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Spectral behaviour of the heat release rate in swirl-stabilized and bluff body flames

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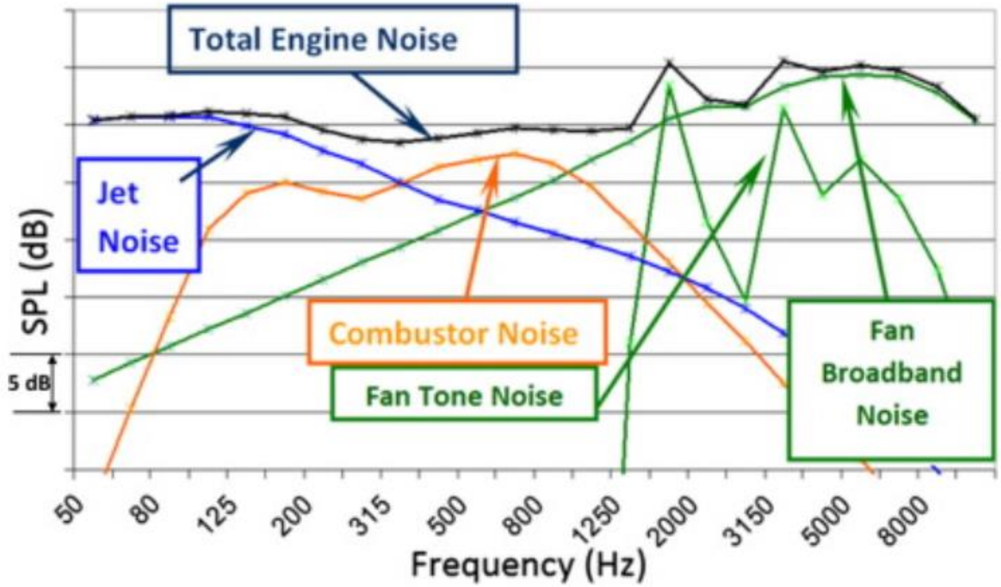
Outline

- Motivation
- Background and Aim
- Description of cases
- Results
- Modelling and discussion
- Conclusion

Motivation



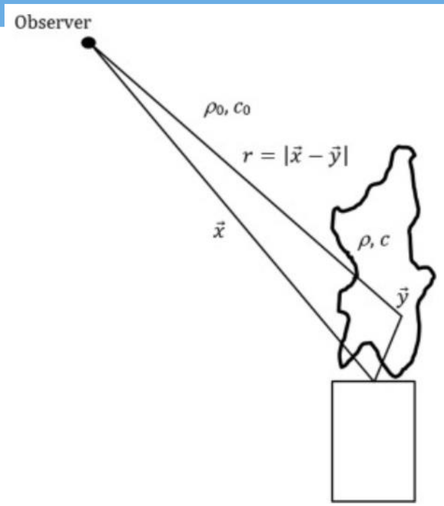
[1]

- Combustion noise is dominant for combustors operating under lean premixed/stratified conditions.
- Combustion noise has a broadband nature and is comparable to other sources.
- Noise is an important design criteria that can be predicted using LES.

1. Dowling, A. P., & Mahmoudi, Y. (2015). Combustion noise. *Proceedings of the Combustion Institute*, *35*(1), 65-100.

Background and Aim

[1]



Acoustic Wave Equation [2,3]:

$$\frac{1}{c_o^2}\frac{\partial^2 p'}{\partial t} - \frac{\partial^2 p'}{\partial x_i^2} = \underbrace{\mathcal{T}_1}_{\approx 0} + \underbrace{\mathcal{T}_2}_{\approx 0} + \underbrace{\mathcal{T}_3}_{\approx 0} + \mathcal{T}_4 \rightarrow \frac{(\gamma-1)}{c_o^2}\frac{\partial \dot{Q}'(\boldsymbol{y},t)}{\partial t}$$

$$\widehat{\mathcal{P}}(\boldsymbol{x},\omega)$$

Low order models

High Fidelity LES

$$\widehat{\mathcal{P}}(\boldsymbol{x},\omega) \approx \frac{\gamma-1}{c_o^2}\omega^2 \int_{V_f} \left|\hat{G}_1(\boldsymbol{y},\boldsymbol{x},\omega)\right|^2 \psi_q(\boldsymbol{y},\omega) V_{\text{cor}}\, d^3\boldsymbol{y}$$

$$\widehat{\mathcal{P}}(\boldsymbol{x},\omega) = \frac{(\gamma-1)}{16\,\pi r^2 c_o^2} Y_{f,u}^2\, H^2\, \mathcal{B}_{int}^2 \omega^2\, \widehat{\Omega}_{int}(\omega) \left(\int_{V_f} \overline{\dot{\omega}(\boldsymbol{y},t)}\, d^3\boldsymbol{y}\right)^2$$

PSD of canonical open flames depends on volume integrated heat release rate (studied previously[4,5])

$\widehat{\mathcal{P}}$ depends on local heat release rate for closed flames seen in practical applications – Focus of this work

- ψ_q is simple to obtain in LES compared to experiments.
- ψ_q from non − reacting flow LES ?

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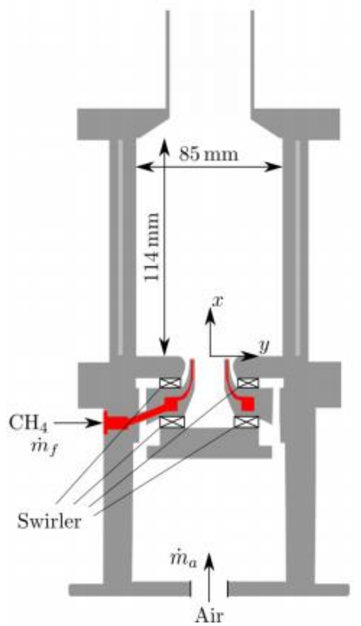
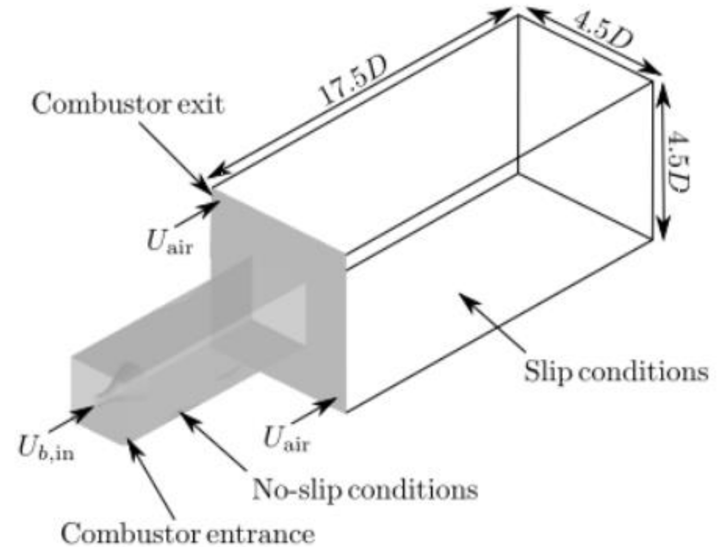
1. Dowling, A. P., & Mahmoudi, Y. (2015). Combustion noise. *Proceedings of the Combustion Institute*, *35*(1), 65-100.
2. Lighthill, M. (1952). On sound generated aerodynamically I. General theory. *Proc. R. Soc. London. Ser. A. Math. Phys. Sci*., 211(1107):564–587.
3. Dowling, A. P in Crighton, D. G., et al. (1992) Modern Methods in Analytical Acoustics, 5, 378–404. *Springer-Verlag, London*.
4. Swaminathan, N., et al. (2011). Heat release rate correlation and combustion noise in premixed flames. *Journal of Fluid Mechanics*, *681*, 80-115.
5. Liu, Y., & Echekki, T. (2015). In *21st AIAA/CEAS aeroacoustics conference* (p. 2970).

Description of cases



[6,7]



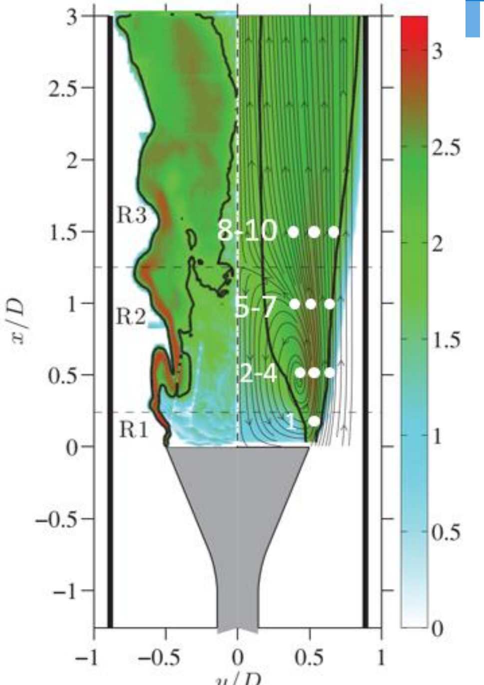
[8,9]

Case	ϕ_{glob}	$\dot{m}_a(gs^{-1})$	$\dot{m}_f(gs^{-1})$	SN	u'/s_L^o	$P_{therm}(kW)$
A	0.65	18.25	0.697	0.9	82.40	34.9
B	0.75	4.68	0.205	0.55	12.09	10.3
C	0.55	4.68	0.15	0.55	44.87	7.6

Case	ϕ_{glob}	$U_b(ms^{-1})$	u'/s_L^o
Bluff body	0.59	15	30.46

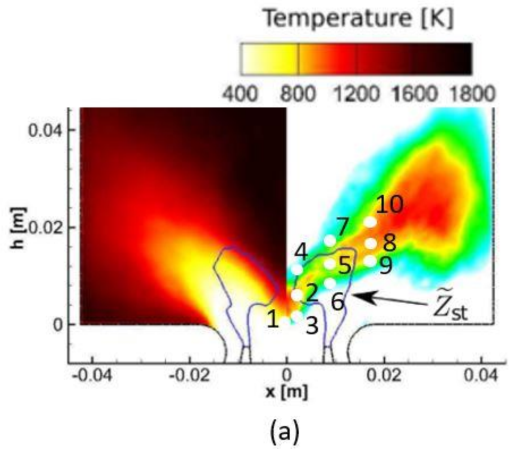
6. Meier, W., et al. (2006). *Combustion and Flame*, 144(1-2):225–236.
7. Weigand, P., et al. (2006). *Combustion and Flame*, 144(1-2):205–224.
8. Pan, J. C., et al. (1992). ASME. *J. Eng. Gas Turbines Power*. October 1992; 114(4): 783–789.
9. Nandula, S. P. (2003). Lean premixed flame structure in intense turbulence: Rayleigh/Raman/LIF measurements and modeling. PhD thesis, Vanderbilt University.

Computational resources and data processing

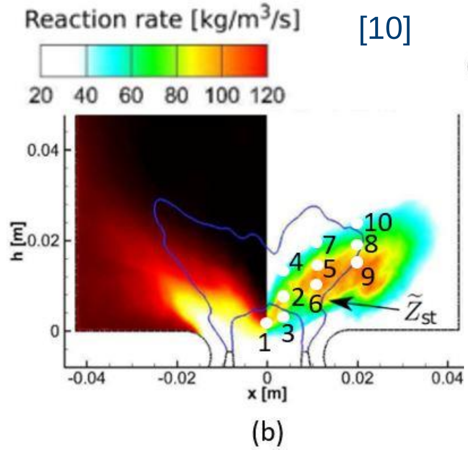


Bluff body

[12,13]

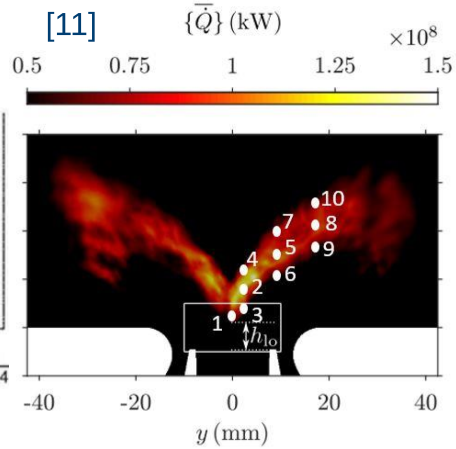


Flame A



[10]

Flame B



[11]

Flame C

$$R_{\phi}(\tau) = \frac{1}{2\overline{\rho}} \overline{\left[\rho(t)\dot{\phi}'(t)\dot{\phi}'(t+\tau) + \rho(t+\tau)\dot{\phi}'(t+\tau)\dot{\phi}'(t)\right]}$$

[14]

$$\psi_{\phi} = \int_V \mathcal{F}\left(R_{\phi}(\tau)\right)$$

Case	$\delta t(s)$	$\mathcal{T}(s)$	N_s	f_{N_s}
Flame A	5×10^{-5}	0.055	20000	10000
Flame B	1.2×10^{-5}	0.099	8333	4166
Flame C	7.5×10^{-5}	0.3	13333	6666
Bluff body	5×10^{-5}	0.2	20000	10000

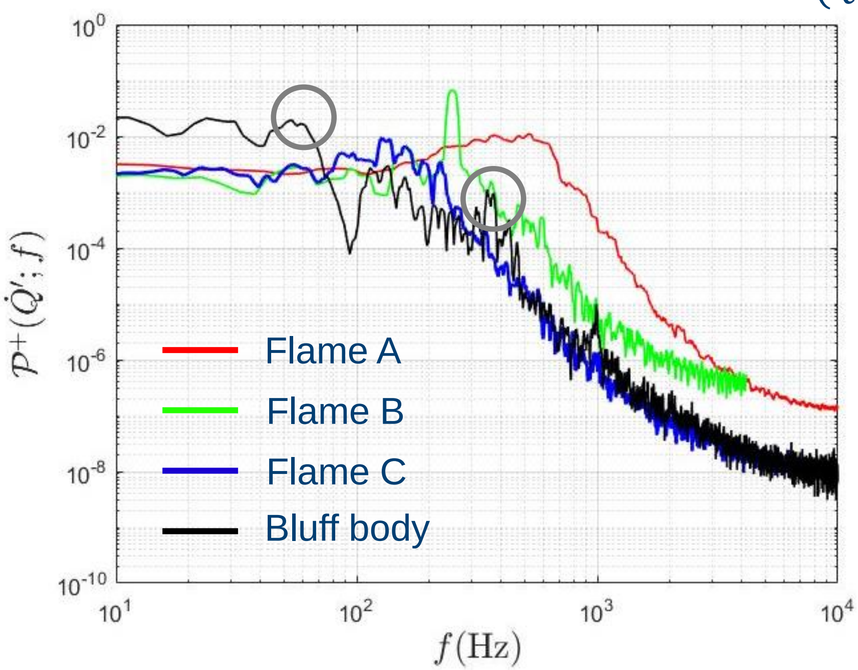
Code(s) used: OpenFOAM v2.3, v7 / FlaRe

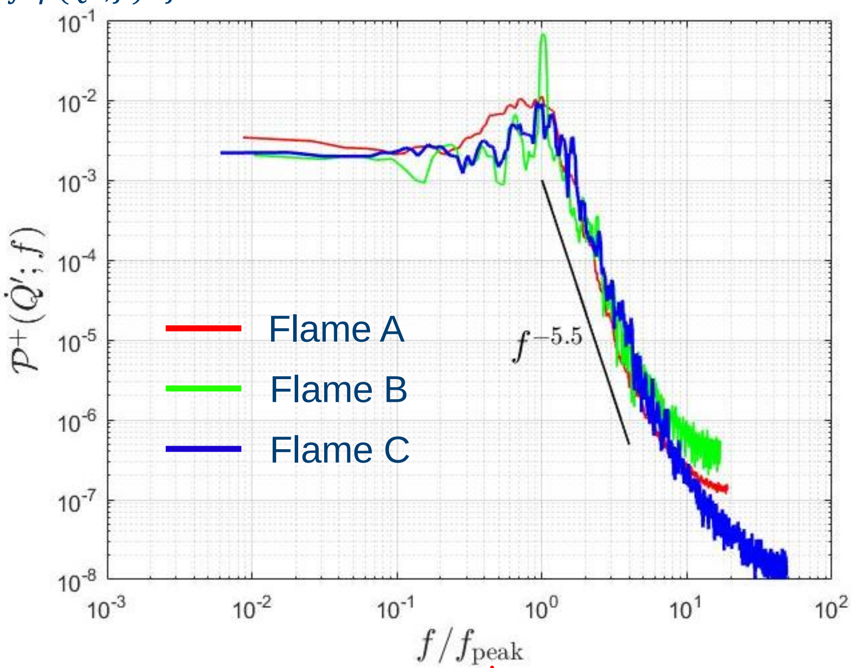
Time usage on ARCHER (approx. CUs): 19,375.00 (since 2019 which resulted in 7 publications)

10. Chen, Z. X., et al. (2019). *Combustion and Flame*, *203*, 279-300.
11. Massey, J. C., et al. (2021). *Flow, Turbulence and Combustion* 106(4), 1355-1378.
12. Langella, I., et al. (2016). *Combustion and Flame* 173, 161-178.
13. Massey, J. C., et al. (2019). *Journal of Fluid Mechanics* 875, 699-724.
14. Kolla, H., et al. On velocity and reactive scalar spectra in turbulent premixed flames. *Journal of fluid mechanics* 754 (2014): 456-487.

Spectrum of $\mathcal{P}^+(\dot{Q}'; f)$

$$\mathcal{P}^+(\dot{Q}'; f) = \frac{\psi(\dot{Q}'; f)}{\int \psi(\dot{Q}'; f)df}$$





$f_{\mathrm{peak}} \approx \frac{U_{\mathrm{b}}}{L_{\mathrm{flame}}}$ [14]

$f_{\mathrm{peak}} \approx \frac{\dot{V}}{V_{\mathrm{flame}}} \equiv f_{\mathrm{conv}}$

At high frequencies, $\mathcal{P}^+ \sim f^{-\frac{5}{2}}$ [15]

At high frequencies, $\mathcal{P}^+ \sim f^{-5.5}$

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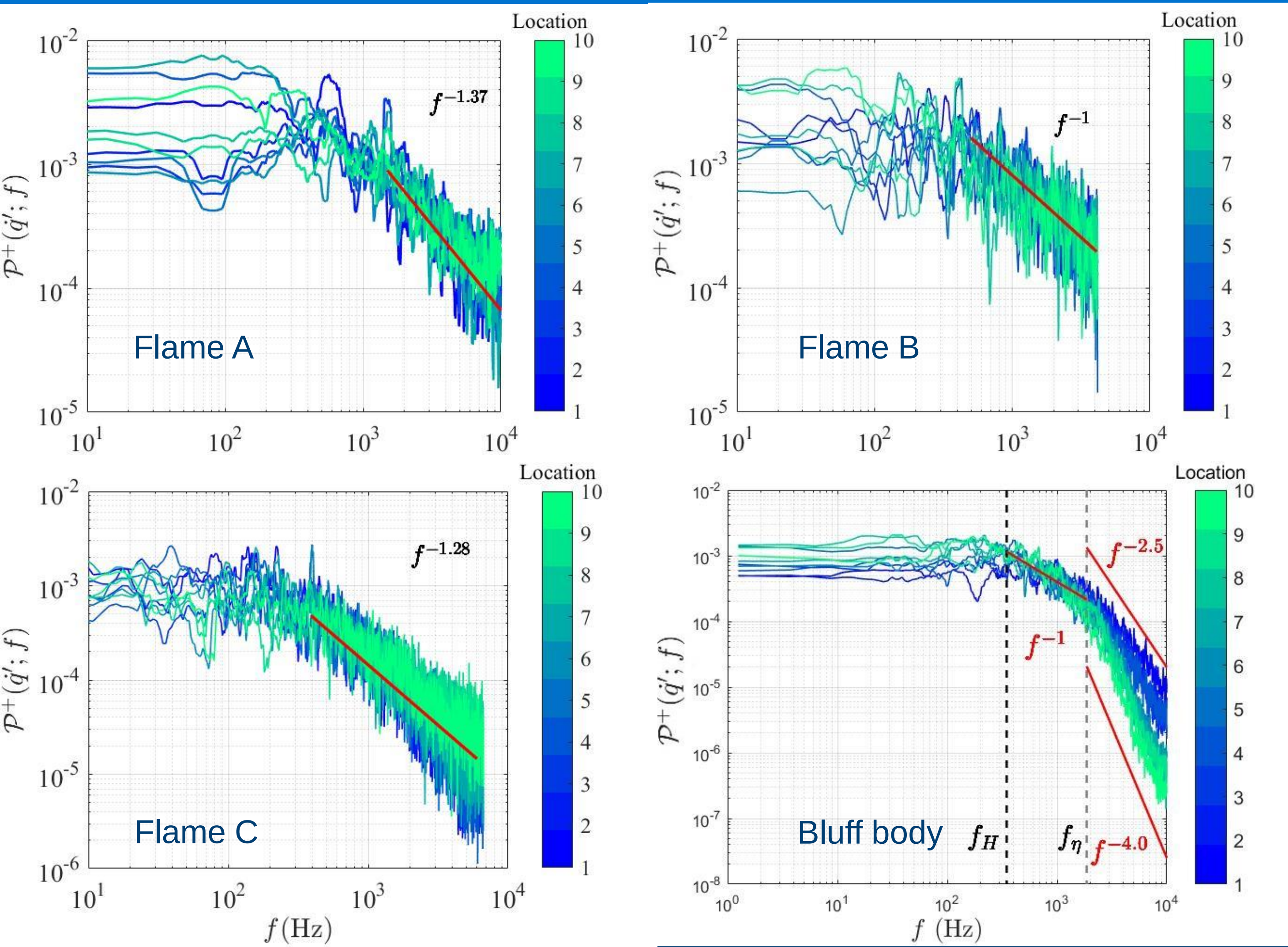
15. Rajaram, R., & Lieuwen,T. (2009). Acoustic radiation from turbulent premixed flames. *Journal of Fluid Mechanics* 637, 357-385.
16. Clavin, P., & Siggia, E. D. (1991). Turbulent premixed flames and sound generation. *Combustion Science and Technology*, *78*(1-3), 147-155.

Spatial variation of $\mathcal{P}^{+}(\dot{q}'; f)$



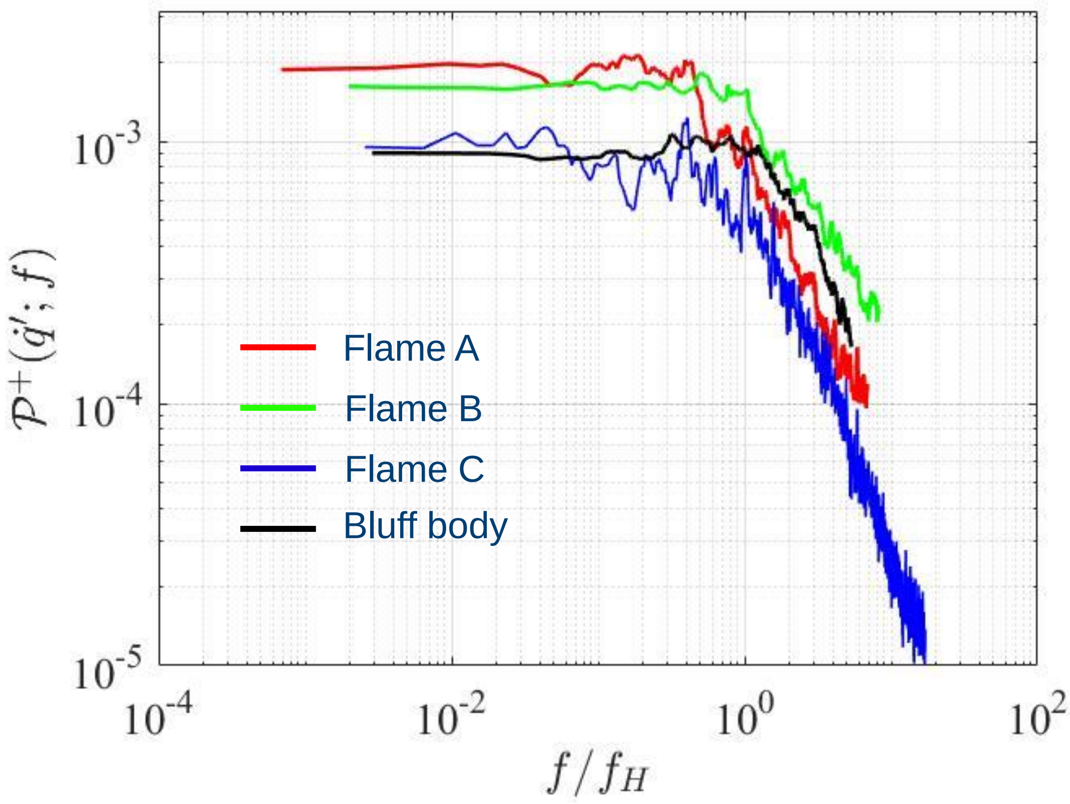
$$\mathcal{P}^{+}(\dot{q}'; f) = \frac{\psi(\dot{q}'; f)}{\int \psi(\dot{q}'; f)\,df}$$

[16,17]

12. Langella, I., et al. (2016). *Combustion and Flame* 173, 161-178.
14. Kolla, H., et al. On velocity and reactive scalar spectra in turbulent premixed flames. *Journal of fluid mechanics* 754 (2014): 456-487.

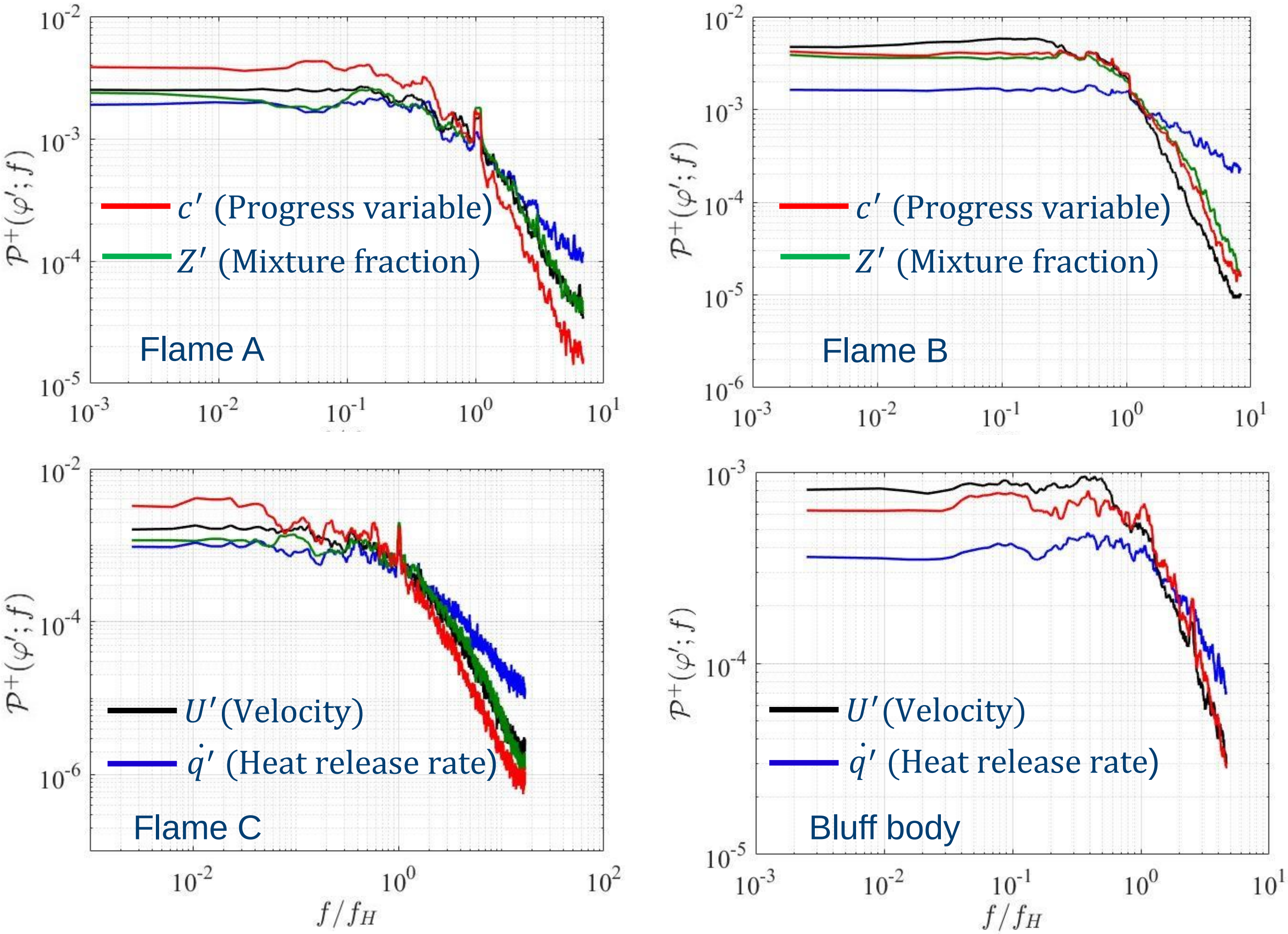
Spatial variation of $\mathcal{P}^+(\dot{q}'; f)$ – Mean spatial variation

$$\mathcal{P}^+(\dot{q}'; f) = \frac{\psi(\dot{q}'; f)}{\int \psi(\dot{q}'; f) df}$$



- Near constant behaviour at low frequencies.
- Roll off at higher frequencies at the rate : $f^{-\alpha}; \alpha = 1 \sim 1.37$.
- Reasonable frequency scaling with PVC and vortex shedding frequency.
- For $\mathrm{CH_4}$-air mixture the order magnitude of $\mathcal{P}^+(\dot{q}'; f)$ is similar irrespective of geometry.

Relation to turbulence and scalar spectra

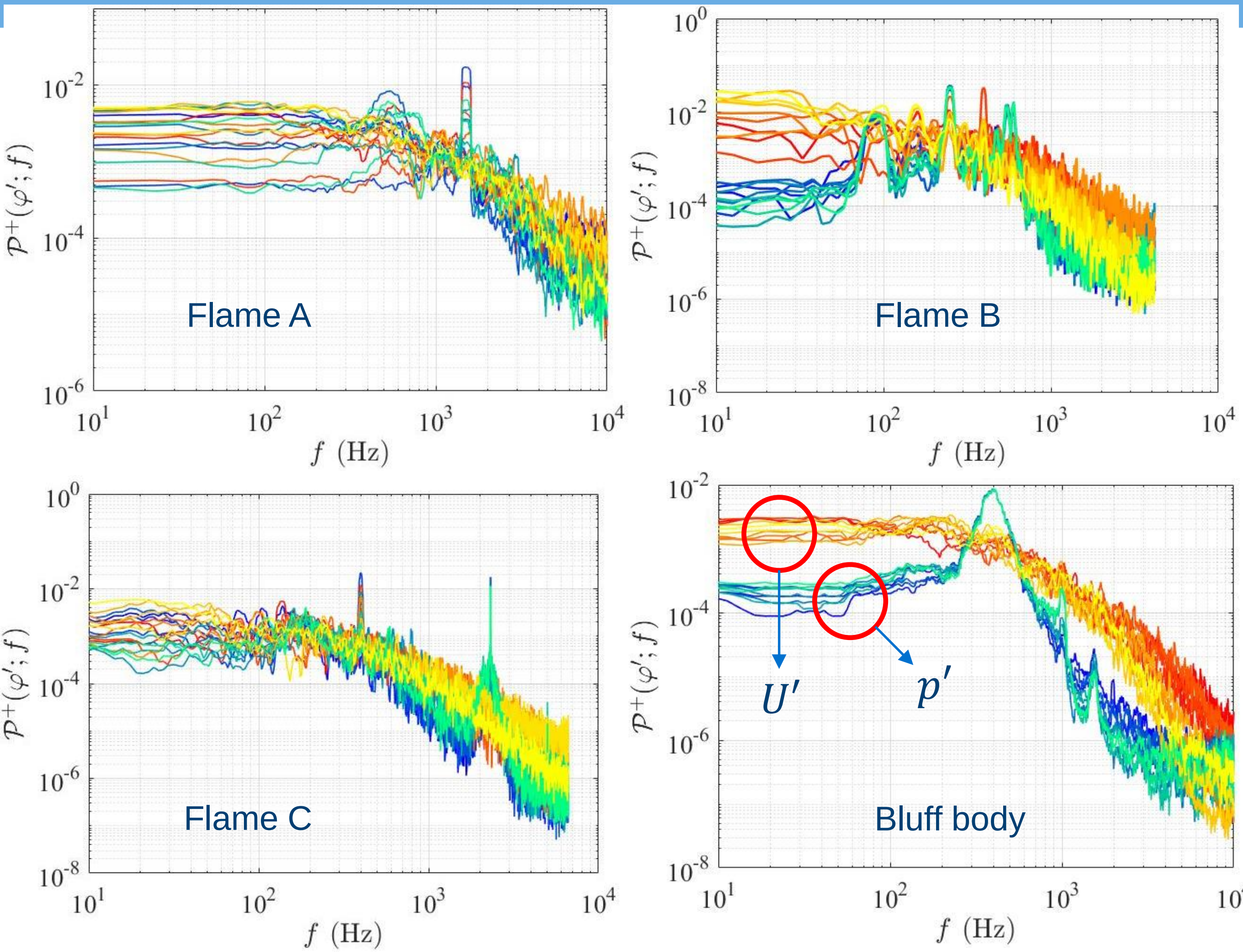


$$\mathcal{P}^{+}(\dot{q}'; f) = \frac{\psi(\dot{q}'; f)}{\int \psi(\dot{q}'; f)\, df}$$

- Flame A and C show close similarity to turbulence spectra.
- Like flame A and flame C, flame B and bluff body flames show a change in behaviour at f_H, but turbulence spectra starts to roll of at $f < f_H$.

17. Bilger, R. W. (2004). Some aspects of scalar dissipation. *Flow, turbulence and combustion*, *72*(2), 93-114.

Pressure-velocity coupling

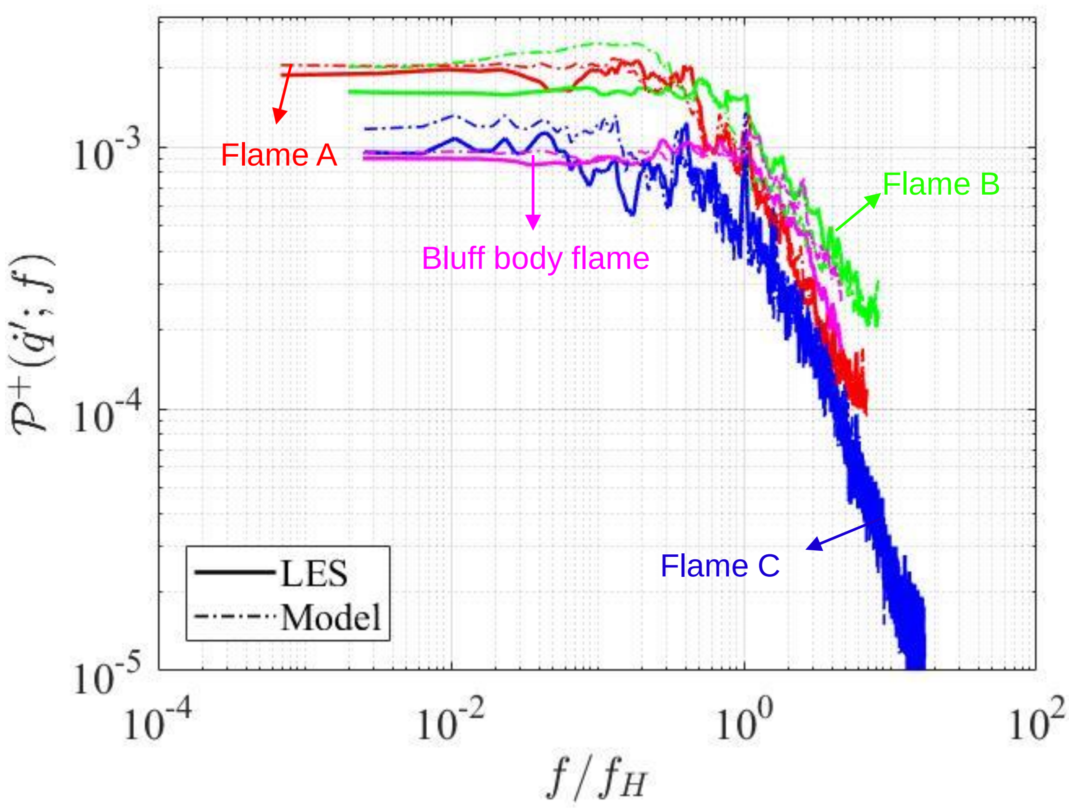


$$\mathcal{P}^+(\dot{q}'; f) = \frac{\psi(\dot{q}'; f)}{\int \psi(\dot{q}'; f)\, df}$$

- p' and U' in Flame A and C are strongly coupled and show similarities in spectral behaviour.
- Flame B and bluff body flames show significant deviations in low frequency regime.

Comparison of LES and model based on turbulence spectra

$$\mathcal{P}^+(\dot{q}';f) = \frac{\psi(\dot{q}';f)}{\int \psi(\dot{q}';f)df}$$

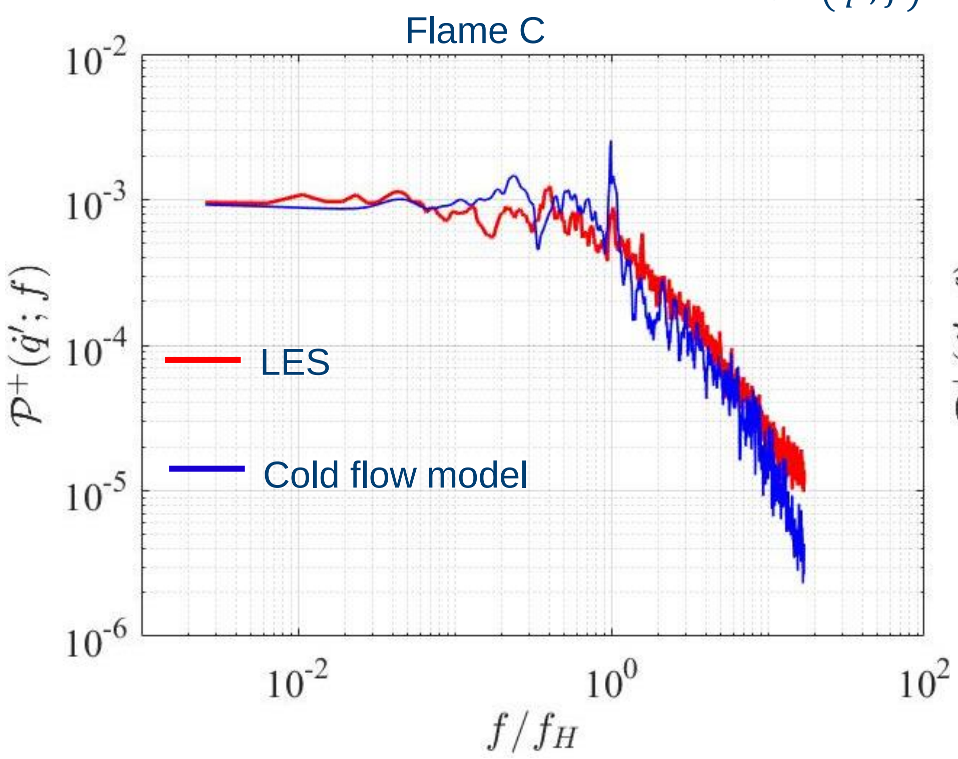


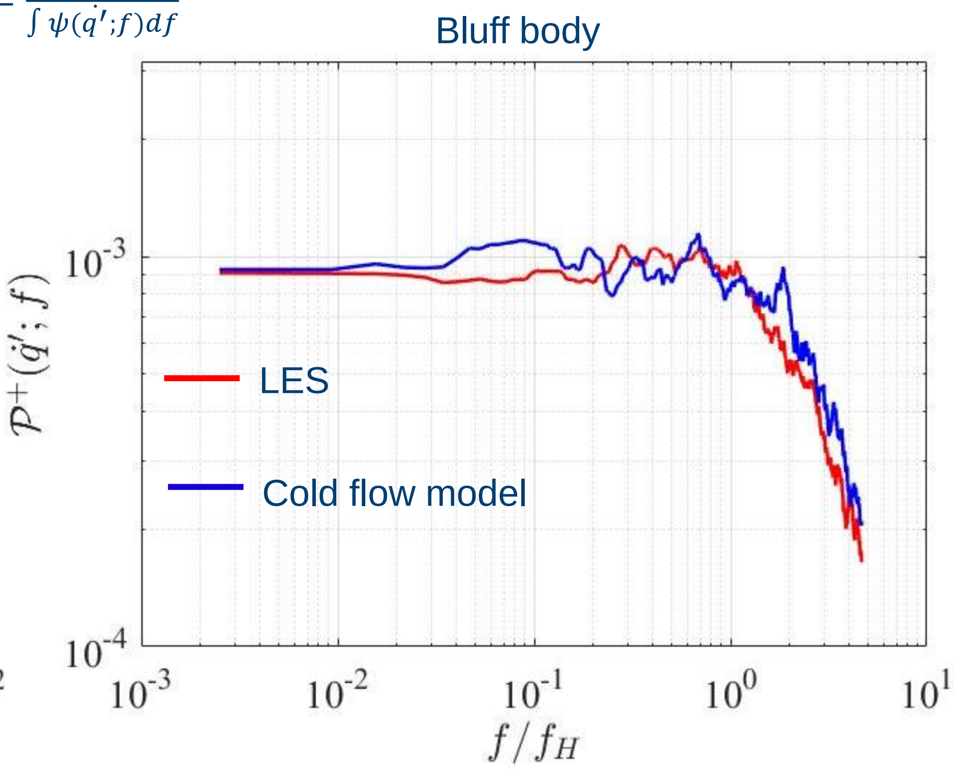
$$\frac{\mathcal{P}^+(\dot{q}';f)}{\mathcal{P}^+(U';f)} = \begin{cases} k_{1U}, & f/f_H < 1 \\ k_{1U}\left(\frac{f}{f_H}\right)^{k_{2U}}, & f/f_H \geq 1 \end{cases}$$

- $\mathcal{P}^+(\dot{q}';f)$ of Flame A and C show better agreement compared to flame B and bluff flames because of stronger correlation with hydrodynamic fluctuations.

Comparison of $\mathcal{P}^+(\dot{q}'; f)$ – LES and cold flow model ($\mathcal{P}^+(U'; f)$)

$$\mathcal{P}^+(\dot{q}'; f) = \frac{\psi(\dot{q}'; f)}{\int \psi(\dot{q}'; f)\,df}$$





Conclusions

- Spectra of volume integrated heat release rate(HRR) shows a -5.5 fall off rate at high frequencies as opposed to -2.5 predicted by previous theoretical work, and a convective frequency scaling is still prevalent with a modified definition.
- Spectra of local heat release rate is qualitatively similar in all flames with minimal spatial variation and shows a reasonable scaling with hydrodynamic frequencies.
- A similar qualitative trend is observed for the spectra of heat release rate, velocity and other scalars under reacting conditions.
- A model relating the velocity spectrum to HRR spectrum under reacting and non-reacting conditions is proposed.
- This model shows a good agreement for various (swirling and non-swirling) flames studied using LES.

Thank you for listening. Any questions?

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