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The effect of swirl on the flame transfer function of premixed flames

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Motivation

- Thermoacoustic instabilities are major challenge in the industry.
- While the flame response for simple non-swirling flames is fairly well understood, swirling flames are a lot more complicated.
- Multiple experiments have been conducted in the last decade and while they have provided some insight into the behaviour of forced swirling flames, we still need better understanding of them.
- Relevant LES studies are scarce, however, they can provide very useful data that are challenging to obtain experimentally.
- This study attempts to close this gap by performing a series of LES on forced swirling bluff body flames.

Previous Research

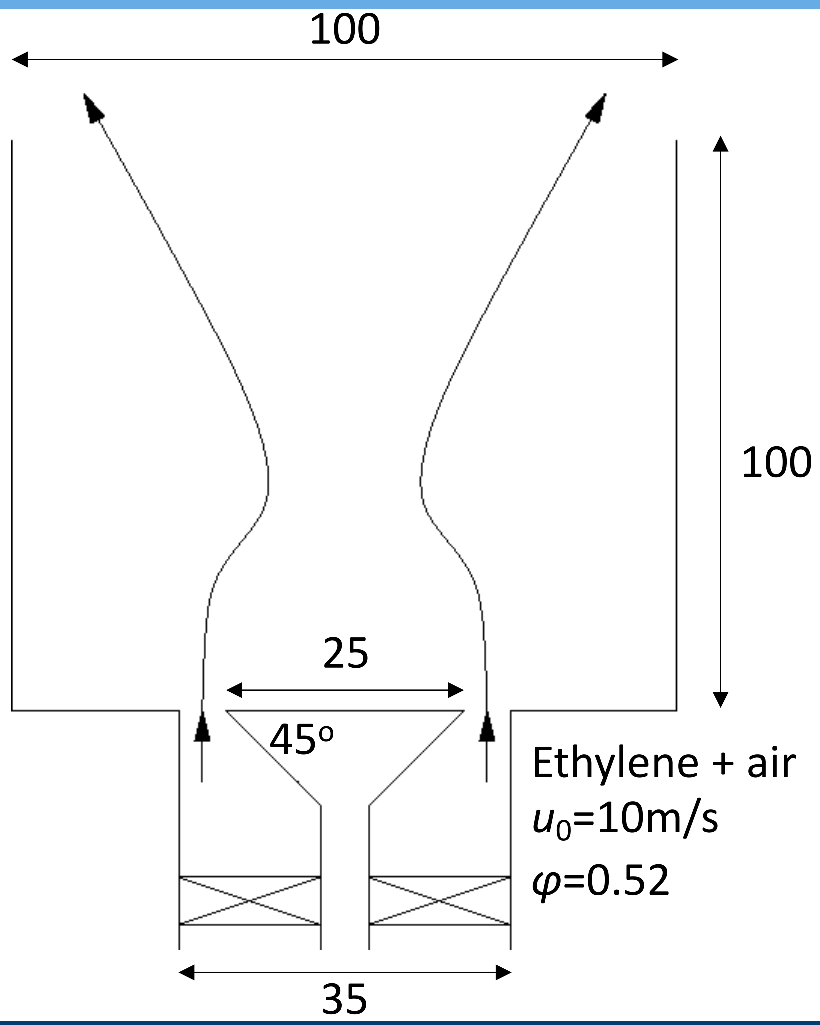
- A trough in the FTF of swirling flows was first observed by Hirsch et al.[1] when they investigated the effect of the injector design on the Flame Transfer Function

- Subsequently, Palies et al.[2] observed that azimuthal disturbances travel at the bulk velocity while axial disturbances travel at the speed of sound and this causes swirl number oscillations at the root of the flame. It was suggested that when the swirl number fluctuations are maximised the FTF gain is minimum.
- While this assumption held well in some cases that were investigated, some conflicting results exist about how the level of swirl affects this.

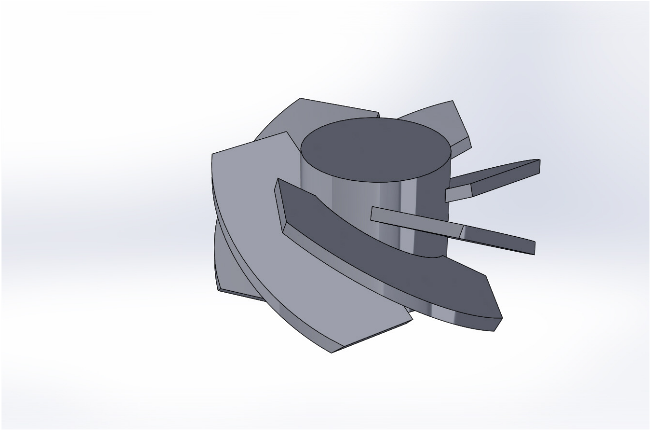
- In a recent study by Liu et al[3], it was observed that the heat release oscillations manifest near the flame tip rather than the base.

1. Hirsch et al., (2005), Proc. ASME Turbo Expo, 11(1)
2. Palies et al., (2010), Combust. Flame, 157(9)
3. Liu et al., (2022), Combust. Flame, 235

Configuration

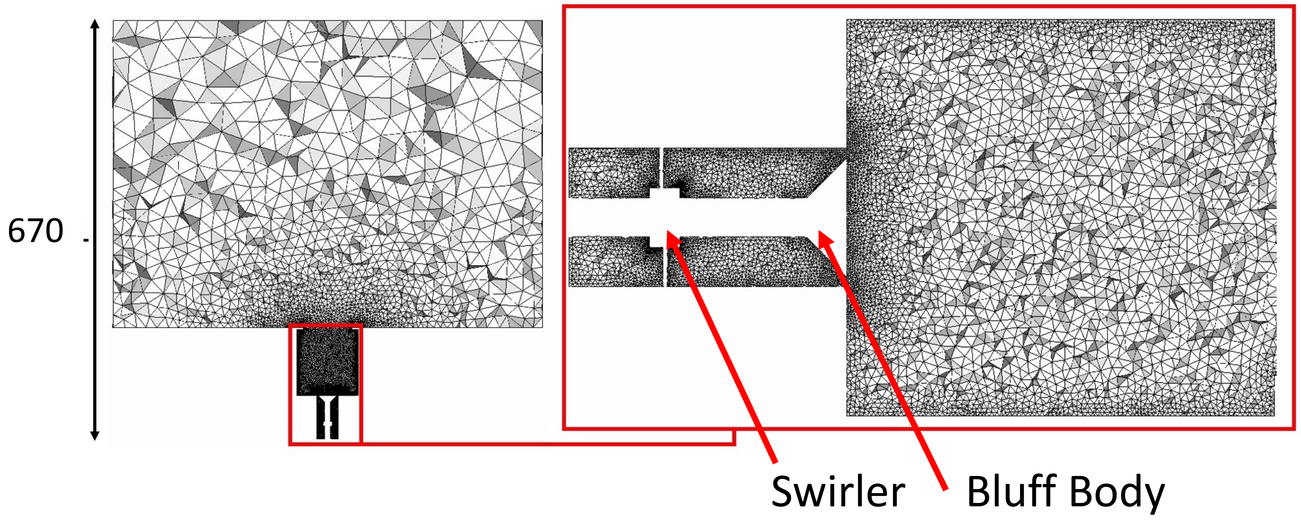


- The burner consists of a square enclosure, a conical bluff body which produces a 50% blockage ratio and an axial swirler placed upstream of the bluff body base (dump plane).
- Two swirlers with flat vanes are used. One with 45^0 angle (S45) which produces a swirl number S=0.44 and one with 60^0 (S60) which gives S=0.56.



- Fully premixed ethylene and air enter the combustor at a bulk velocity of 10 m/s.
- Both experiments and LES are performed.

Computational Setup



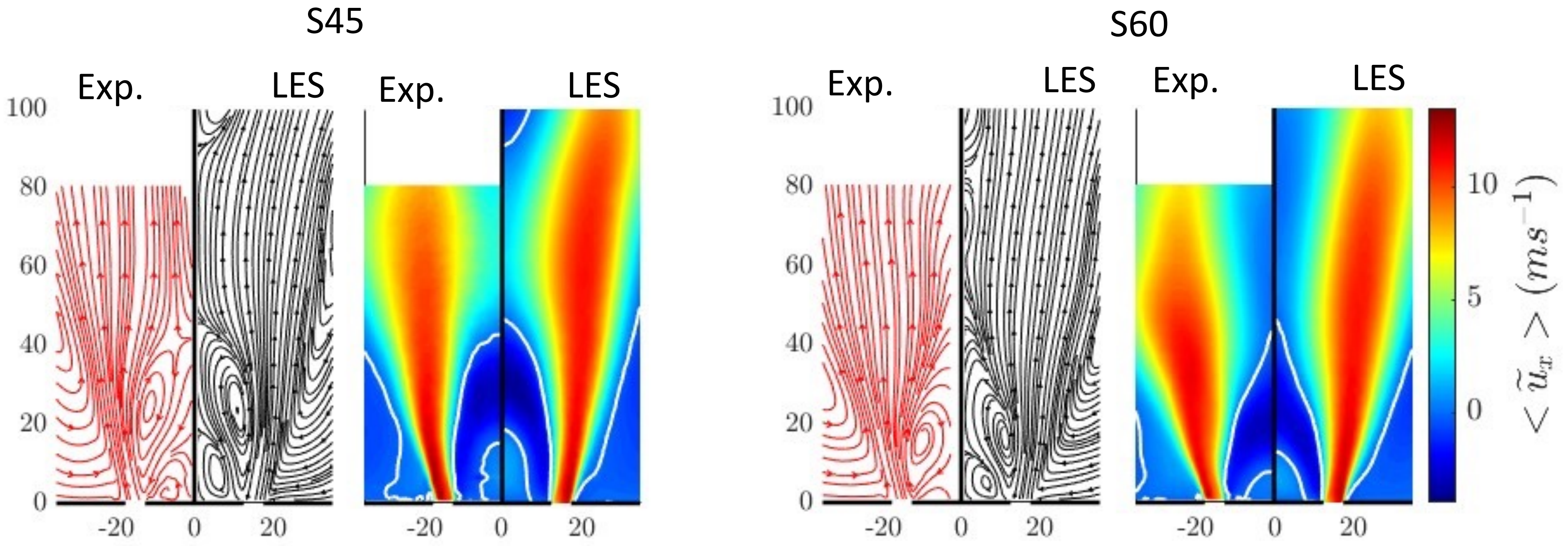
- Dynamic Smagorinsky Model for subgrid turbulence
- Cambridge FlaRe model for combustion
- 2.5 million tetrahedral cells
- Extended domain as the VBB extends outside the confined region of the combustor and the outlet conditions are unambiguous
- Second order numerical schemes for spatial derivatives and first order time scheme
- Statistics are obtained for at least 10 flow through times for the unforced simulations
- Computation cost is roughly 100-200 CUs.

Forcing

- In experiments, the flame is excited by two speakers positioned in a plenum upstream of the swirler. The amplitudes are obtained using the two microphone method.
- Heat Release oscillations are obtained through OH*.
- The forcing level was set to A=0.07 of the mean bulk velocity in experiments. This was replicated in the LES by applying a sinusoidal boundary condition for velocity upstream of the swirler.
- In experiments, measurements of the FTF are taken after a few minutes when the combustor walls are hot and a Fast Fourier Transform (FFT) for a period of 2 seconds is calculated.
- For the computations, it was found that 30 cycles after the initial transient are enough to obtain a reliable FTF estimate.
- A range of frequencies between 70 Hz and 300 Hz are considered both computationally and experimentally.

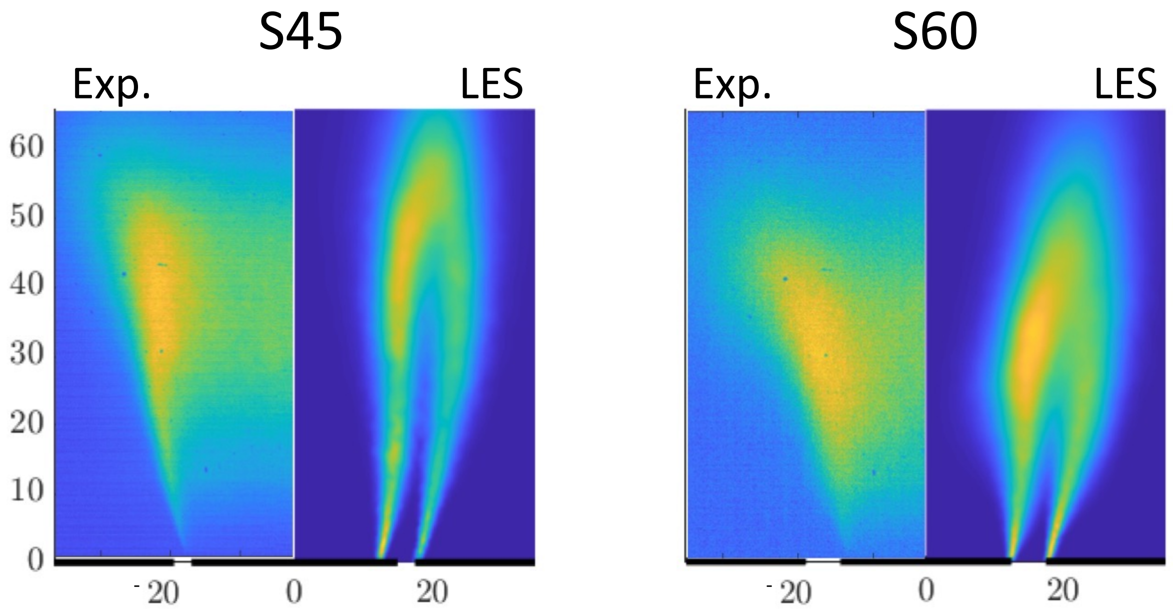
Validation – Flow Field

- The unforced characteristics of the cold and hot flow have been thoroughly described in a previous study[1] and good agreement has been observed in terms of the flow features of this configuration under cold and hot conditions.
- The computed length and shape of the recirculation zone match well the experiment in hot flow as seen below



1. Kallifronas et al. (2022), Combust. Sci. Technol.

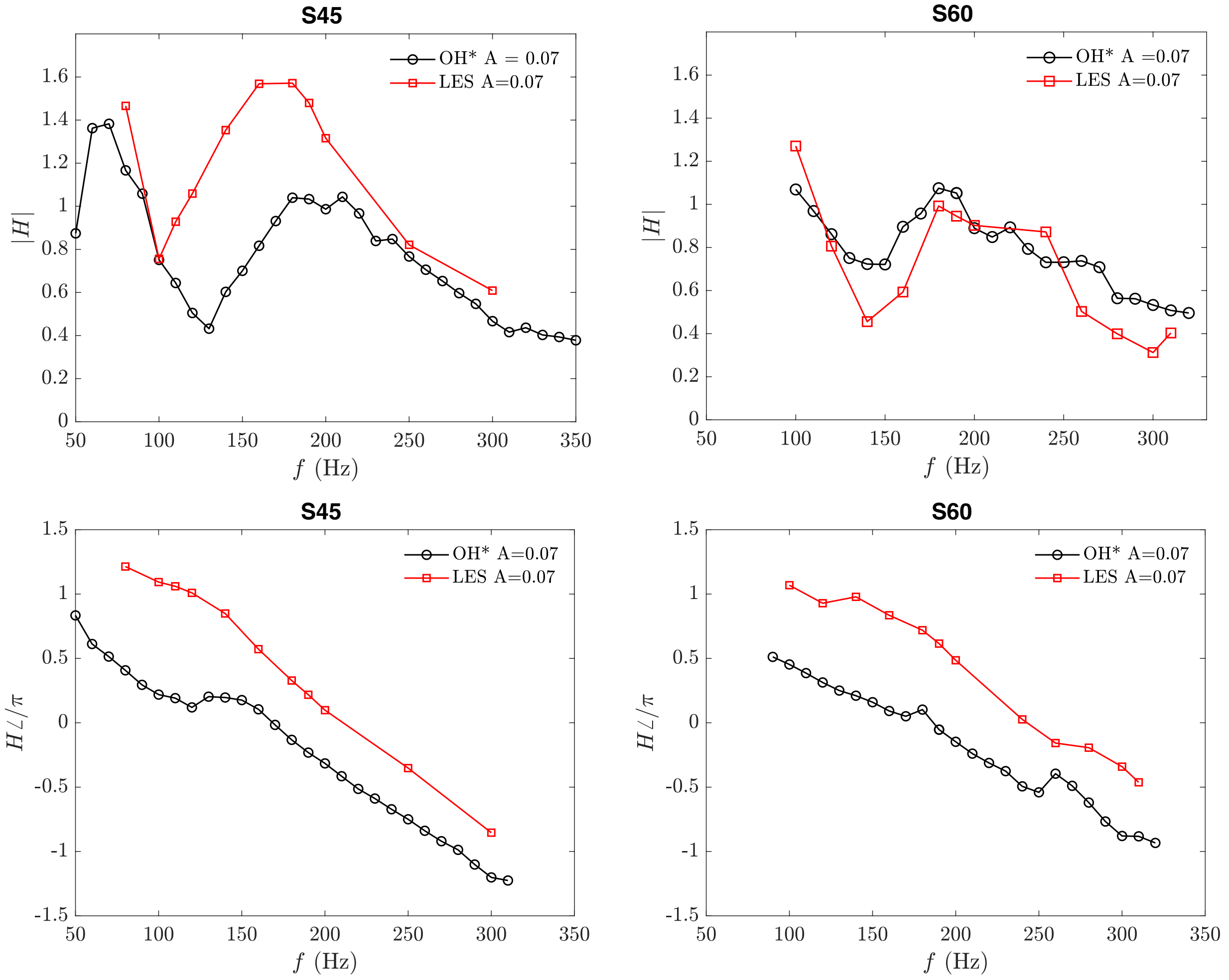
Validation – Flame Shape



- The computed flame shapes for both S45 and S60 flames match well the experiment in terms of flame height, brush size and reaction rate distribution.
- Stronger reaction rate is observed on the outer flame in the LES which is a result of the adiabatic conditions used at the walls.
- There is some evidence that in non-swirling flames this affects the phase of the FTF/FDF[1], in other studies adequate results have been obtained using adiabatic conditions[2,3]

1. Cheng et al., (2021), AIP Advances, 11(1)
2. Han & Morgans, (2015), Combust. Flame, 162(5)
3. Ruan et al., (2016), Combust. Sci. Technol, 188(7)

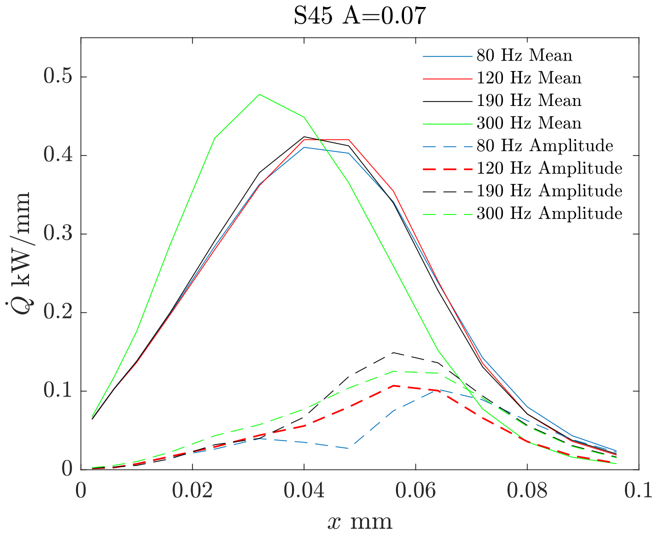
Flame Transfer Function

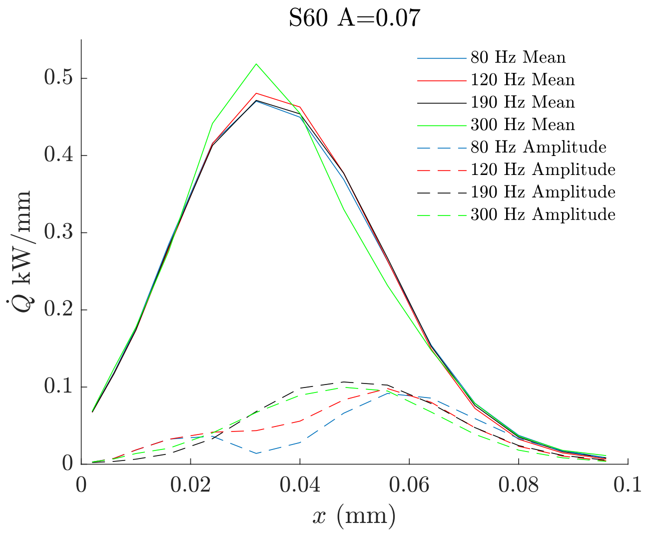


- In both the S45 and S60 flames, the characteristic trough can be observed, followed by a second peak.
- The trough shifts to a higher frequency and the peak to a lower one when the swirl increases.
- The phase of the FTF is increased slightly when swirl is increased.
- Good agreement is observed for the gain in case S60. The gain is overpredicted for case S45.
- In both cases there is an almost constant overprediction in the phase.
- While the exact cause is still under investigation, the simulations correctly capture all the trends.

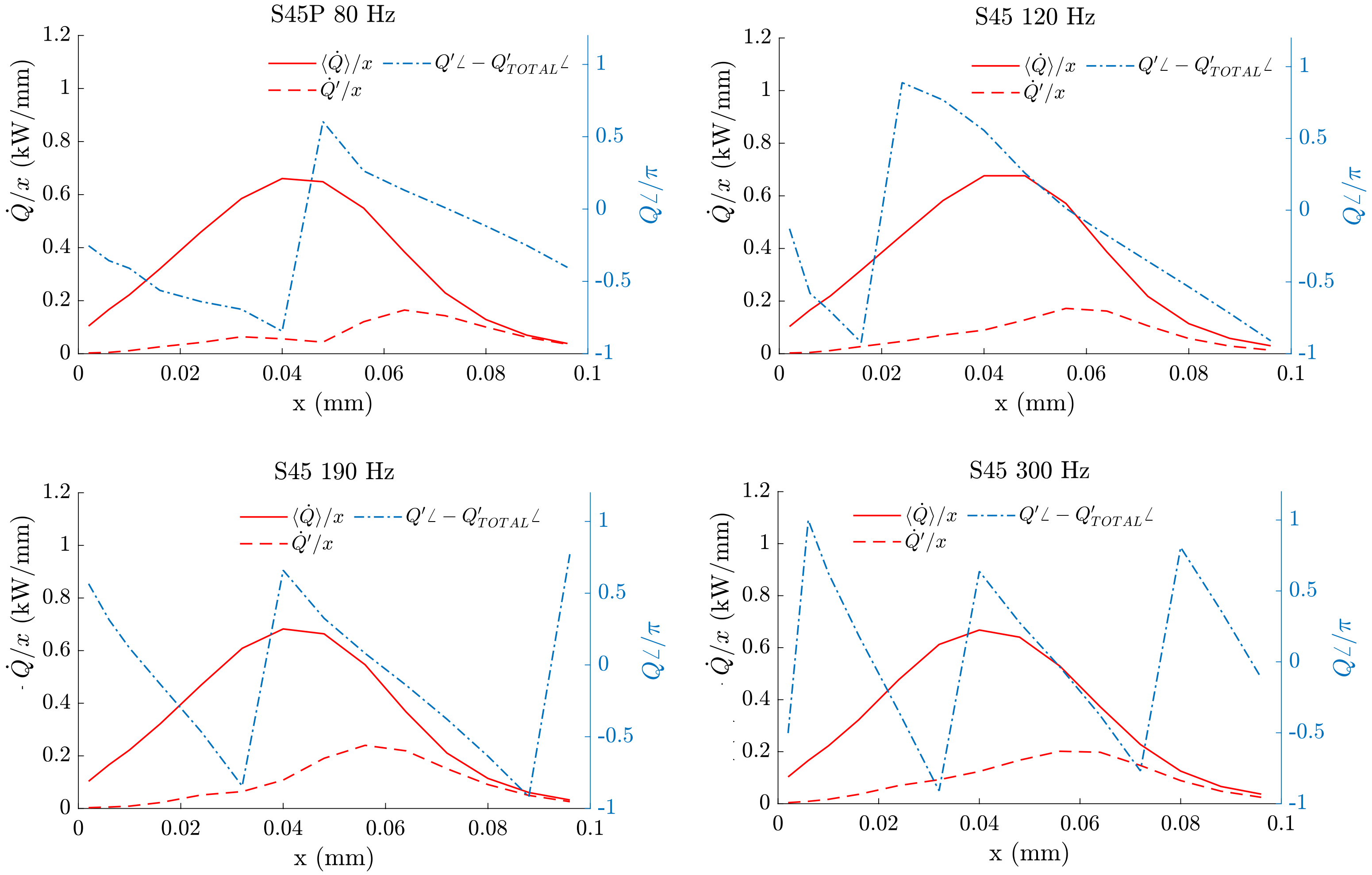
Heat Release Oscillations

- The shift in the trough can be understood by considering the variation of mean heat release rate and heat release rate fluctuations as a function of streamwise distance.
- For the S45 flame, the peak mean heat release rate occurs further downstream compared to S60.
- The heat release rate fluctuation at all frequencies occur near the tip of the flame which suggests that the flame base dynamics do not have an important role.





Swirl



- IAt 80 Hz, due to the large convective wavelength, almost the entire flame is in phase.
- At 120 Hz, parts of the flame are out of phase and this reduces the flame response.
- At 190 Hz, the peak heat release rate amplitude is higher.
- At 300 Hz, the peak heat release rate amplitude is still high, but now the convective wavelength is small and many part of the flame are out of phase.

Conclusions

- The amount of swirl can affect the characteristics of the Flame Transfer Function significantly.
- While some differences were observed between the measured and computed FTF, LES was able to captures correctly the trends associated with the two configurations studied.
- Most of the heat release rate fluctuations occur near the tip of the flame.
- An increase in swirl can change the location of the trough and peak as the spatial distribution of the local heat release rate fluctuation is altered by swirl. This is associated with parts of the flame being at different phases with respect the heat release rate fluctuations.

Questions?

Thank you