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CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

EM2C

IMFT
INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE

Acoustically induced vortex core flashback in a staged swirl-stabilized combustor

C. Lapeyre[1], M. Mazur[2], F. Richecoeur[2], P. Scouflaire[2], S. Ducruix[2], T. Poinsot[3]

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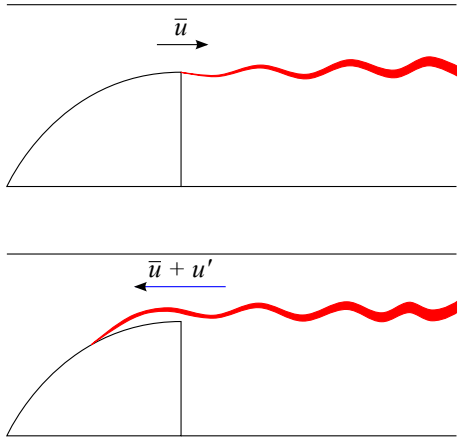
[1]CERFACS — [2]EM2C - Centrale Supélec — [3]IMFT

Context of the study

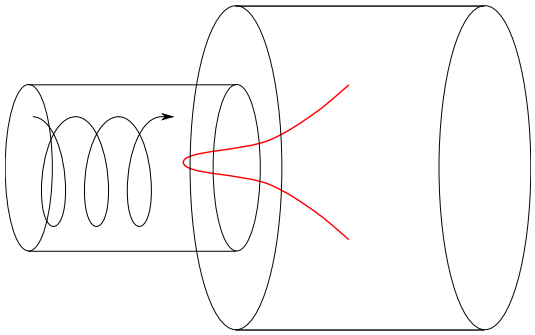
Aerodynamically stabilized premixed flames are flashback prone via several mechanisms:

- Wall boundary layer FB (Lewis & von Elbe 1943)
- Acoustic forcing FB (Keller *et al.* 1982)
- Combustion induced vortex breakdown (Kröner *et al.* 2002)
- Vortex core FB (Ishizuka 2002, Domingo & Vervisch 2007)
- Autoignition in the injection duct

The present study aims to show that a setup can be resistant to all these mechanisms separately, but flashback when two or more combine



Flashback experiment of Keller *et al.* (1982)

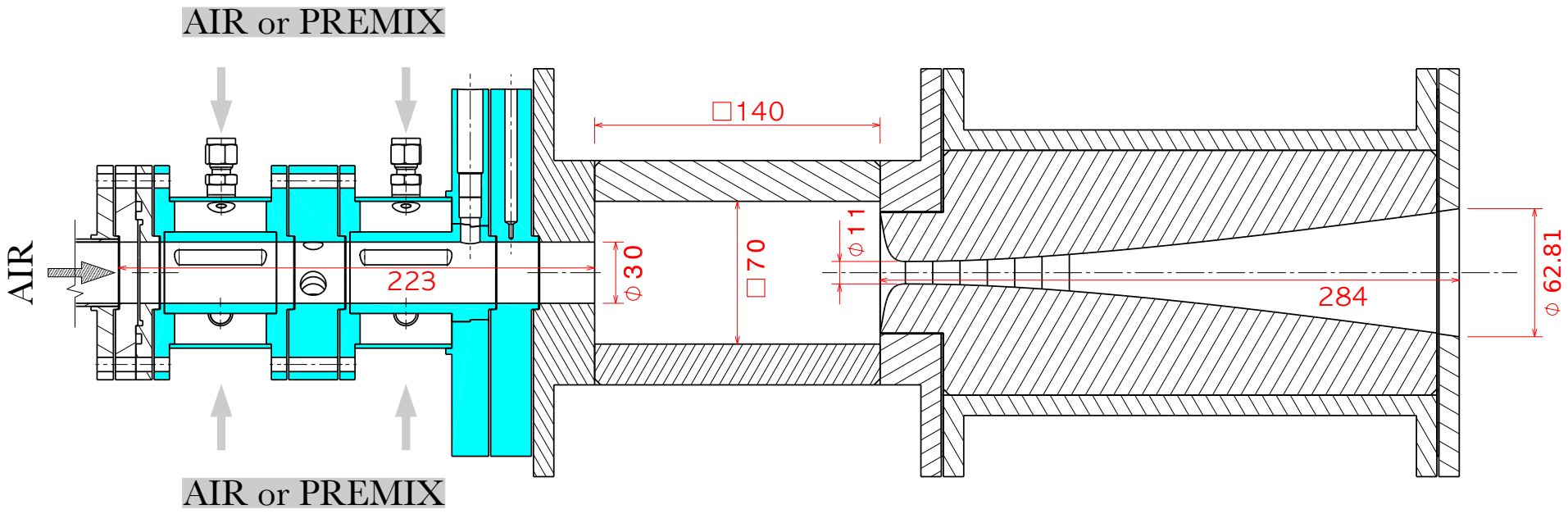


CIVB mechanism of Kröner *et al.* (2002)

The CESAM-HP Bench at EM2C

Pressurized bench (up to 2.5 bar) with lean premixed combustion:

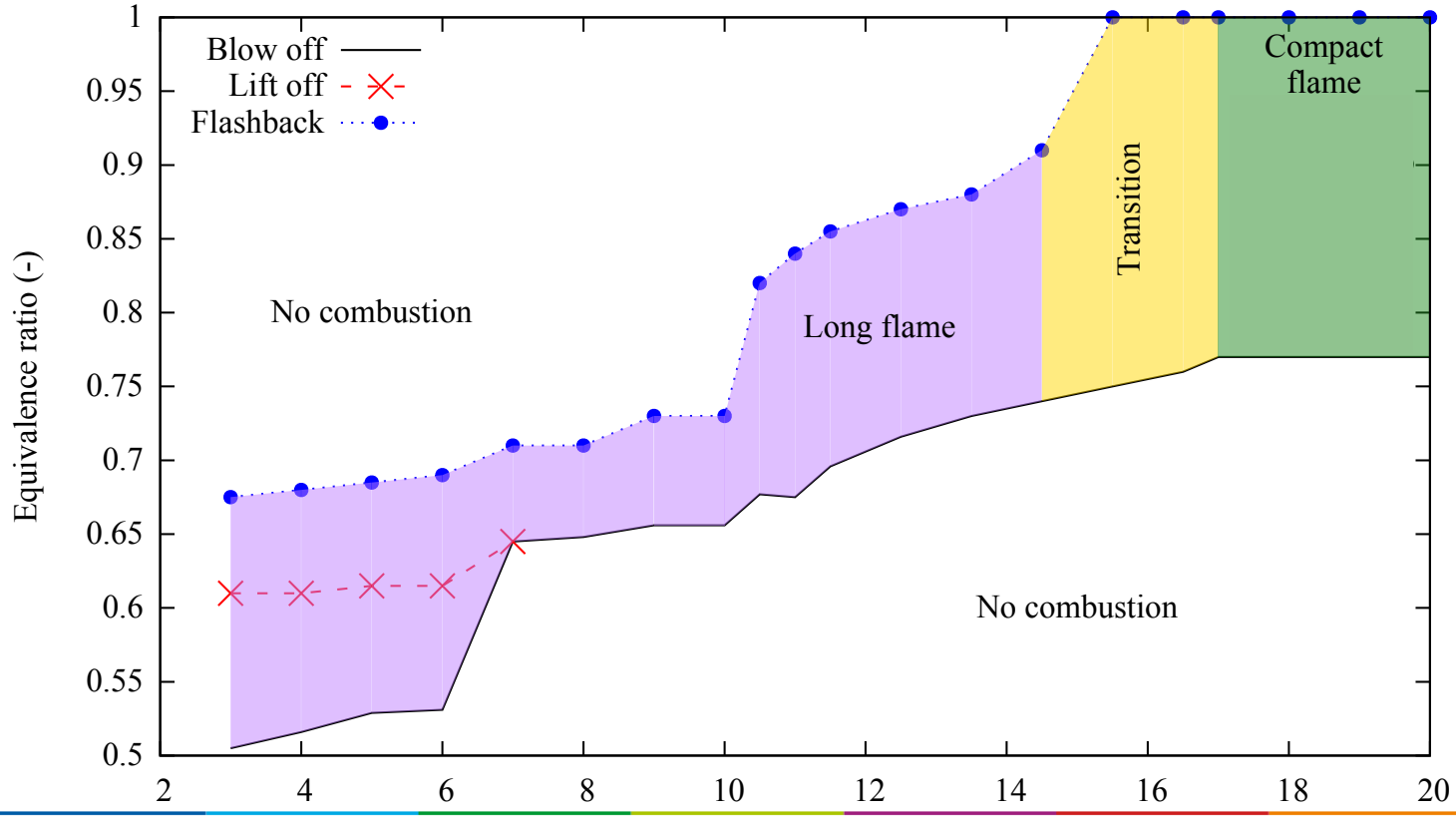
- Study of aerodynamic flame stabilization in a confined chamber
- Choked nozzle offers realistic outlet conditions
- Air and fuel mass flow rate can be split, offering a wide investigation range



Operation range

An experimental investigation has identified :

- Long fluttering flame regimes for low mass flow rates
- Compact flame regimes for air mass flow rate above 17 g/s



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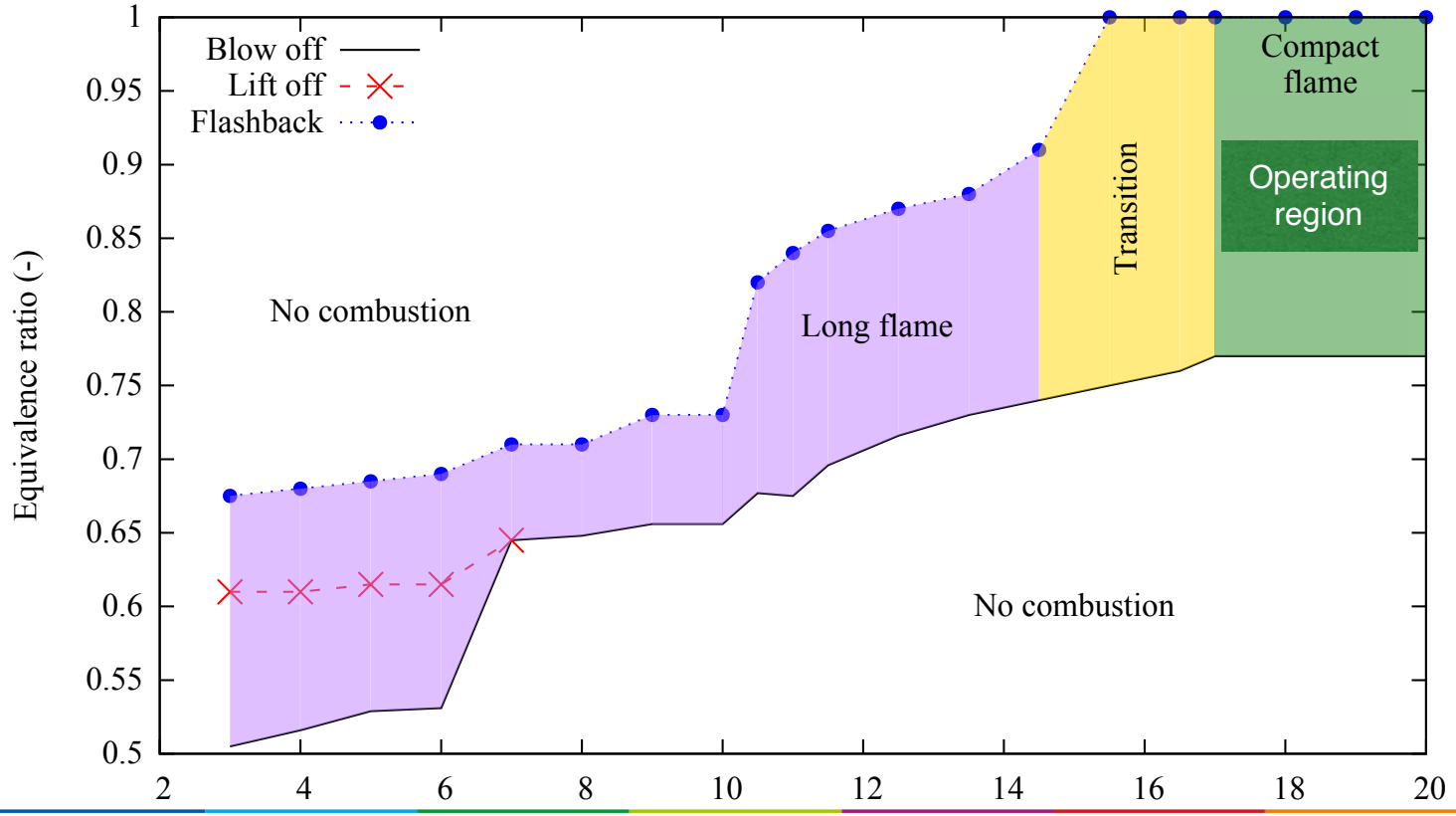
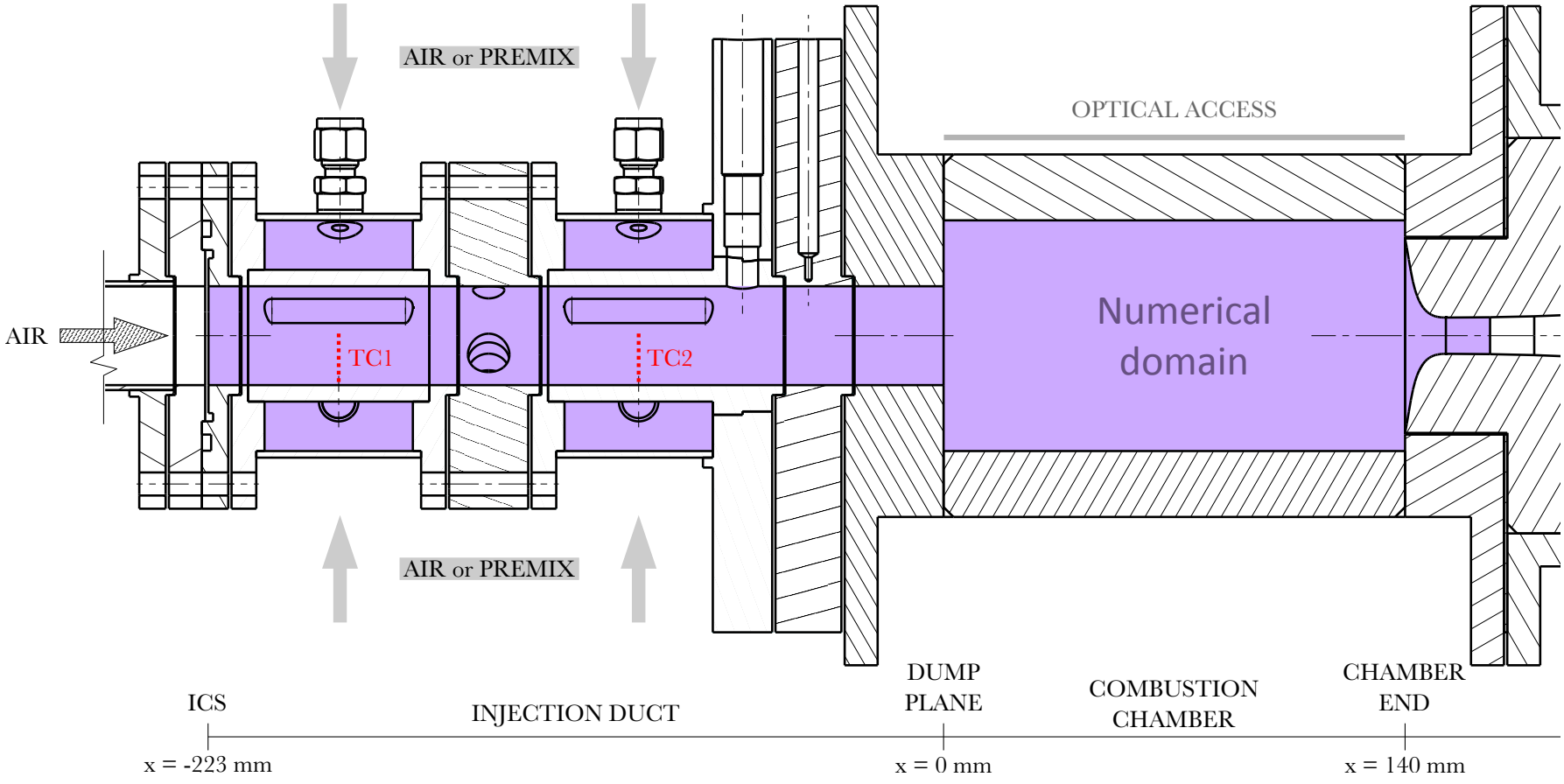
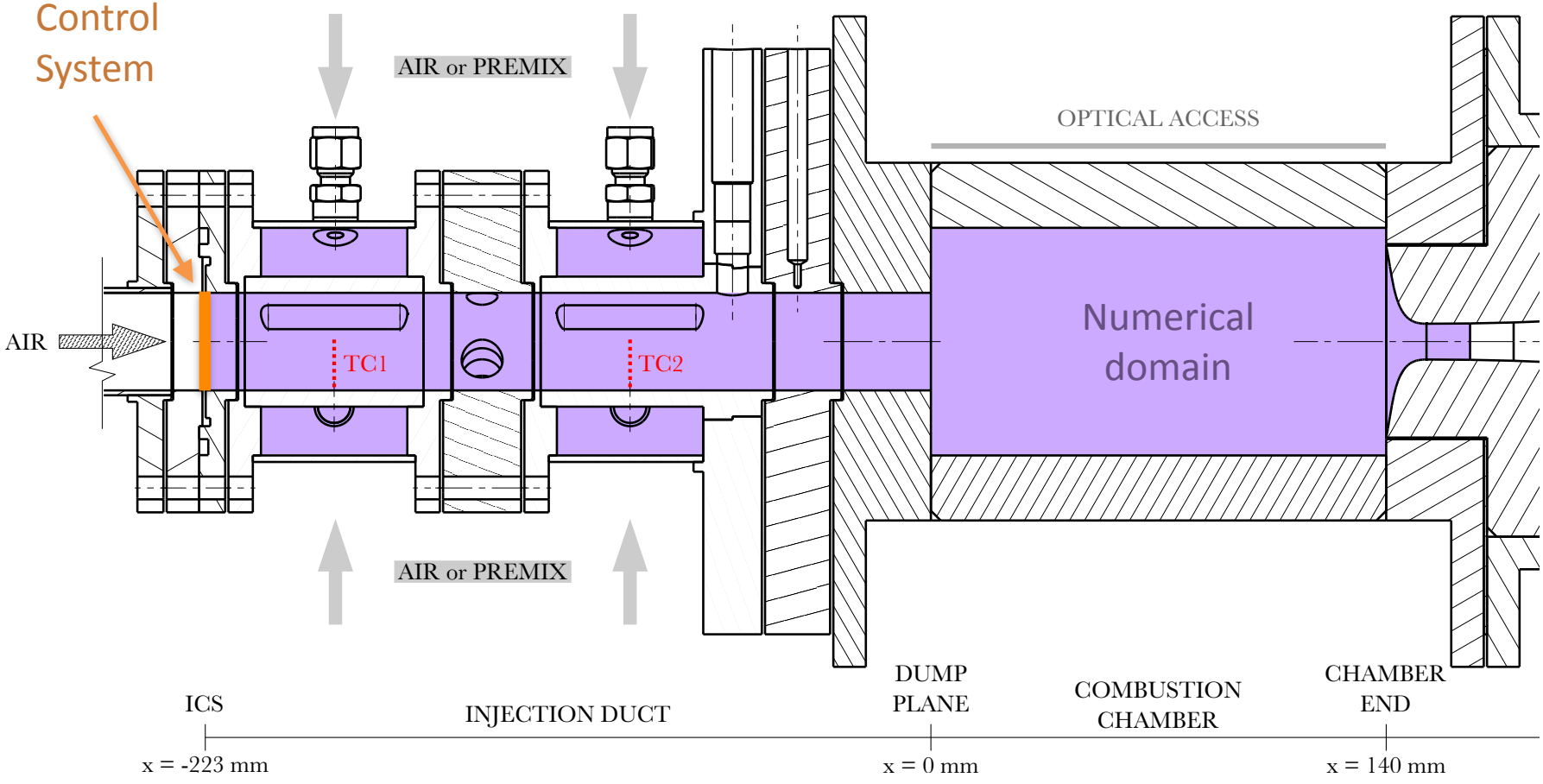


Numerical domain



Numerical domain

Tran *et al.* (2009)
Impedance
Control
System



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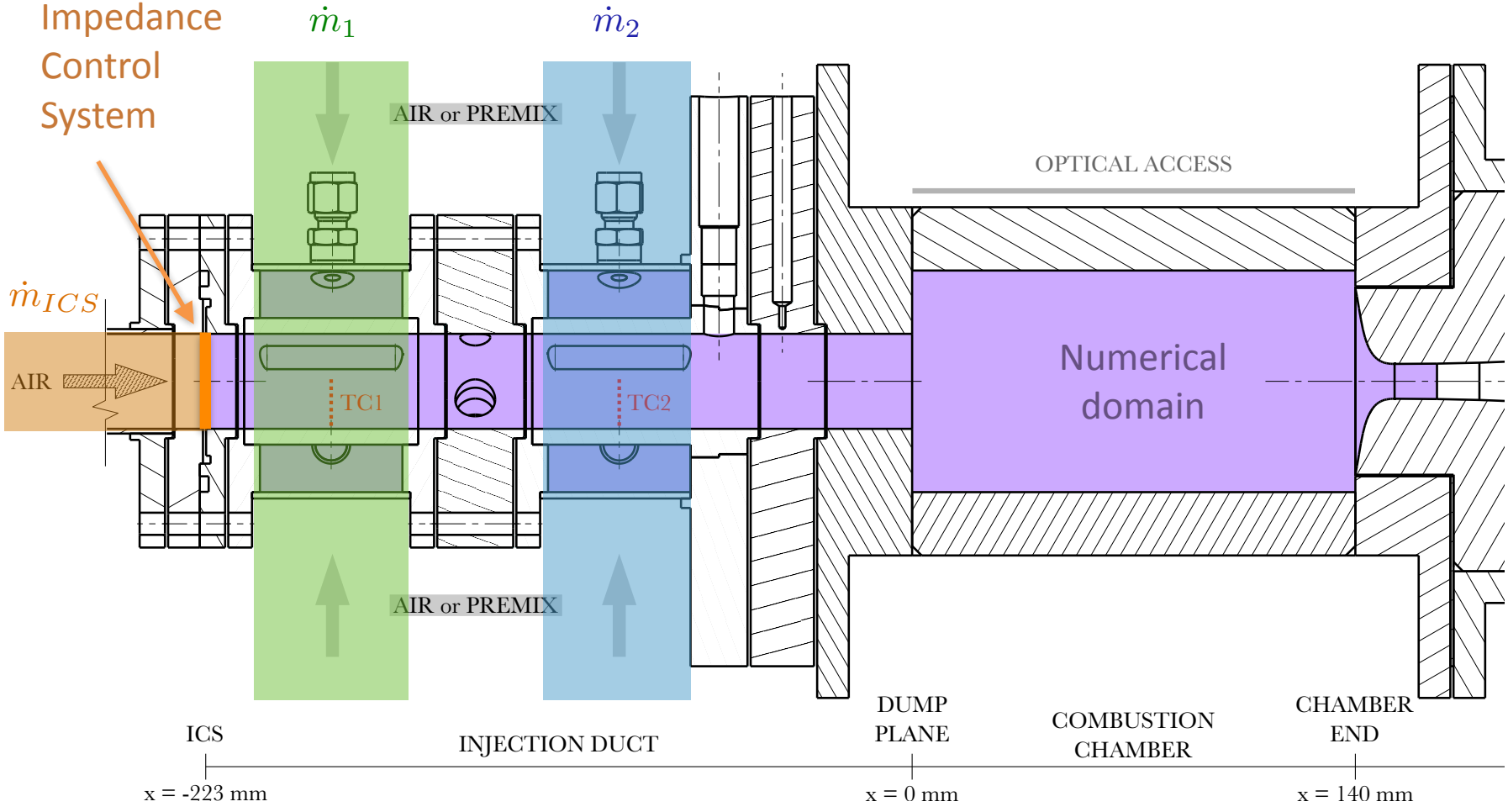

Operating points

Bench can be operated in fully premixed or fuel staging configurations.

Matching numerical setups are available for LES with the AVBP code

(http://cerfacs.fr/4-26334-The-AVBP-code.php)

	PREMIXED		**STAGED**	
	$\phi_{prem} = 0.9$		$\phi_{stag} = 0.85$	
	$\dot{m}^{air}$	ϕ	$\dot{m}^{air}$	ϕ
Experiment				
ICS	1.0	0.0	1.0	0.0
Injector 1	8.5	0.95	7.0	0.0
Injector 2	8.5	0.95	10.0	1.53
LES				
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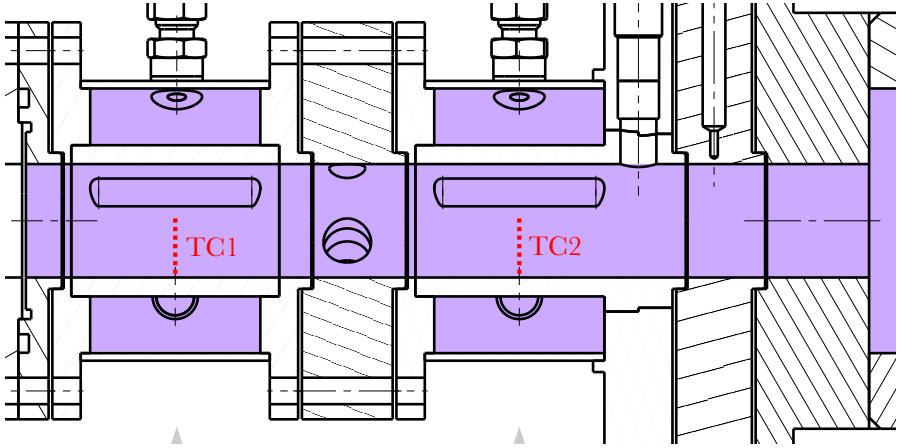

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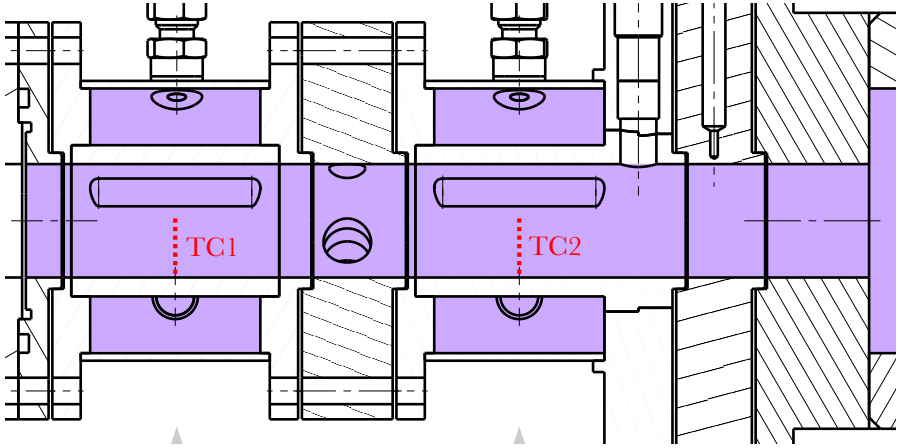
	PREMIXED		STAGED	
r [mm]	TC1	TC2	TC1	TC2
0	1021	1203	28	621
5	1171	1362	29	607
10	1012	1152	28	598
15	852	841	24	575

Mean temperature measurements in the injection duct (°C)



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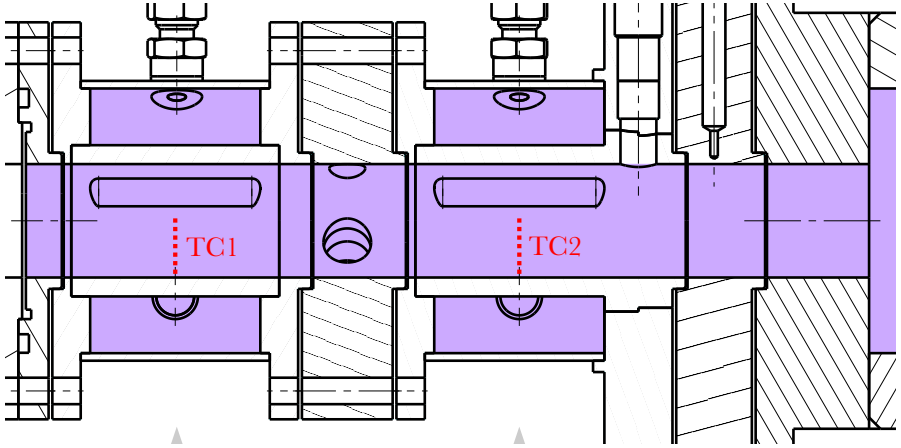

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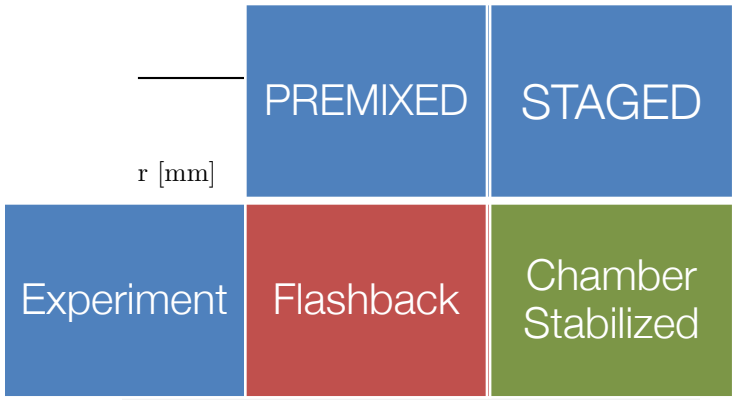

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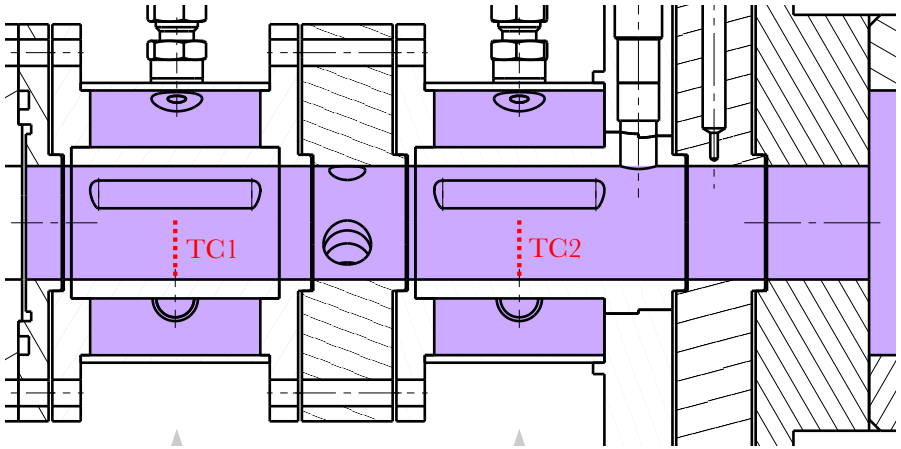
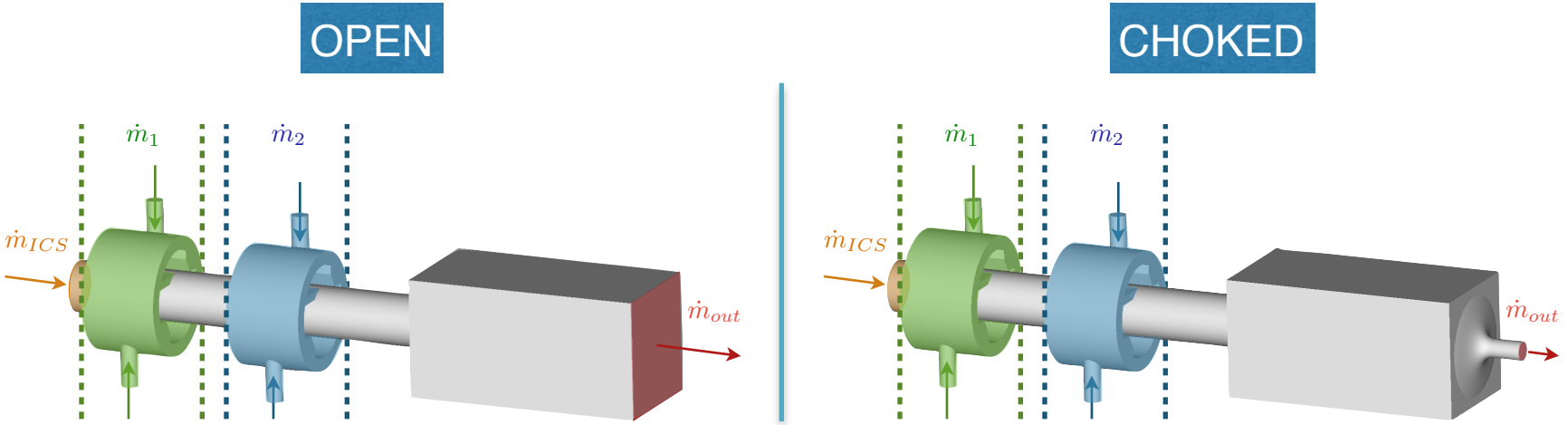


Numerical domains

Numerical simulations offer the possibility to explore the effect of outlet condition. « OPEN » (non reflecting or forced) condition or realistic choked nozzle (highly reflecting) can be used.



	OPEN Setup		**CHOKED** Setup	
Case name	OPEN-NR	OPEN-FO	CHOKED-PR	CHOKED-ST
Domain	OPEN	OPEN	CHOKED	CHOKED
Outlet	**Non-reflecting**	**Acoustic forcing**	Choked nozzle	Choked nozzle
Operating Point	PREMIXED	PREMIXED	**PREMIXED**	**STAGED**
Exp. data	NO	NO	YES	YES

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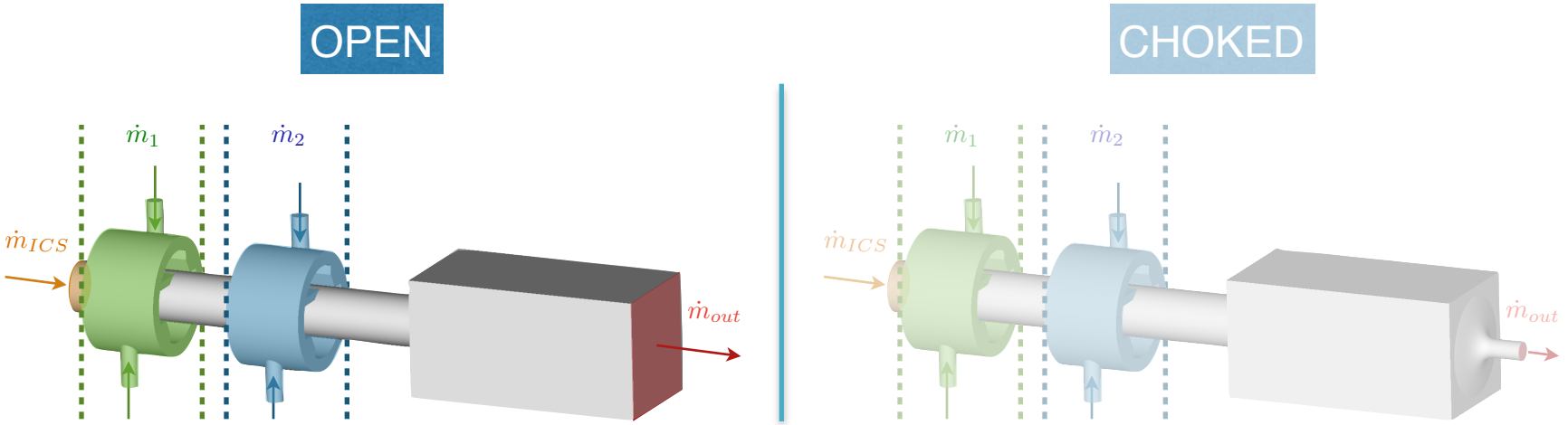

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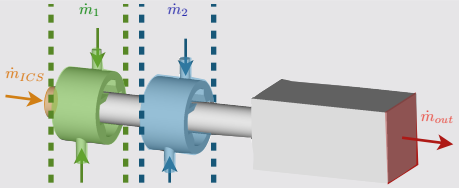
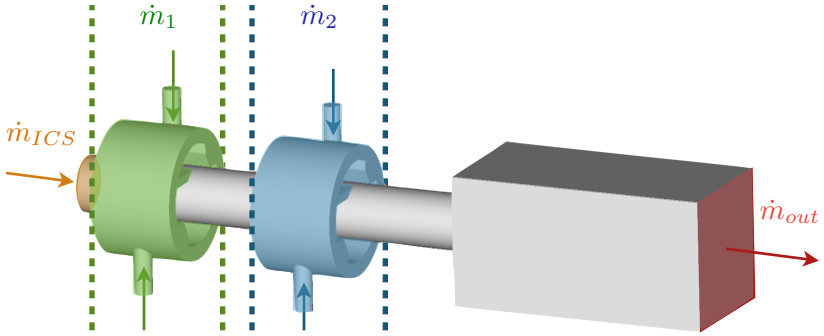
OPEN setup numerical investigations

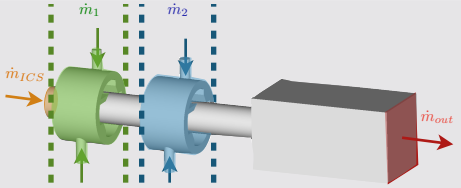


Acoustic forcing of the OPEN setup shows flame robustness to acoustic flashback.



Non reflecting
No flashback
Flame stabilized in the chamber

OPEN setup numerical investigations



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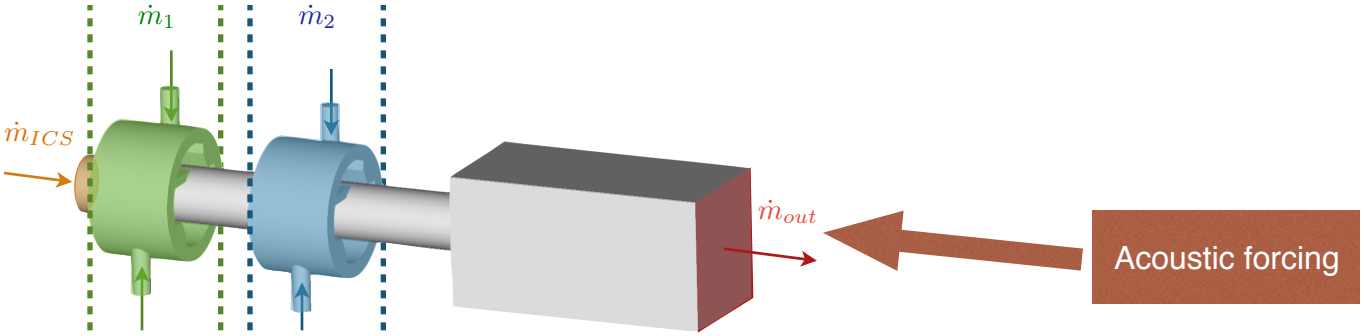

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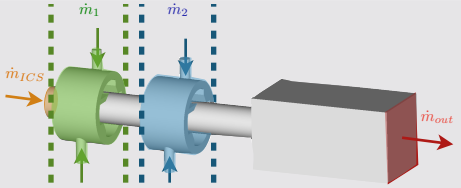

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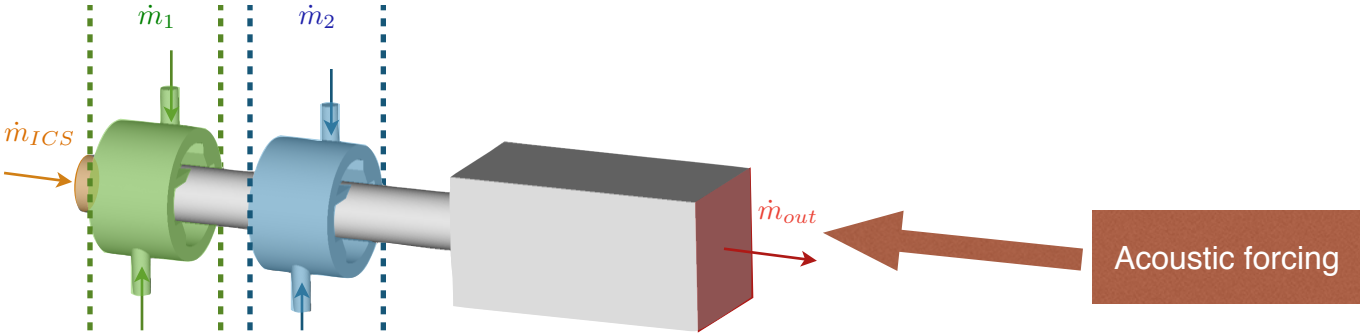
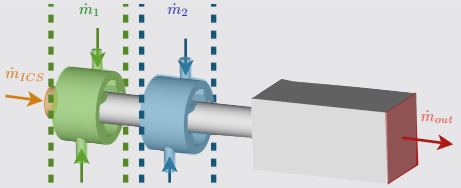


Non reflecting	10 kPa forcing
No flashback	Intermittent flashback
Flame stabilized in the chamber	Flame does not exceed swirler n°2

OPEN setup numerical investigations



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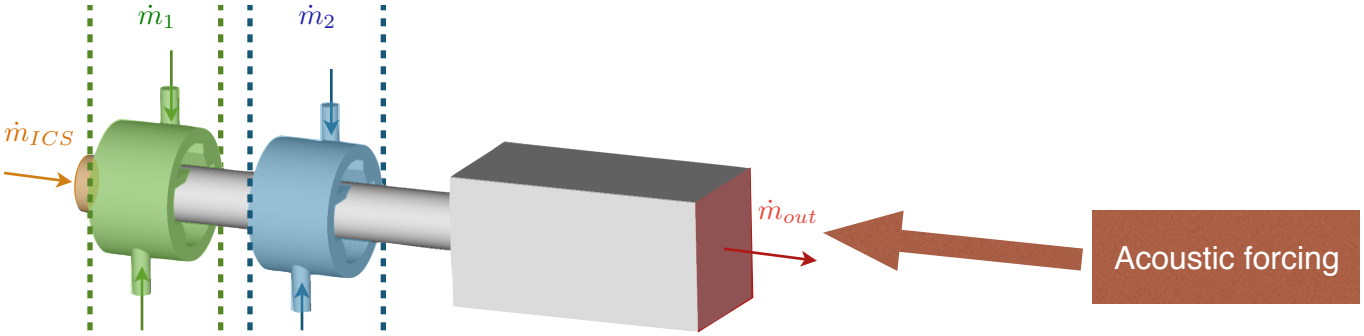
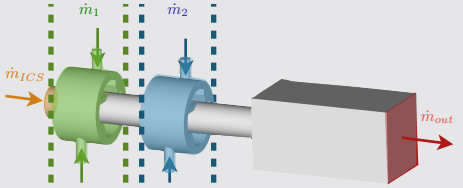
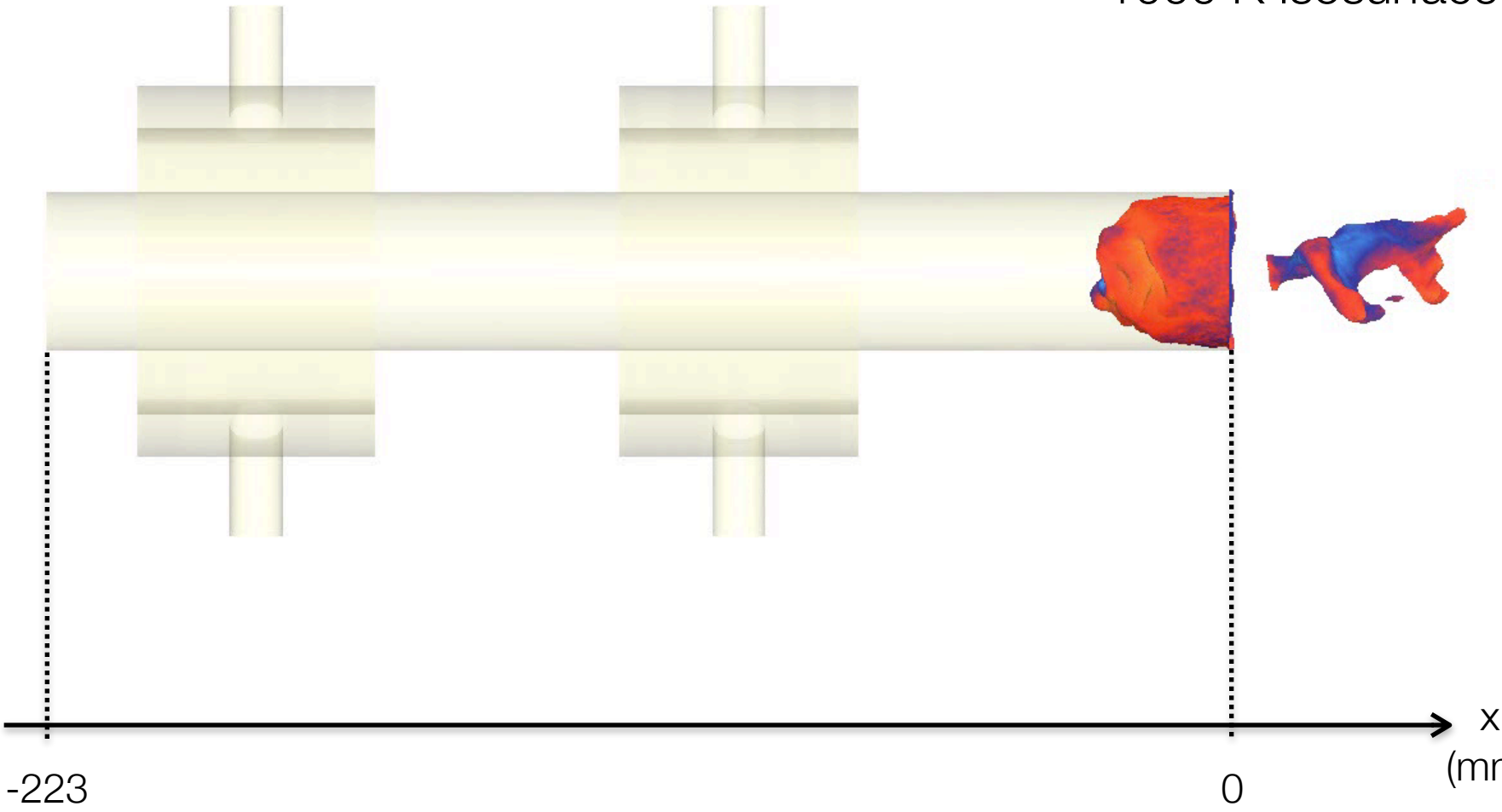


Non reflecting	10 kPa forcing	20 kPa Forcing
No flashback	Intermittent flashback	Full flashback
Flame stabilized in the chamber	Flame does not exceed swirler n°2	Flame is gradually forced back to the beginning of the injection tube

Flame tracking



1000 K Isosurface



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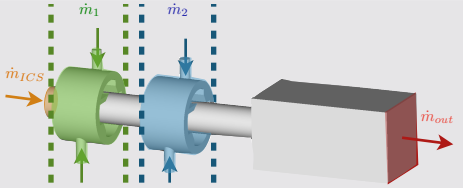

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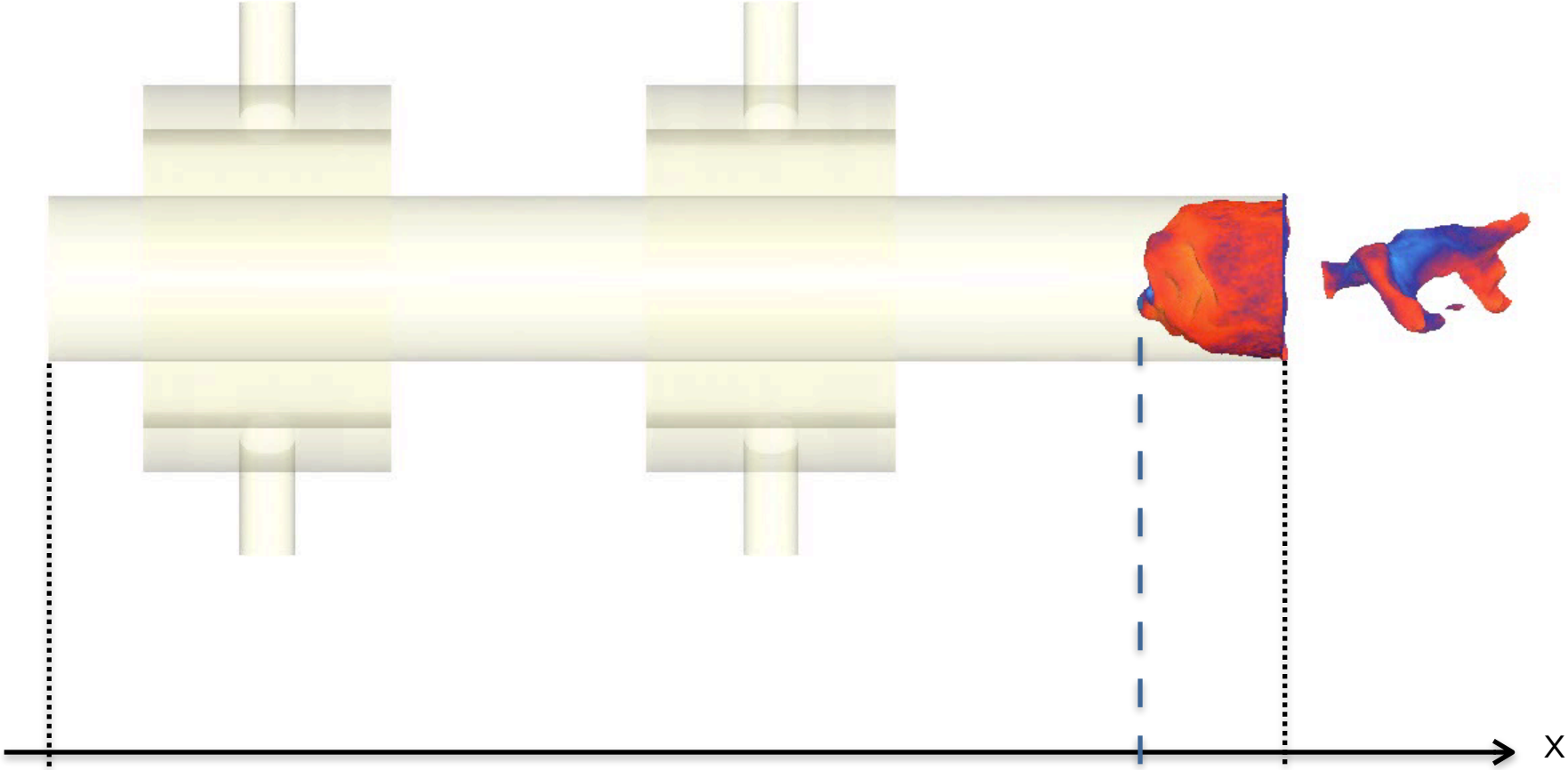

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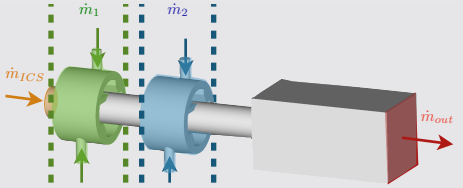

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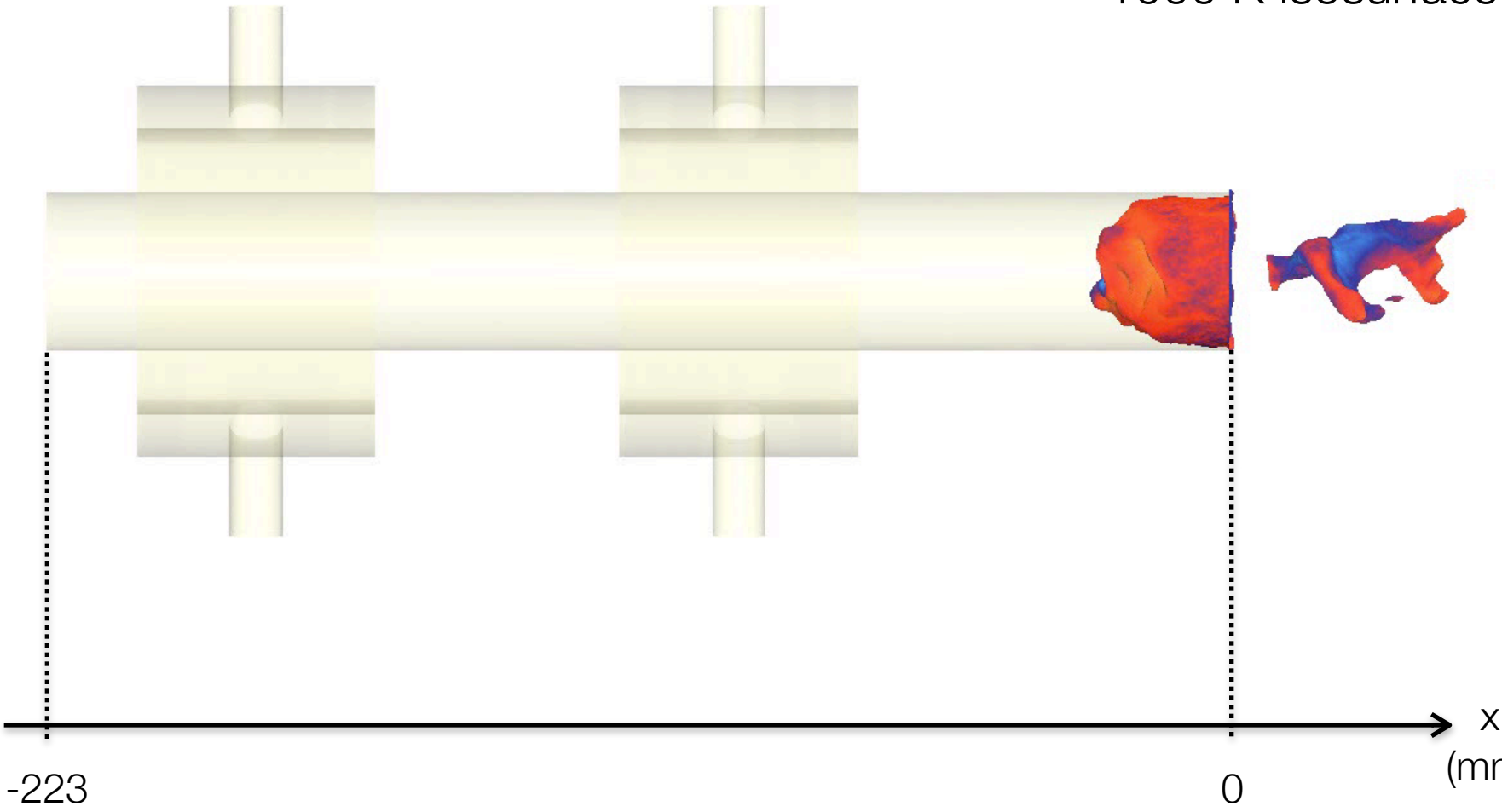

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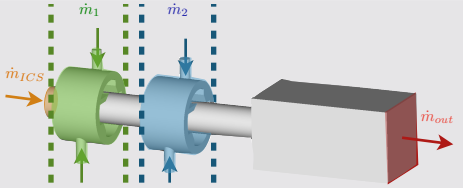

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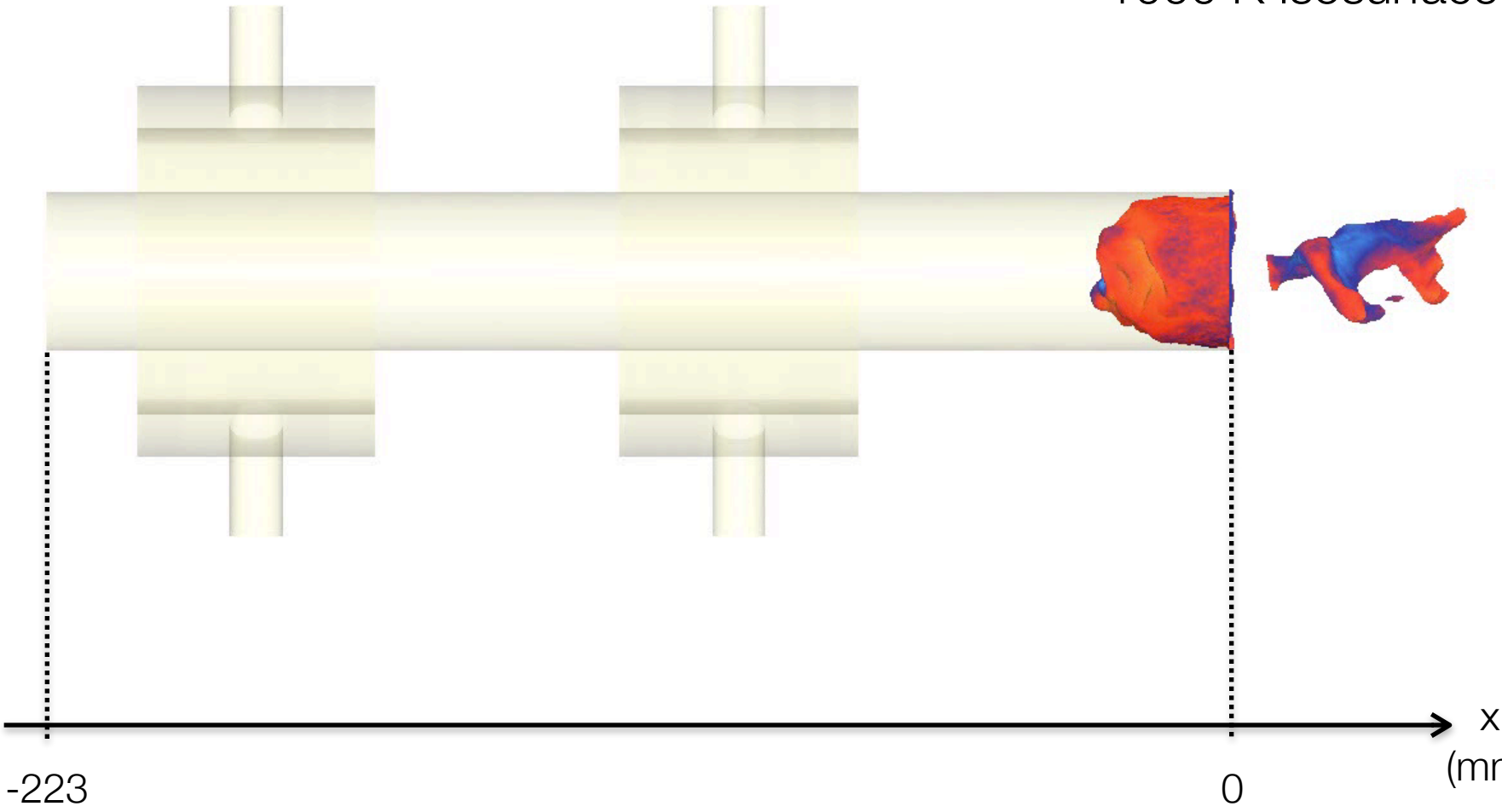
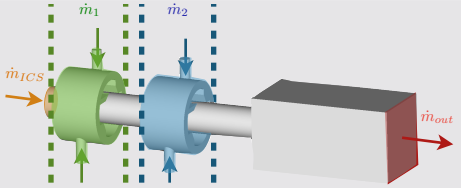


OPEN setup numerical investigations



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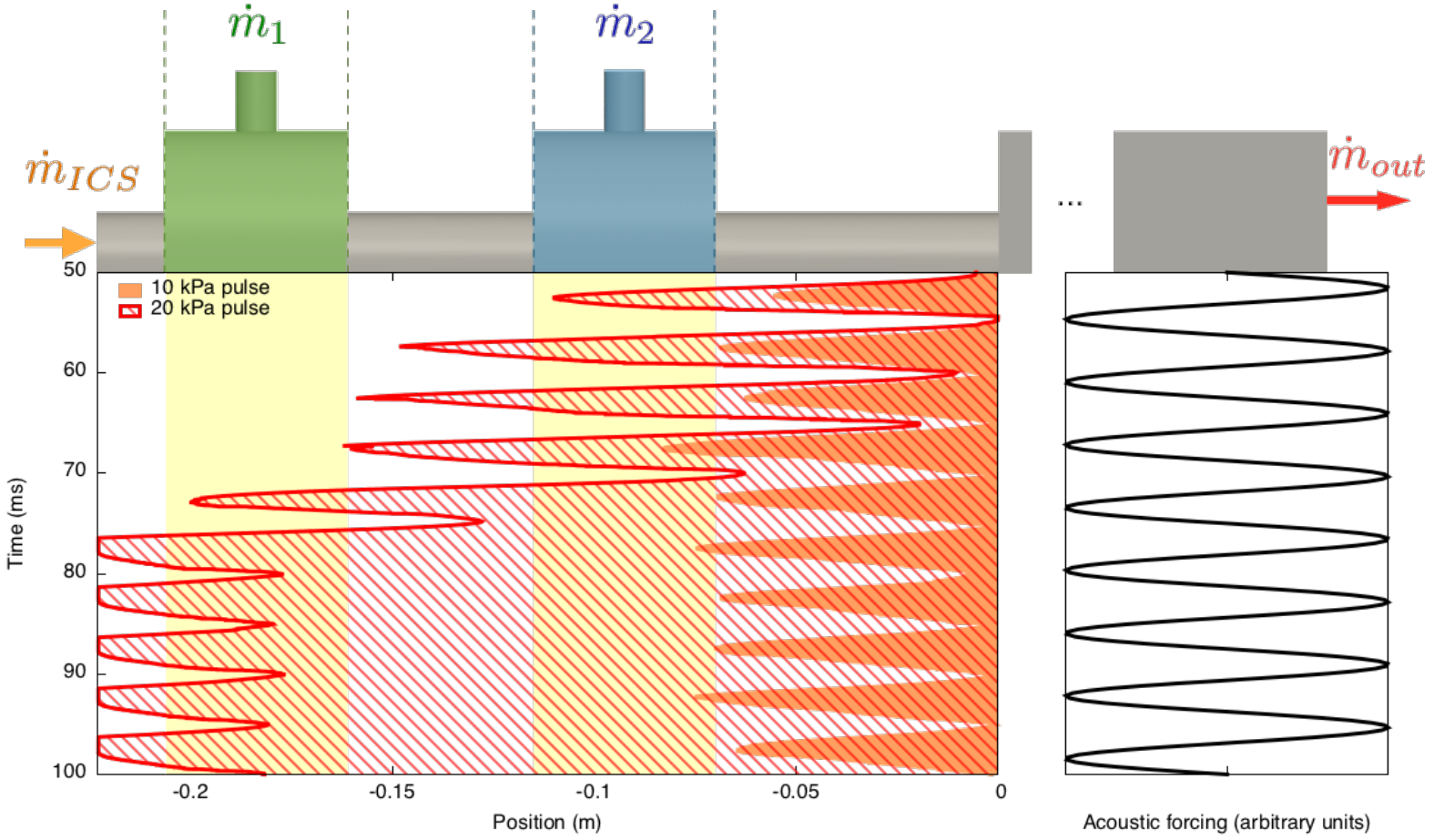
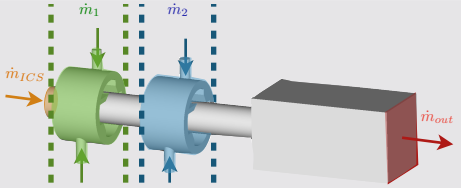


Flame position versus time for 2 forcing strengths

OPEN setup numerical investigations



OPEN numerical setup shows:

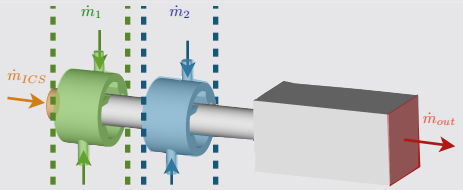
- The « quiet » setup is flashback-resistant
- Classical acoustic flow reversal produces intermittent flashback…
- … or full flashback for high amplitude forcing

0 kPa :
Chamber stabilized

10 kPa :
Intermittent flashback

20 kPa :
Full flashback

OPEN setup numerical investigations



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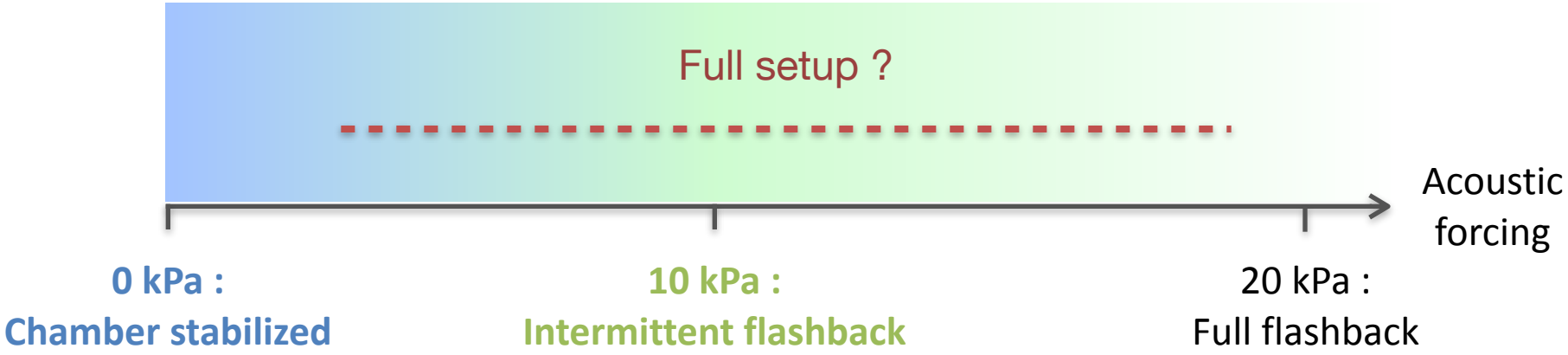
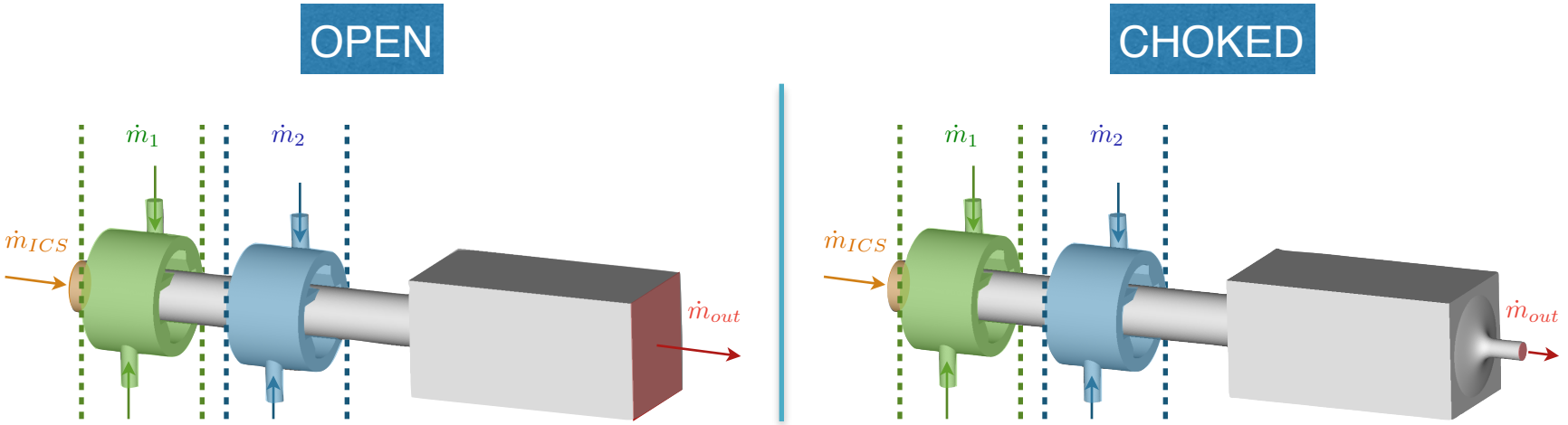


CHOKED setup numerical investigations

CHOKED domain represents the exact behavior of the outlet



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Operating Point	PREMIXED	PREMIXED	**PREMIXED**	**STAGED**
Exp. data	NO	NO	YES	YES

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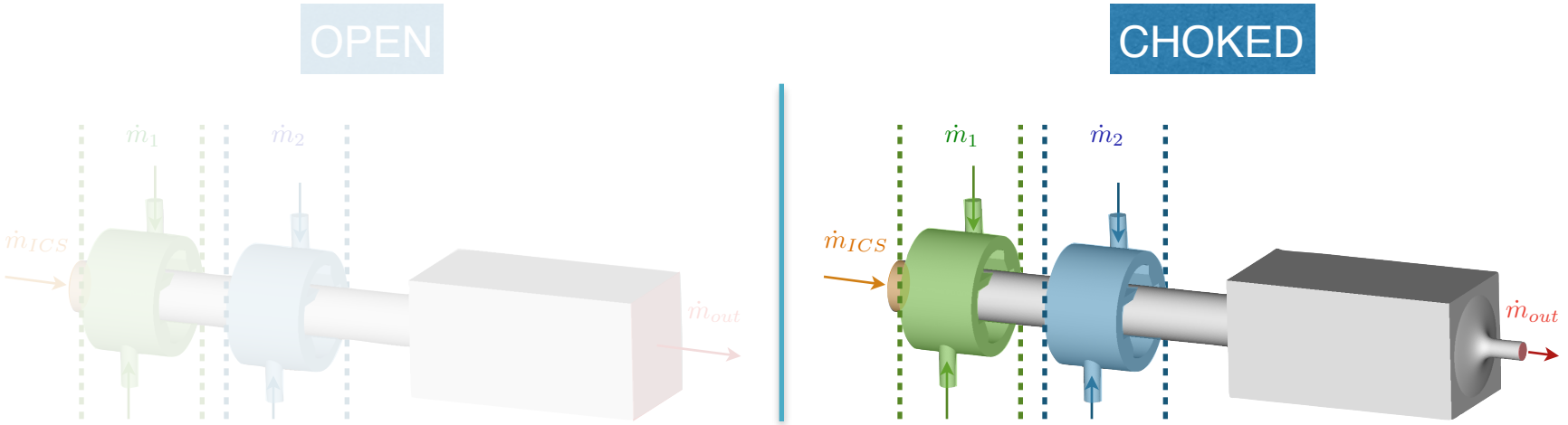

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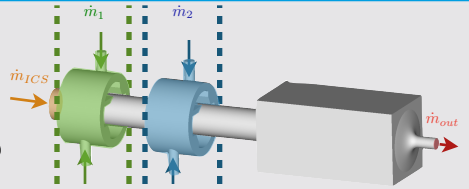
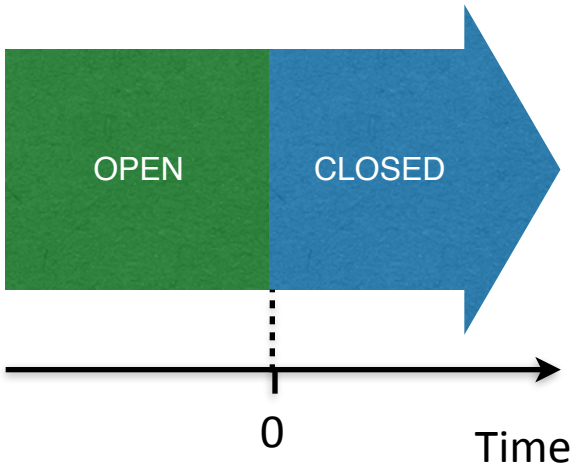
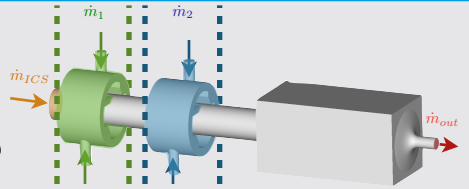


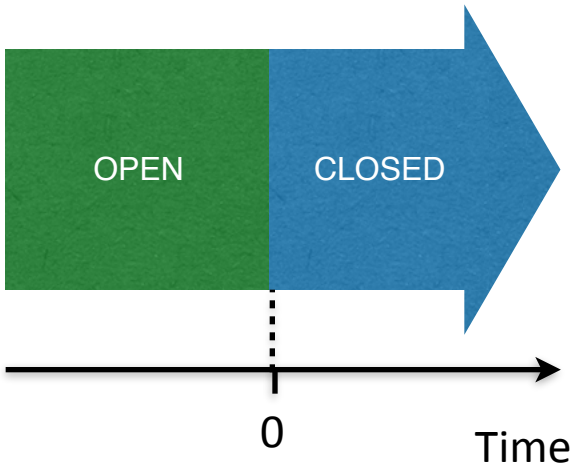
Quiet initialization strategy :

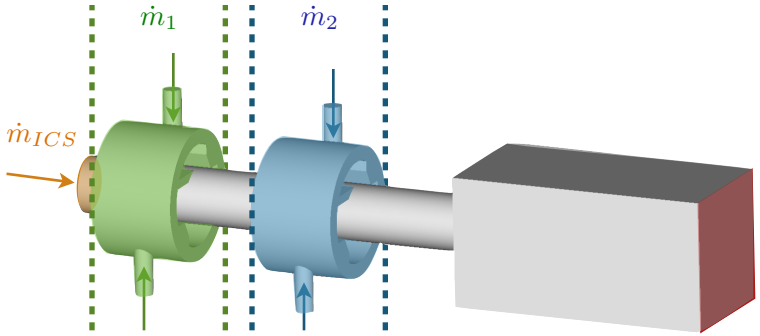


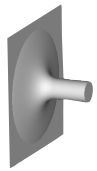
CHOKED setup numerical investigations



Quiet initialization strategy :



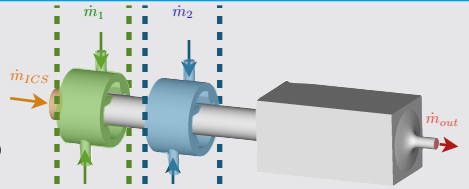


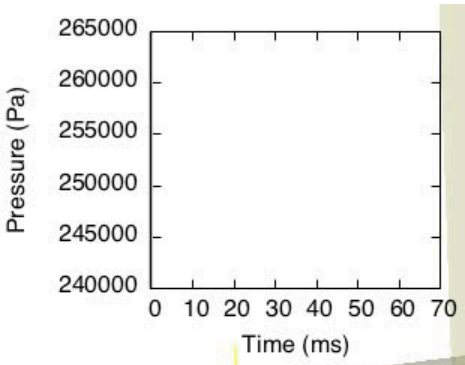


OPEN - No forcing solution + Matching Nozzle solution

The initial solution is « quiet » : very low acoustic levels in the chamber because OPEN solution is used

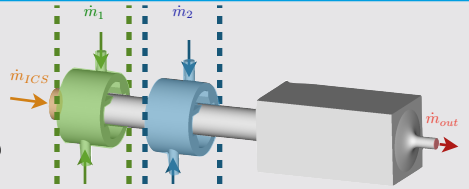
CHOKED setup numerical investigations

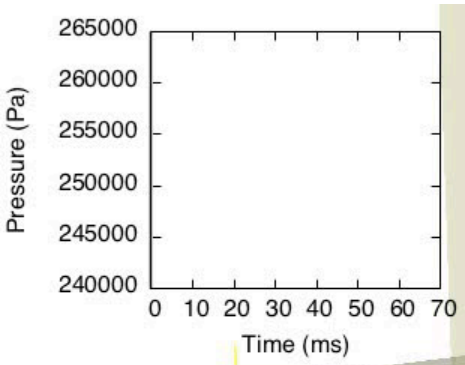




u [m/s]
30
20
10
0
-5

CHOKED setup numerical investigations





u [m/s]
30
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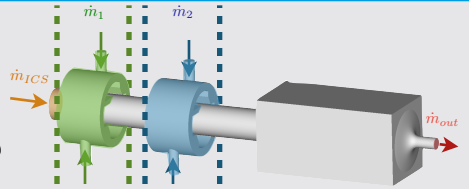
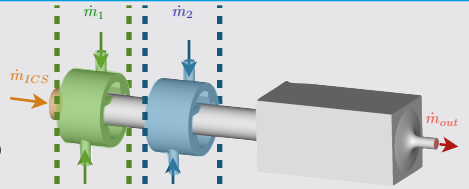
CHOKED setup numerical investigations



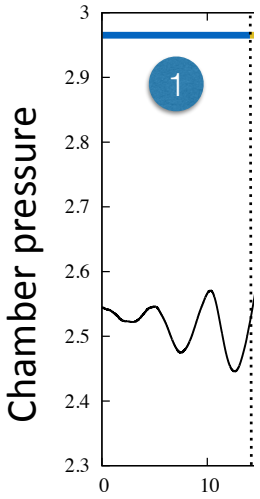
The following sequence of events is observed :

CHOKED setup numerical investigations



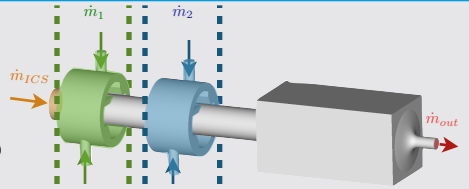
The following sequence of events is observed :

1. Starting from a « silent » solution, the LES presents an initial growth of the acoustic activity



Time (ms)

CHOKED setup numerical investigations



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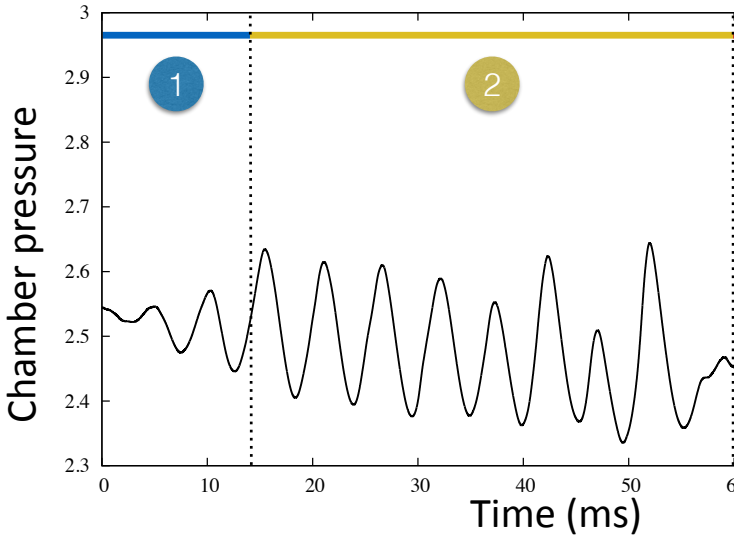
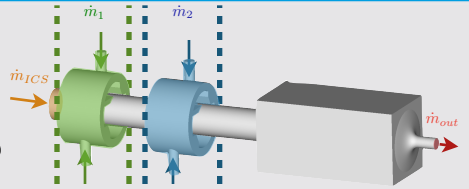


2. A period of thermoacoustic activity inducing intermittent flashback is observed, and acoustic levels continue to rise

CHOKED setup numerical investigations



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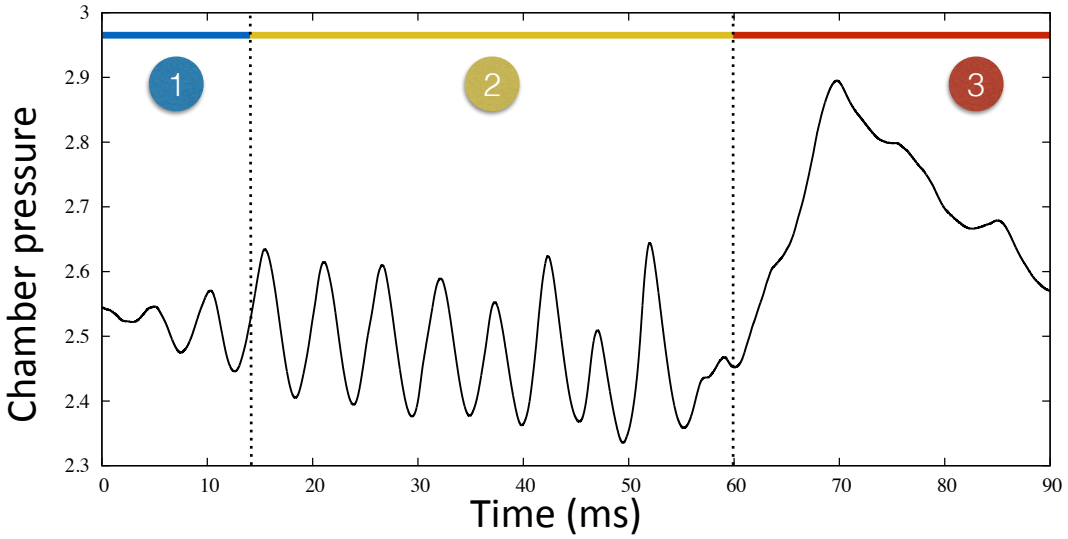
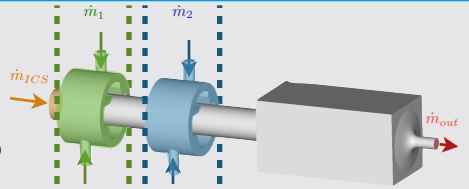
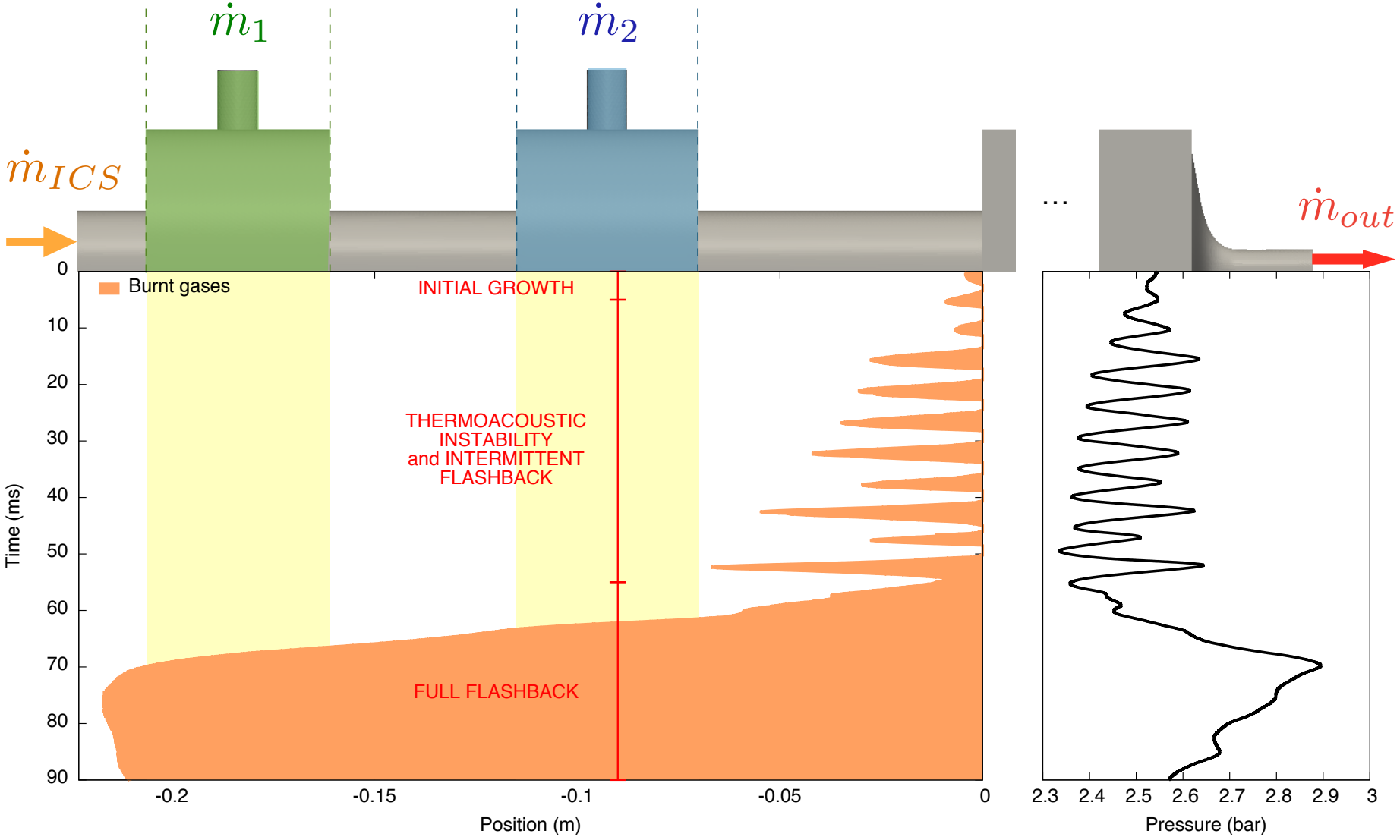


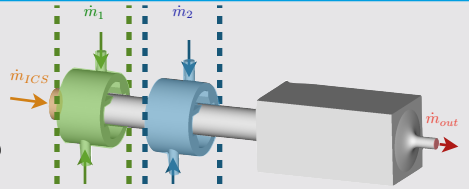
2. A period of thermoacoustic activity inducing intermittent flashback is observed, and acoustic levels continue to rise
3. Acoustic levels reach a critical threshold and trigger full flashback

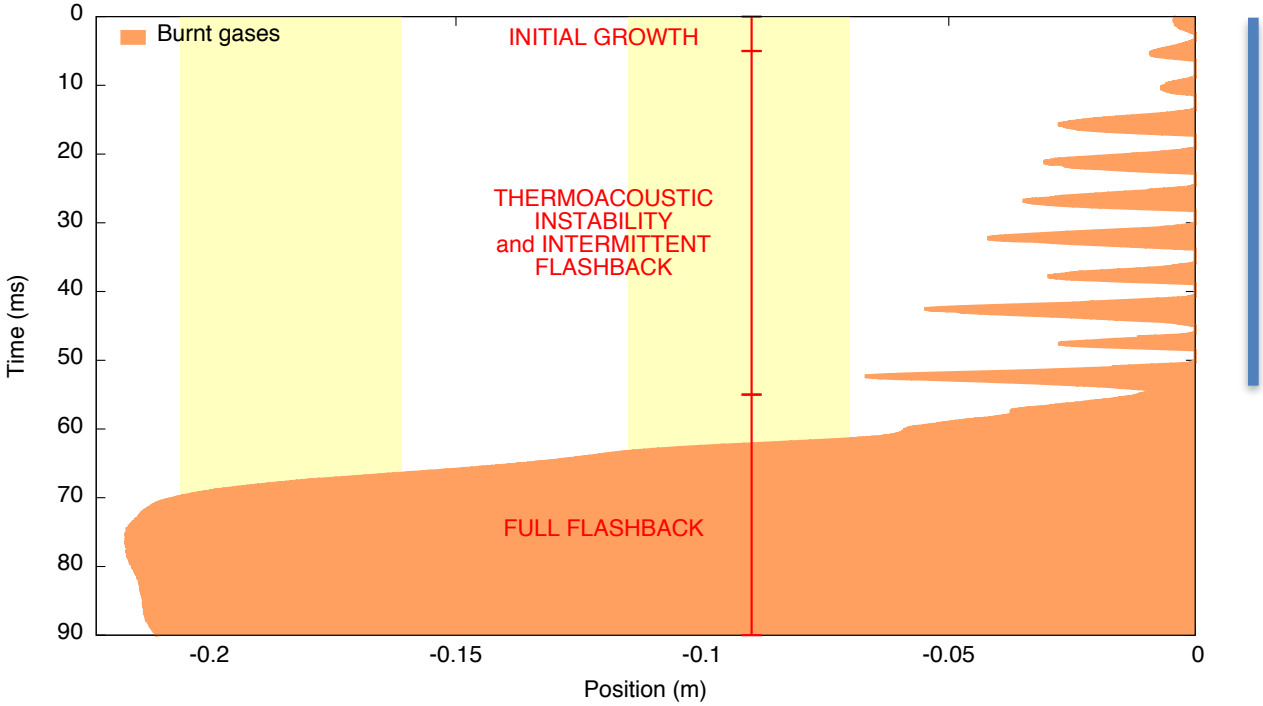
CHOKED setup numerical investigations





CHOKED setup numerical investigations

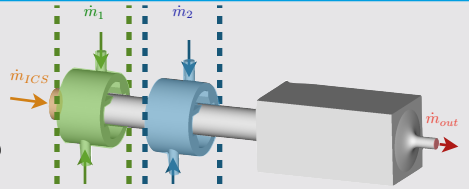


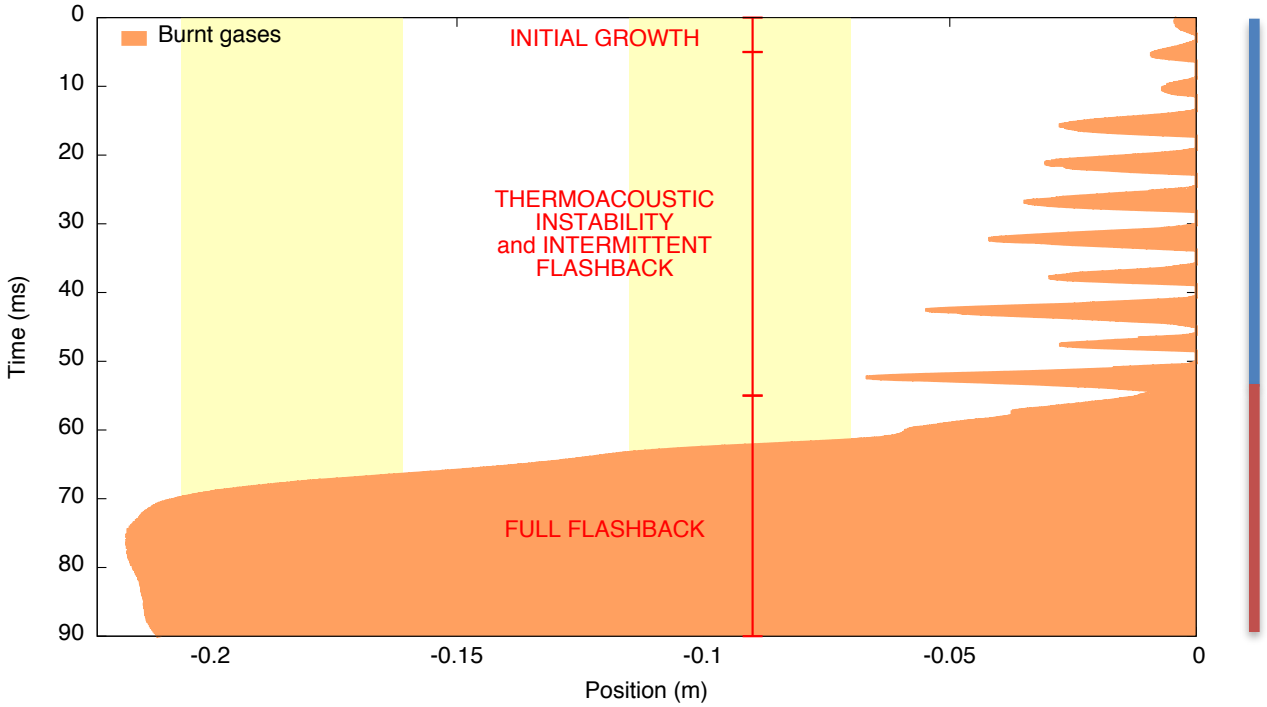


Classical flow reversal intermittent flashback

Flame position versus time in the CHOKED - PREMIXED setup

CHOKED setup numerical investigations





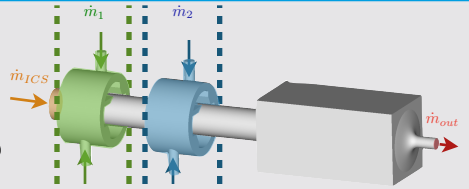
Classical flow reversal intermittent flashback

Permanent flashback through the vortex core

Self-excited thermoacoustic instability induces:

- Classical flow reversal intermittent flashback…
- …and eventually permanent vortex core flashback

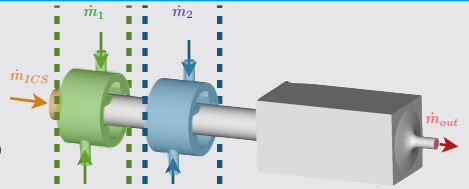
CHOKED setup numerical investigations



	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	?

	PREMIXED $\phi_{prem} = 0.9$		STAGED $\phi_{stag} = 0.85$	
	$\dot{m}^{air}$	ϕ	$\dot{m}^{air}$	ϕ
Experiment				
ICS	1.0	0.0	1.0	0.0
Injector 1	8.5	0.95	7.0	0.0
Injector 2	8.5	0.95	10.0	1.53
LES				
ICS	1.0	0.9	1.0	0.0
Injector 1	8.5	0.9	7.0	0.0
Injector 2	8.5	0.9	10.0	1.53

CHOKED setup numerical investigations



	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	?

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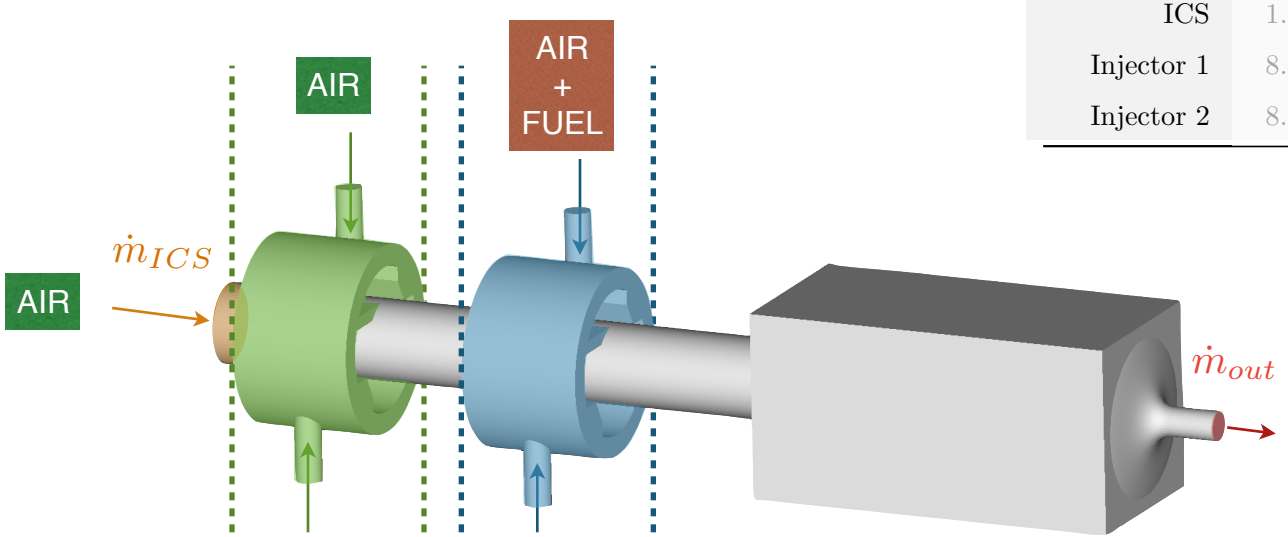
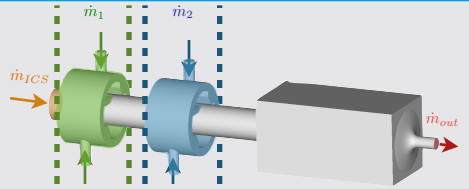
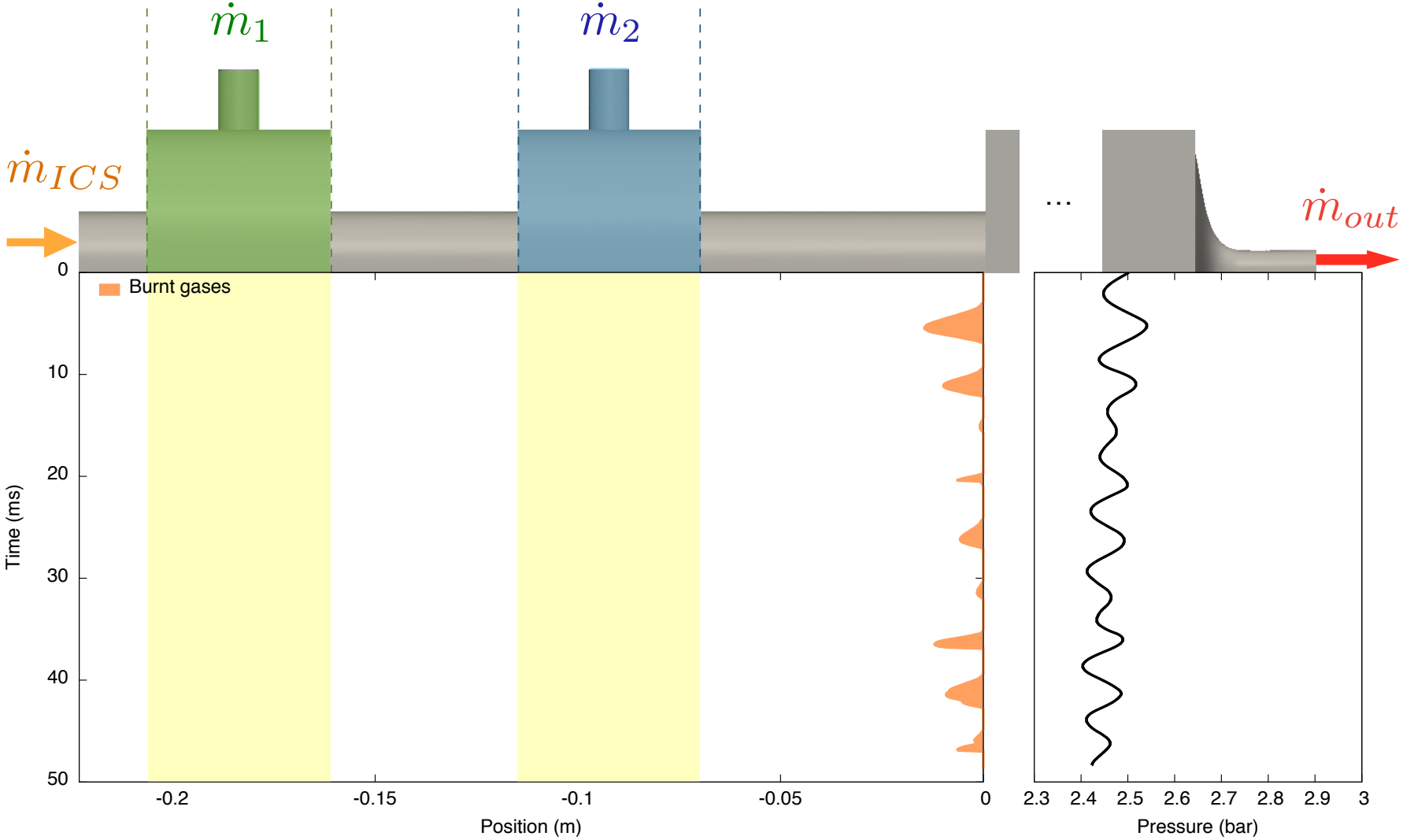


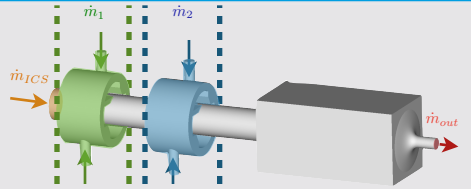
CHOKED STAGED : No flashback

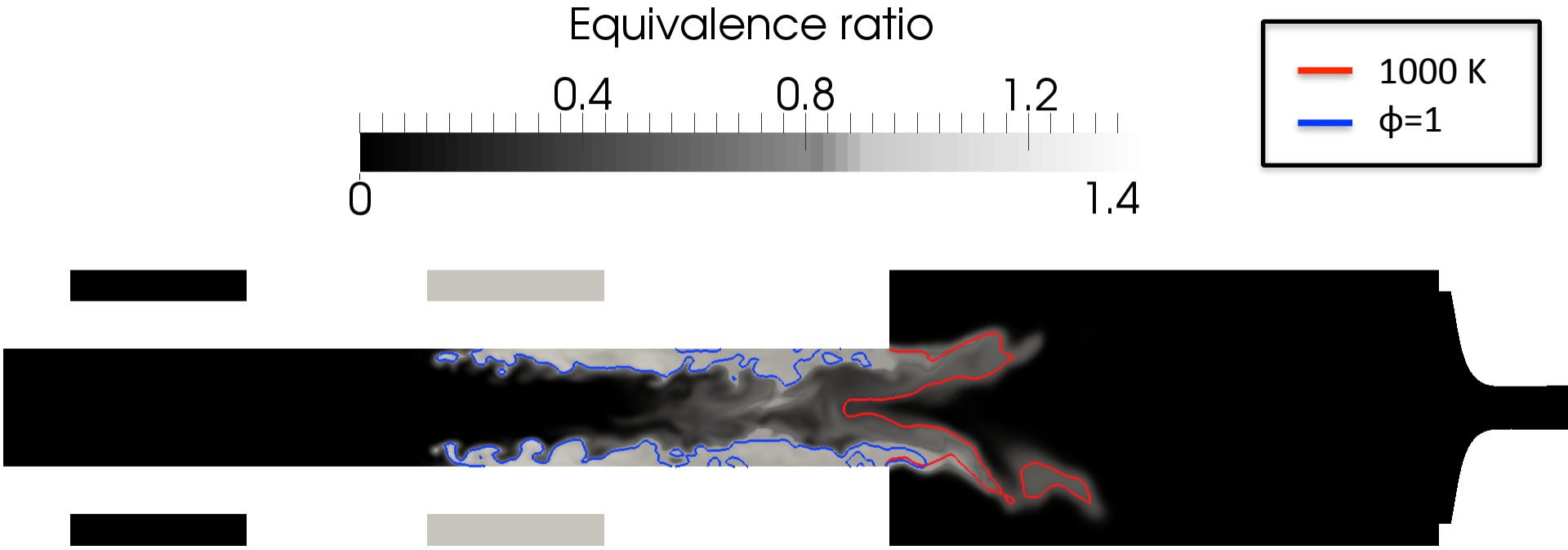




Flame position versus time in the CHOKED - STAGED setup

CHOKED STAGED : No flashback





Fuel staging between injectors 1 and 2 leads to a lean core and prevents flame propagation along the vortex axis.

CONCLUSION

	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	Chamber Stabilized

CONCLUSION

	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	Chamber Stabilized

The LES predicted flashback *before* the experimental confirmation

CONCLUSION

	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	Chamber Stabilized

The LES predicted flashback *before* the experimental confirmation

- Quiet system is flashback robust
- Full flashback can be triggered by sufficiently strong acoustic forcing combined with vortex core flame propagation
- This forcing occurs naturally due to a self-excited thermoacoustic instability

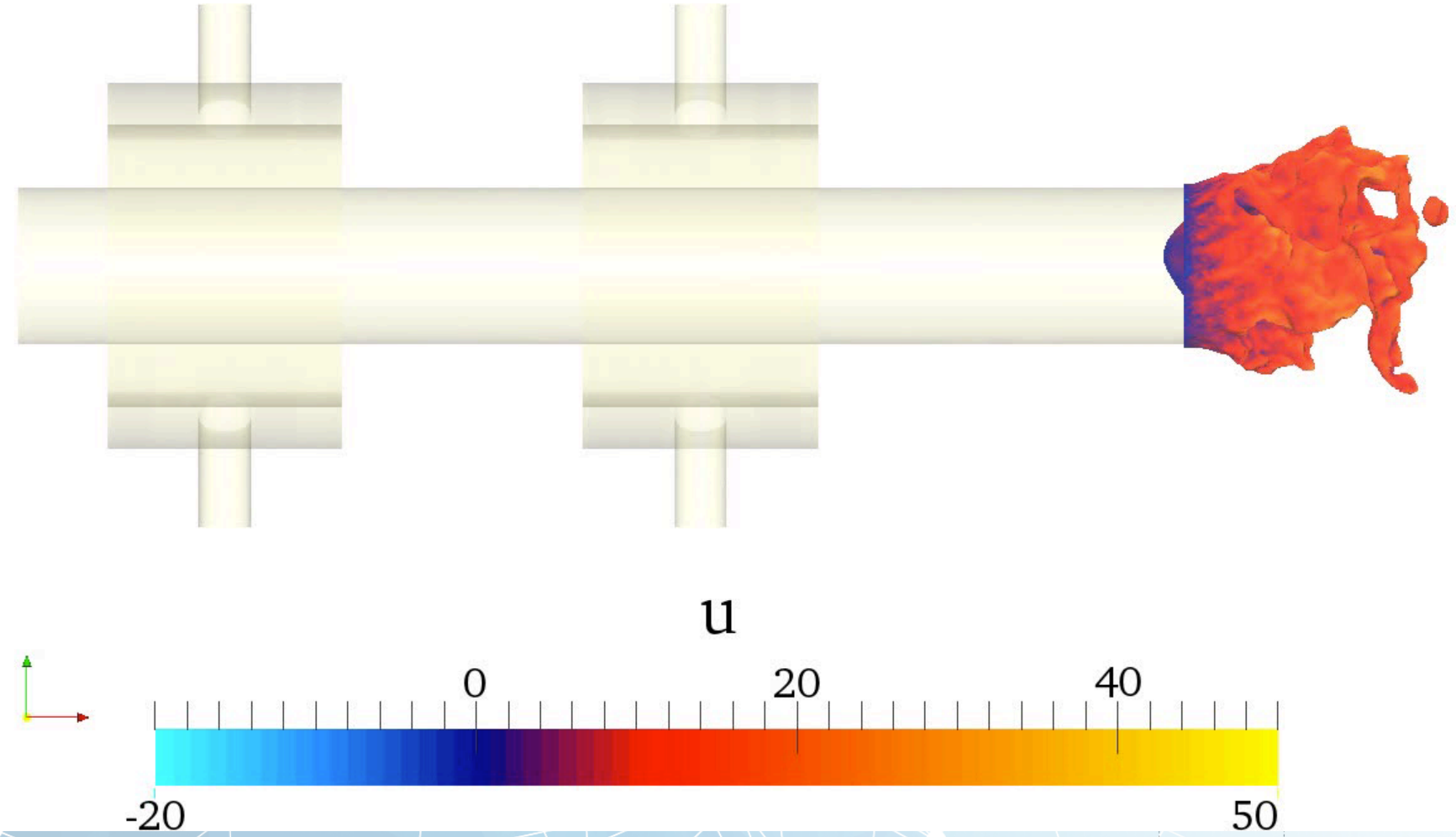
CONCLUSION

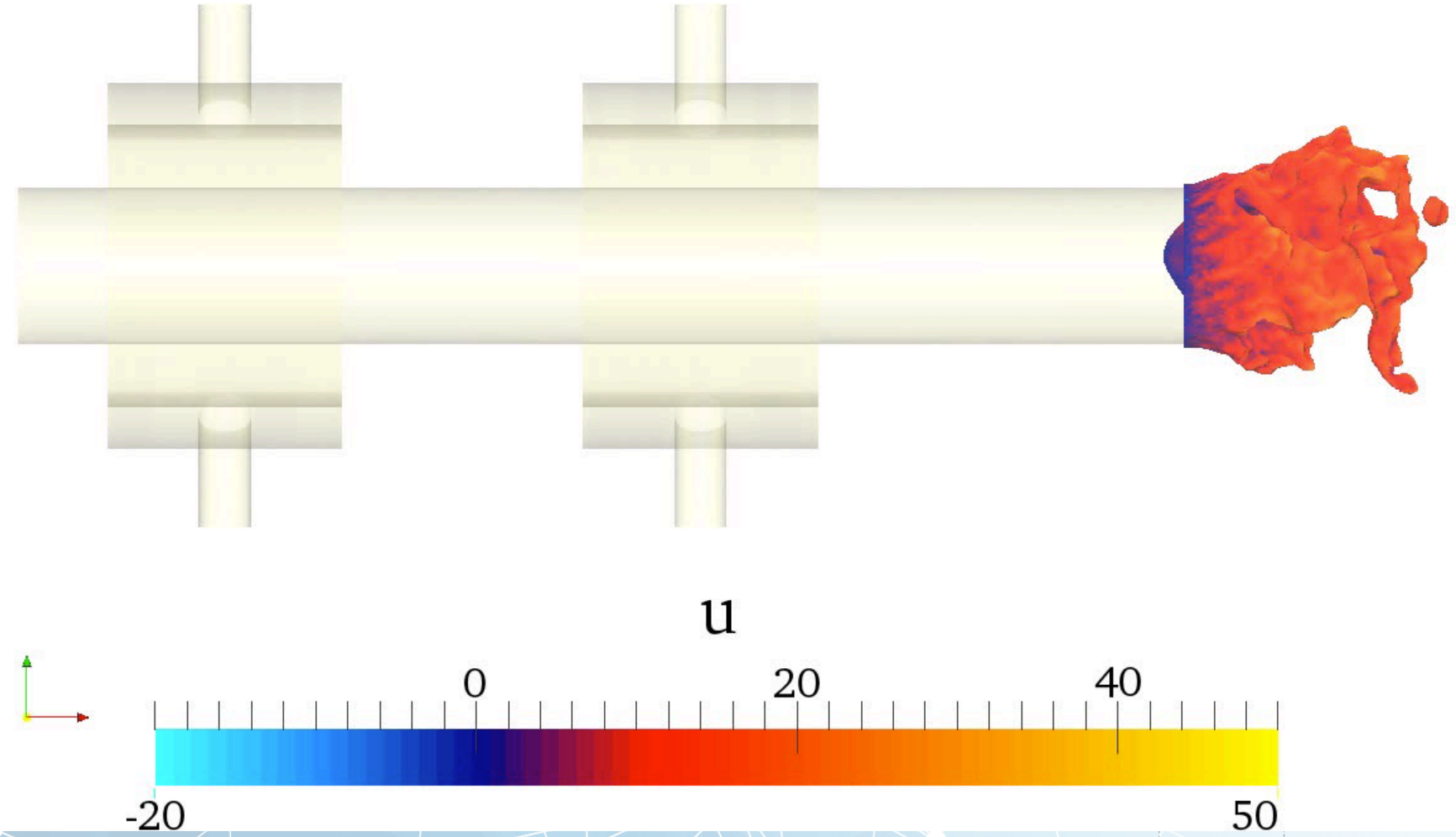
	PREMIXED	STAGED
Experiment	Flashback	Chamber Stabilized
LES	Flashback	Chamber Stabilized

The LES predicted flashback *before* the experimental confirmation

- Quiet system is flashback robust
- Full flashback can be triggered by sufficiently strong acoustic forcing combined with vortex core flame propagation
- This forcing occurs naturally due to a self-excited thermoacoustic instability

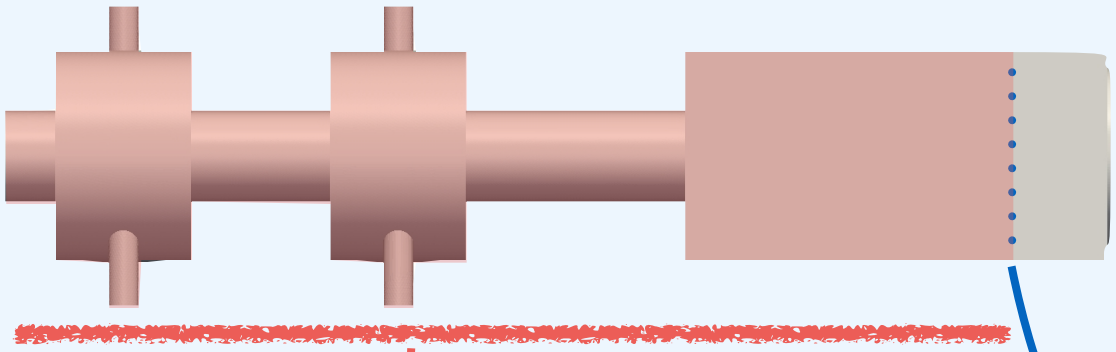
- Fuel staging produces a lean vortex core and prevents flame propagation


u
0
20
40
-20
50

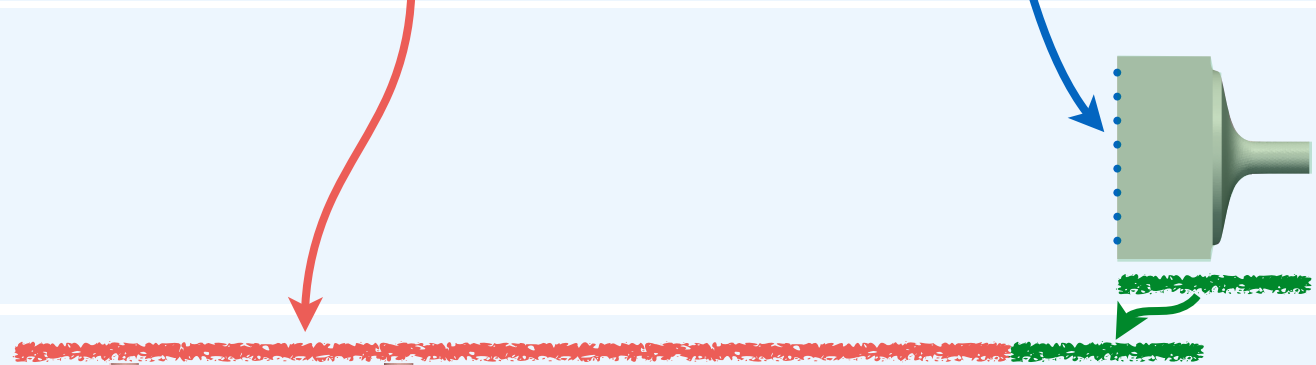

u
0
20
40
-20
50

Additional Content

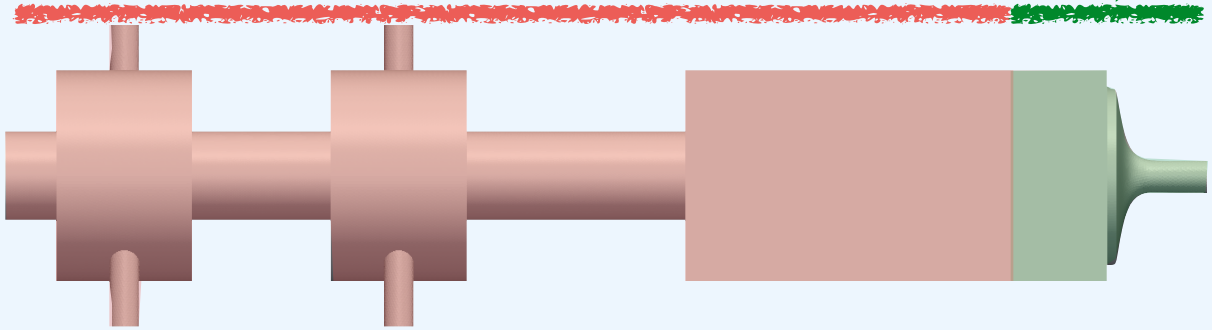
Initialization strategy



OPEN
Non-reflecting
Outlet



NOZZLE
Non-reflecting
Inlet



CHOKED
Natural
conditions