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Unsteady 1D Gas Dynamics in Ejectors: a Pipeline Analogy

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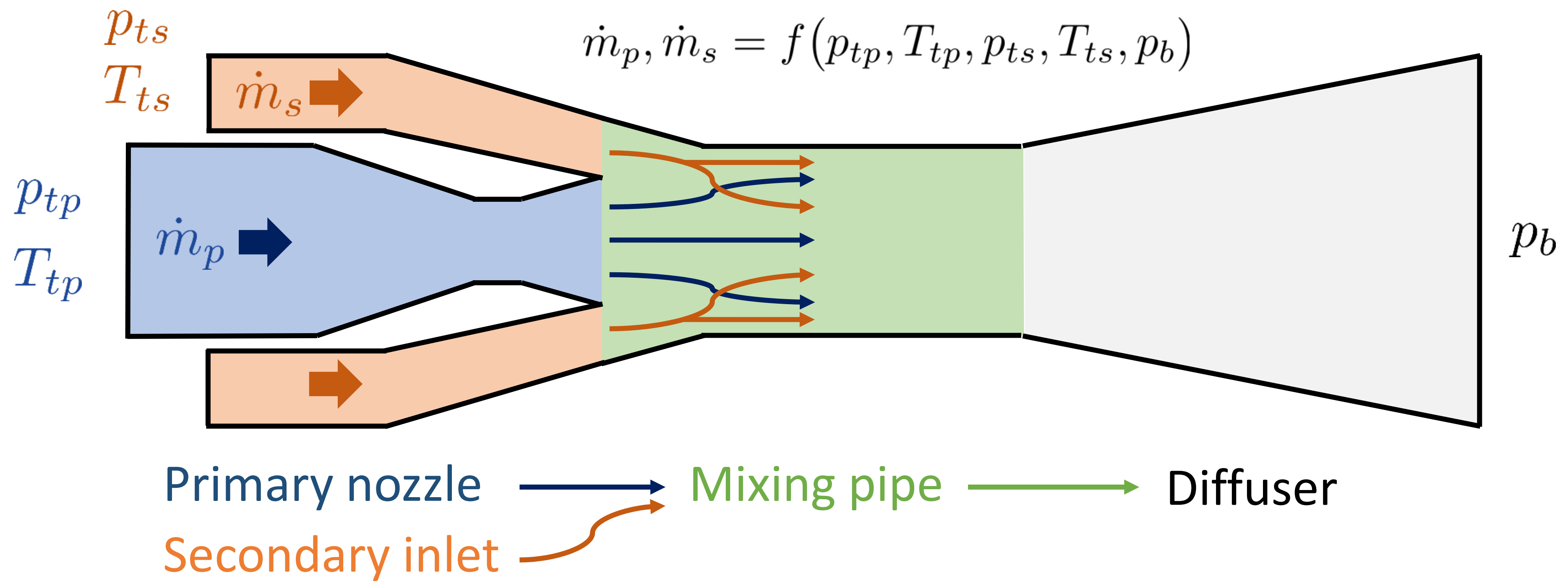
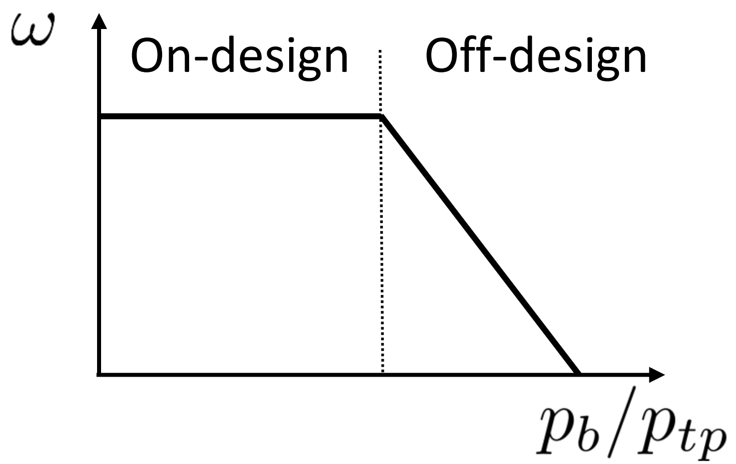
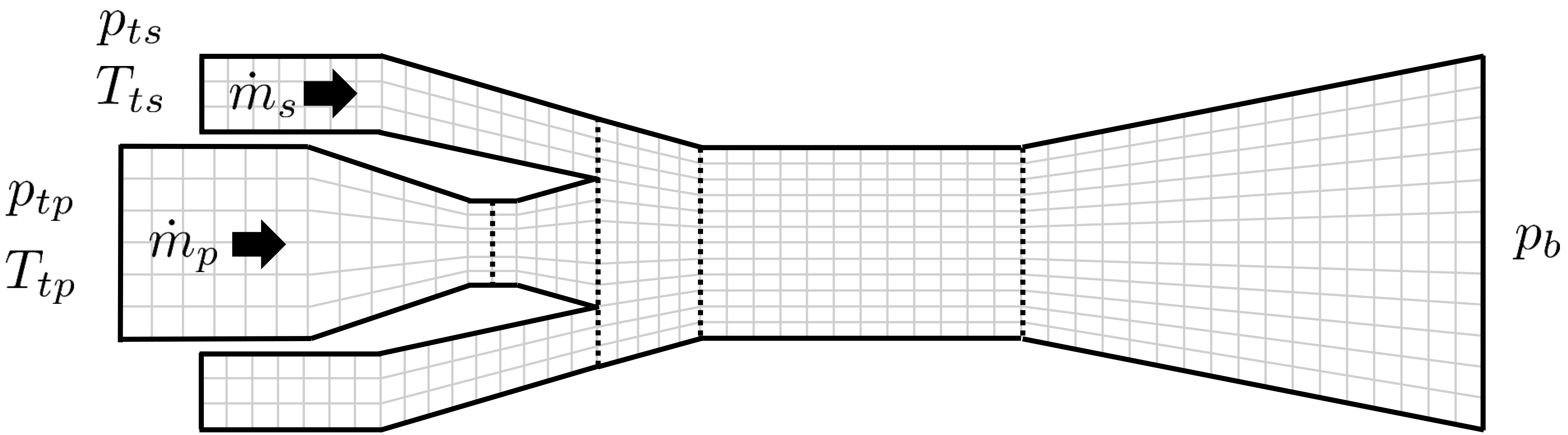
What is an ejector?



The entrainment ratio $\omega = \dot{m}_s/\dot{m}_p$ is maximal in the on-design regime due to choking of the mixed flow



What are the modelling options?



0D

- Integral quantities
- Steady

2/3D: classic CFD

- Detailed flow field
- Steady + unsteady

Goal:

Obtain unsteady 1D distributions of integral quantities

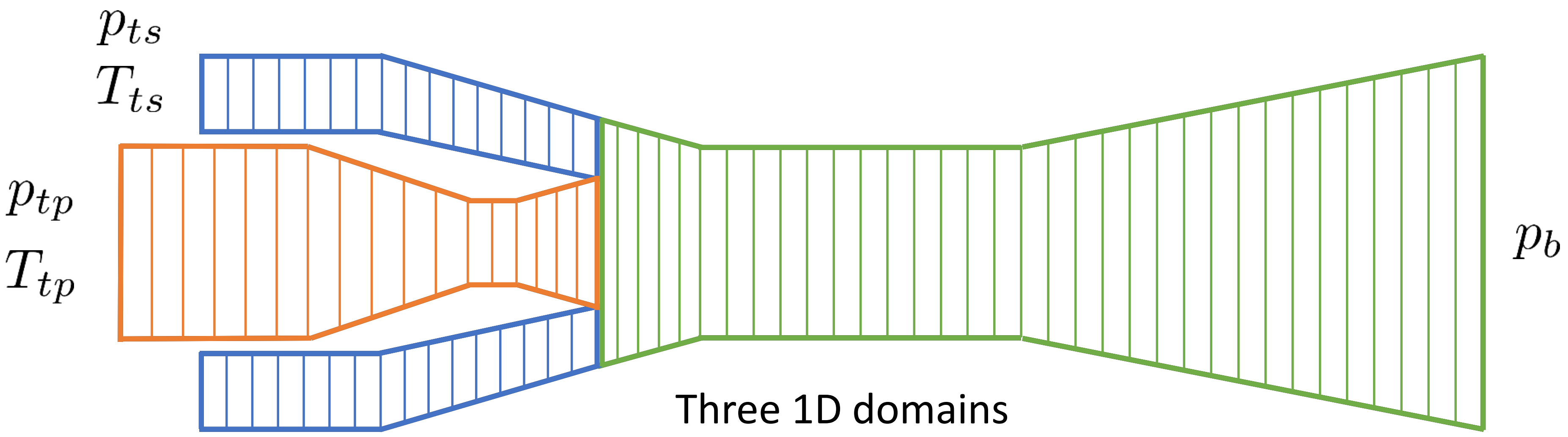
Research questions

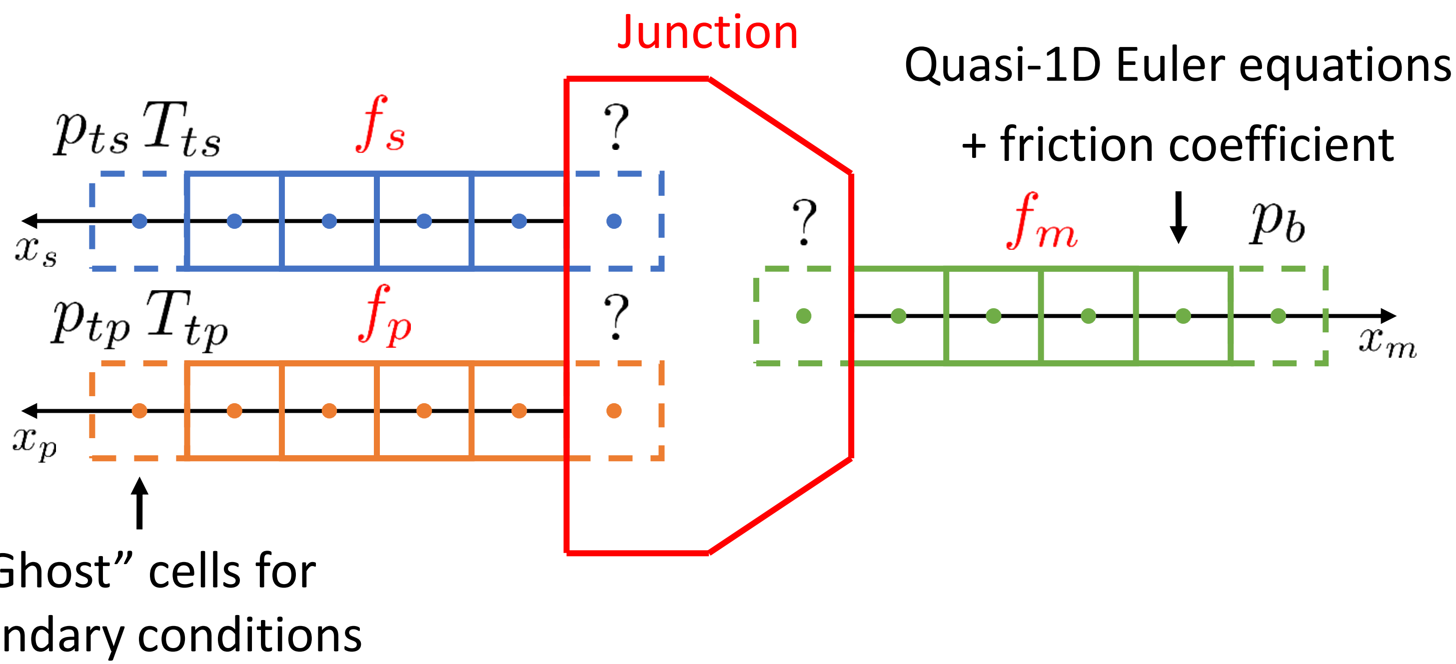
1. How does such a 1D model relate to the existing 0D models and experiments? (validation)
2. How accurate are the spatial distributions compared to (un)steady CFD? (verification)

Contents

- **Model definition**
- Results
- Conclusion

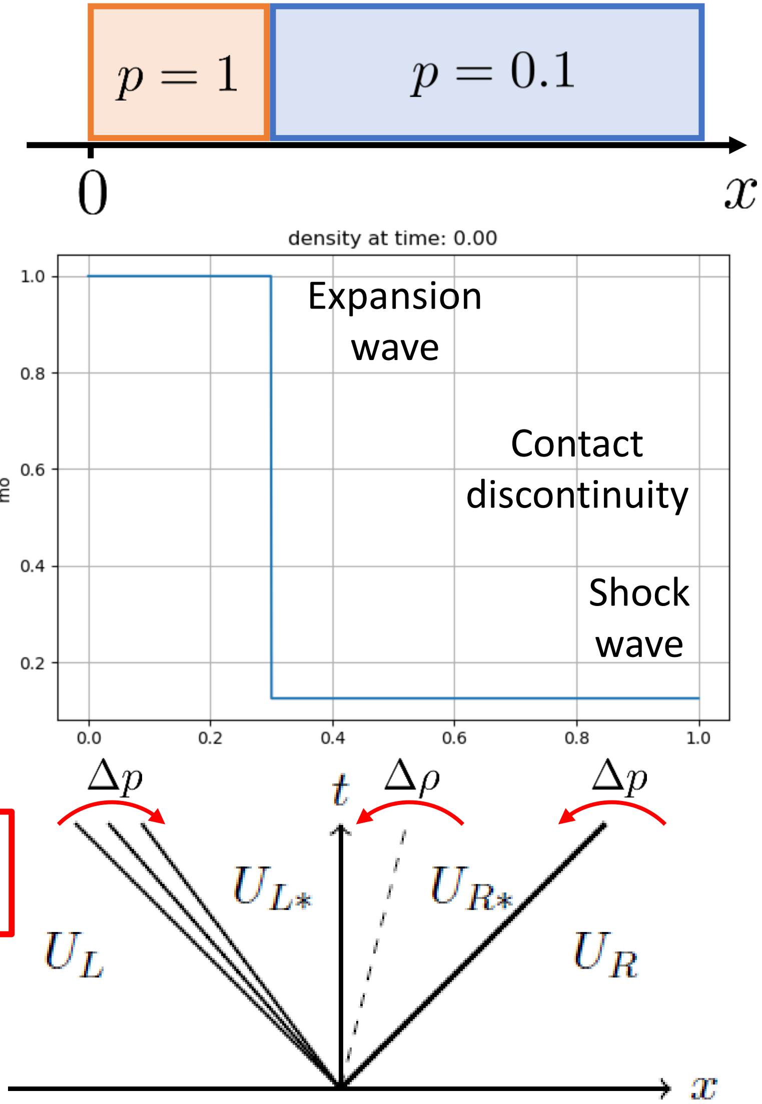
A pipeline analogy for ejectors





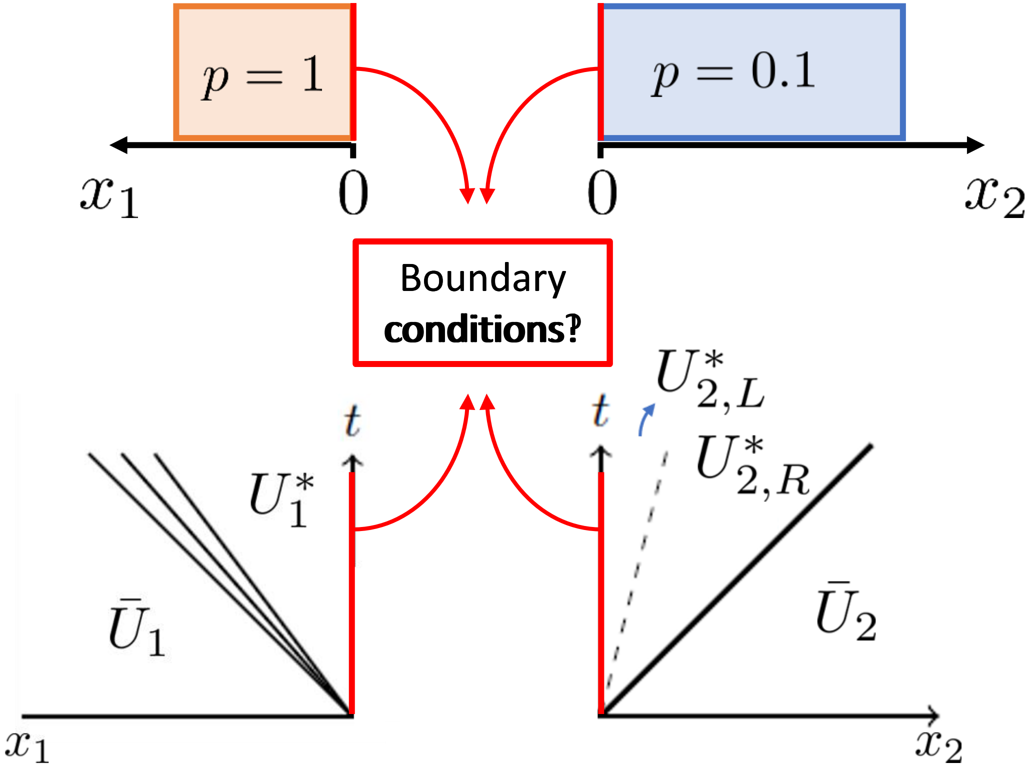
A step back: a junction of two pipes

Continuous shock tube



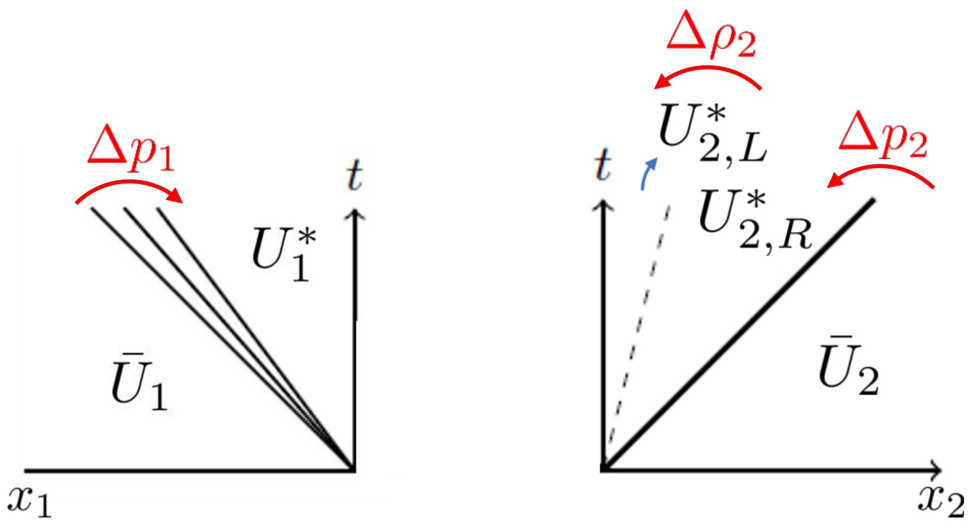
Rankine-Hugoniot "jump relations"

Junction of two pipes



1. The star states serve as boundary conditions
2. They should respect the jump relations and conservation across the junction

How are the boundary conditions computed?



1. The star states serve as boundary conditions
2. They should respect the jump relations and conservation across the junction

1. Compute the star states with the jump relations

$$U_1^* = f_{exp}\left(\bar{U}_1, \Delta p_1\right) \qquad \begin{cases} U_{2,R}^* &= f_{comp}\left(\bar{U}_2, \Delta p_2\right) \\ U_{2,L}^* &= f_{disc}\left(U_{2,R}^*, \Delta \rho_2\right) \end{cases}$$

$\Delta p_1, \Delta p_2$ and $\Delta \rho_2$ are unknown!

2. Iterate on the jumps until the conservation equations are respected

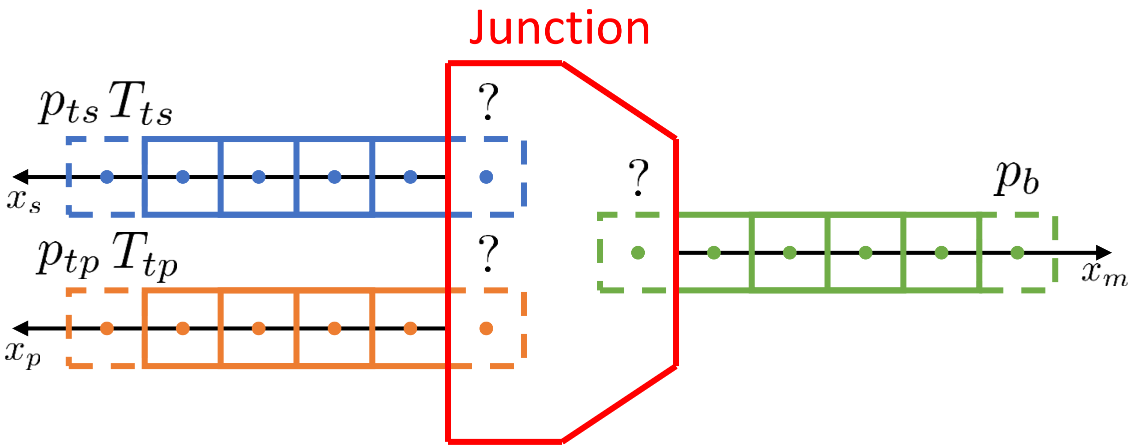
Initial guess $\left[\Delta p_1, \Delta p_2, \Delta \rho_2\right] \longrightarrow \left[U_1^*, U_{2,L}^*\right]$

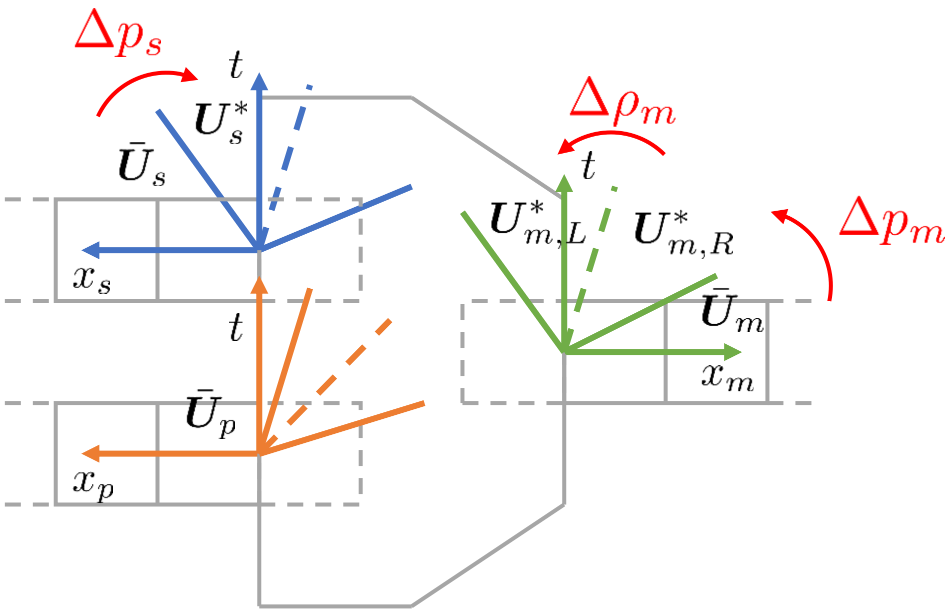
$$\dot{m}_1 \stackrel{?}{=} \dot{m}_2$$

$$\dot{m}_1 u_1 + A_1 p_1 \stackrel{?}{=} \dot{m}_2 u_2 + A_2 p_2$$

$$\dot{m}_1 h_{t,1} \stackrel{?}{=} \dot{m}_2 h_{t,2}$$

What about the three pipes of the ejector model?



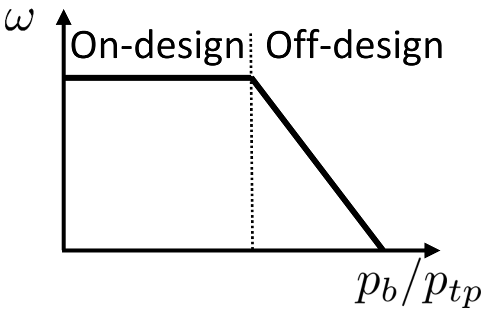


1. **Look at the characteristics**

Normal operation

$u_s > 0 \longrightarrow \Delta p_s$

$u_m > 0 \longrightarrow \Delta p_m, \Delta \rho_m$



Choked primary nozzle

$M_p \geq 1 \longrightarrow$ No boundary condition needed!

$\Delta p_s, \Delta p_m$ and $\Delta \rho_m$ are unknown!

2. **Iterate on the jumps until the conservation equations are respected (as before)**

$$\dot{m}_p + \dot{m}_s \stackrel{?}{=} \dot{m}_m$$

$$\dot{m}_p u_p + A_p p_p + \dot{m}_s u_s + A_s p_s \stackrel{?}{=} \dot{m}_m u_m + A_m p_m$$

$$\dot{m}_p h_{t,p} + \dot{m}_s h_{t,s} \stackrel{?}{=} \dot{m}_m h_{t,m}$$

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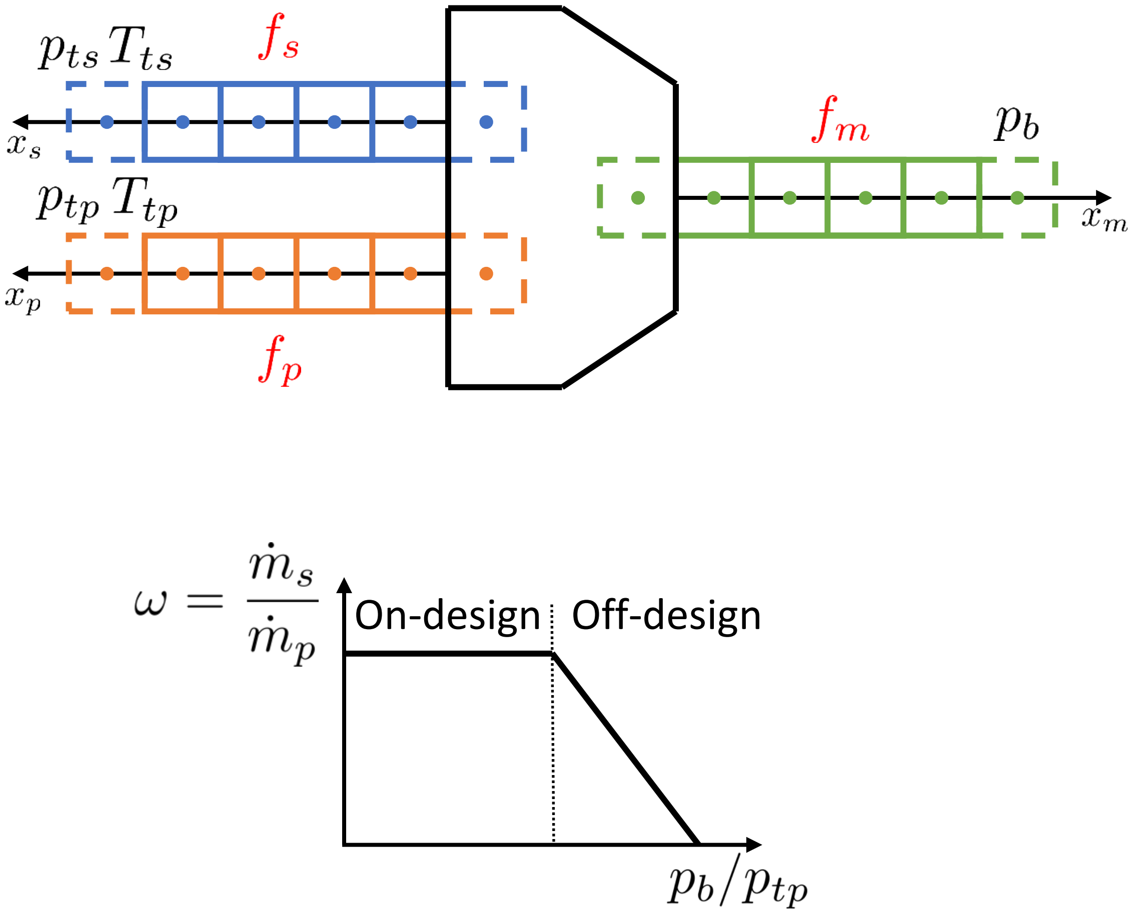
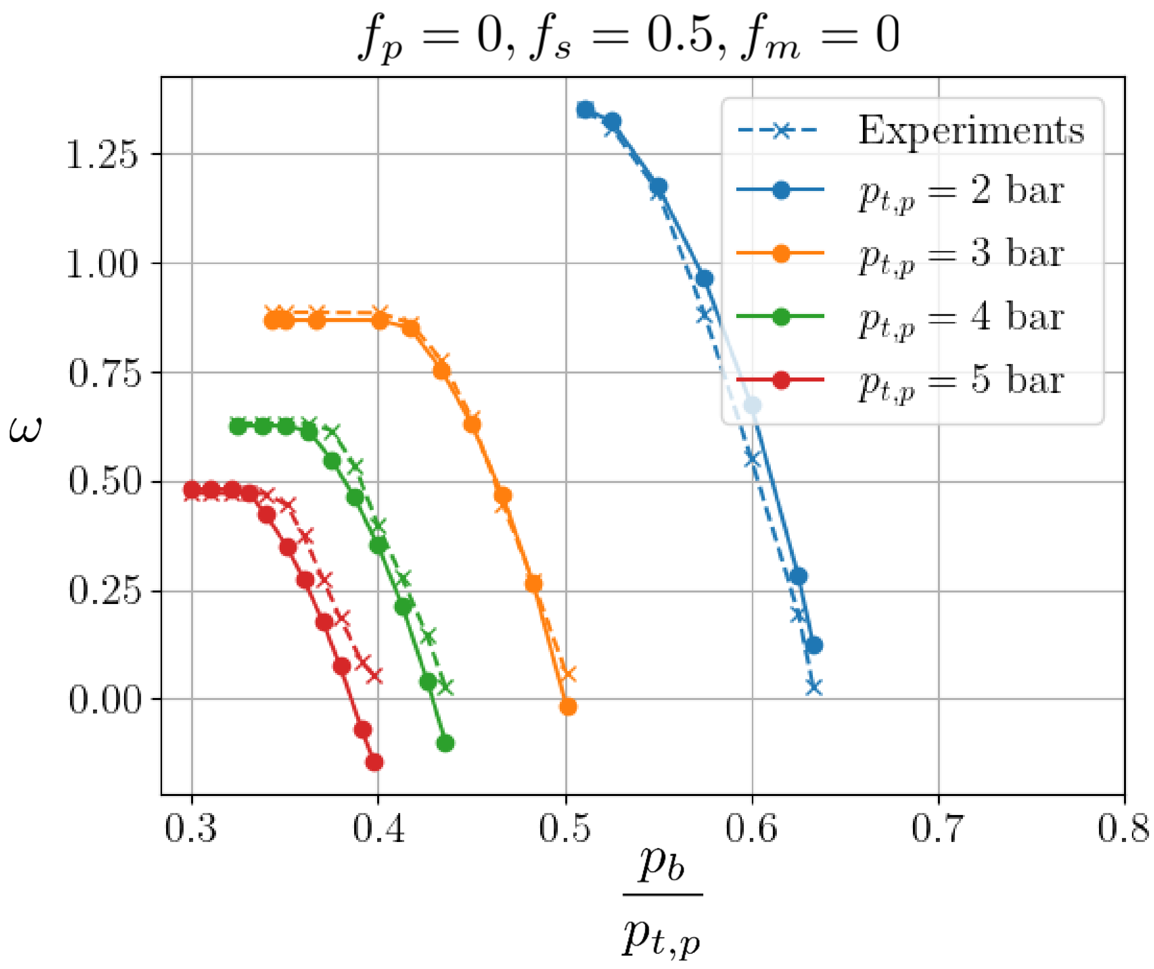
- **Results**
  - **Global validation and local inspection**
  - Local verification URANS
- Conclusion

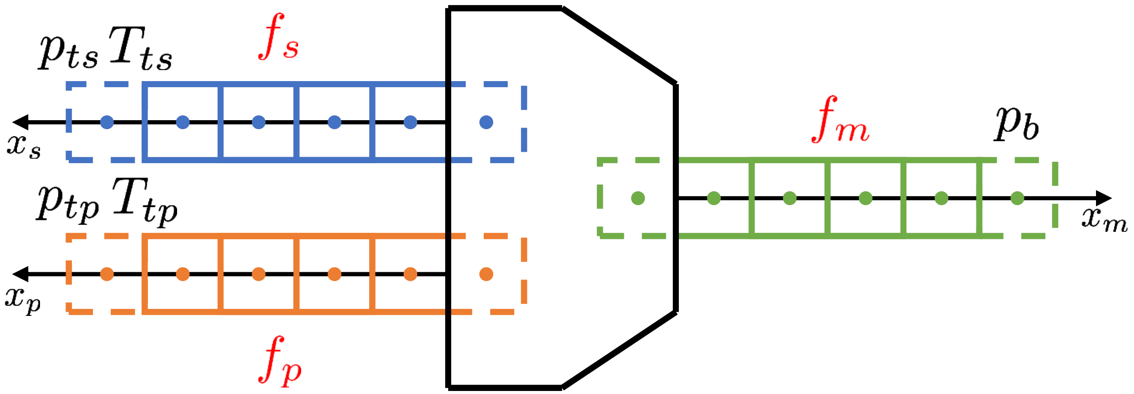
Global validation against experiments

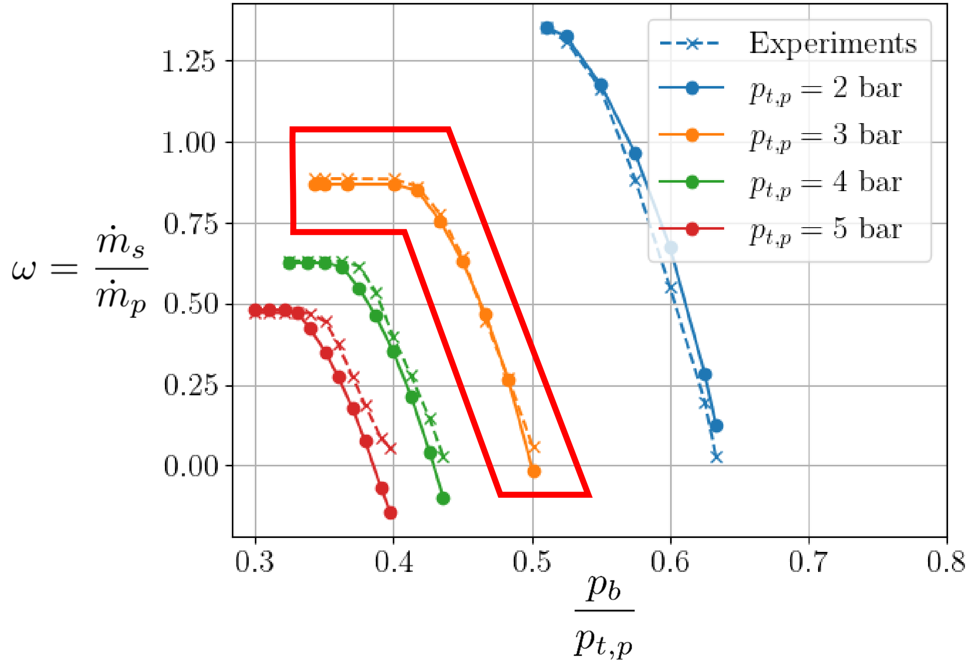




The model is validated globally

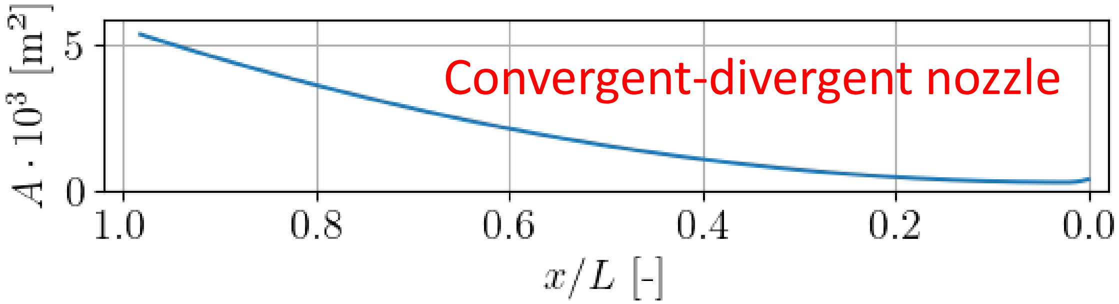
Inspection of the local solution



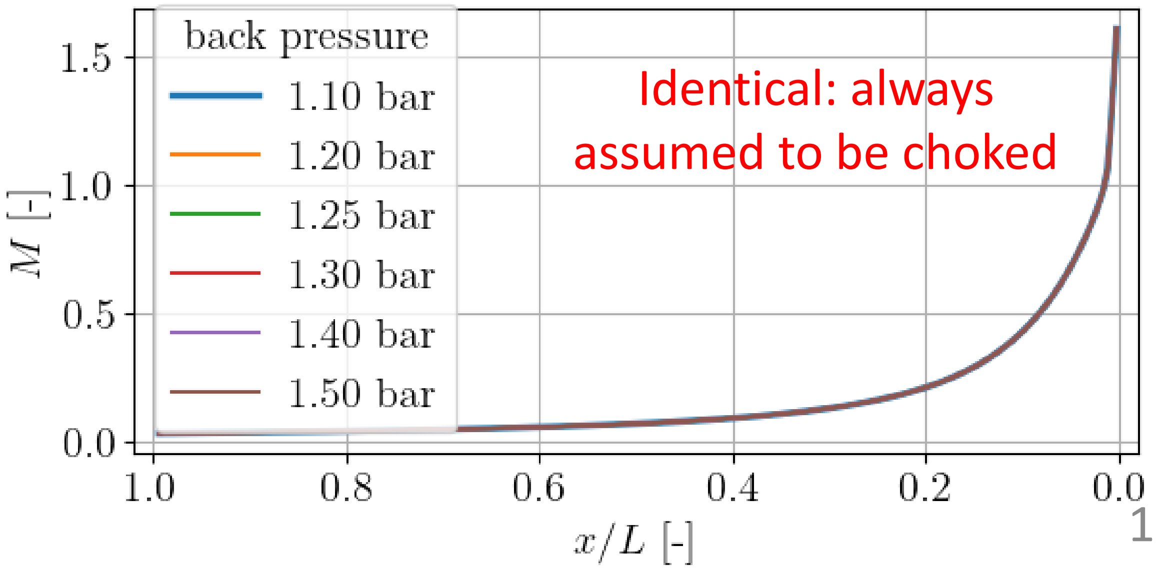


Primary inlet

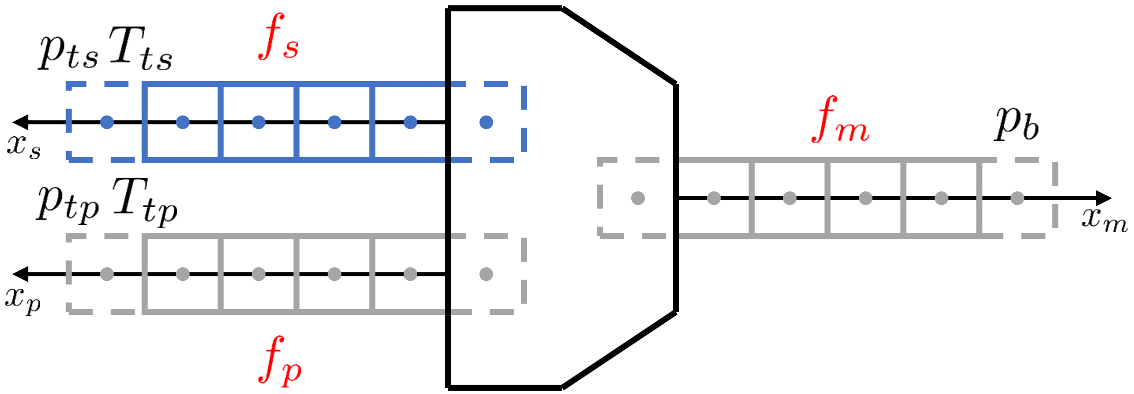
Cross-section

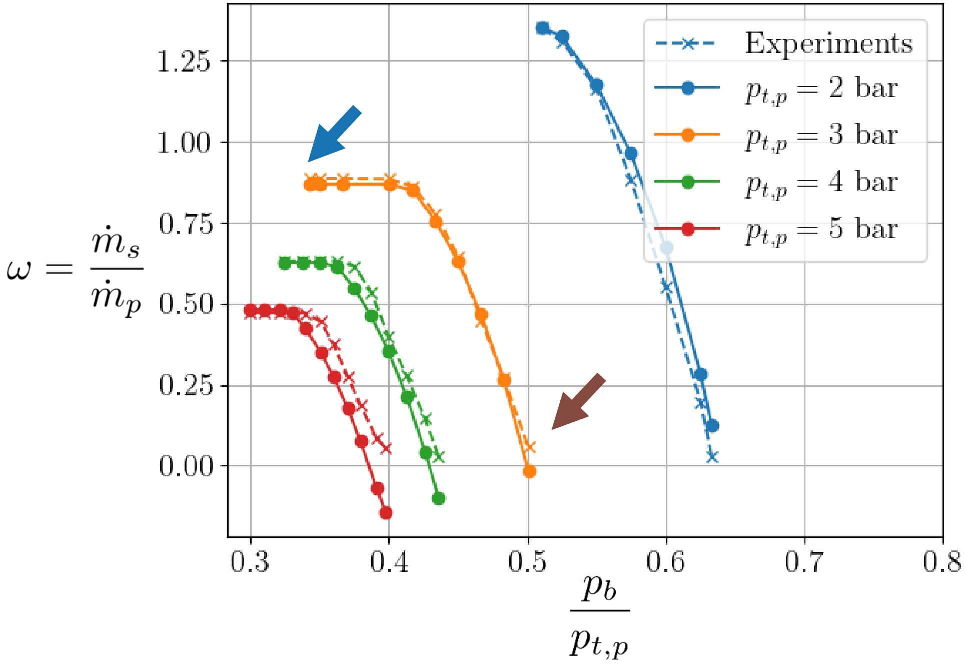


Mach number

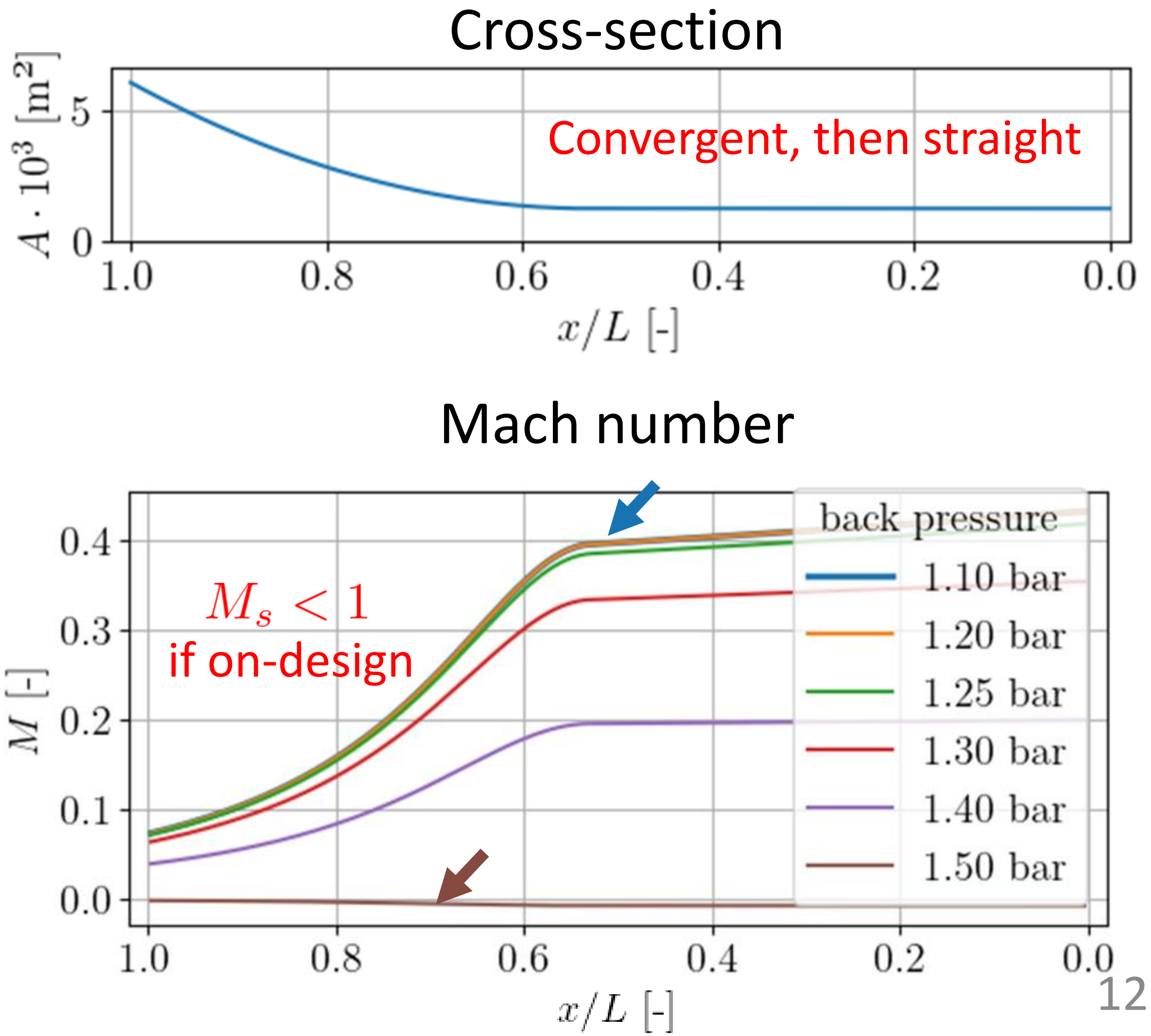


Inspection of the local solution

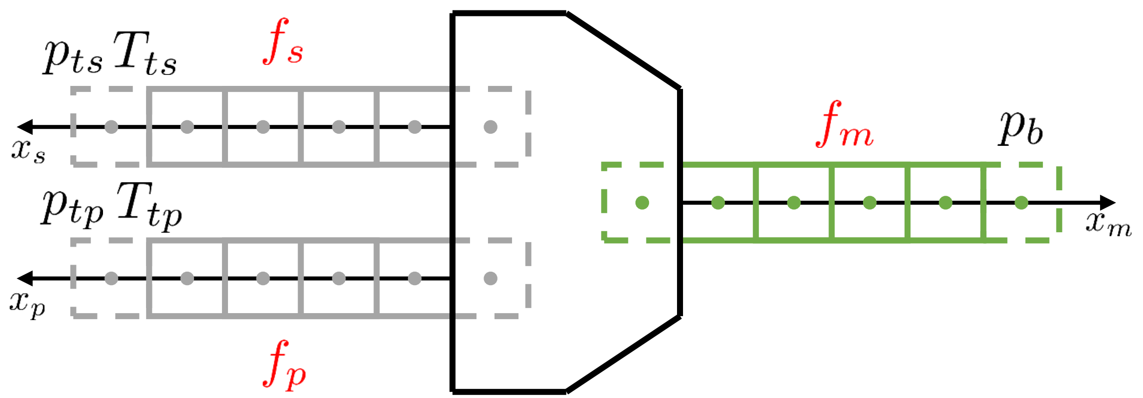


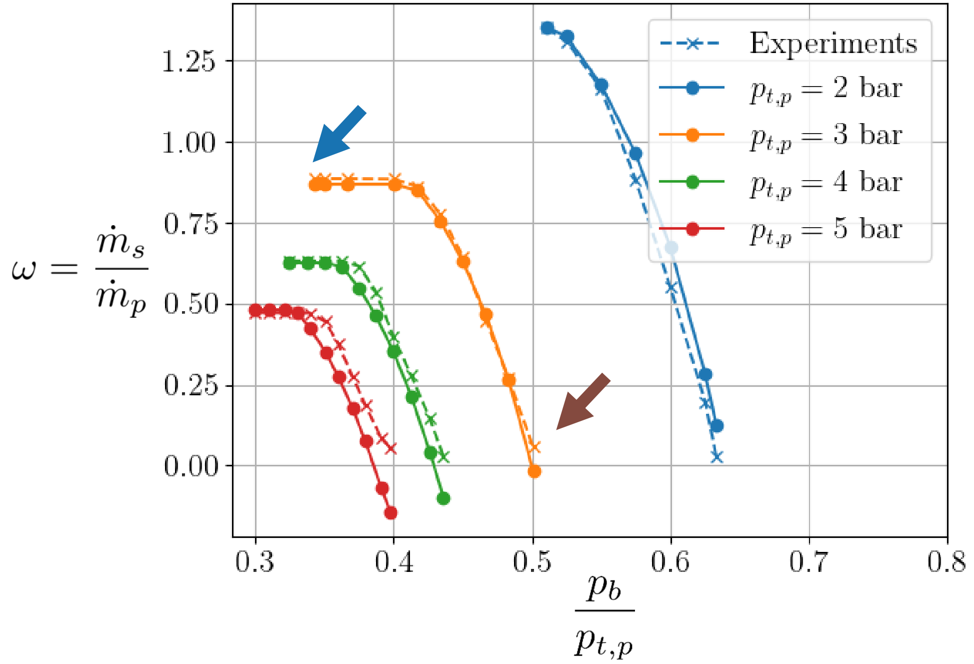


Secondary inlet

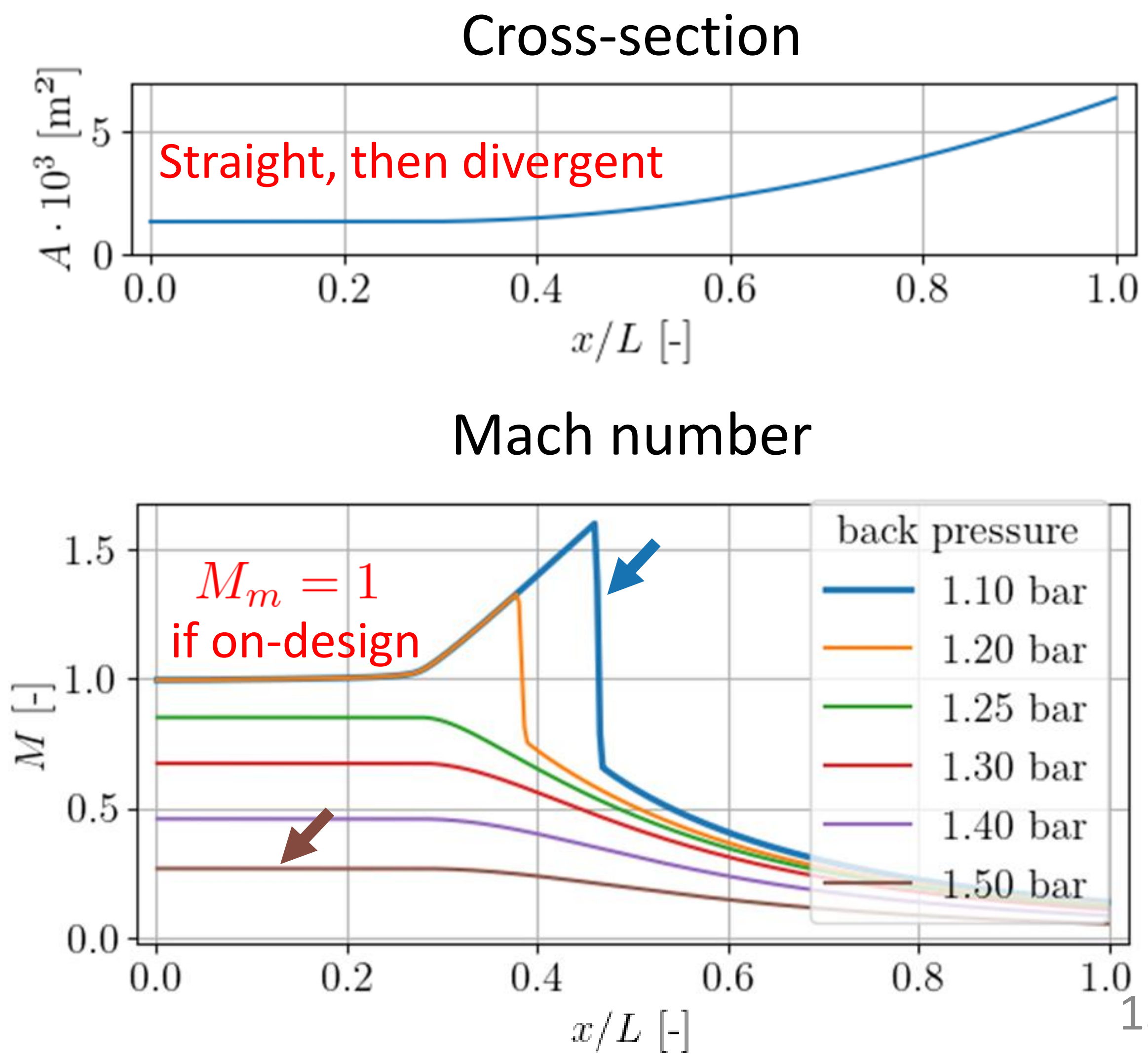


Inspection of the local solution





Mixing pipe



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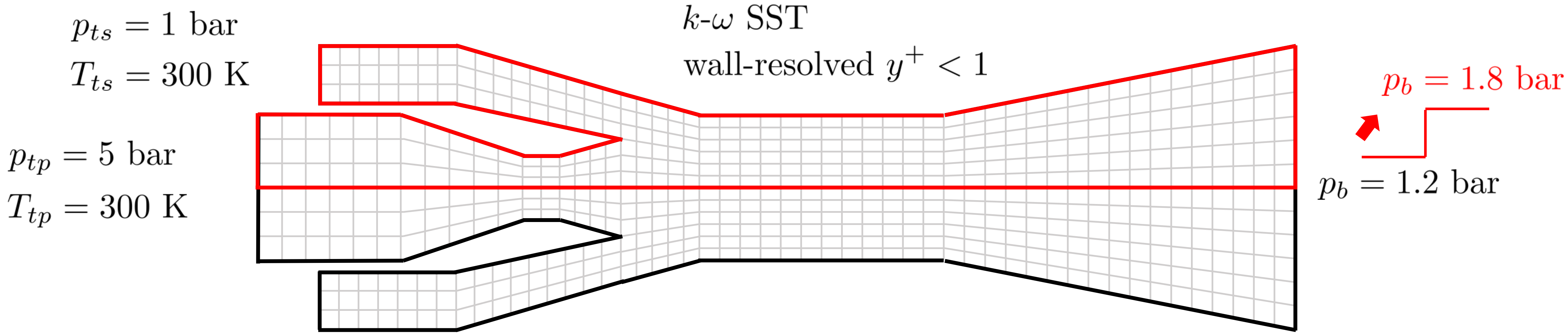
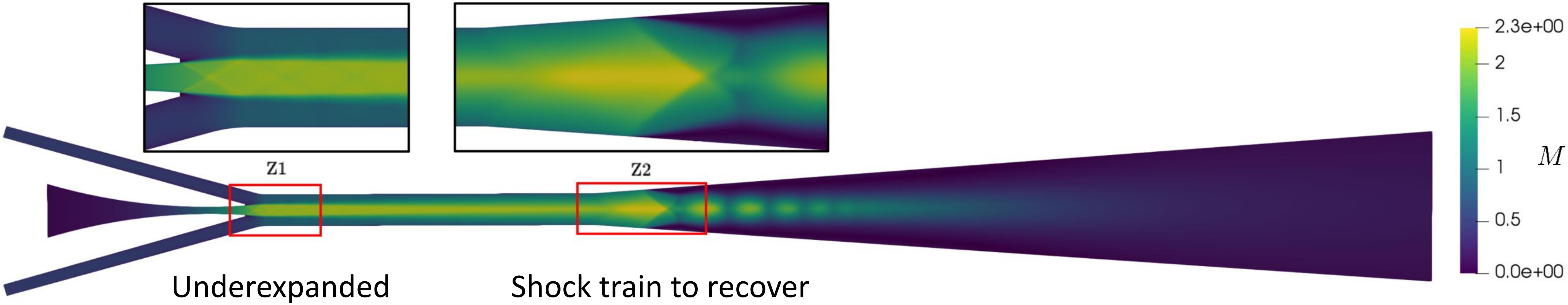
Set-up of 2D axisymmetric CFD

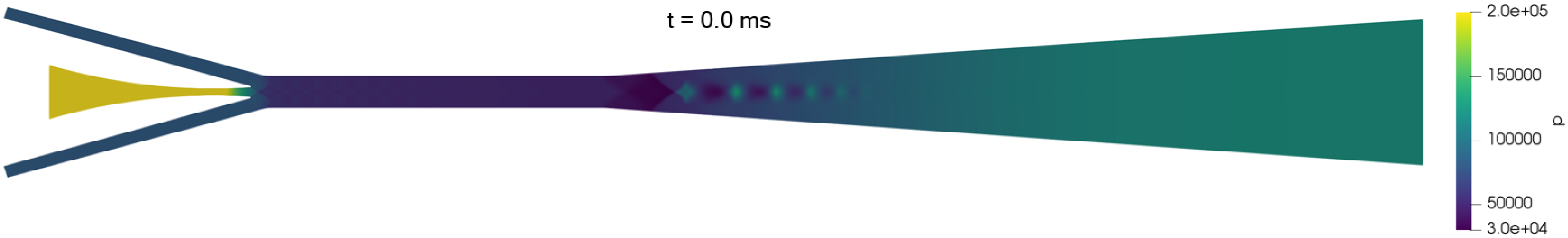




Underexpanded primary jet

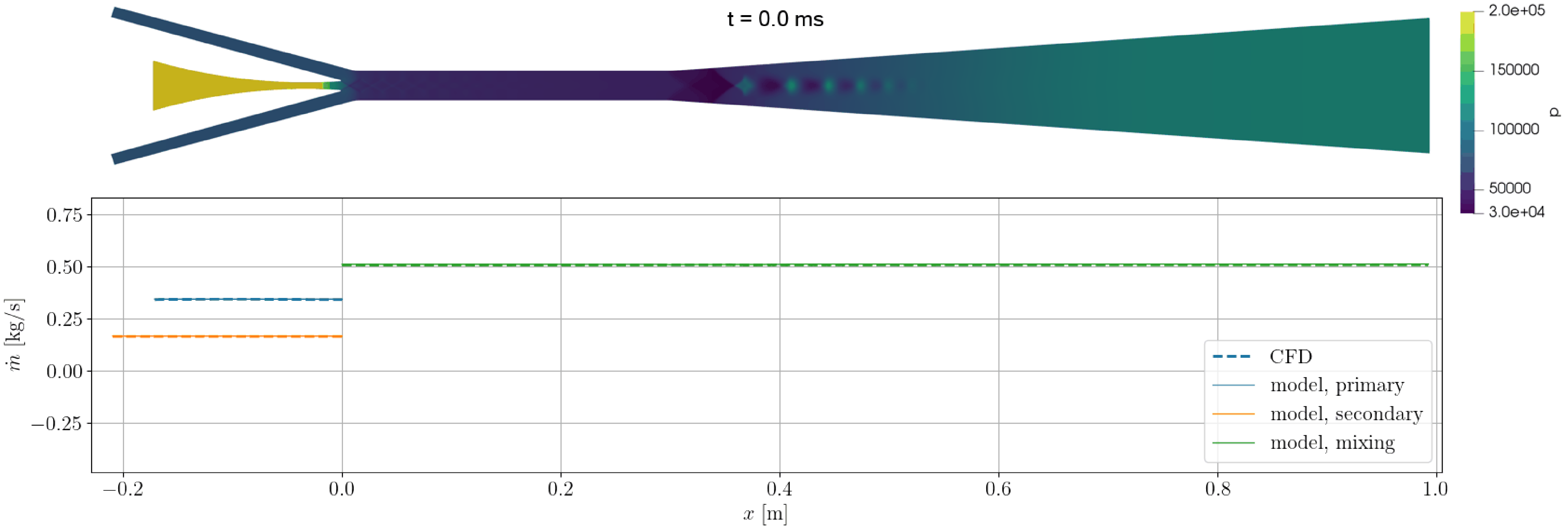
Shock train to recover back pressure

Static pressure field and 1D mass flow rates



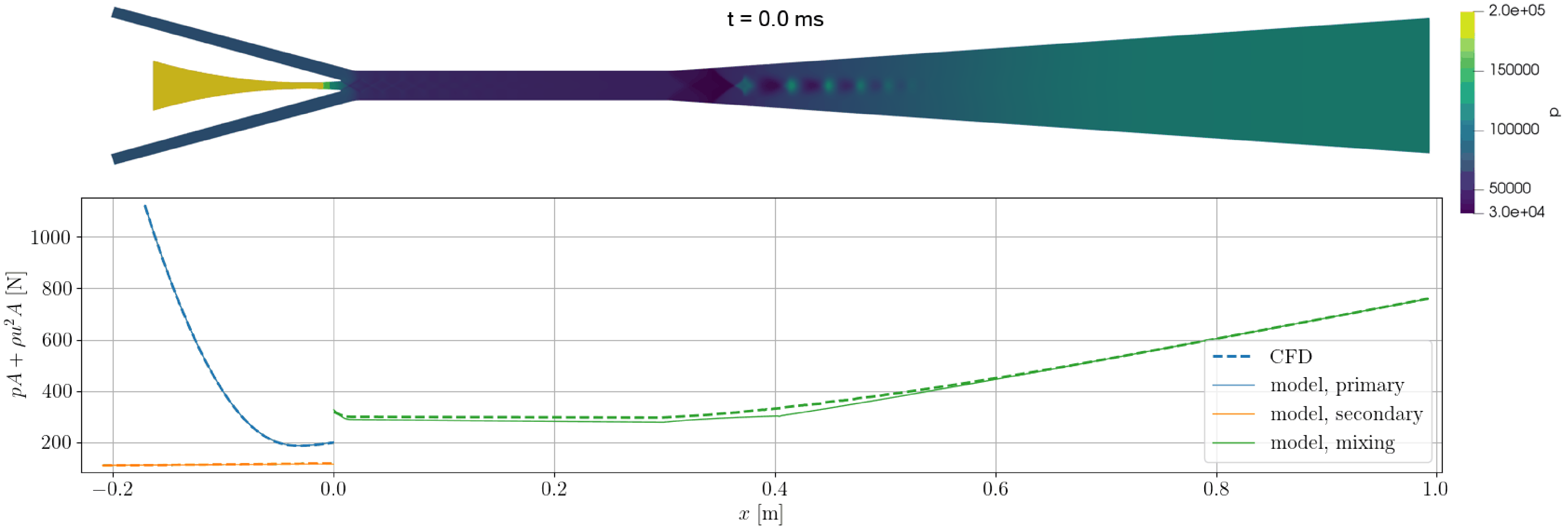
$$\dot{m} = \int \rho u dA$$

Static pressure field and 1D mass flow rates



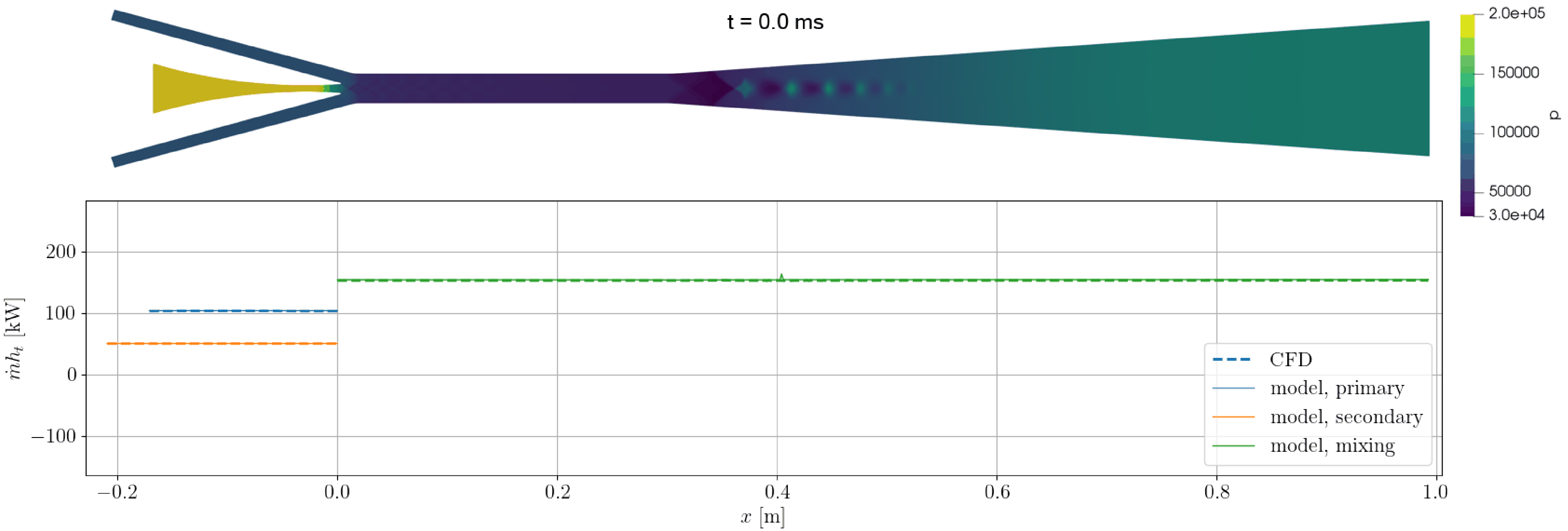
$$\dot{m} = \int \rho u dA$$

Static pressure field and 1D momentum



$$\mathcal{M} = \int (\rho u^2 + p) dA$$

Static pressure field and 1D enthalpy flow rate



$$\dot{m}h_t = \int \rho u h_t dA$$

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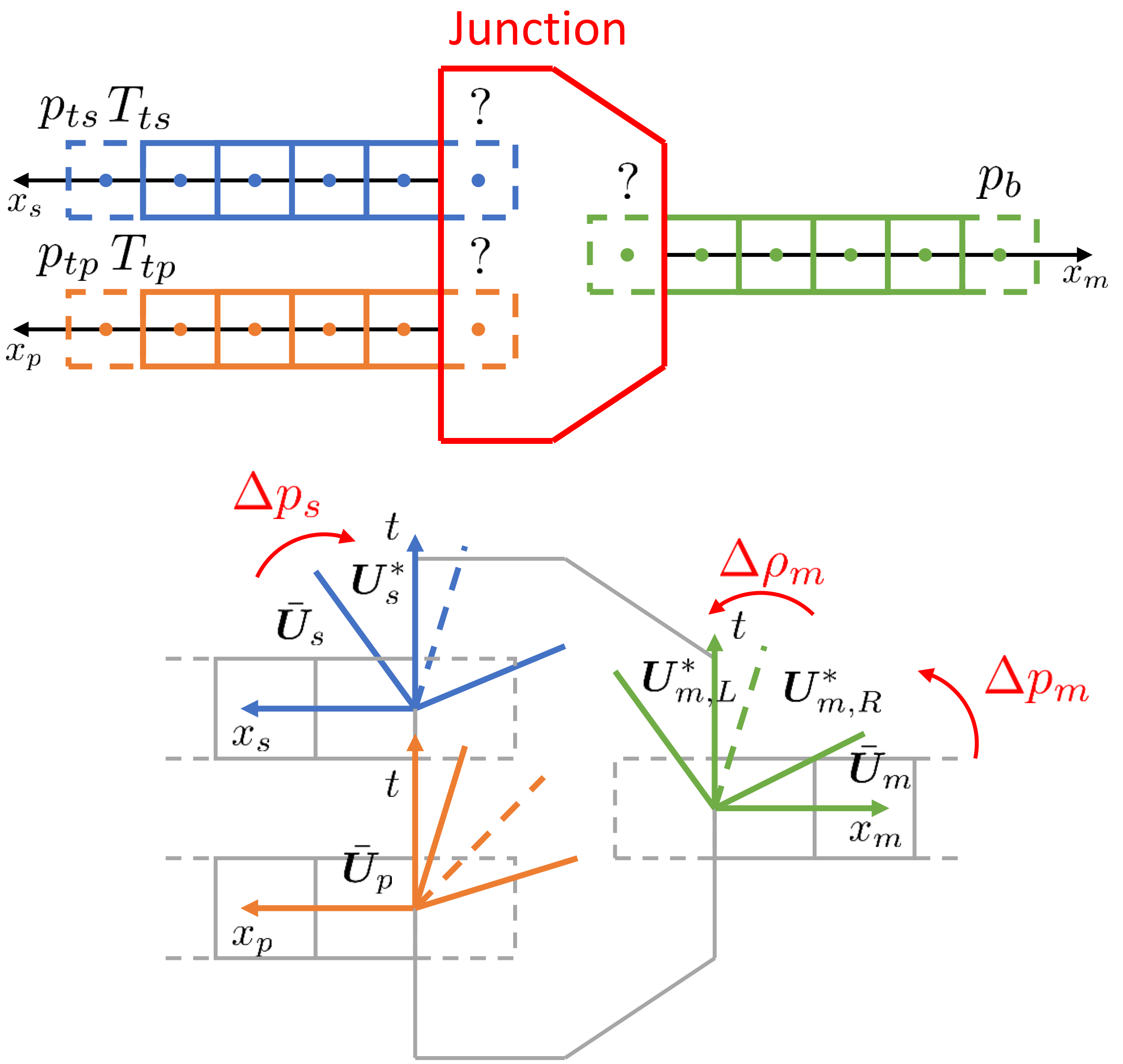
Conclusion

Goal:
Obtain unsteady 1D distributions of integral quantities

Research questions

1. How does such a 1D model relate to the existing 0D models and experiments?



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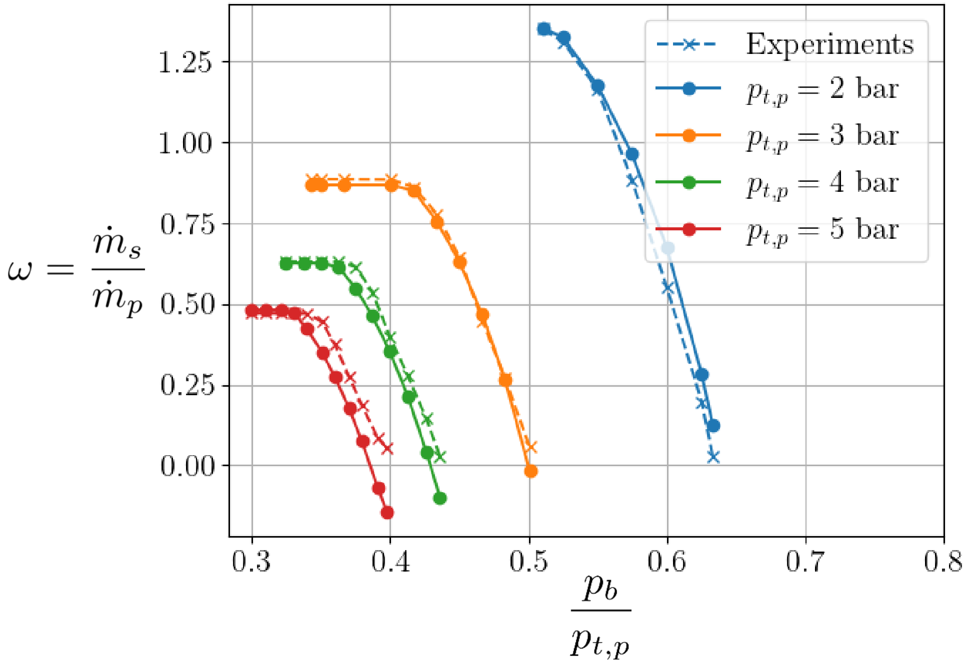
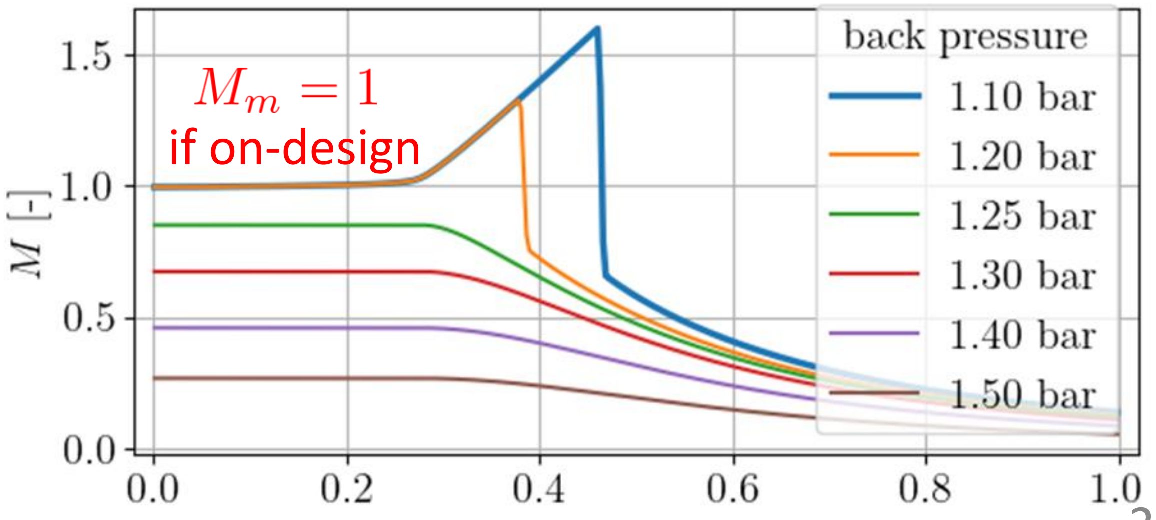
Global validation



Locally coherent with existing models



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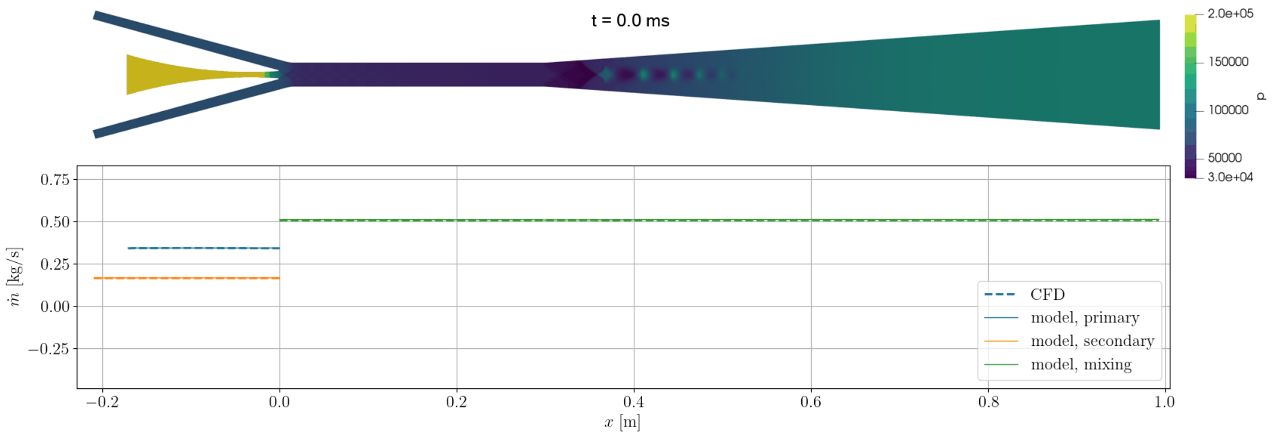
2. How accurate are the spatial distributions compared to (un)steady CFD?



- Matching mass flow rate, momentum and energy flow rate
- Matching characteristic response time

Conclusion

Goal:
Obtain unsteady 1D distributions of integral quantities

Research questions

1. How does such a 1D model relate to the existing 0D models and experiments?
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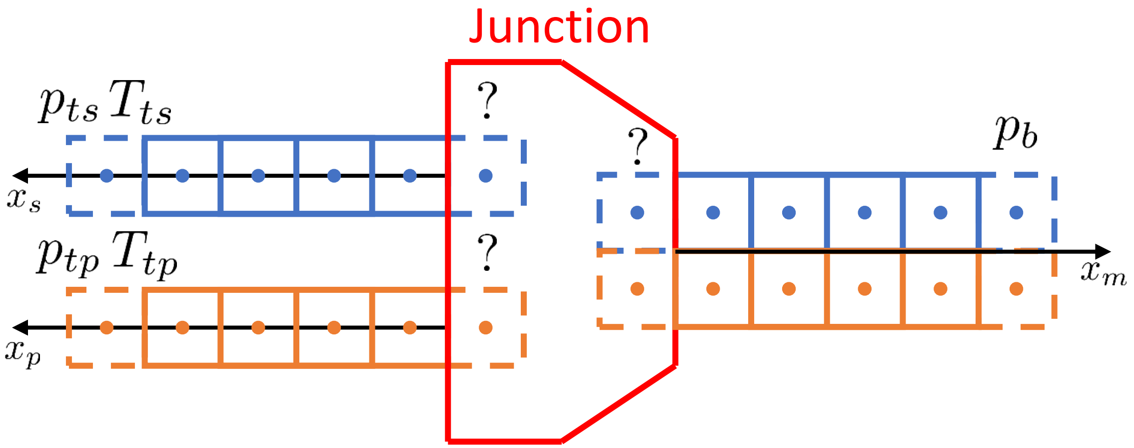
Ongoing work:
A 1D ejector model with two streams to analyze intensive quantities and mixing



$$[\dot{m}, \dot{m}V + pA, \dot{m}h_t] \rightarrow [M, p, \rho, ...]$$

References

1. 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.
2. Mazzelli F, Little AB, Garimella S, Bartosiewicz Y. Computational and experimental analysis of supersonic air ejector: Turbulence modeling and assessment of 3D effects. Int J Heat Fluid Flow 2015;56:305–16.

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