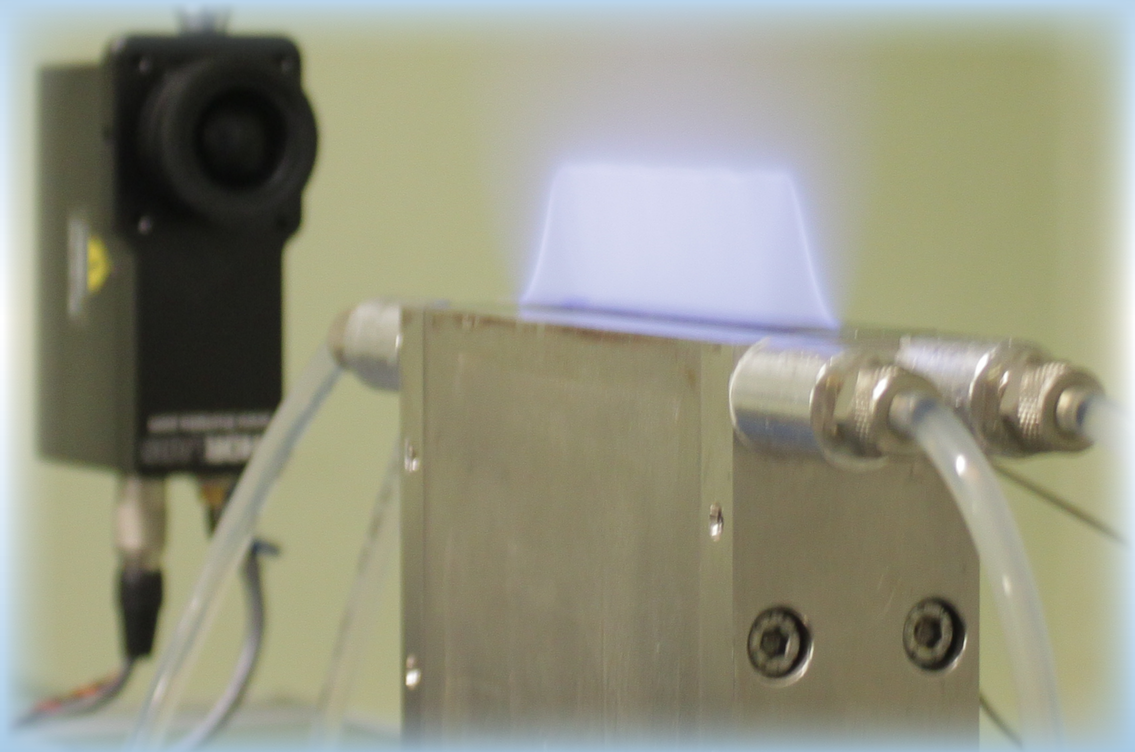
Ph.D Defense

Wall-Temperature Effects on Flame Response to Acoustic Oscillations



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Tuesday 20 Mai 2014
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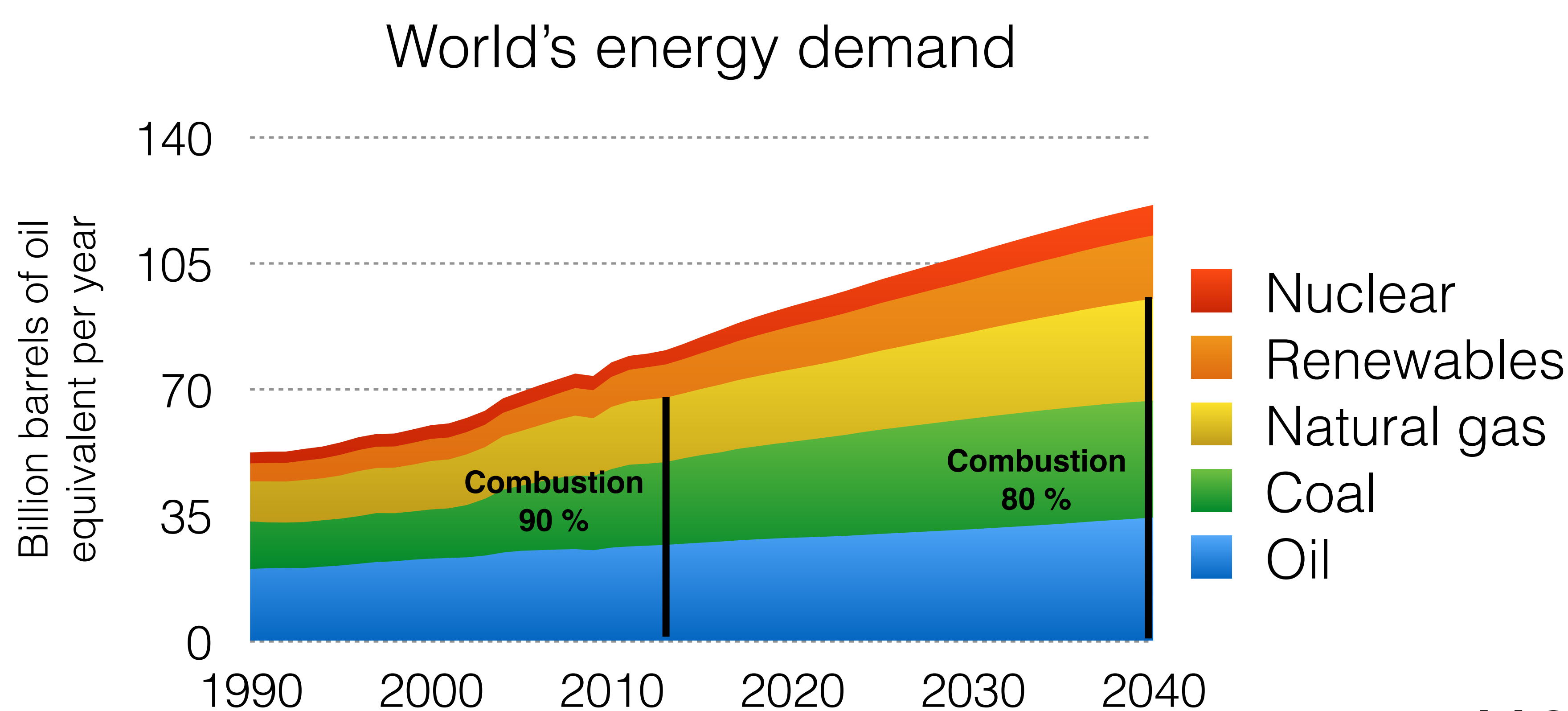
Context

- ★ **Energy production** constitutes one of the major challenges of the new era and comprises electricity generation, industrial processes, transportation and alimentation.

- ★ Despite the growth of renewable energies, **combustion is up to date, responsible for 90 % of the total energy generated on earth**, and it will remain the main source for a long time (up to 80 % in 2040).



Source: US Energy Information Administration, 2013 Report.

[1] Sawyer 2009 *pci.*

★ Combustion systems come in a wide range of scales:

Gaz central power station

$\sim$ 1 GW

Turbofan engine

$\sim$ 100 MW

Domestic boiler

$\sim$ 10 kW

Micro turbine

$\sim$ 1 W

★ But… Combustion is also responsable for:

Air pollution (CO, NOx…)

Solution?

Lower flame temperature

How?

Lean premixed combustion

Global warming (CO_2)

Solution?

Increase efficiency

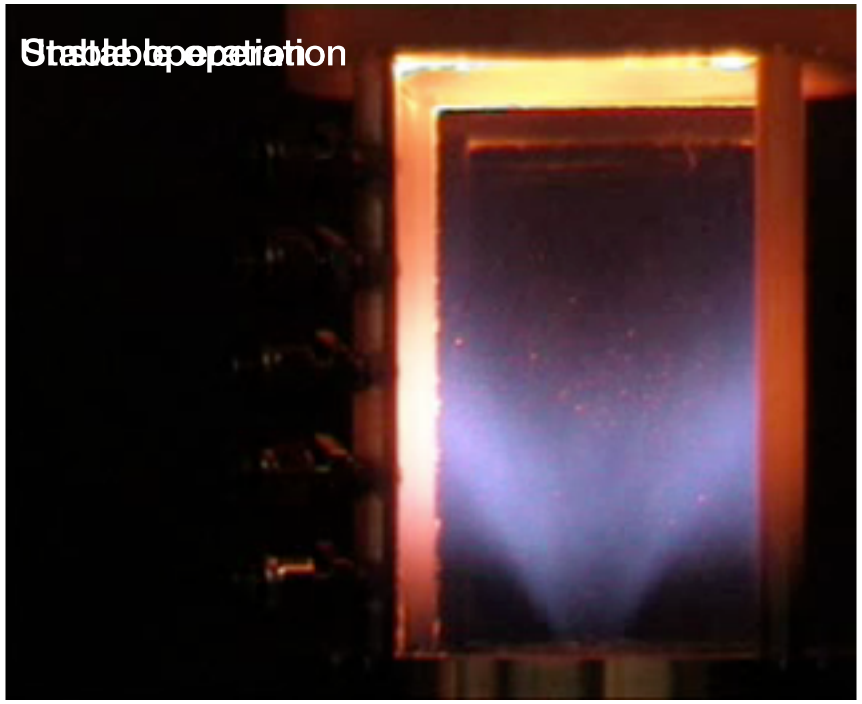
How?

High pressures and compact design systems

New technologies are very sensitive to combustion instabilities !

[1] Penner *et al.* 1999

★ **Combustion instabilities (CI's)** are a major problem in the operation of many power-generation systems.

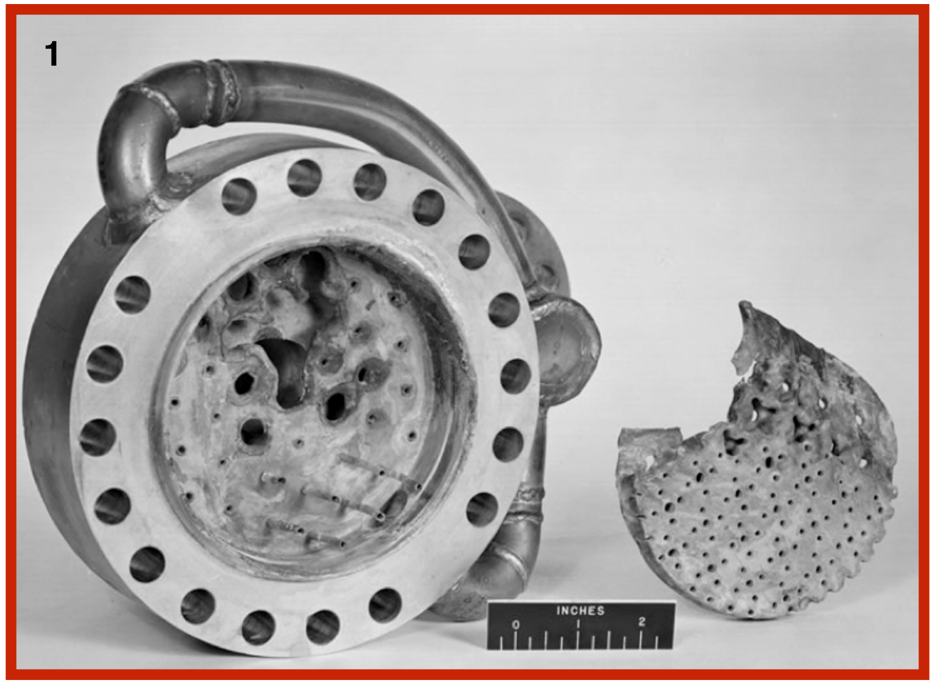


Source: PRECCINSTA burner DLR

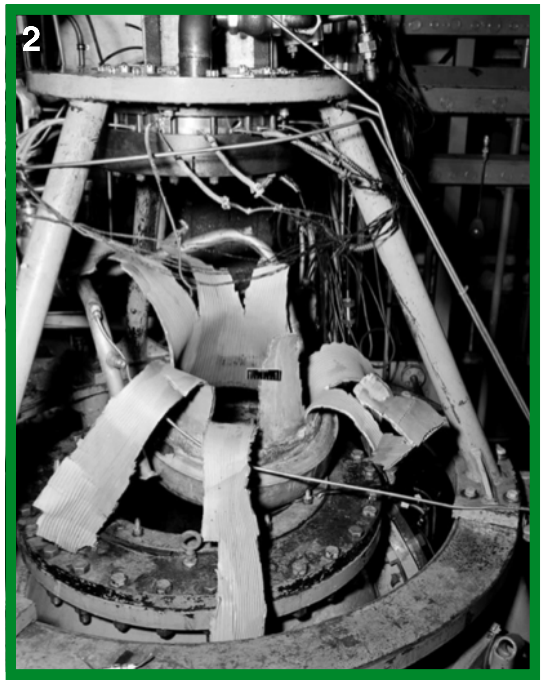
CI's consequences:

- Flame flash-back,
- Flame blow-off,
- High pressure fluctuations,
- High heat fluxes,
- Mechanical vibrations.

★ In some cases CI's can cause a **catastrophic failure** of the system:



1. Burner injectors of NASA rocket engine.



2. Rocket engine NASA damaged by CI's.

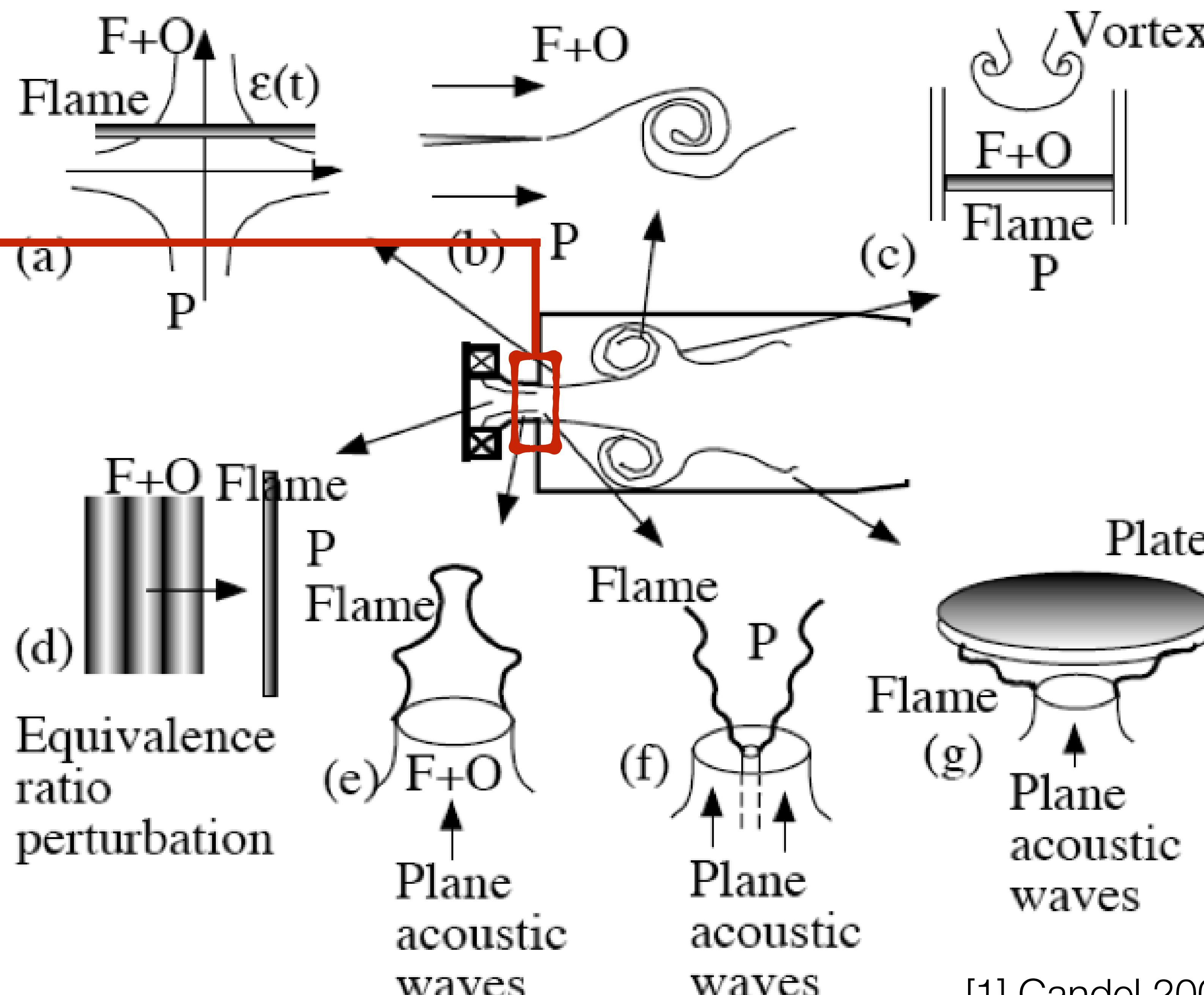
3. Turbine disk detached from a turbofan engine after CI's.

★ The ultimate goal of CI's is to **anticipate when a combustion chamber will be unstable** at the design stage, avoiding the high costs and reducing time of prototype testing.

★ The challenge for understanding and predicting CI's lies in the **multiplicity of physical phenomena** involved:

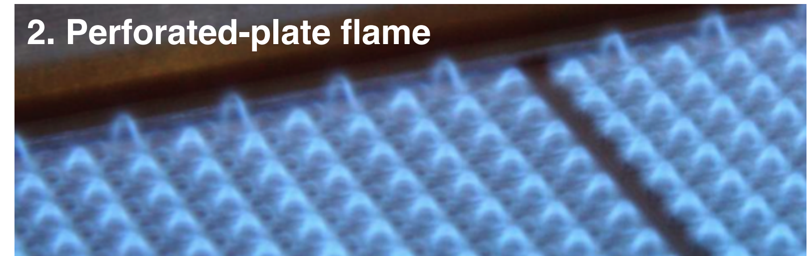
Wall temperature

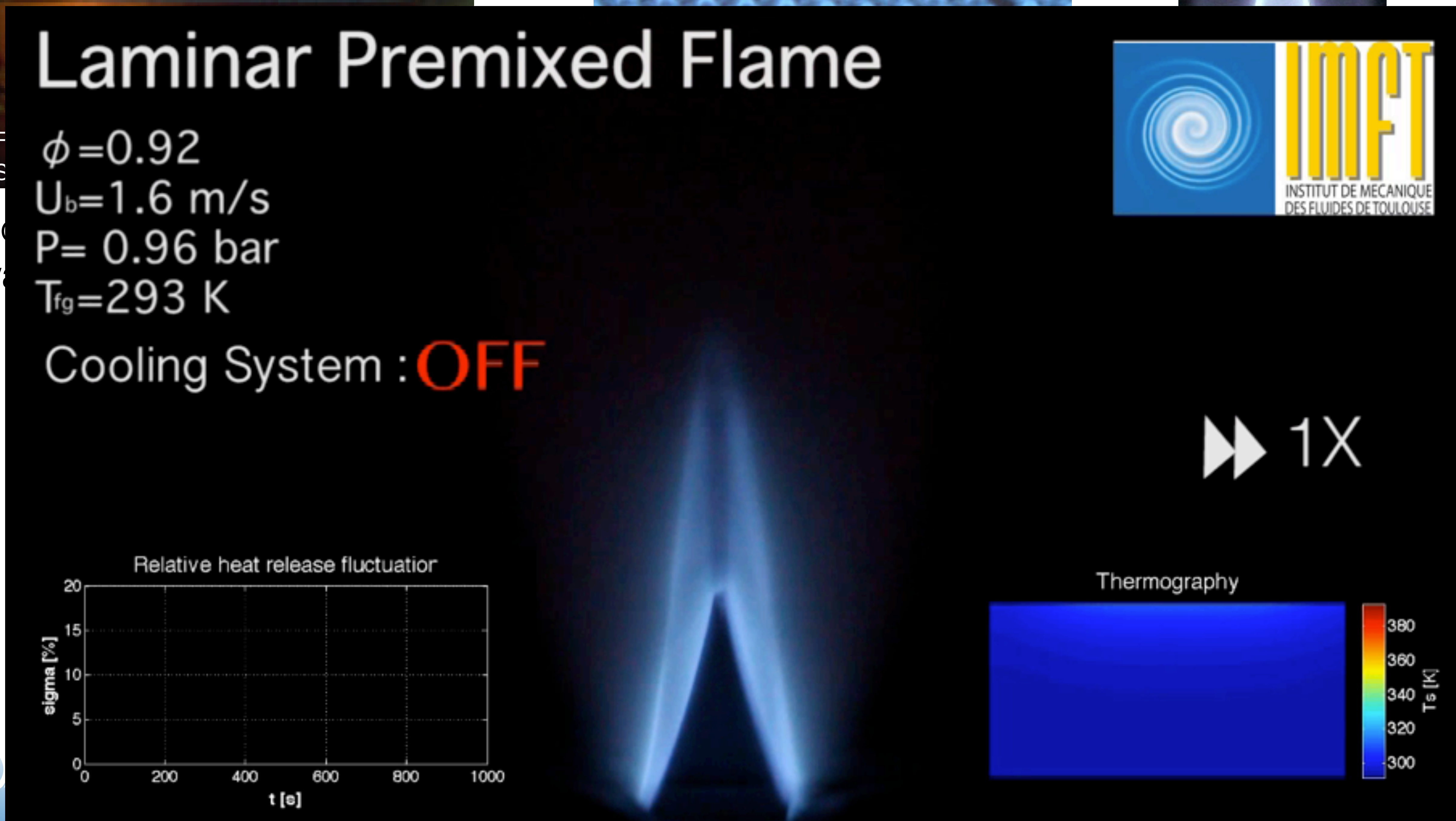
Most systems behave differently at cold start and in permanent regime.



[1] Candel 2002 *pci.*

★ 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.

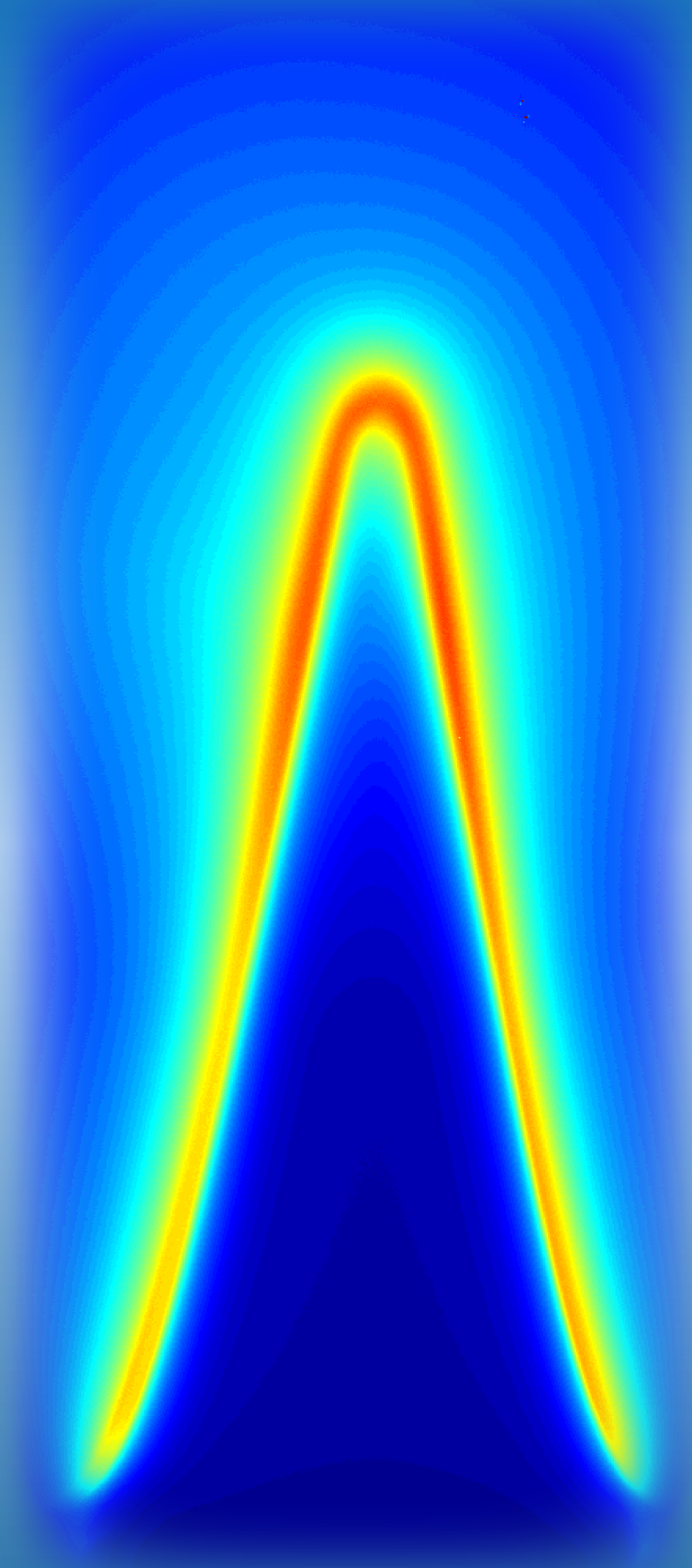




★ We sh
that **w**

Objectives

1. Derive a stability model which can predict the experimental observations.
2. Determine which mechanism(s) is/are responsible for stabilizing the flame.
3. Understand how this mechanism(s) work(s).



Outline

Part I: The Slot Burner

1. Experimental setup
2. Evidence of wall-temperature effect → 50 °C / 90 °C / 120 °C
3. Stability model → Five parameters

Part II: Experimental Measurements

4. Burner acoustics — Do they depend on the wall temperature?
5. Combustion noise — Do they depend on the wall temperature?
6. Flame response — Do they depend on the wall temperature?
7. Burner stability

Part III: Flame Dynamics

8. Flame front dynamics
9. Flame root dynamics

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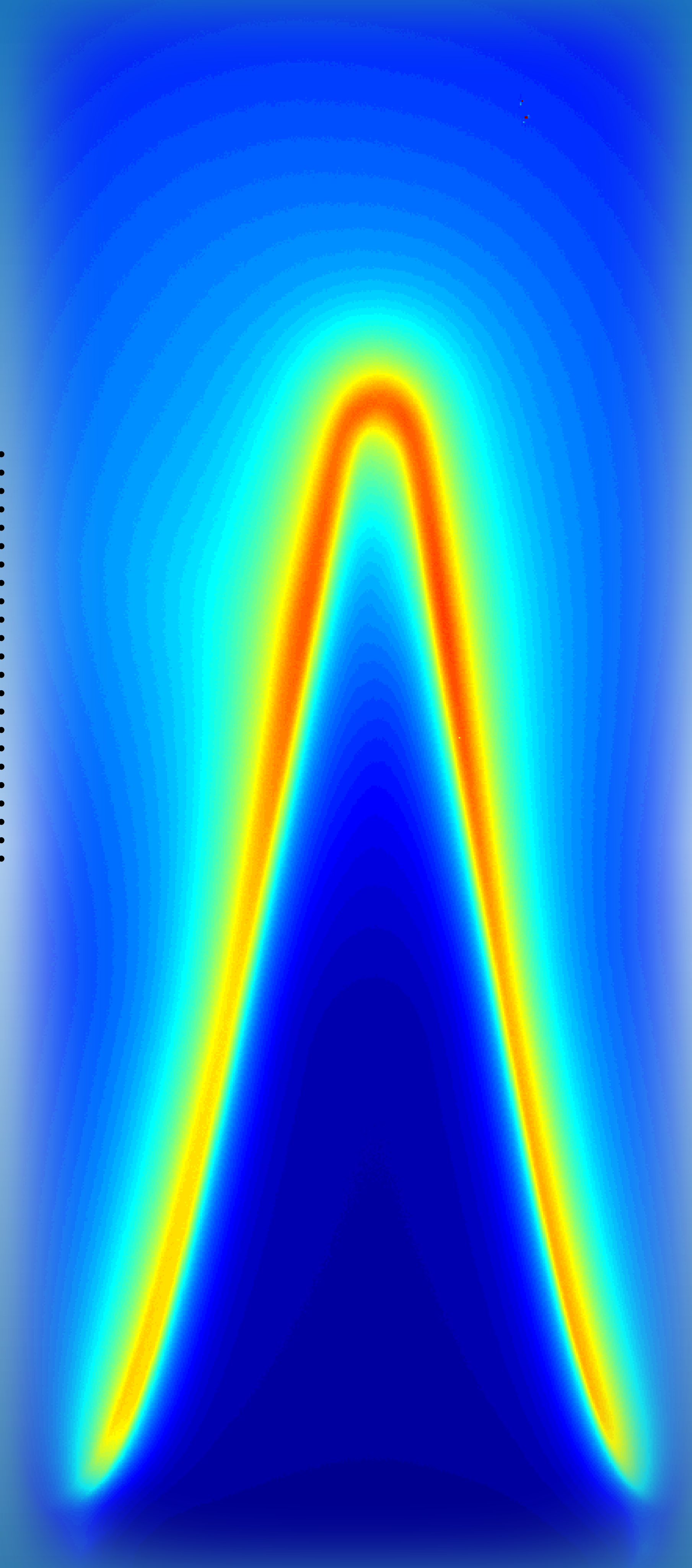
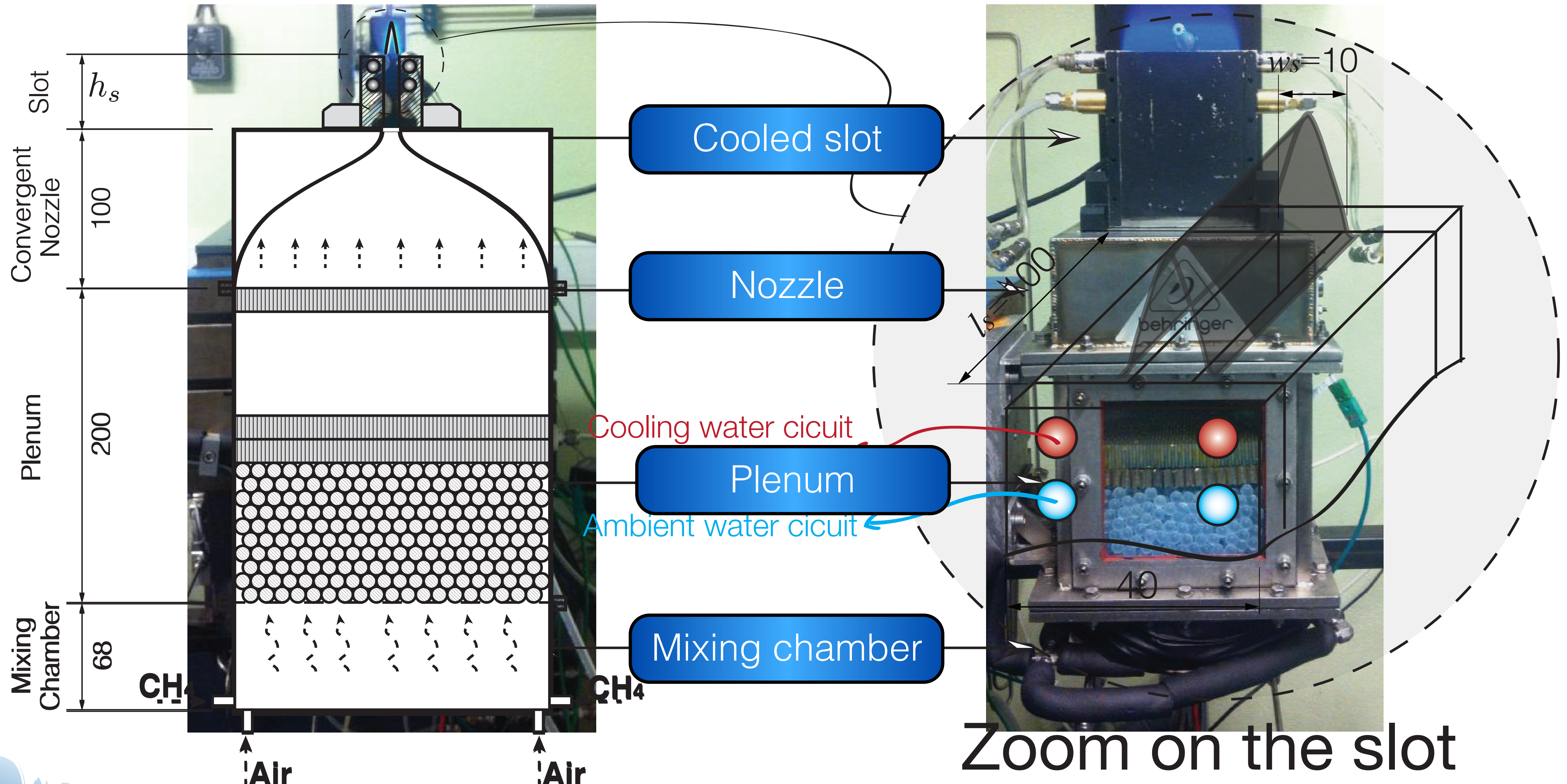


1. Experimental set-up

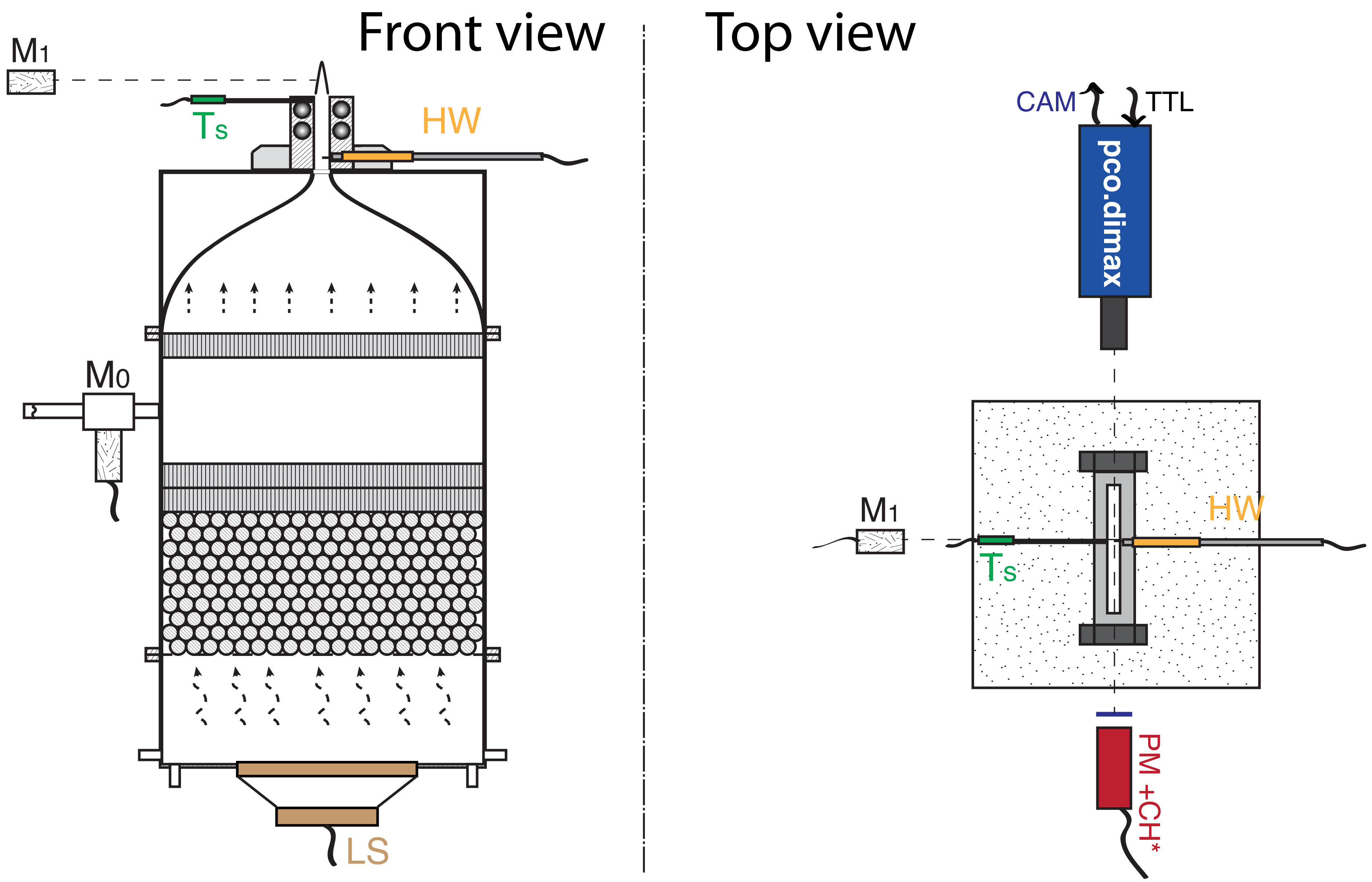


Zoom on the slot

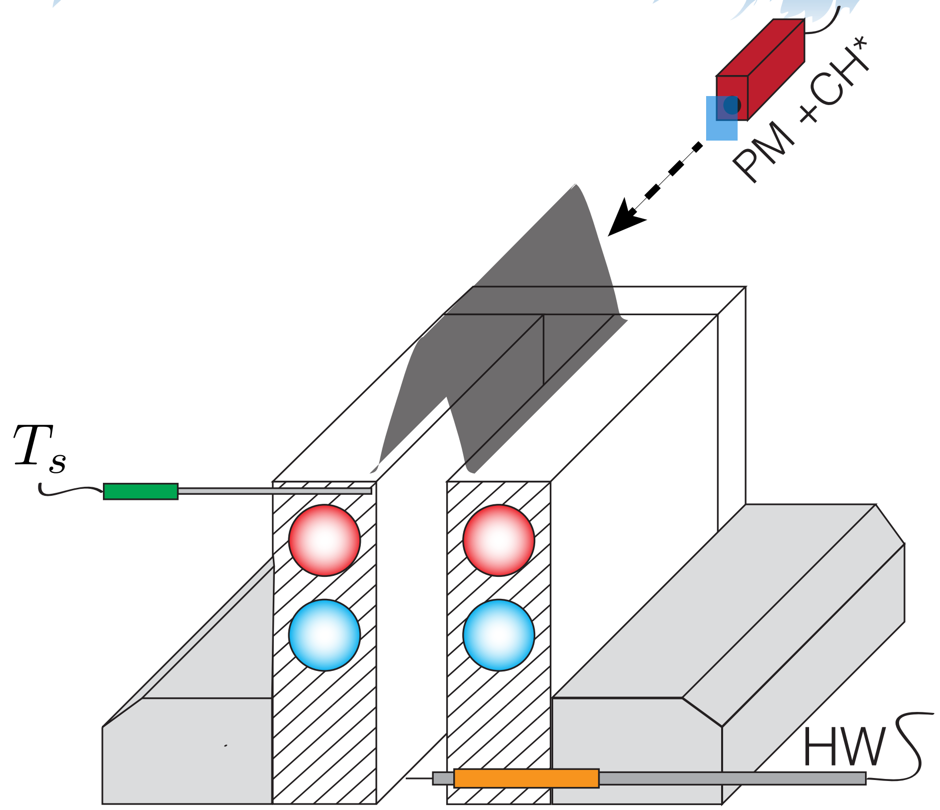
[1] Selle *et al.* 2011 *cf.*

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).



2. Description of the unstable behavior

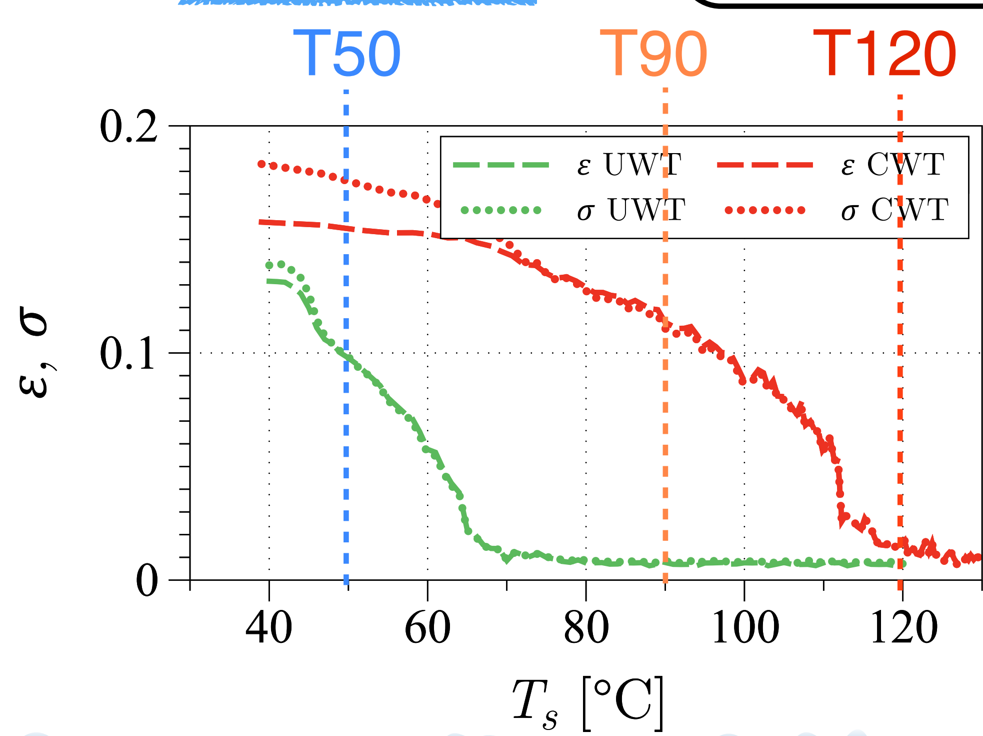


Measurements	
Slot temperature	T_s
RMS Heat release fluctuation magnitude	$\sigma = \dfrac{I_{CH^*}^{rms}}{\bar{I}_{CH^*}}$
RMS Velocity fluctuation magnitude	$\varepsilon = \dfrac{v_1^{rms}}{\bar{v}}$

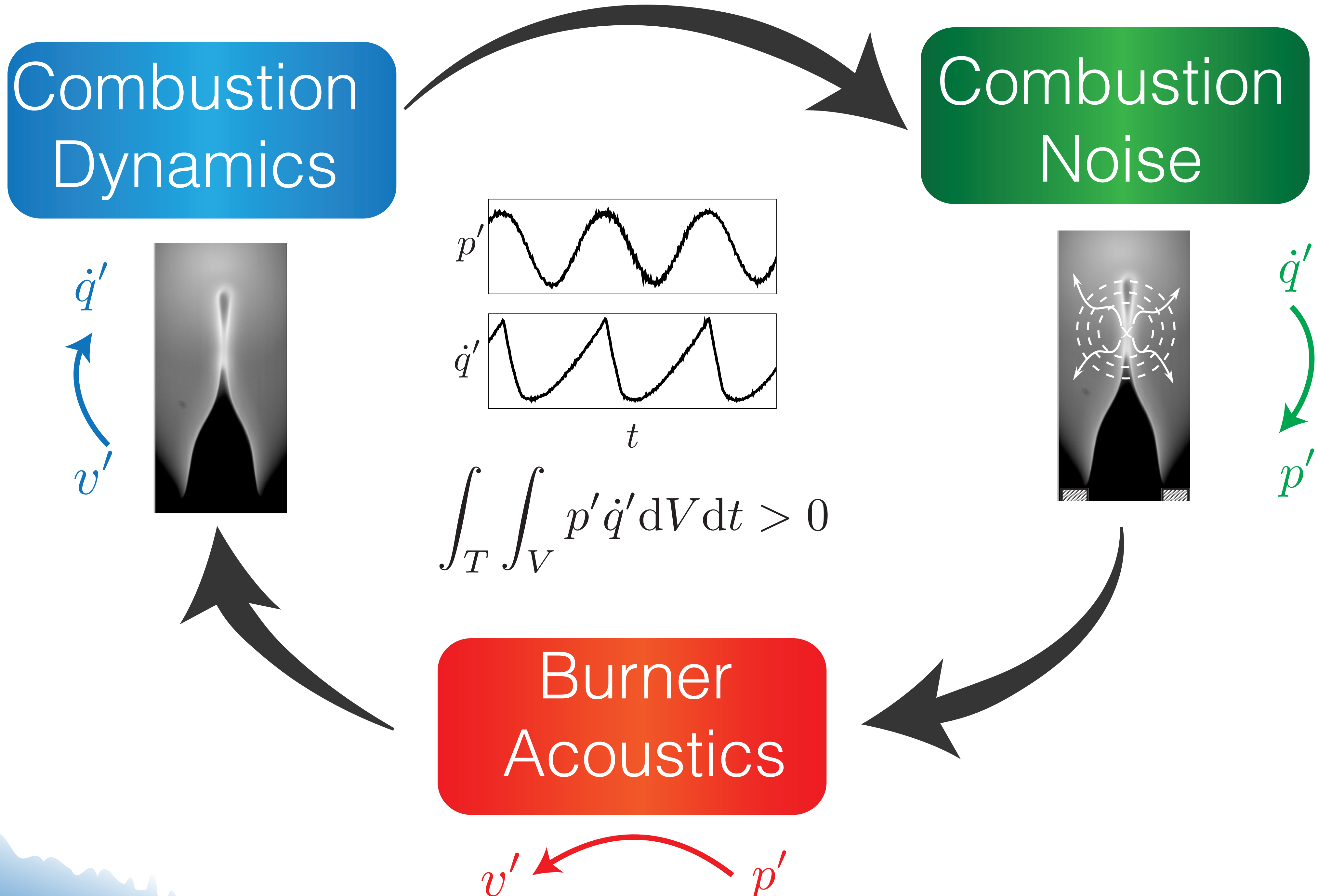
Two type of analysis

- **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]

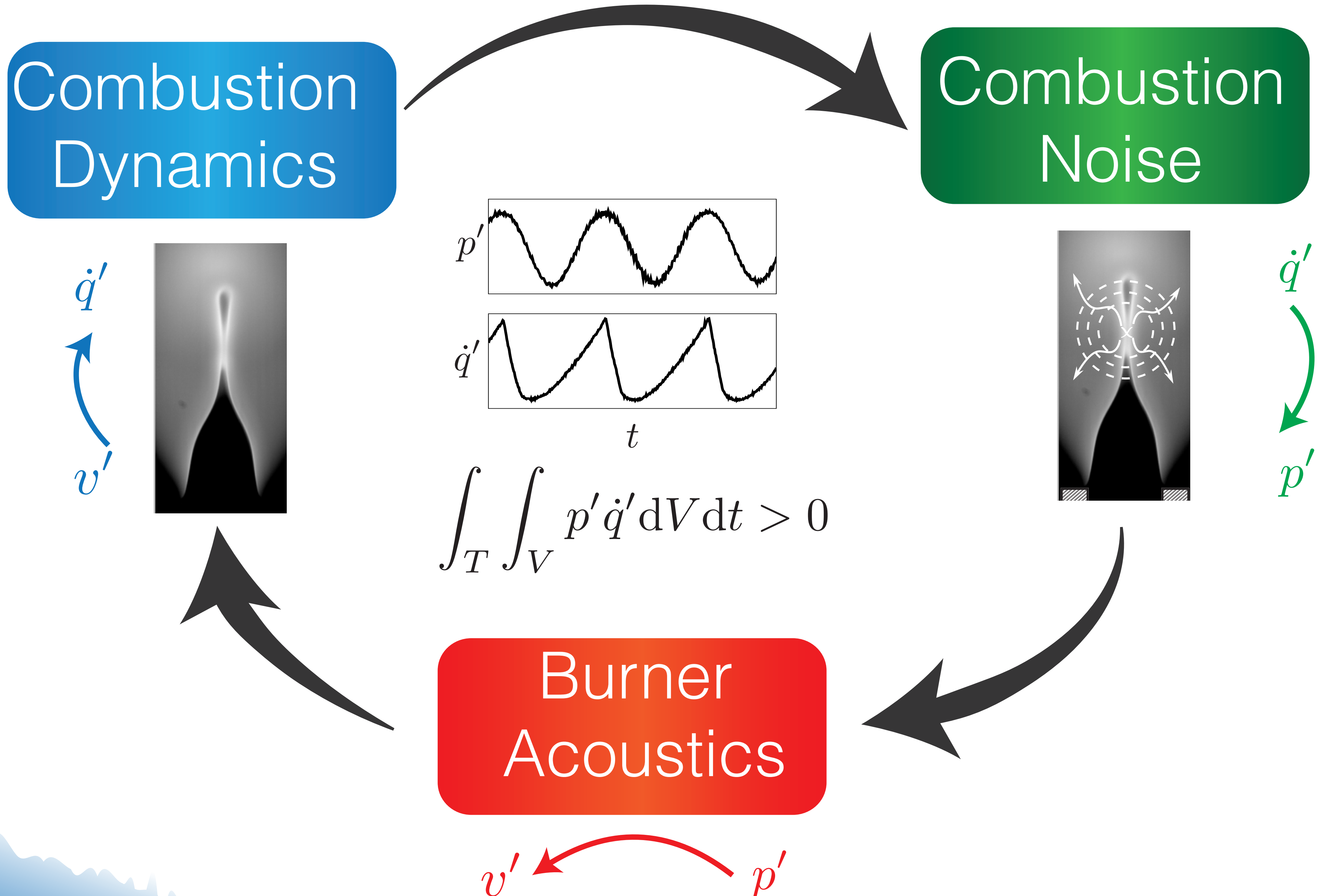
$f_r = 58$ Hz



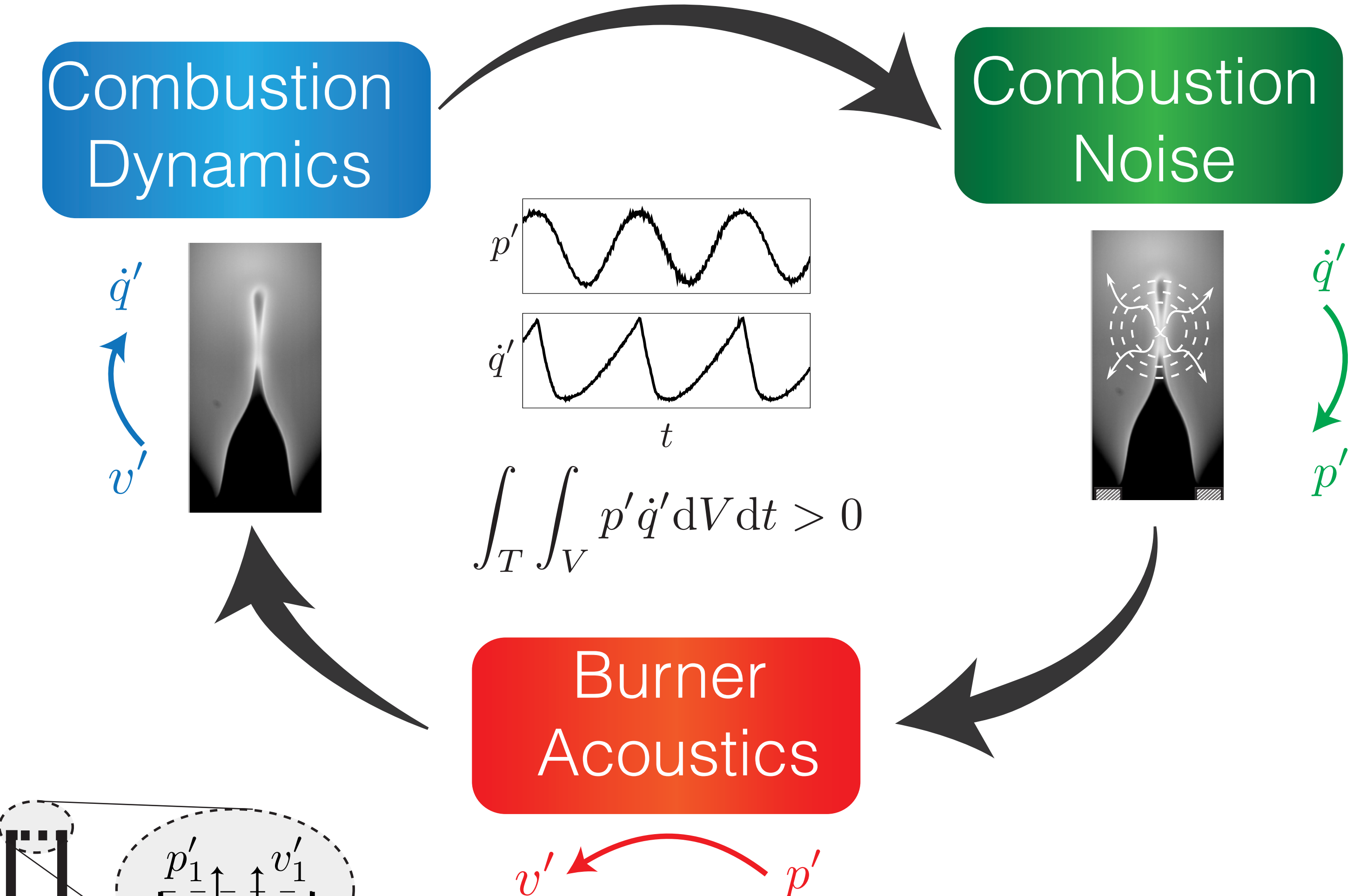
3. Stability model

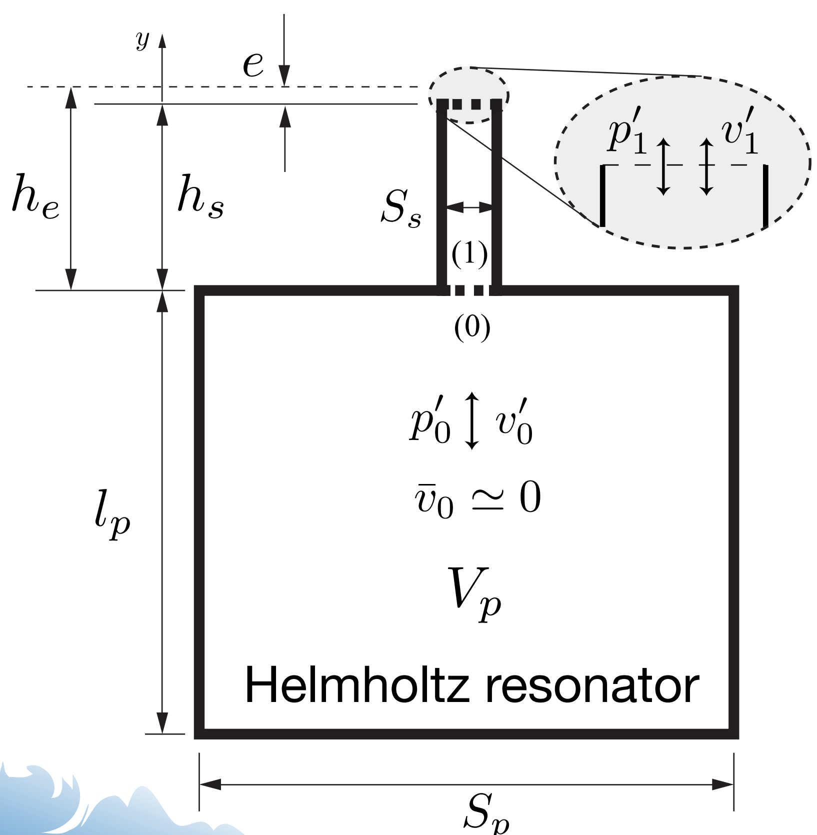


$$\int_T \int_V p'\dot{q}'\,\mathrm{d}V\,\mathrm{d}t > 0$$



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





Relation between p' and v'

$$\frac{\mathrm{d}^2 v'_1}{\mathrm{d}t^2} + 2\delta \frac{\mathrm{d}v'_1}{\mathrm{d}t} + \omega_0^2 v'_1 = -\frac{1}{\rho_u h_e}\frac{\mathrm{d}p'_1}{\mathrm{d}t}$$

$$\boxed{\mathcal{Z}_1 = \frac{\tilde p_1}{\tilde v_1} = \frac{i\rho_u h_e}{\omega}\left[\omega^2 + 2i\delta\omega - \omega_0^2\right]}$$

[1] Pierce 1981.
[2] Rienstra 1983 *jsv*.
[3] Durox *et al.* 2002 *pci*.

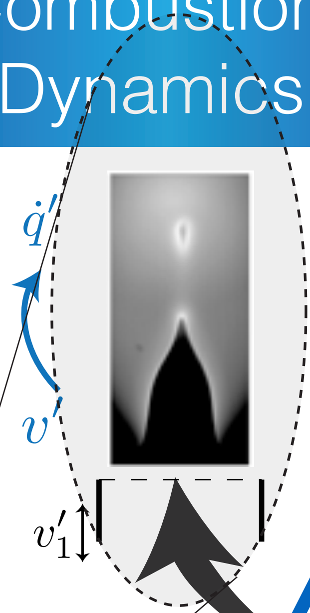
[4] Crocco 1951 *jars.*
[5] Keller and Saito 1987 *cst.*

Relation between v' and $\dot{q}'$

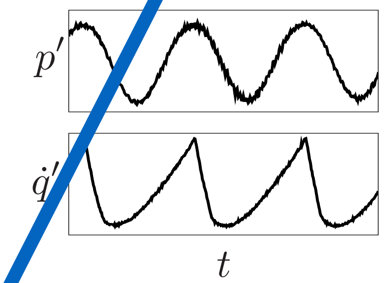
$$\mathcal{F}(\omega) = \frac{\dot{q}'/\bar{\dot{q}}}{v_1'/\bar{v}} = \mathcal{G}(\omega)e^{i\varphi(\omega)}$$

$$\boxed{\tilde{A} = \frac{S_s}{s_L}\mathcal{G}(\omega)e^{i\varphi(\omega)}\tilde{v}_1}$$

Combustion Dynamics

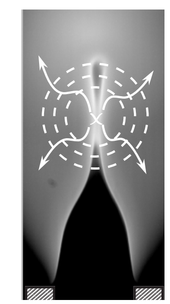


FTF



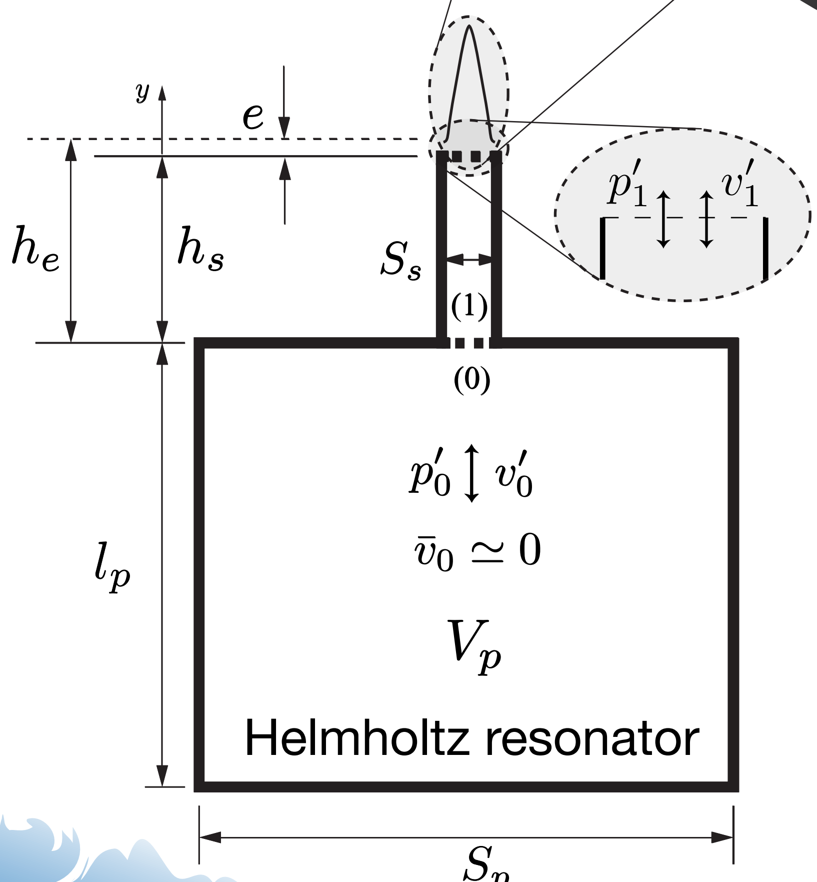
$$\int_T \int_V p'\dot{q}' \mathrm{d}V \mathrm{d}t > 0$$

Combustion Noise



Burner Acoustics

$v' \leftarrow p'$



Relation between p' and v'

$$\frac{\mathrm{d}^2 v_1'}{\mathrm{d}t^2} + 2\delta\frac{\mathrm{d}v_1'}{\mathrm{d}t} + \omega_0^2 v_1' = -\frac{1}{\rho_u h_e}\frac{\mathrm{d}p_1'}{\mathrm{d}t}$$

$$\boxed{\mathcal{Z}_1 = \frac{\tilde{p}_1}{\tilde{v}_1} = \frac{i\rho_u h_e}{\omega}\left[\omega^2 + 2i\delta\omega - \omega_0^2\right]}$$

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[6] Strahke 1971 *jfm.*
[7] Clavin and Siggia 1991 *cst.*

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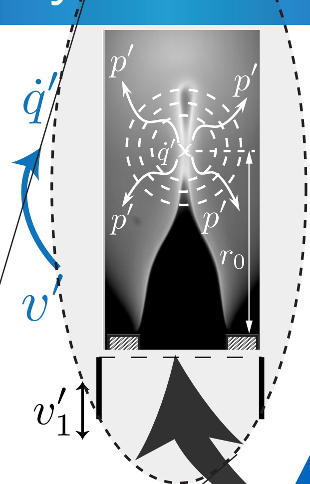
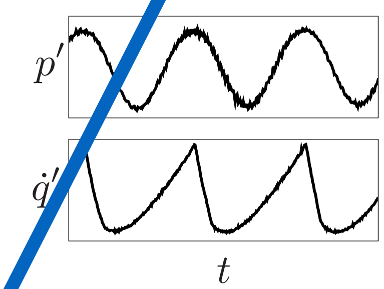
Combustion Dynamics

FTF

Combustion Noise





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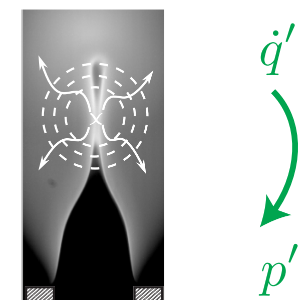


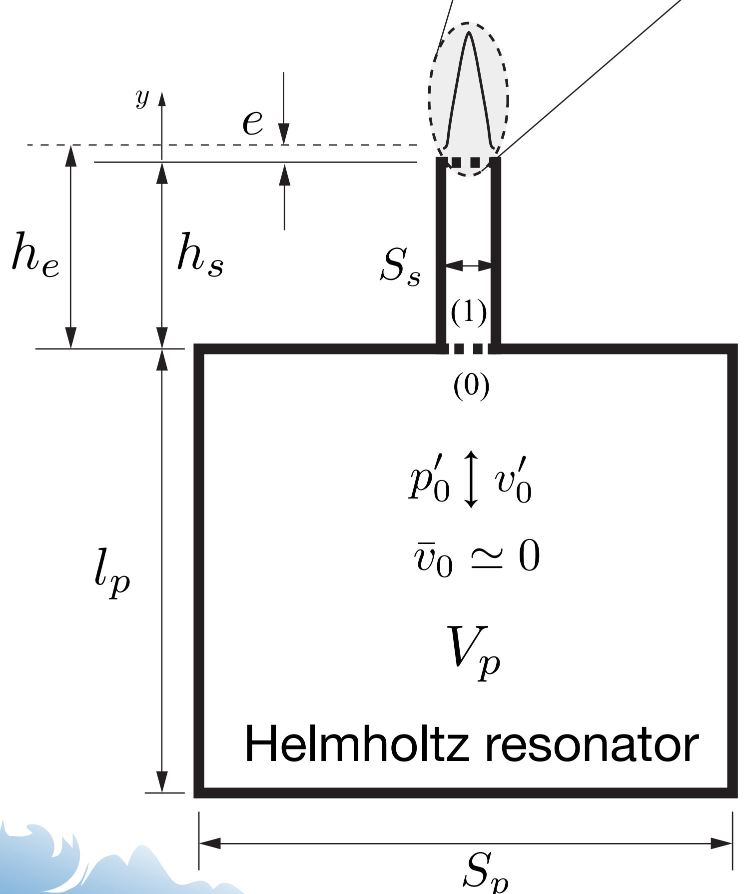
Relation between $\dot{q}'$ and p'

$$p_1'(t) = \frac{\rho_u(E-1)s_L}{4\pi r_0}\left[\frac{\mathrm{d}\mathcal{A}}{\mathrm{d}t}\right]_{t-\tau_{ac}}$$

$$\tilde{p}_1 = -\frac{\rho_u(E-1)s_L}{4\pi r_0}i\omega\tilde{A}$$

Burner Acoustics

v' p'



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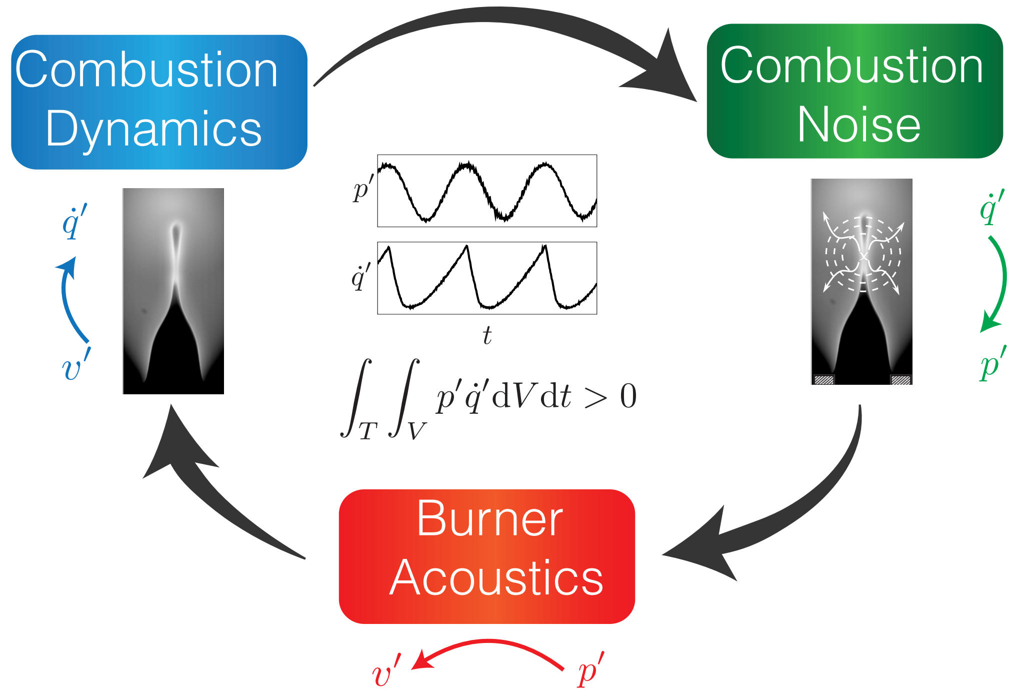


Dispersion relation:

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

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:

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

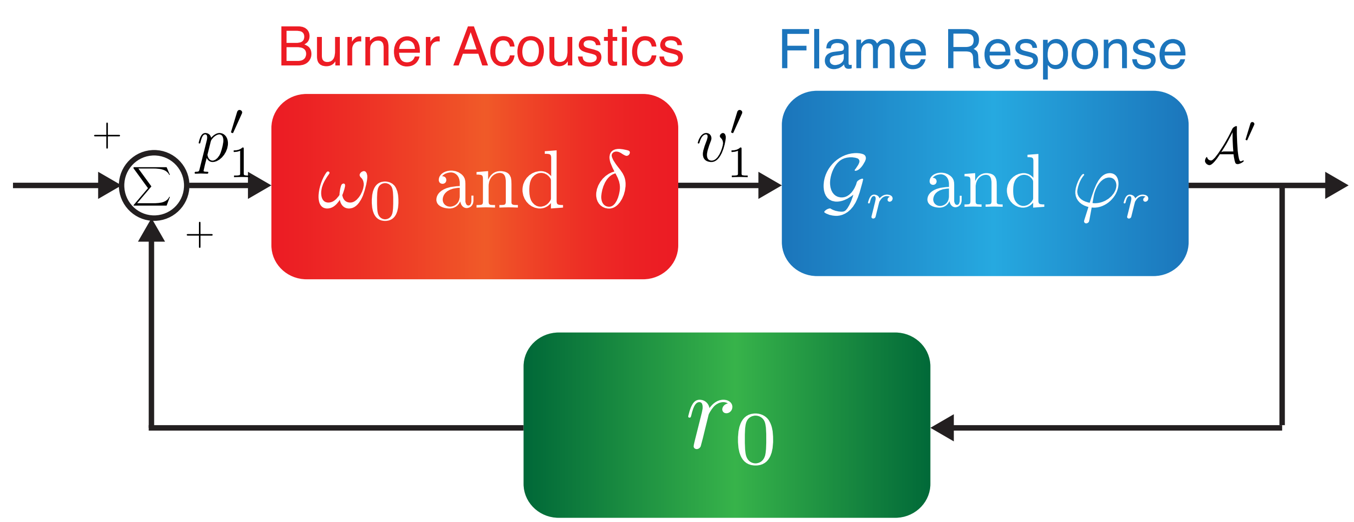
$\Re(\omega) = \omega_r \rightarrow$ Resonance frequency

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

The system will develop combustion instabilities if:

$$\omega_i > 0$$

The stability of the system depends on five parameters:



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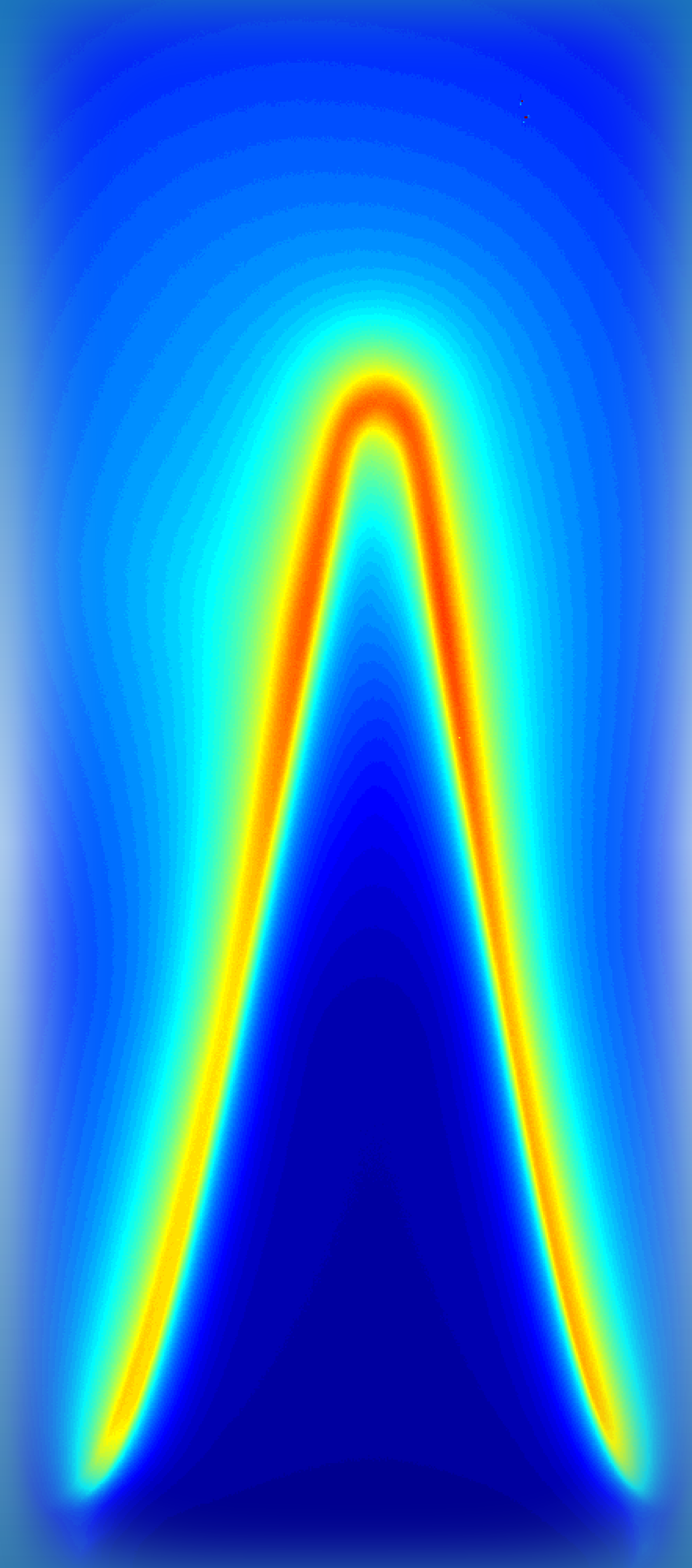

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8. Flame front dynamics
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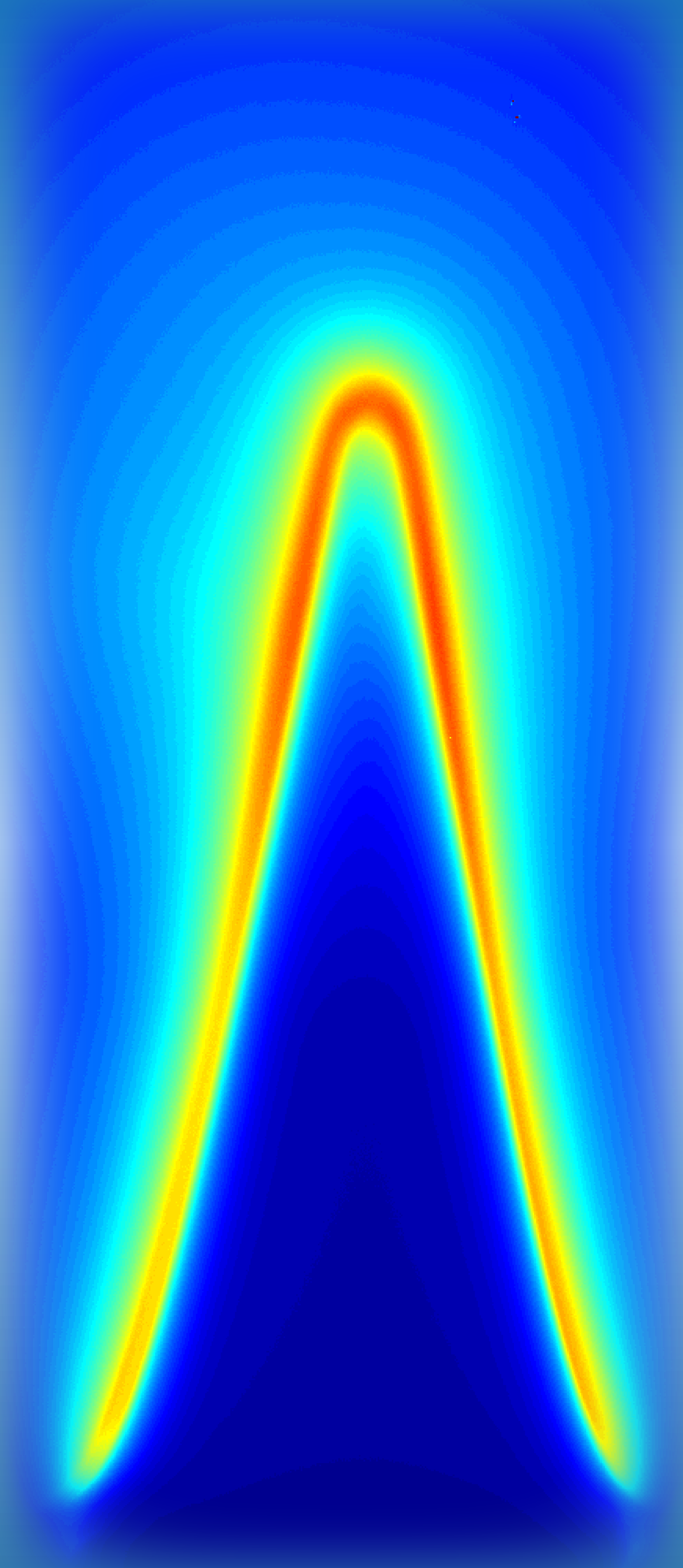
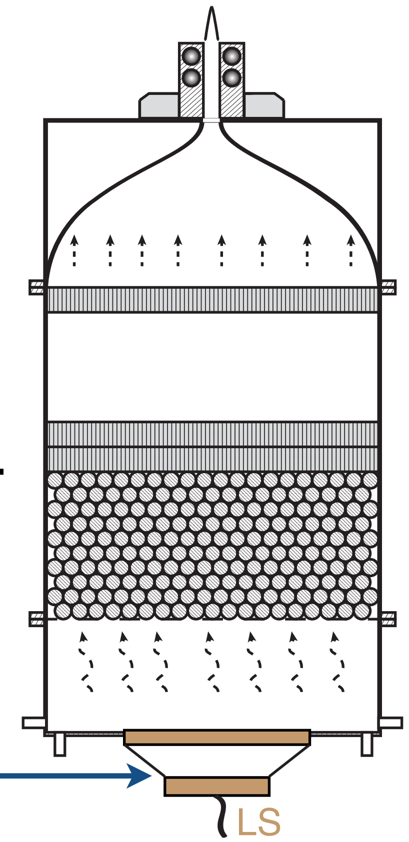
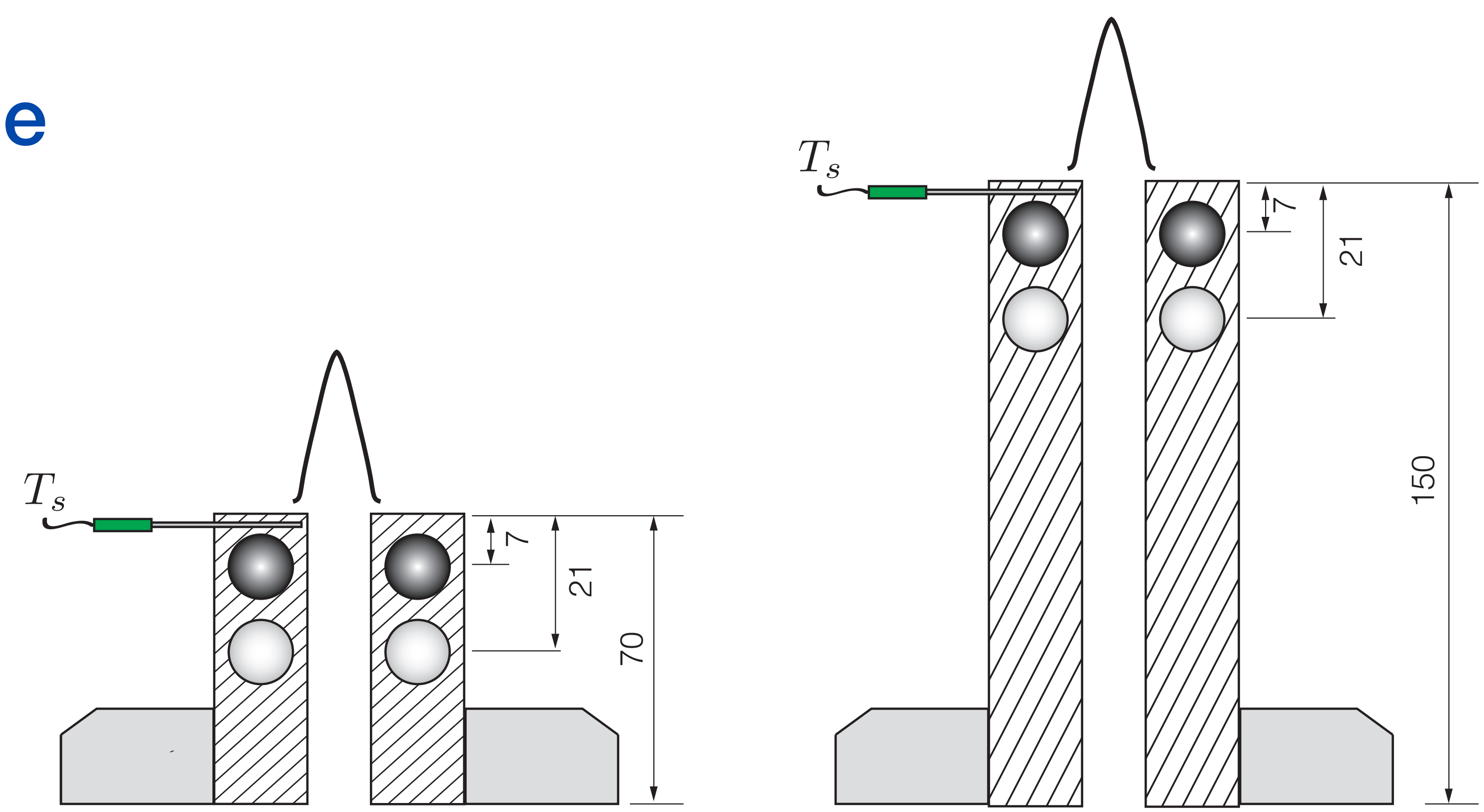


Methodology:

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



Stabilizing the flame



B07

B15

★ In all cases, the operating conditions are keep constant

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

★ 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:

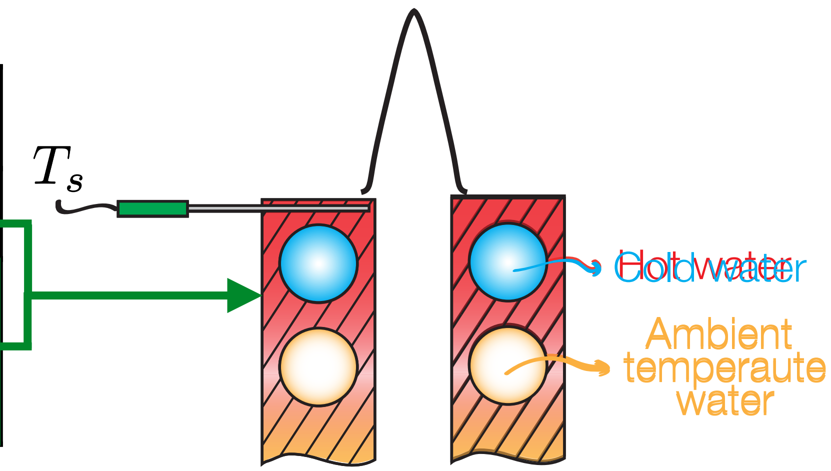
T50	T90	T120

★ Code for the experiments:

T50c → c: cold (non-reacting)
h: hot (reacting)

T50 ↓ $T_s \ [^\circ \mathrm{C}]$

	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				



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50 °C

90 °C

120 °C

3. Stability model

Five parameters

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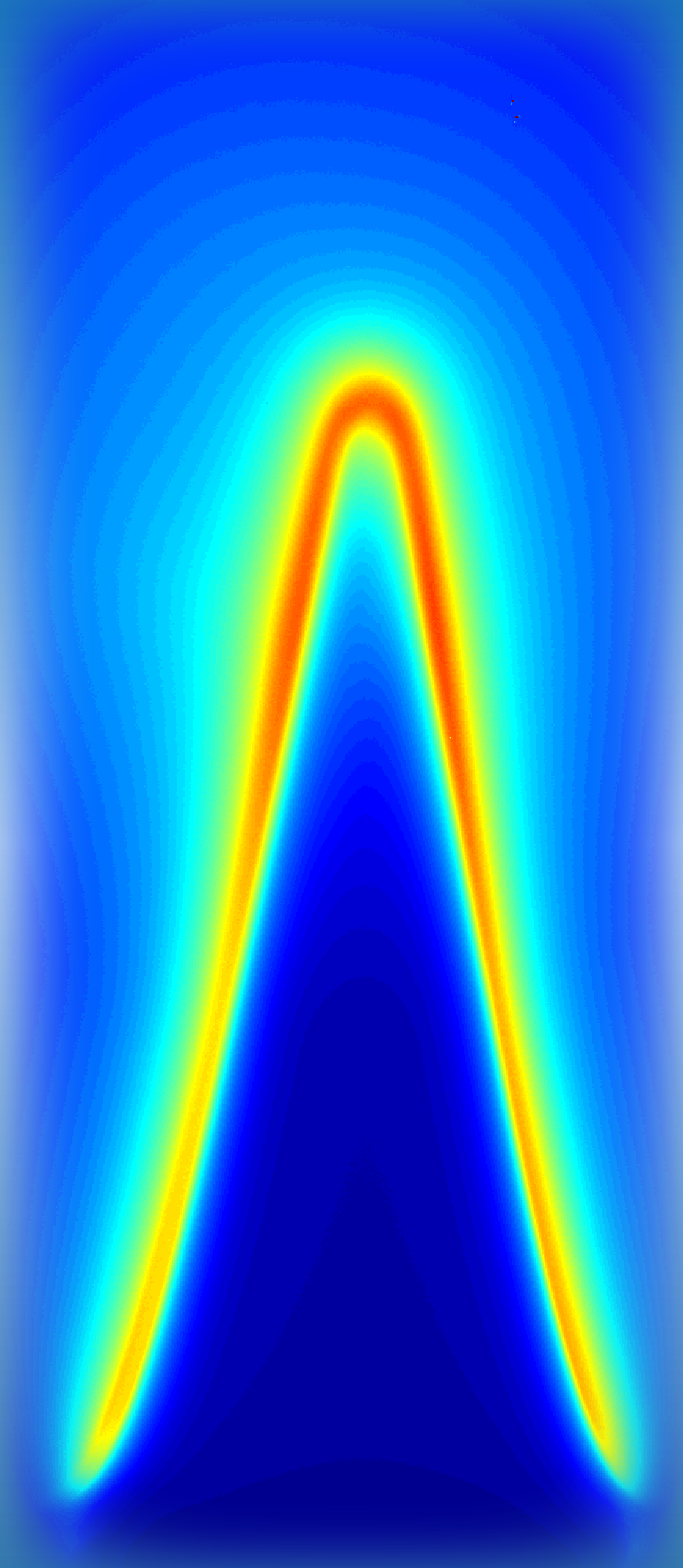


4. Burner acoustics

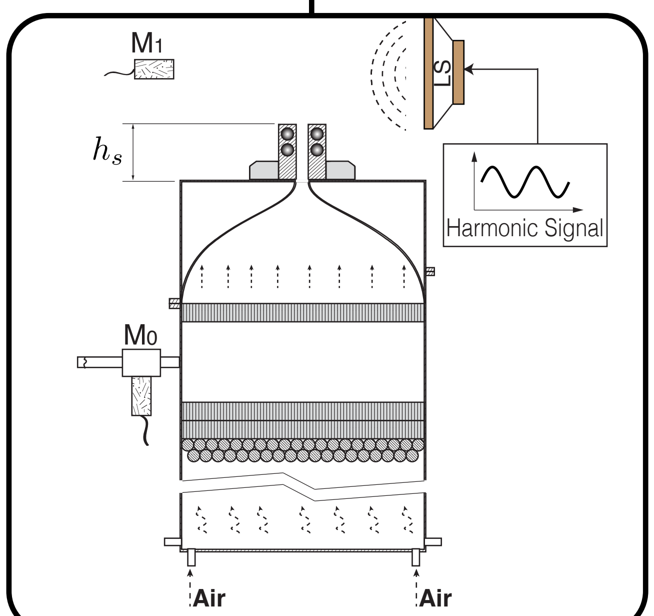
1. How to measure the natural ω_0 pulsation and the dissipation δ of the burner?
2. Do they depend on wall temperature T_s?

Burner acoustics

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

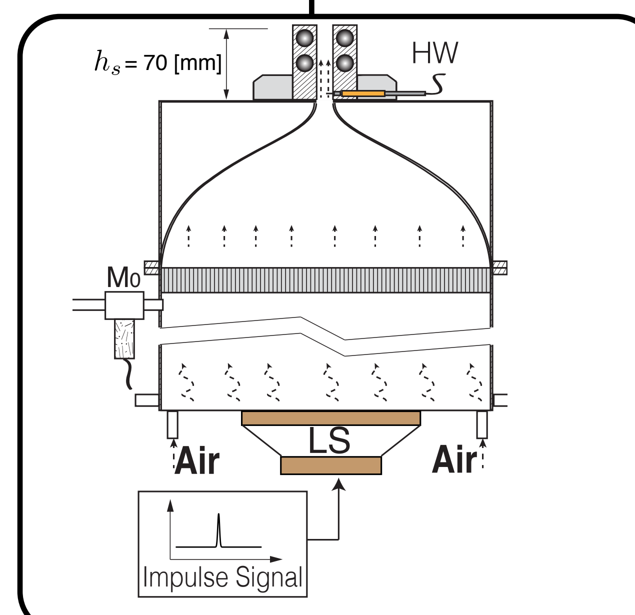
Harmonic response

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

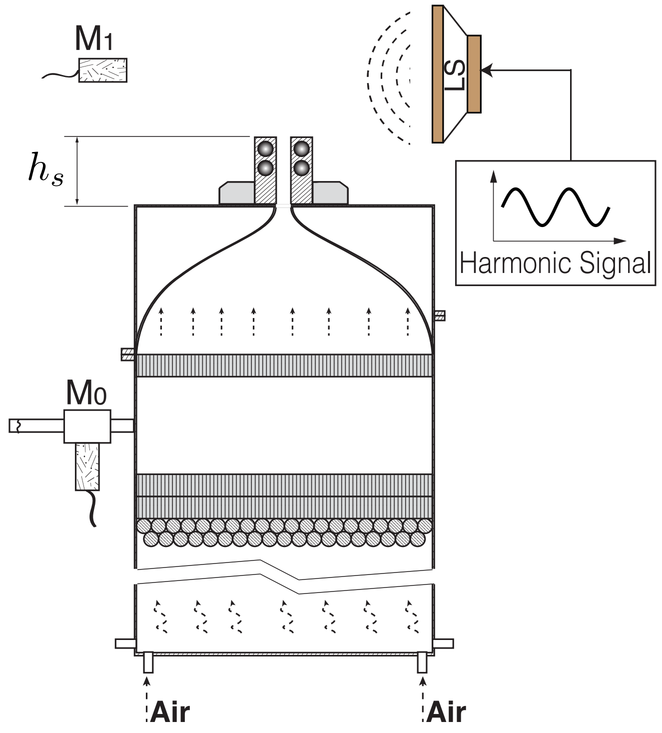


Impulse response

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

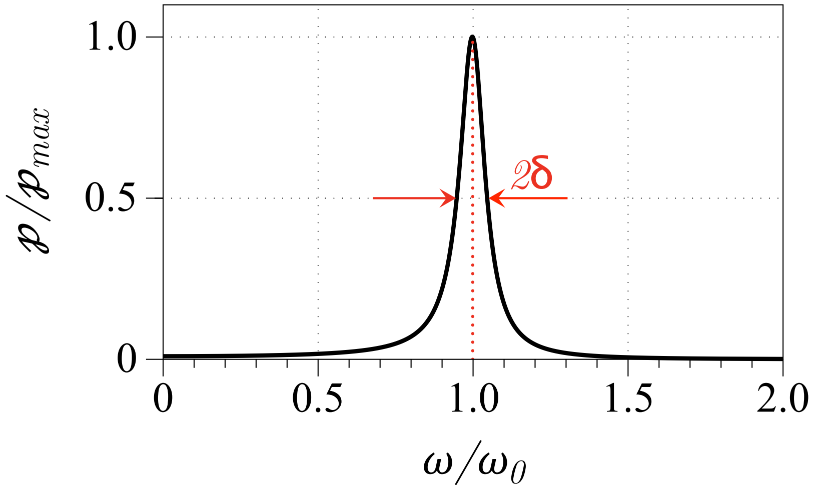


1. Harmonic response:

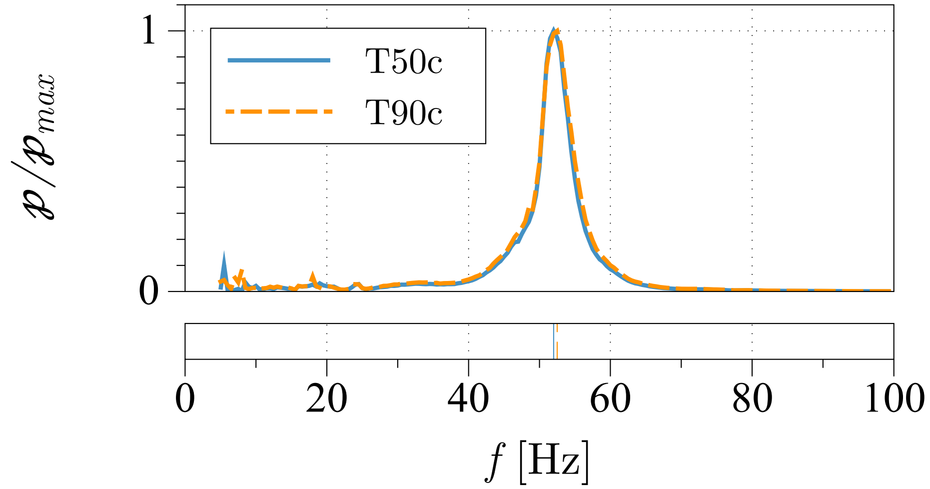


$$\frac{d^2 p'_0}{dt^2} + 2\delta \frac{dp'_0}{dt} + \omega_0^2 p'_0 = \omega_0^2 p'_1$$

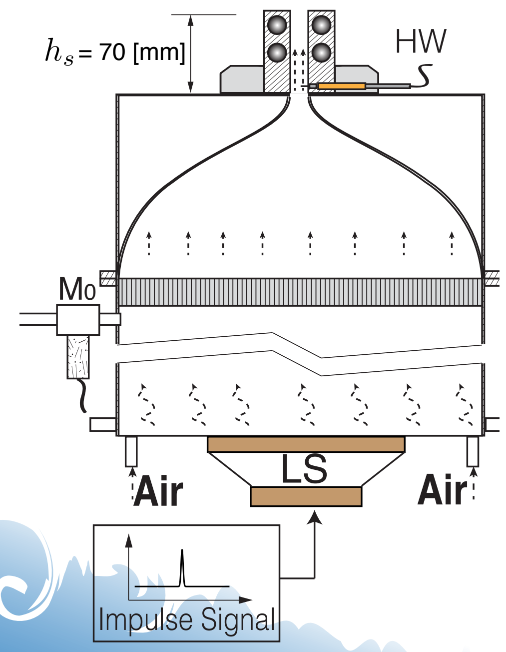
$$\mathcal{P} = \left(\frac{\tilde{p}_0}{\tilde{p}_1}\right)^2$$



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

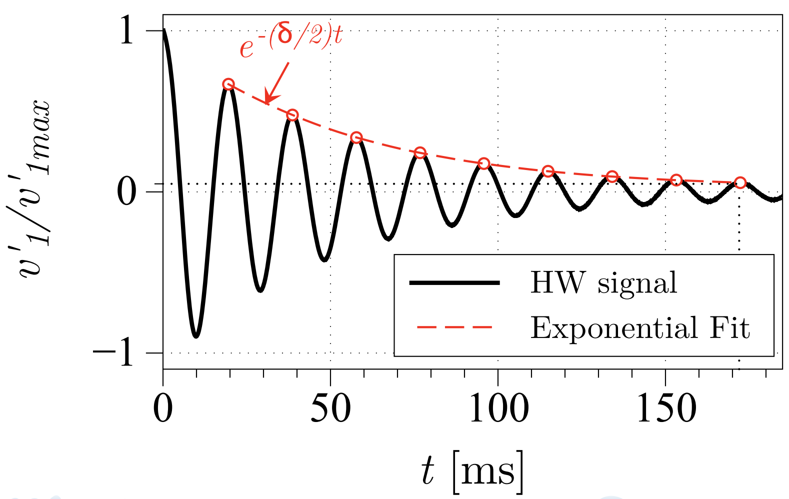


2. Impulse response:

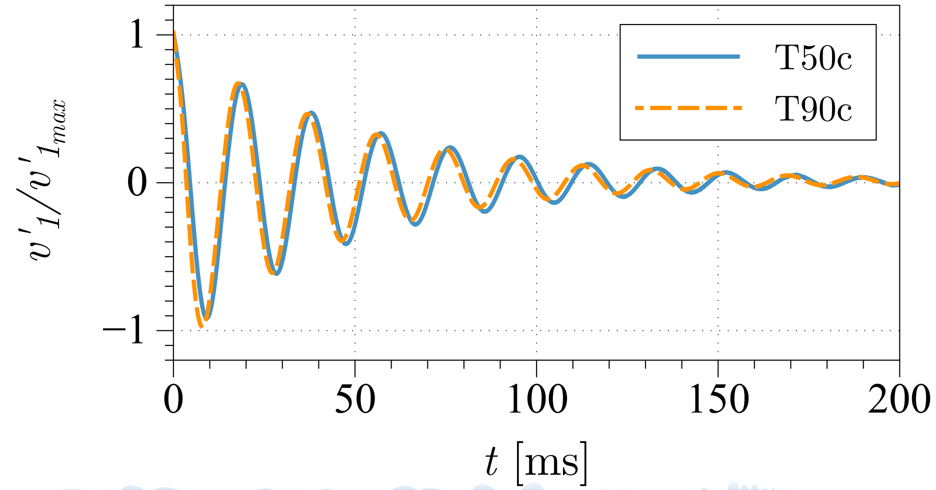


$$\frac{d^2 v'_1}{dt^2} + 2\delta \frac{dv'_1}{dt} + \omega_0^2 v'_1 = 0$$

$$v'_1(t)/v'_{1_{max}} = e^{-(\delta/2)t}\cos(\omega_0 t)$$



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



Outline

Part I: The Slot Burner

1. Experimental setup

2. Evidence of wall-temperature effect

50 °C

90 °C

120 °C

3. Stability model

Five parameters

Part II: Experimental Measurements

4. Burner acoustics

No Ts dependency

5. Combustion noise

Do they depend on the wall temperature?

6. Flame response

Do they depend on the wall temperature?

7. Burner stability

Part III: Flame Dynamics

8. Flame front dynamics

9. Flame root dynamics

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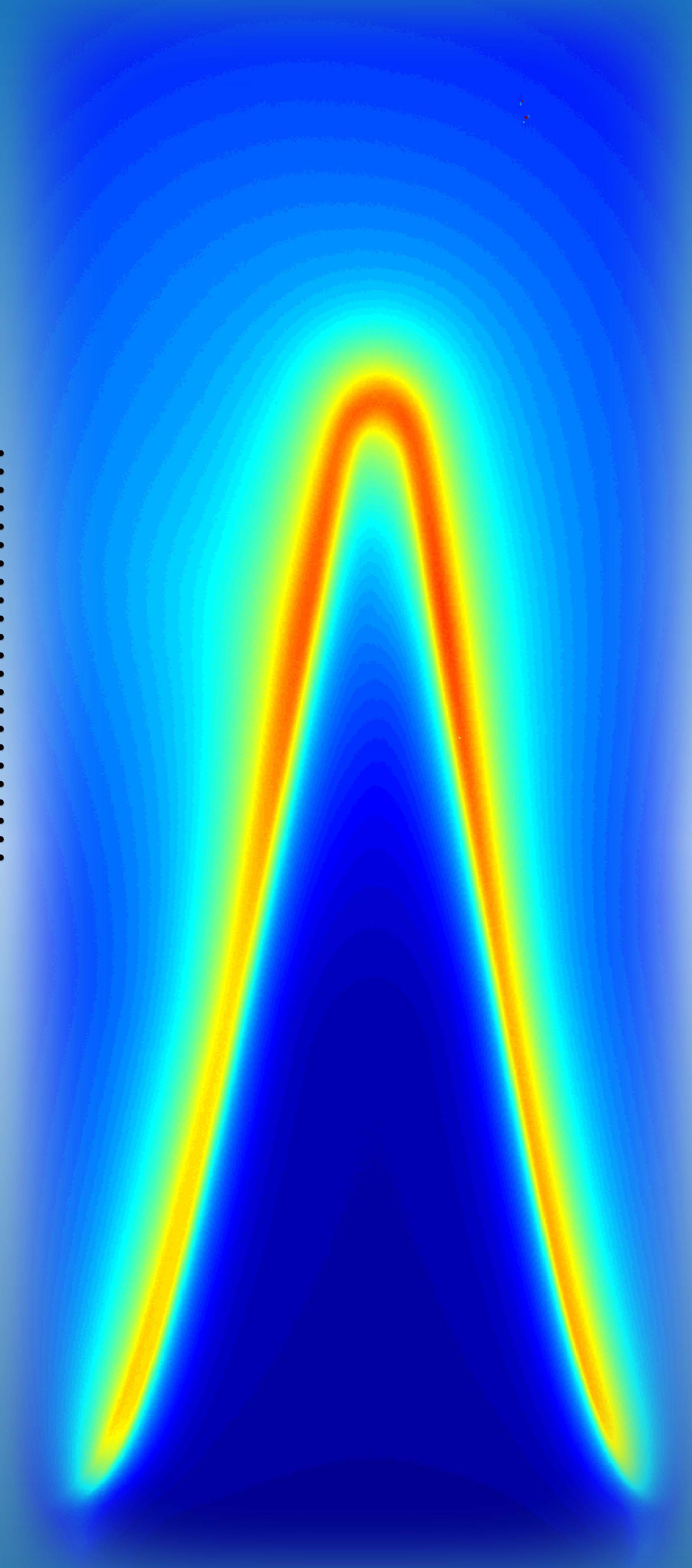
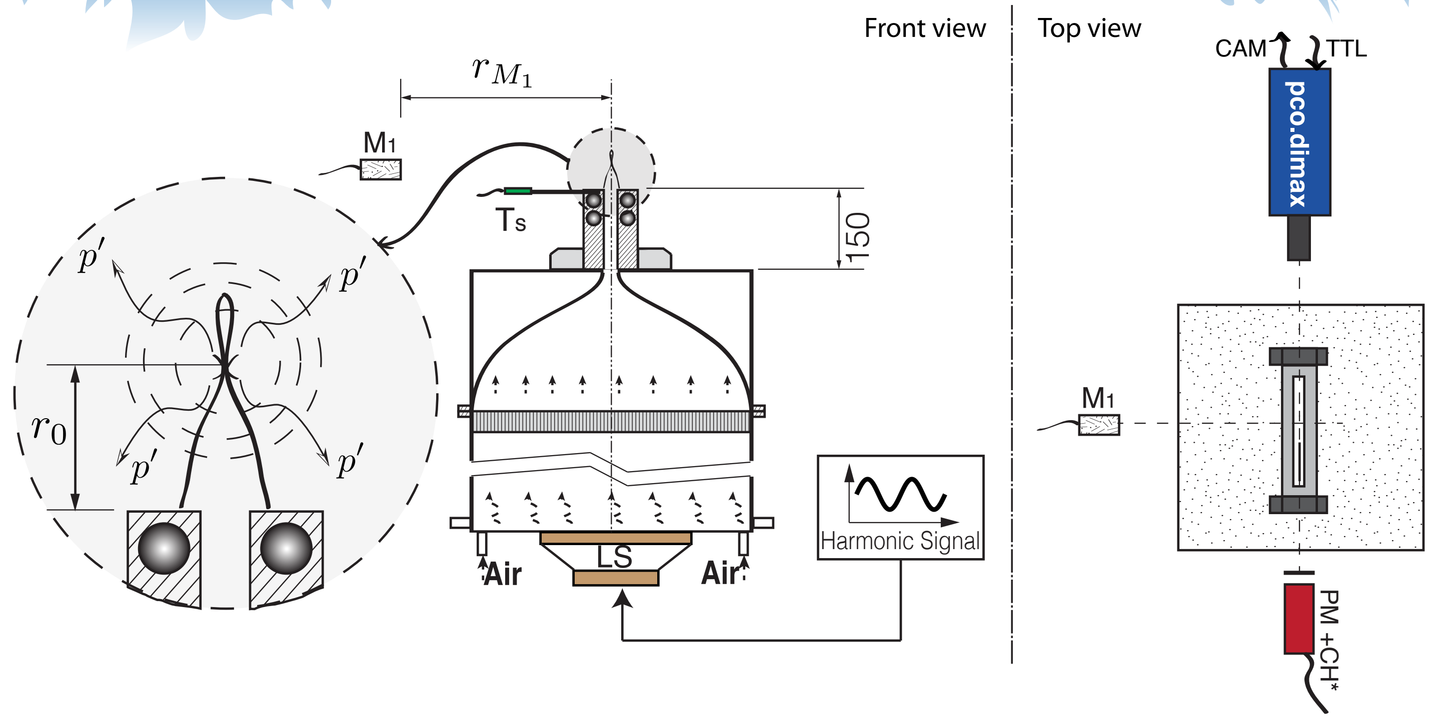


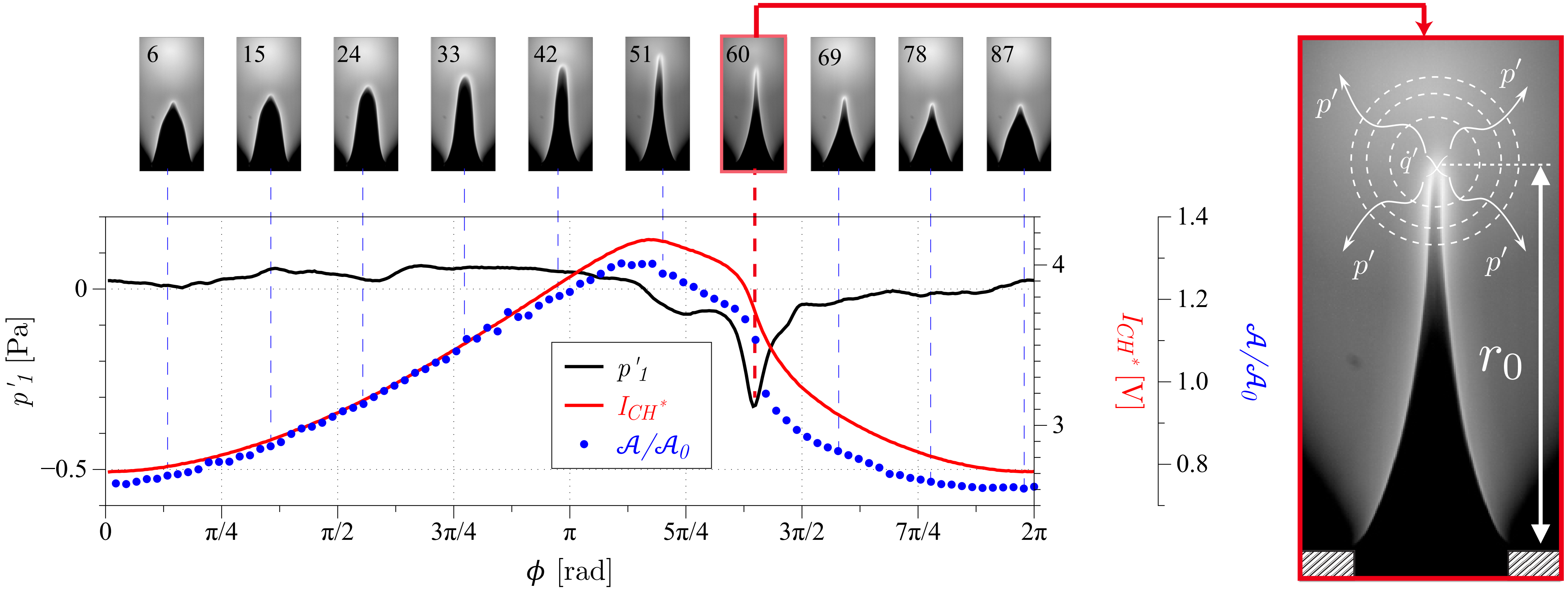
5. Combustion noise

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



Outline

Part I: The Slot Burner

1. Experimental setup
2. Evidence of wall-temperature effect
3. Stability model

50 °C
90 °C
120 °C

Five parameters

Part II: Experimental Measurements

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No Ts dependency

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No Ts dependency

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Do they depend on the wall temperature?

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8. Flame front dynamics
9. Flame root dynamics

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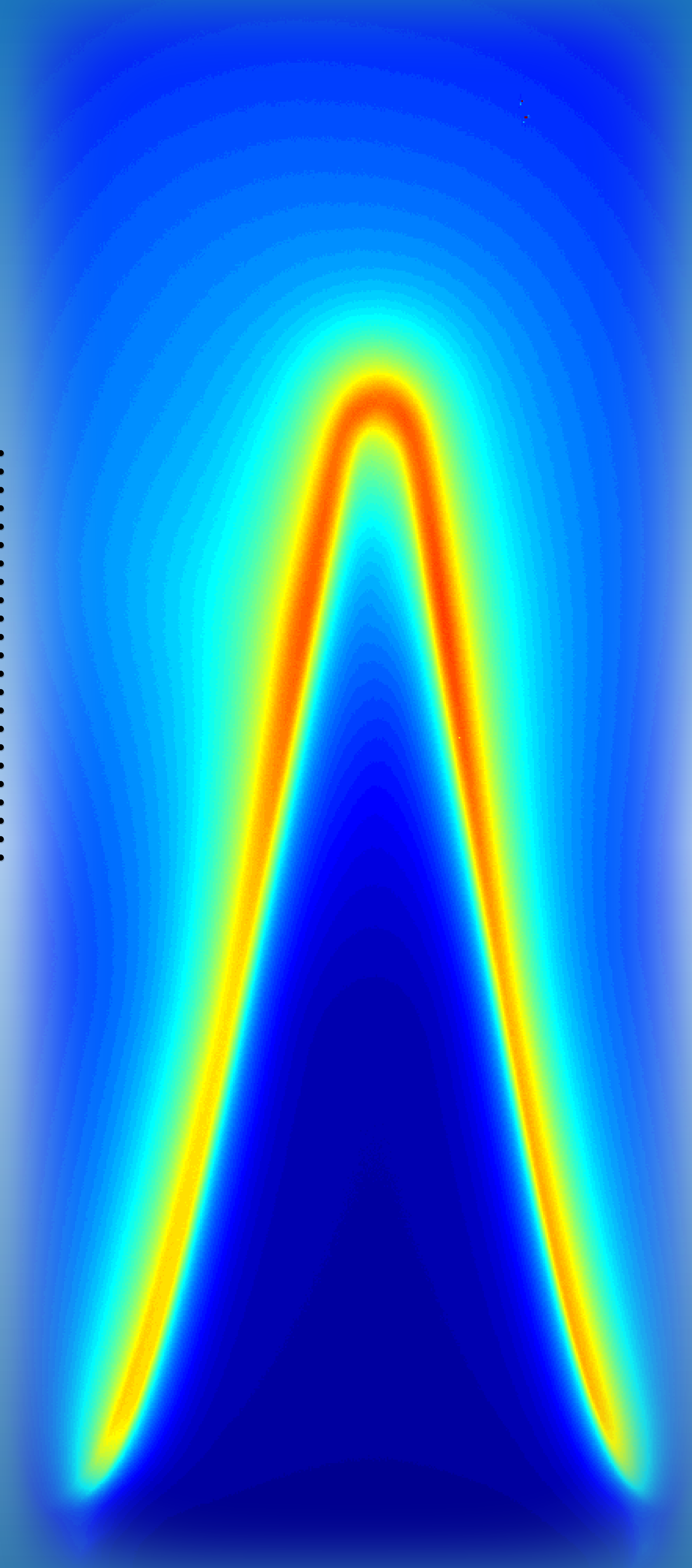
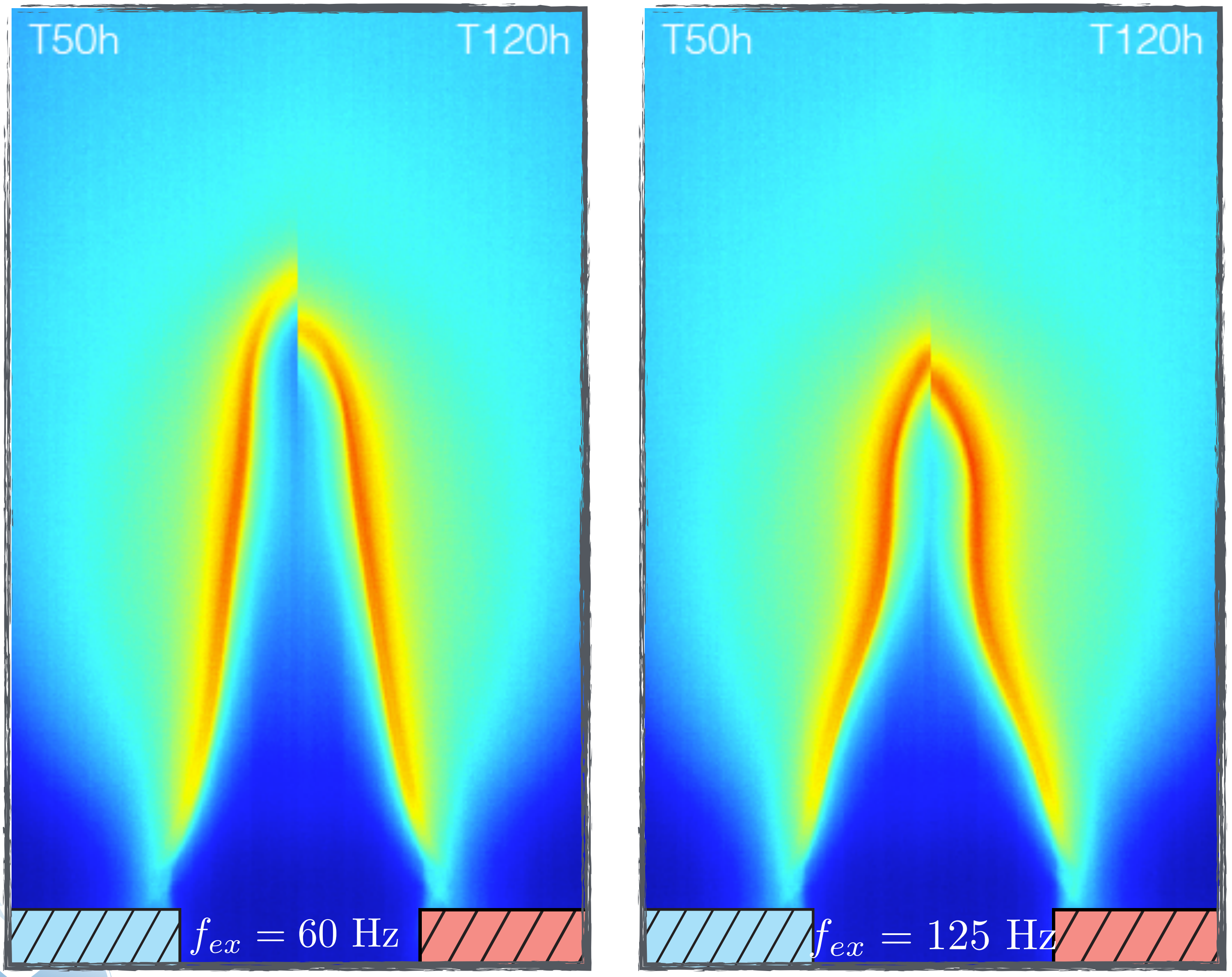
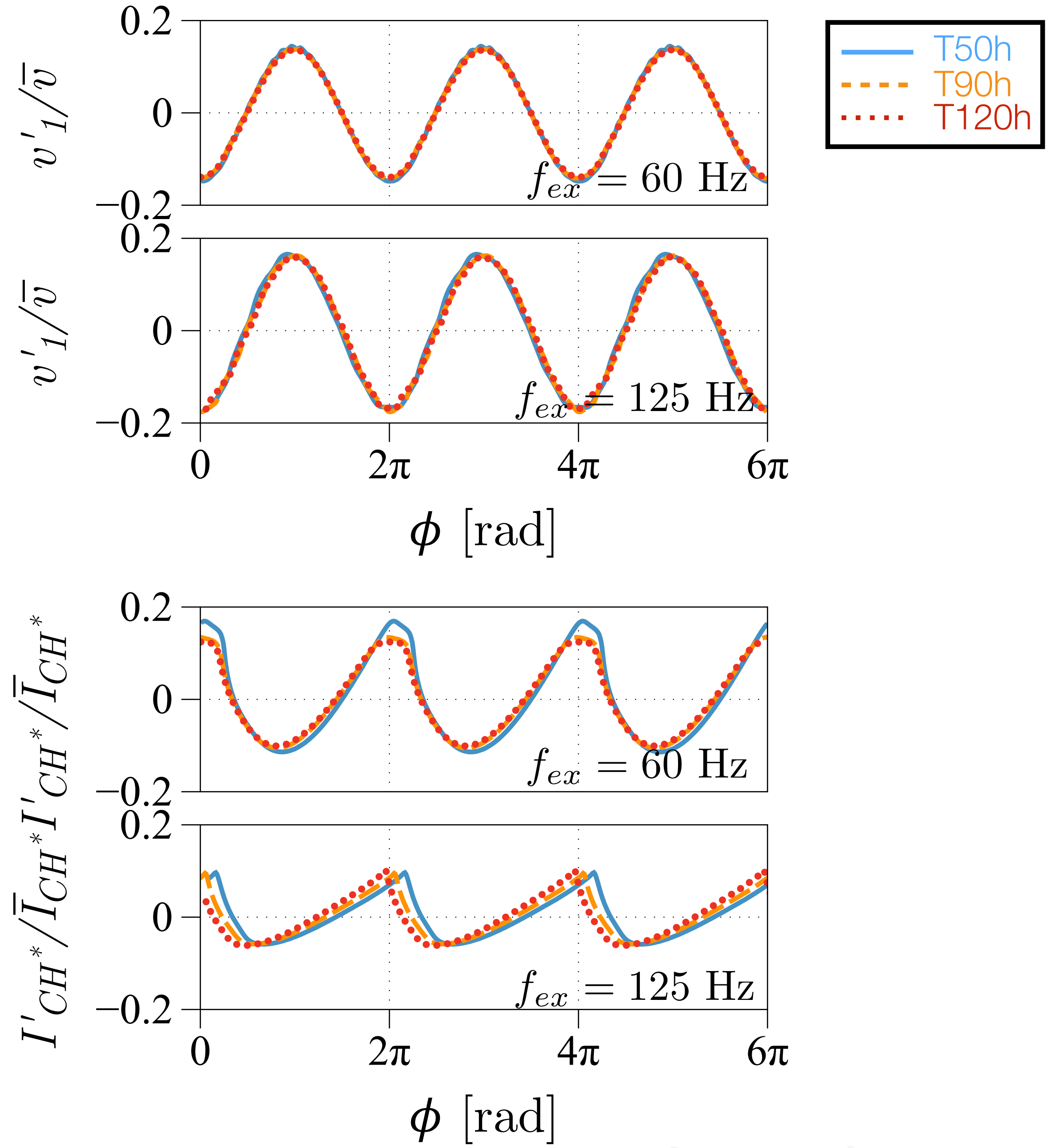


6. Flame response

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



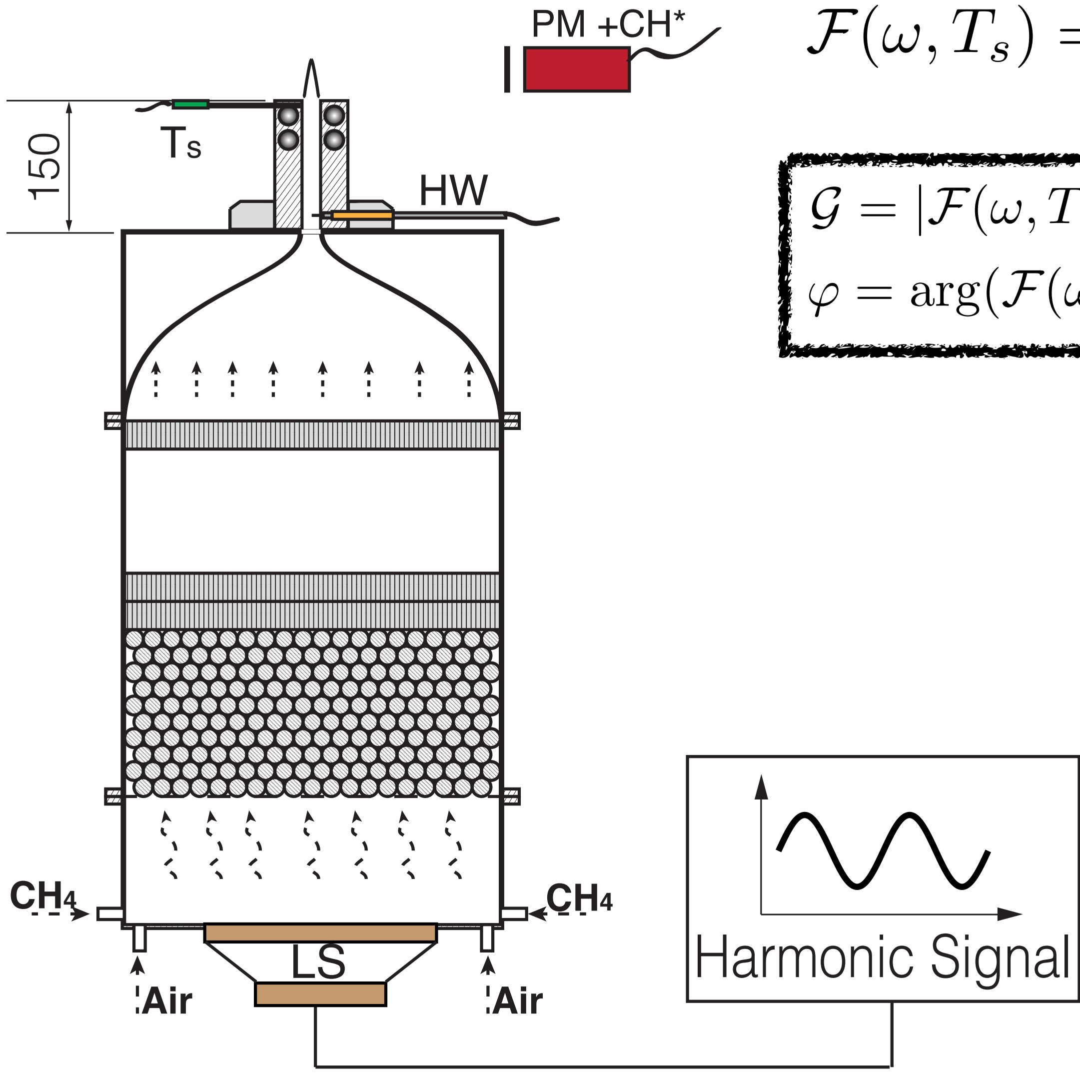
2. **Is the velocity fluctuation the same for all cases?**

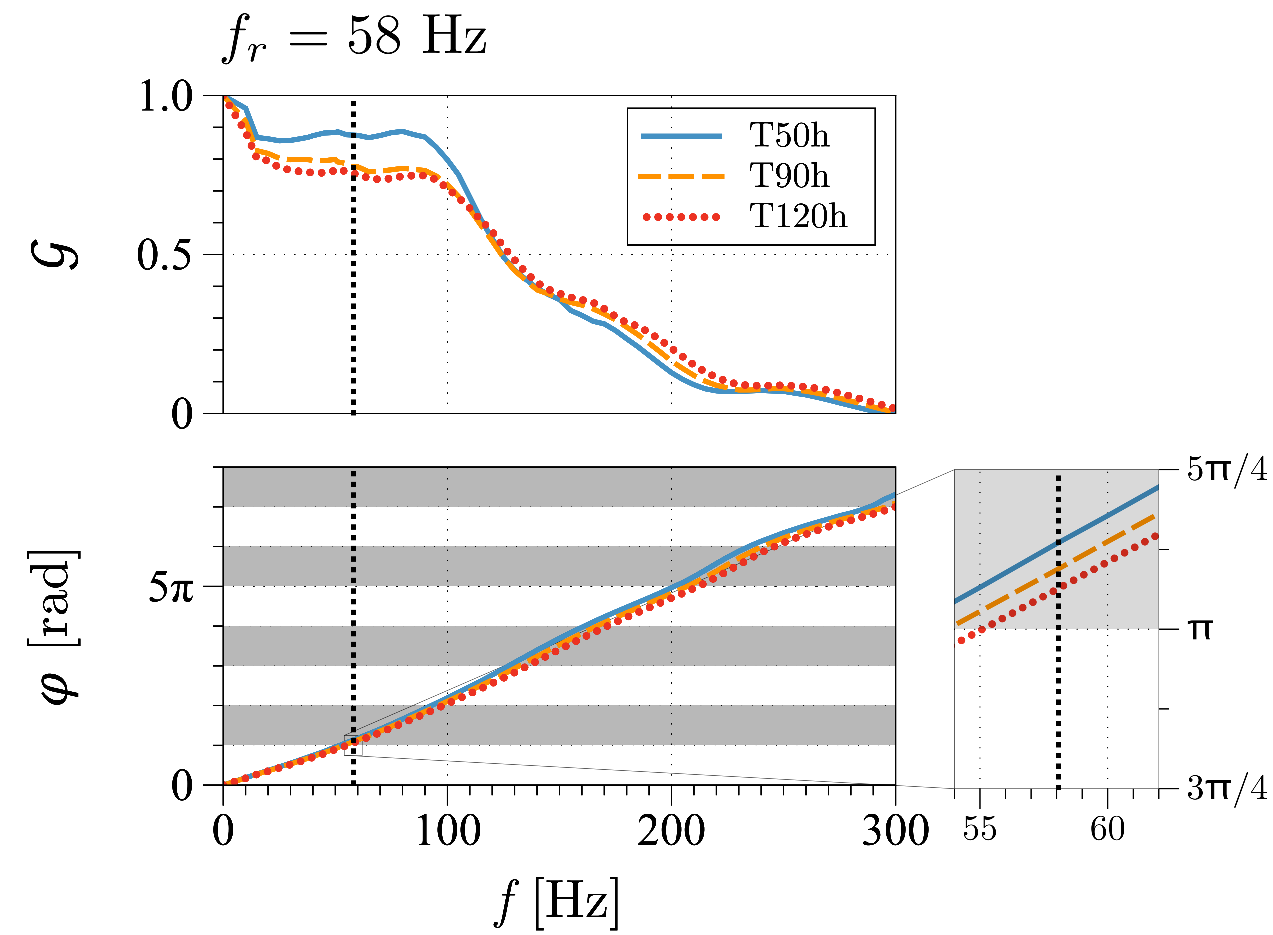


3. How does it affect the FTF?

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

$$\boxed{\begin{aligned}\mathcal{G} &= |\mathcal{F}(\omega, T_s)| \\ \varphi &= \arg(\mathcal{F}(\omega, T_s))\end{aligned}}$$





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

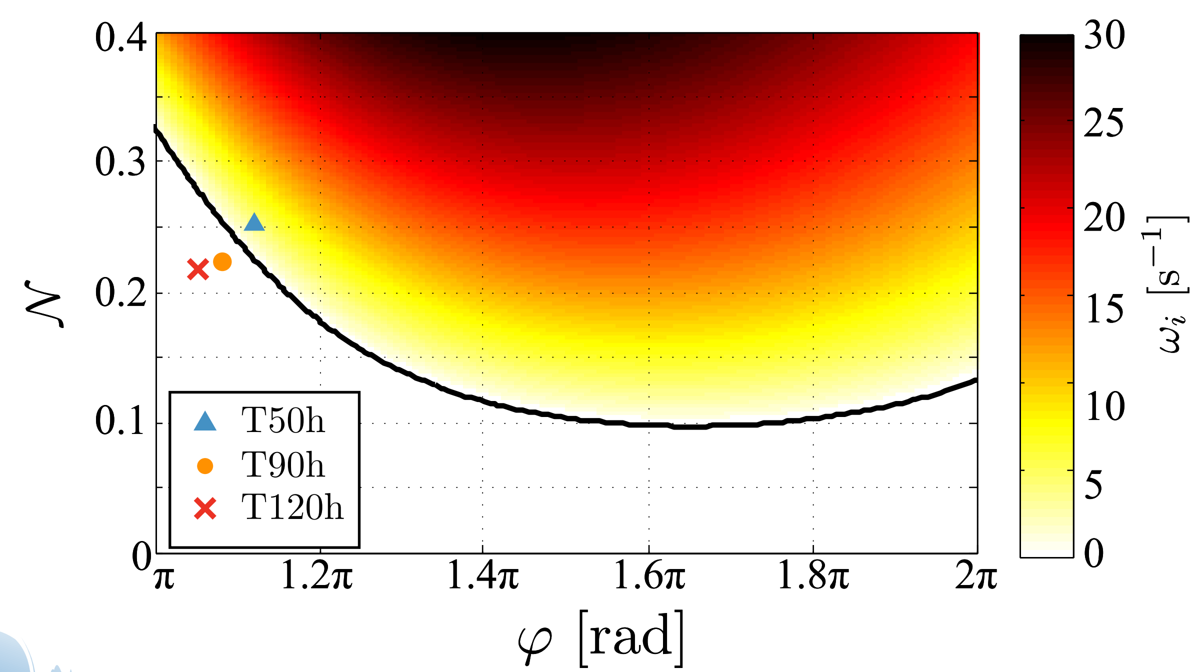
	$\mathcal{G}_r$	φ_r [rad]
T50h	0.88	1.13π
T90h	0.78	1.09π
T120h	0.75	1.06π
T50h-T120h	**14 %**	**6 %**

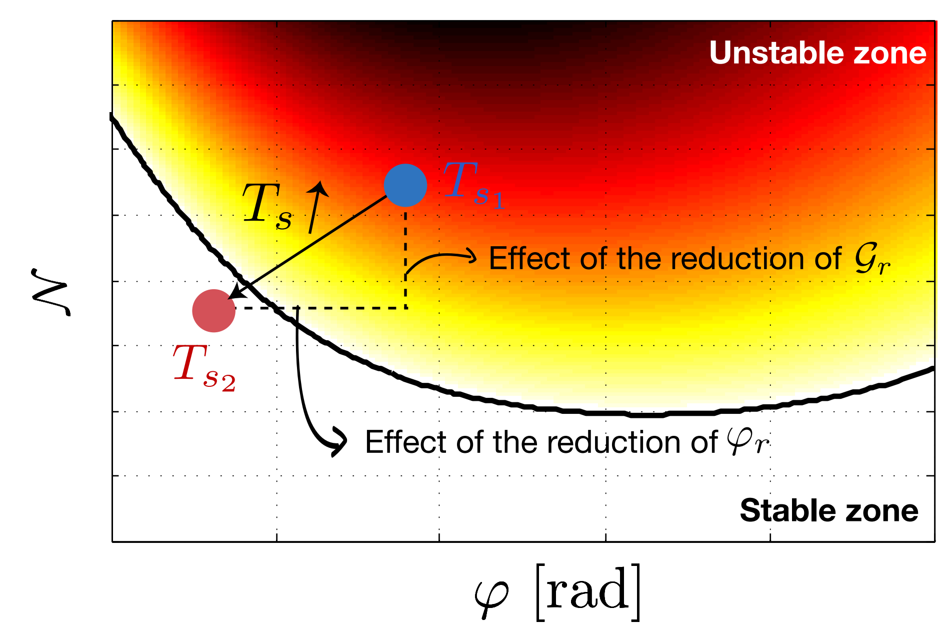
7. Burner Stability

Do the changes on the FTF explain the stability variations?

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

	Acoustics		Noise	Flame response		$\mathcal{N}$	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	0.25	59.1	2.4	Unstable
T90				0.77	1.08π	0.23	59.4	-6.9	Stable
T120				0.75	1.05π	0.22	59.3	-12.0	Stable

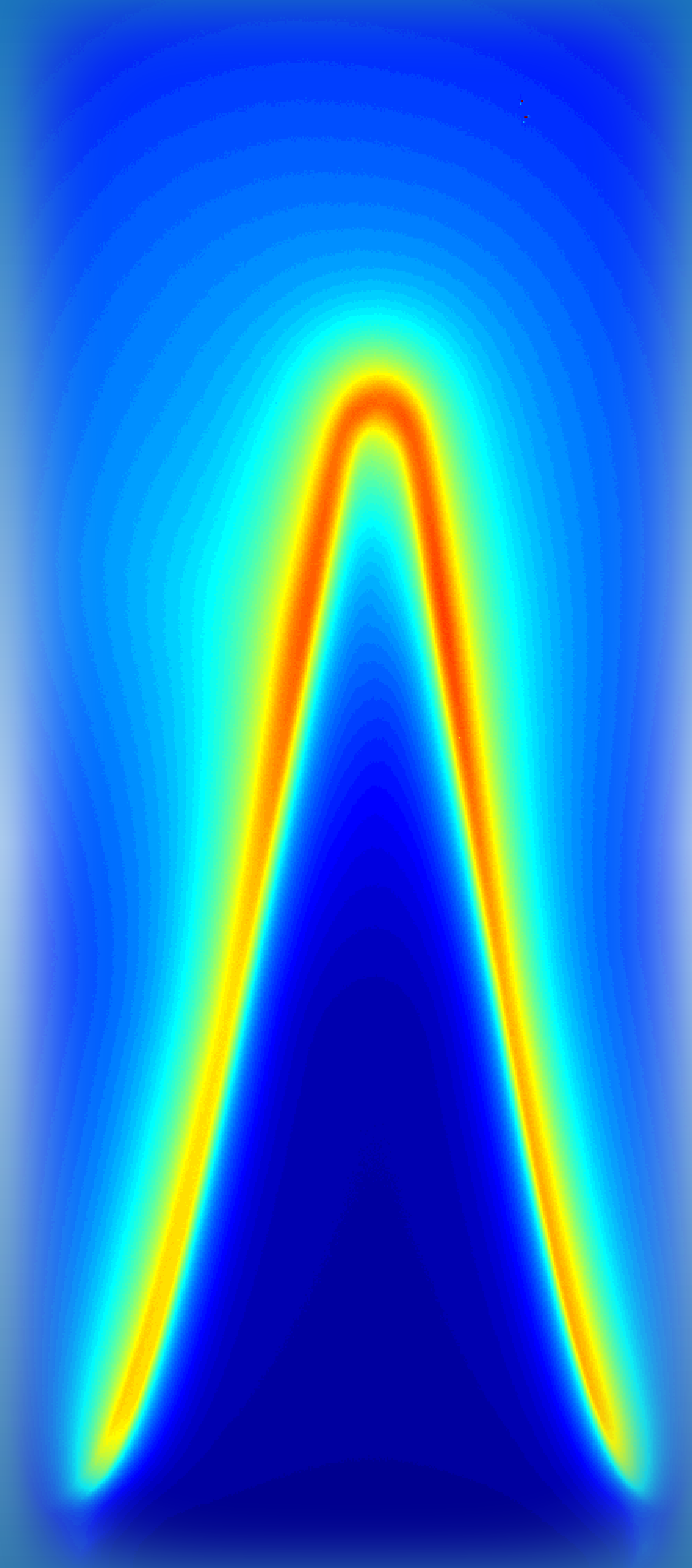




The flame's natural instability can be suppressed by increasing T_s by just 40 K.
This 40 K variation changes the gain from 0.87 to 0.77 and the phase from 1.12π rad to 1.08π rad; This is sufficient to stabilize the system.

Objectives

1. Derive a stability model able to predict the experimental observations.
2. Determine which mechanism(s) is/are responsable for stabilizing the flame.
3. Understand how this mechanism(s) work(s).



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Outline

Part I: The Slot Burner

1. Experimental setup
2. Evidence of wall-temperature effect → 50 °C / 90 °C / 120 °C
3. Stability model → Five parameters

Part II: Experimental Measurements

4. Burner acoustics — No Ts dependency
5. Combustion noise — No Ts dependency
6. Flame response — Very sensitive to Ts

7. Burner stability

Part III: Flame Dynamics

8. Flame front dynamics
9. Flame root dynamics

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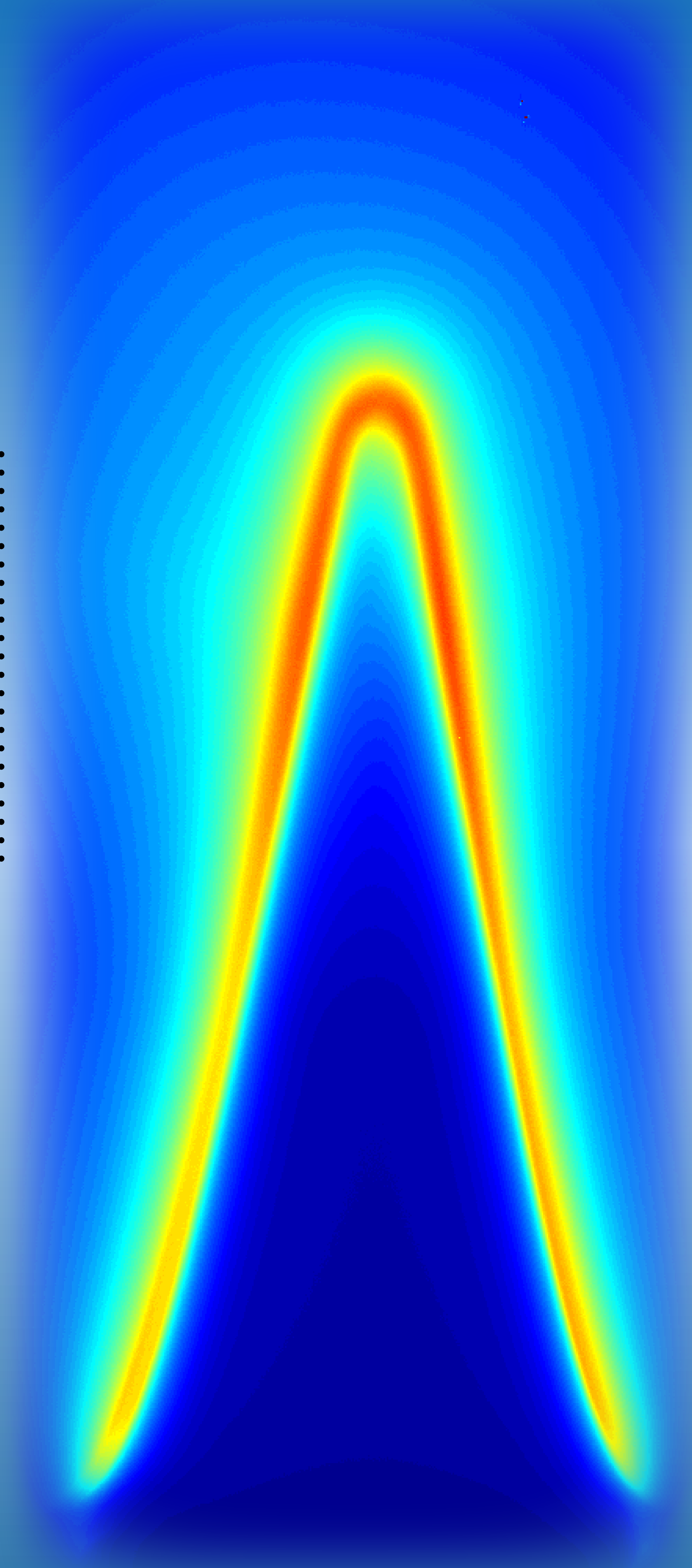
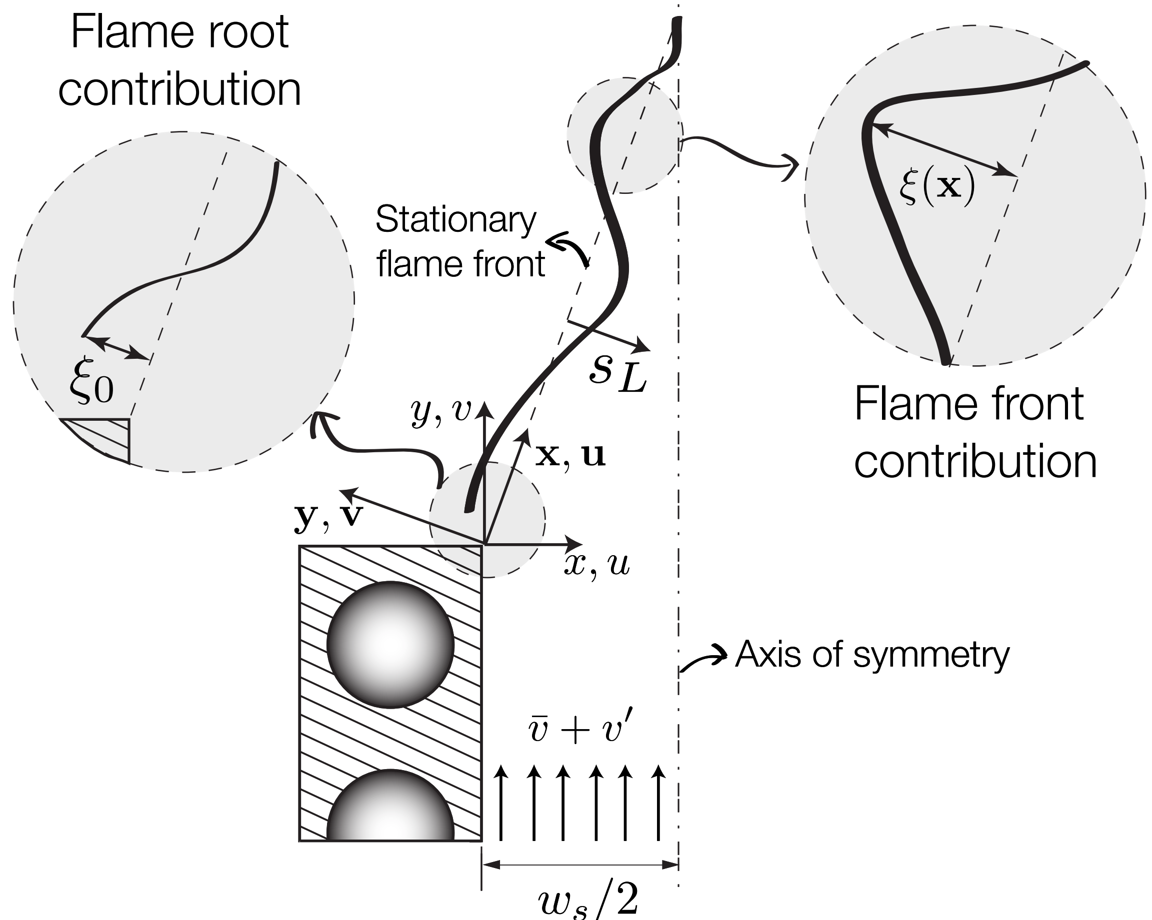
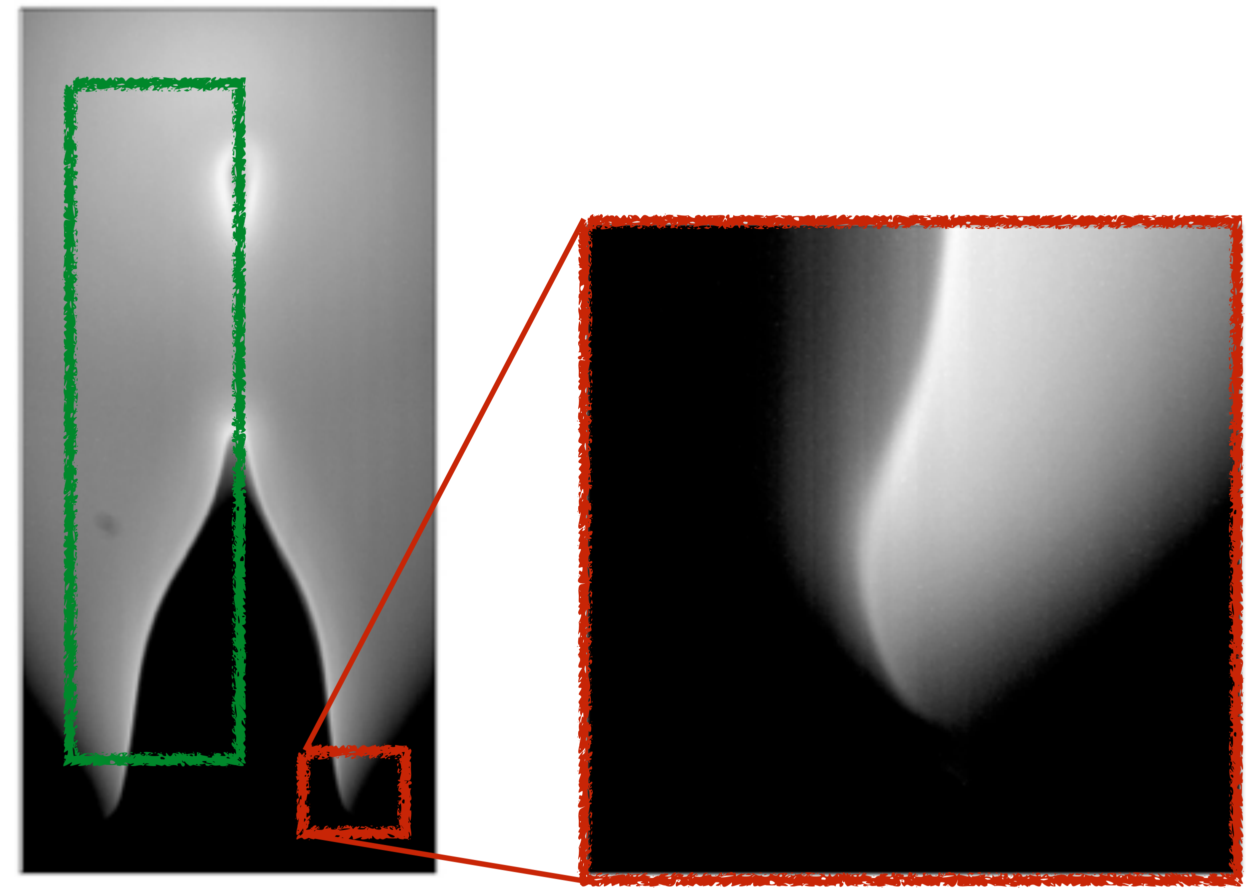


Brief review of flame dynamics theory:





G-equation:

$$\frac{\partial G}{\partial t} + \vec{v}.\nabla G = s_L|\nabla G|$$

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:

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

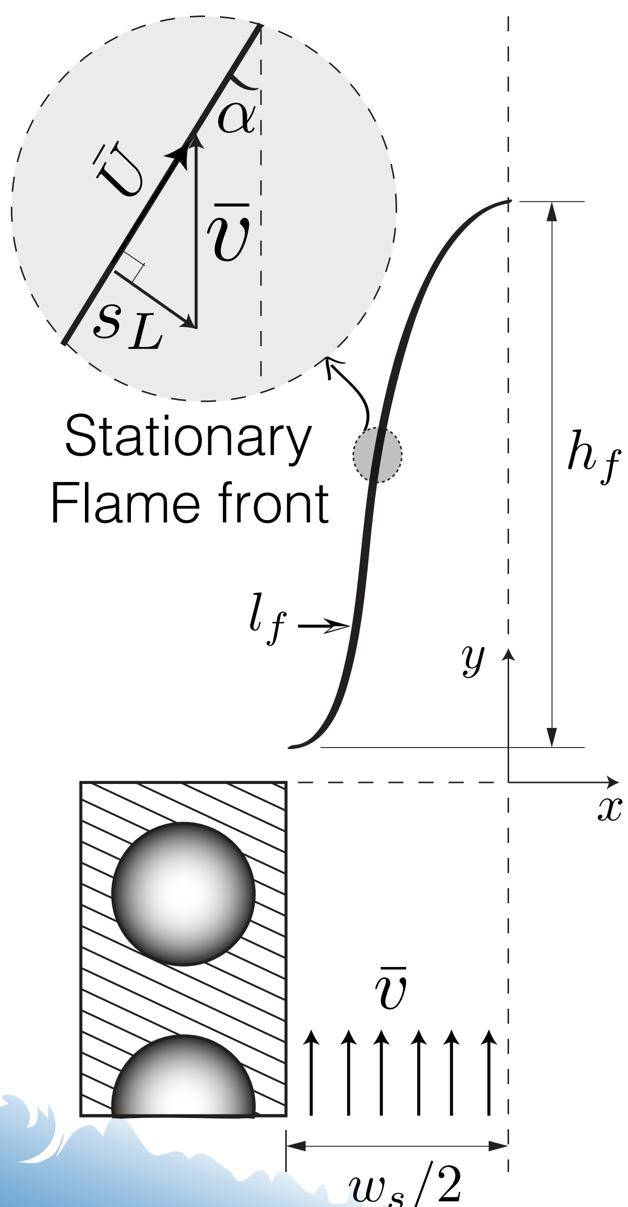
Two contributions to the FTF

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

[1] Boyer and Quinard 1990 *cf.*
[2] Fleifil *et al.* 1996 *cf.*
[3] Lee and Lieuwen 2003 *jpp.*

8. Flame Front Dynamics

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



Flame front dynamics is controlled to the first order by two parameters:

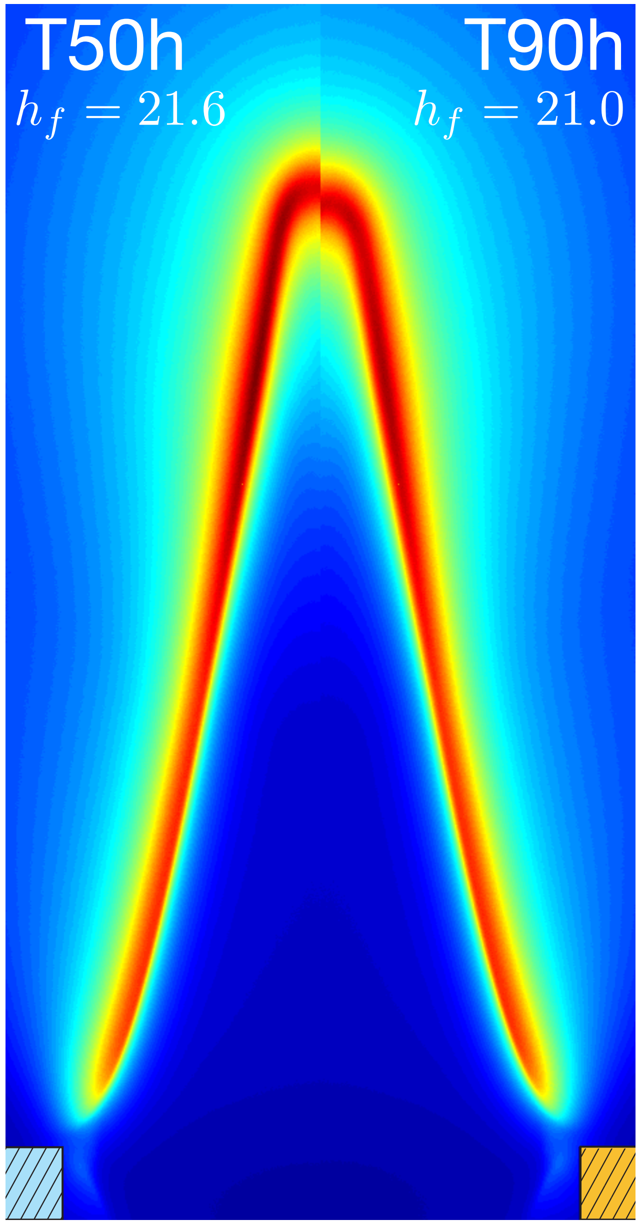
$$\mathcal{F}_A = f(\omega_*, k_*)$$

$$\omega_* = \frac{\omega}{\bar{v}\cos(\alpha)} l_f$$

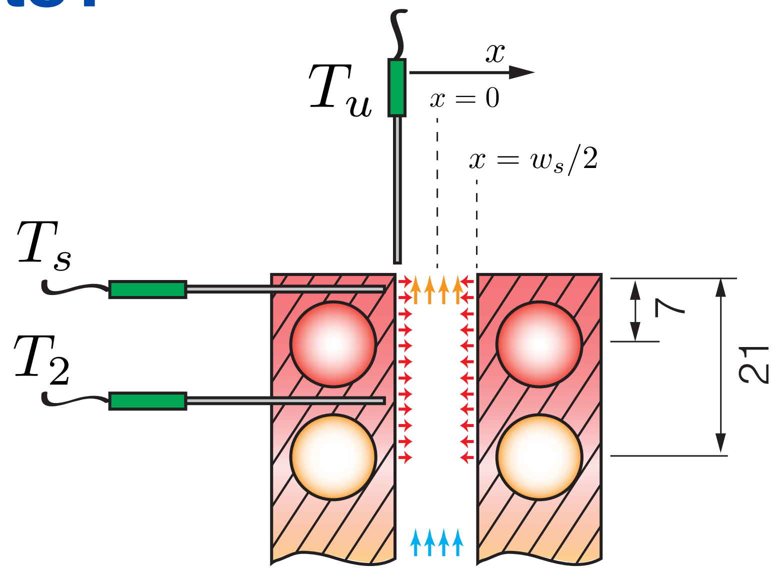
$$k_* = \frac{\omega}{\bar{v}} h_f$$

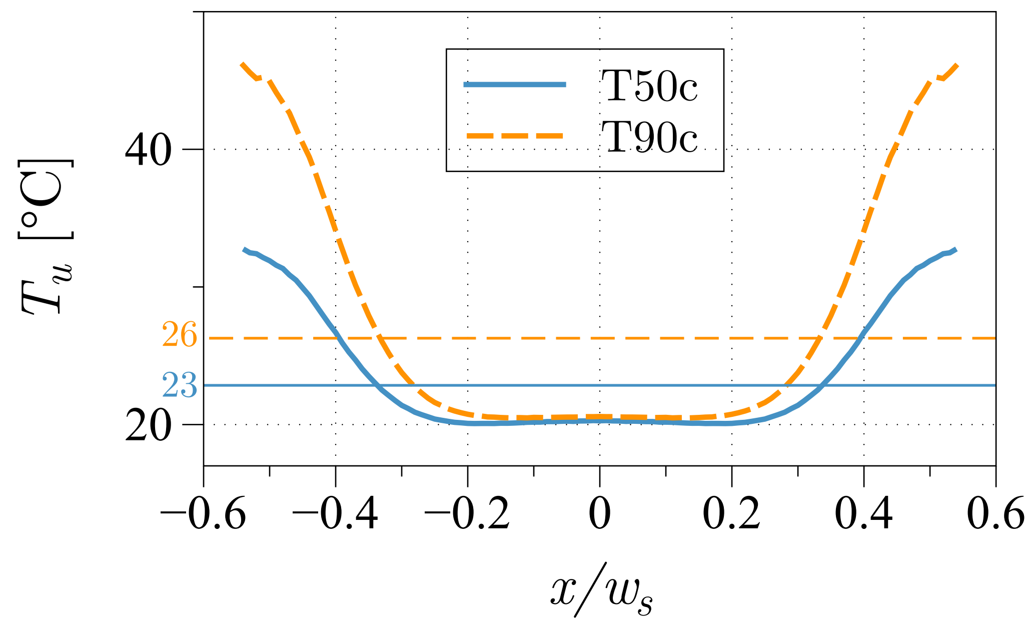
2. **Is the flame geometry affected by the wall temperature T_s?**

[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.*



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

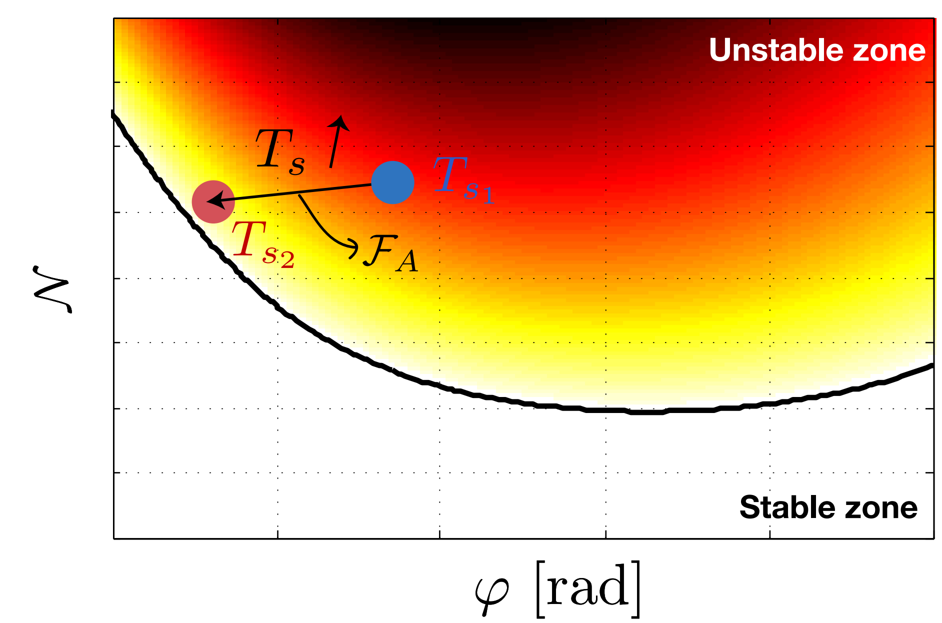




$$s_L = f(T_u)$$

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	

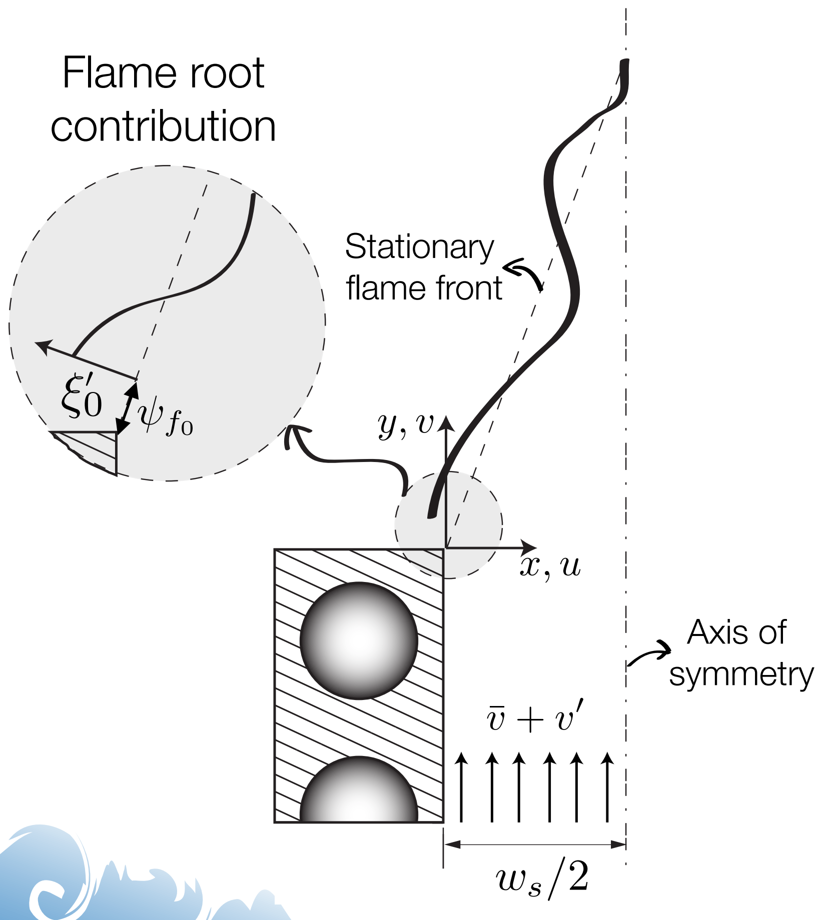


1. Does the theory predicts a change in the flame root response when Ts changes?

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

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

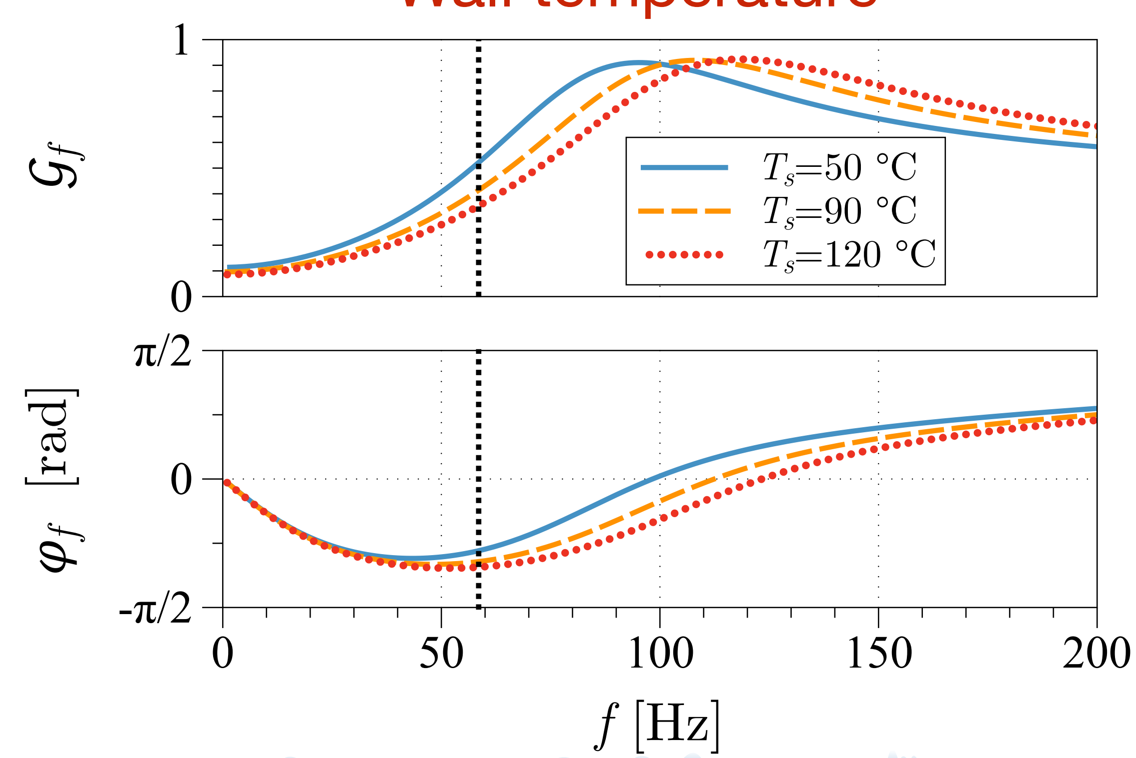
$$\psi_{f_0} = \delta_f \log \left(\frac{T_{ad} - T_u}{T_{ad} - T_b + \boxed{T_s} - T_u} \right)$$

Wall temperature

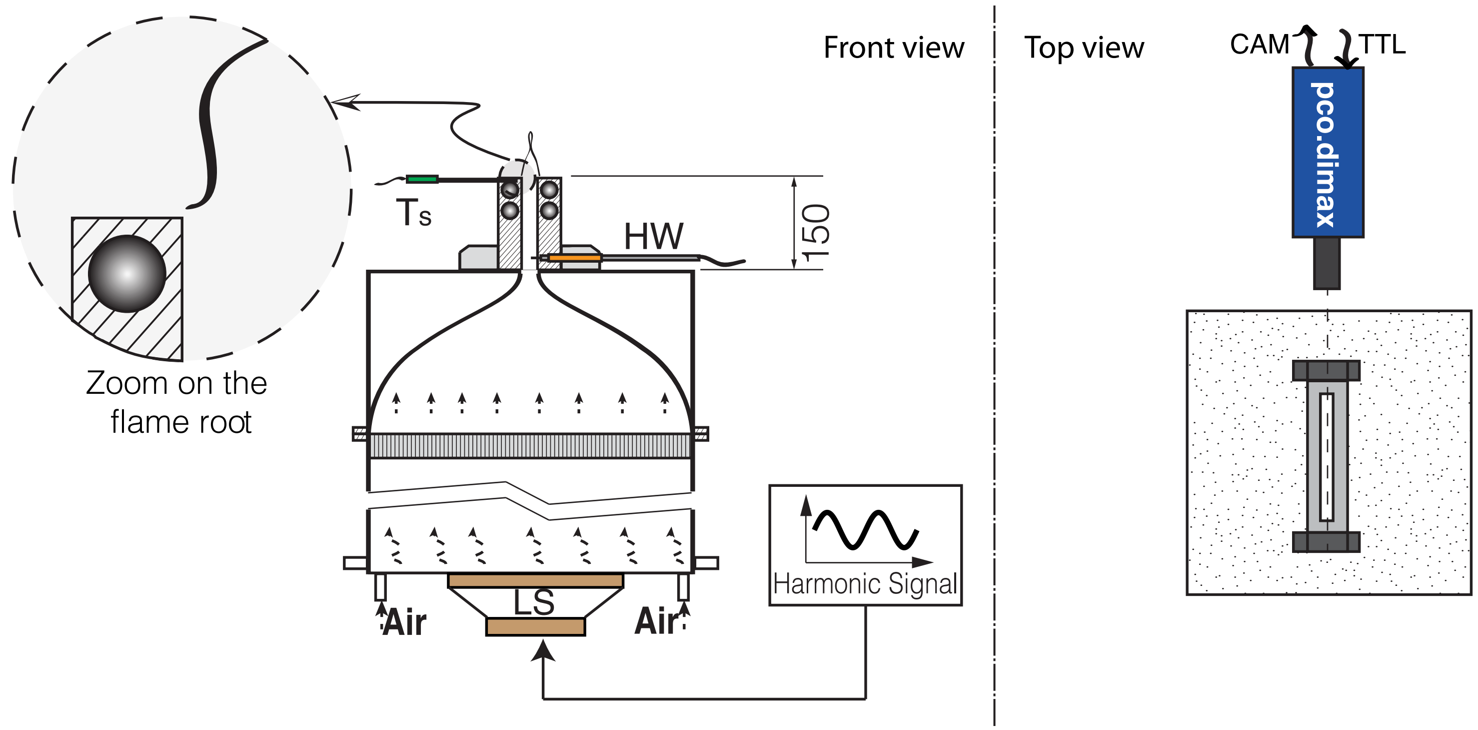
$$\boxed{\begin{aligned} \mathcal{G}_f &= |\Xi(\hat{\omega}, \mathrm{Ze}, \psi_{f_0})| \\ \varphi_f &= \arg(\Xi(\hat{\omega}, \mathrm{Ze}, \psi_{f_0})) \end{aligned}}$$

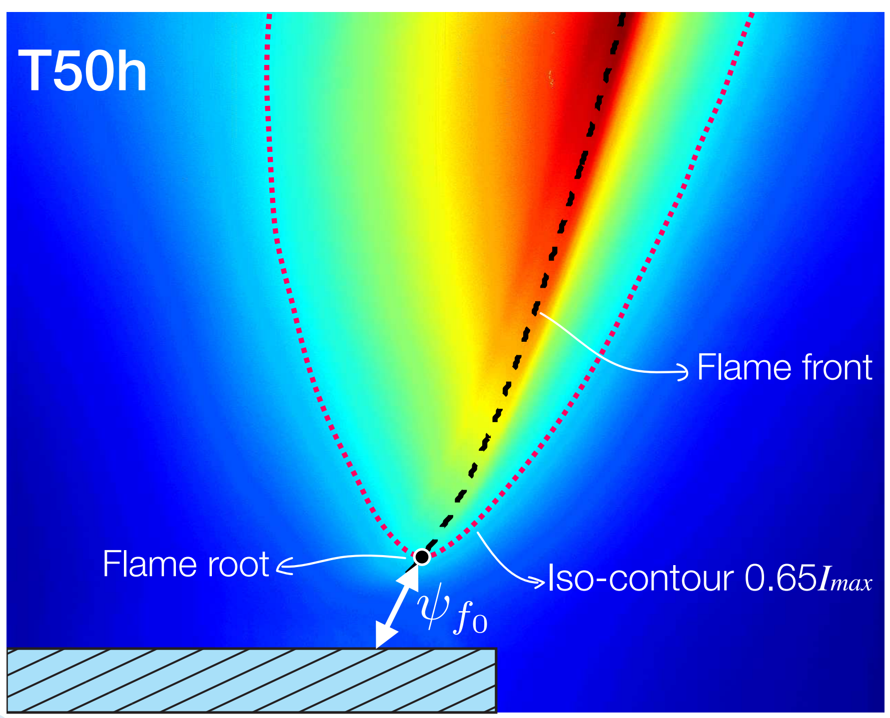
$$f_r = 58 \text{ Hz}$$

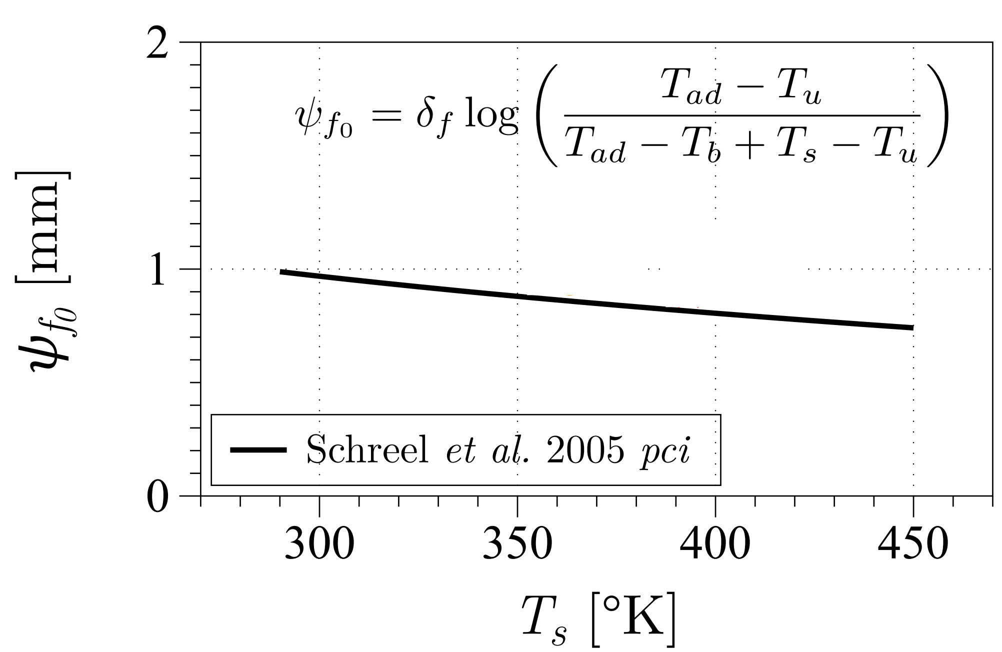
[1] Kornilov *et al.* 2007 *pci.*
[3] Cuquel *et al.* 2013 *crm.*
[4] Rook *et al.* 2002 *ctm.*
[5] Schreel *et al.* 2005 *pci.*
[6] Altay *et al.* 2009 *pci.*



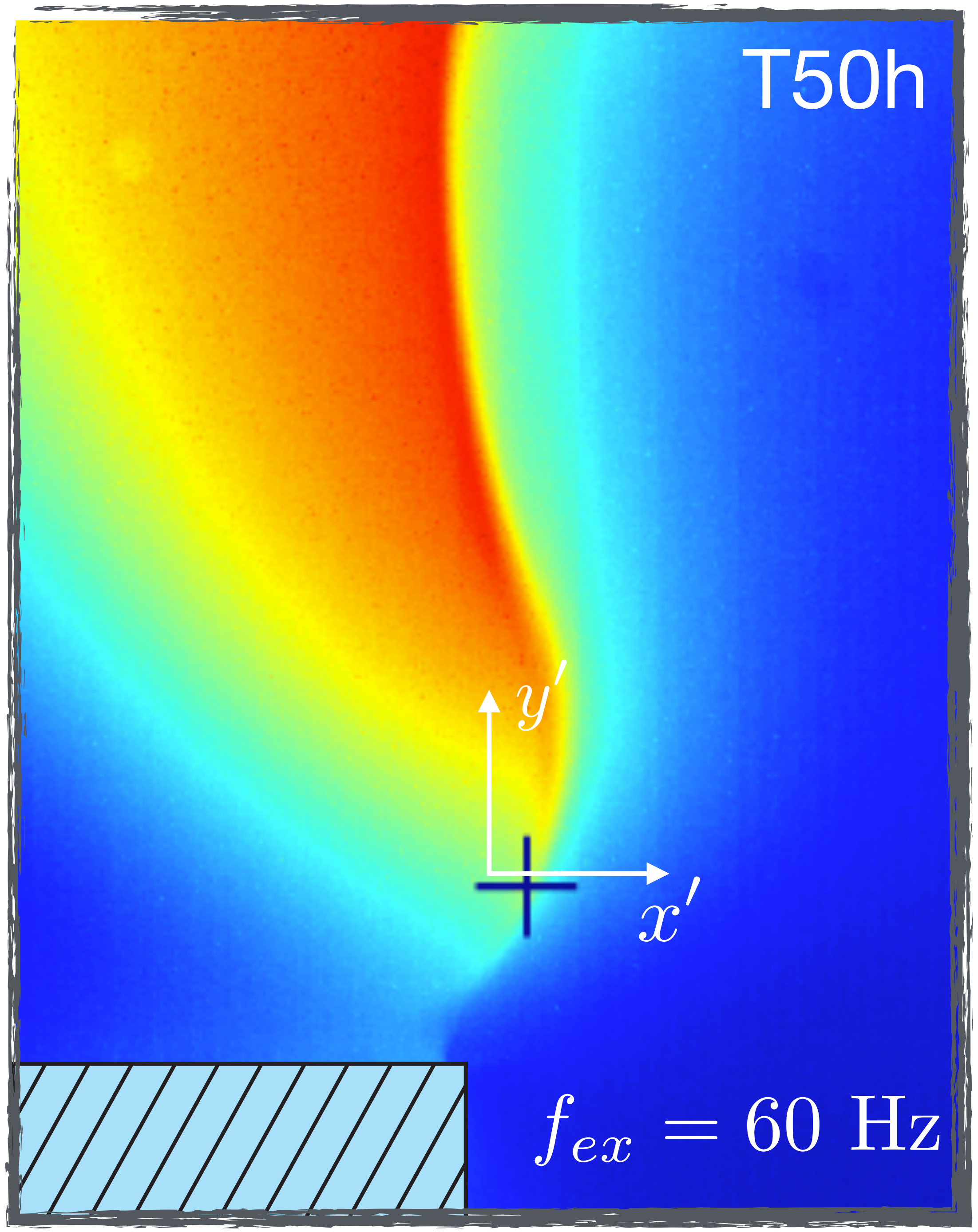
2. Does the experiment predict a change in the flame root response when Ts changes?



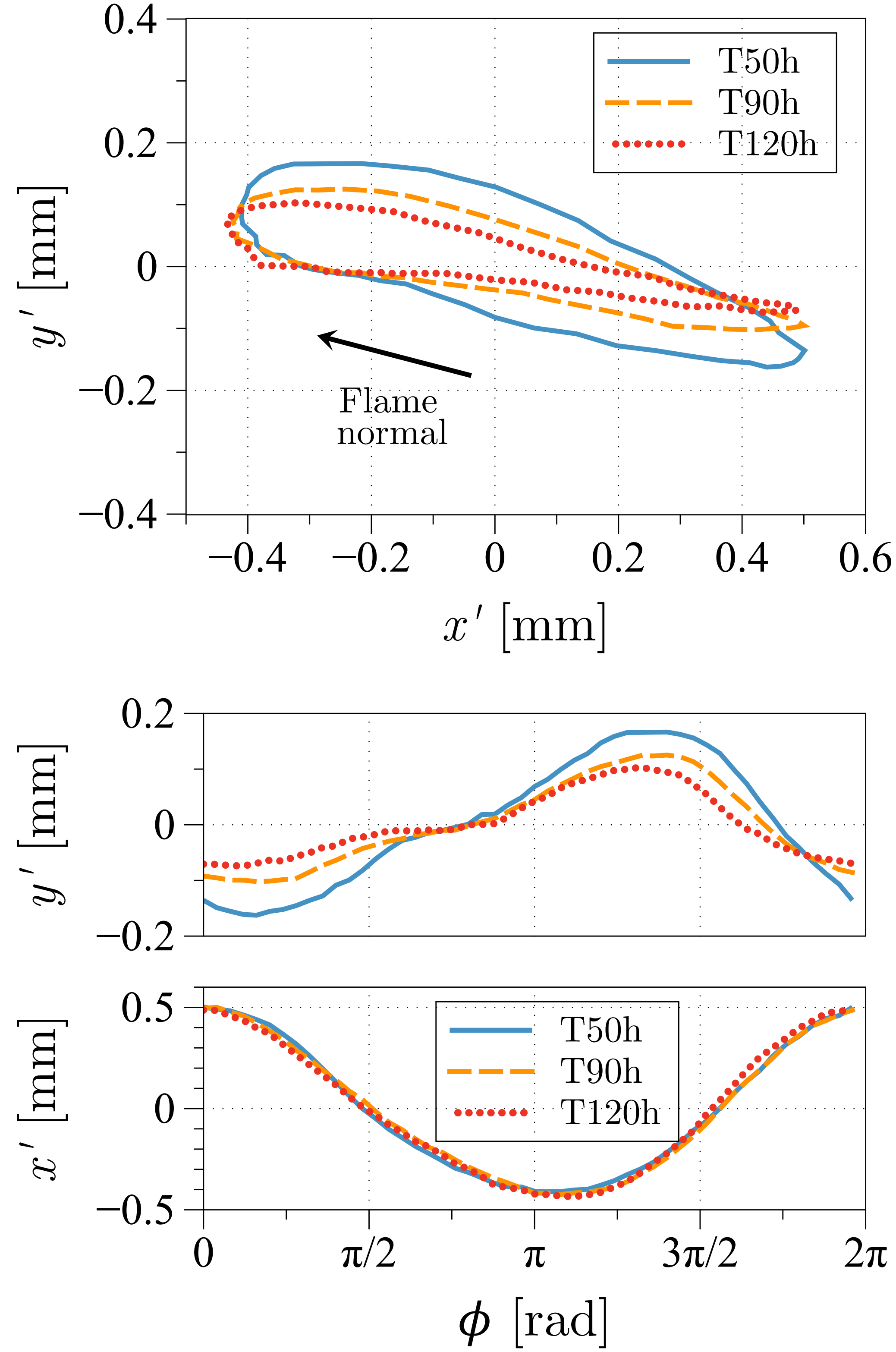




Flame root trajectoires

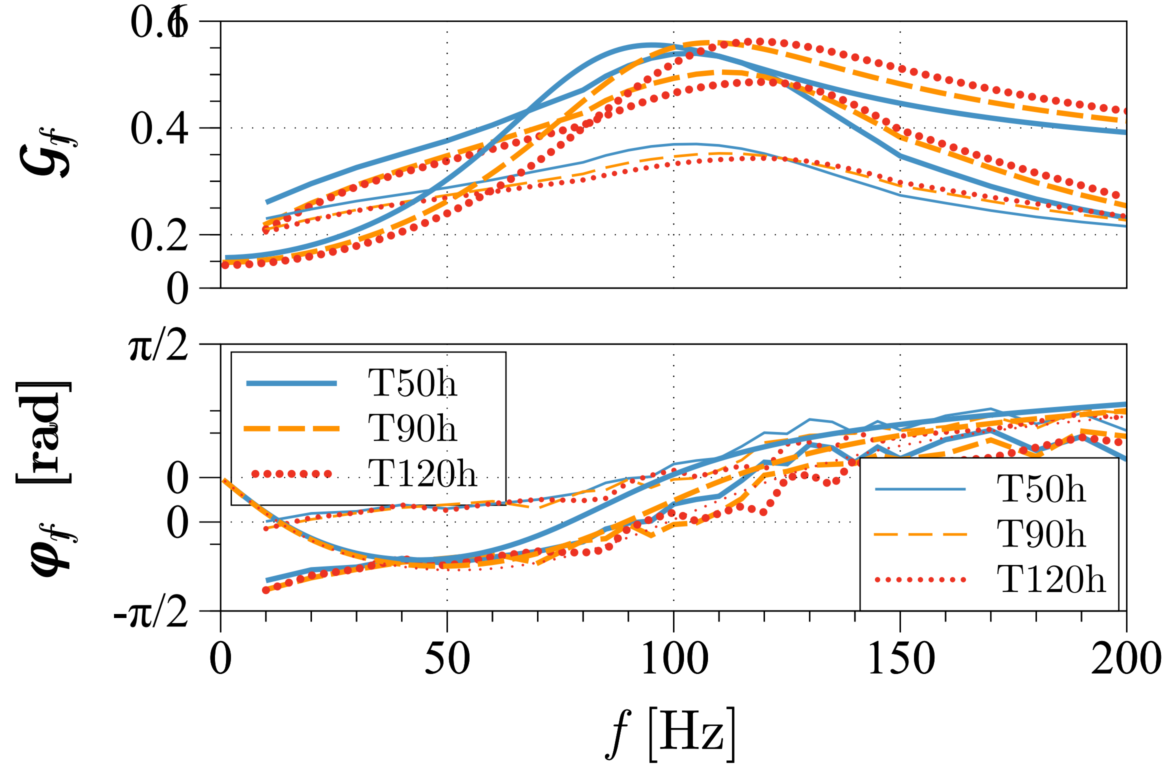


$$x' = x - x_0$$
$$y' = y - y_0$$



Experimental flame root transfer function

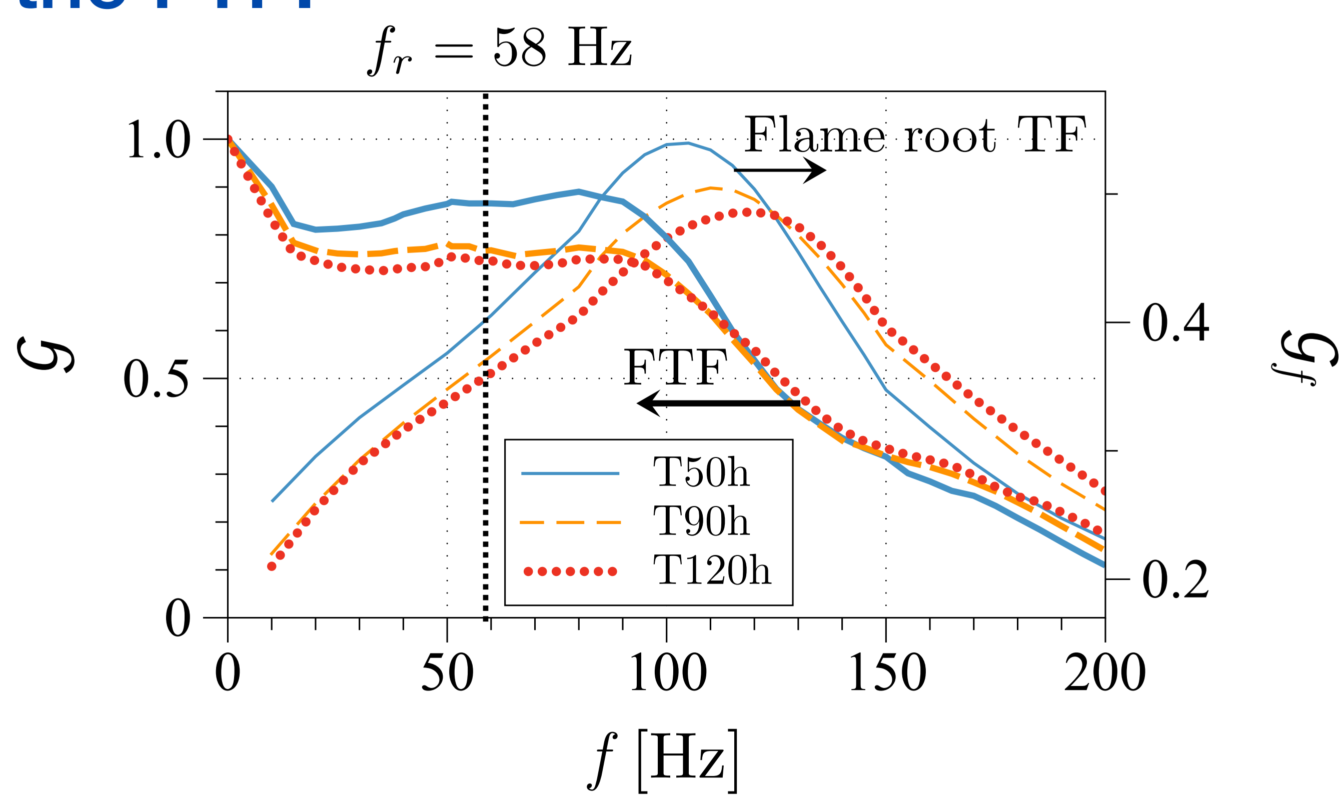
$$\mathcal{G}_r = |\Xi(\omega, T_s)|$$
$$\varphi_r = \arg(\Xi(\omega, T_s))$$



Model	Expe	
		T50h
		T90h
		T120h

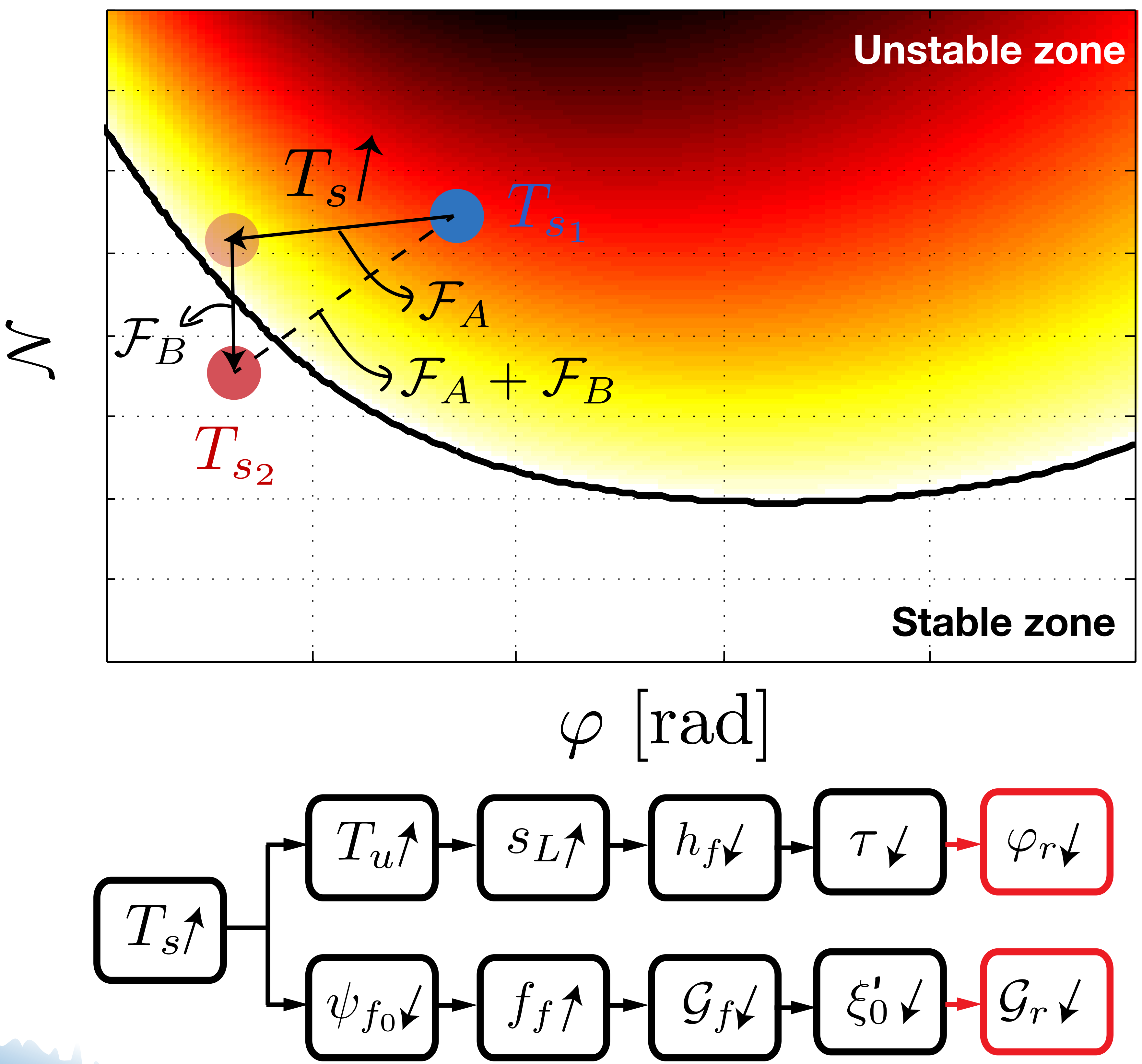
Comparison with the FTF:

FTF	FRTF	
		T50h
		T90h
		T120h



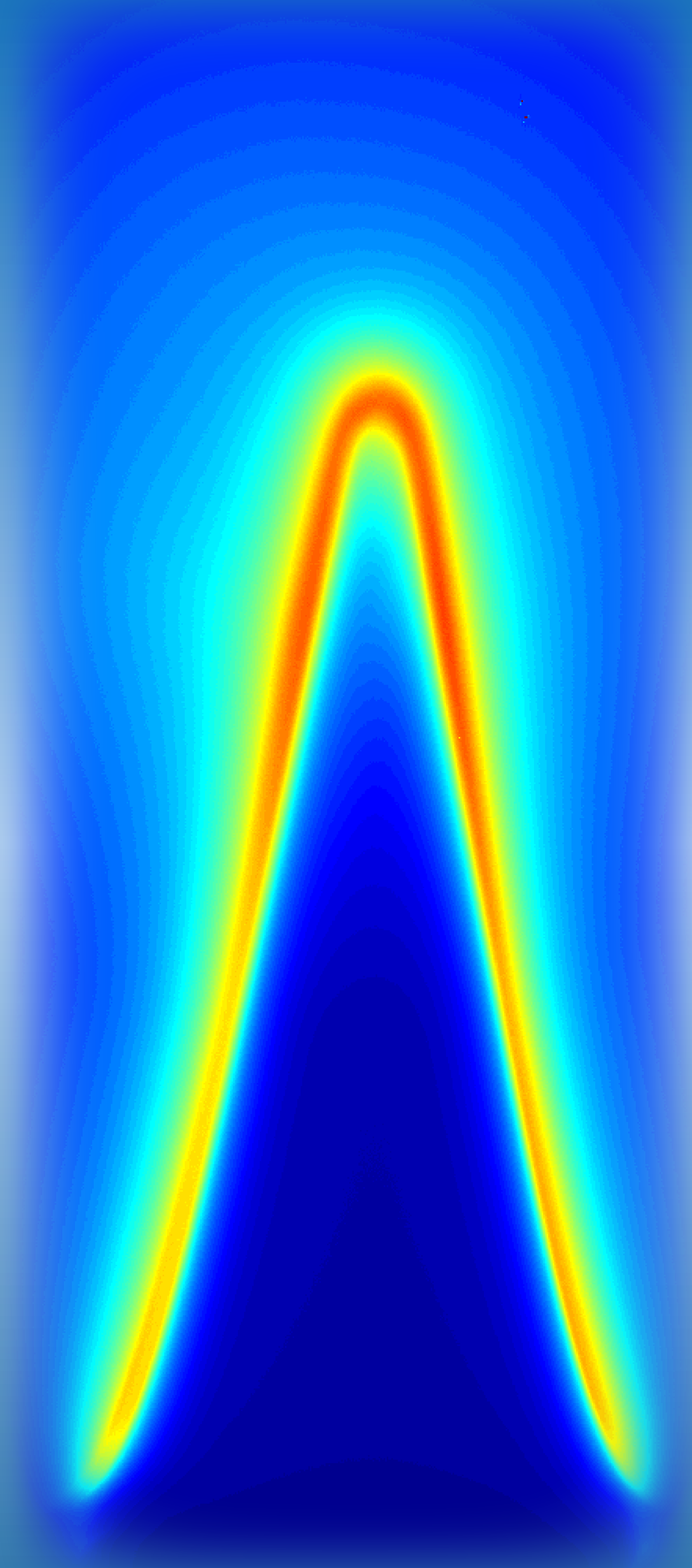
Difference T50h-T120h	$\mathcal{G}_r$
Flame root FTF	11 %
Actual FTF	14 %

So, how is the flame stabilized?



Objectives

1. Derive a stability model able to predict the experimental observations.
2. Determine which mechanism(s) is/are responsable for stabilizing the flame.
3. Understand how this mechanism(s) work(s).



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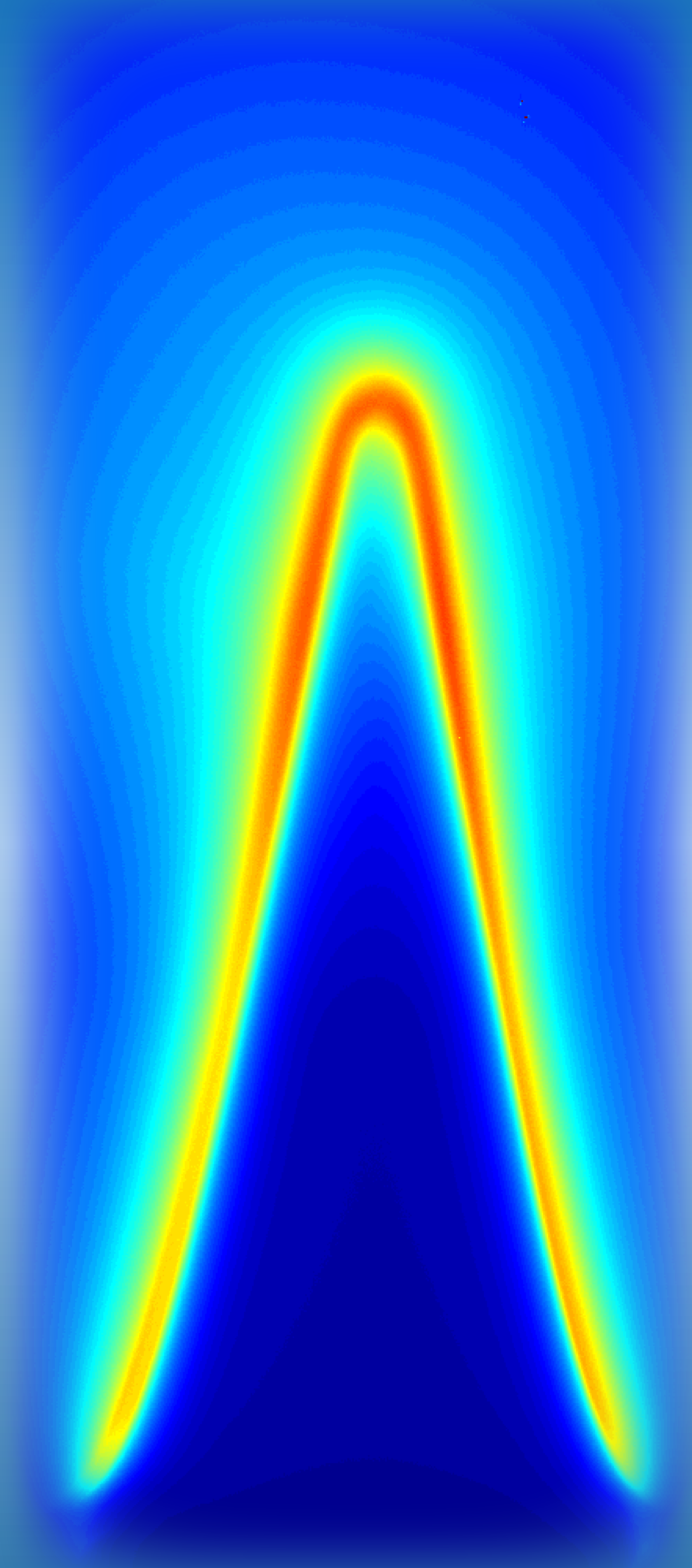
Conclusions

1. We show an experiment where the wall temperature Ts can be controlled.
2. We have shown an experiment where the stability of the flame can be controlled by changing only the wall temperature Ts.
3. A stability model was proposed and we show that the wall temperature modifies the stability limits of the system by small modifications on the flame response to acoustic oscillations.
4. We use existing results to propose a model and we show that the flame root dynamics must be taken into account in order to predict the stability limit of the system.



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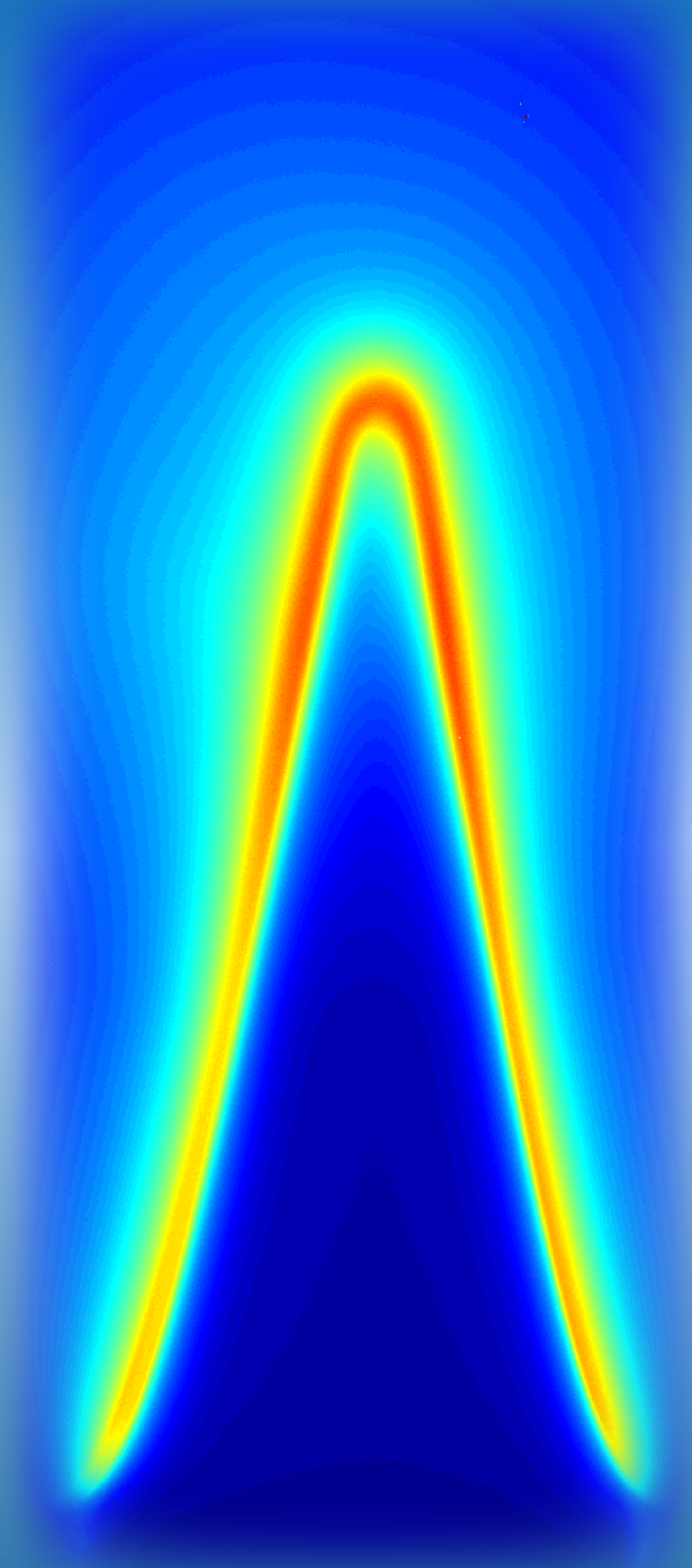
Perspectives

1. Perform DNS simulations and evaluate the ability of CFD solvers to account for parameters such as the slot temperature in the predictions of the combustion instabilities (Work in progress at the IMFT).

2. Improve the analytical model of the flame root response and expand to the scenario of the non-linear response of the flame.

3. It will be interesting to expand this study to more realistic configurations such as turbulent flames and more complicated geometries.



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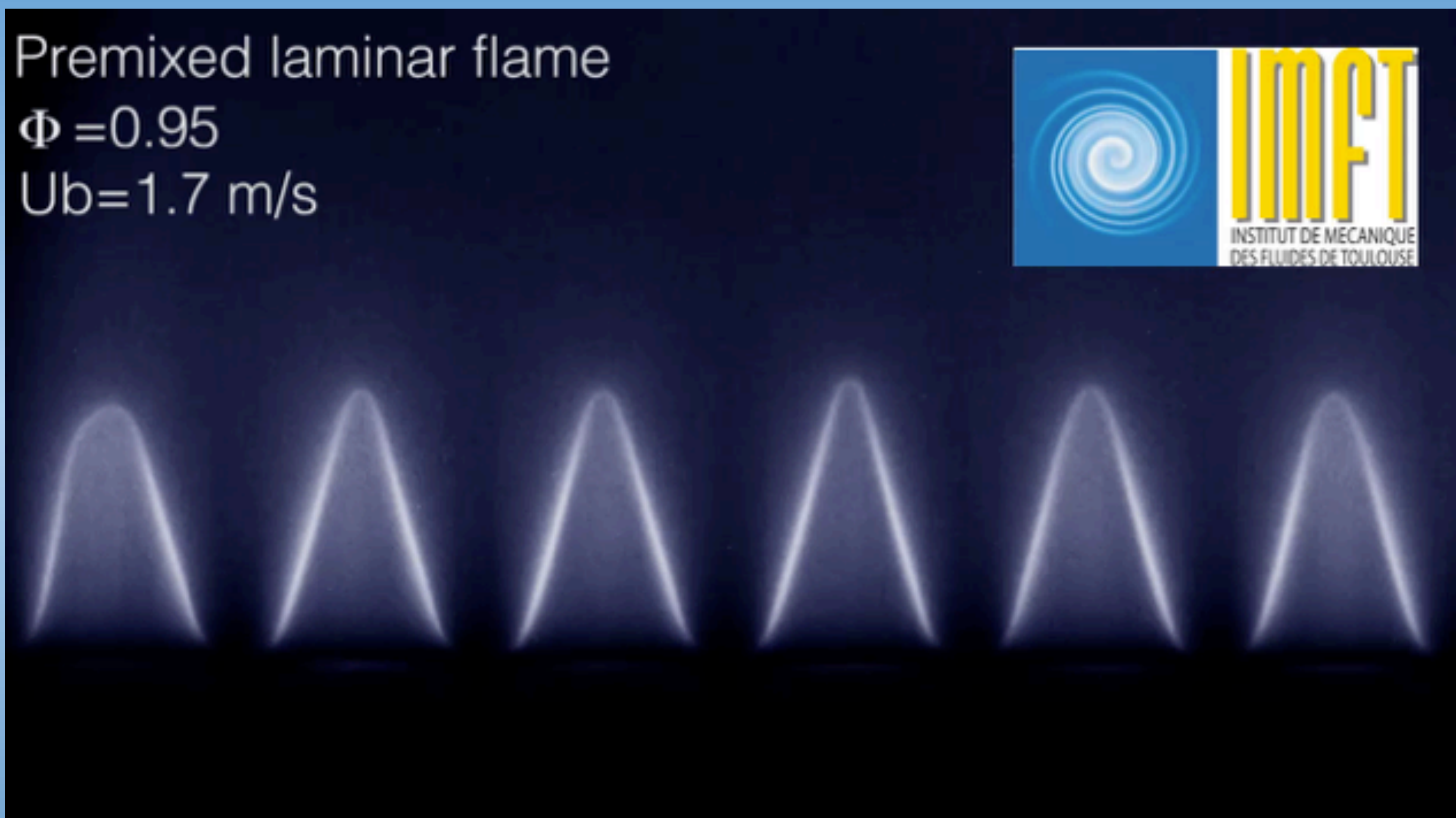
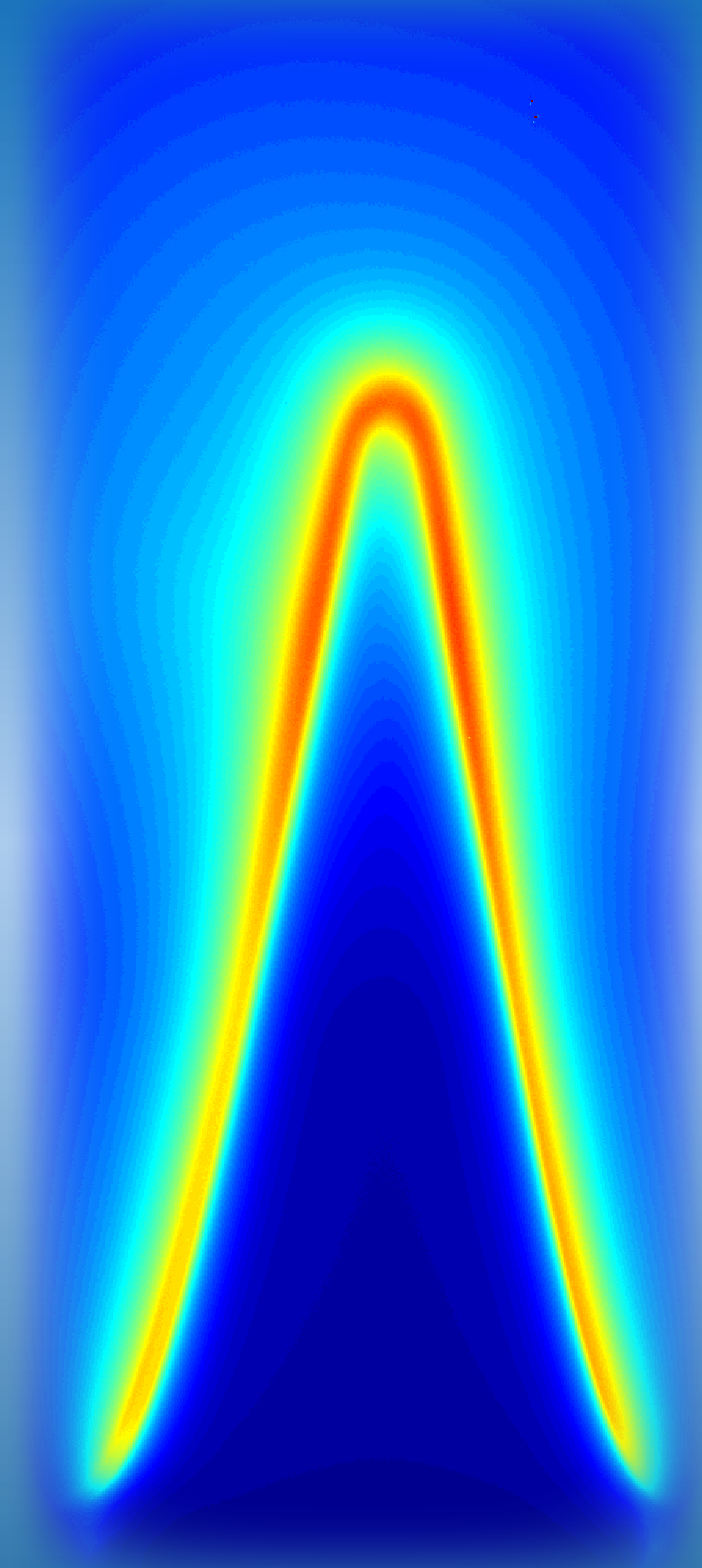
Thanks for your attention !





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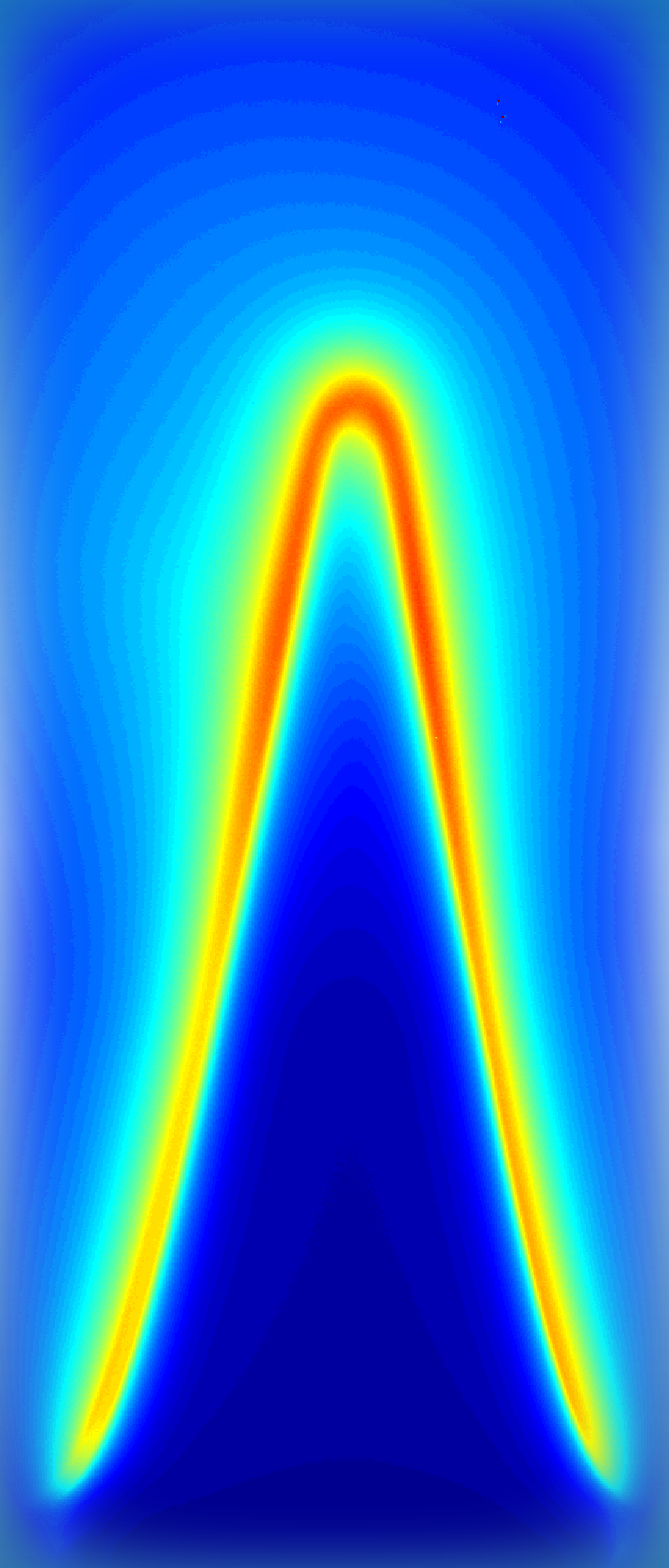
Backup



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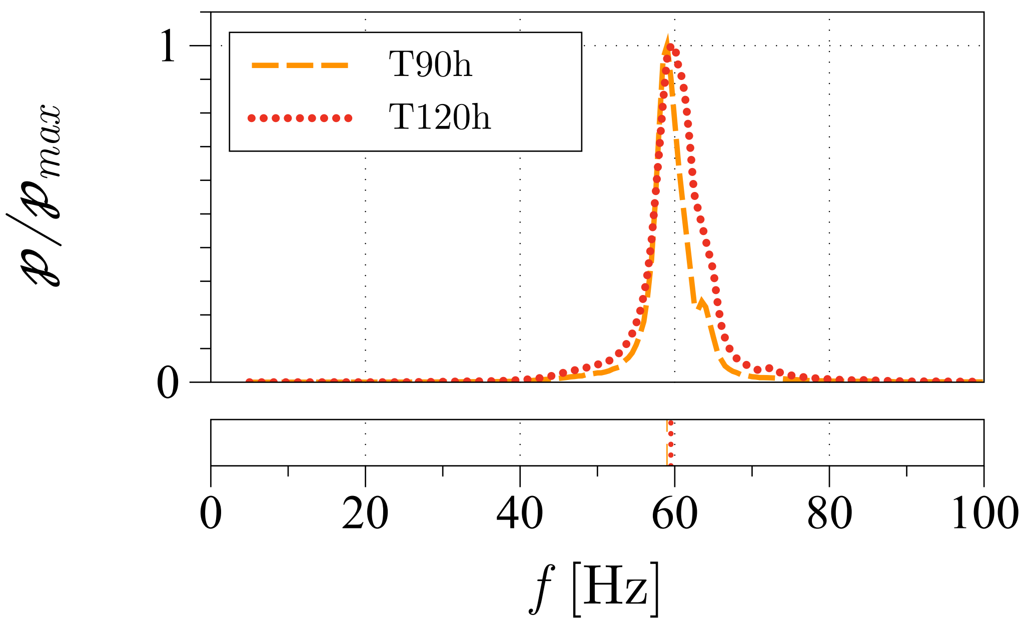
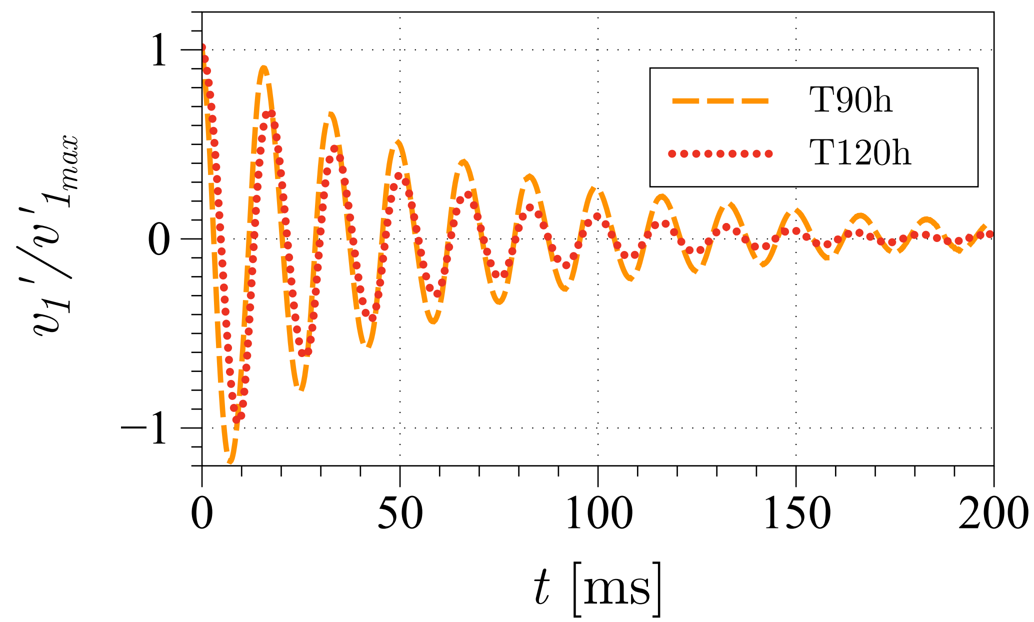
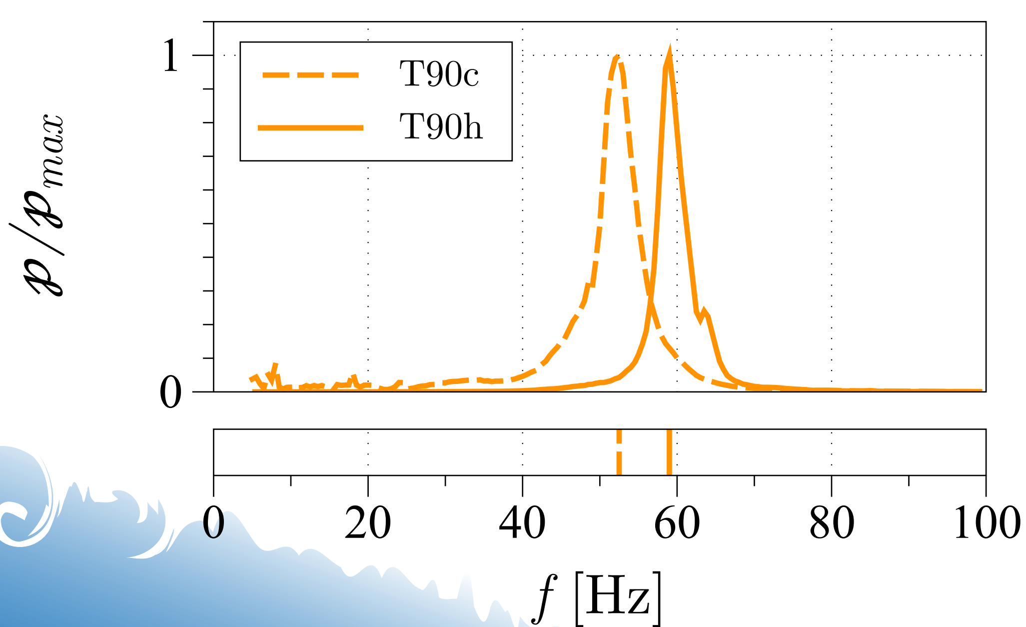
Reacting acoustics

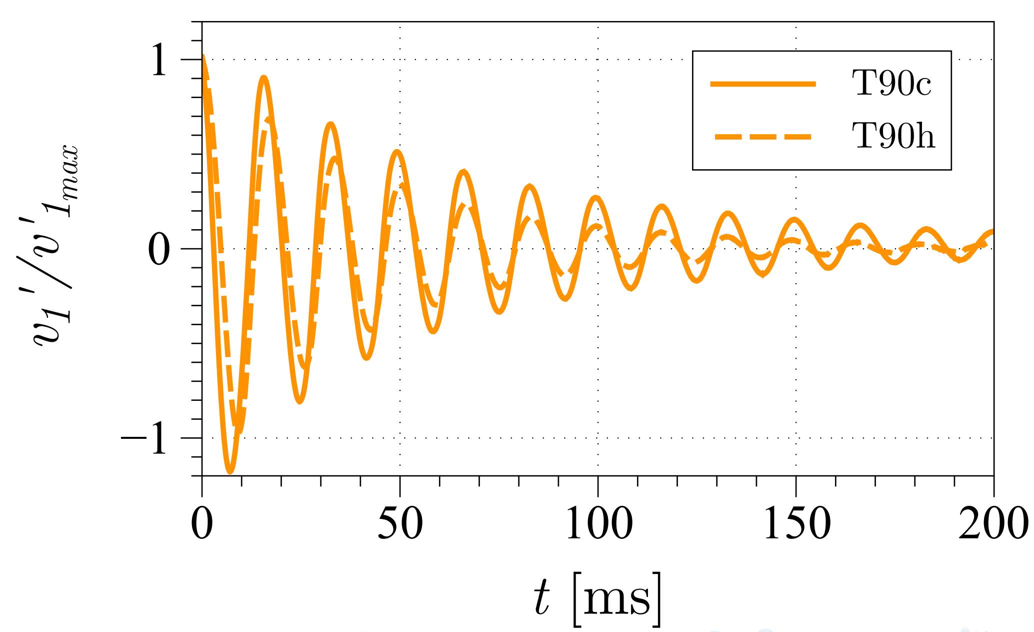
1. Comparison between two reacting cases



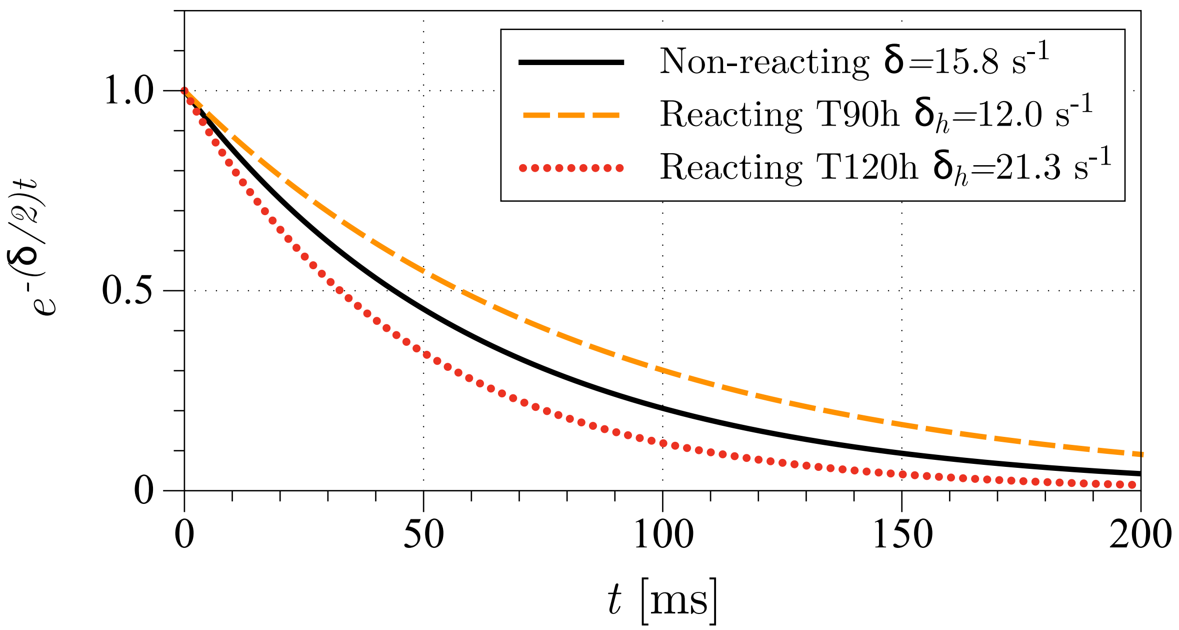


2. Comparison between two equivalent reacting and non-reacting cases





3. Flame effect on the system stability

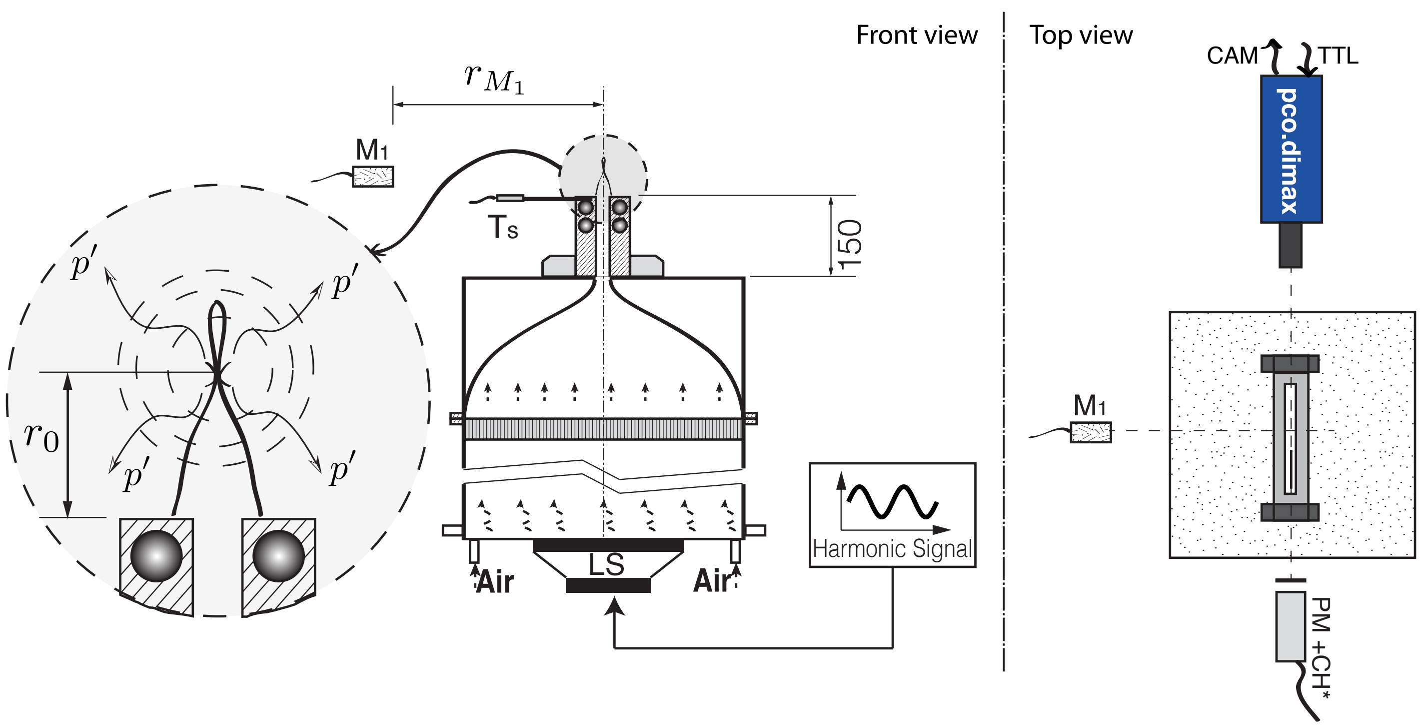


	$\delta\ [s^{-1}]$
T50c	15.8
T90h	12.0
T120h	21.3

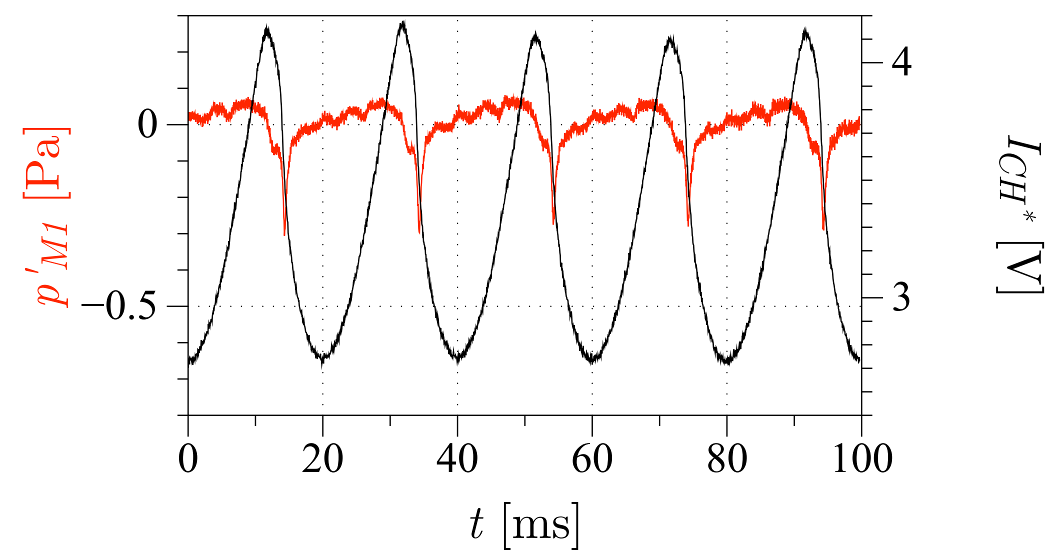
Combustion noise

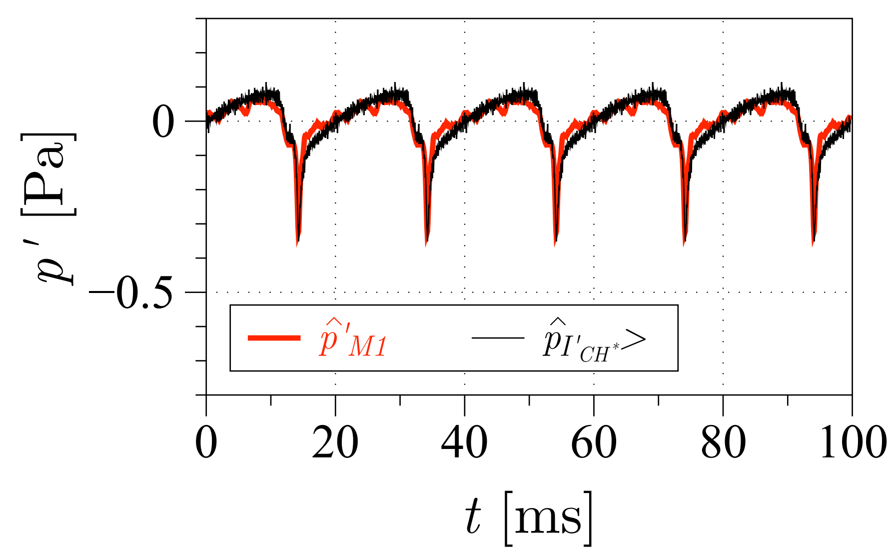
1. Is classical combustion noise theory suitable for a slot burner?

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



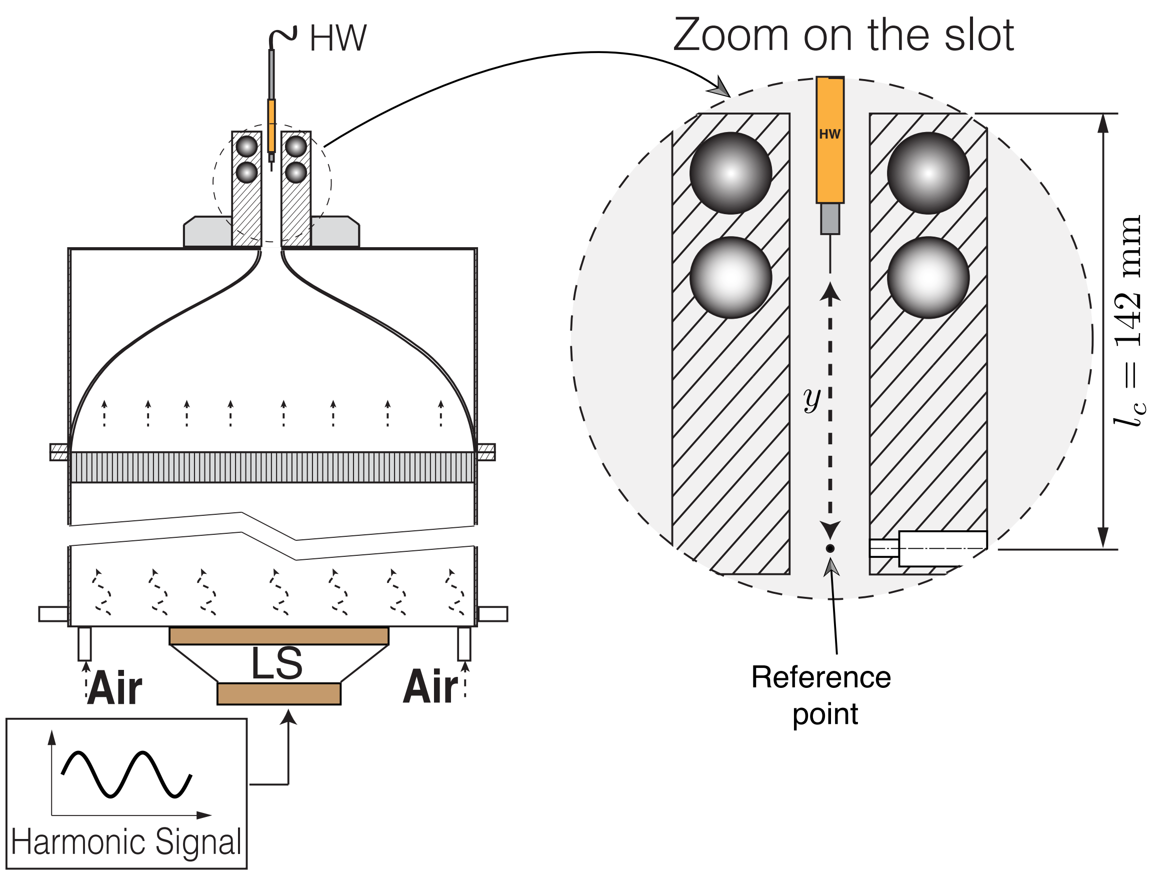
T50h $f_{ex} = 60$ Hz

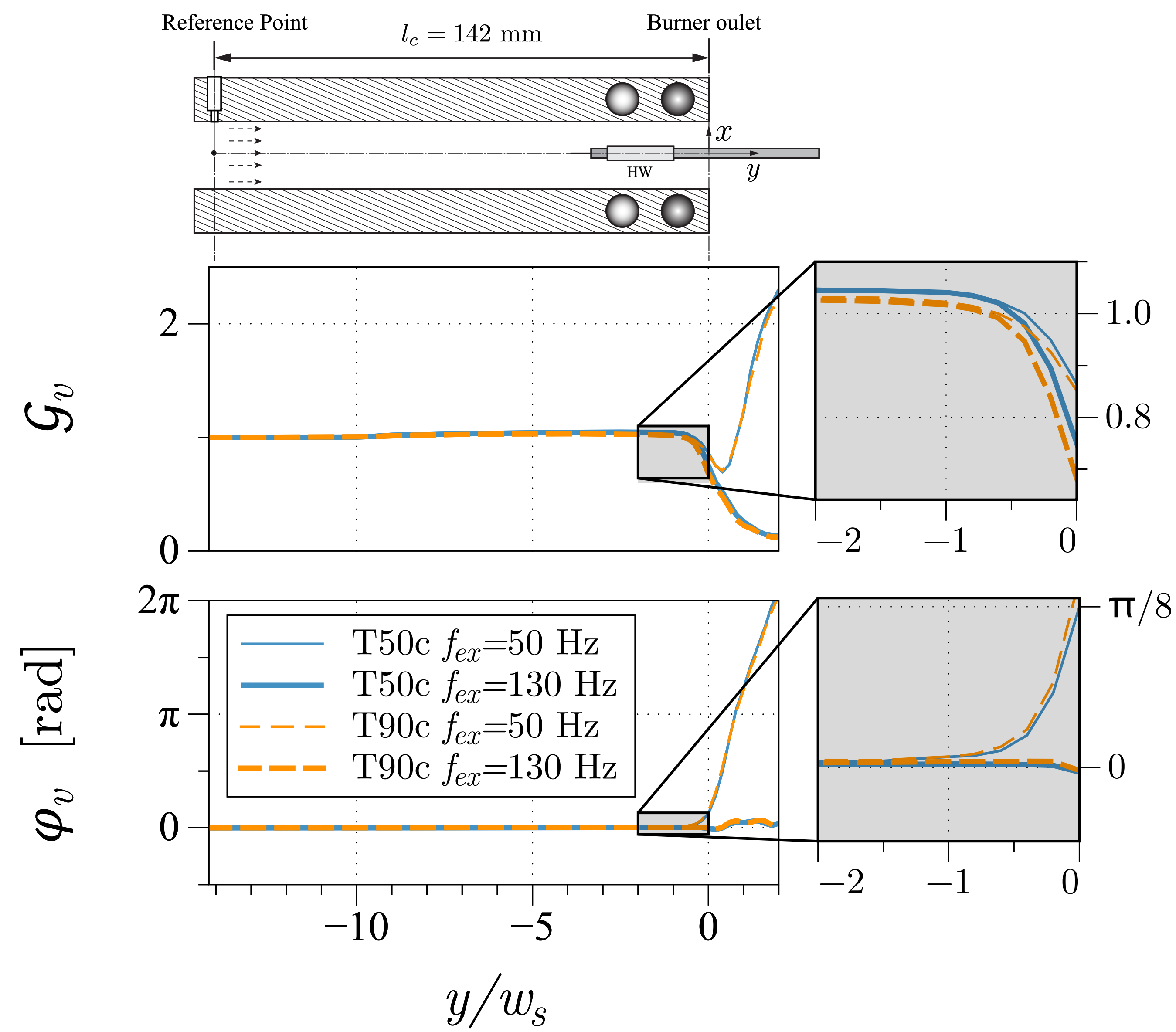




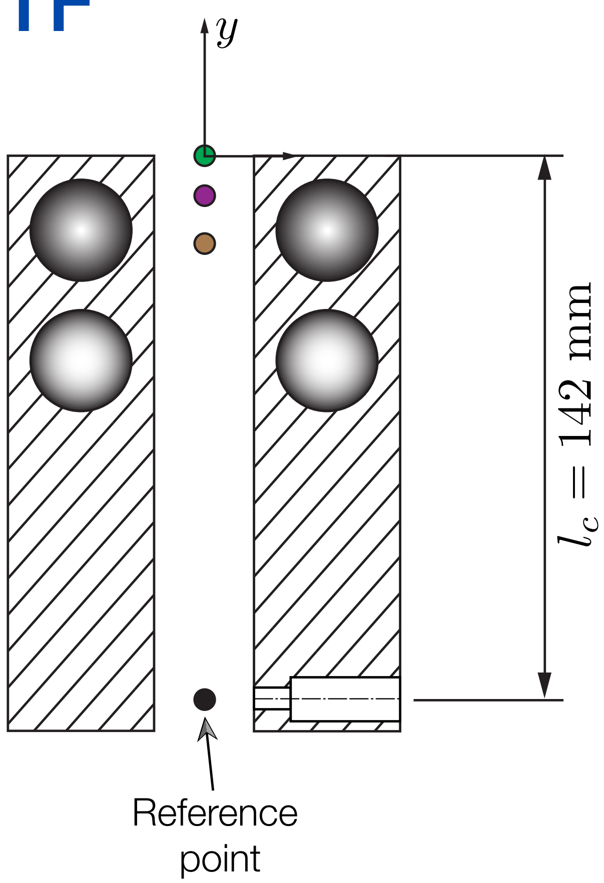
Velocity transfer function

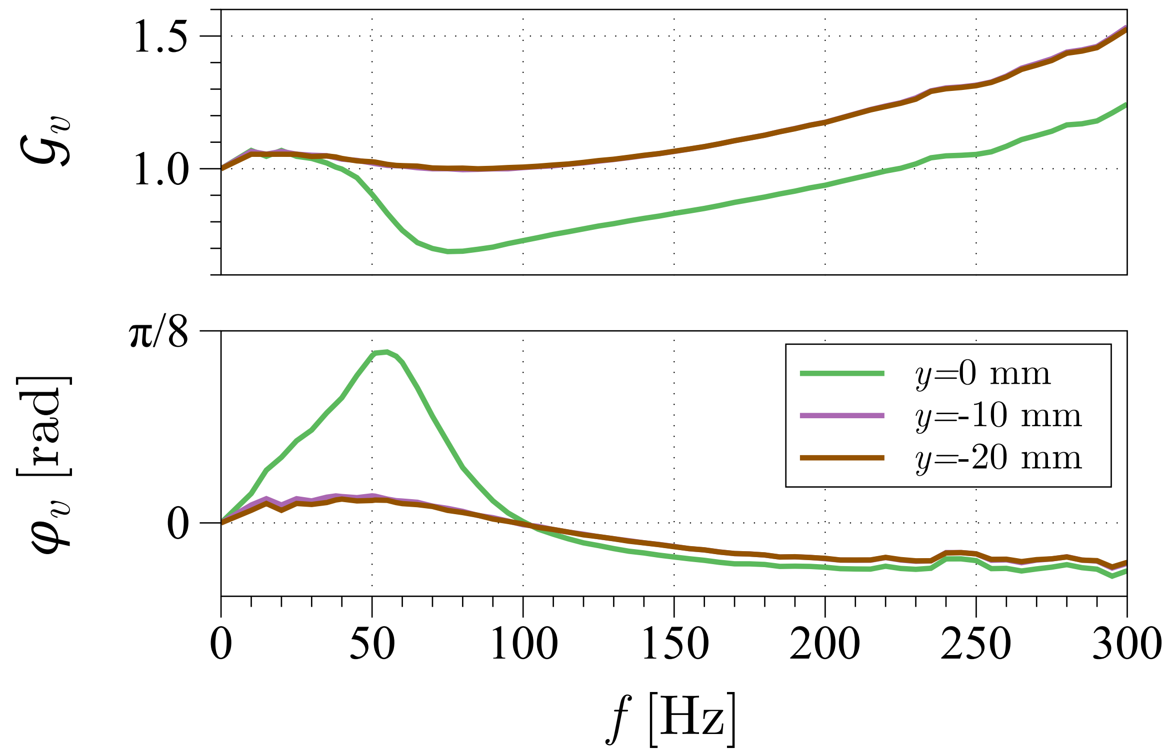
Does the FTF depends on the reference point ?

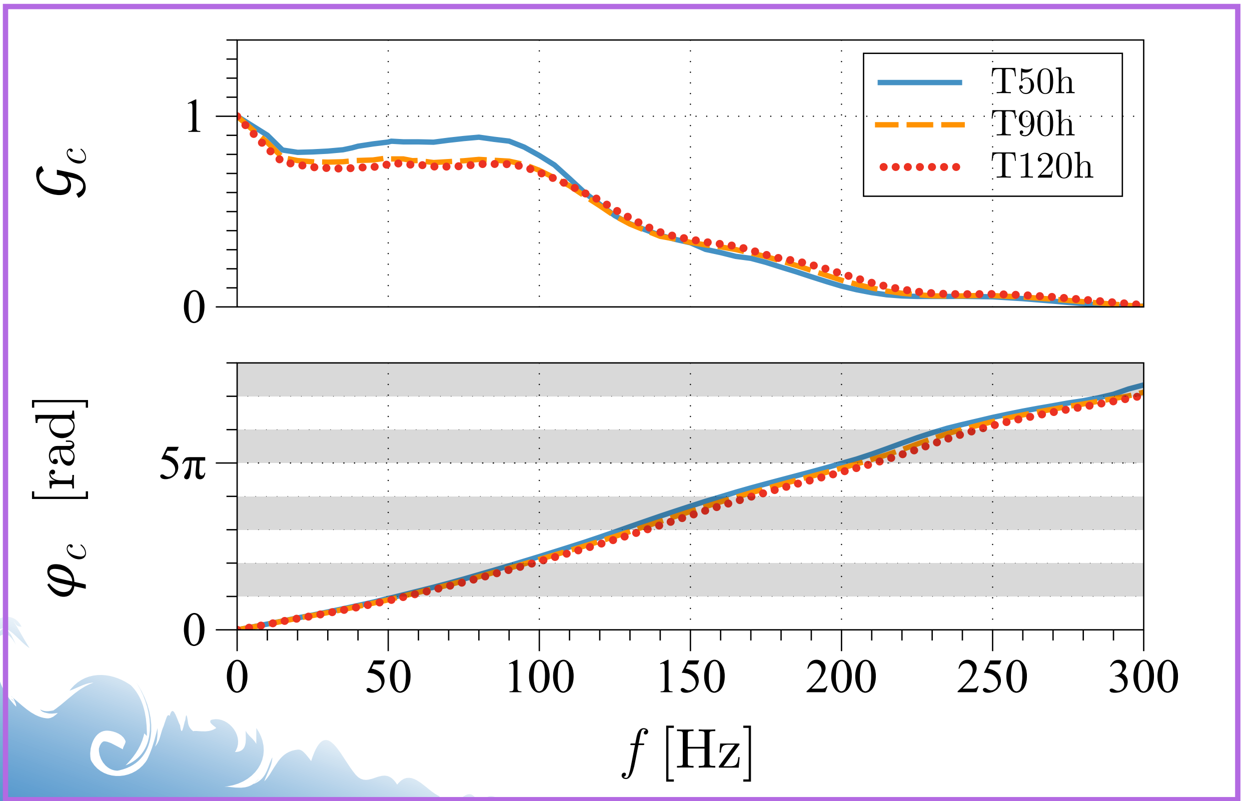


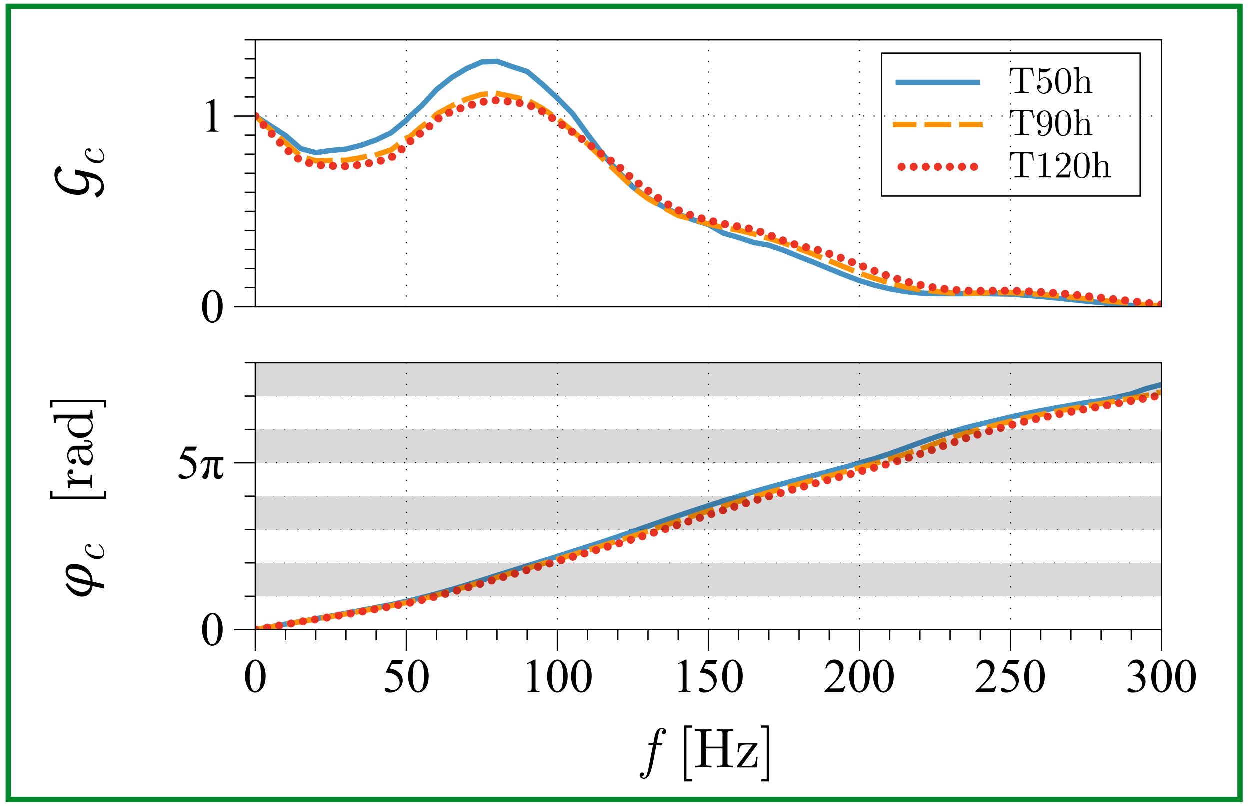


Corrected FTF



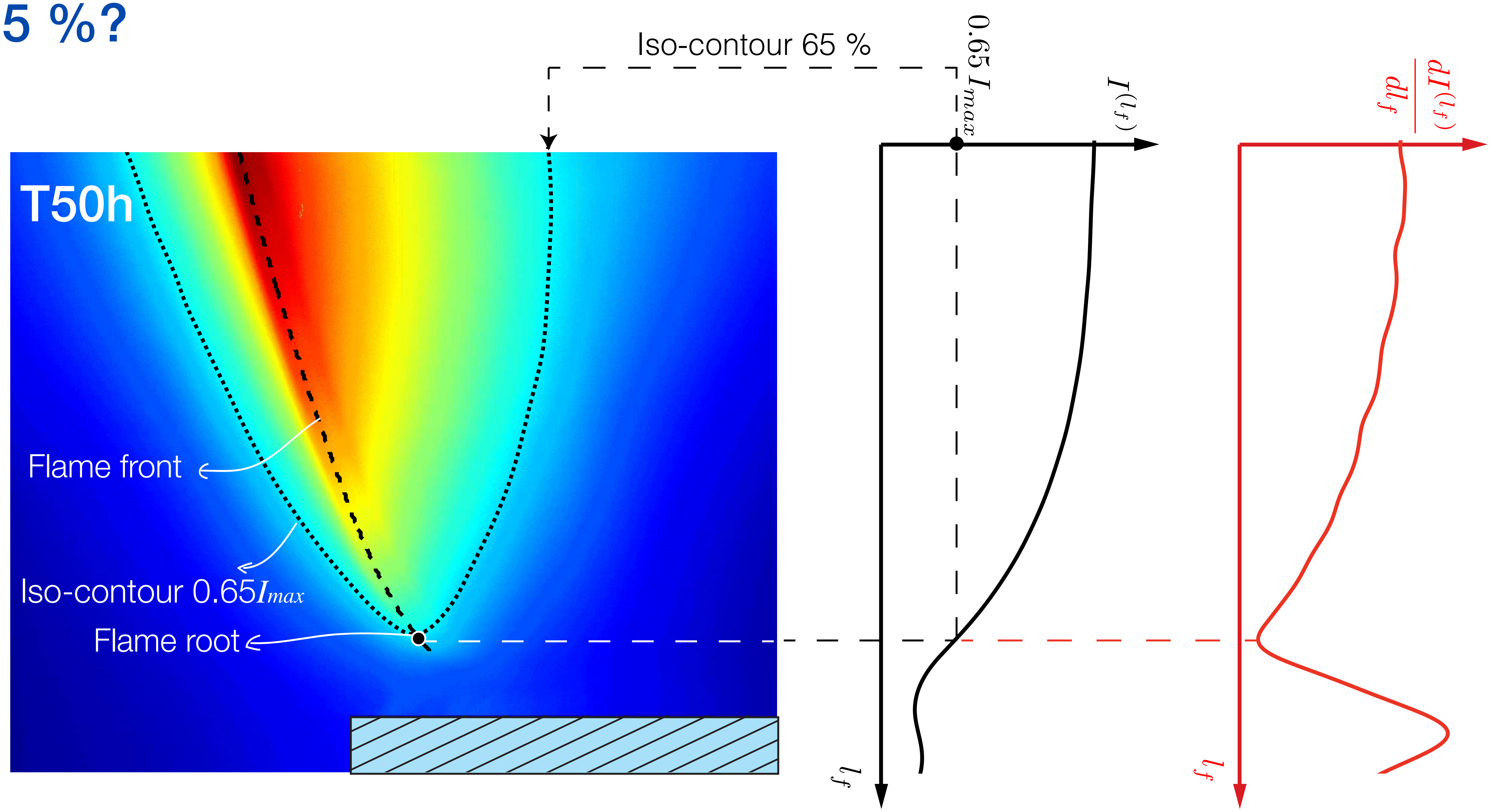




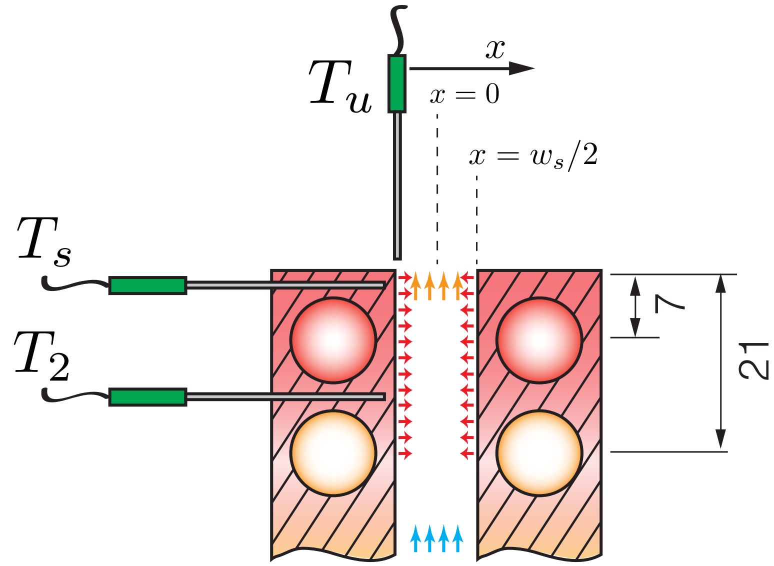


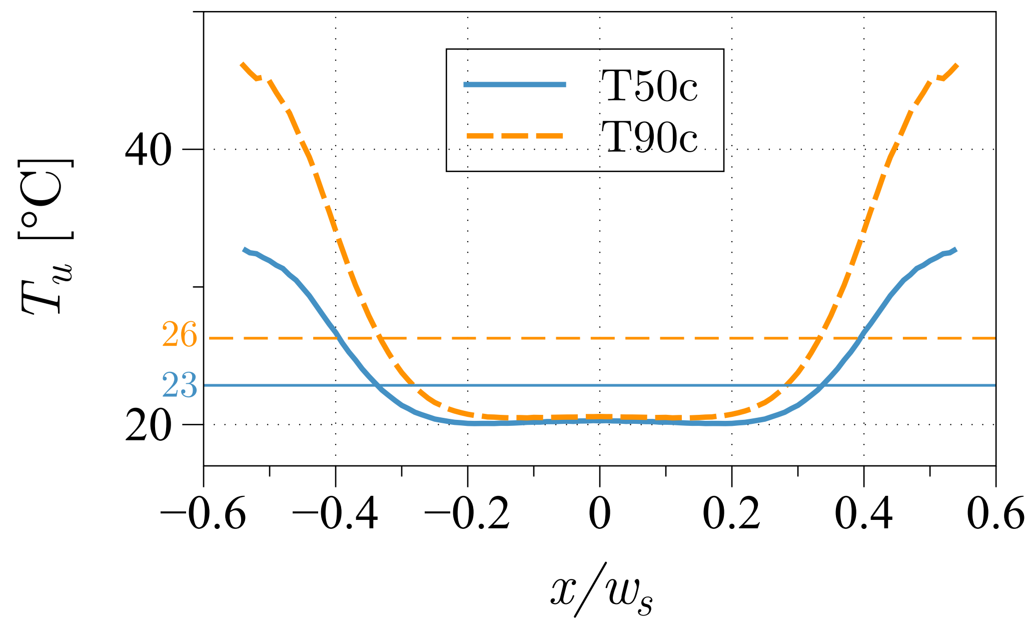
Flame Root Definition

Why 65 %?



3. Does wall temperature modify the reactants temperature profile ?

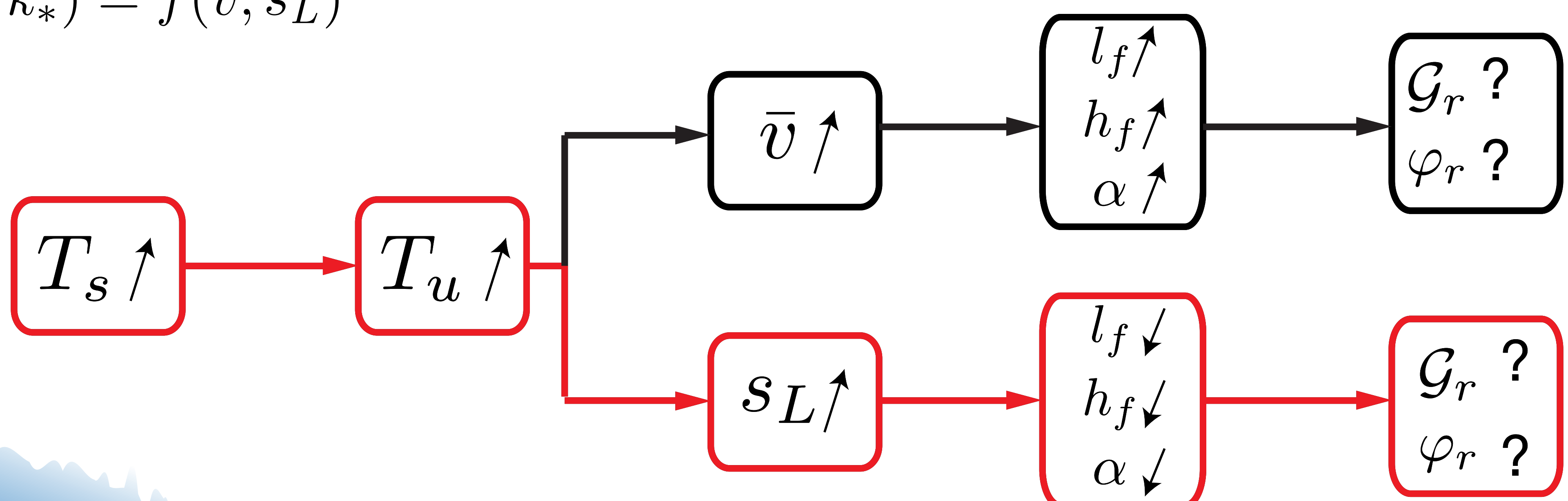




The pre-heating of the fresh gases cause:

- ★ 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 $\quad f = 58$ Hz $\quad \Phi = 0.9$ to 1.02