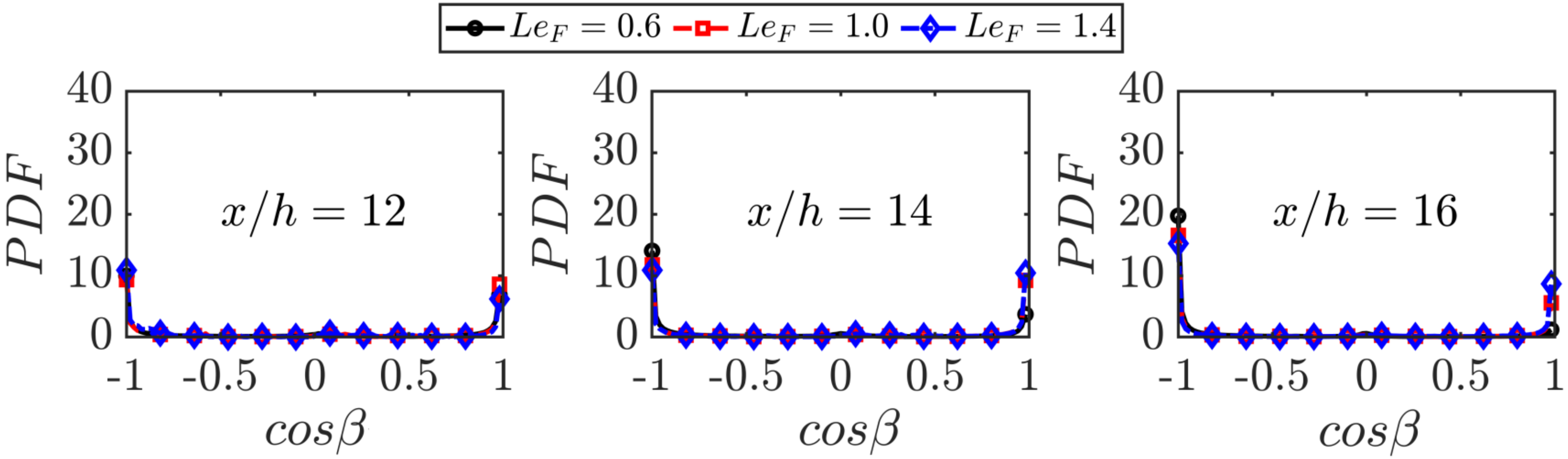
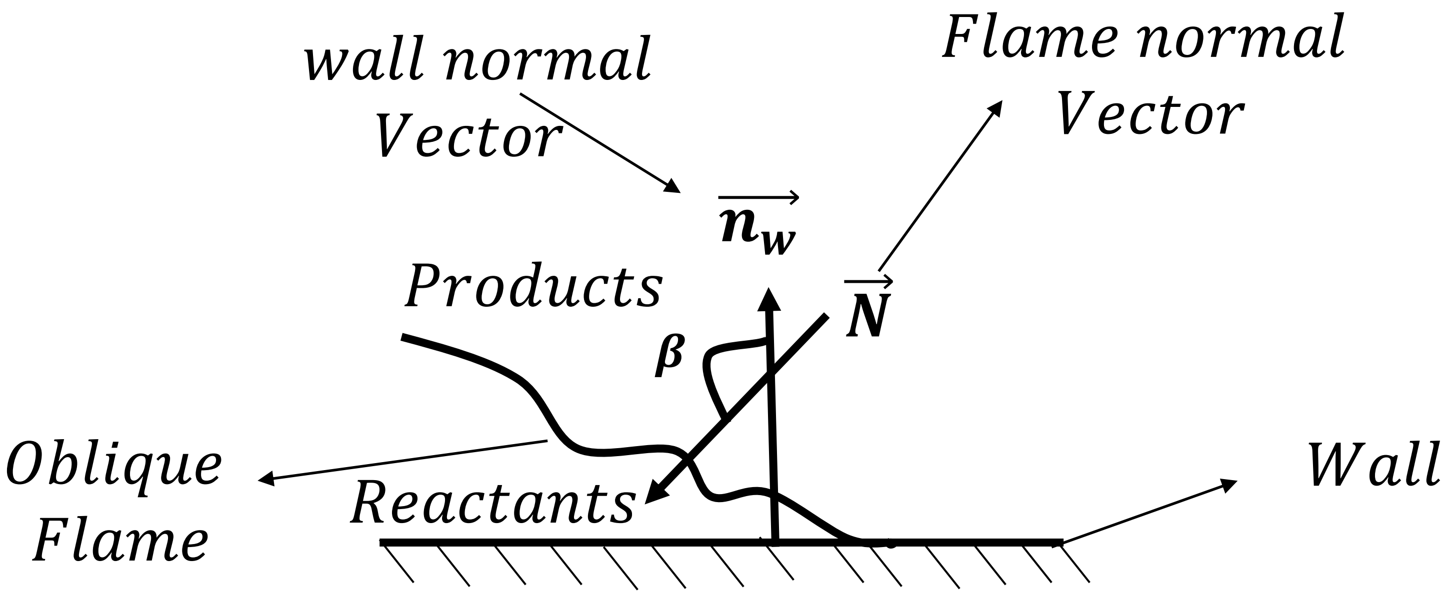
Flame Orientation



PDFs of $cos\beta = \vec{N} \cdot \vec{n}_w$ in the region given by distance $Pe \geq y/\delta_z \geq 0$ where Pe is normalised wall normal distance $Pe = y/\delta_z$ of the $\theta^* = 0.75$ isosurface



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