Wall-Temperature Effects on Flame Response to Acoustic Oscillations

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INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE

Introducing Exascale Computing in Combustion Instabilities Simulations

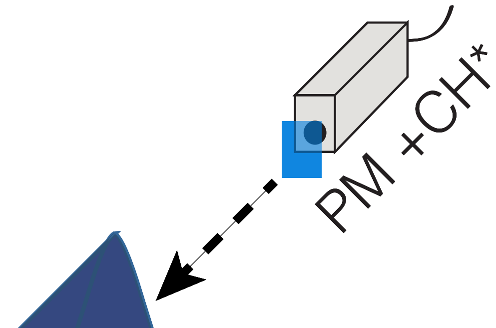
Context

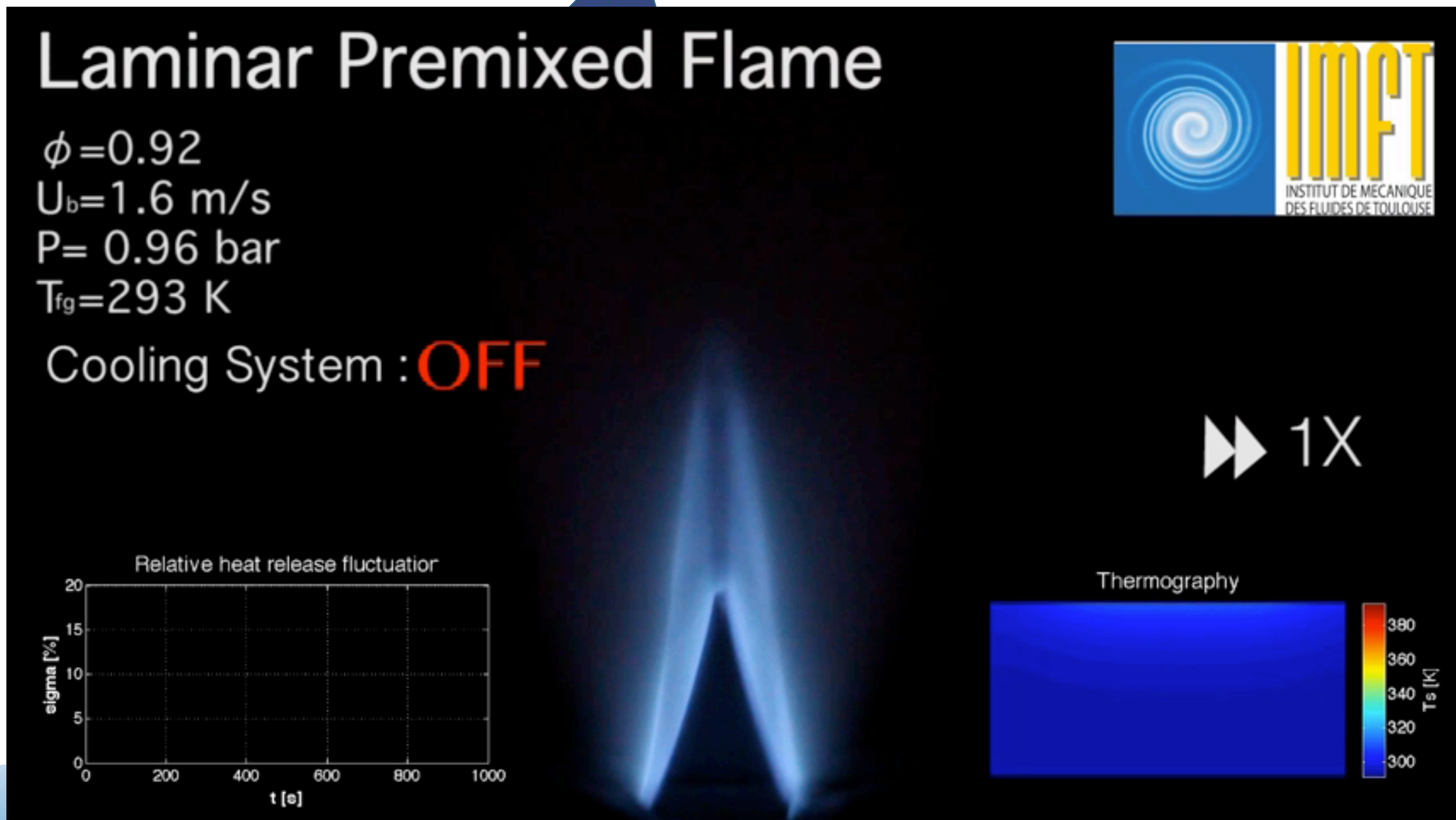
★ This work focuses on the study of **combustion instabilities (CI's)**.

★ The challenge for understanding and predicting CI's lies in the **multiplicity of physical phenomena** involved. We are only going to address **one specific question**:

> Why do most systems behave differently at cold start and in permanent regime?

★ One of the **canonical configurations** for the study of CI's is the **laminar premixed flame**, for which, there already exist analytical solutions for the flame response to acoustic perturbation.


PM +CH*


Laminar Premixed Flame
ϕ=0.92
Ub=1.6 m/s
P= 0.96 bar
Tfg=293 K
Cooling System : OFF
1X
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Relative heat release fluctuatior
sigma [%]
t [s]
0
200
400
600
800
1000
0
5
10
15
20
Thermography
Ts [K]
300
320
340
360
380

Outline

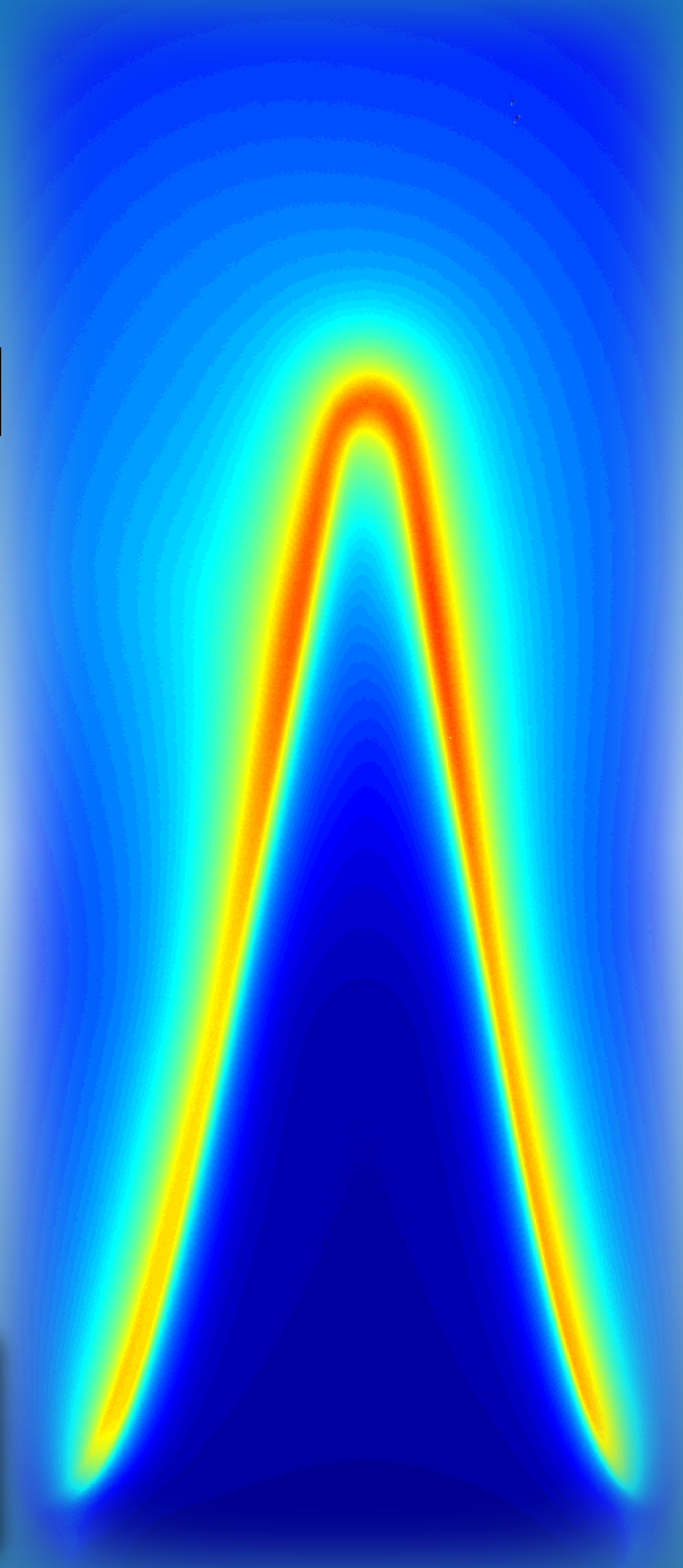
Part I:
Stability model

Five parameters

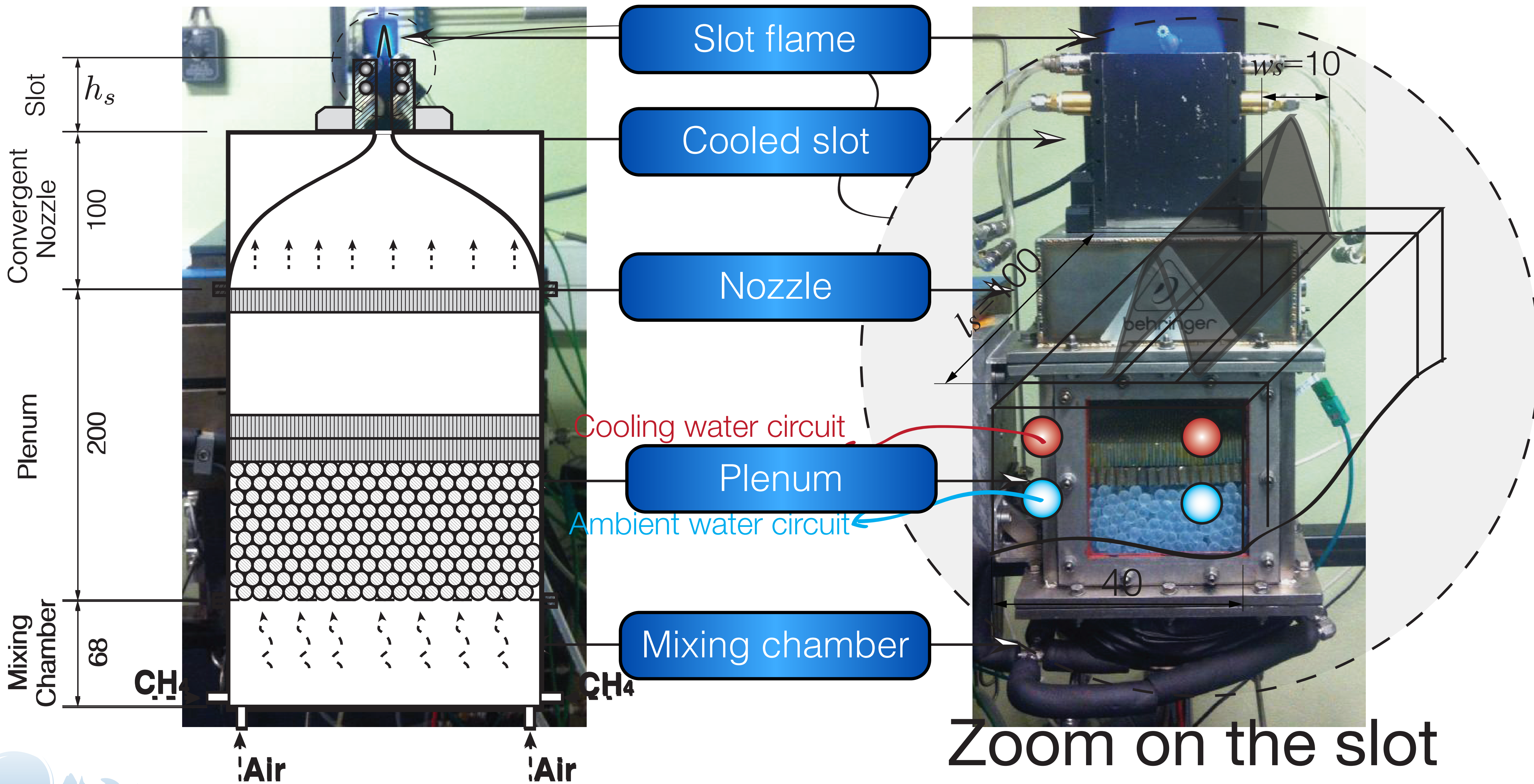
50 °C
90 °C
120 °C

Part II:
Experimental Measurements

Part III:
Flame Dynamics



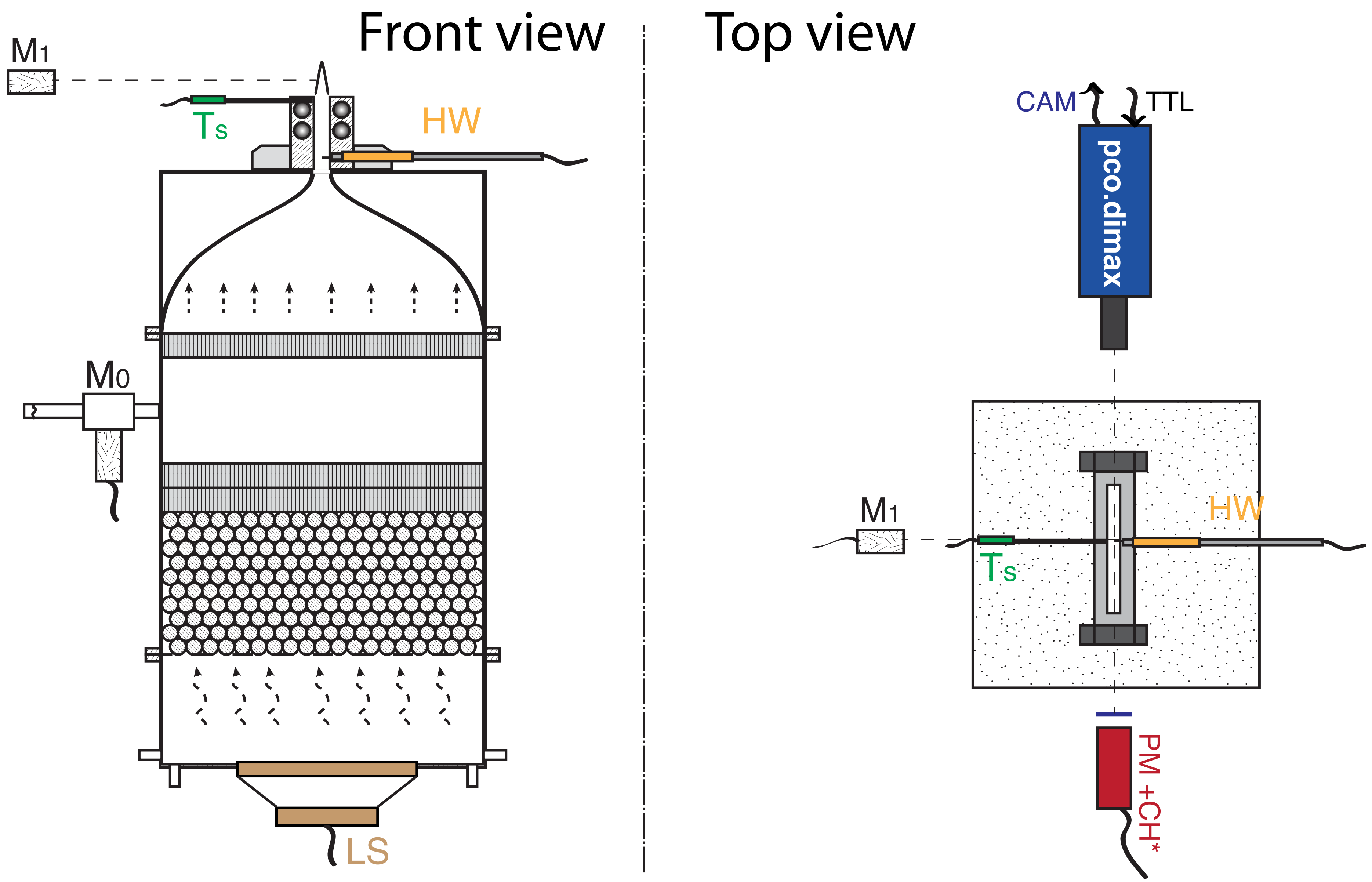
1. Experimental set-up



[1] Selle *et al.* 2011 *cf.*

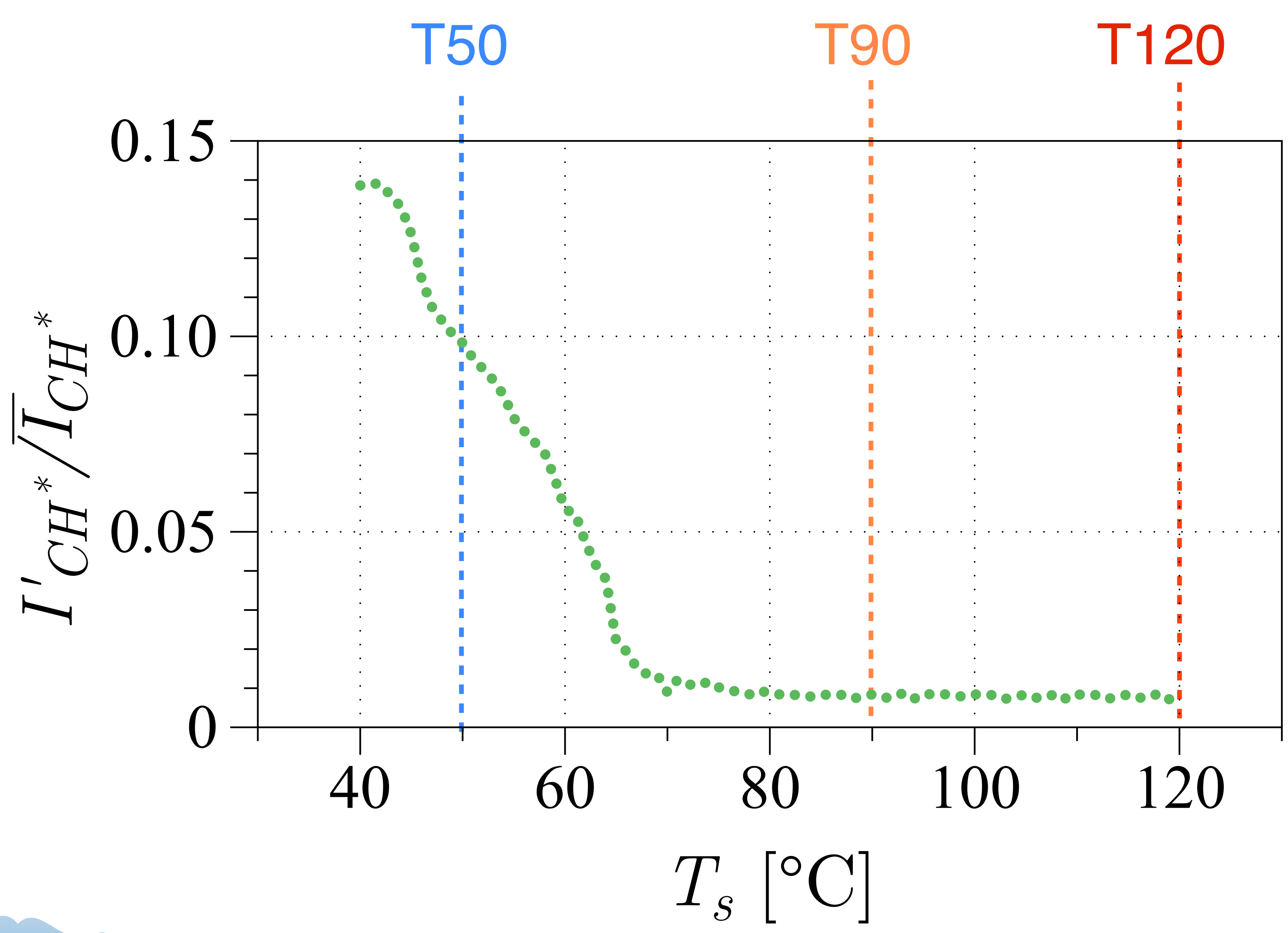
Diagnostics

- ★ Acoustic pressure (two microphones),
- ★ velocity (hot-wire),
- ★ heat release rate (photomultiplier + CH* filter),
- ★ temperature (k-thermocouple),
- ★ flame visualization (high speed camera),
- ★ flow modulation (loud-speaker).

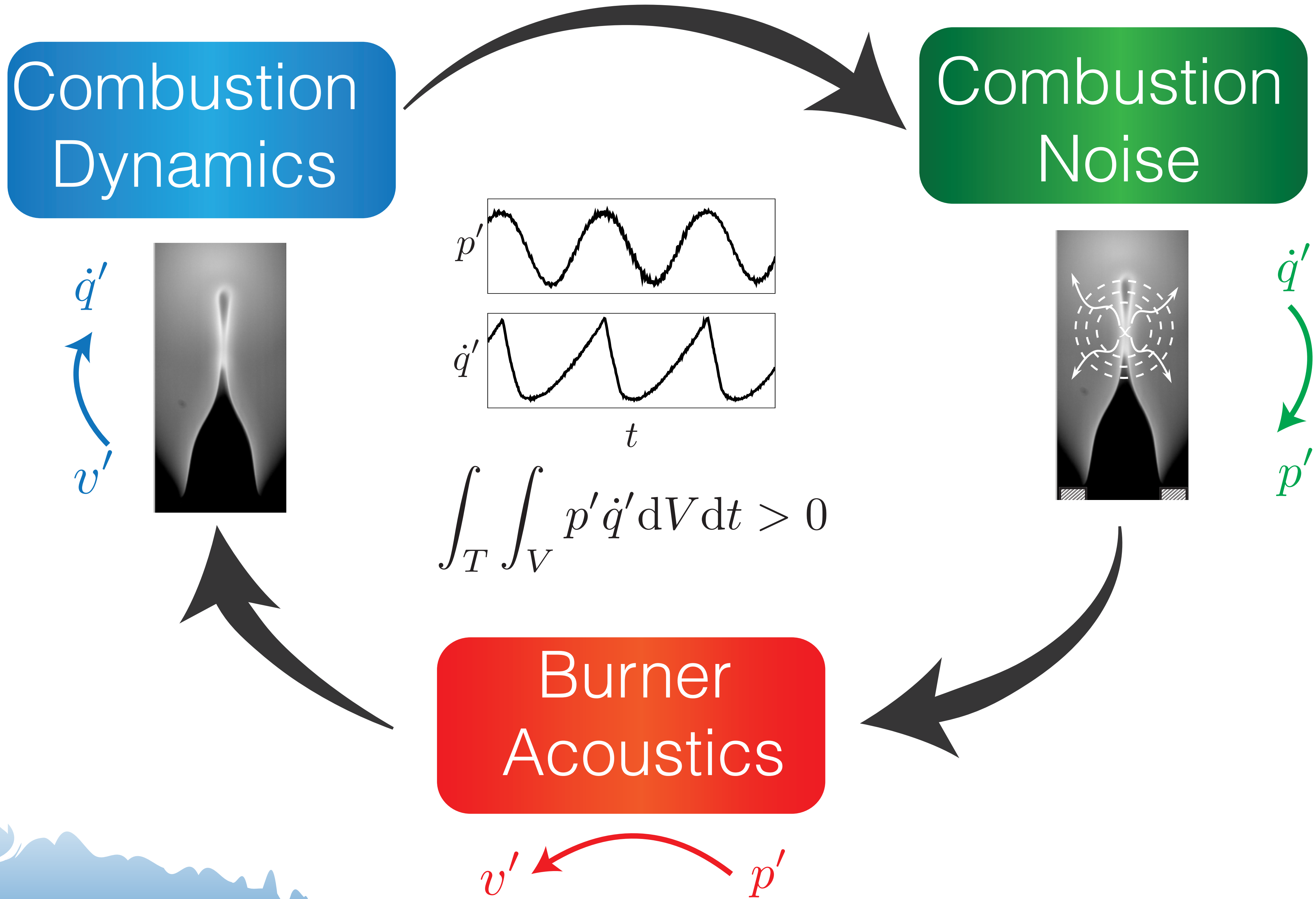


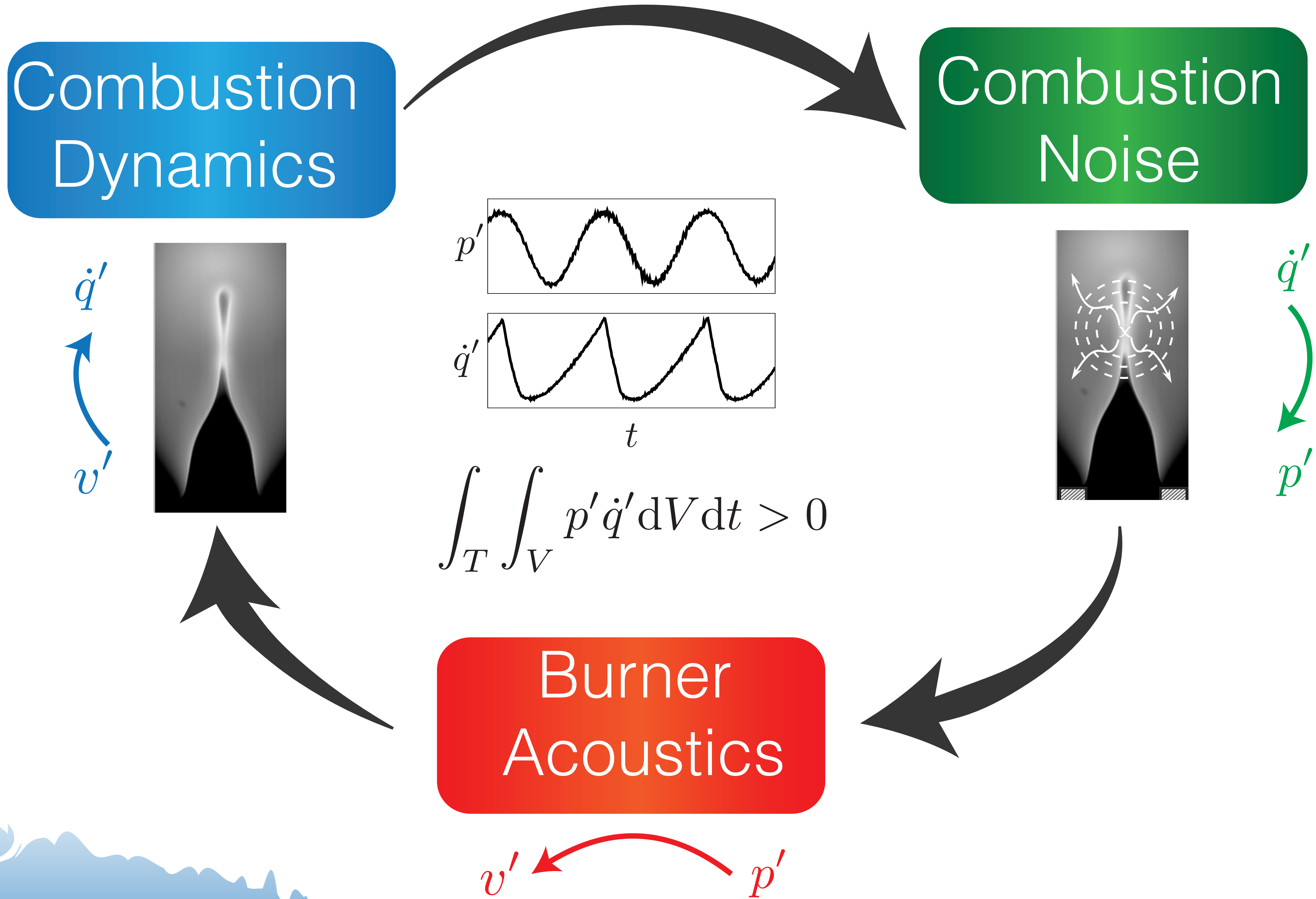
Controlled wall temperature analysis

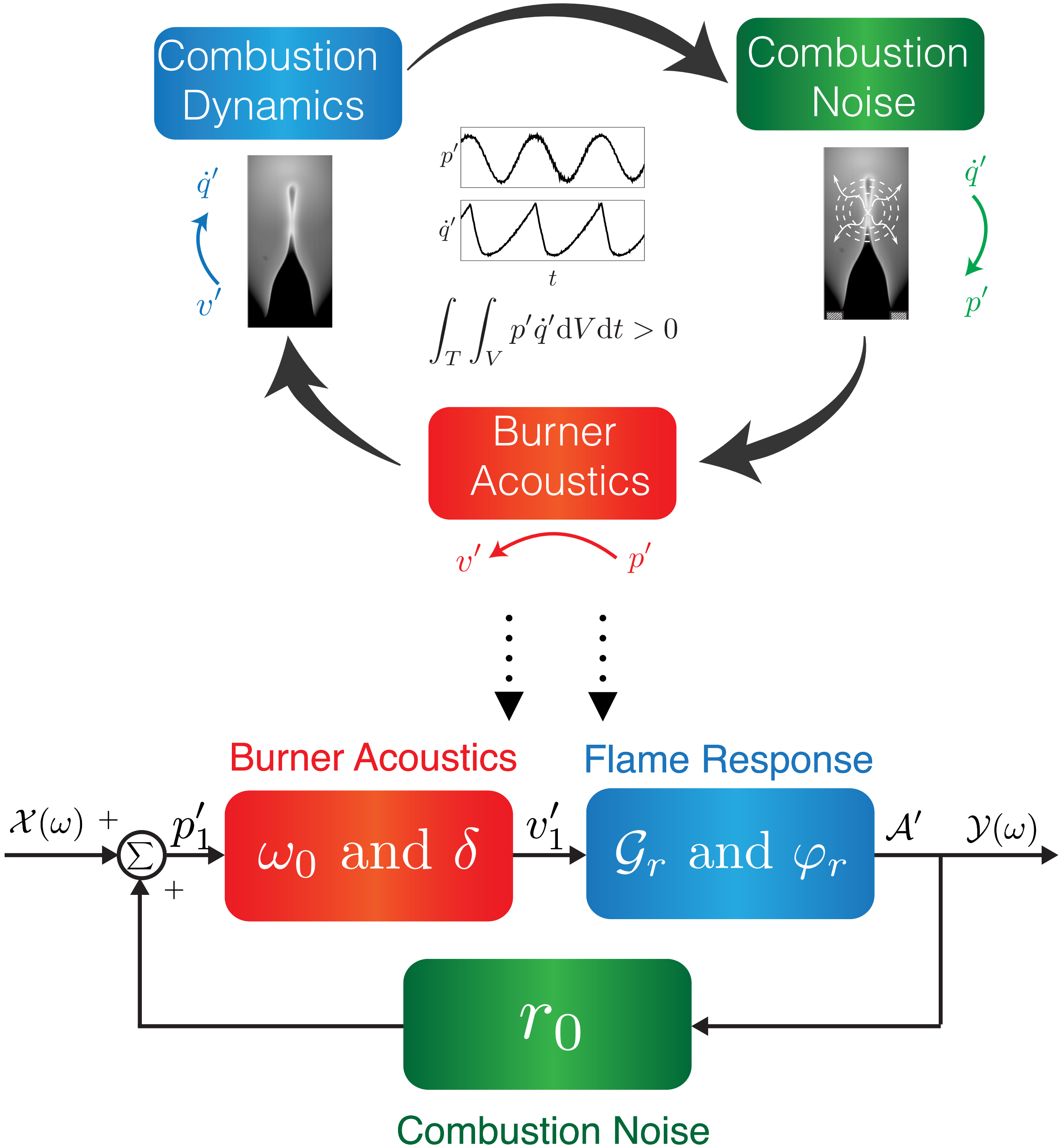
$f_r = 58$ Hz



3. Stability model




Combustion Dynamics
Combustion Noise
Burner Acoustics
$\dot{q}'$
v'
p'
$\dot{q}'$
t
$\dot{q}'$
p'
v'
p'
$\int_T \int_V p'\dot{q}' \mathrm{d}V \mathrm{d}t > 0$



[1] Pierce 1981.
[2] Rienstra 1983 *jsv.*
[3] Schuller *et al.* 2003 *cf.*
[4] Durox *et al.* 2009 *cf.*
[5] Crocco 1951 *jars.*
[6] Keller and Saito 1987 *cst.*
[7] Strahke 1971 *jfm.*
[8] Clavin and Siggia 1991 *cst.*

Dispersion relation:

$$\left[1 + \mathcal{N} e^{i\varphi(\omega)}\right] \omega^2 + 2i\delta\omega - \omega_0^2 = 0$$

Interaction index:

$$\mathcal{N} = \frac{1}{4\pi} \frac{S_s(E-1)}{h_e} \frac{\mathcal{G}(\omega)}{r_0}$$

The solution of the system is:

$$\omega = \omega_r + i\omega_i$$

$\Re(\omega) = \omega_r \rightarrow$ Resonance frequency

$\Im(\omega) = \omega_i \rightarrow$ Growth rate

The system will develop combustion instabilities if:

$$\omega_i > 0$$

For fixed operating conditions, the stability of the system depends on **five parameters !**

Outline

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Five parameters

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90 °C

120 °C

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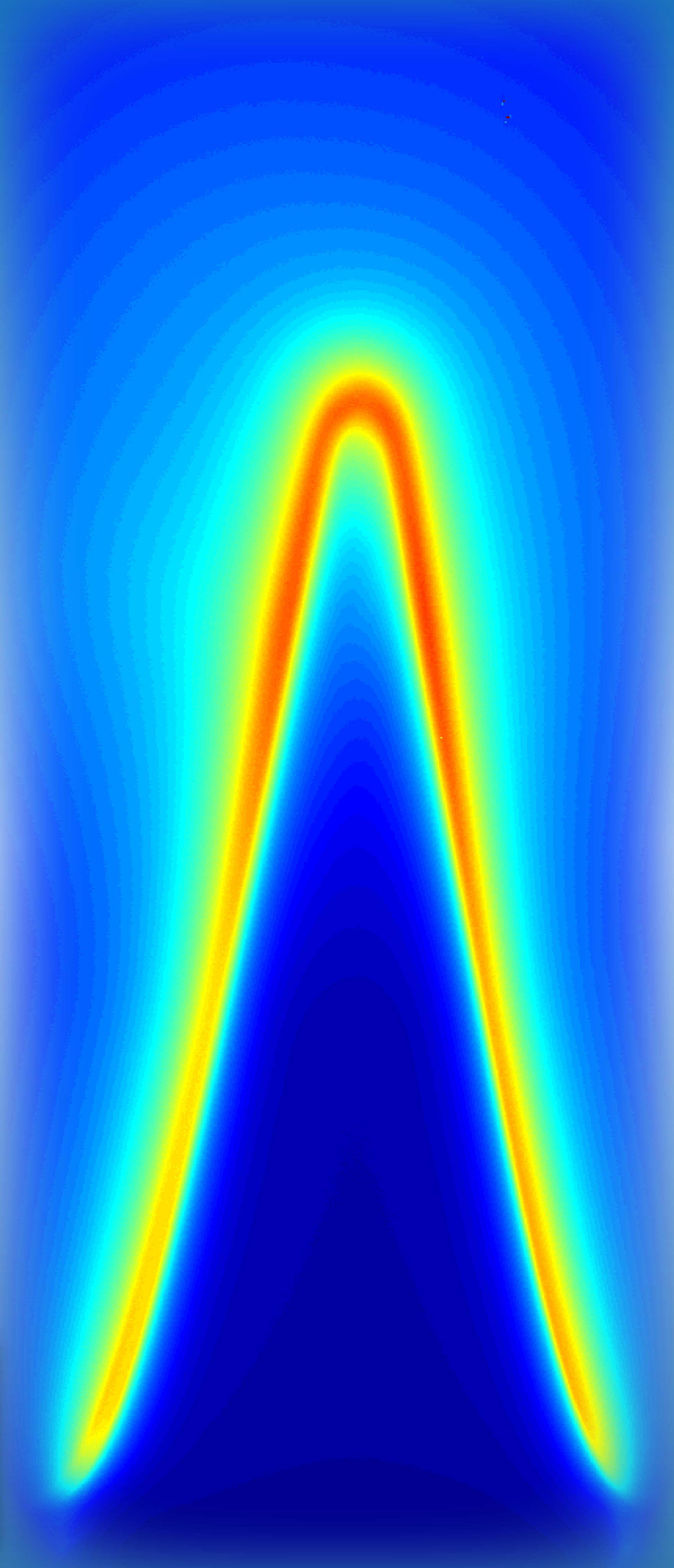
Part III: Flame Dynamics



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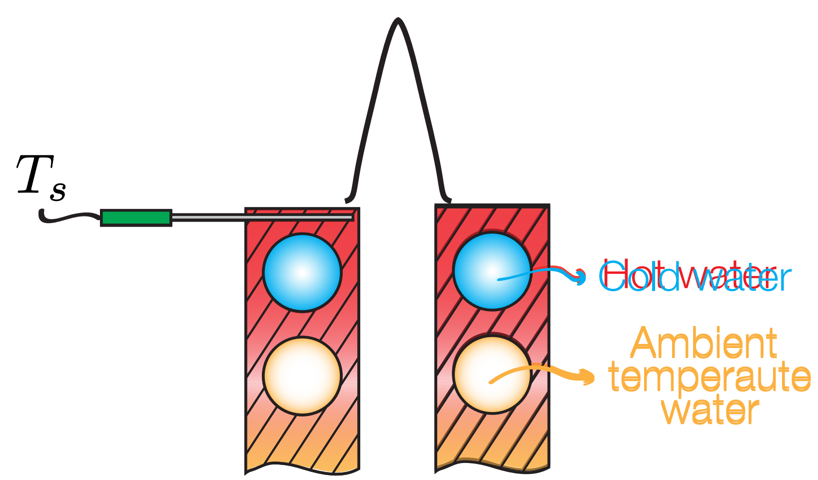
Burner Stability

$$\left[1 + \mathcal{N} e^{i\varphi(\omega)}\right] \omega^2 + 2i\delta\omega - \omega_0^2 = 0$$

	Acoustics		Noise	Flame response		Solution DR		Experimental observation
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]	r_0 [mm]	$\mathcal{G}_r$	φ_r [rad]	$\omega_r/2\pi$ [Hz]	ω_i [s^{-1}]	
T50								Unstable
T90								Stable
T120								Stable
	Non-reacting		Reacting					



4. Burner Acoustics

$$\left[1+\mathcal{N}e^{i\varphi(\omega)}\right]\omega^2+2i\delta\omega-\omega_0^2=0$$

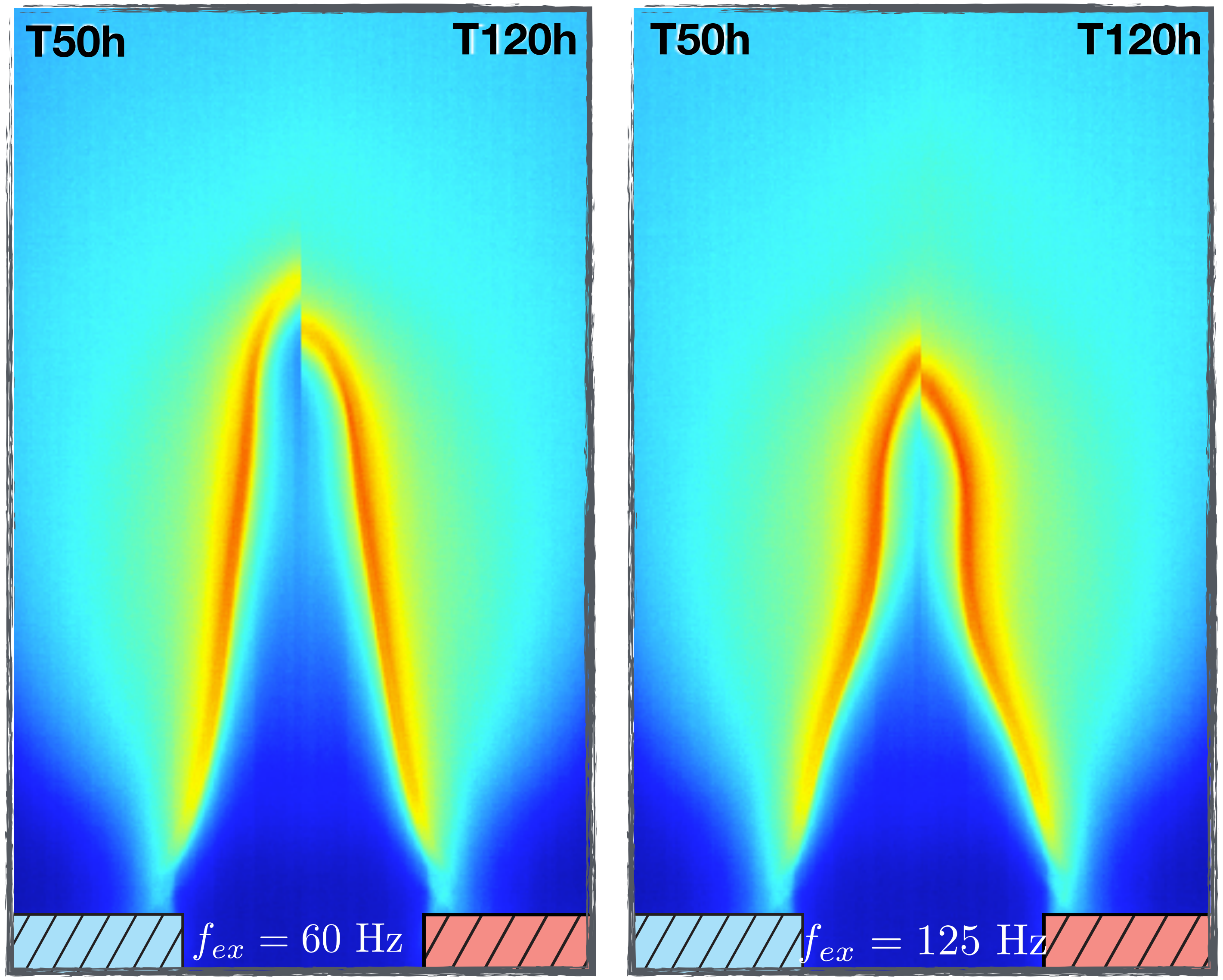
	Acoustics		Noise	Flame response		Solution DR		Experimental observation
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]	r_0 [mm]	$\mathcal{G}_r$	φ_r [rad]	$\omega_r/2\pi$ [Hz]	ω_i [s^{-1}]	
T50	52.5	15.8						Unstable
T90								Stable
T120								Stable

5. Combustion Noise

$\left[1+\mathcal{N}e^{i\varphi(\omega)}\right]\omega^2+2i\delta\omega-\omega_0^2=0$								
	Acoustics		Noise	Flame response		Solution DR		Experimental observation
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]	r_0 [mm]	$\mathcal{G}_r$	φ_r [rad]	$\omega_r/2\pi$ [Hz]	ω_i [s^{-1}]	
T50	52.5	15.8	21.5					Unstable
T90	52.5	15.8	21.5					Stable
T120	52.5	15.8	21.5					Stable

6. Flame response

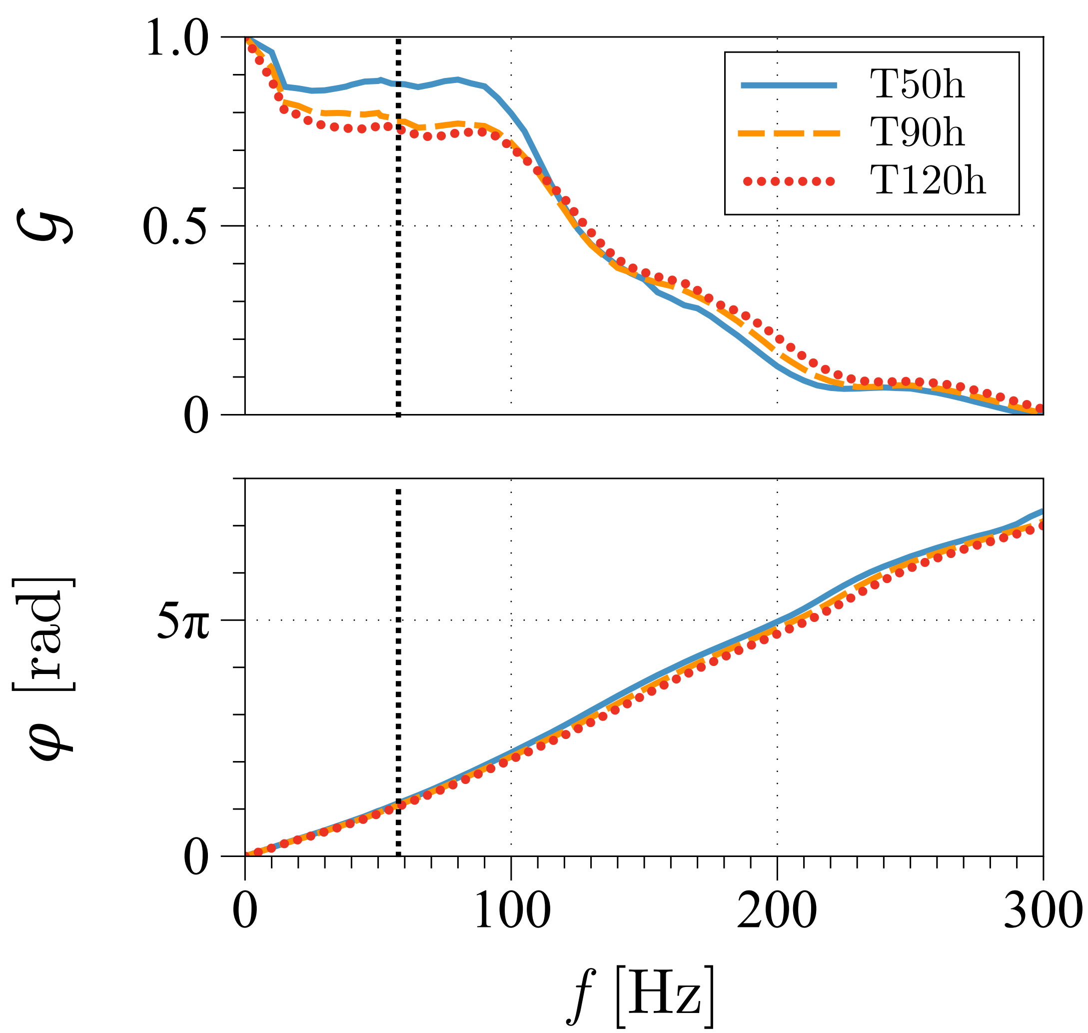
1. Is the flame response affected by the wall temperature T_s?



$$\mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{\dot{q}}}{v'/\bar{v}}$$

$$\mathcal{G} = |\mathcal{F}(\omega, T_s)|$$
$$\varphi = \arg(\mathcal{F}(\omega, T_s))$$

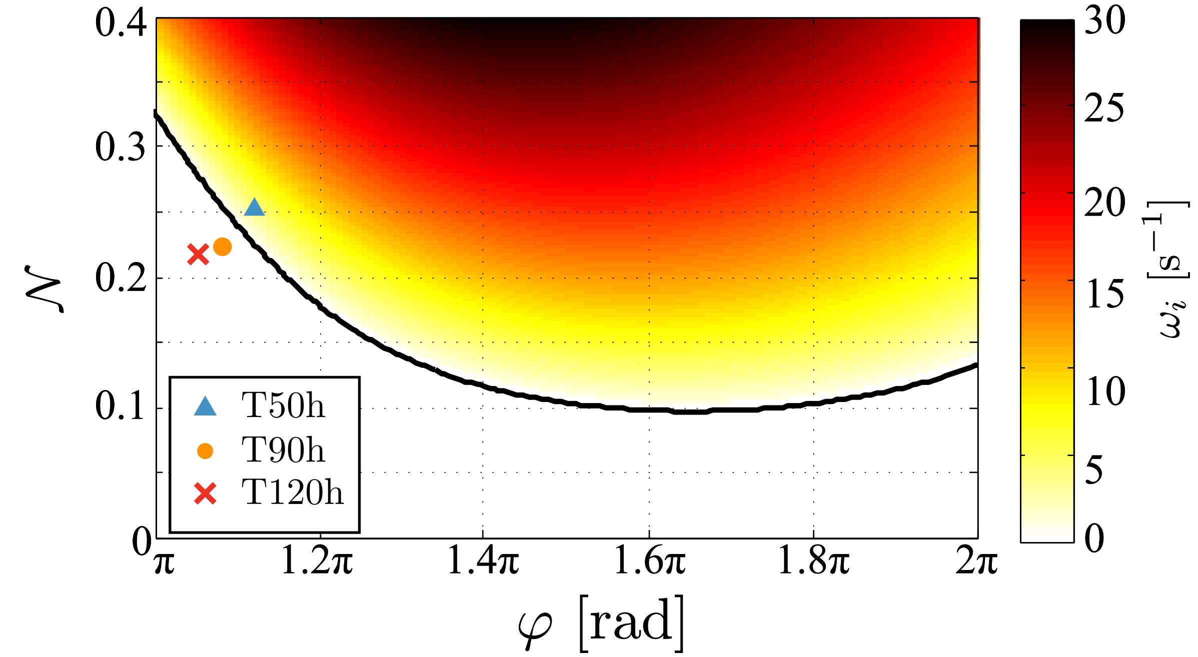
$f_r = 58$ Hz

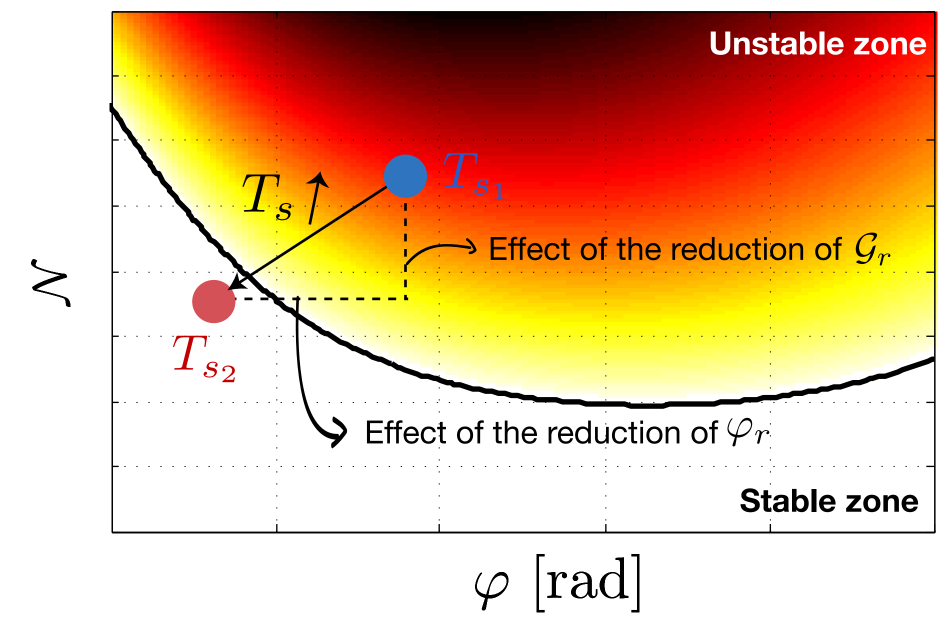


7. Burner Stability

$$\left[1 + \mathcal{N} e^{i\varphi(\omega)}\right] \omega^2 + 2i\delta\omega - \omega_0^2 = 0$$

	Acoustics		Noise	Flame response		Solution DR		Experimental observation
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]	r_0 [mm]	$\mathcal{G}_r$	φ_r [rad]	$\omega_r/2\pi$ [Hz]	ω_i [s^{-1}]	
T50	52.5	15.8	21.5	0.87	1.12π			Unstable
T90				0.77	1.08π			Stable
T120				0.75	1.05π			Stable





The flame's natural instability can be suppressed by increasing *Ts* by just 40 K. This small variation changes the gain from 0.87 to 0.77 and the phase from 1.12π rad to 1.08π rad; This is sufficient to stabilize the system.

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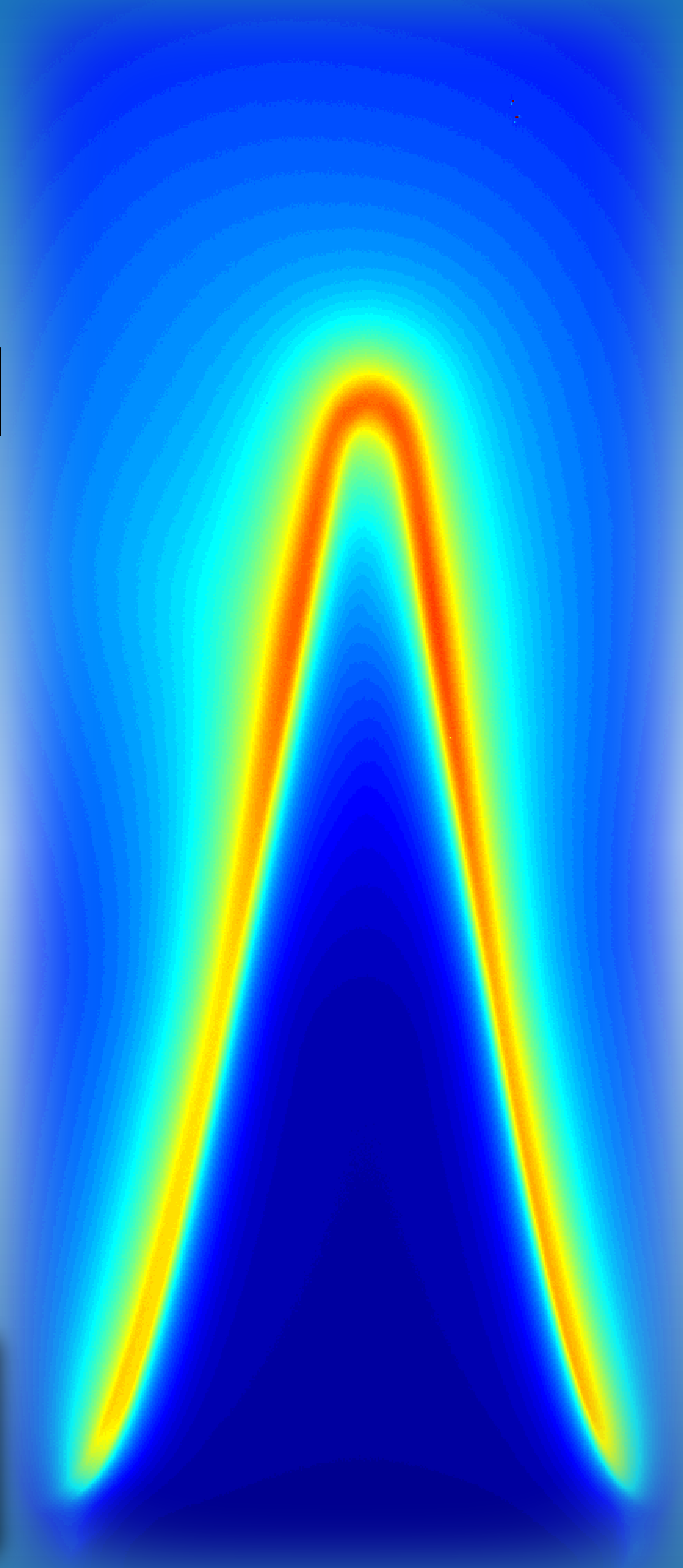

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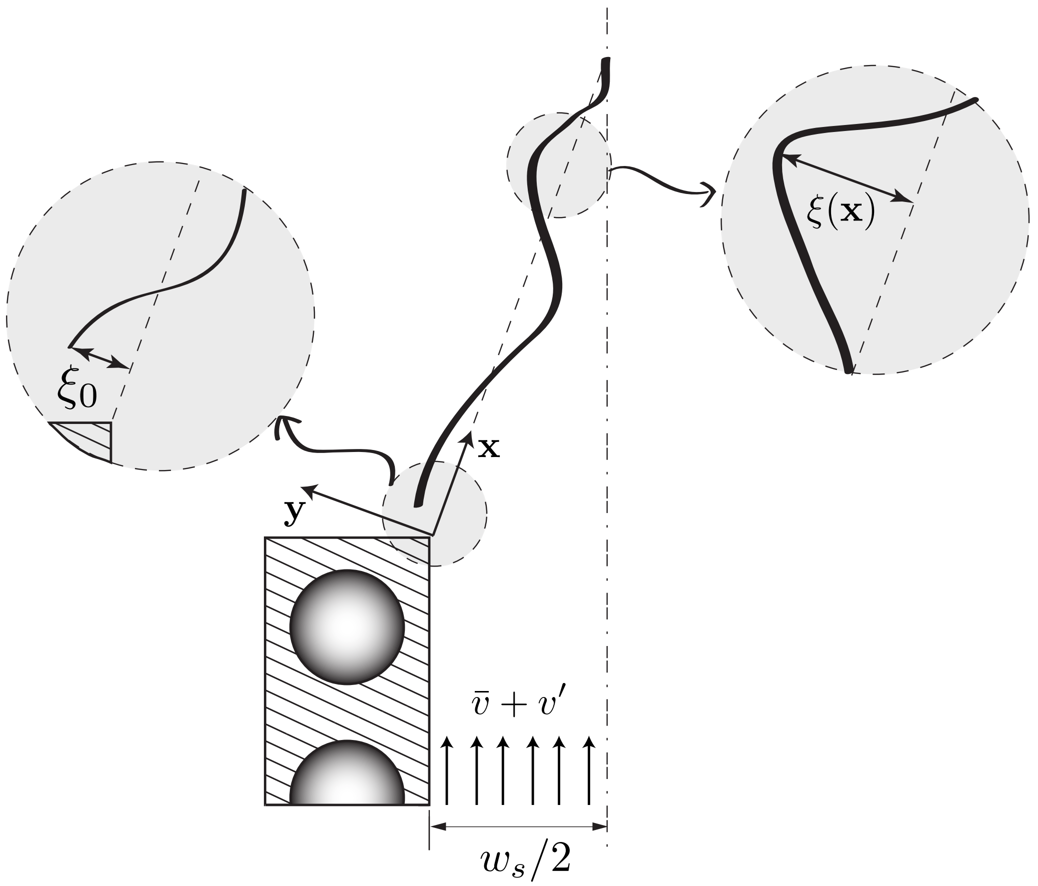
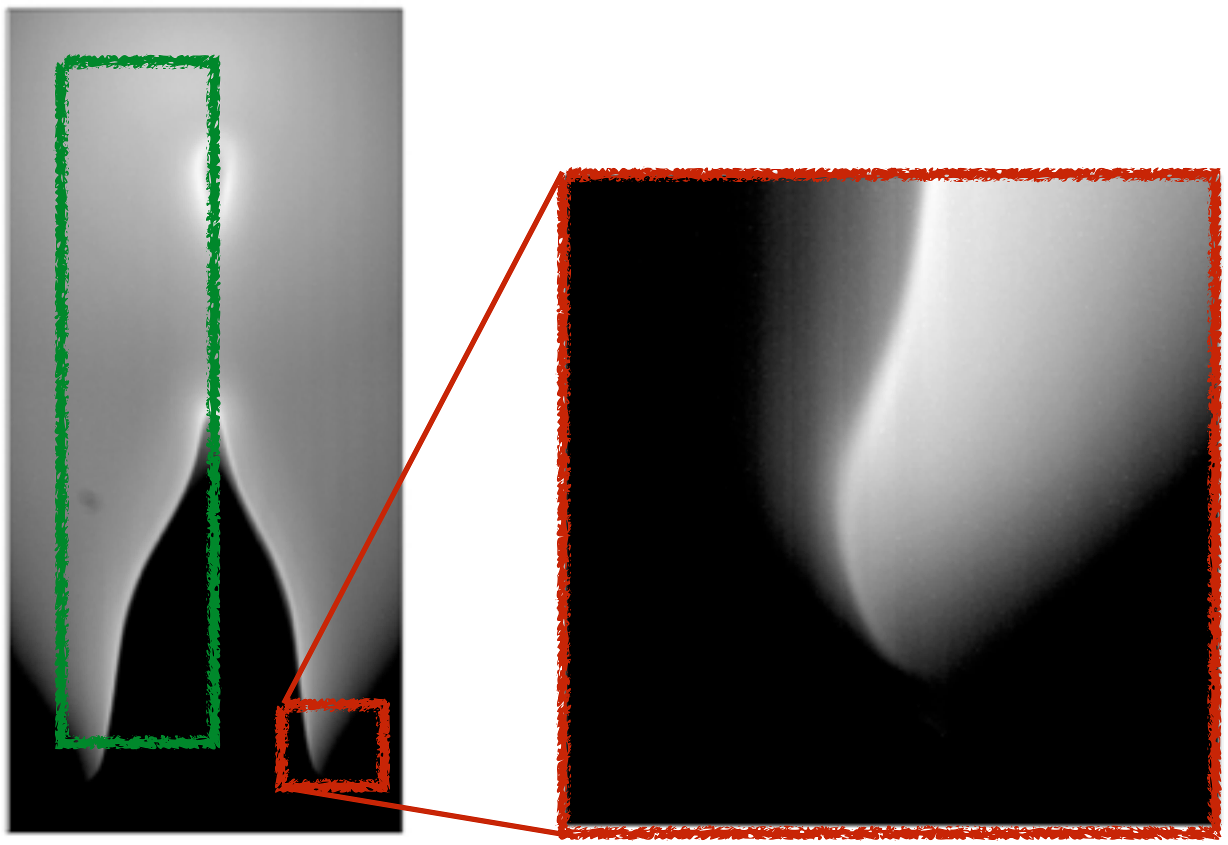
Brief review of flame dynamics theory:





G-equation in the reference frame attached to the steady flame front:

$$\frac{\partial \xi}{\partial t} + \bar{\mathbf{u}}.\nabla \xi = \mathbf{v}'(\mathbf{x}, t)$$

Solution:

$$\tilde{\xi}(\mathbf{x}) = \boxed{\frac{e^{i\kappa\mathbf{x}}}{\bar{\mathbf{u}}} \int_0^{\mathbf{x}} \tilde{\mathbf{v}}(\mathbf{x}') e^{-i\kappa\mathbf{x}'} \mathrm{d}\mathbf{x}'} + \boxed{\tilde{\xi}_0 \mathrm{e}^{\mathrm{i}\kappa\mathbf{x}}}$$

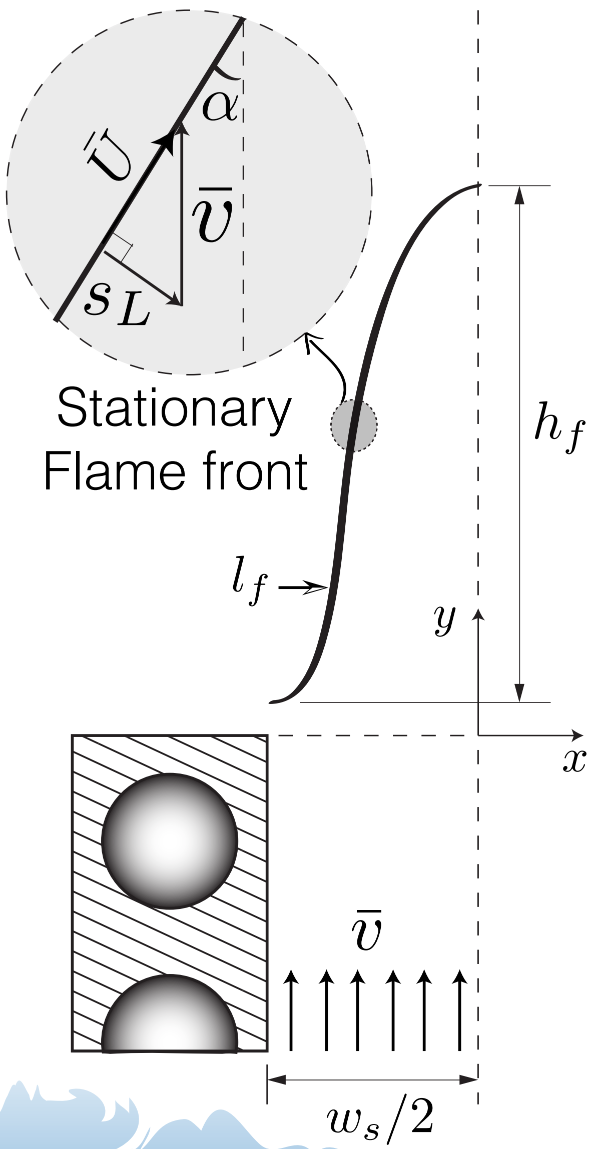
Two contributions to the FTF

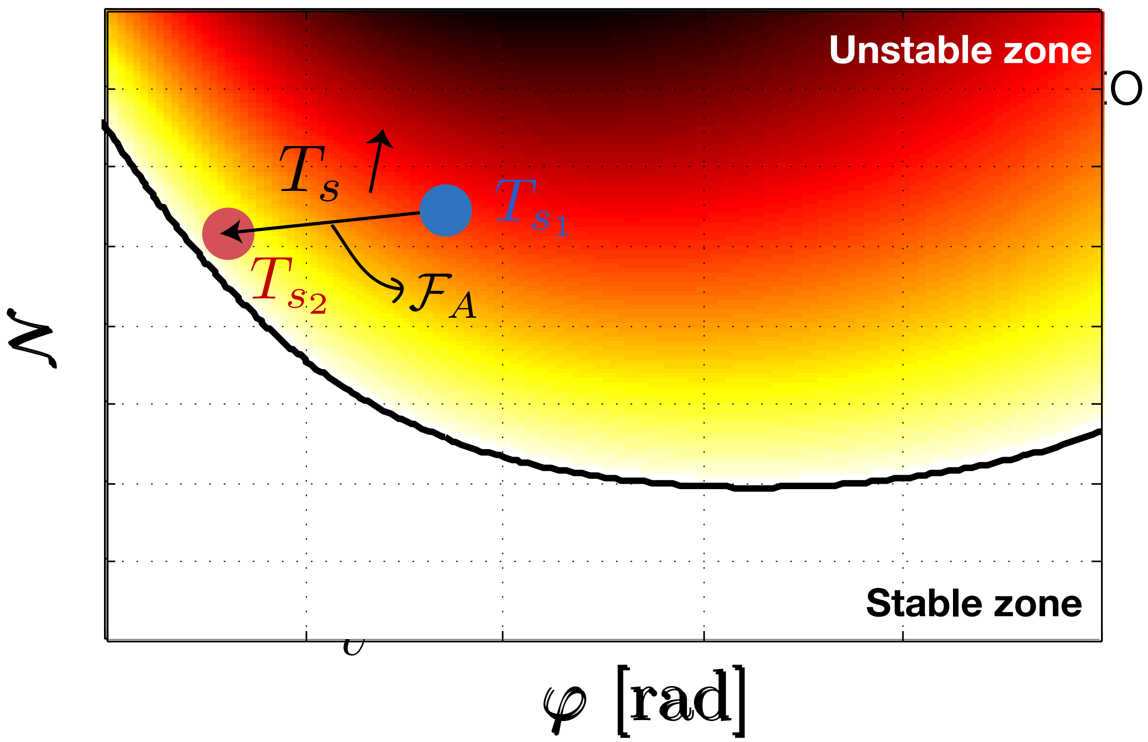
$$\mathcal{F} = \boxed{\mathcal{F}_A} + \boxed{\mathcal{F}_B}$$

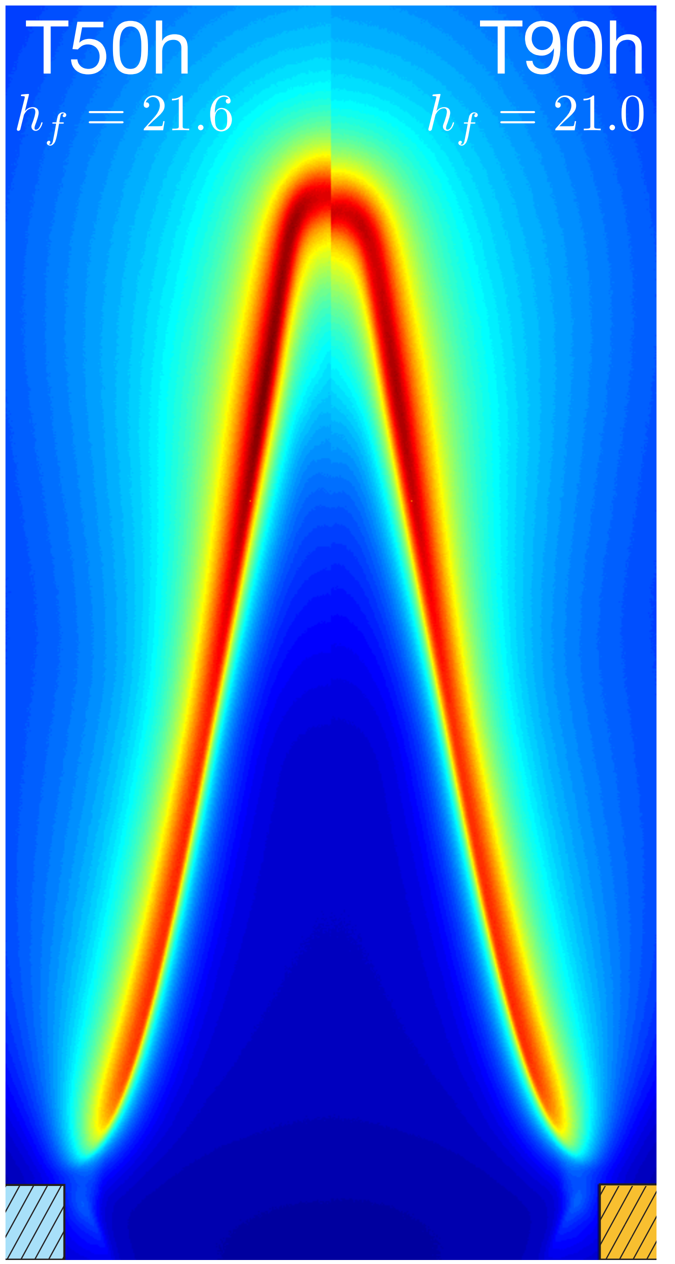
[1] Boyer and Quinard 1990 *cf.*
[2] Fleifil *et al.* 1996 *cf.*
[3] Schuller *et al.* 2003 *cf.*
[4] Lee and Lieuwen 2003 *jpp.*
[5] Cuquel *et al.* 2011 *mcs.*

8. Flame Front Dynamics

1. Does the theory predict a change in the flame front response when wall temperature, T_s changes?







2. Is the flame geometry affected by the wall temperature T_s?

[1] Baillot *et al.* 1992 *cf.*
[2] Fleifil *et al.* 1996 *cf.*
[3] Ducruix *et al.* 2000 *pci.*
[4] Schuller *et al.* 2003 *cf.*
[5] Birbaud *et al.* 2006 *cf.*
[6] Cuquel *et al.* 2011 *mcs.*

9. Flame Root Dynamics

1. Does the theory predicts a change in the flame root response when T_s changes?

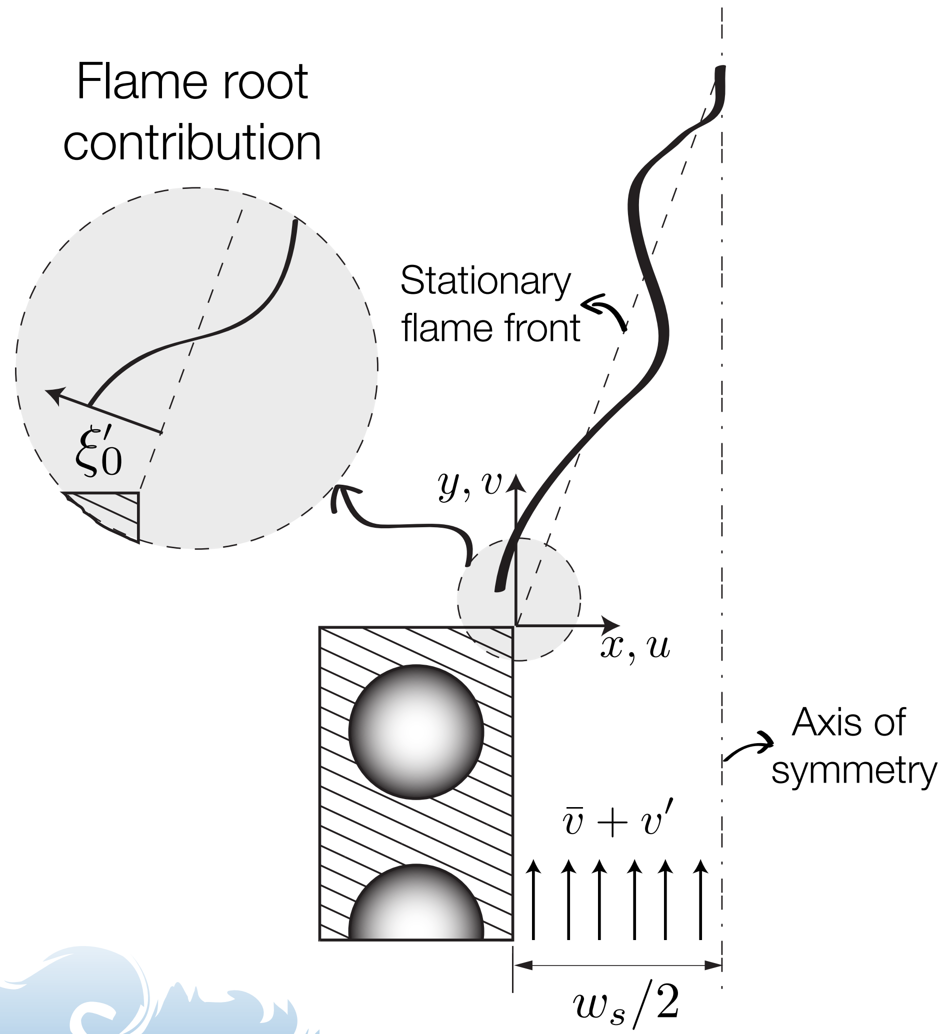
Flame root contribution

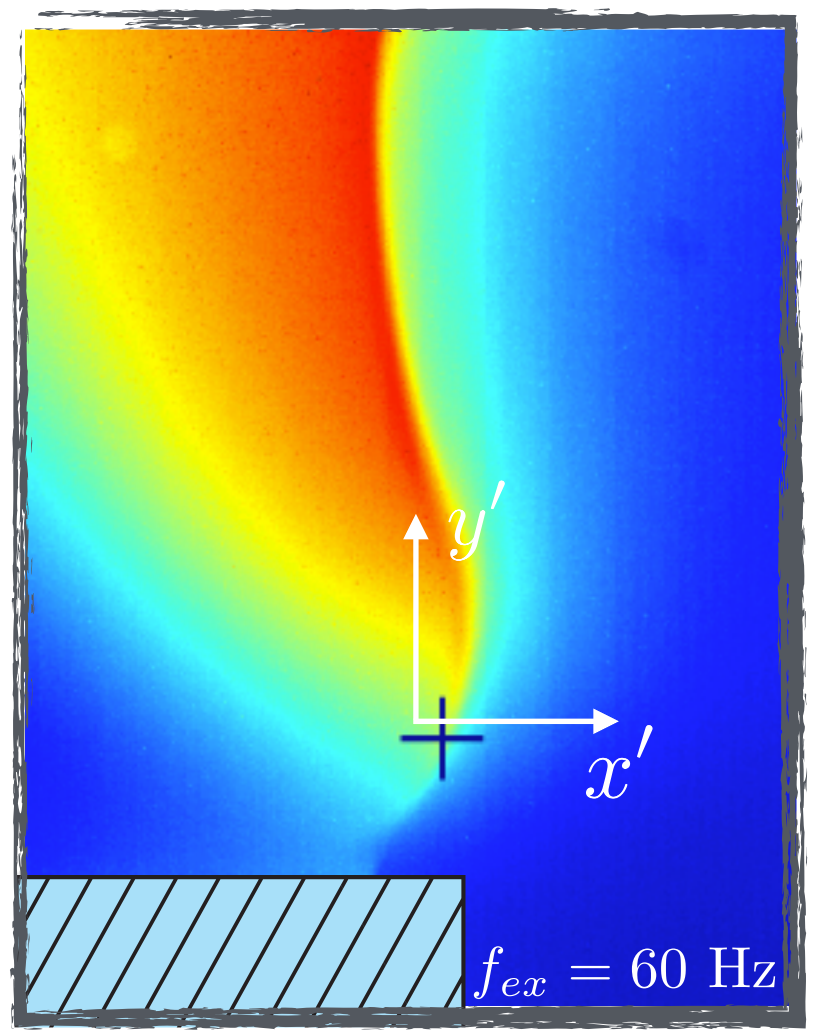
$$\mathcal{F}_B \propto \Xi$$

Flame root transfer function

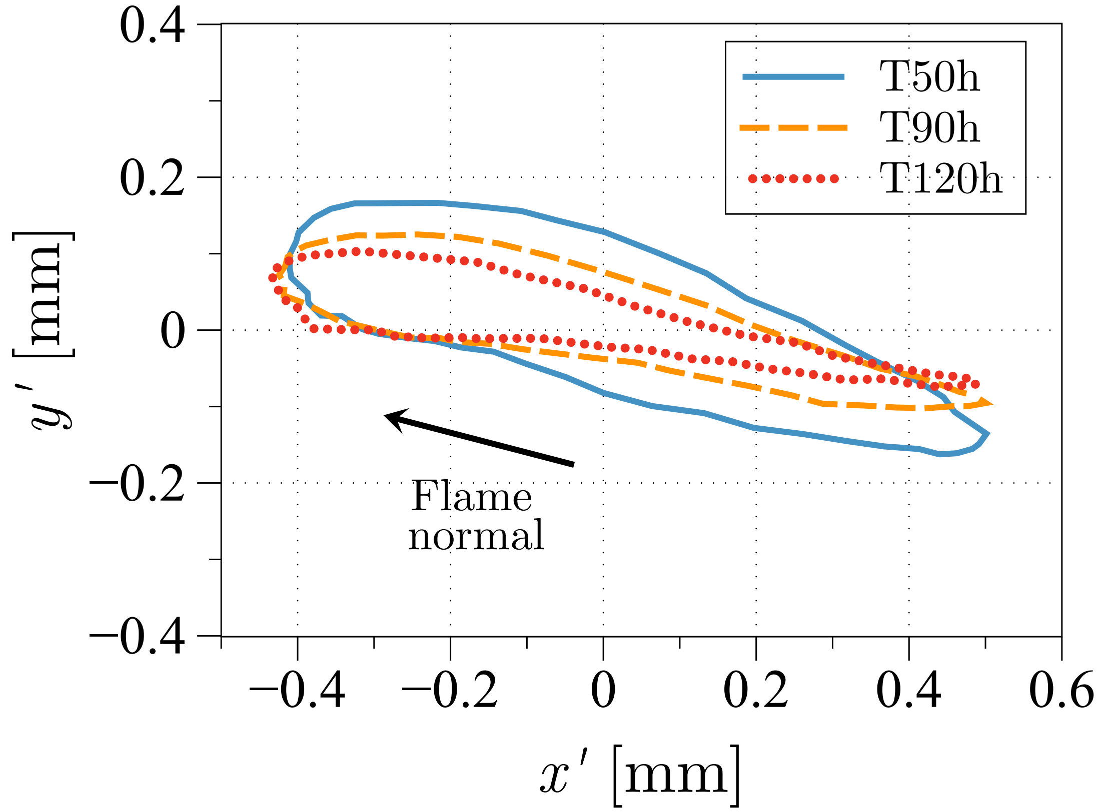
$$\Xi = \frac{\xi_0'/(w_s/2)}{v'/\bar{v}}$$

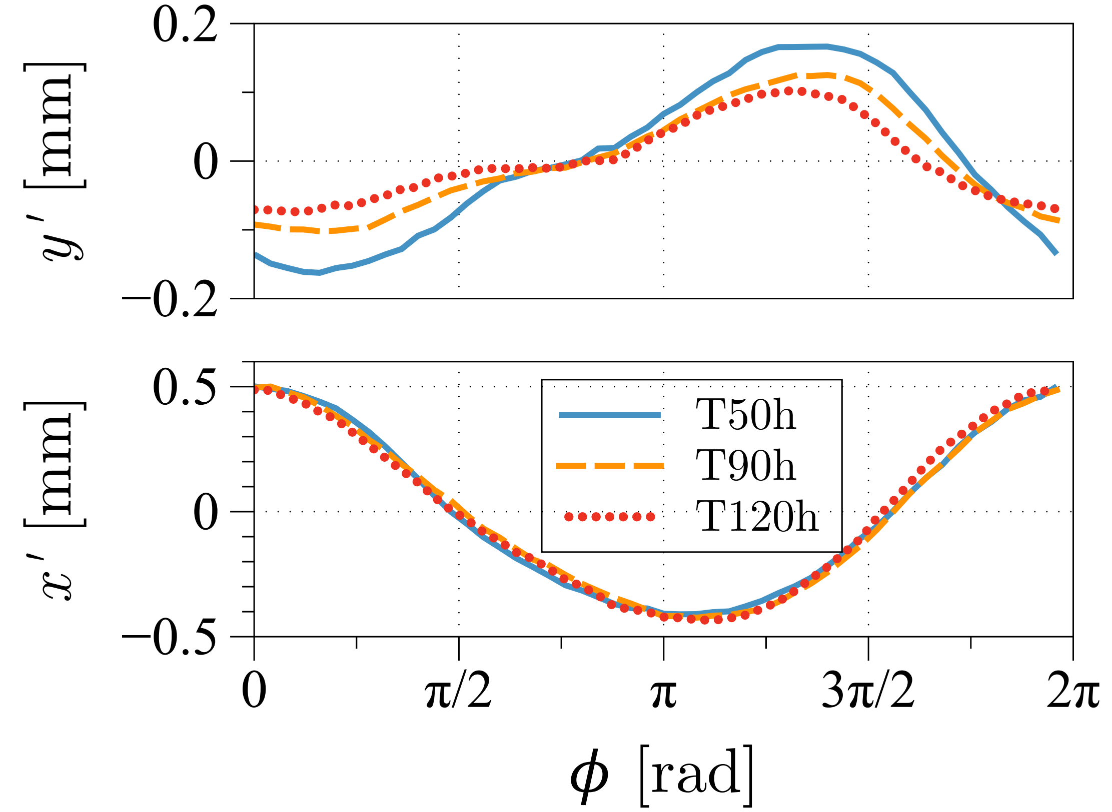
[1] Kornilov *et al.* 2007 *pci.*
[3] Cuquel *et al.* 2013 *crm.*
[4] Rook *et al.* 2002 *ctm.*
[5] Schreel *et al.* 2005 *pci.*
[6] Altay *et al.* 2009 *pci.*





Flame root trajectoires



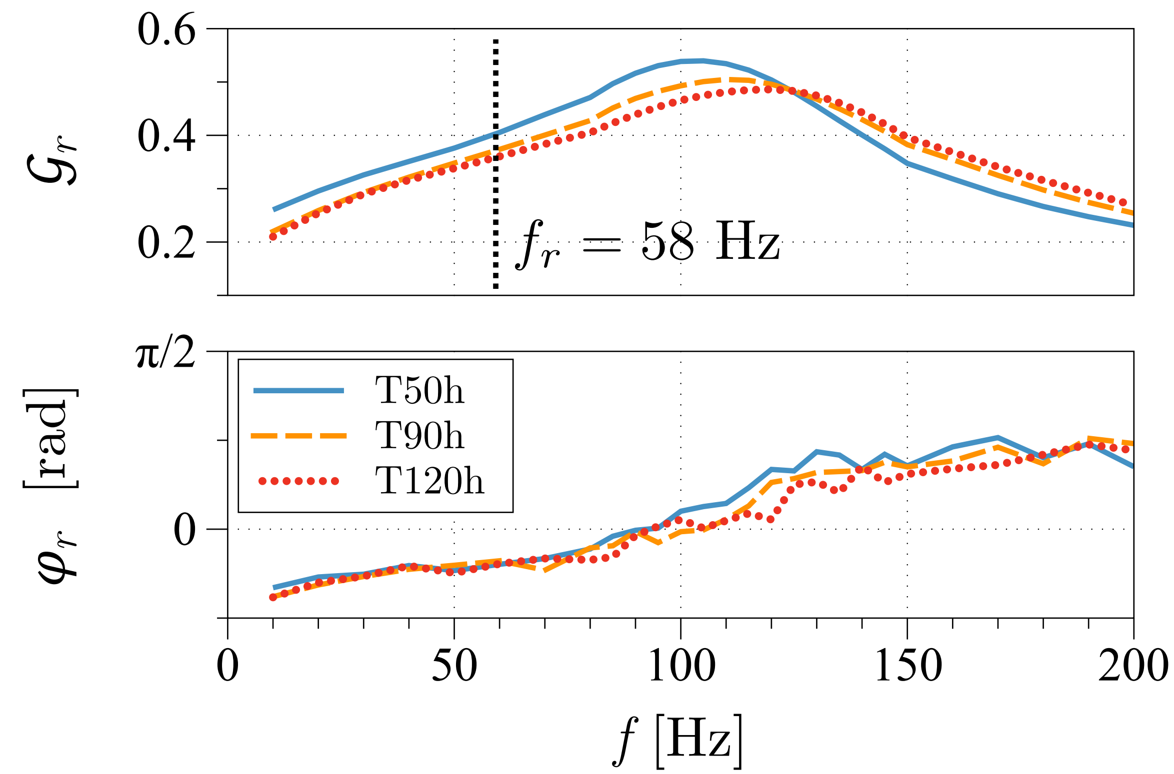


Experimental flame root transfer function

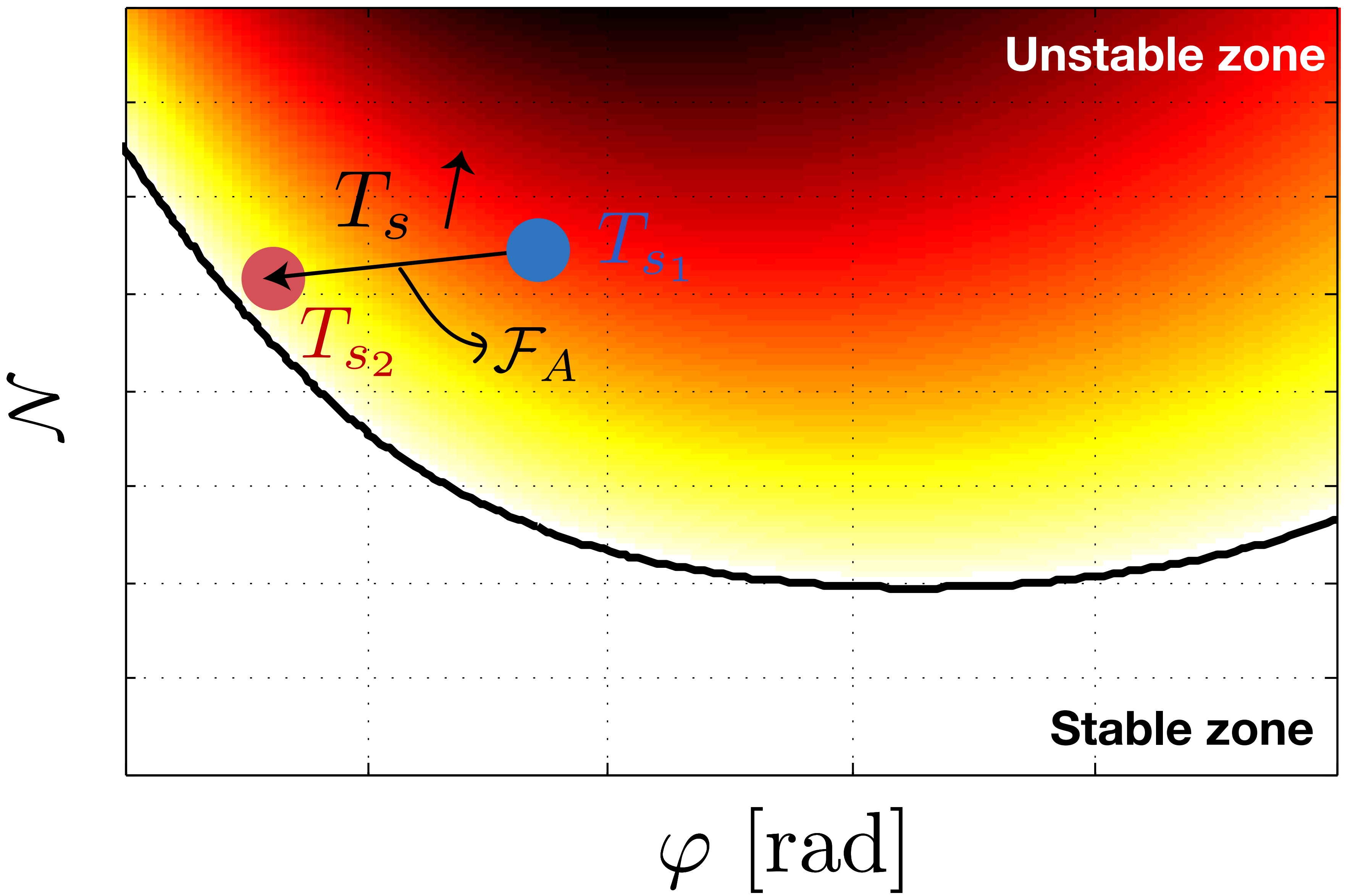
$$\Xi = \frac{\xi_0'/(w_s/2)}{v'/\bar{v}}$$

$$\mathcal{G}_r = |\Xi(\omega, T_s)|$$

$$\varphi_r = \arg(\Xi(\omega, T_s))$$



So, how is the flame stabilized?

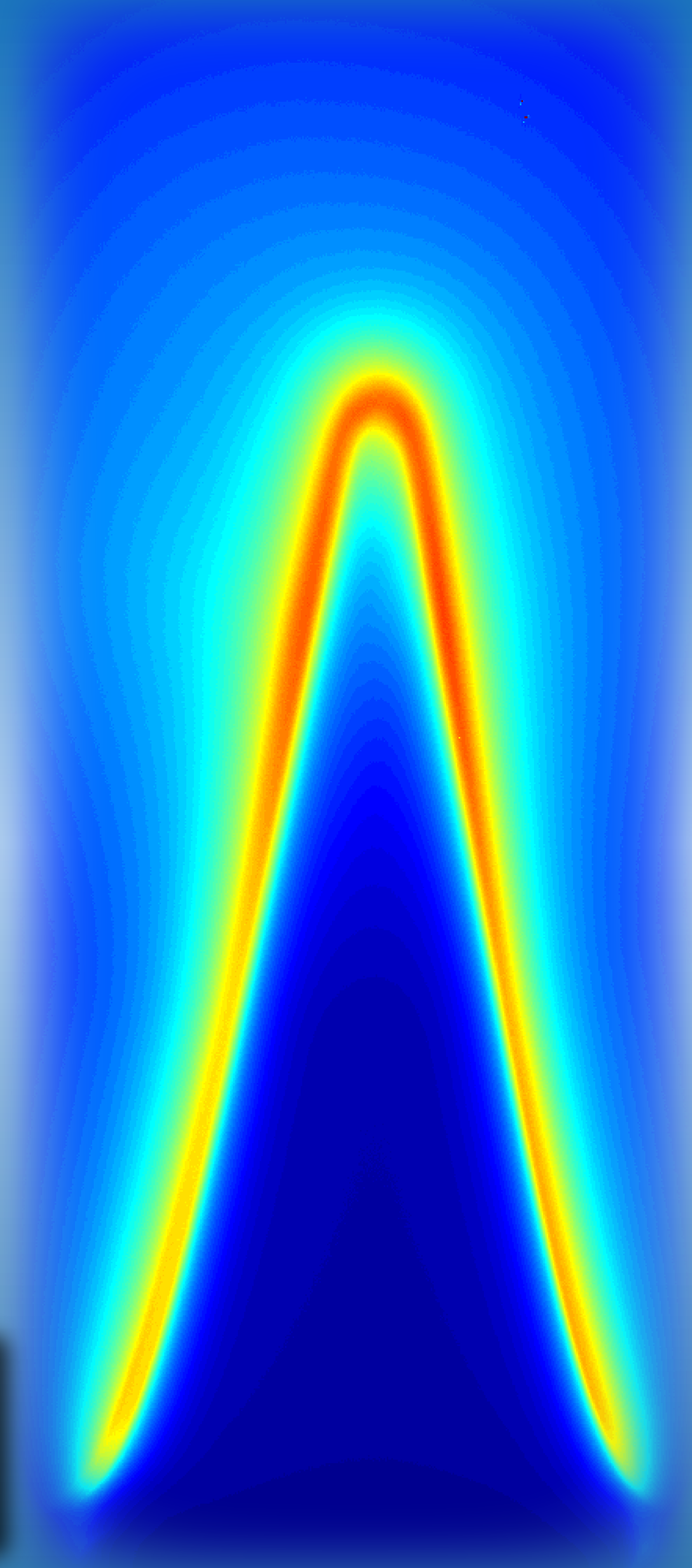


Conclusions

1. CI can be controlled by heat transfer at the walls: we have an experiment **unstable at startup** and **stable once hot**.

2. We devised a **cooling system** so that the occurrence of **CI is controlled by the wall temperature** Ts.

3. Using the most resent results on flame dynamics theory, we were able to conclude that: the flame is stabilized by the **combined effect** of the wall temperature on the **flame front** and the **flame root dynamics**.



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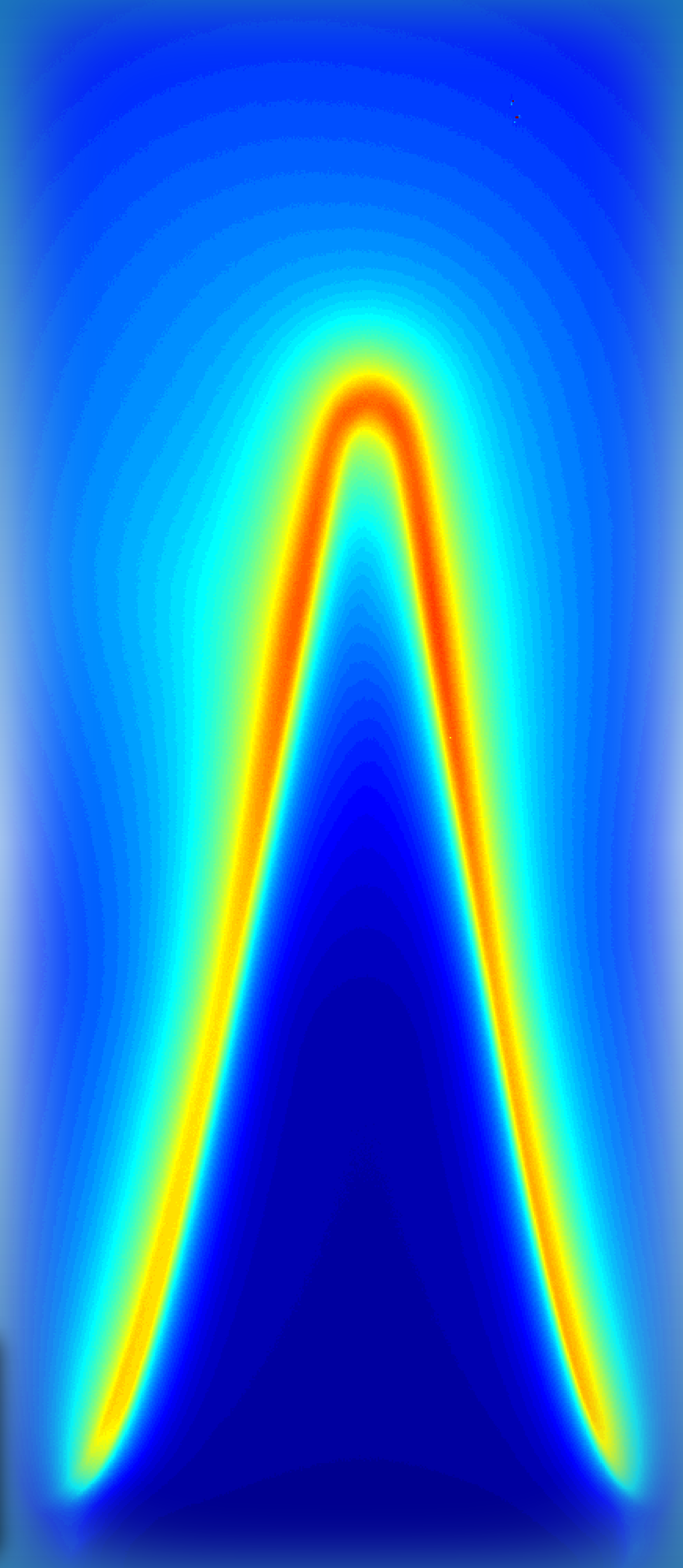
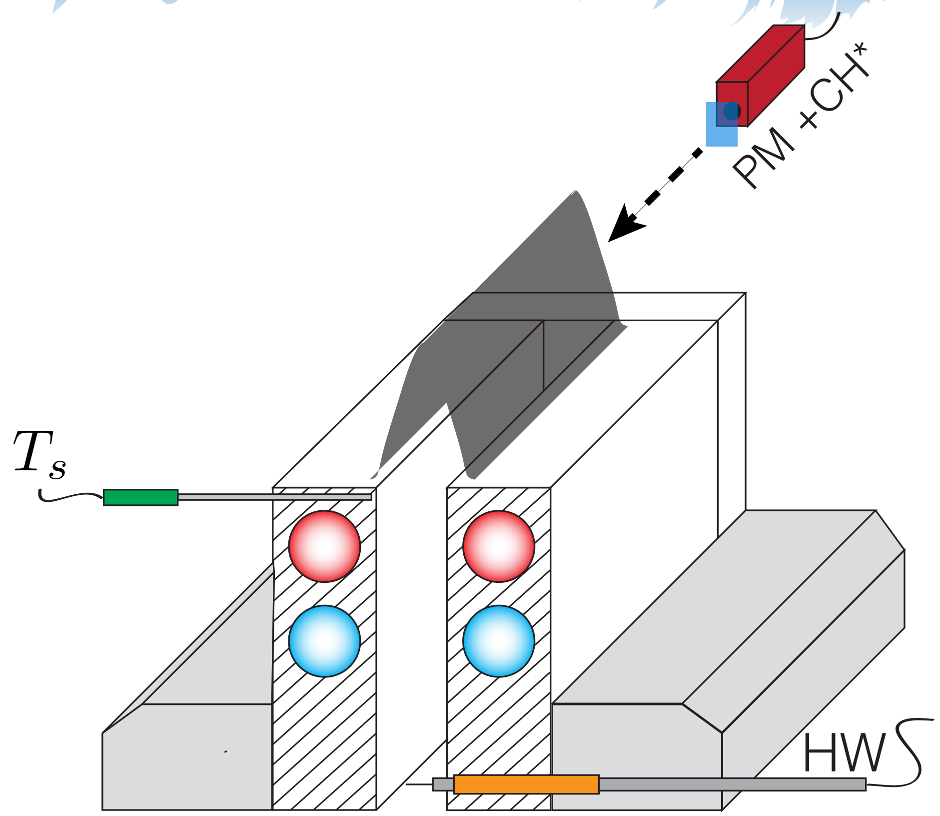
Thanks for your attention !



2. Description of the unstable behavior

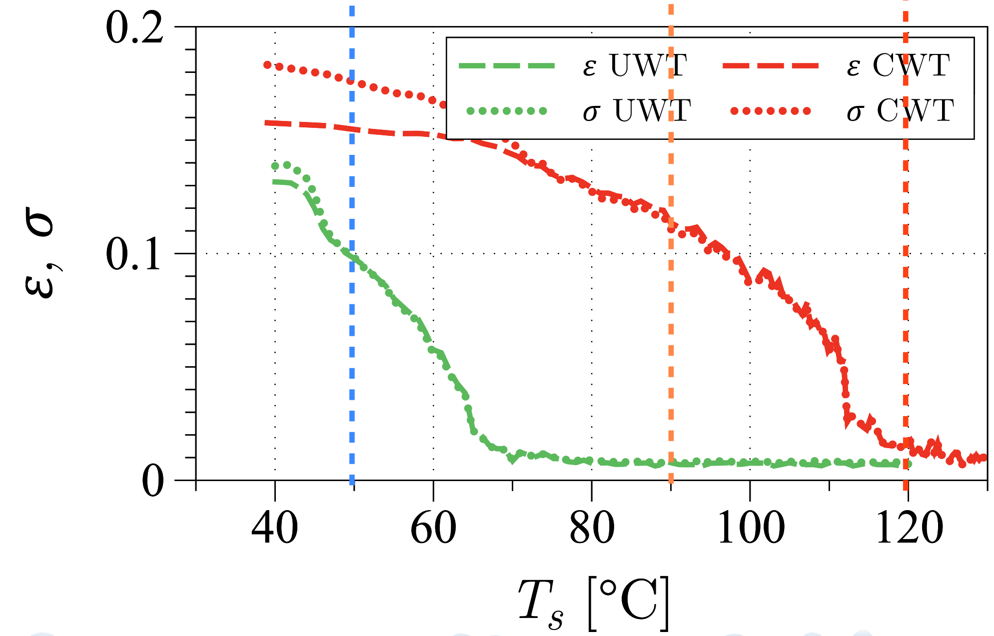


Measurements	
Slot temperature	T_s
RMS Heat release fluctuation magnitude	$\sigma = \frac{I_{CH^*}^{rms}}{\bar{I}_{CH^*}}$
RMS Velocity fluctuation magnitude	$\varepsilon = \frac{v_1^{rms}}{\bar{v}}$

Two type of analysis

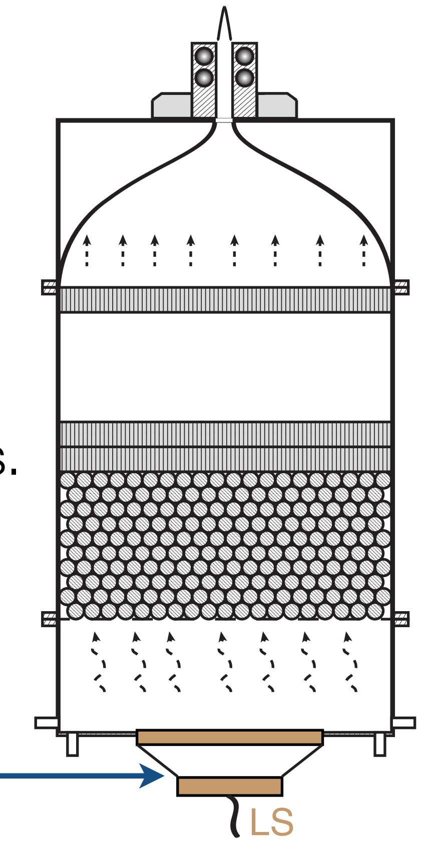
- **Transient**
  - **UWT** (Uncontrolled wall temperature)
  - Cooling OFF
- **Steady-state**
  - **CWT** (Controlled wall temperature)
  - Cooling ON
  - $T_{H_2O} = 1 - 99$ [°C]
  - $\Delta T_{H_2O} = 1$ [°C]

$f_r = 58$ Hz

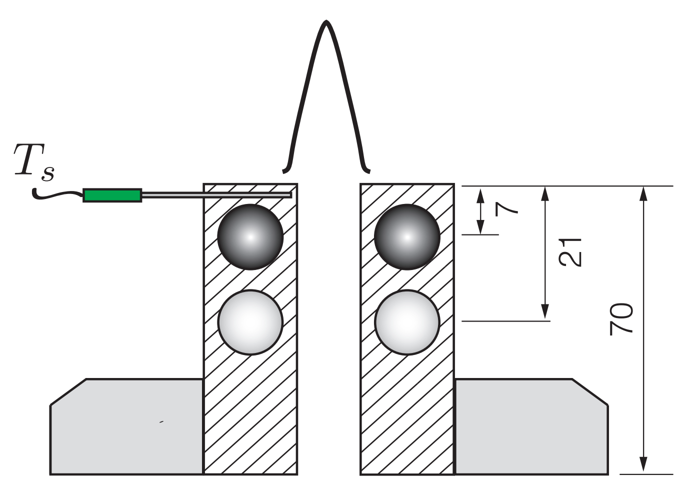


Methodology:

- Methodology
  - Experimentally
    - Self-sustained oscillations ➡ Limited to one frequency.
    - Forced oscillations ➡ Wide range of frequencies.
  - Analytically
  - Numerically



Stabilizing the flame



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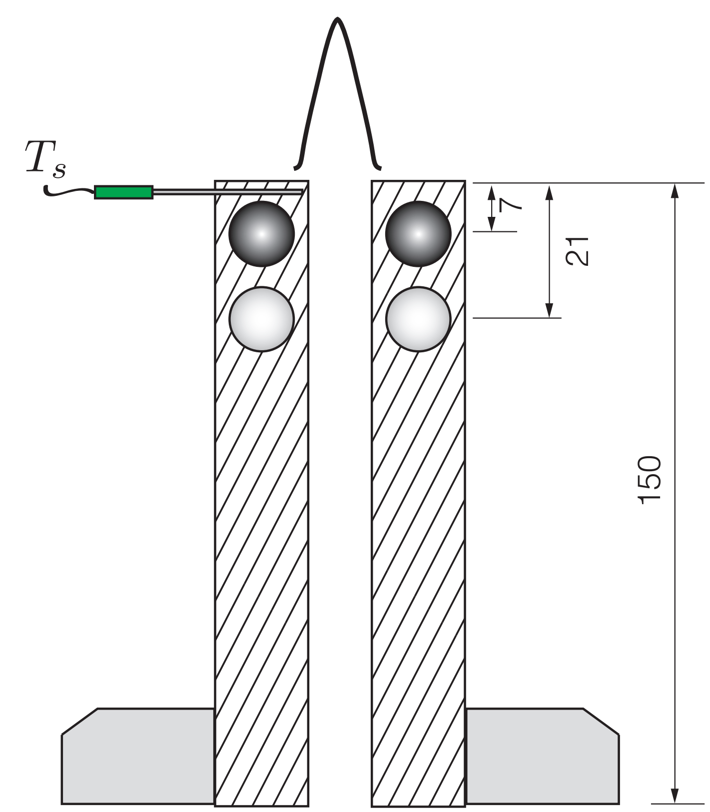


B15

★ In all cases, the operating conditions are keep constant

$\Phi = 0.95 \quad \bar{v} = 1.6\ \mathrm{ms}^{-1} \quad \boxed{\varepsilon = 0.1}$ → T50 → CWT

★ In all cases, the wall temperature is controlled and it is parametrized here by T_s

★ Three temperature reference cases with three different dynamic behaviors:

T50	T90	T120

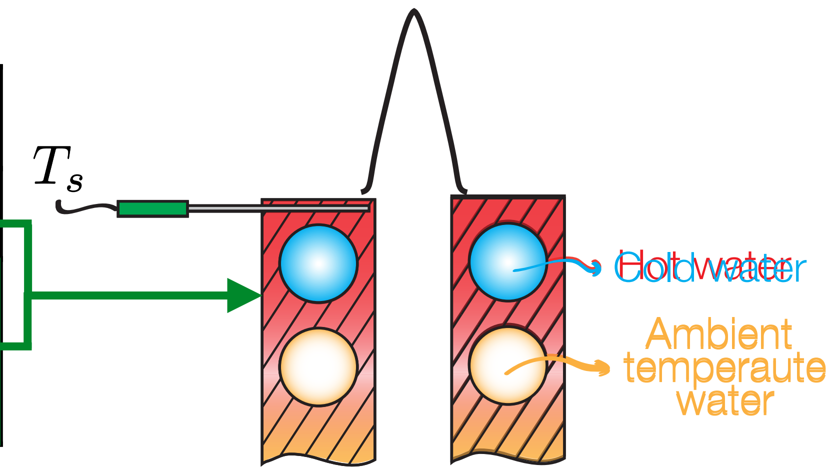
★ Code for the experiments:

T50c

50 → T_s [°C]

c → c: cold (non-reacting)
h: hot (reacting)

	Measure		Burner	Wall temperature			Configuraion
Burner Acoustics	ω_0	δ	B07	T50c	T90c		Non-reacting
Combustion Noise	r_0		B15	T50h	T90h	T120h	Reacting
Flame Response	$\mathcal{G}_r$	φ_r	B15	T50h	T90h	T120h	Reacting



4. Burner acoustics

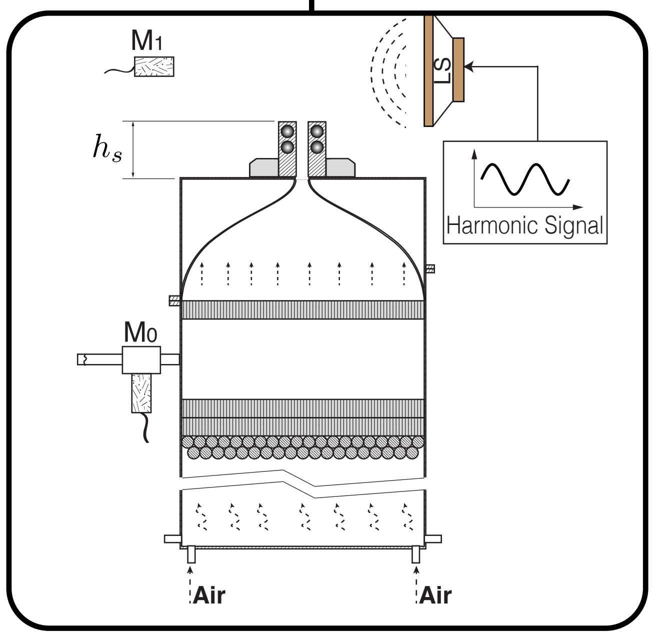
1. How to measure the natural ω_0 pulsation and the dissipation δ of the burner?
2. Do they depend on wall temperature T_s?

Burner acoustics

- **Non-reacting**
- **Reacting**

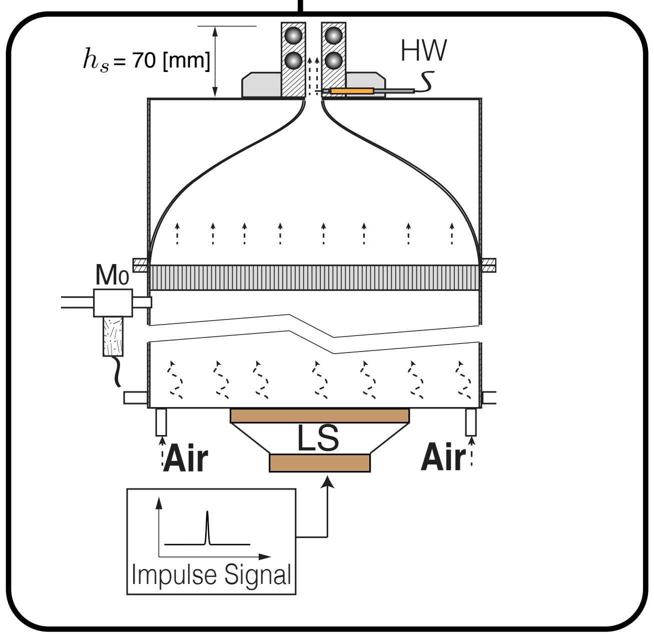
Harmonic response

$$\frac{\mathrm{d}^2 p_0'}{\mathrm{d}t^2} + 2\delta \frac{\mathrm{d}p_0'}{\mathrm{d}t} + \omega_0^2 p_0' = \omega_0^2 p_1'$$

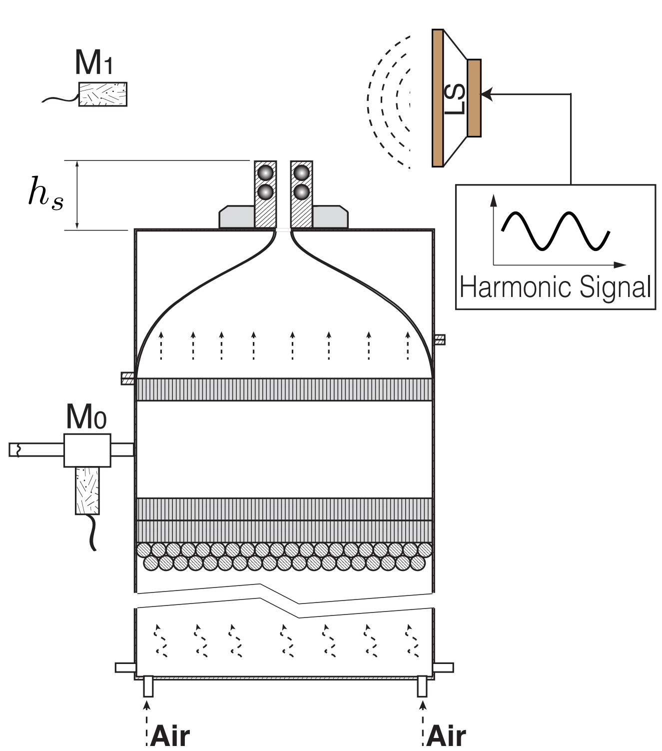


Impulse response

$$\frac{\mathrm{d}^2 v_1'}{\mathrm{d}t^2} + 2\delta \frac{\mathrm{d}v_1'}{\mathrm{d}t} + \omega_0^2 v_1' = 0$$

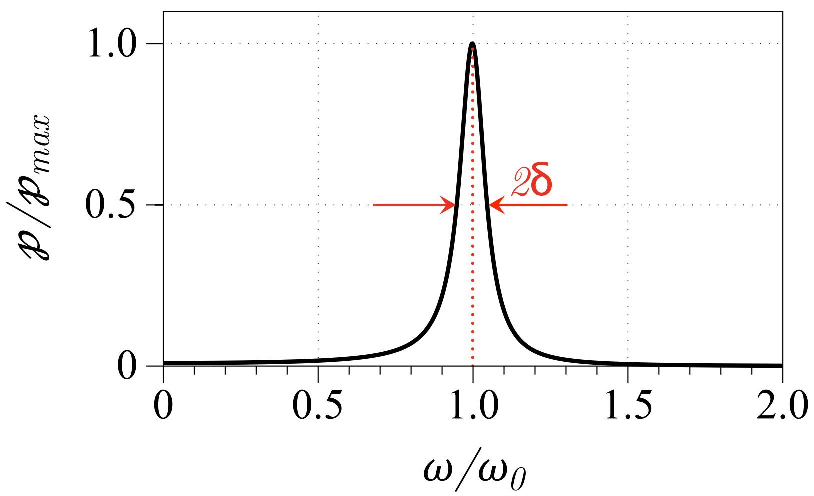


1. Harmonic response:

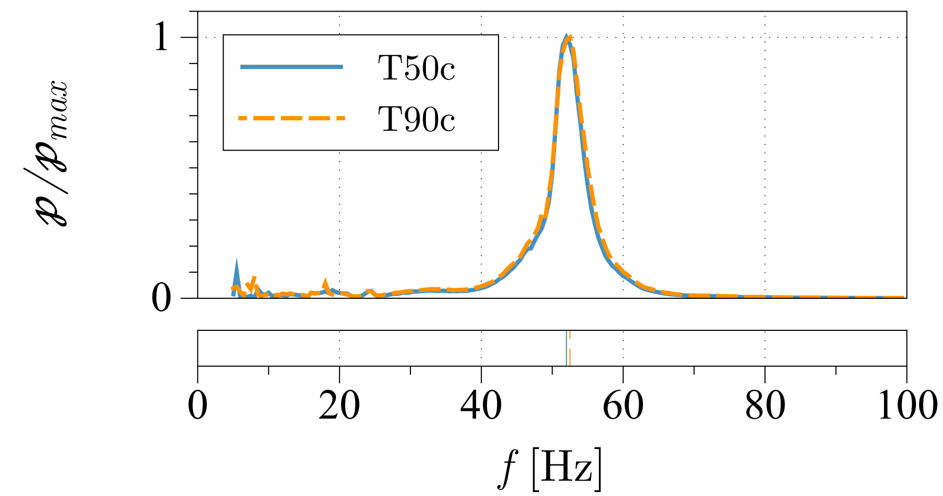


$$\frac{\mathrm{d}^2 p_0'}{\mathrm{d}t^2} + 2\delta \frac{\mathrm{d}p_0'}{\mathrm{d}t} + \omega_0^2 p_0' = \omega_0^2 p_1'$$

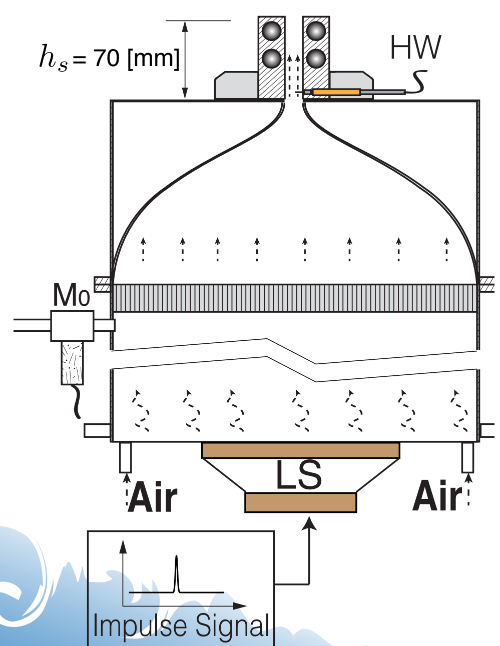
$$\mathcal{P} = \left(\frac{\tilde{p}_0}{\tilde{p}_1}\right)^2$$



	HR	
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]
T50c	52.0	14.5
T90c	52.5	15.7

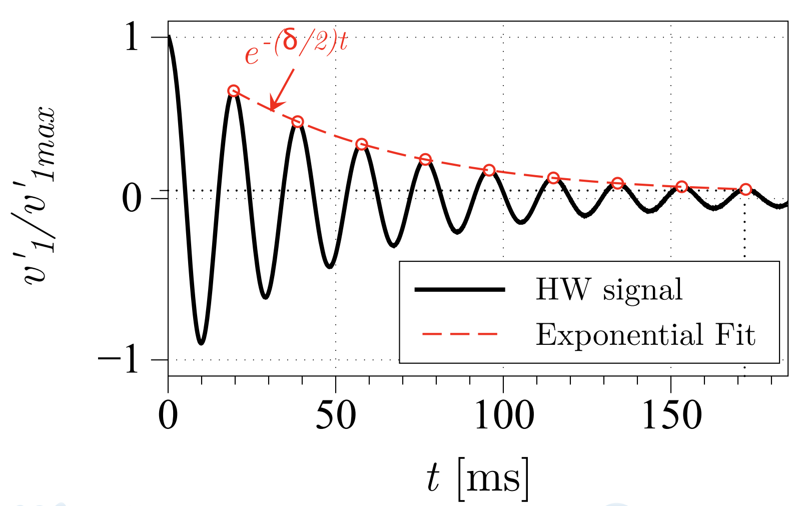


2. Impulse response:

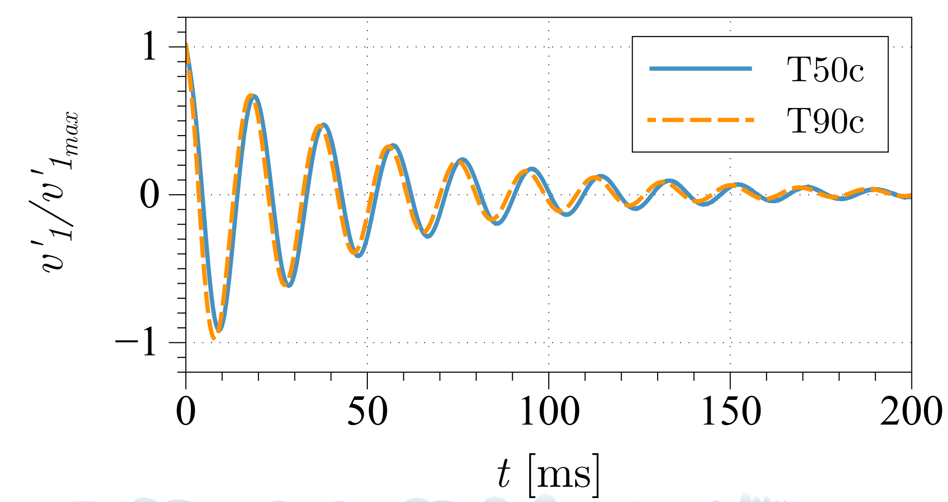


$$\frac{\mathrm{d}^2 v_1'}{\mathrm{d}t^2} + 2\delta \frac{\mathrm{d}v_1'}{\mathrm{d}t} + \omega_0^2 v_1' = 0$$

$$v_1'(t)/v_{1_{max}}' = e^{-(\delta/2)t}\cos(\omega_0 t)$$

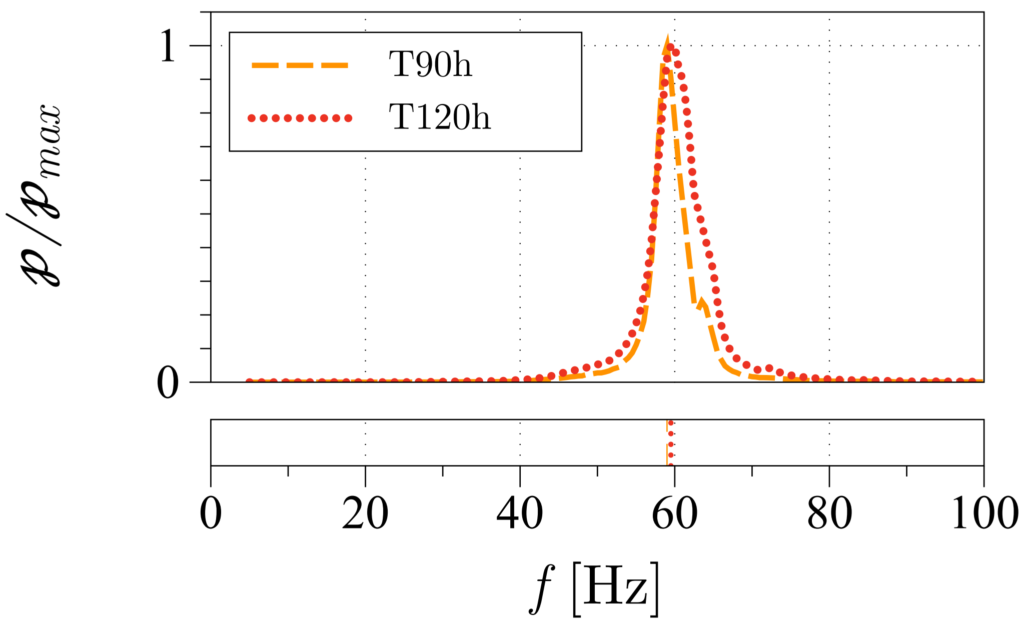


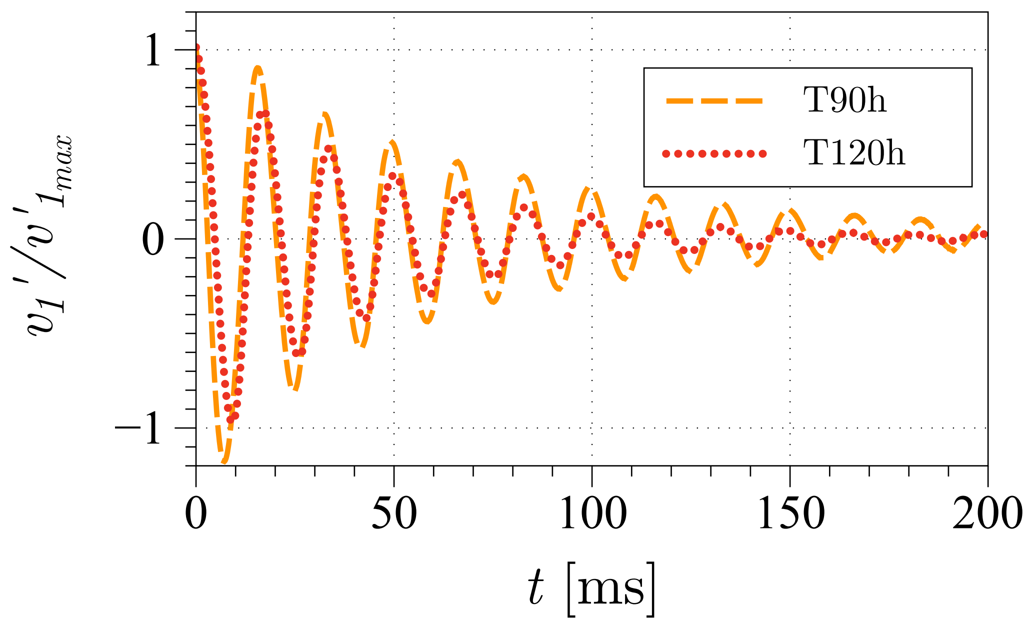
	IR	
	$\omega_0/2\pi$ [Hz]	δ [s^{-1}]
T50c	52.4	16.3
T90c	53.1	16.8



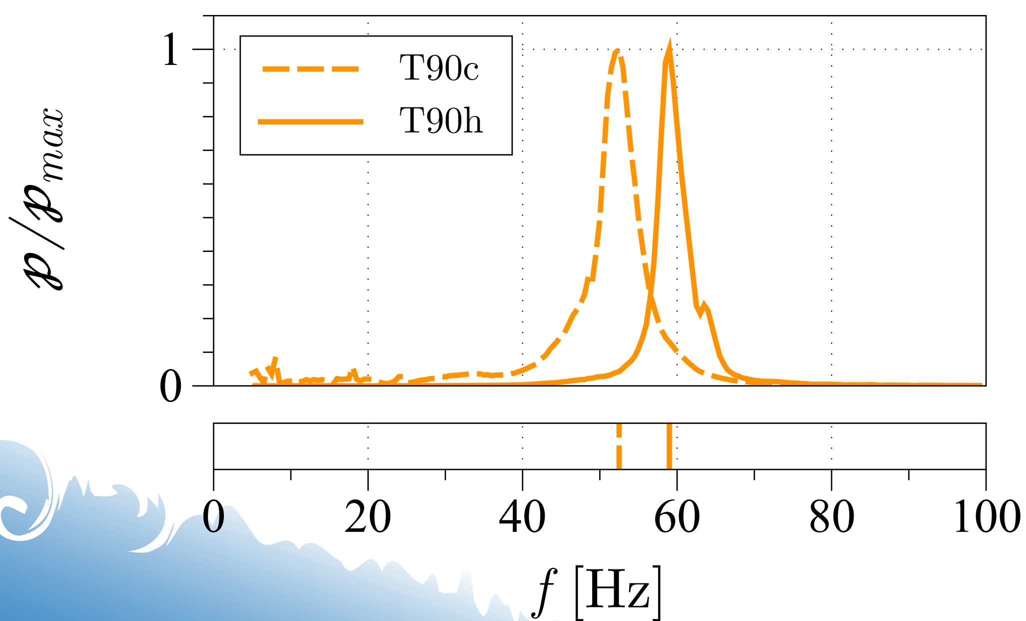
Reacting acoustics

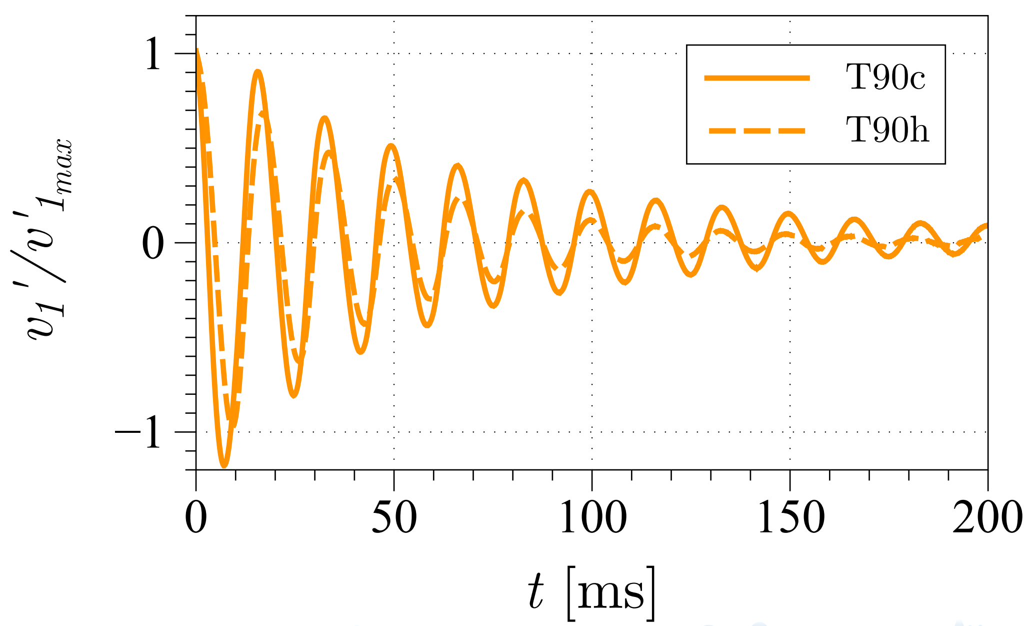
1. Comparison between two reacting cases



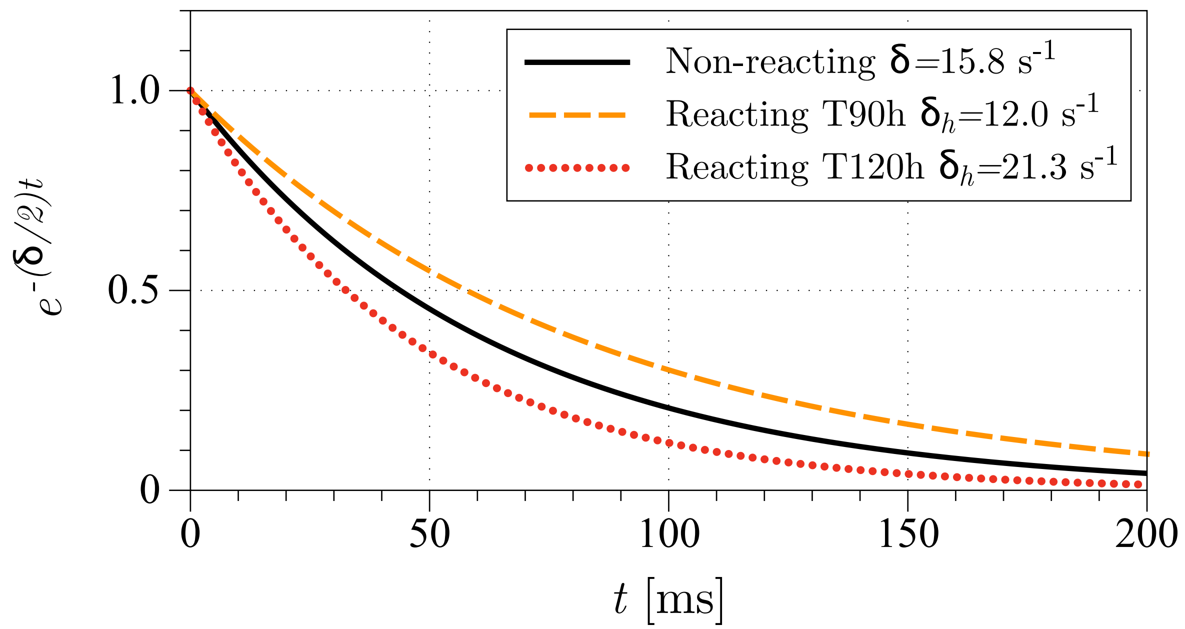


2. Comparison between two equivalent reacting and non-reacting cases





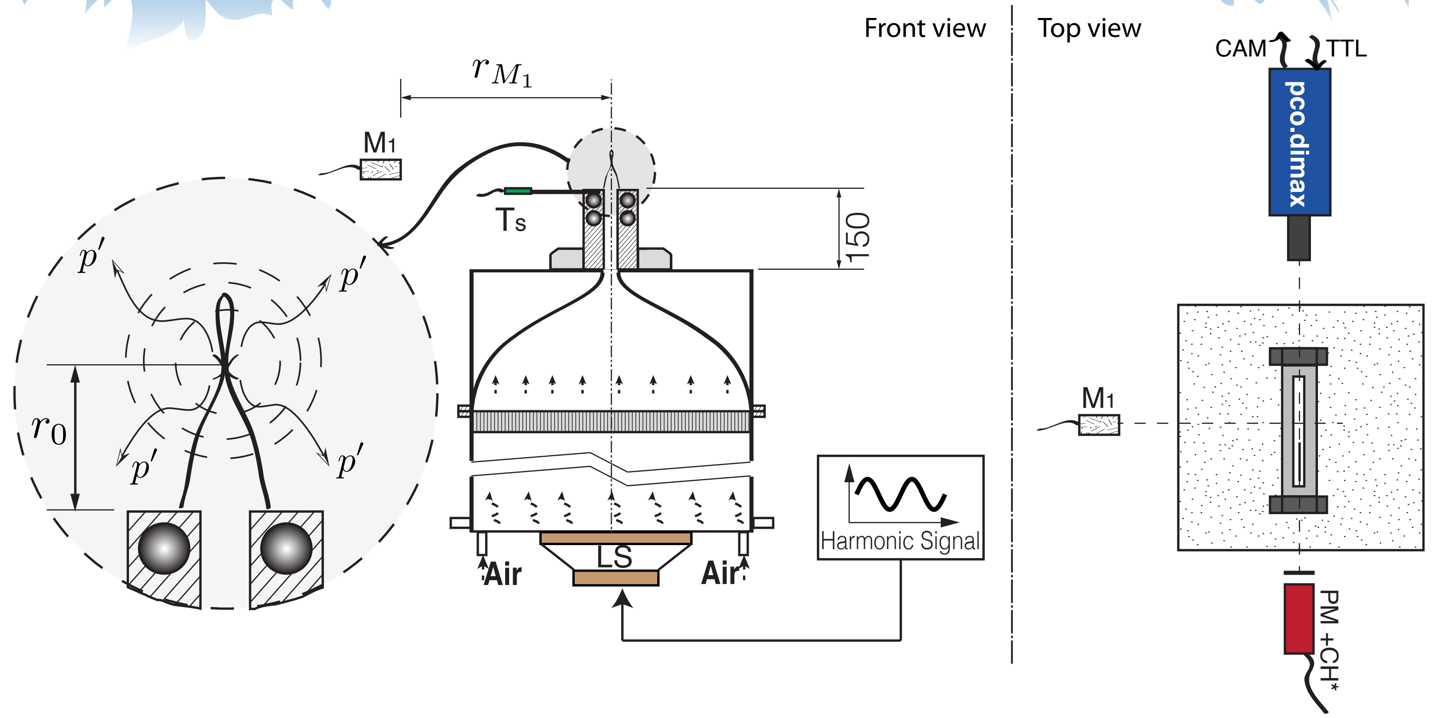
3. Flame effect on the system stability



	$\delta\ [s^{-1}]$
T50c	15.8
T90h	12.0
T120h	21.3

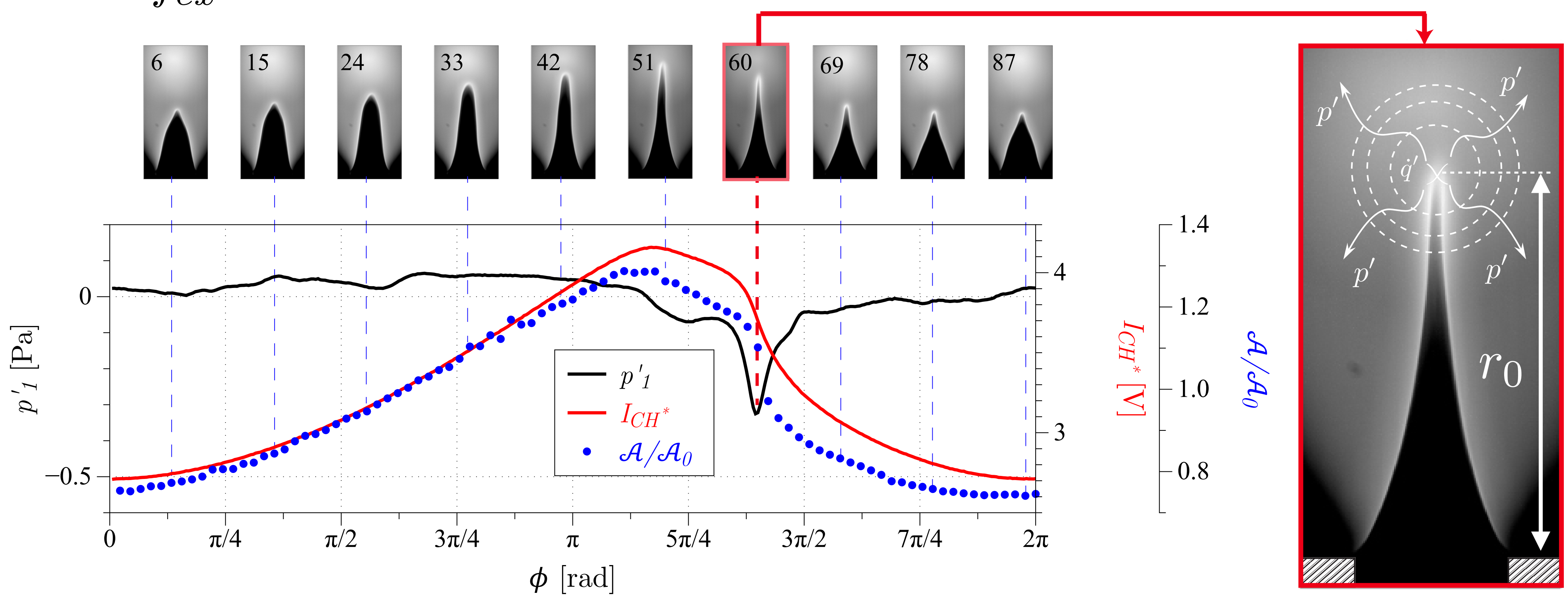
5. Combustion noise

1. Can we reproduce the far-field pressure from the PM signal?
2. How to measure the pinching distance r_0?
3. Does r_0 depend on the wall temperature T_s?



	r_0 [mm]
T50h	22.5
T90h	21.8
T120h	20.1
Mean	**21.5**

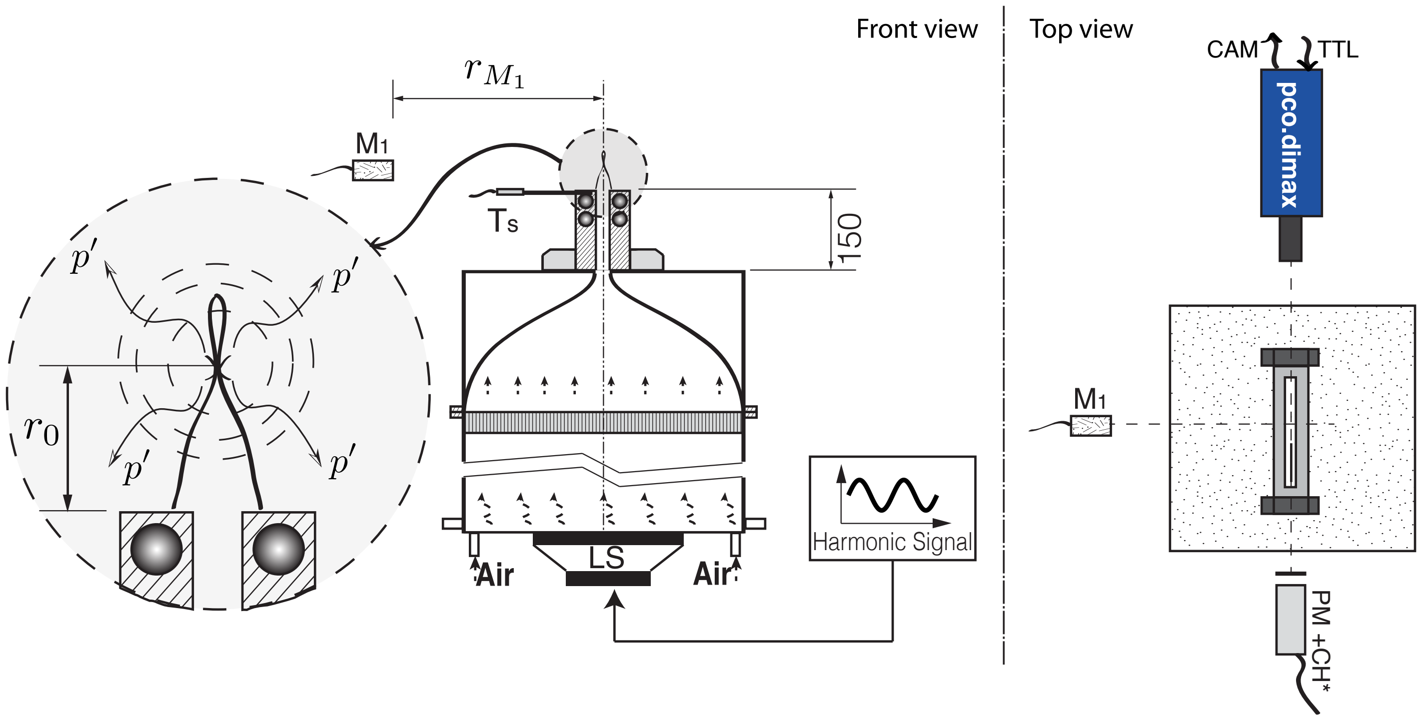
$f_{ex} = 60$ Hz

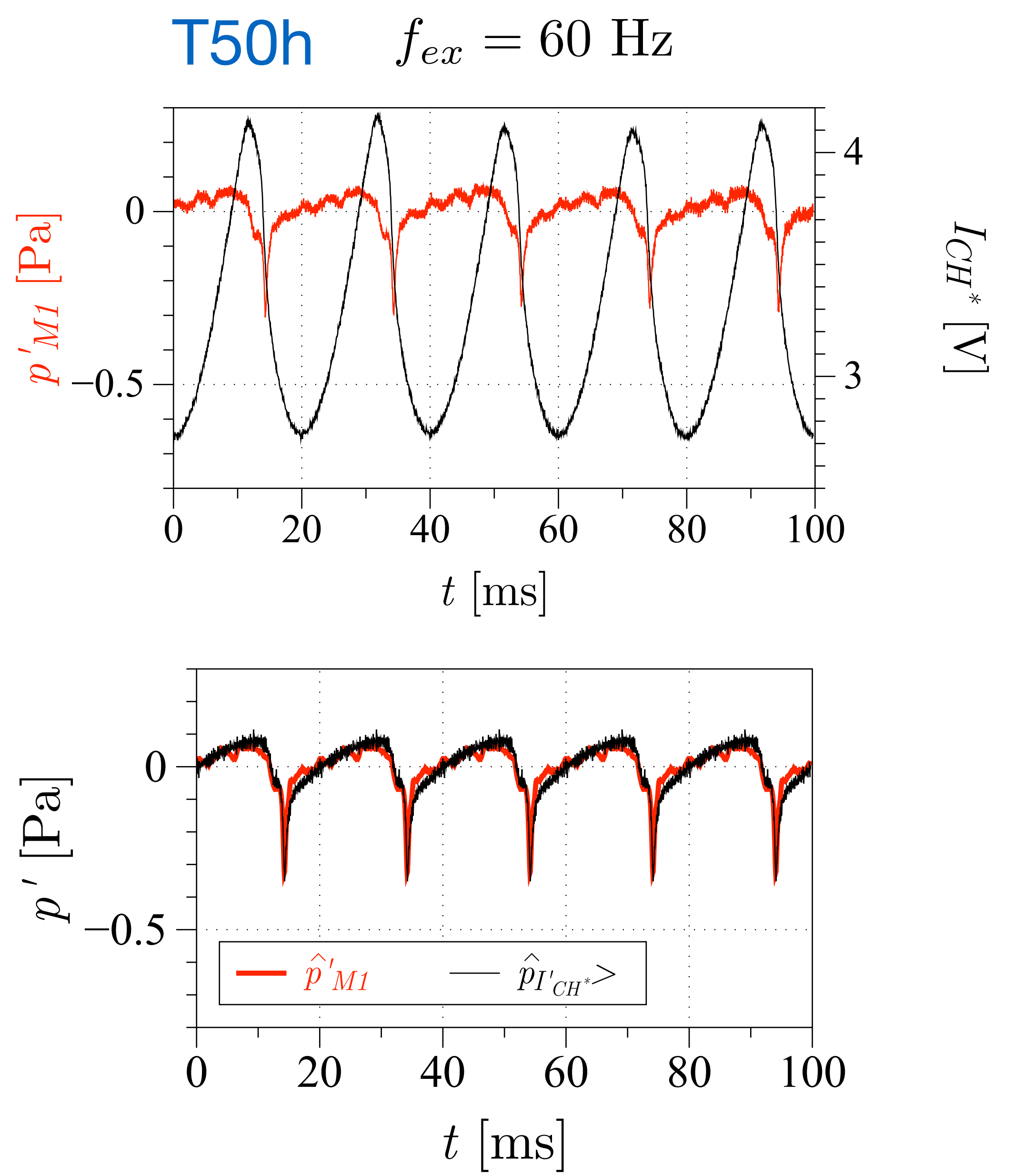


Combustion noise

1. Is classical combustion noise theory suitable for a slot burner?

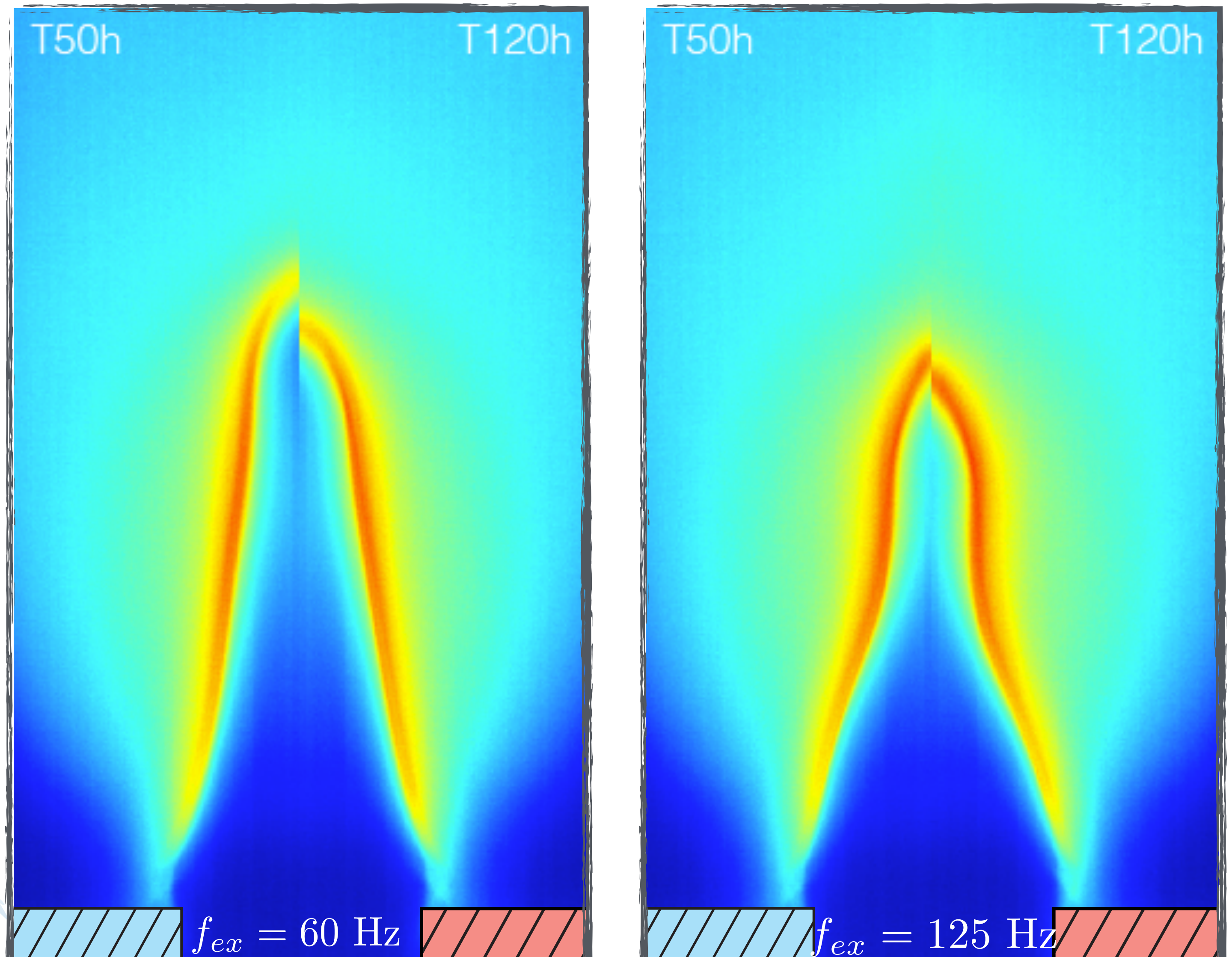
$$p'_{M1}(r_{M_1},t) = \frac{\rho_u (E-1)}{4\pi r_{M_1}} \varkappa \left[\frac{d I_{CH^*}}{dt}\right]_{t-\tau_{M_1}}$$



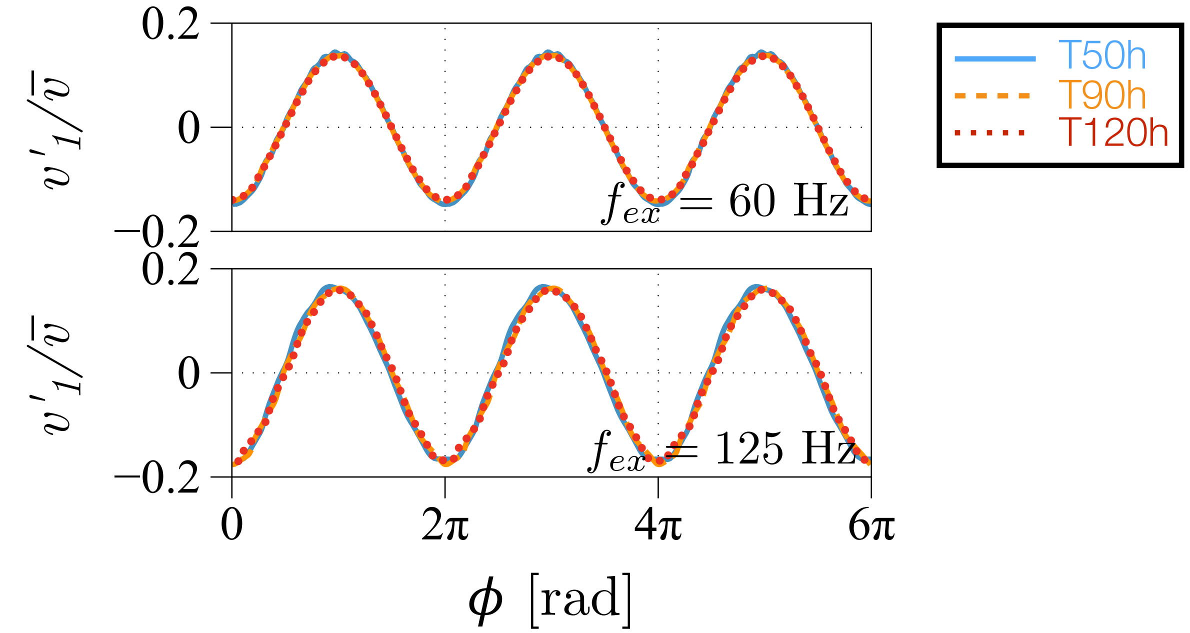


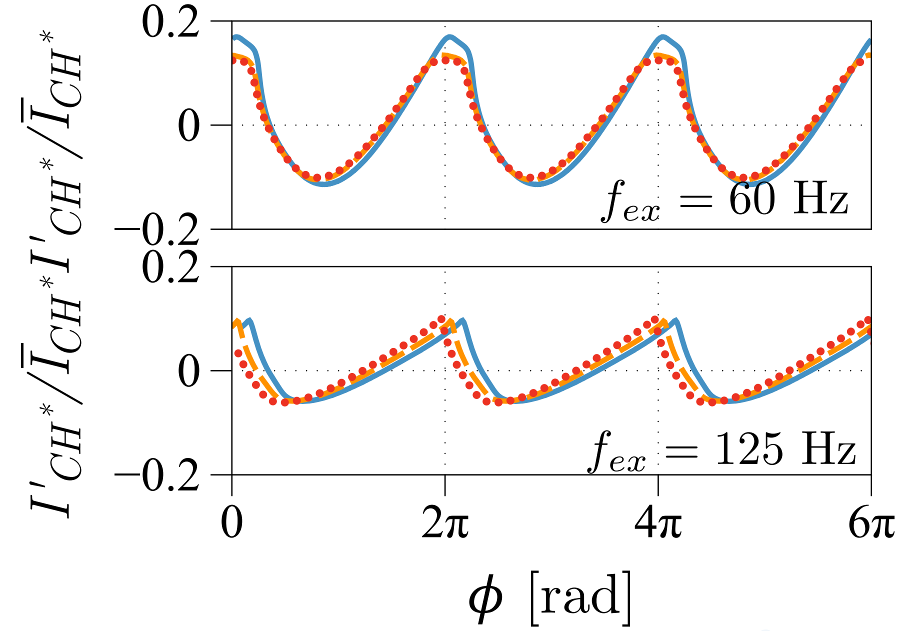
6. Flame response

1. Is the flame response affected by the wall temperature T_s?

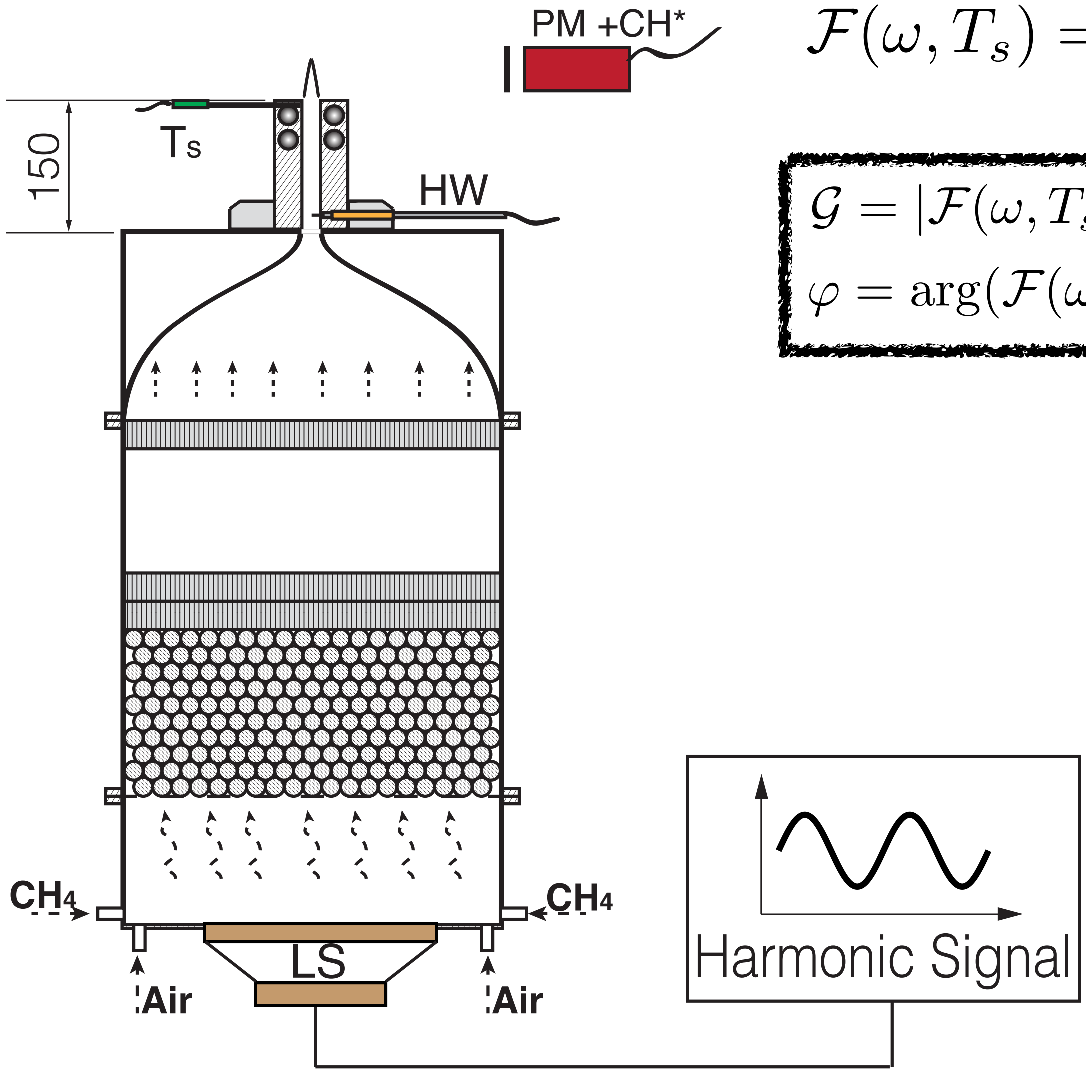


2. Is the velocity fluctuation the same for all cases?



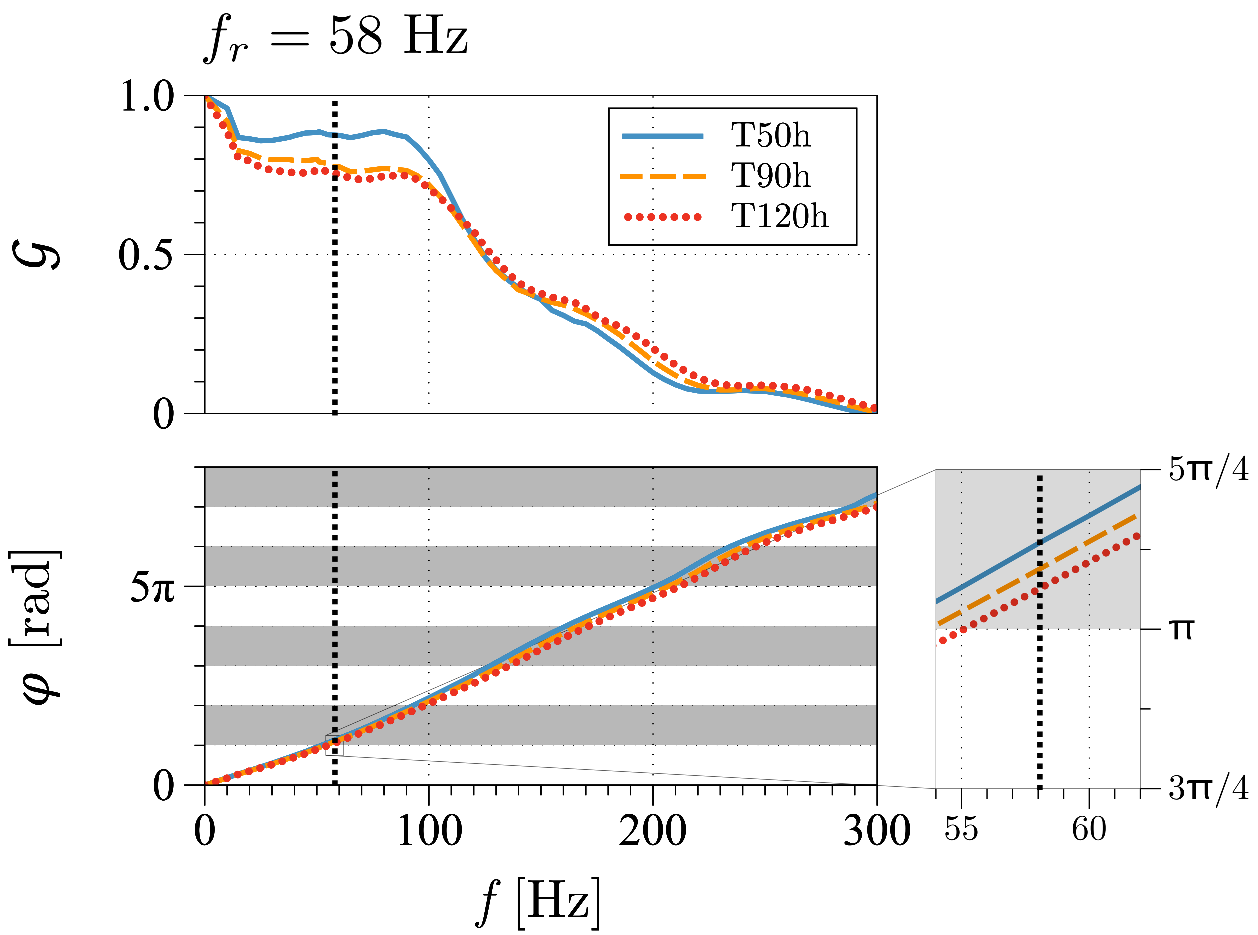


3. How does it affect the FTF?



$$\mathcal{F}(\omega, T_s) = \frac{\dot{q}'/\bar{\dot{q}}}{v'/\bar{v}}$$

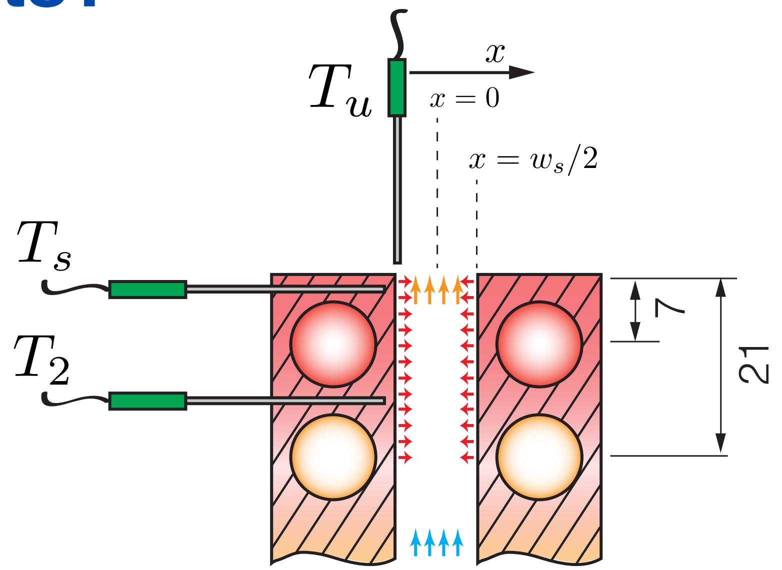
$$\mathcal{G} = |\mathcal{F}(\omega, T_s)|$$
$$\varphi = \arg(\mathcal{F}(\omega, T_s))$$

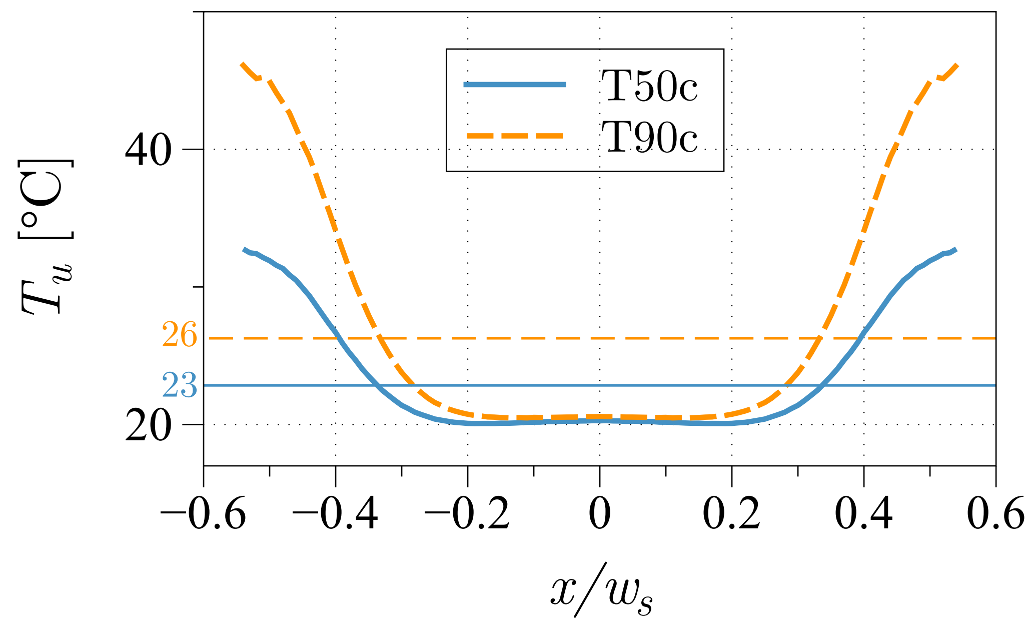


✳ Instability bands are determined for an idealized case without dissipation: $\varphi \in [\pi, 2\pi]$ modulo 2π

	$\mathcal{G}_r$	φ_r [rad]
T50h	0.88	1.13π
T90h	0.78	1.09π
T120h	0.75	1.06π
T50h-T120h	**14 %**	**6 %**

3. Does wall temperature modify the temperature profile of the reactants?

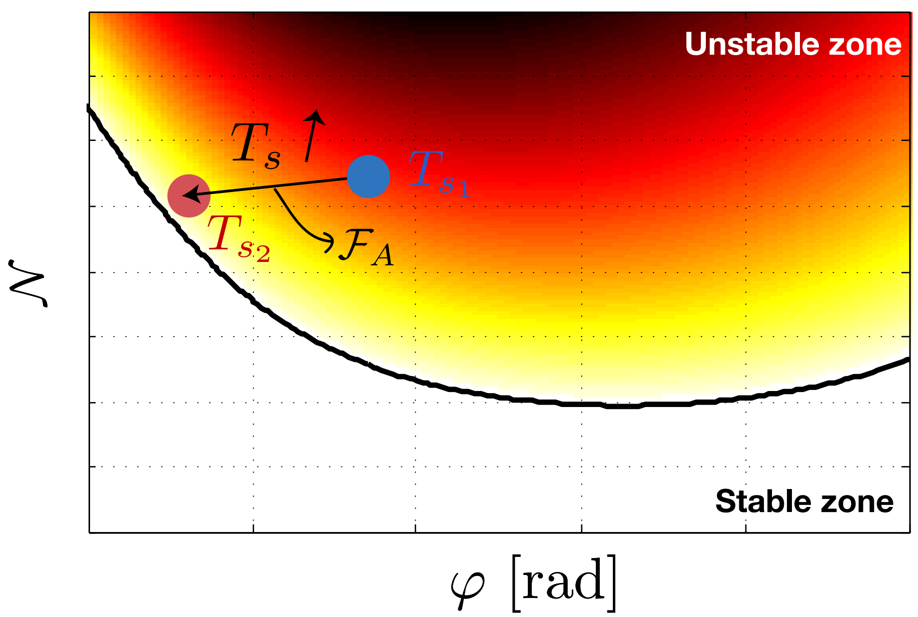




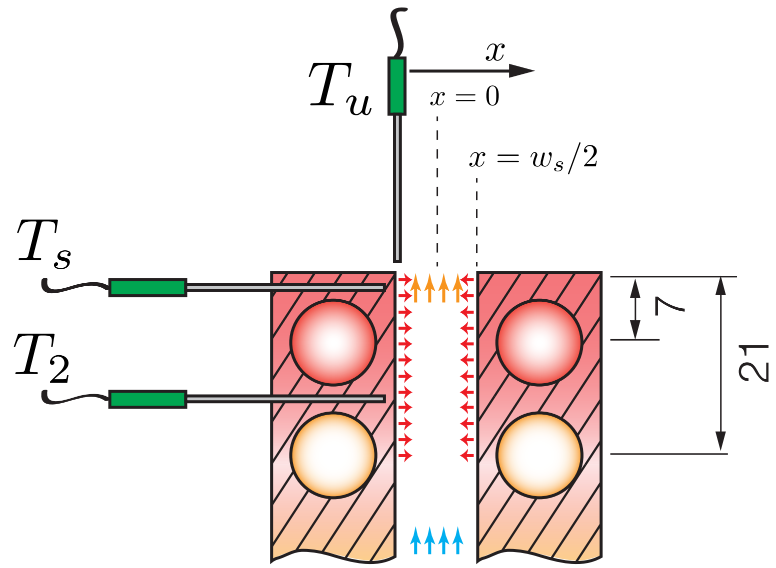
$$s_L = f(T_u)$$

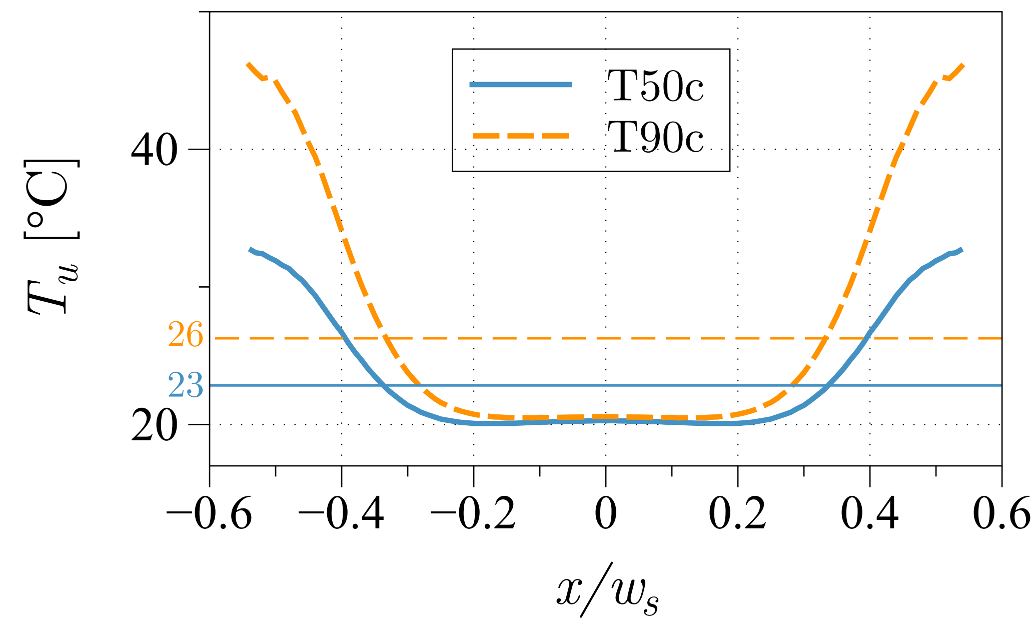
4. Does the increase in s_L explain the changes in the FTF ?

T50h-T90h		s_L Impact on the FTF	
ΔT_u [°]	Δs_L [cm s^{-1}]	$\mathcal{G}_r$	φ_r
3	1	3.4 %	2.2 %
		11.5 %	3.6 %
		Actual FTF difference T50h-T90h	



3. Does wall temperature modify the reactants temperature profile ?

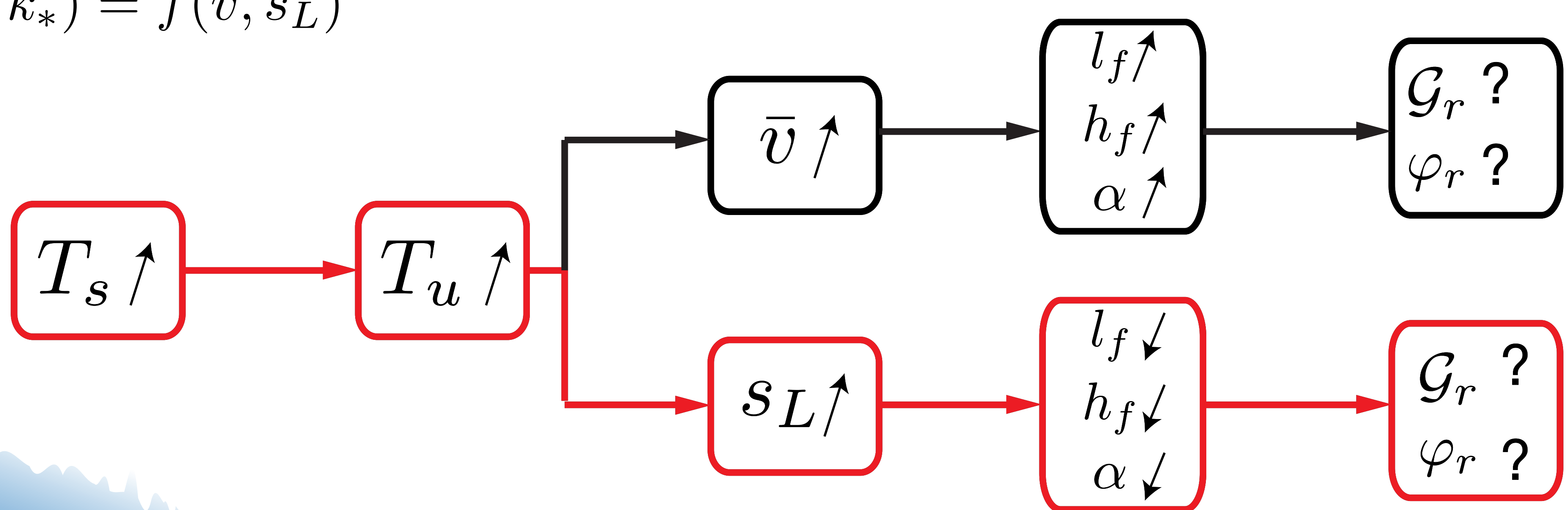




The pre-heating of the fresh gases cause:

- ★ Acceleration of the reactants $\bar{v} \uparrow$
- ★ Increase of the flame speed $s_L \uparrow$

$$\mathcal{F}_A = f(\omega_*, k_*) = f(\bar{v}, s_L)$$



4. Does the increase in sL explain the changes on the FTF ?

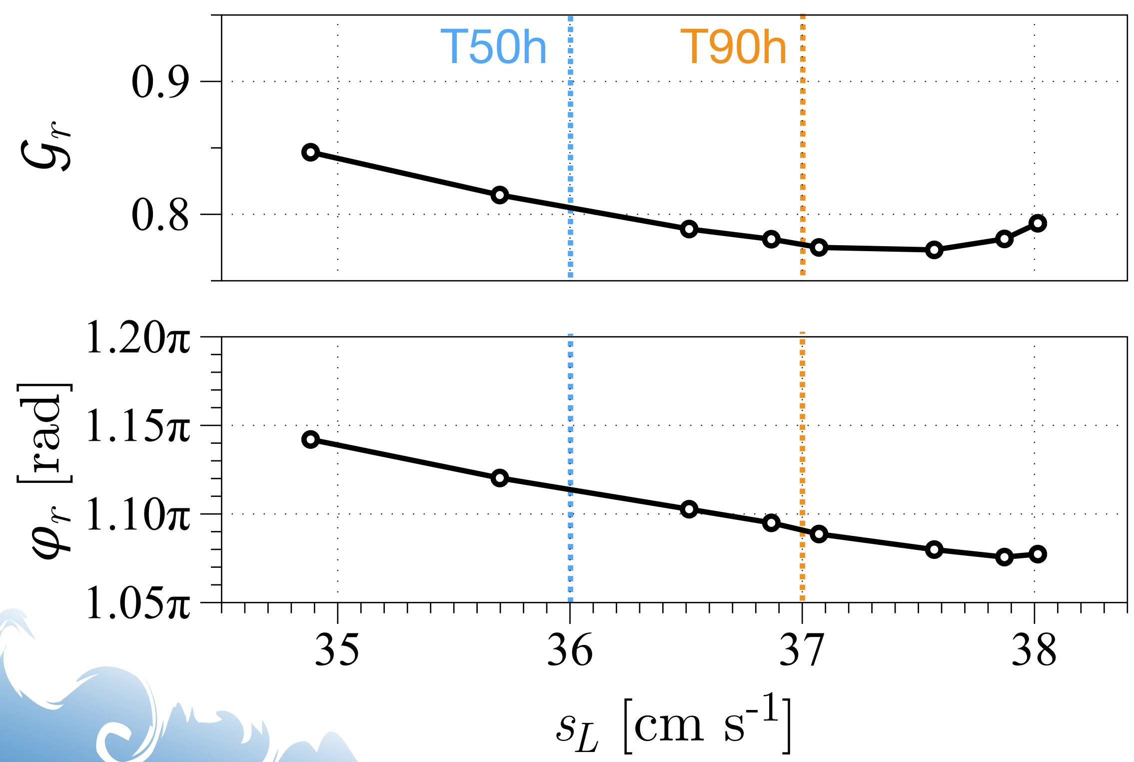
$$s_L \propto \left(\frac{T_{fg}}{T^0_{fg}}\right)^{\alpha_T}$$

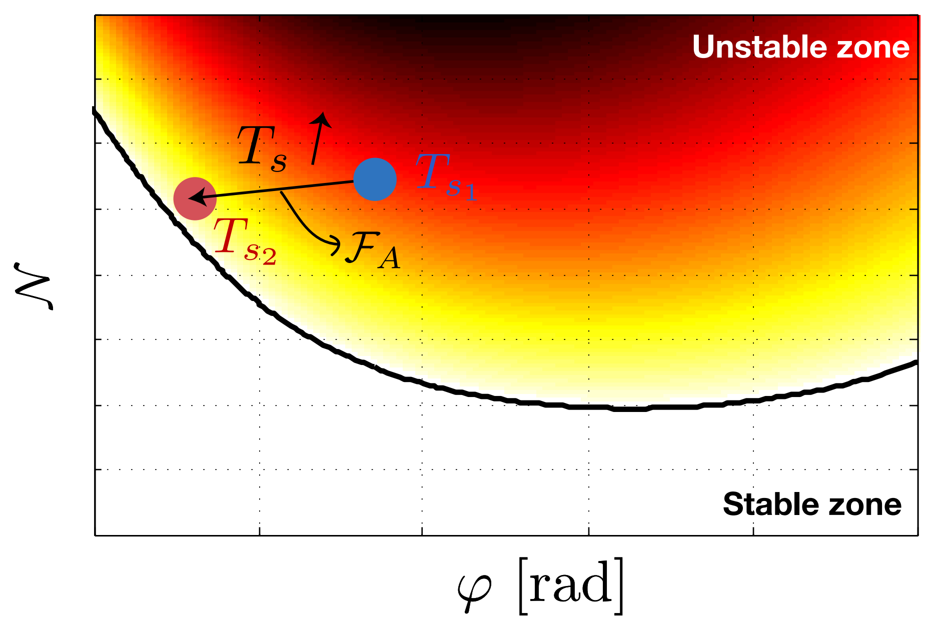
$$\alpha_T \approx 1.9$$

[1] Gu *et al. 2000 cf.*

T50h-T90h		s_L Impact on the FTF	
ΔT_u [°]	Δs_L [cm s^{-1}]	$\mathcal{G}_r$	φ_r
3	1	3.4 %	2.2 %
		11.5 %	3.6 %
		Actual FTF difference T50h-T90h	

$T_s = 90$ °C $f = 58$ Hz $\Phi = 0.9$ to 1.02





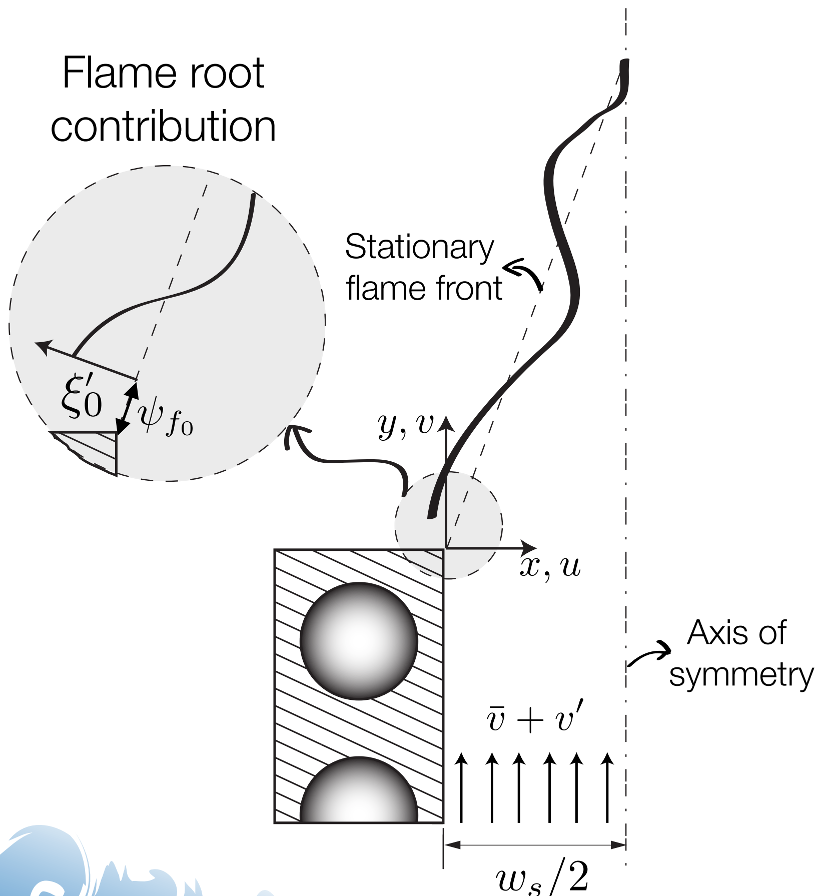
9. Flame Root Dynamics

1. Does the theory predicts a change in the flame root response when Ts changes?

Flame root dynamics is controlled to the first order by the heat transfer between the burner and the flame anchoring point.

Flame root contribution

$$\mathcal{F}_B \propto \Xi$$



Flame root transfer function

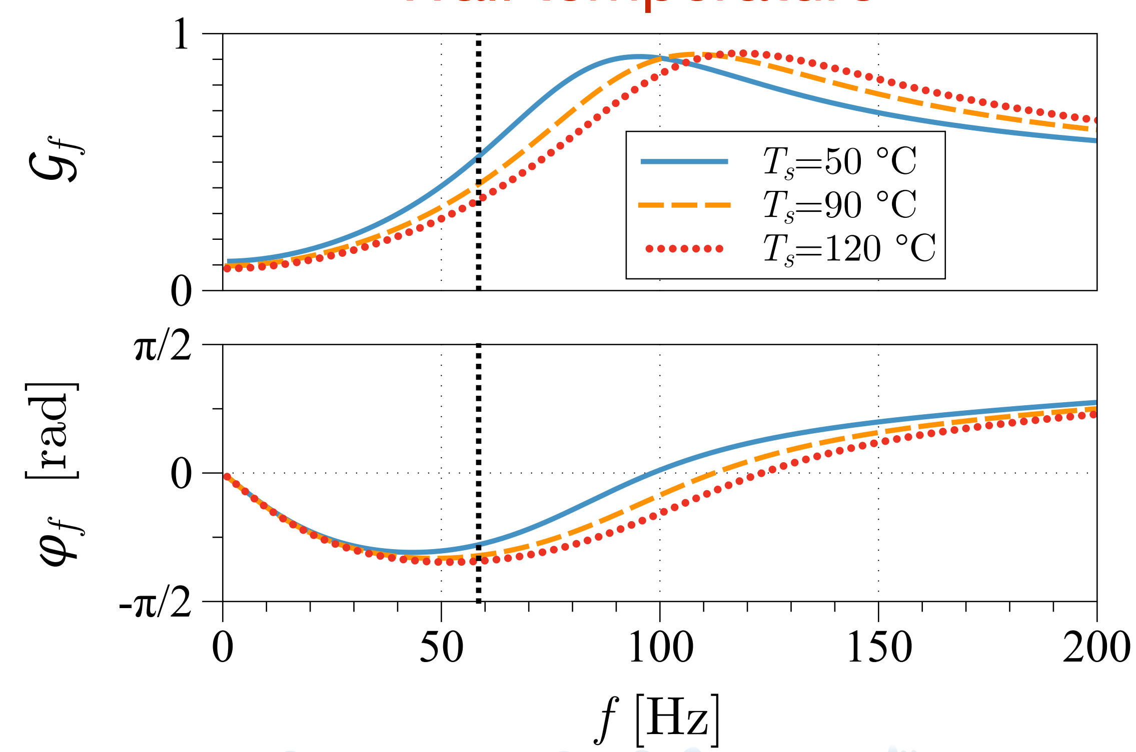
$$\Xi = \frac{\xi_0'/(w_s/2)}{v'/\bar{v}}$$

$$\psi_{f_0} = \delta_f \log\left(\frac{T_{ad} - T_u}{T_{ad} - T_b + \boxed{T_s} - T_u}\right)$$

Wall temperature

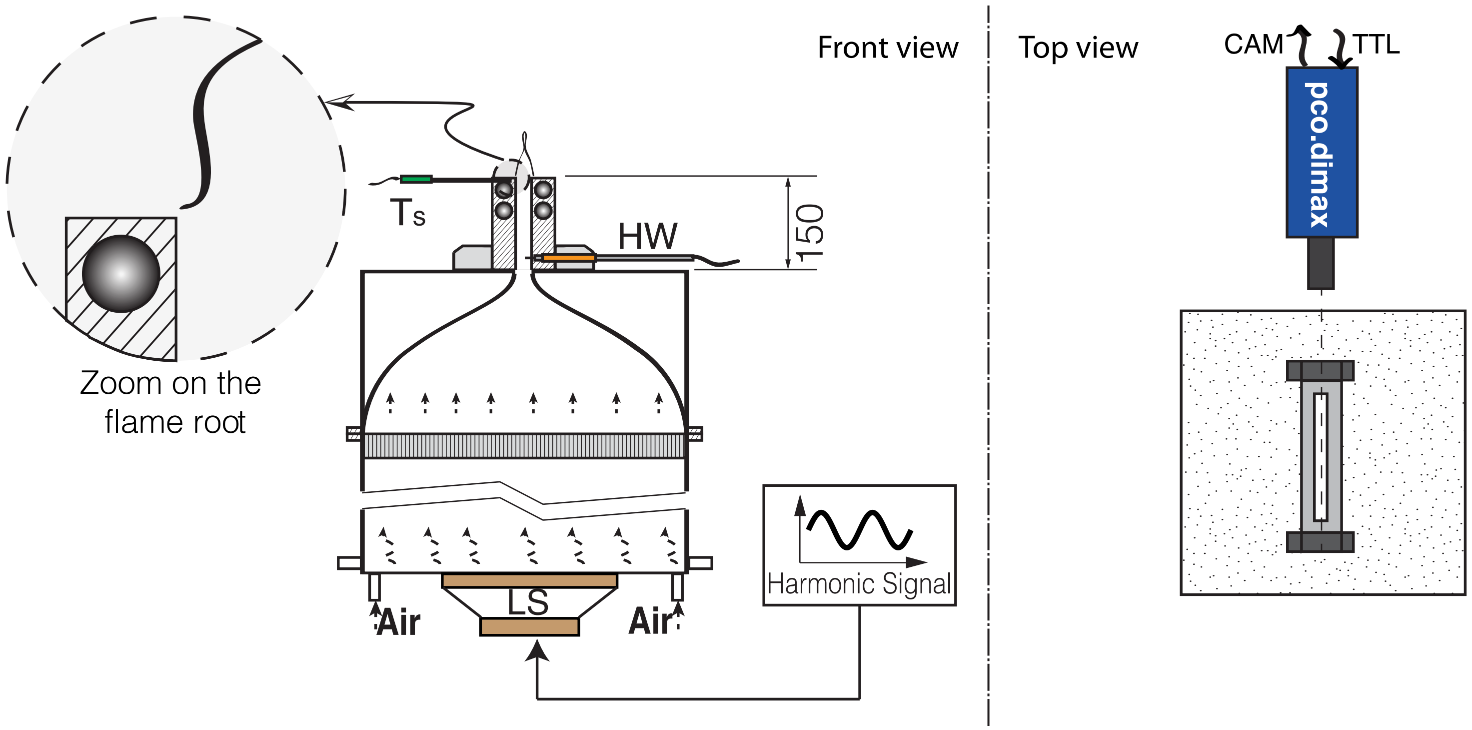
$$\boxed{\begin{aligned} \mathcal{G}_f &= |\Xi(\hat{\omega}, \mathrm{Ze}, \psi_{f_0})| \\ \varphi_f &= \arg(\Xi(\hat{\omega}, \mathrm{Ze}, \psi_{f_0})) \end{aligned}}$$

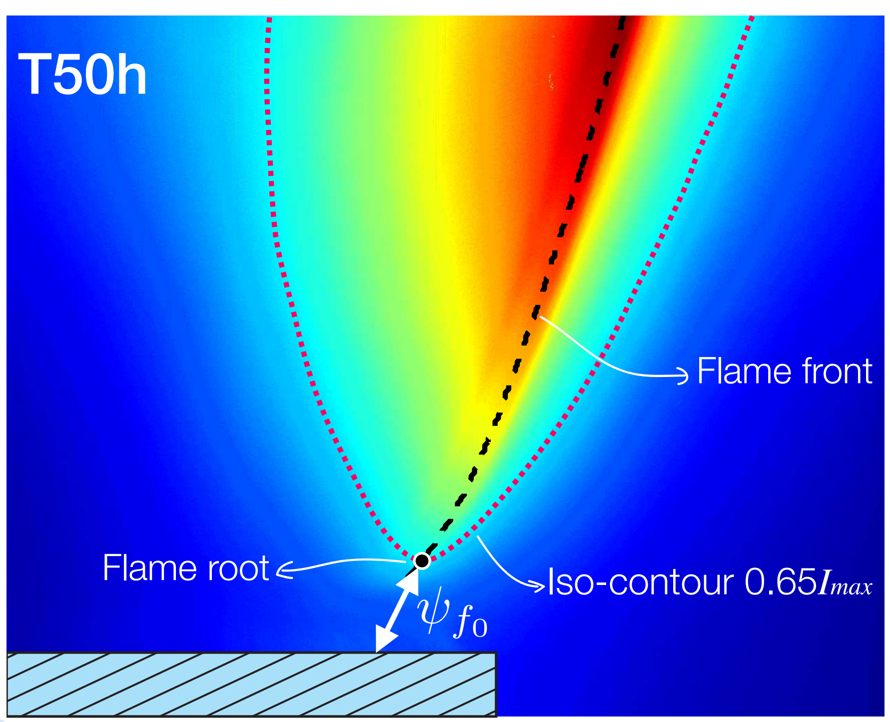
$$f_r = 58 \text{ Hz}$$

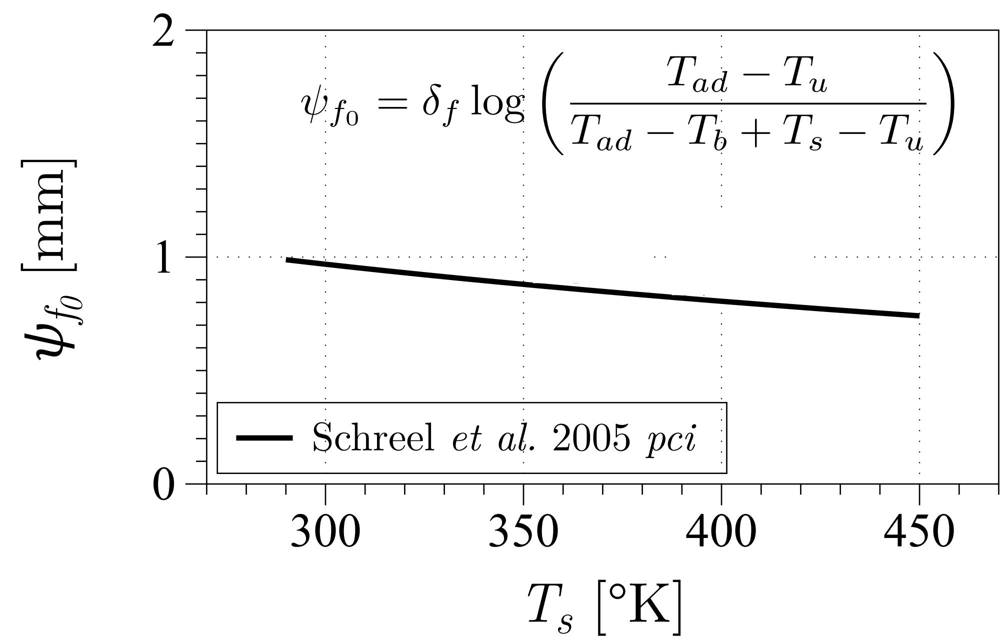


[1] Kornilov *et al.* 2007 *pci.*
[3] Cuquel *et al.* 2013 *crm.*
[4] Rook *et al.* 2002 *ctm.*
[5] Schreel *et al.* 2005 *pci.*
[6] Altay *et al.* 2009 *pci.*

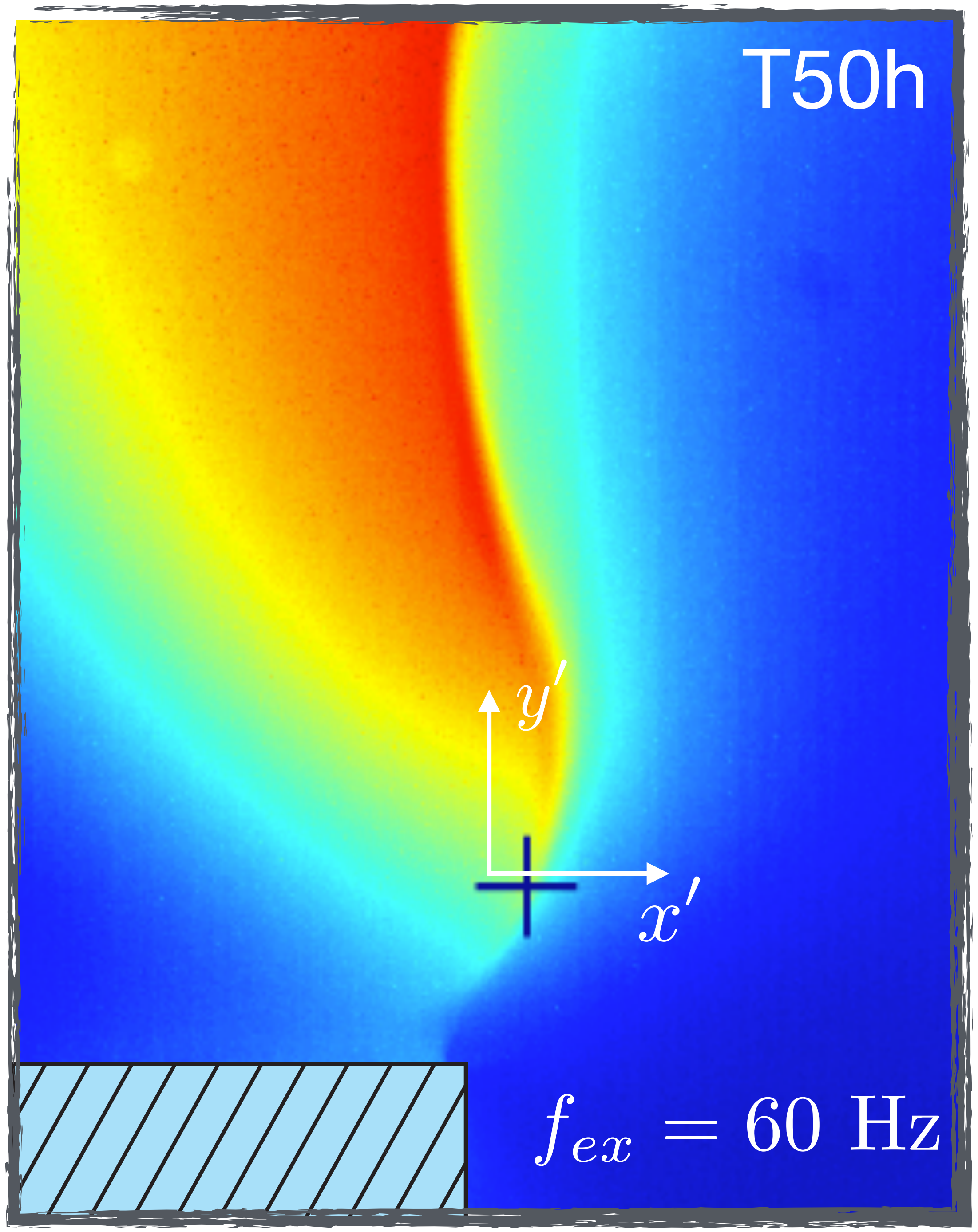
2. Does the experiment predict a change in the flame root response when Ts changes?



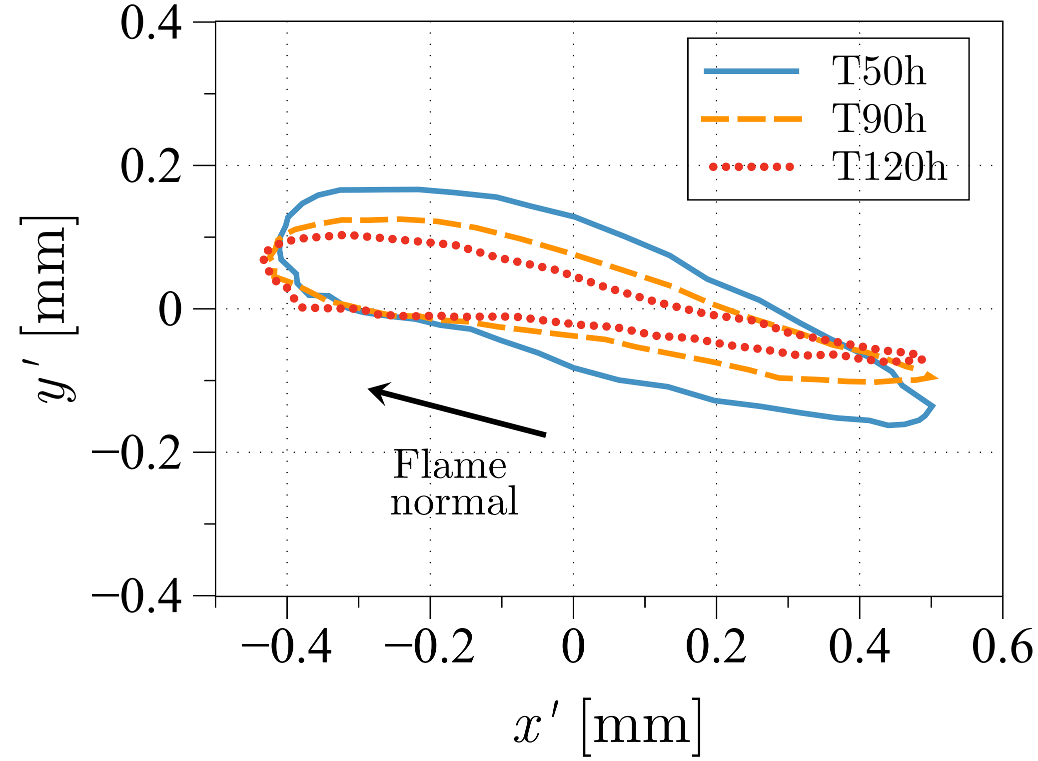


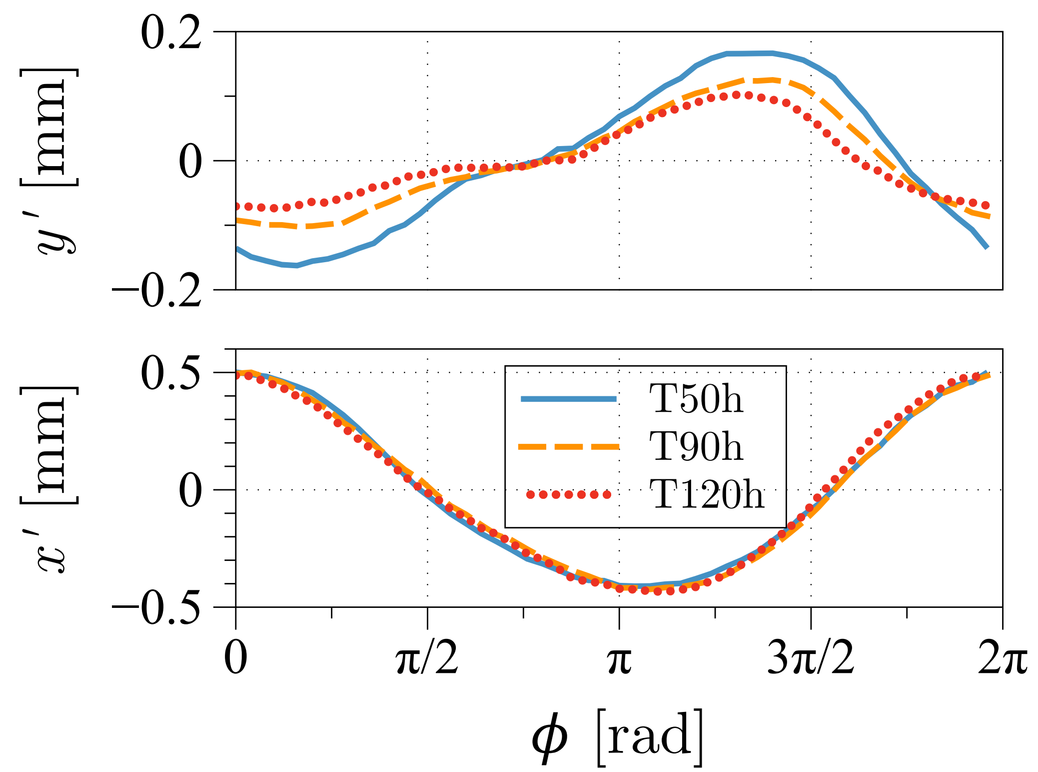


Flame root trajectoires



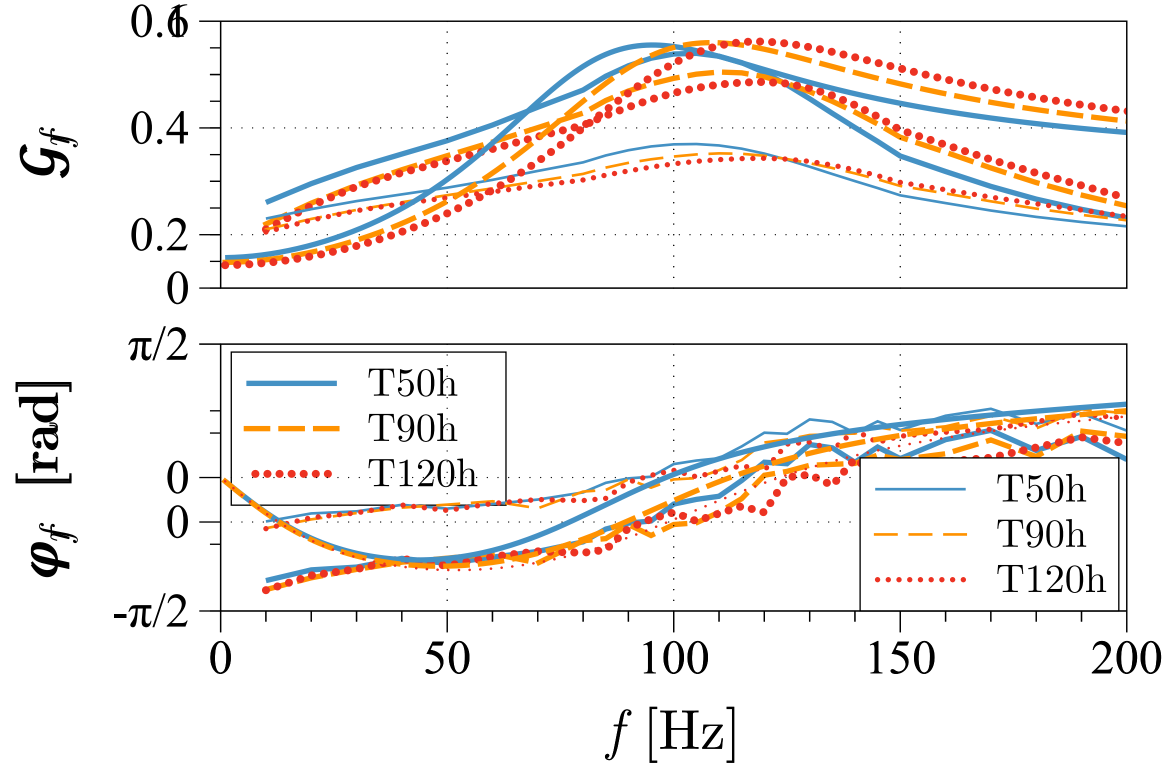
$$x' = x - x_0$$
$$y' = y - y_0$$





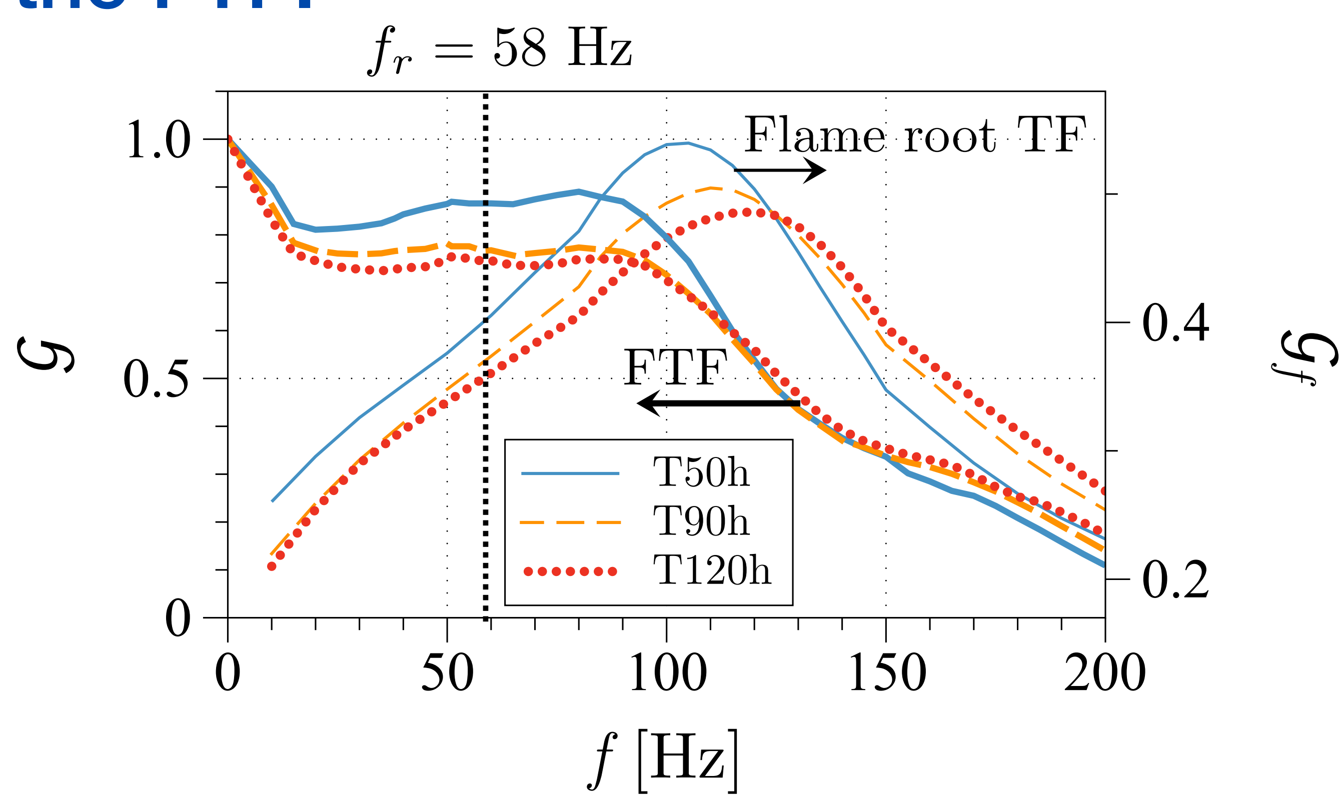
Experimental flame root transfer function

$$\mathcal{G}_r = |\Xi(\omega, T_s)|$$
$$\varphi_r = \arg(\Xi(\omega, T_s))$$



Model	Expe	
		T50h
		T90h
		T120h

Comparison with the FTF:

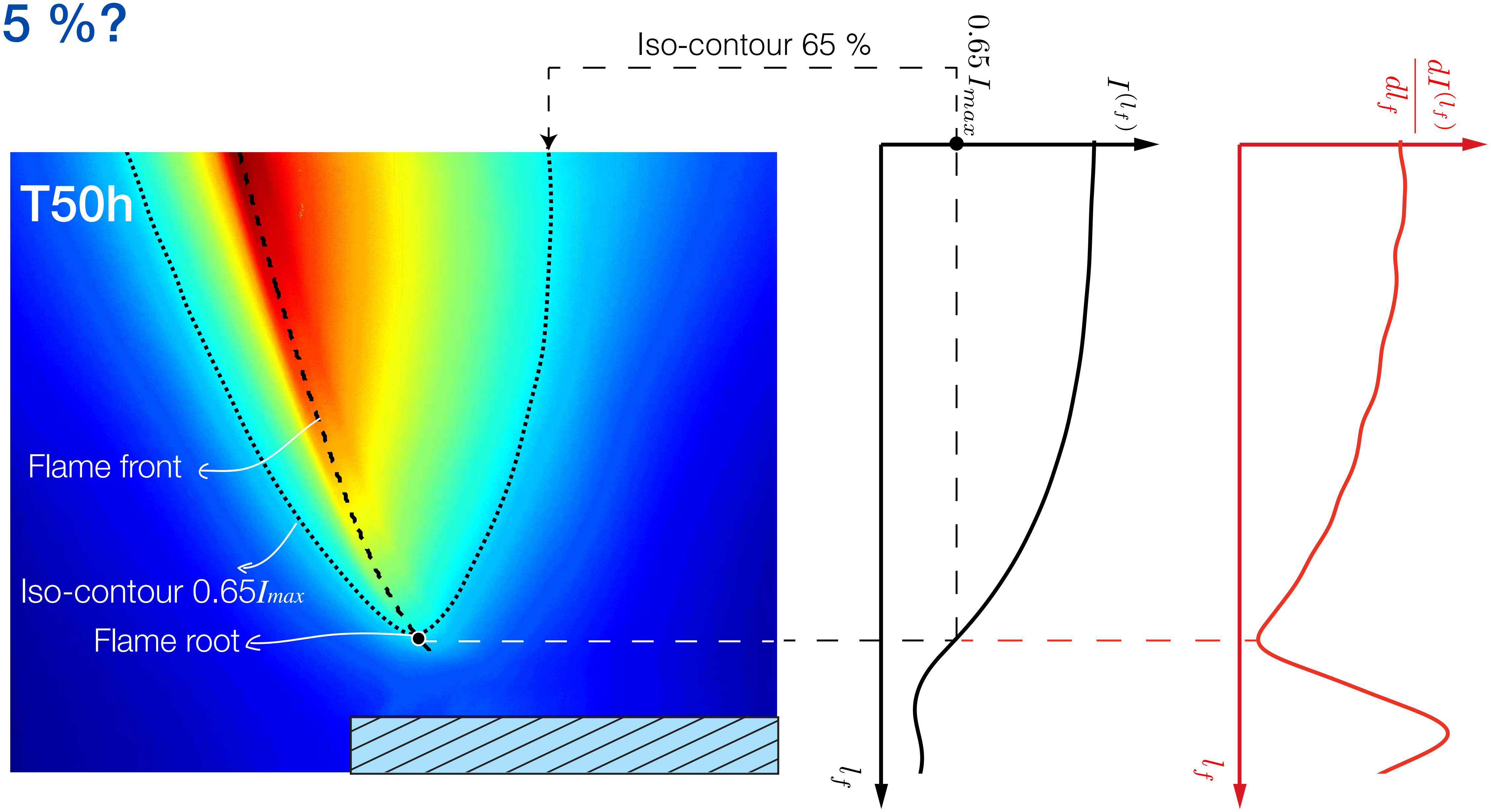


FTF	FRTF	
		T50h
		T90h
		T120h

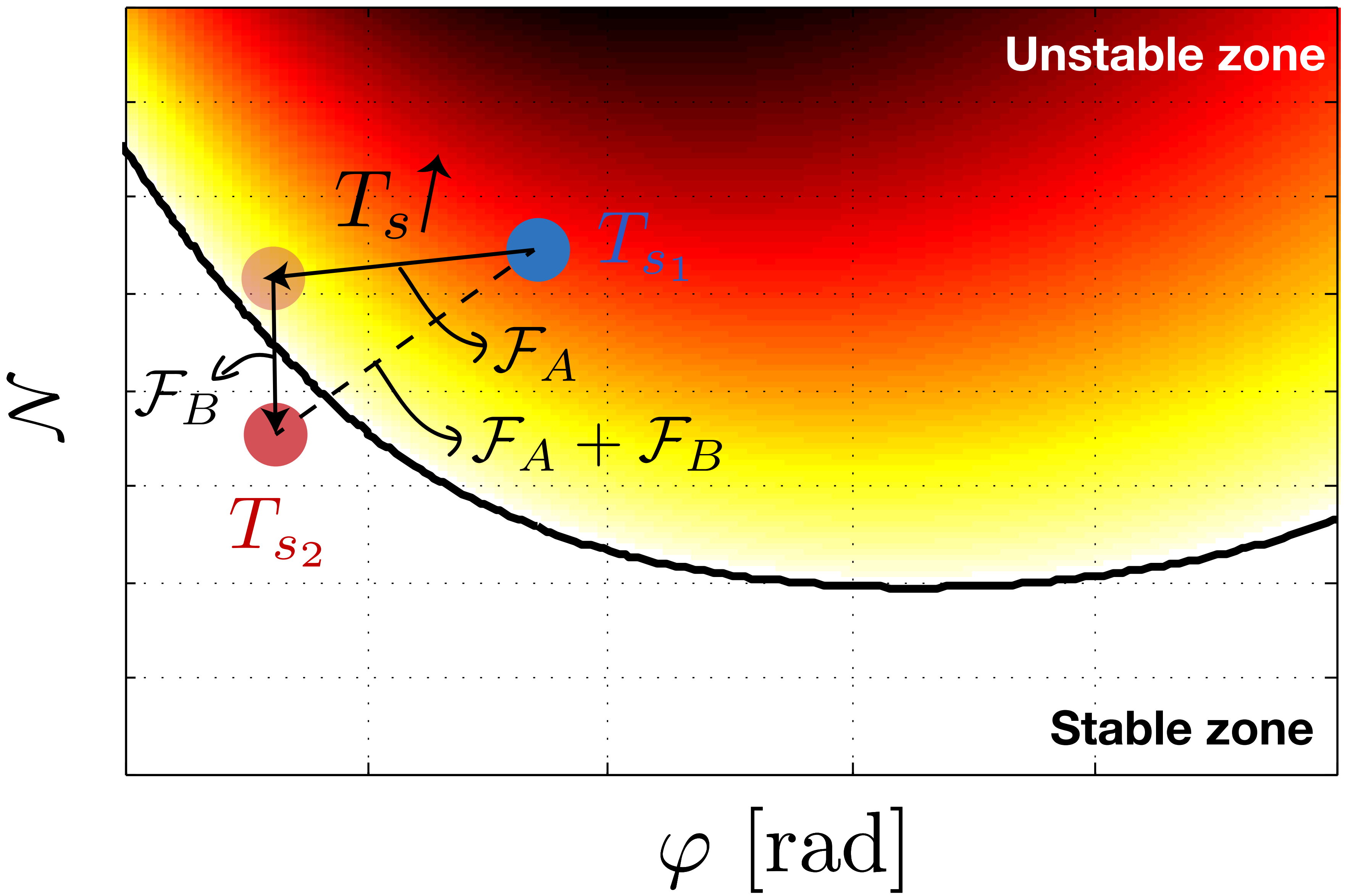
Difference T50h-T120h	$\mathcal{G}_r$
Flame root FTF	11 %
Actual FTF	14 %

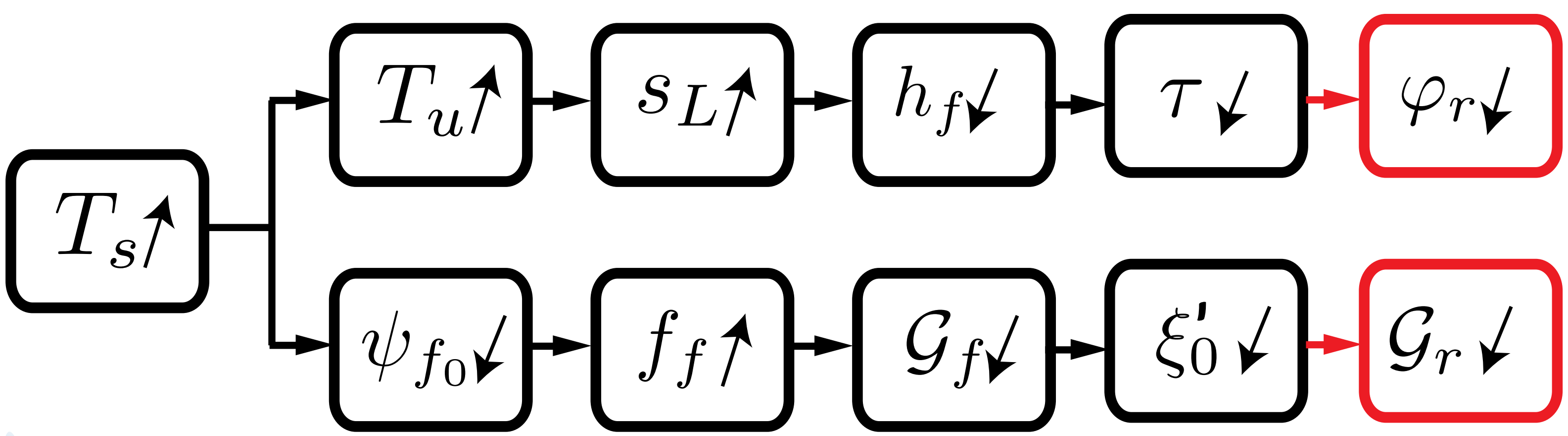
Flame Root Definition

Why 65 %?



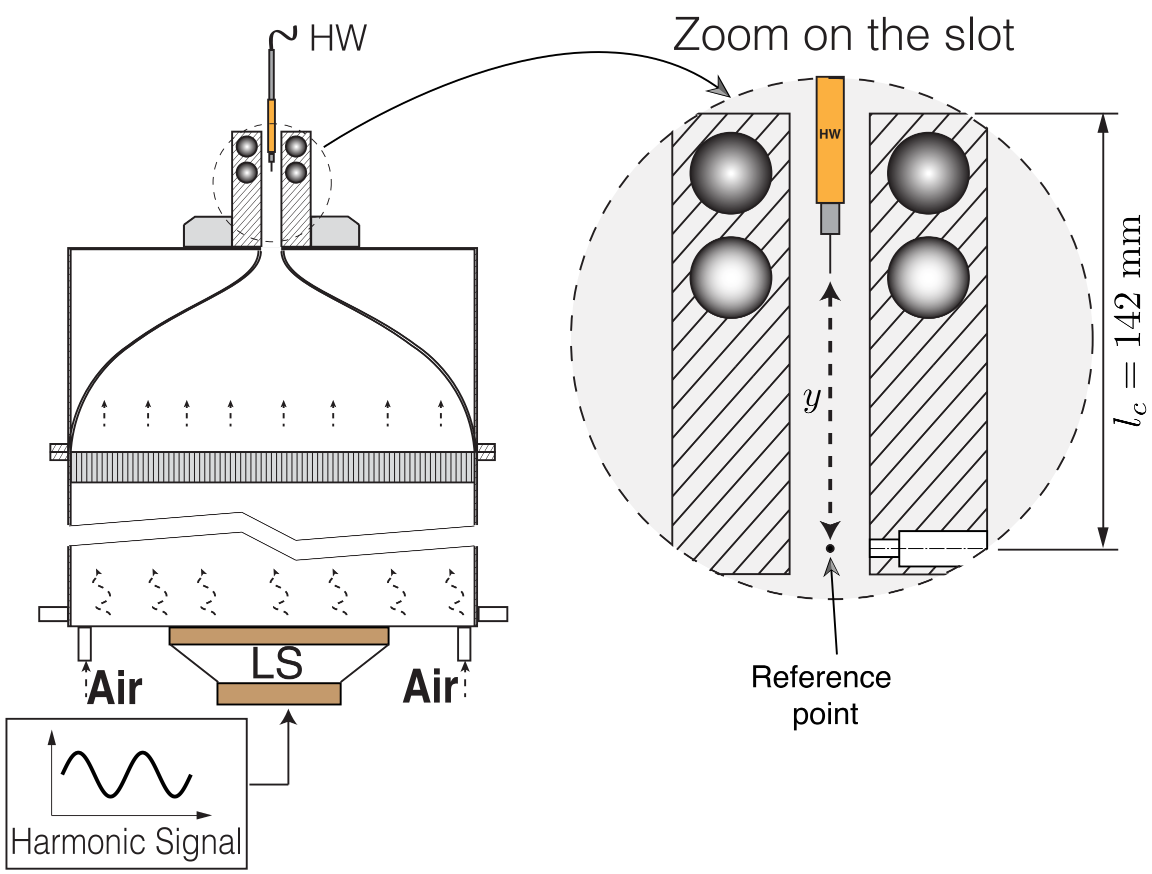
So, how is the flame stabilized?

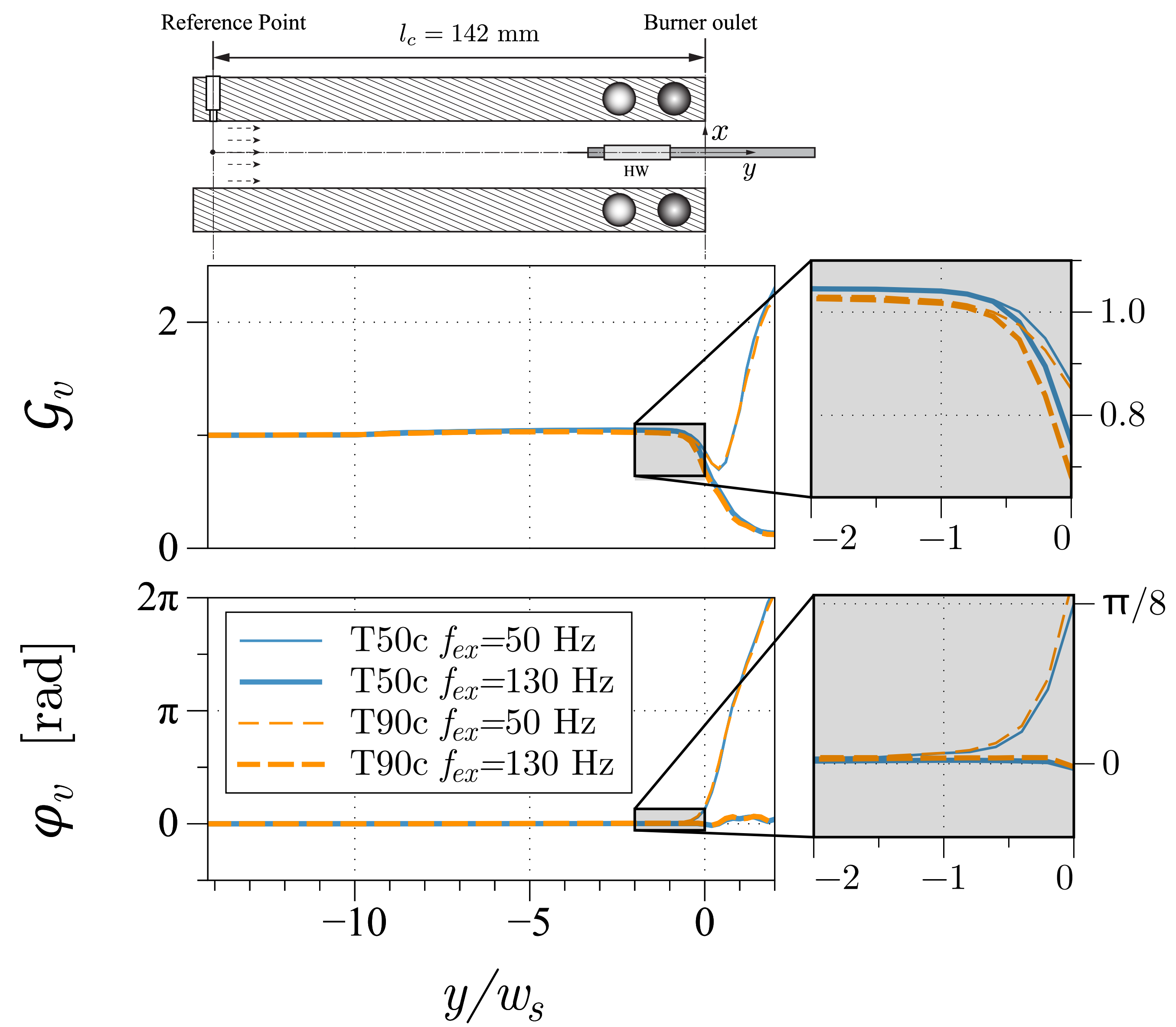




Velocity transfer function

Does the FTF depends on the reference point ?





Corrected FTF