8th Thermal and Fluids Engineering Conference (TFEC)

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Calibration of a 1D ejector model from full-scale experiments

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European Union Funding
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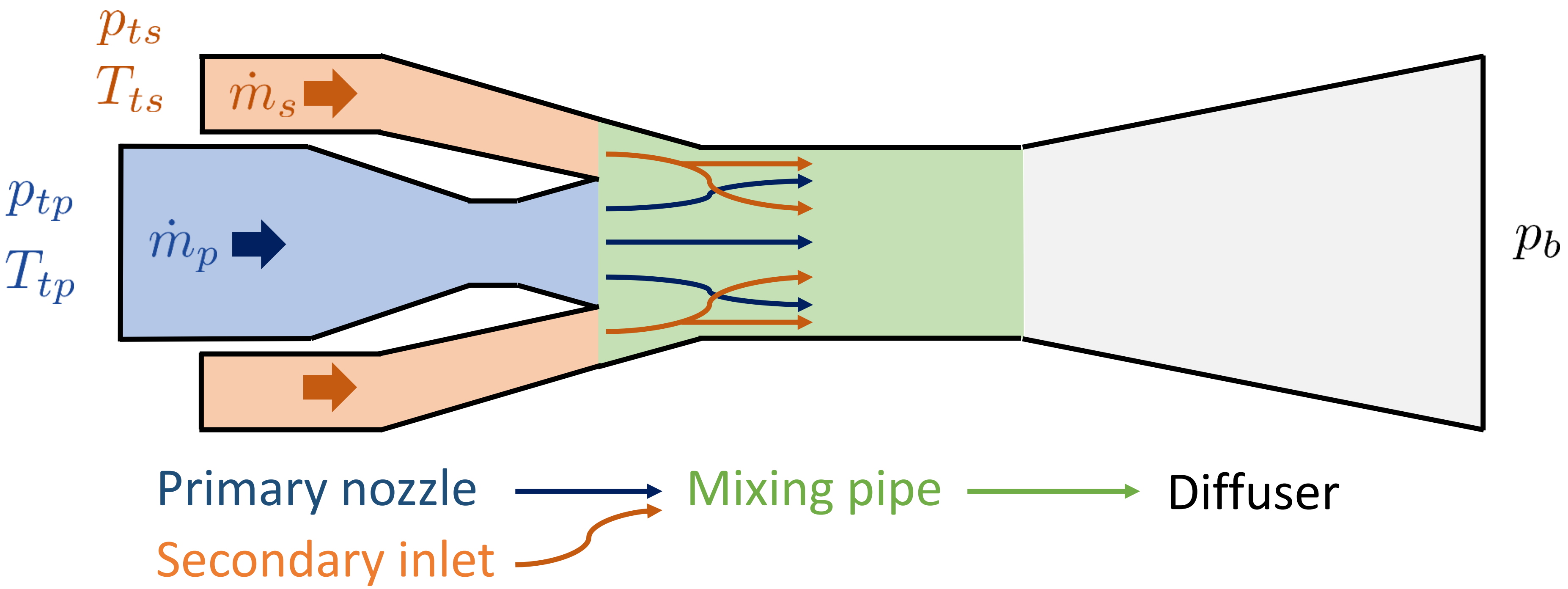
Clean Sky 2

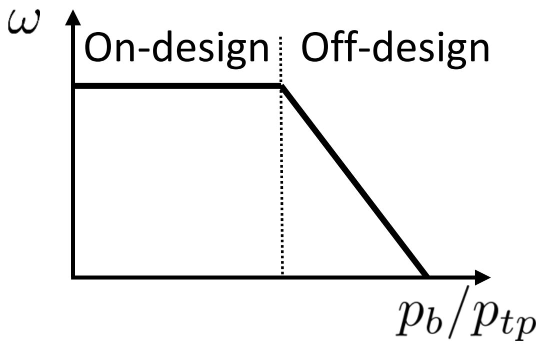
What is an ejector?



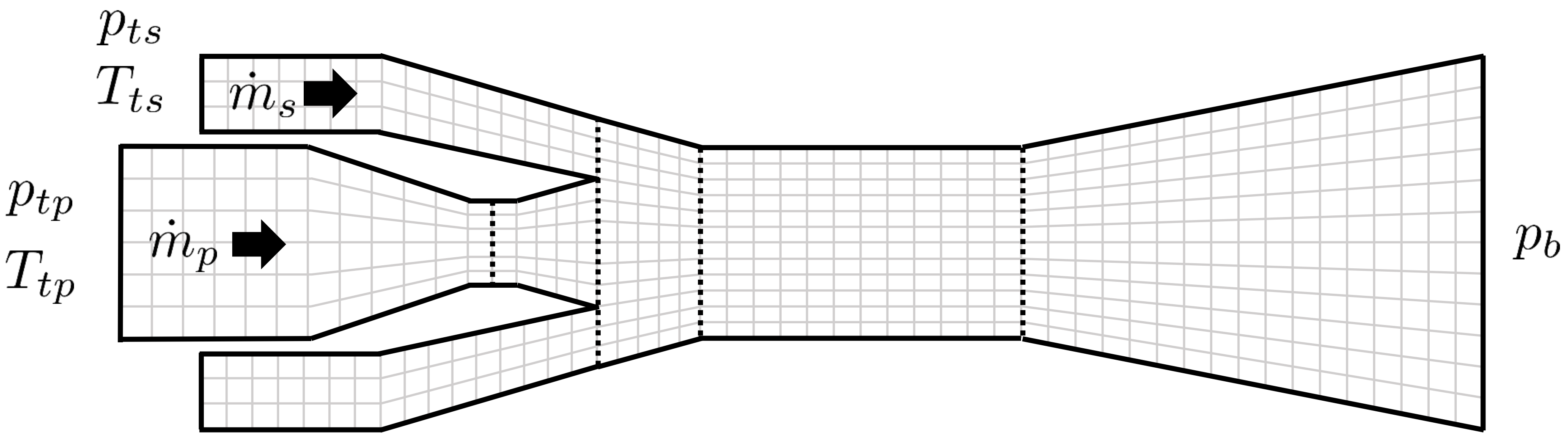
The back pressure p_b determines the entrainment ratio $\omega = \dot{m}_s/\dot{m}_p$

The mixed flow is choked in the on-design regime

$$\dot{m}_p, \dot{m}_s = f\left(p_{tp}, T_{tp}, p_{ts}, T_{ts}, p_b\right)$$



What are the modelling options?



0D: global balances

- ✓ Fast
- ✗ Only global information
- ✗ Calibration

1D: a compromise

- ✓ Local information
- ✓ Fast
- ✗ Calibration (2D effects)
- ✗ Complex

2/3D: classic CFD

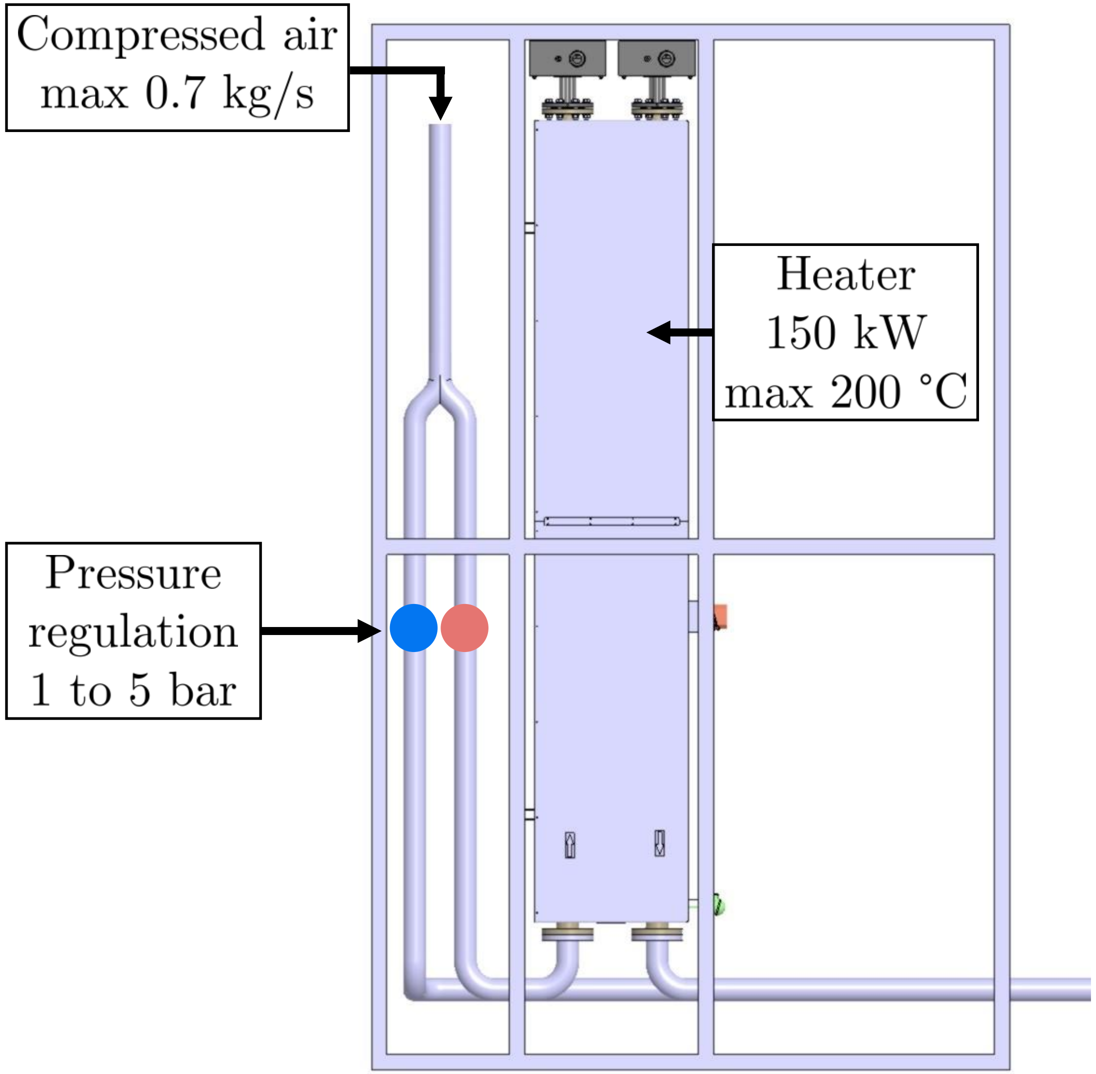
- ✓ Detailed flow field
- ✓ No calibration
- ✗ Computational cost
- ✗ Meshing and modelling

Fast models require data and calibration tools!

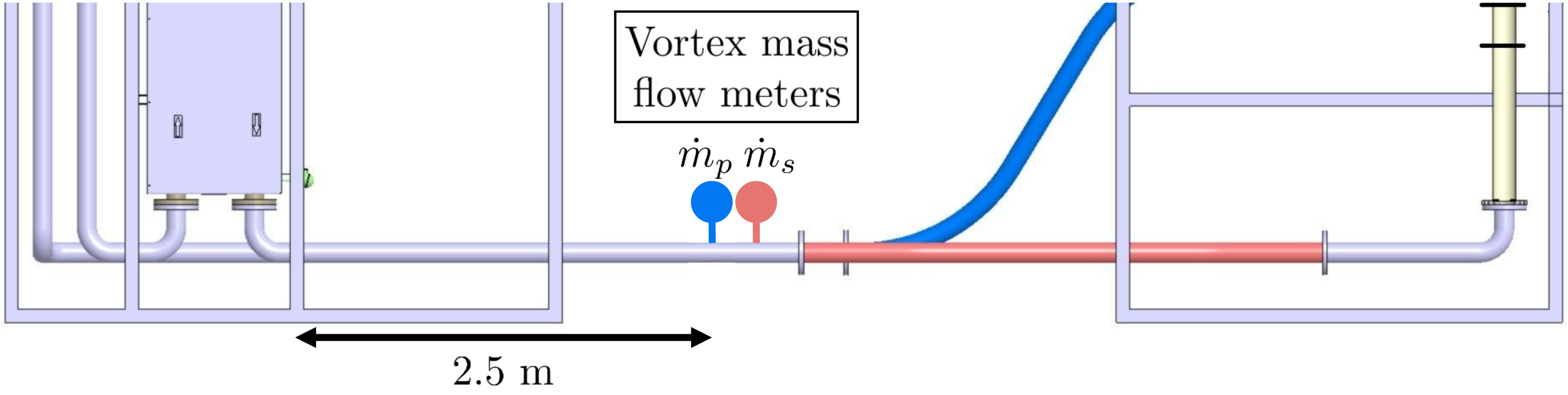
Contents

- **Experimental campaign: data**
- Calibration of a 1D ejector model: tools
- Conclusion

Experimental facility



Experimental facility

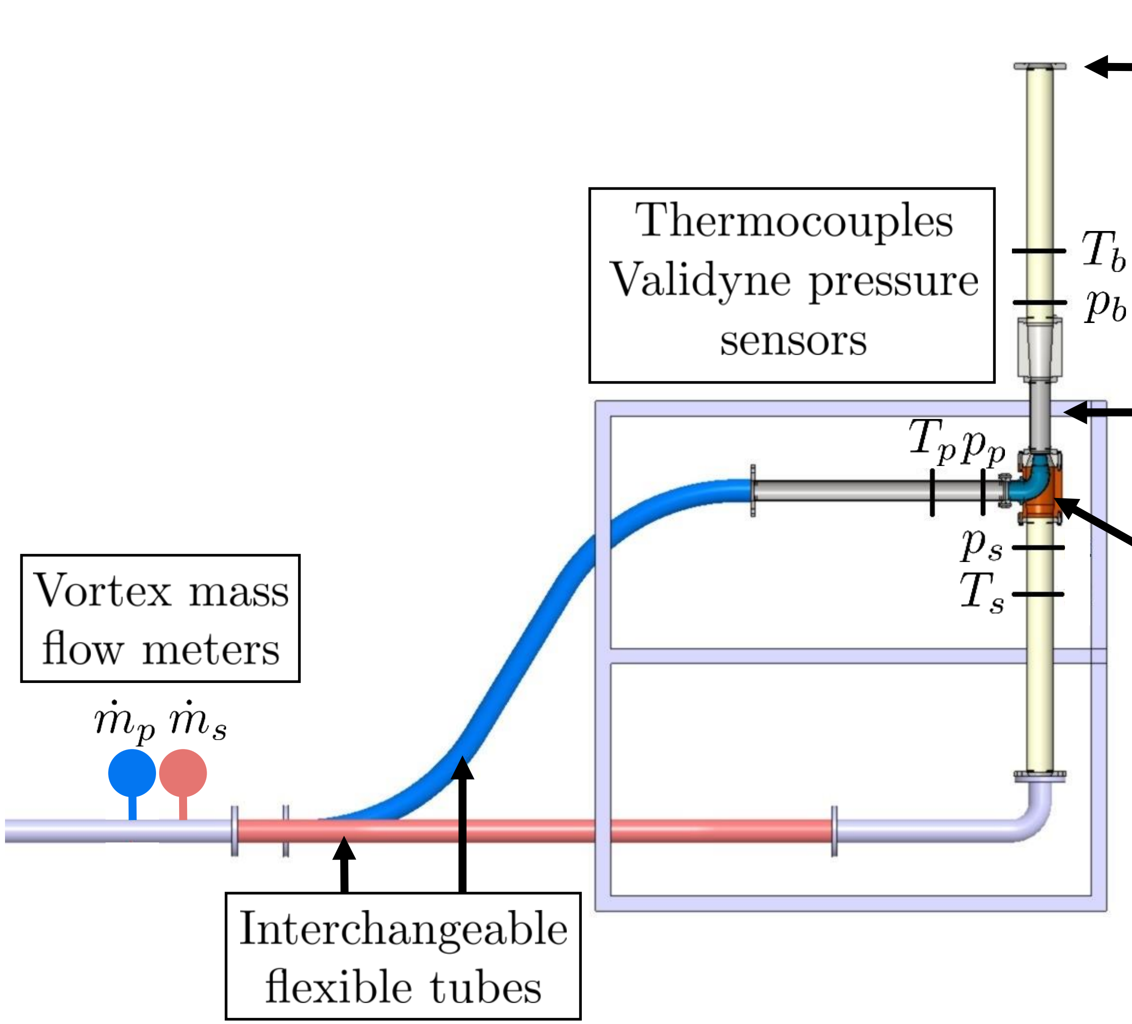


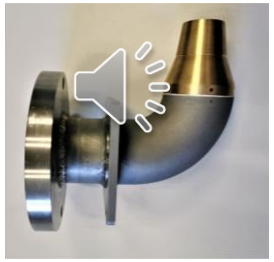
Experimental facility

(not included here)

Data consists of:

$$\dot{m}_p, \dot{m}_s = f\left(p_{tp}, T_{tp}, p_{ts}, T_{ts}, p_b\right)$$

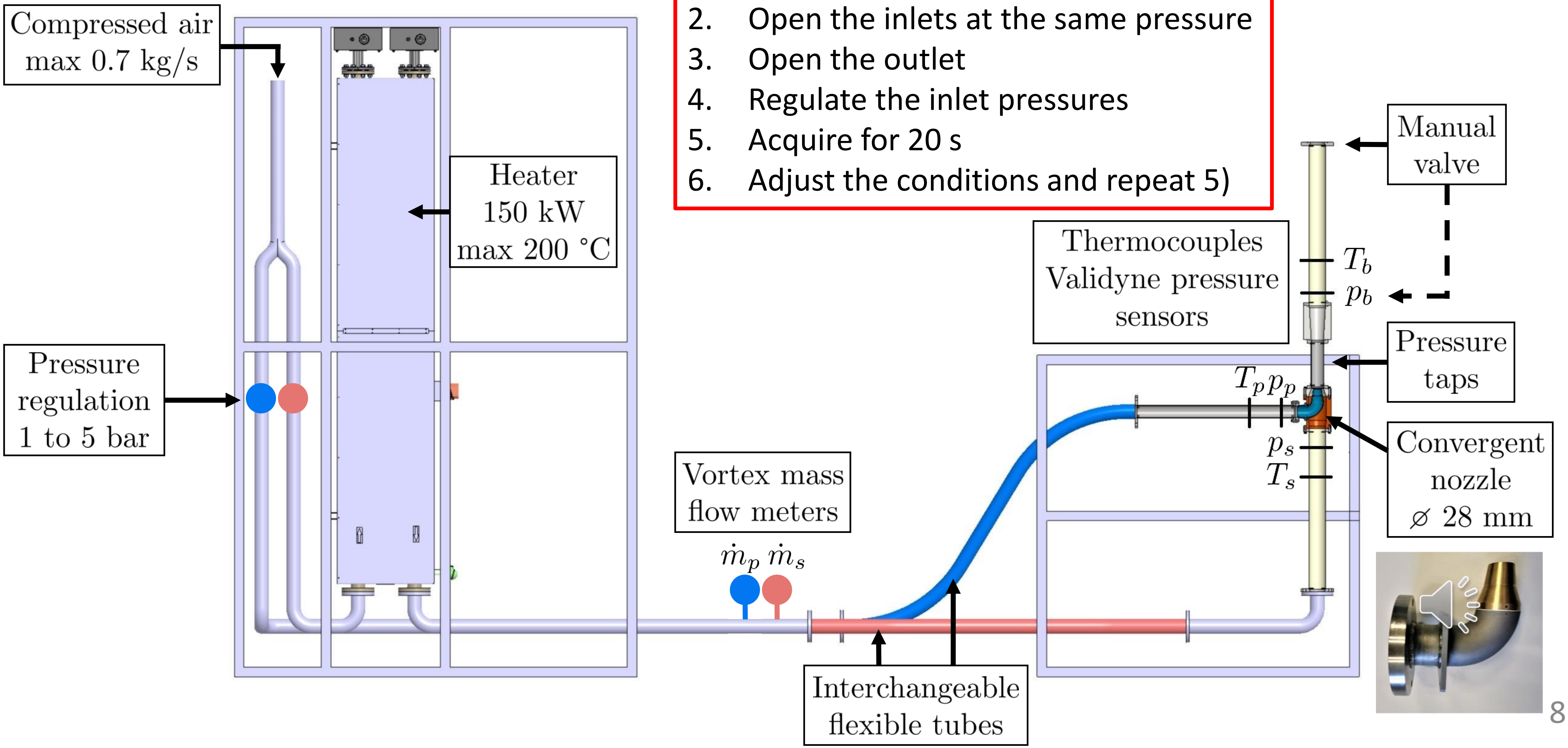




Experimental facility

Procedure for an operating curve

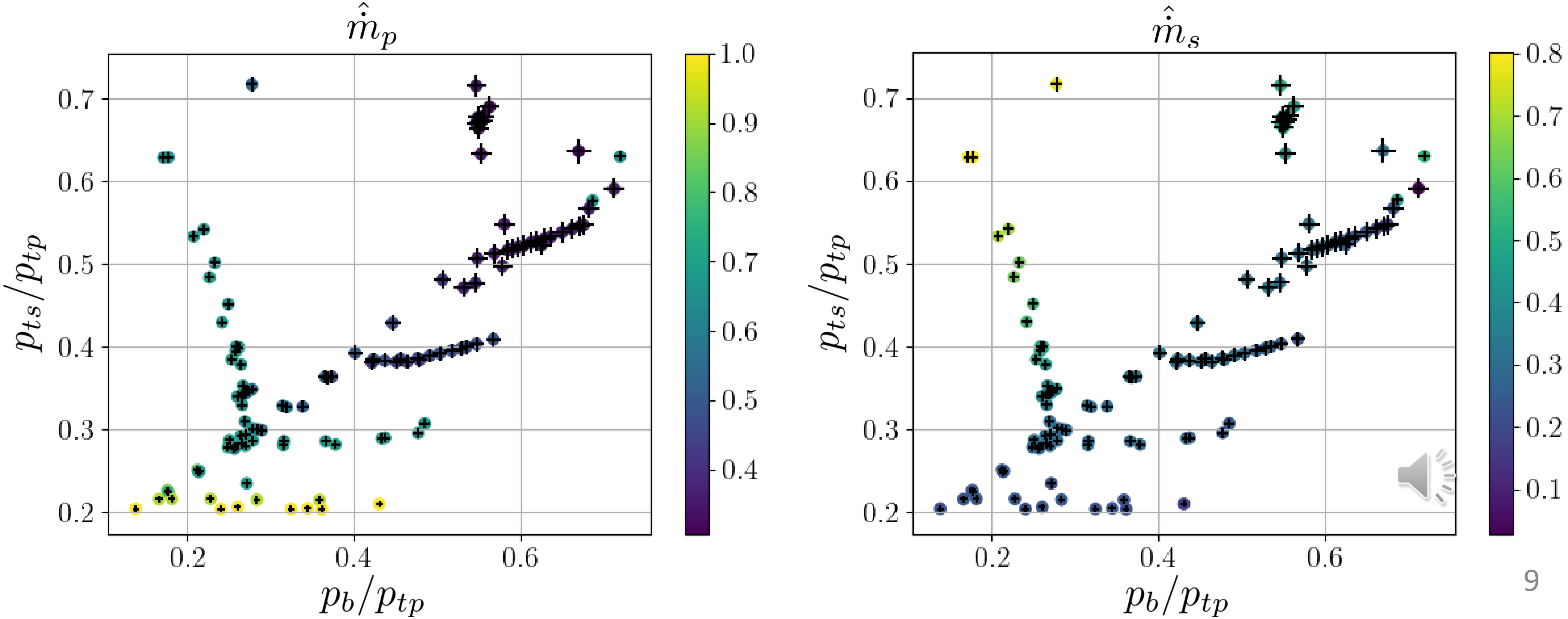
1. Close the outlet
2. Open the inlets at the same pressure
3. Open the outlet
4. Regulate the inlet pressures
5. Acquire for 20 s
6. Adjust the conditions and repeat 5)



Experimental results

$$\dot{m}_p, \dot{m}_s = f\left(p_{tp}, T_{tp}, p_{ts}, T_{ts}, p_b\right) \qquad \text{(1.5 \% uncertainty)}$$

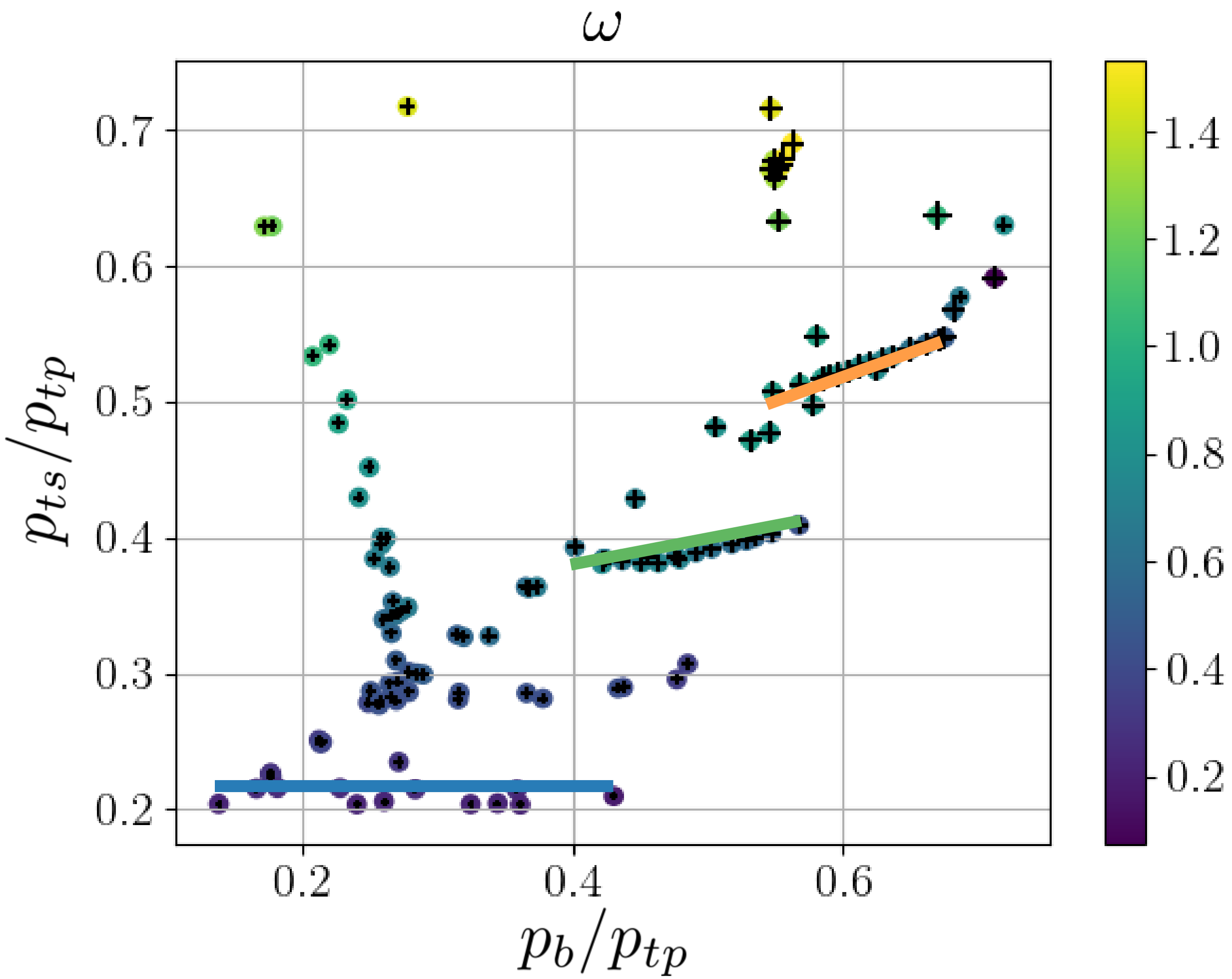
$$\rightarrow \text{dimensionless: } \hat{\dot{m}} = \dot{m}/\dot{m}_{p,max}$$

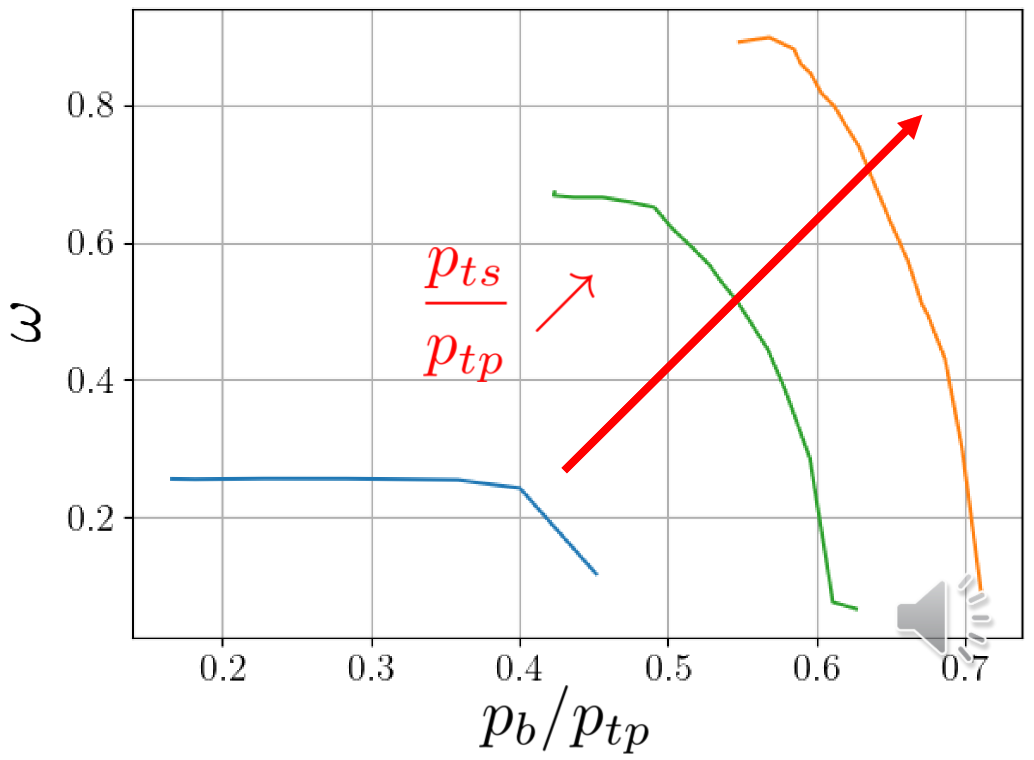


Experimental results

$$\dot{m}_p, \dot{m}_s = f\left(p_{tp}, T_{tp}, p_{ts}, T_{ts}, p_b\right) \qquad \text{(1.5 \% uncertainty)}$$

$$\rightarrow \text{entrainment ratio: } \omega = \dot{m}_s / \dot{m}_p$$





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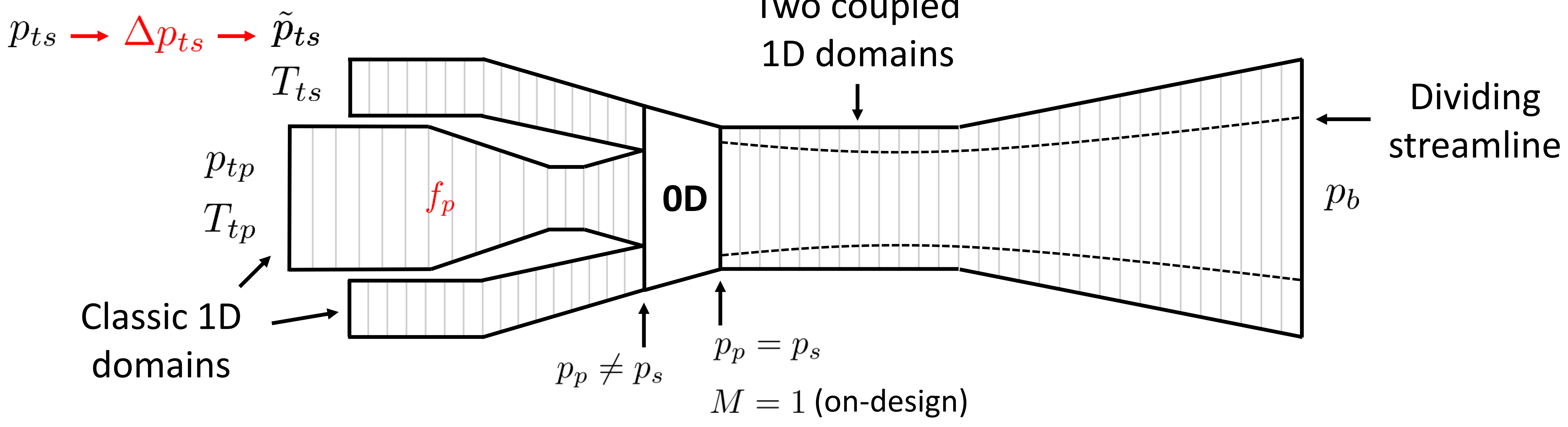
A 1D ejector model



Euler equations in the primary nozzle:

$$\begin{cases} d_x(\rho_p A_p V_p) &= 0 \\ d_x(\rho_p A_p V_p^2) &= -A_p d_x p_p - \frac{1}{2} f_p \rho_p V_p^2 l_w \\ d_x(\rho_p A_p V_p h_{t,p}) &= 0 \end{cases}$$

All remaining losses are lumped in a single pressure loss at the inlet:

$$\Delta p_{ts} = p_{ts} - \tilde{p}_{ts}$$

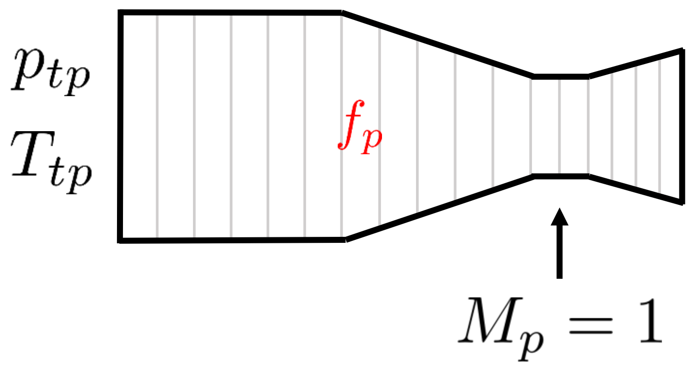
How do the losses change with the operating conditions?

Adapted from Banasiak and Hafner (2011) [1] and Van den Berghe et al. (2023) [2]

Calibration procedure

Primary friction coefficient

Nozzle always choked (normal operation)

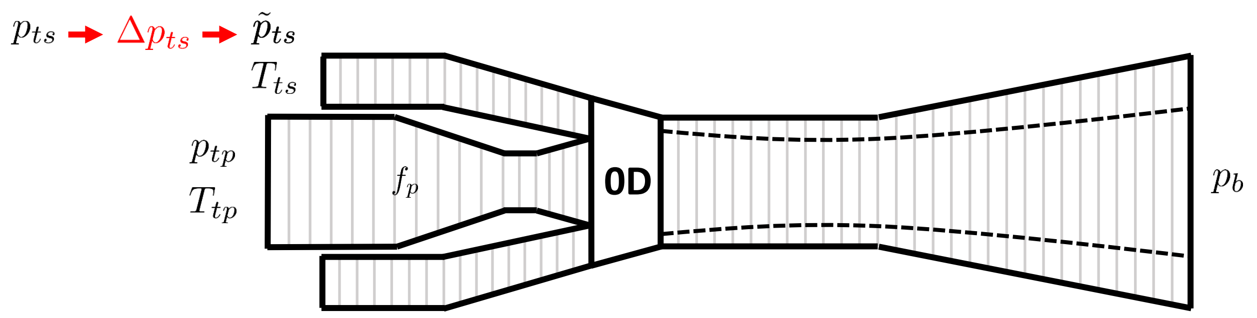


1. Isolate the nozzle
2. Calibrate f_p to minimize the error on $\dot{m}_p$ on the **complete** dataset:

$$J(f_p) = \sum_i \left(\dot{m}_{p,i} - \tilde{\dot{m}}_{p,i} \right)^2$$

Secondary pressure loss

Goal: link the pressure loss to the conditions

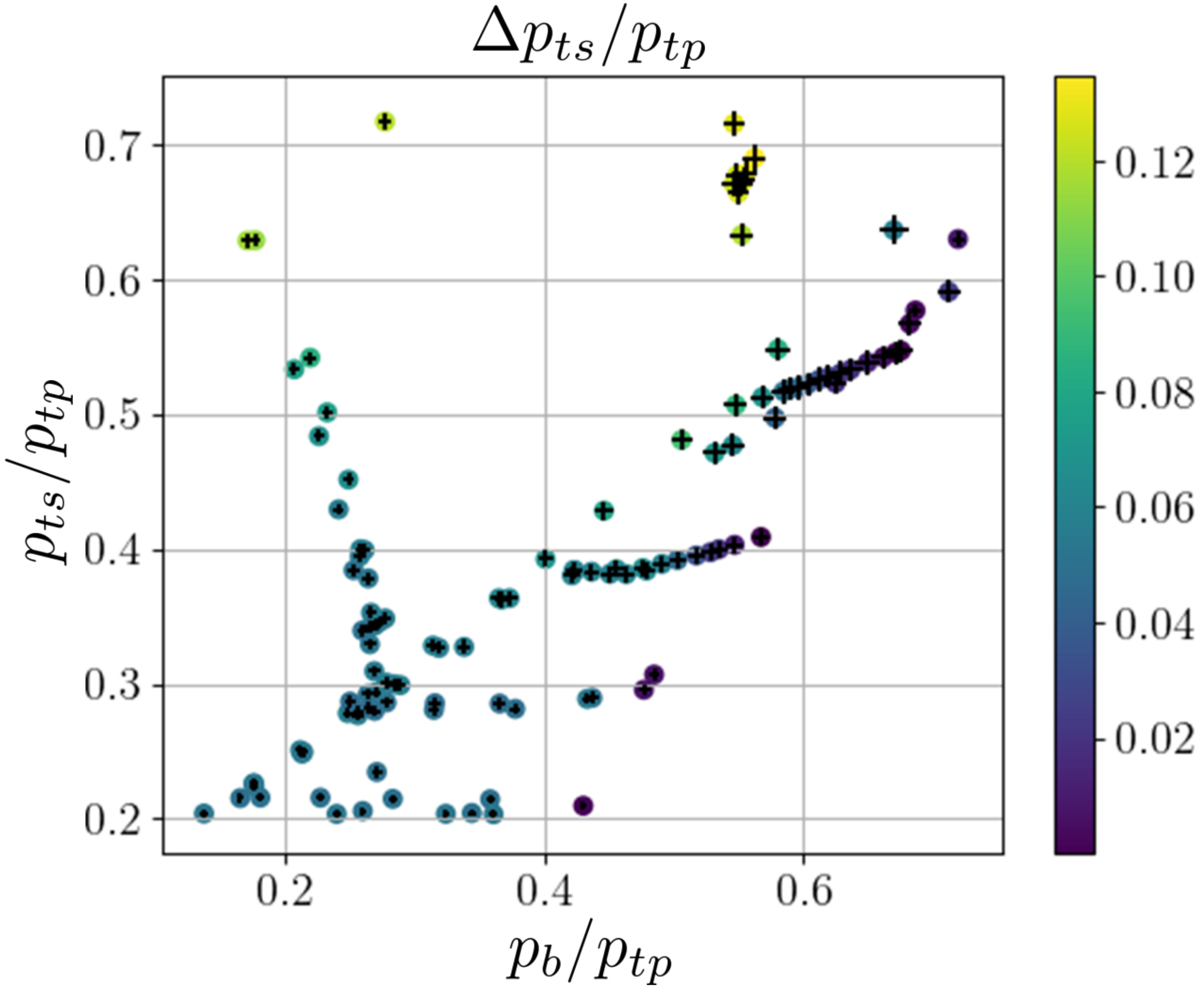


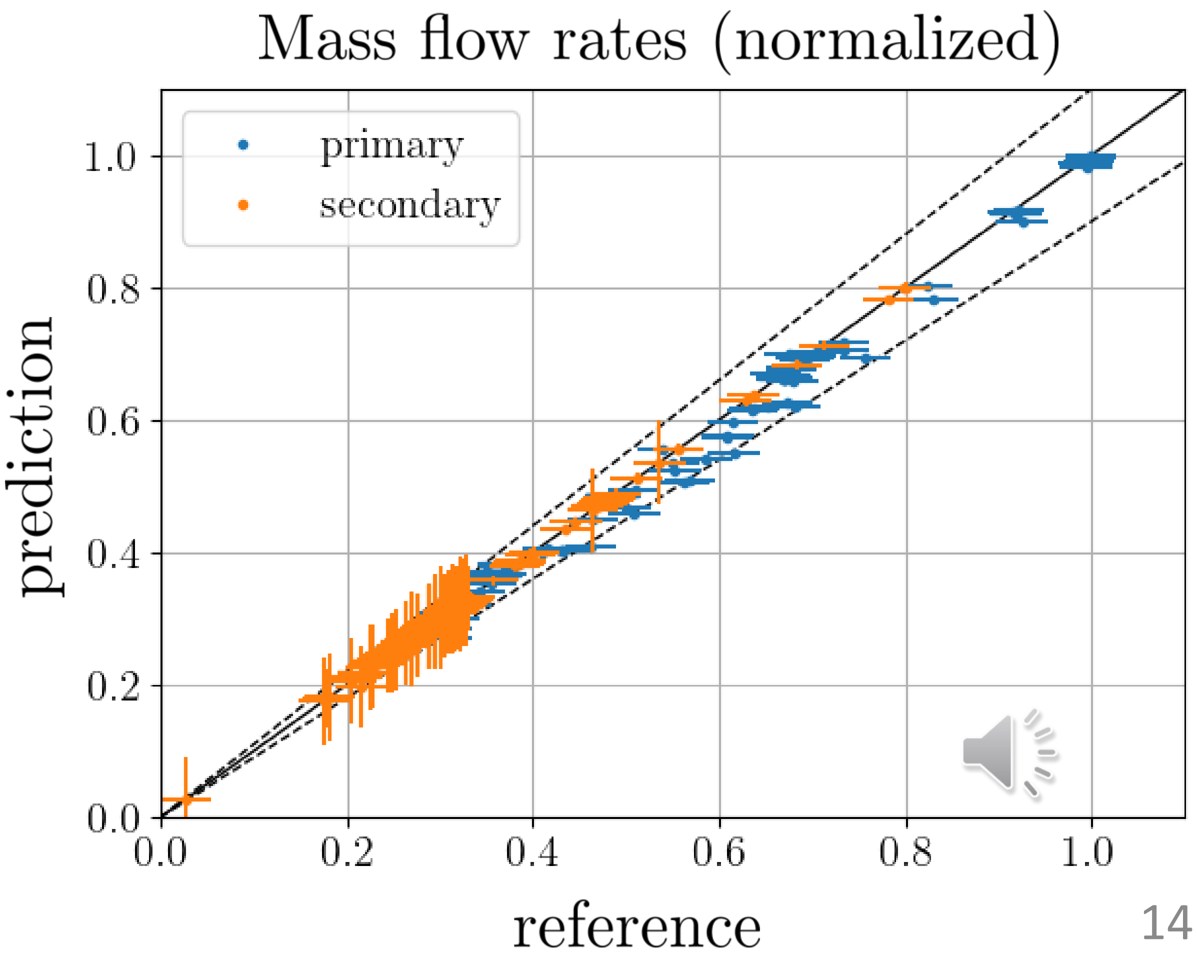
1. Use the calibrated f_p
2. Calibrate Δp_{ts} to minimize the error on $\dot{m}_s$ **point by point**:

$$J(\Delta p_{ts,i}) = \left(\dot{m}_{s,i} - \tilde{\dot{m}}_{s,i} \right)^2$$

Calibration results

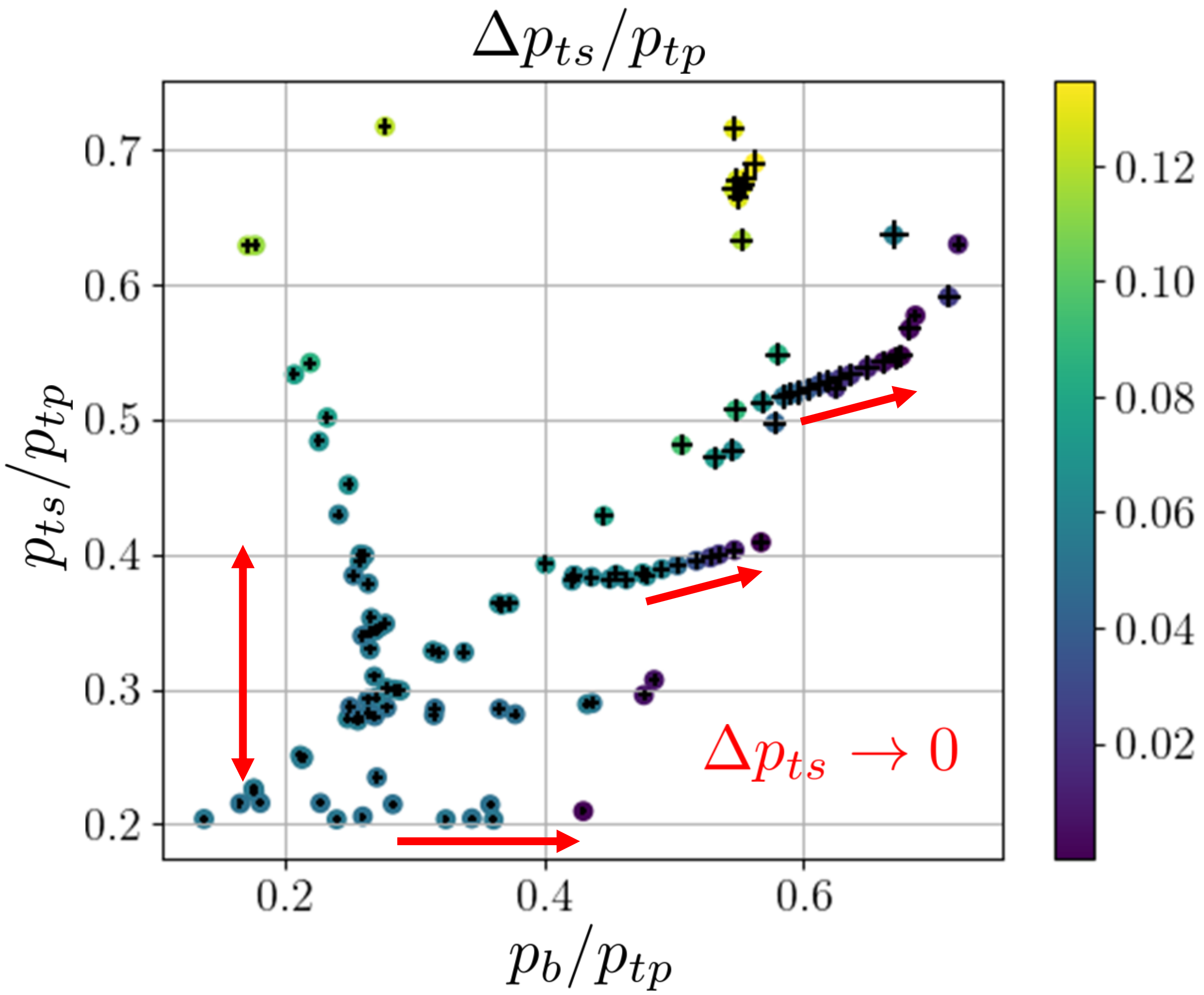
$f_p = 0.0017$





Calibration results

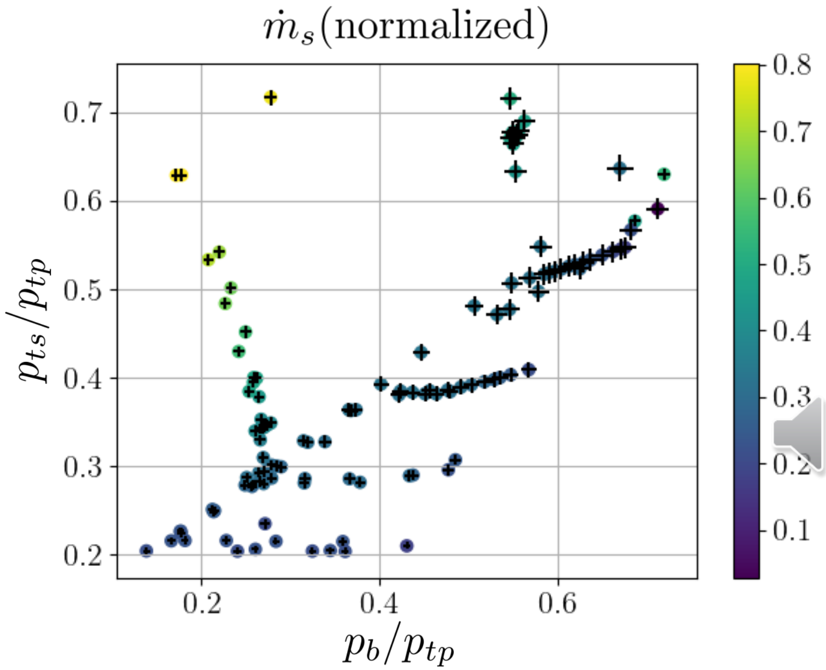
$f_p = 0.0017$



Primary friction coefficient: reasonable

Secondary pressure loss:

- Most sensitive to the back pressure
- Less sensitive to inlet pressure ratio
- Correlates with the secondary mass flow rate



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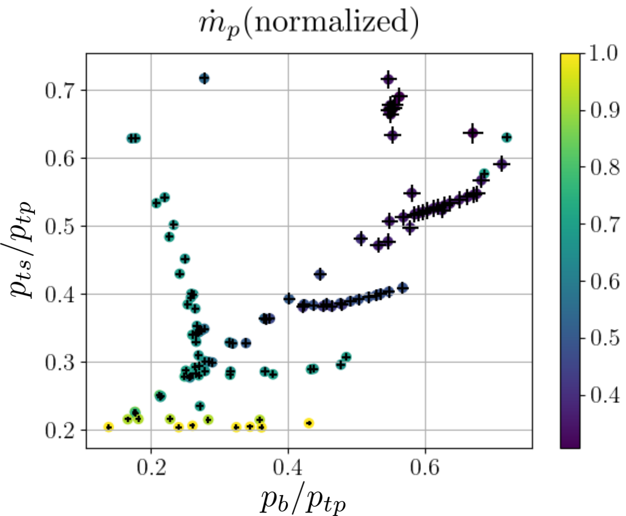
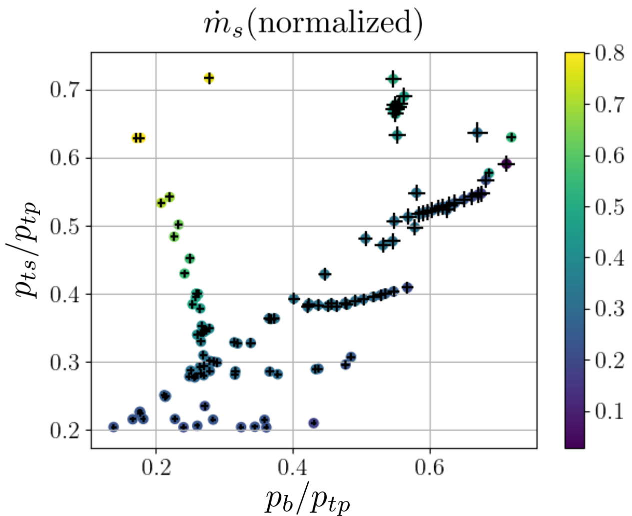
Conclusion

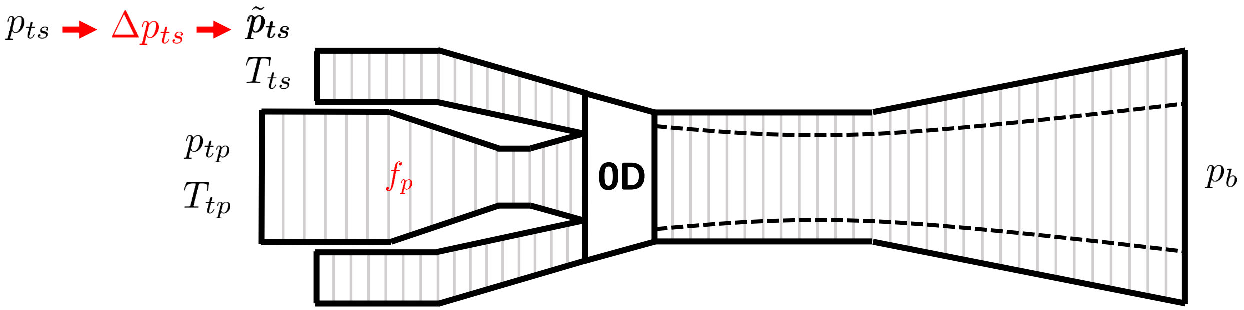


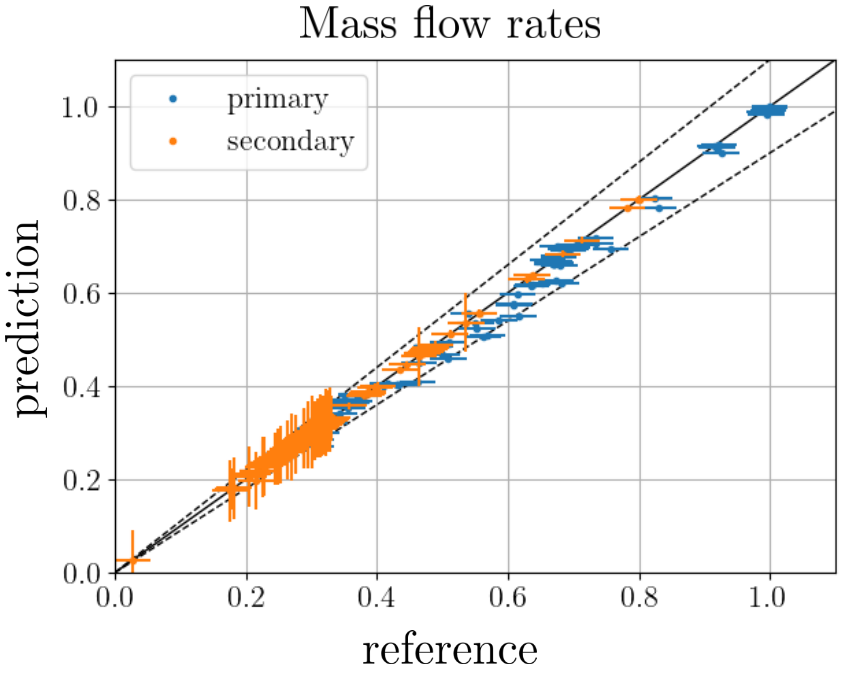


- Experimental campaign at aeronautical scale in various conditions

🎯 Obtain local data from pressure taps

Conclusion



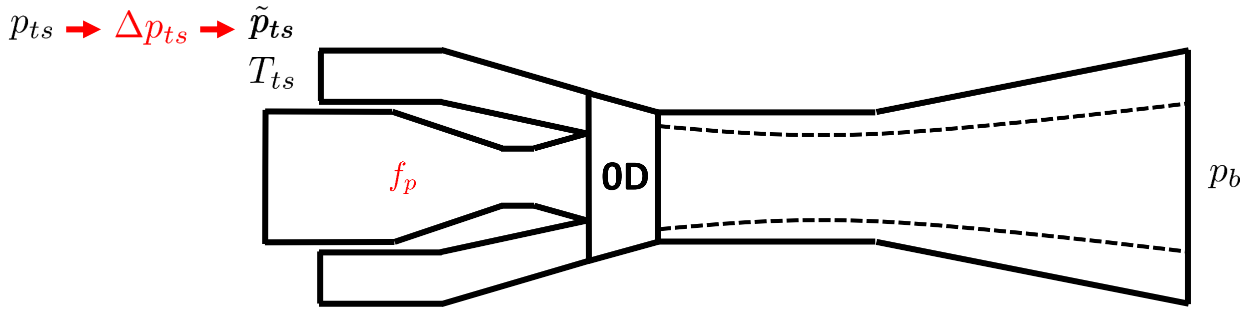


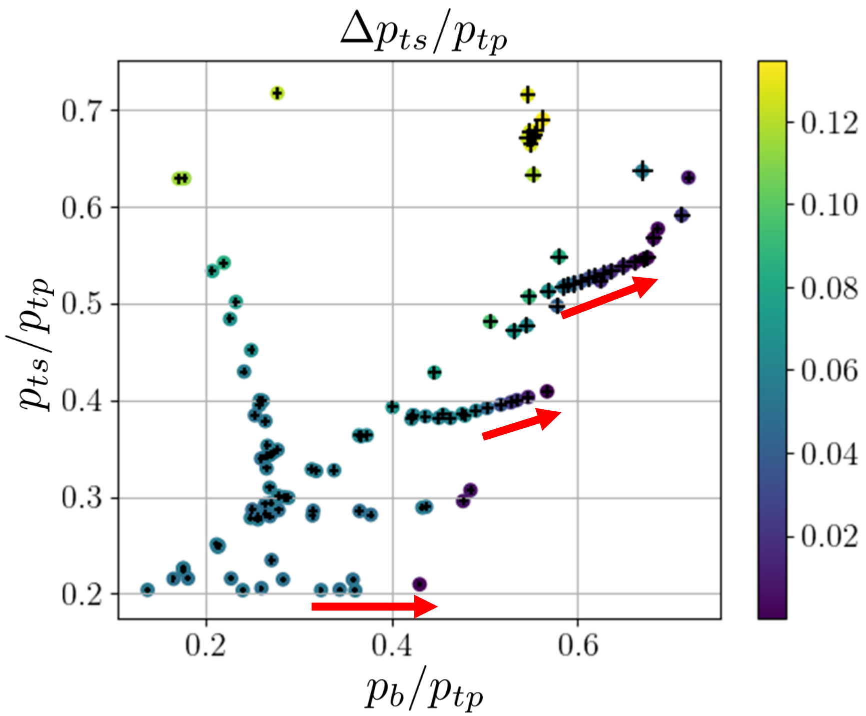
- Experimental campaign at aeronautical scale in various conditions

🎯 Obtain local data from pressure taps

- Calibration of a 1D model, accuracy of 10 %

Conclusion





- Experimental campaign at aeronautical scale in various conditions

Obtain local data from pressure taps

- Calibration of a 1D model, accuracy of 10 %
- The loss coefficient is most sensitive to the back pressure
- The loss coefficient correlates to the secondary mass flow rate

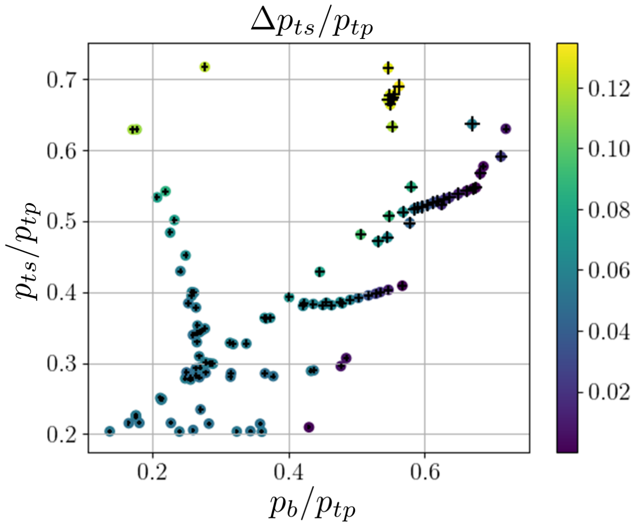
Localize losses, calibrate the shear force

Link the closure to the state variables

Ongoing work: regressing the closure coefficients with physics-constrained machine learning

Physics-separated

1. Calibrate "manually": $\Delta \tilde{p}_{ts}$



2. Regress a function a posteriori

$$\Delta p_{ts} = g(p_b/p_{tp}, \ldots; \boldsymbol{w})$$

$$J(\boldsymbol{w}) = \sum_i \left(\Delta p_{ts,i} - \Delta \tilde{p}_{ts,i}\right)^2$$

Physics-integrated

Calibrate the weights directly through the model:

$$J(\boldsymbol{w}) = \sum_i \left(\dot{m}_{s,i} - \tilde{\dot{m}}_{s,i}\right)^2$$

The physical model acts as a constraint on the optimization

$$\frac{dJ}{d\boldsymbol{w}} = 2\sum_i \left(\dot{m}_{s,i} - \tilde{\dot{m}}_{s,i}\right) \frac{d\dot{m}_{s,i}}{d\Delta_{p_{ts}}} \frac{d\Delta_{p_{ts}}}{d\boldsymbol{w}}$$

Calculating the sensitivity of the model can be avoided with **the adjoint method**

References

1. K. Banasiak and A. Hafner. “1d computational model of a two-phase r744 ejector for expansion work recovery”, International Journal of Thermal Sciences, 50(11): 2235–2247, 2011.
2. J. Van den Berghe, B. R. Dias, Y. Bartosiewicz, M. A. Mendez. “A 1D model for the unsteady gas dynamics of ejectors”, Energy 267, 2023.

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Uncertainty on the pressure ratios

Absolute uncertainty on the Validyne sensors (all pressures): $\delta p = 1375 \text{ Pa}$

$$\Pi_1 = \frac{p_b}{p_{tp}}$$

$$\delta \Pi_1 = \sqrt{\left(\frac{\partial \Pi_1}{\partial p_b}\right)^2 \delta p^2 + \left(\frac{\partial \Pi_1}{\partial p_{tp}}\right)^2 \delta p^2} = \delta p \sqrt{\left(\frac{\partial \Pi_1}{\partial p_b}\right)^2 + \left(\frac{\partial \Pi_1}{\partial p_{tp}}\right)^2}$$

$$\downarrow \qquad\qquad \downarrow$$

$$\frac{1}{p_{tp}} \qquad\qquad \frac{-p_b}{p_{tp}^2}$$

$$\delta \Pi_1 = \delta p \sqrt{\frac{1}{p_{tp}^2}\left[1 + \left(\frac{p_b}{p_{tp}}\right)^2\right]} = \frac{\delta p}{p_{tp}}\sqrt{1 + \Pi_1^2}$$

$$\mathrm{O}\left(\frac{1375}{5 \cdot 10^5}\sqrt{1 + 0.2^2}\right) = \mathrm{O}(0.3\%)$$

$$\mathrm{O}\left(\frac{1375}{1 \cdot 10^5}\sqrt{1 + 1^2}\right) = \mathrm{O}(2\%)$$