Wave speed measurements in non-ideal compressible flows

Using the Flexible Asymmetric Shock Tube (FAST)

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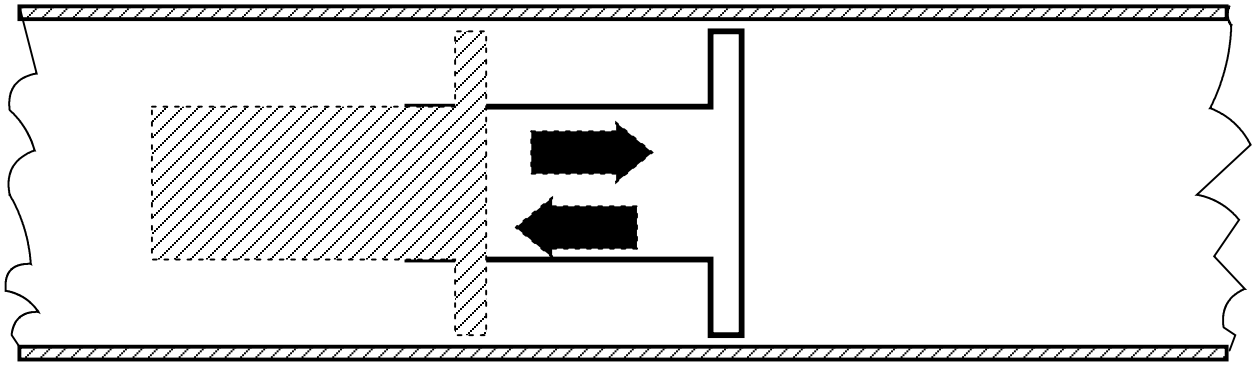
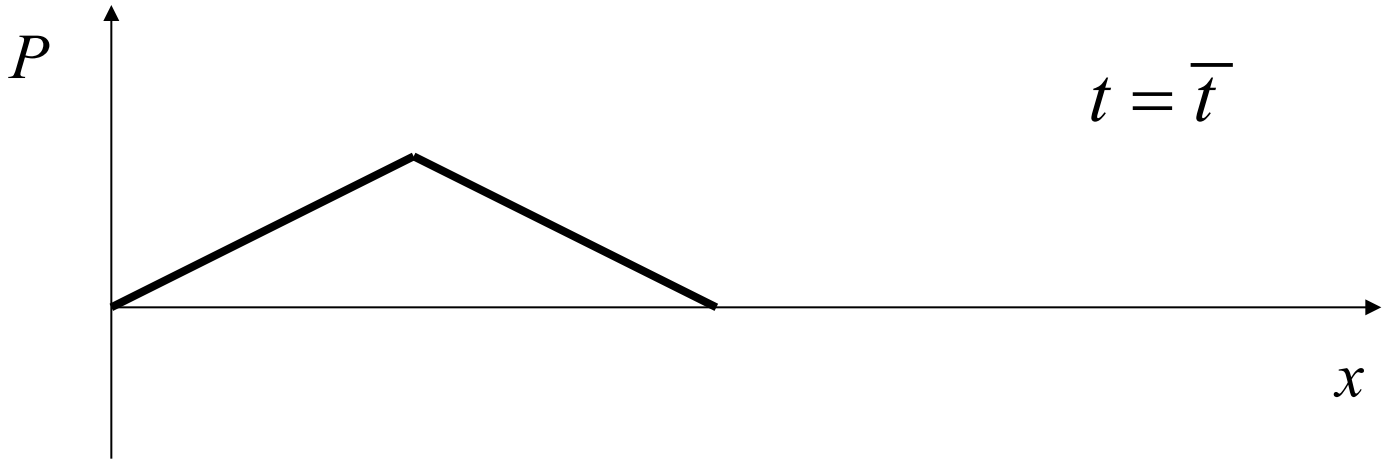
Outline

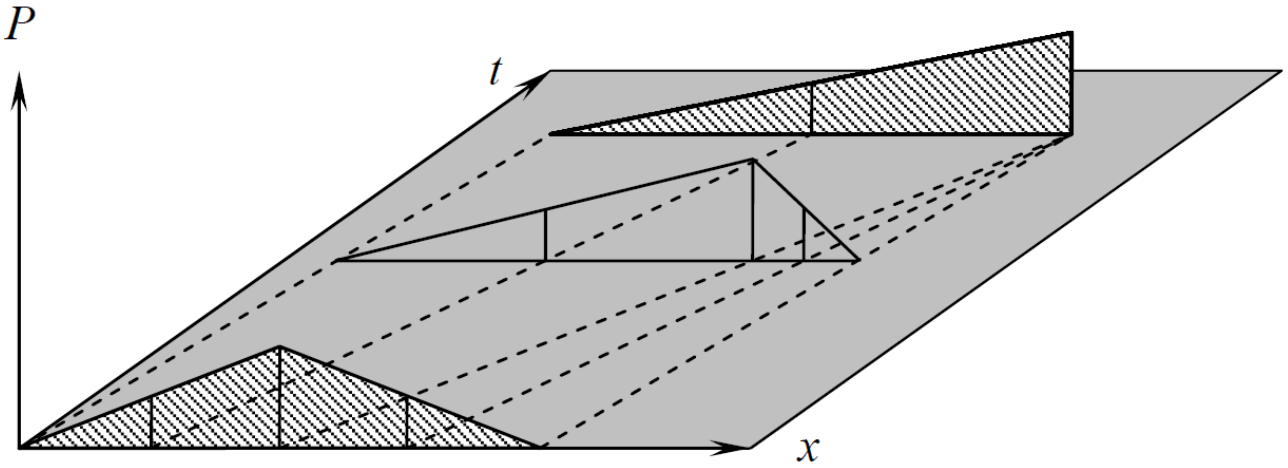
- Non-ideal compressible fluid dynamics (NICFD)
- Flexible Asymmetric Shock Tube (FAST) setup
- N_2 measurements
- D6 siloxane measurements
- Conclusions & Future Work

Example: propagation of a weak pressure wave (piston)





Shock formation and the role of Γ



wave propagation speed: $w = u + c$

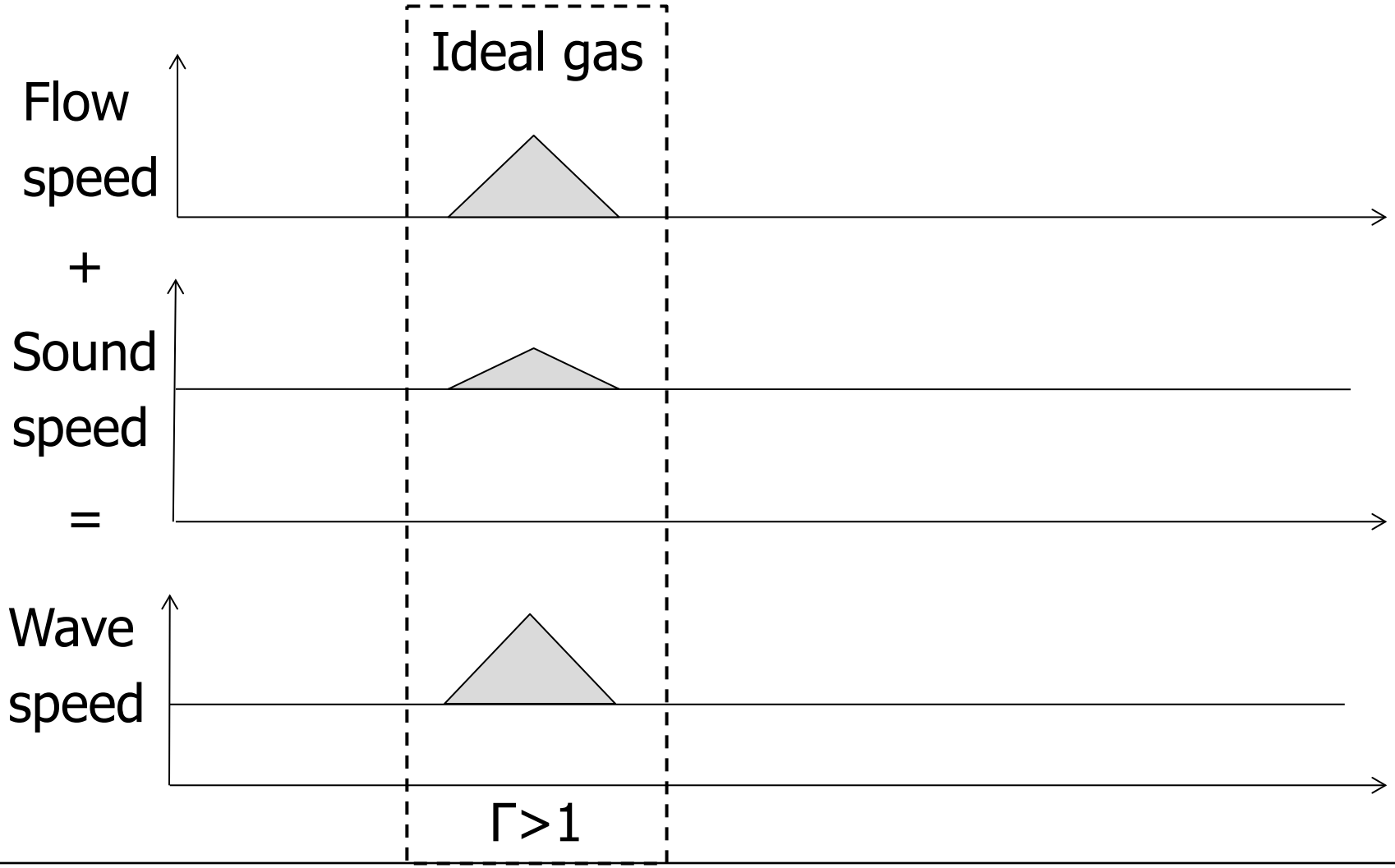
sound speed: $c^2 \equiv -v^2 \left(\frac{\partial P}{\partial v} \right)_s$

$$dw = \left[\frac{v}{c} - \frac{v^2}{c^2} \left(\frac{\partial c}{\partial v} \right)_s \right] dP$$

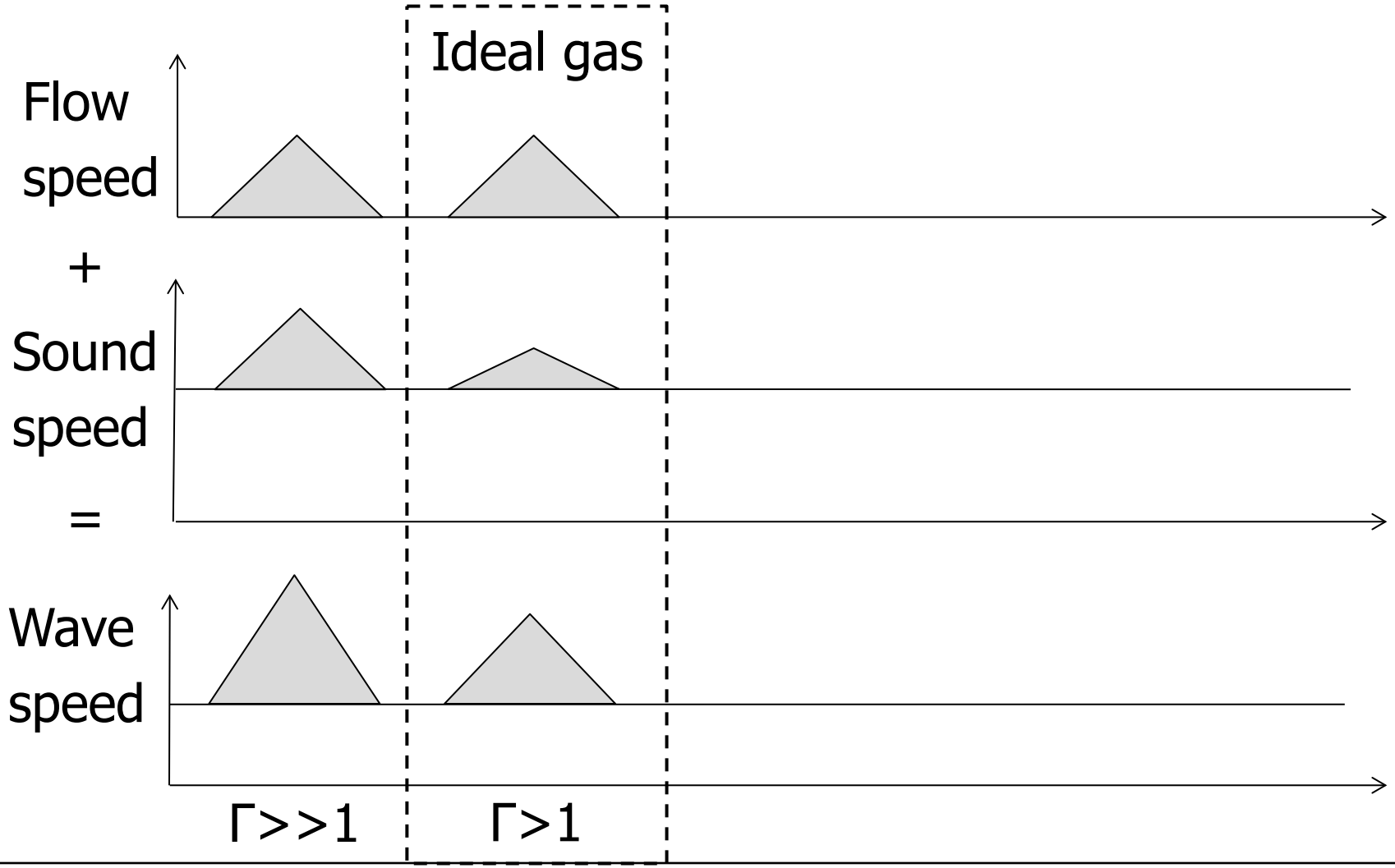
Fndmtl. derivative: $\Gamma \equiv 1 - \frac{v}{c} \left(\frac{\partial c}{\partial v} \right)_s$

$$\Rightarrow dw = \frac{v}{c} \Gamma \, dP$$

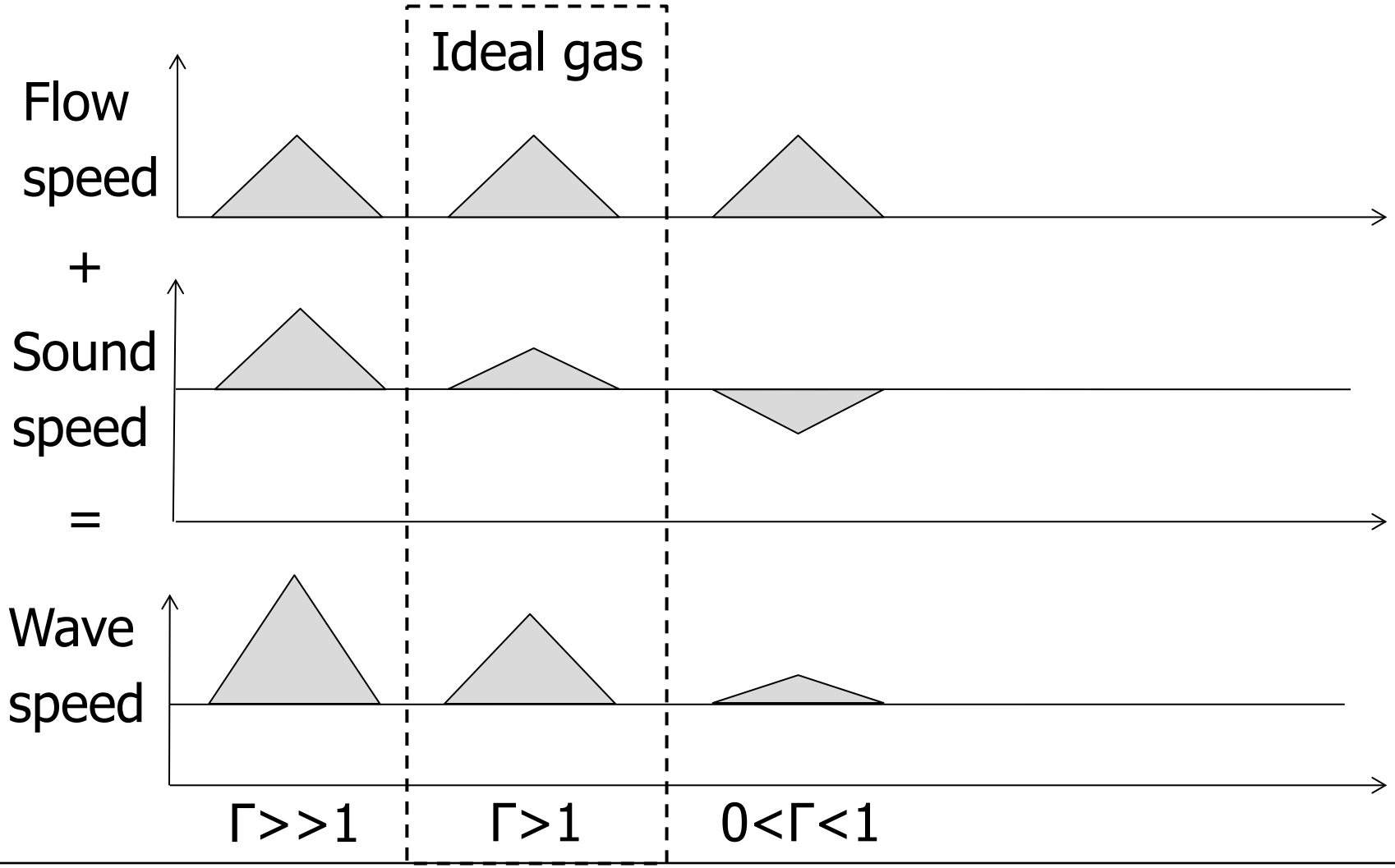
Wave propagation speed



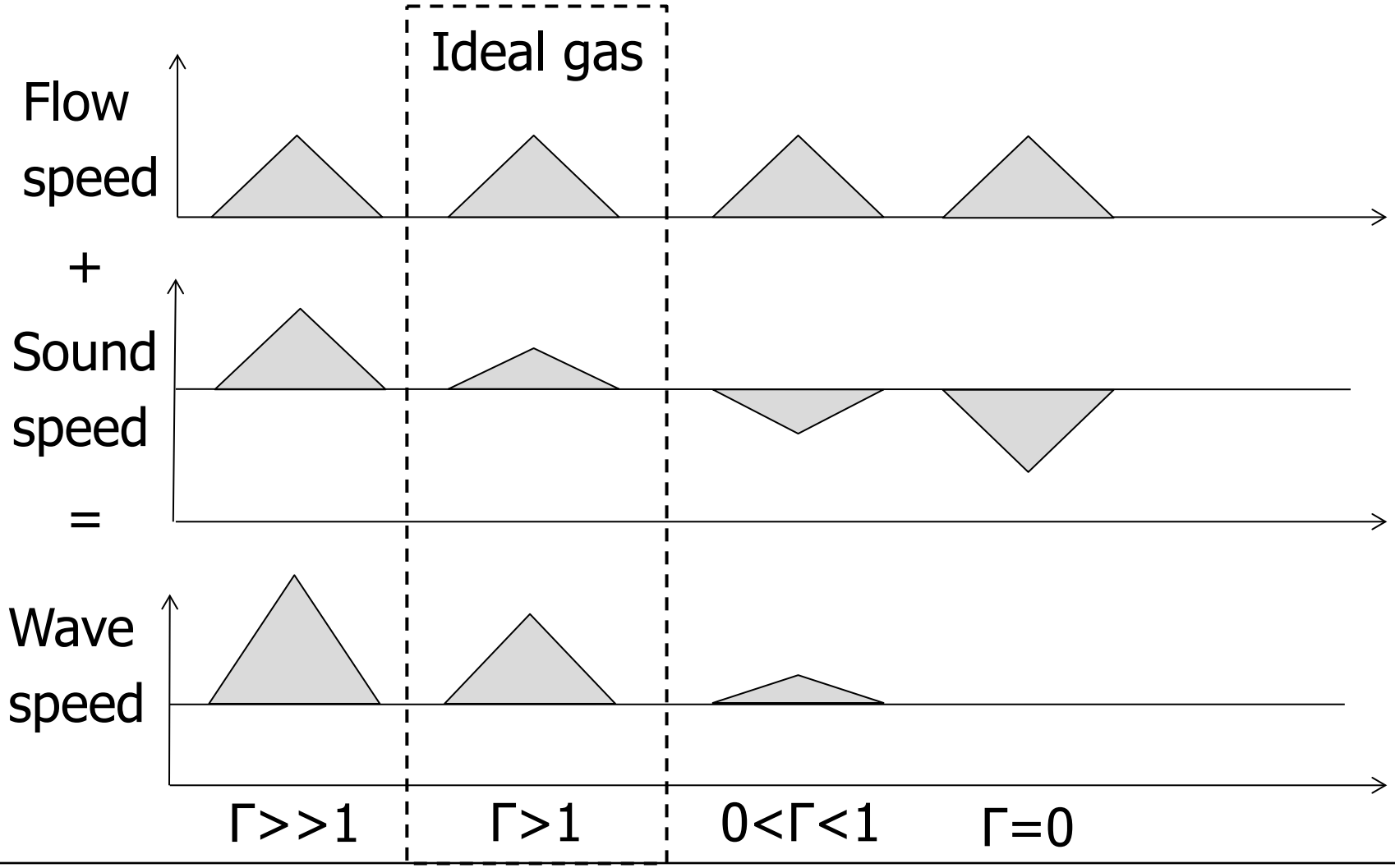
Wave propagation speed



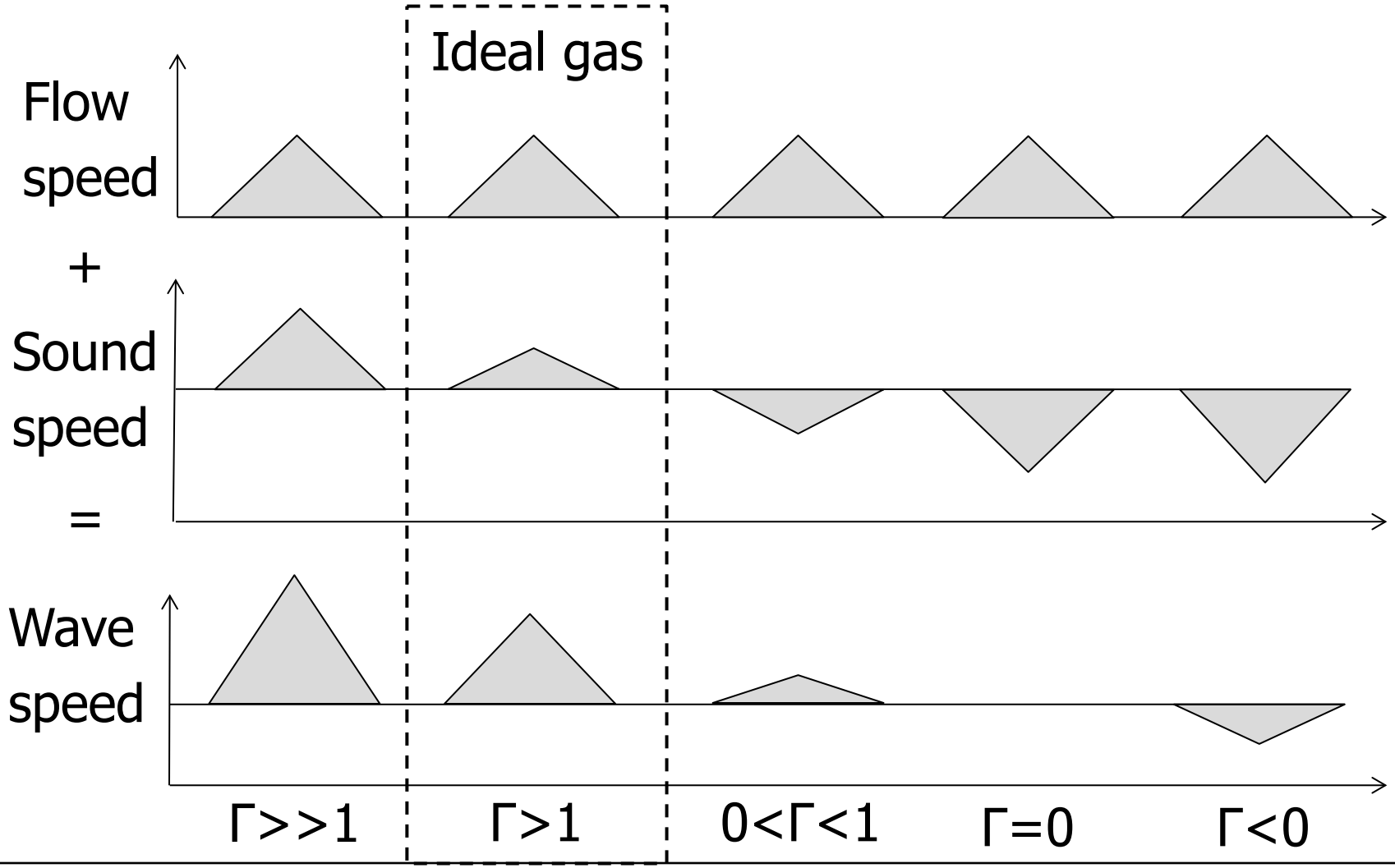
Wave propagation speed



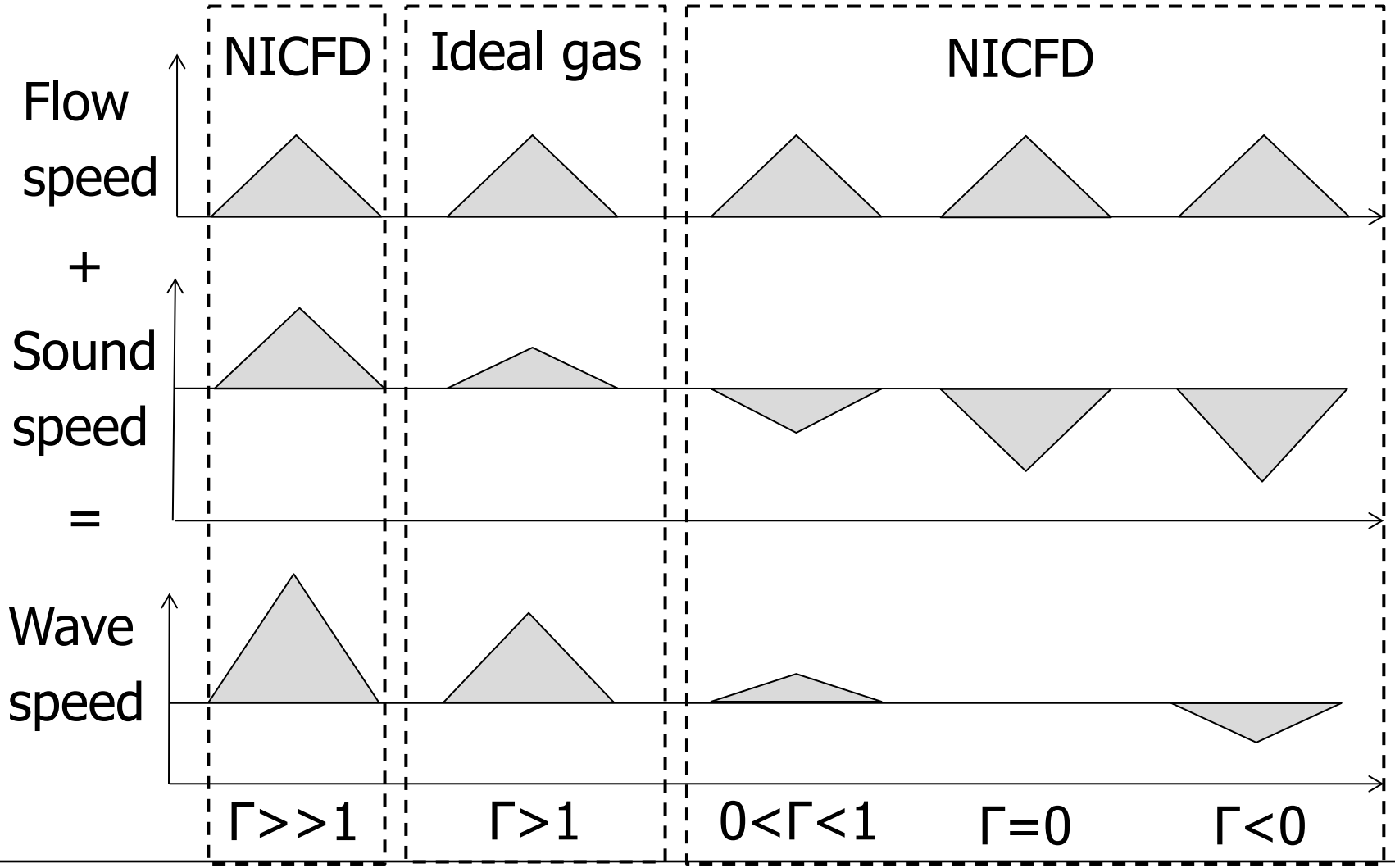
Wave propagation speed



Wave propagation speed



Wave propagation speed



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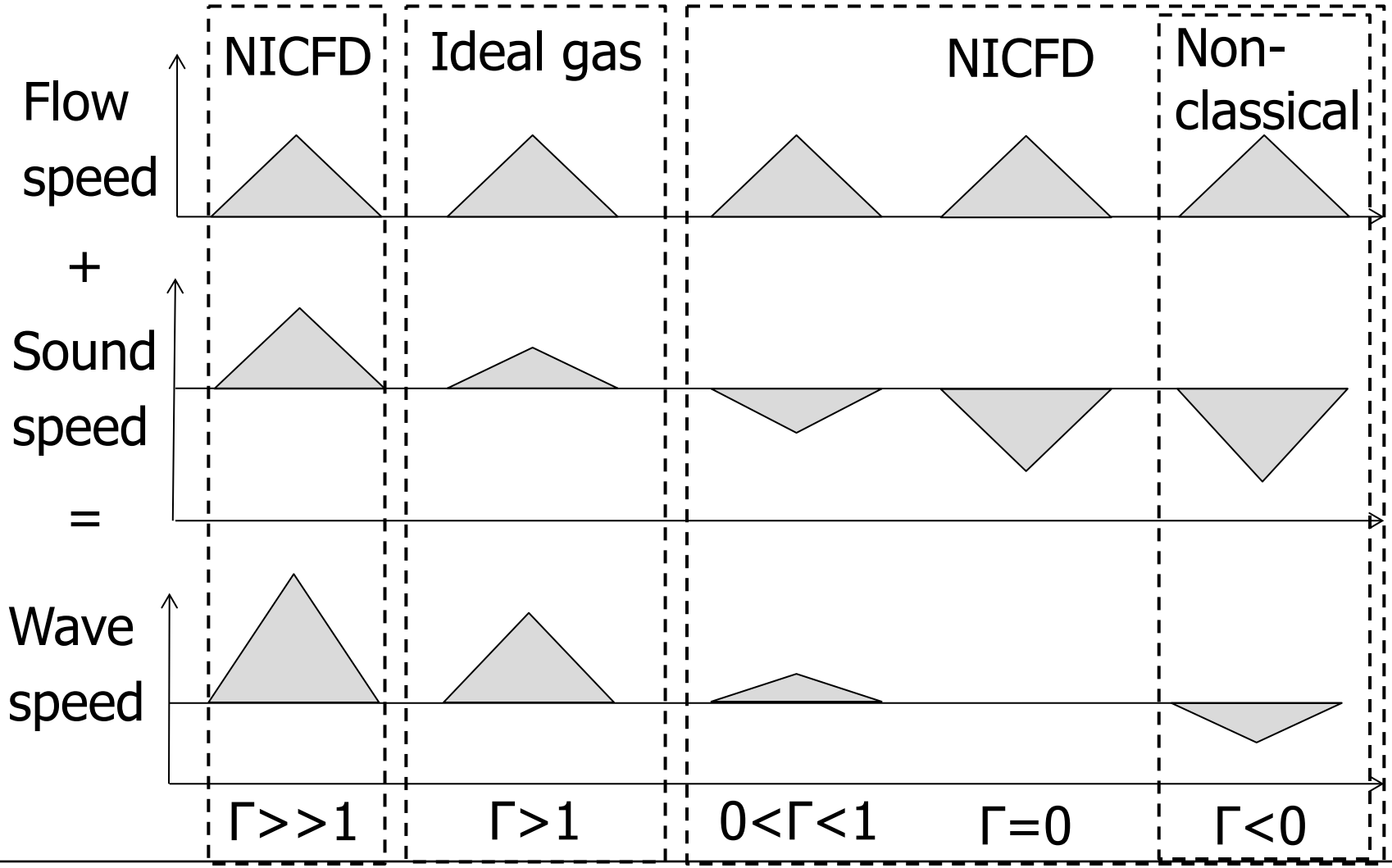
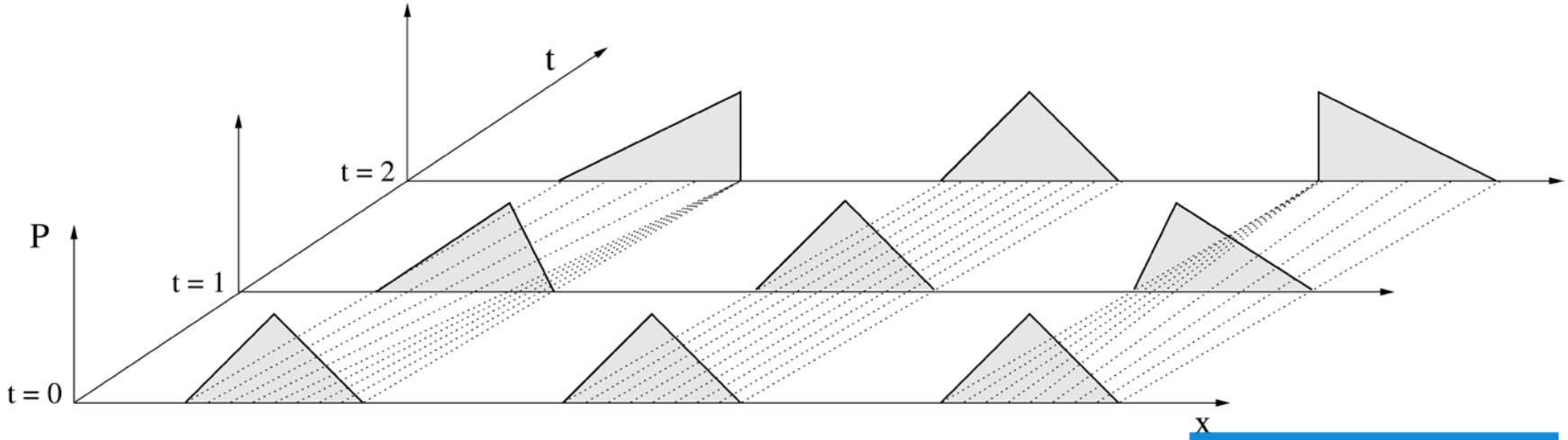


Γ and shockwaves



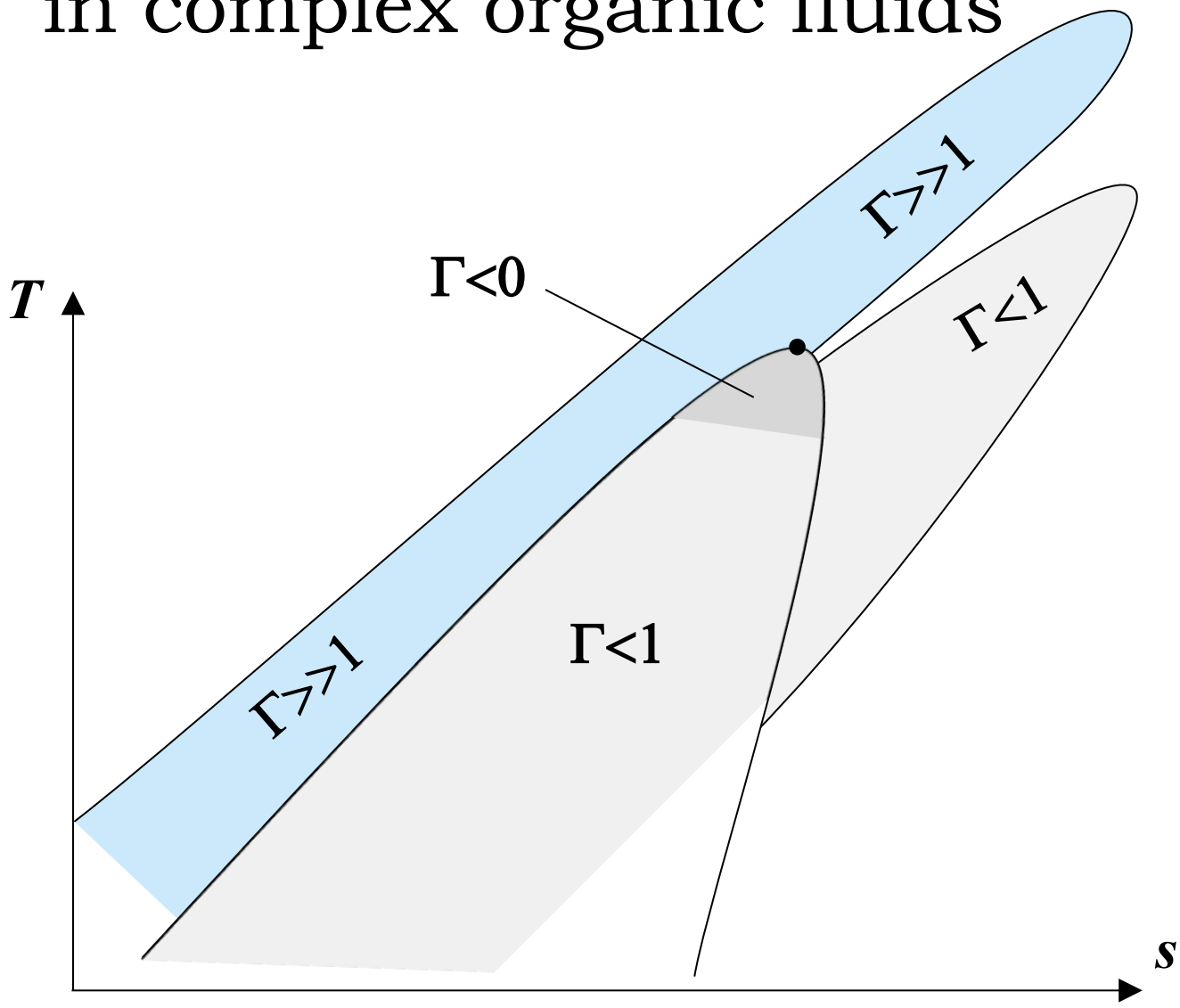
$\Gamma > 0$ $\Gamma = 0$ $\Gamma < 0$

$\Gamma>0$	$dP>0 \Rightarrow dw>0$ $dP<0 \Rightarrow dw<0$	Compression shock Rarefaction (isentropic) fan
$\Gamma=0$	$\forall dP \Rightarrow dw=0$	Stationary wave profile
$\Gamma<0$	$dP>0 \Rightarrow dw<0$ $dP<0 \Rightarrow dw>0$	Compression (isentropic) fan Rarefaction shock

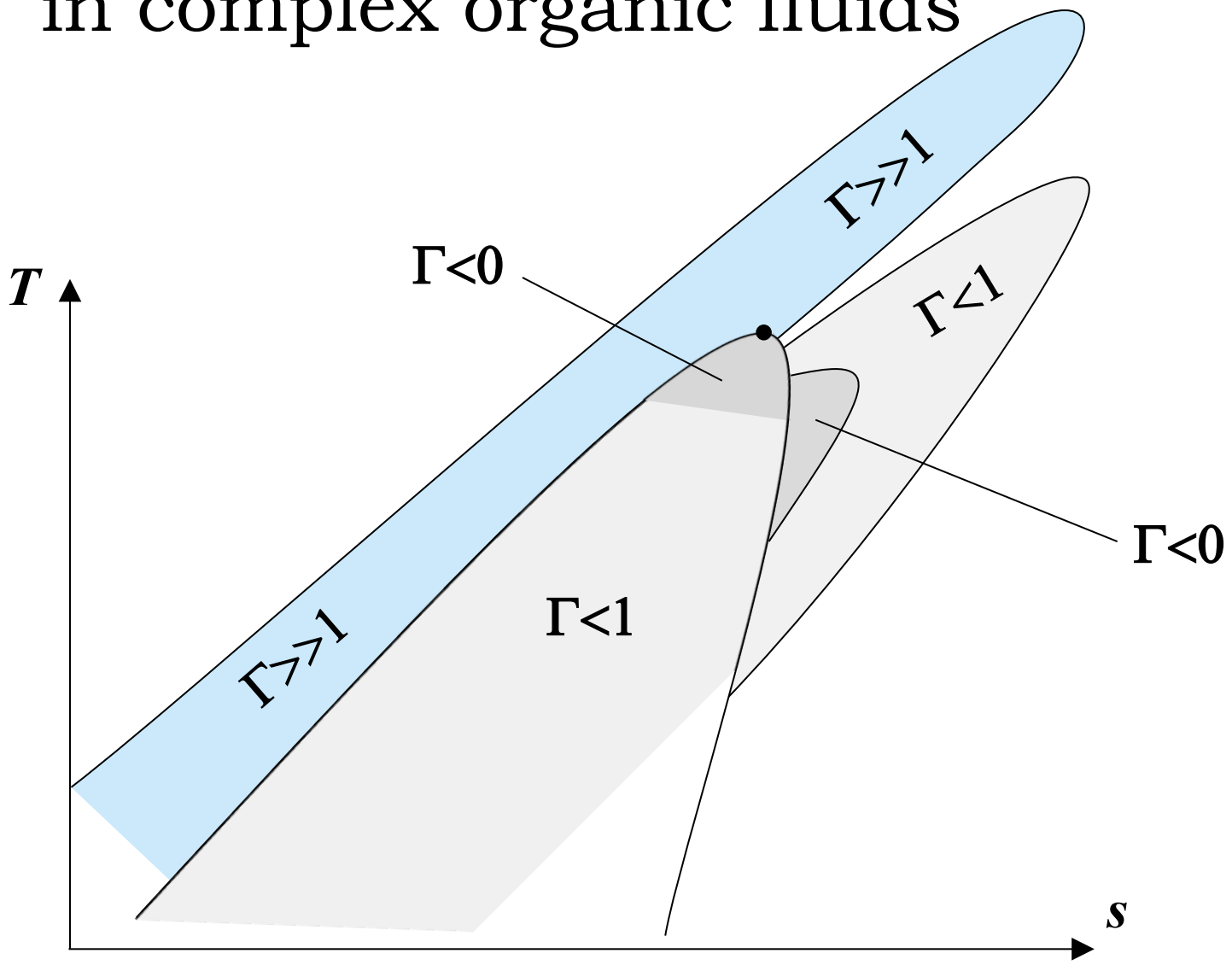
Classical

Non classical

Γ in complex organic fluids



Γ in complex organic fluids



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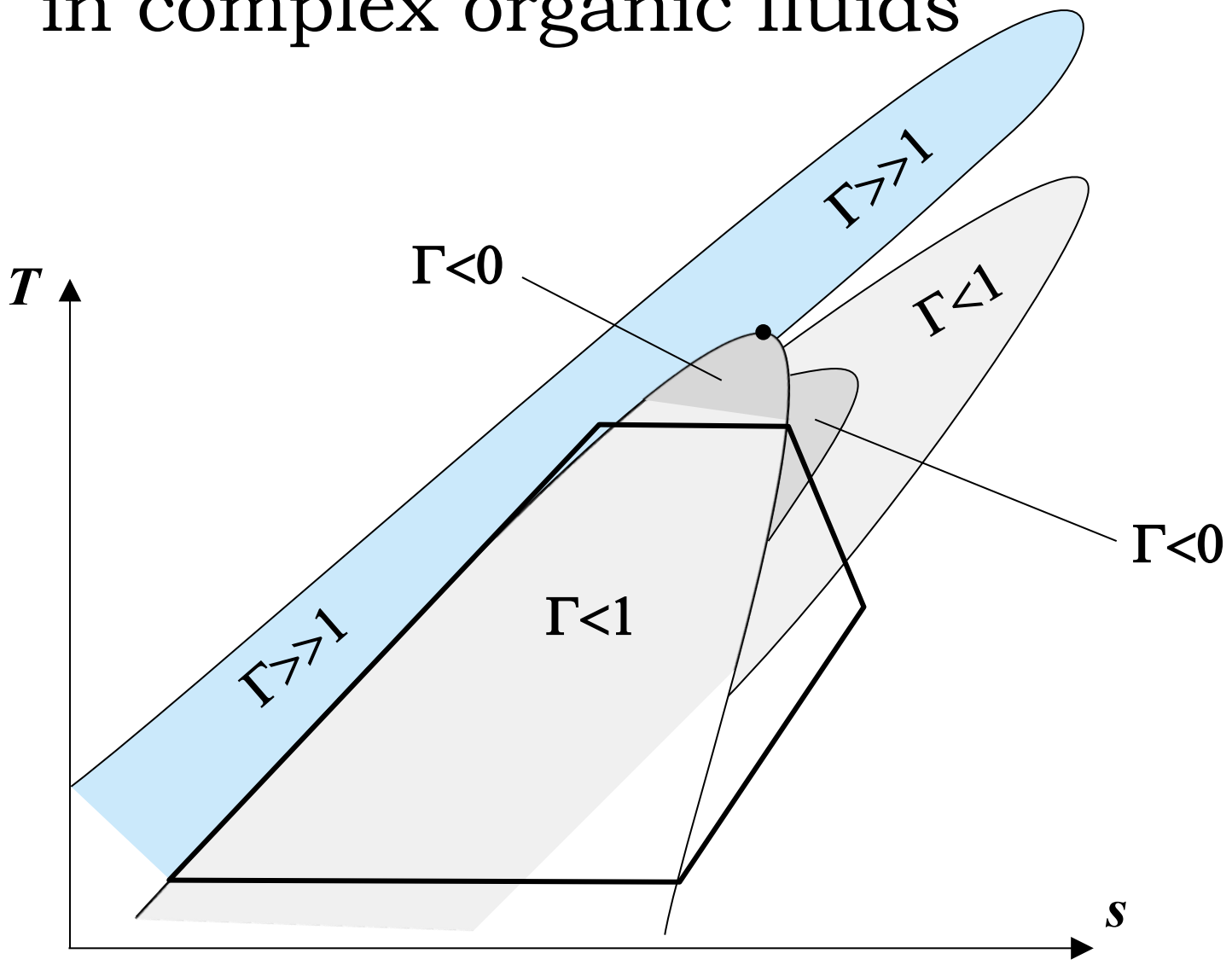

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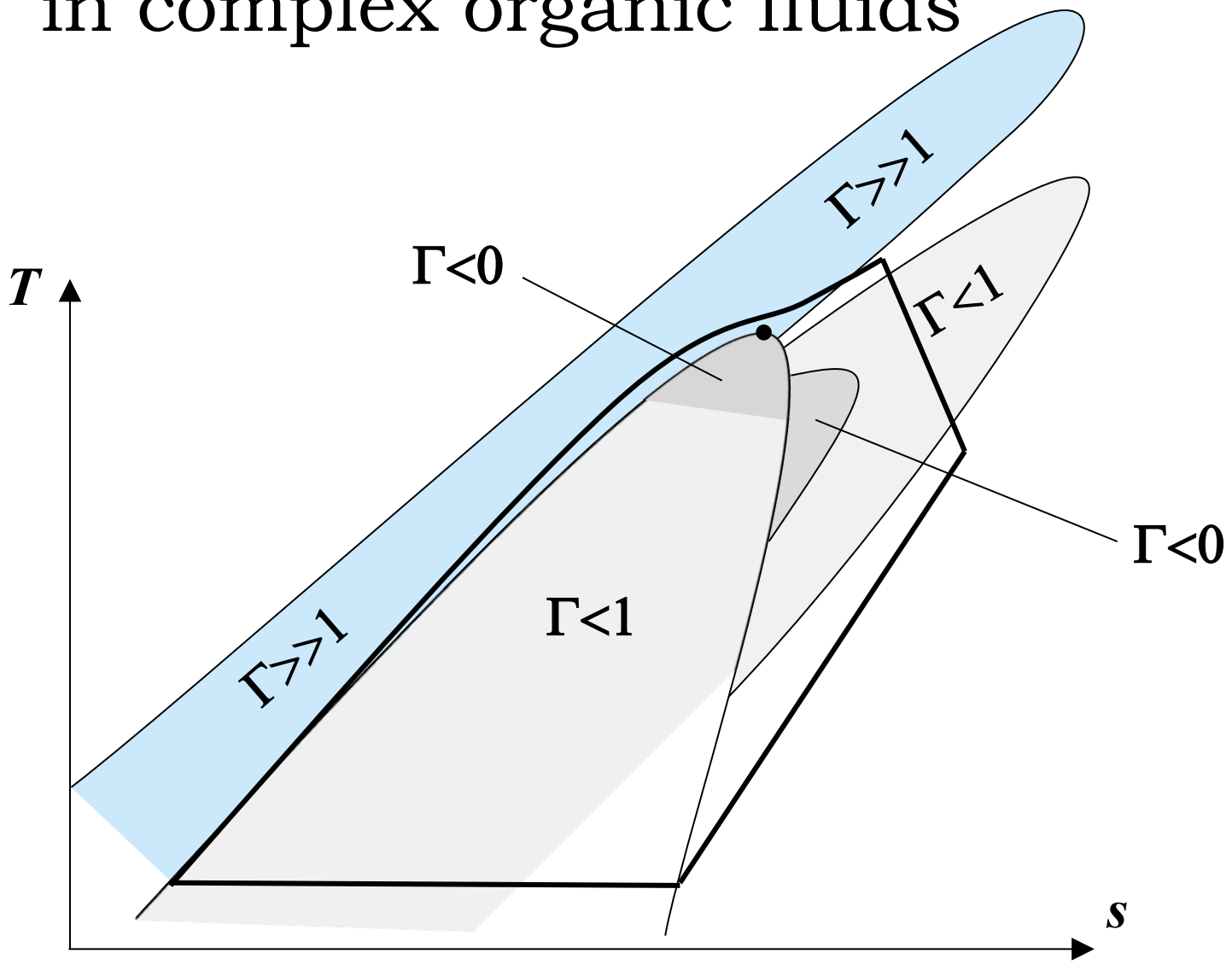
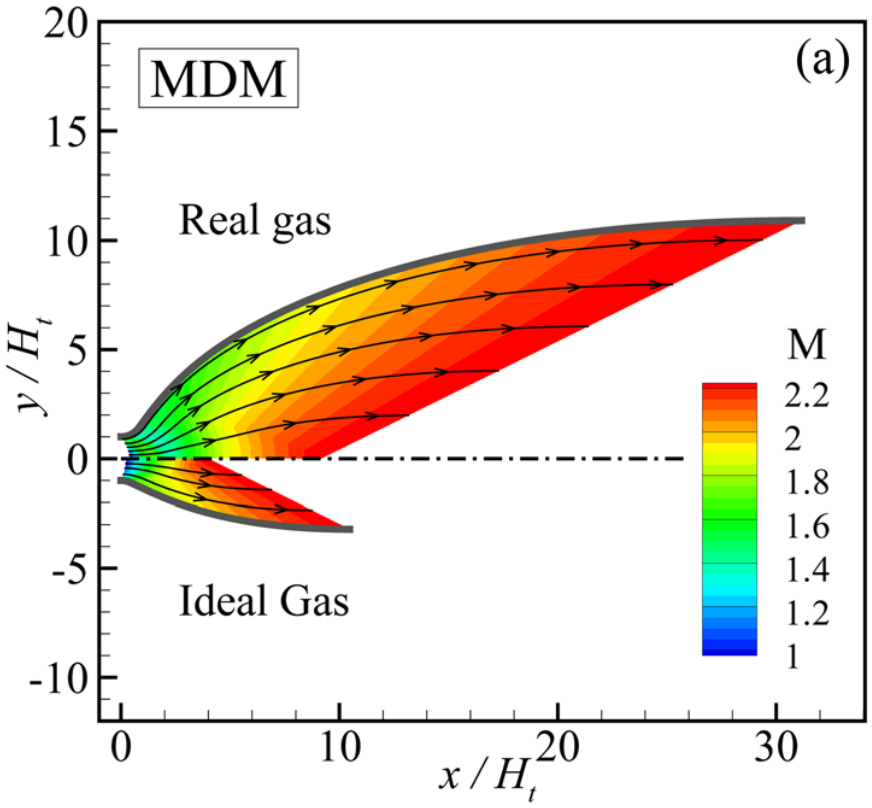


ORC windtunnel nozzle design

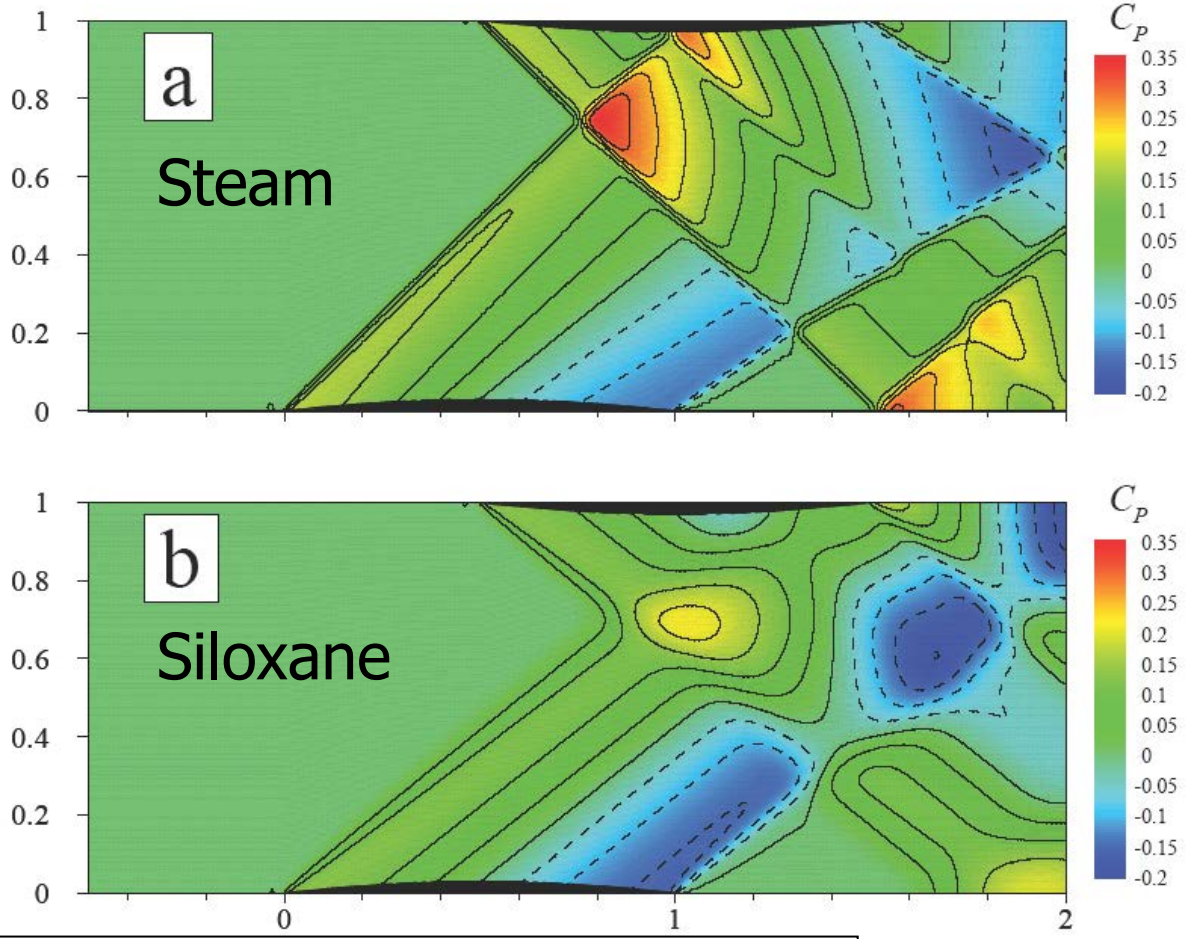


A. Guardone, A.Spinelli, V. Dossena, "Influence of Molecular Complexity on Nozzle Design for an Organic Vapor Wind Tunnel", *J. Eng. Gas Turbines Power* 135(4), 042307, Mar 18, 2013.

Non classical effect in a "simplified" turbine cascade

Inflow:

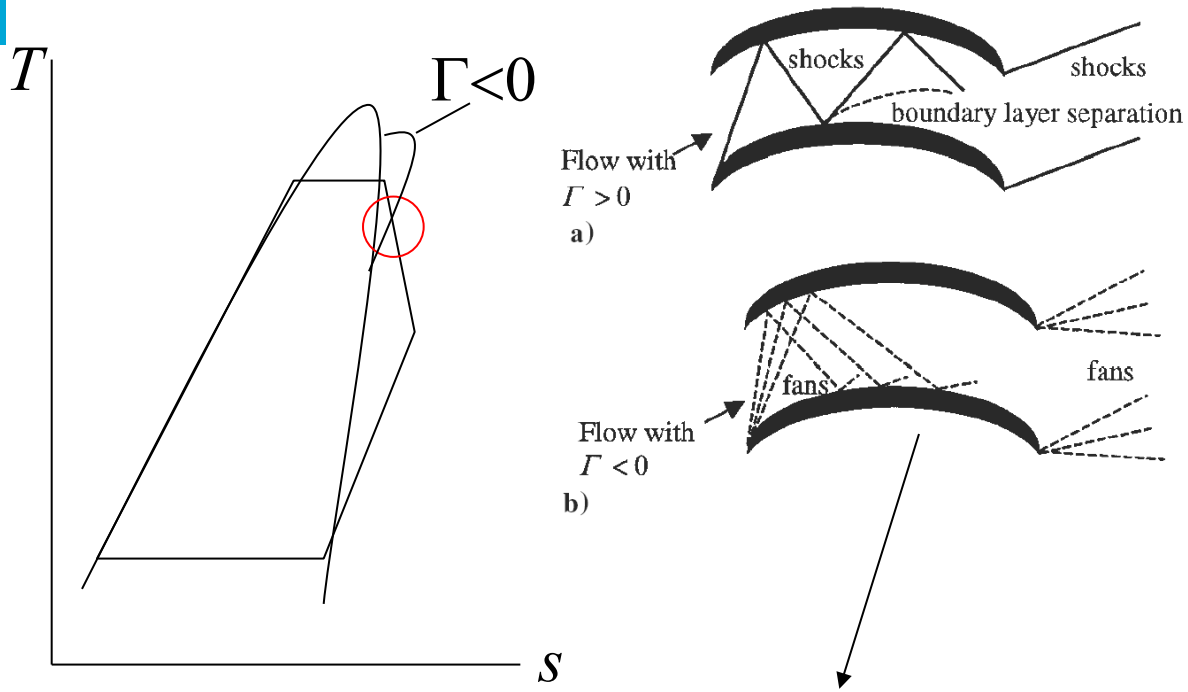
- $M = 1.6$
- Same reduced tmd state

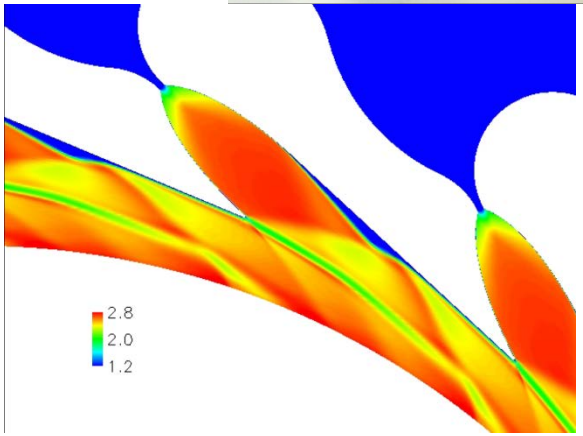


P. Colonna and S. Rebay, ``Numerical simulation of dense gas flows on unstructured grids with an implicit high resolution upwind Euler solver," Int. J. Numer. Meth. Fl., vol. 46, no. 7, pp. 735-765, 2004.

Shock-free ORC turbine: Compression fan!

150 kW ORC turbine





B. P. Brown and B. M. Argrow, ``Application of Bethe-Zel'dovic-Thompson fluids in Organic Rankine Cycle Engines," J. Propul. Power., vol. 16, pp. 1118-1123, November-December 2000.

Experiments in NICFD

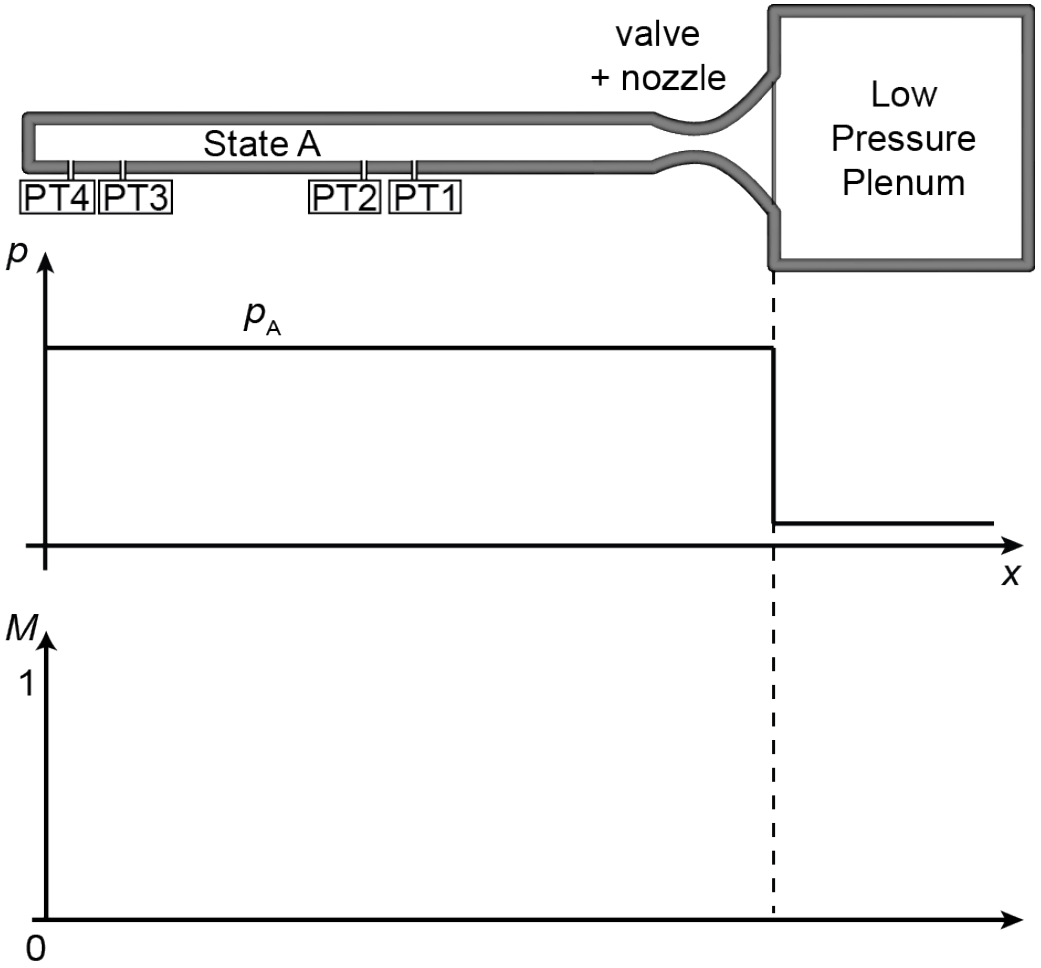
- Borisov (1983)
- Argrow (2000)
- TU Delft (2014-2015)
- Milano (2014-2015)

Delft: Flexible Asymmetric Shock Tube (FAST)

Milano: Trova

The FAST: the concept

- Ludwieg Tube
- speed-of-flight measurement of wave
- D6 Siloxane as working fluid



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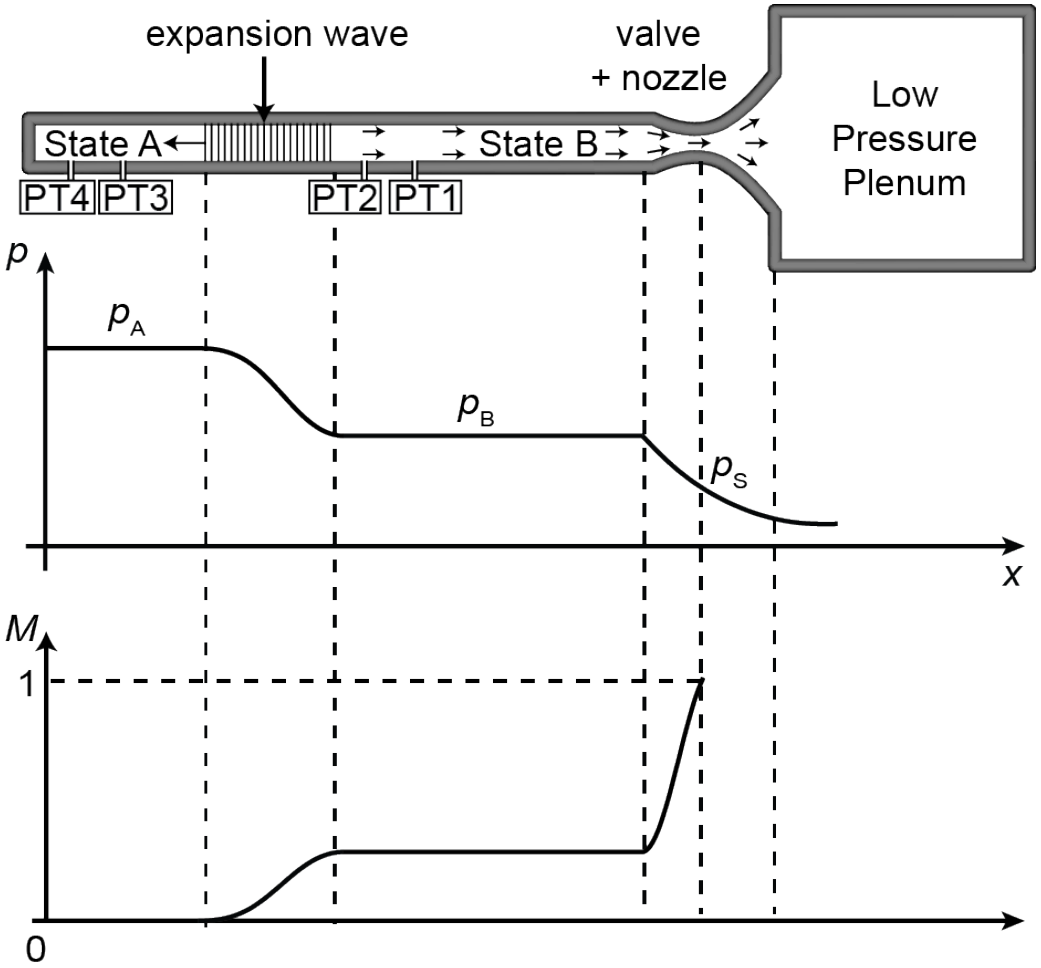
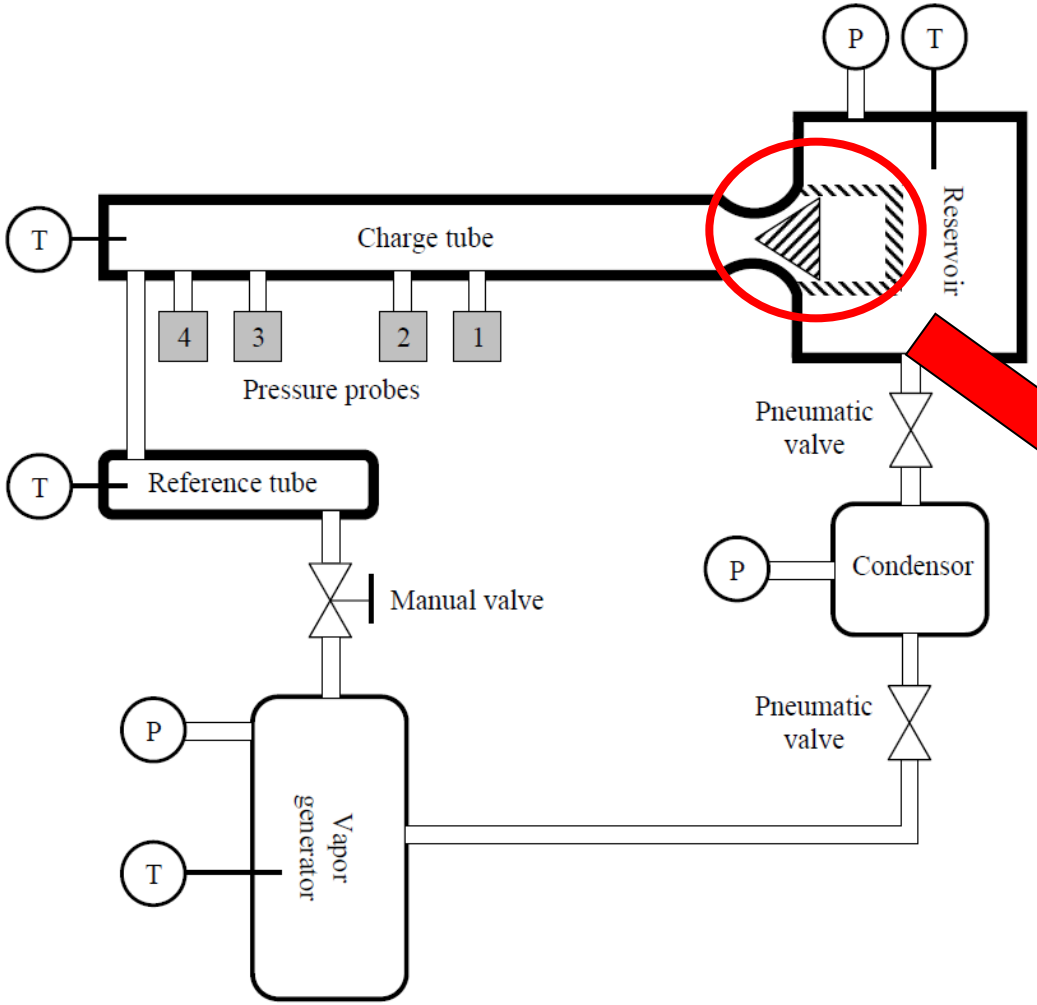
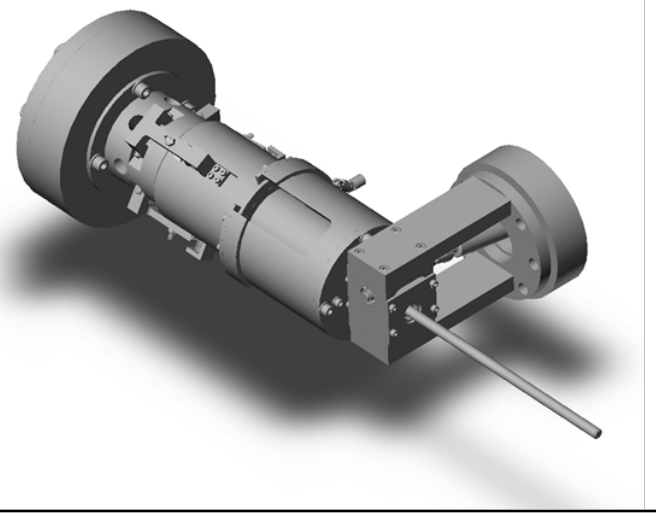
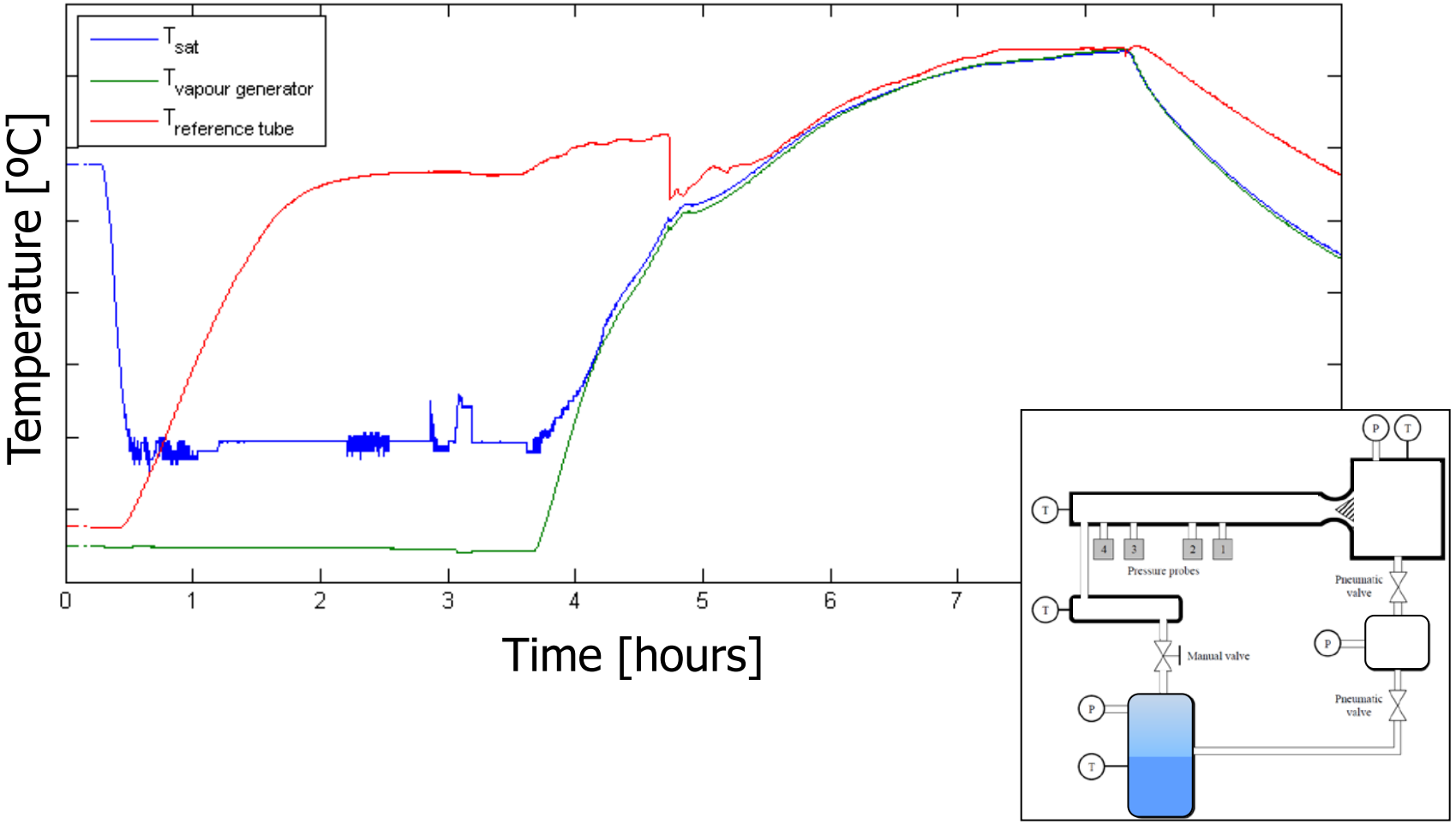


The FAST: realization





D6 experiment



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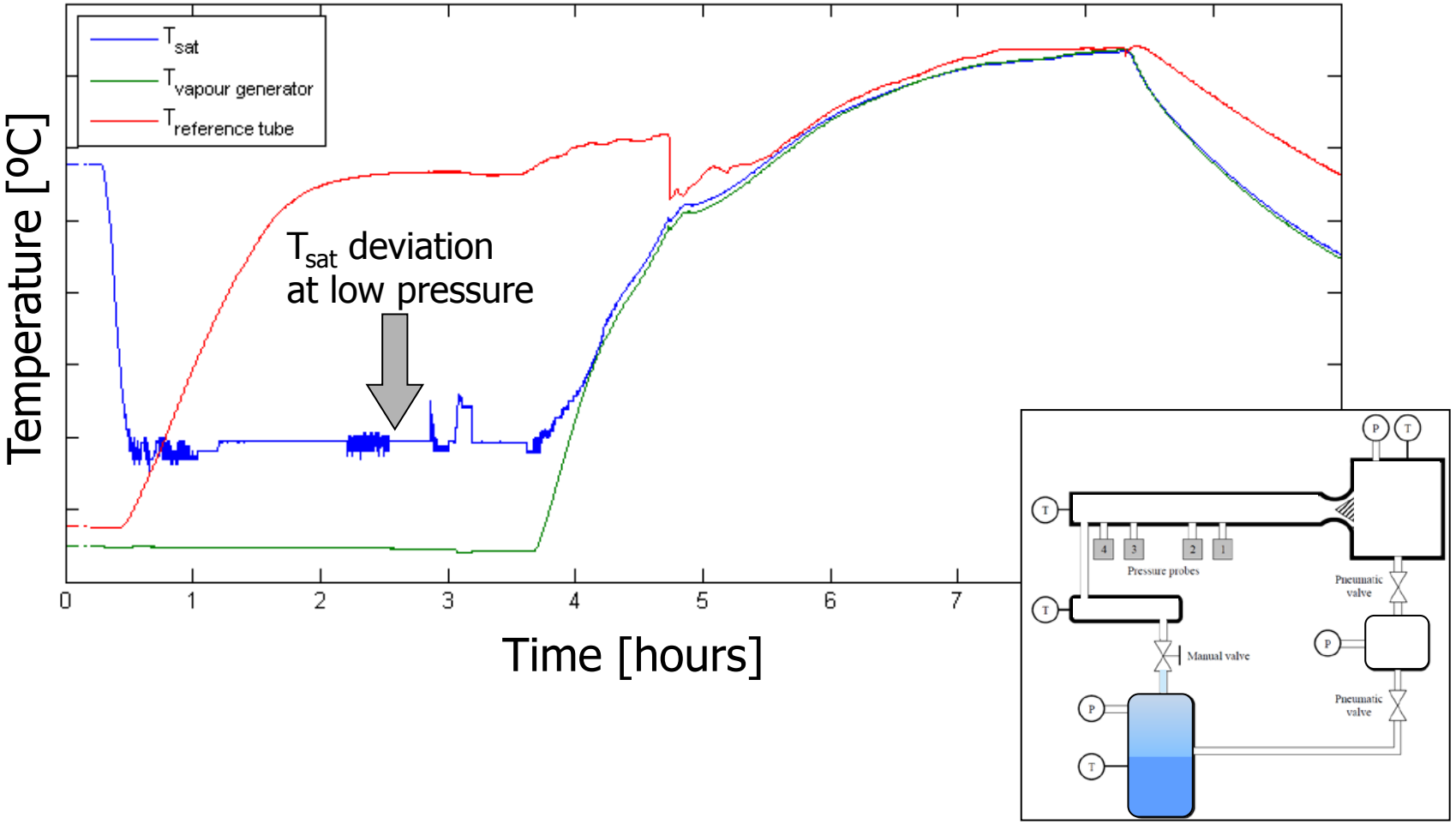

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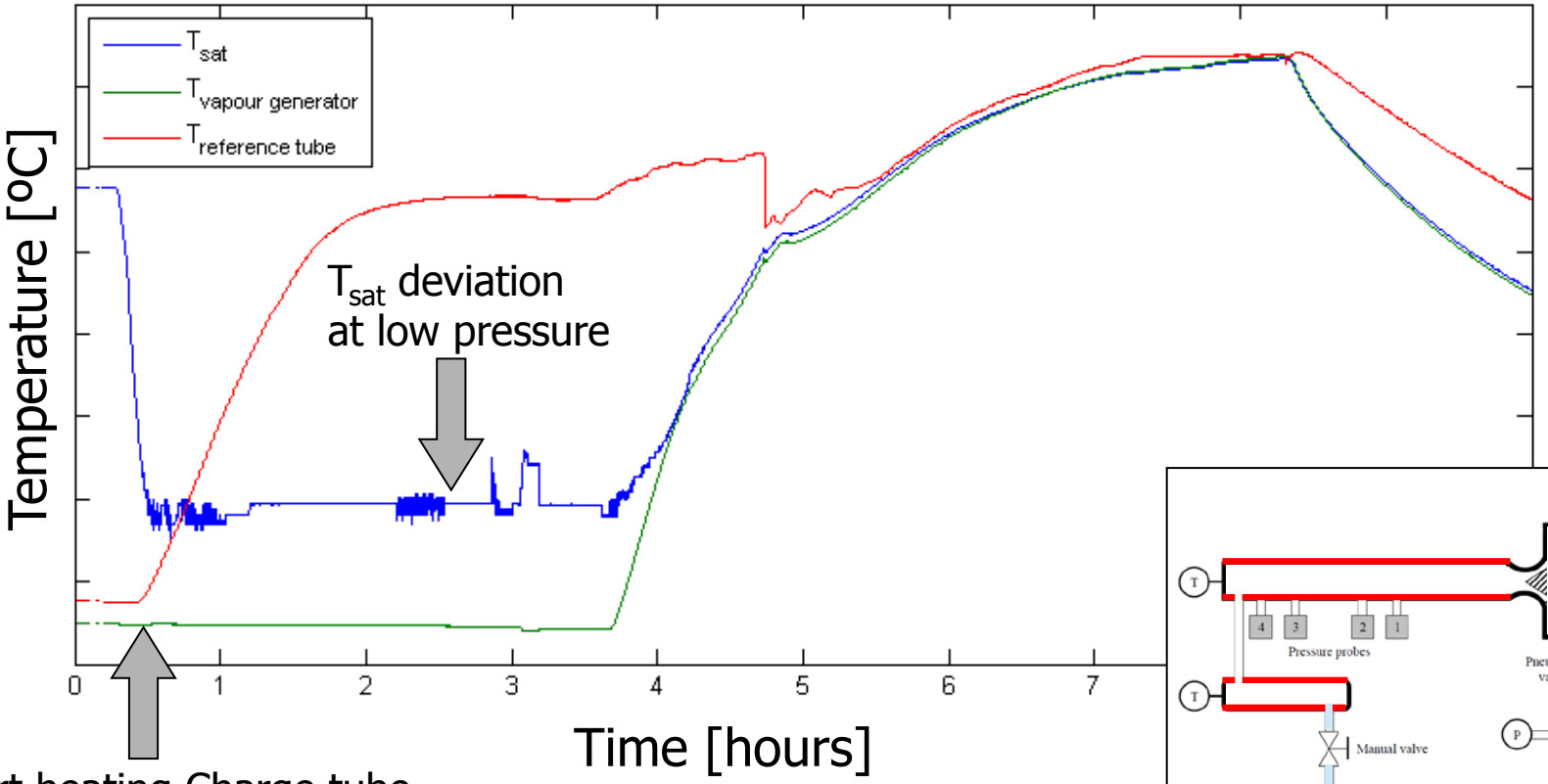

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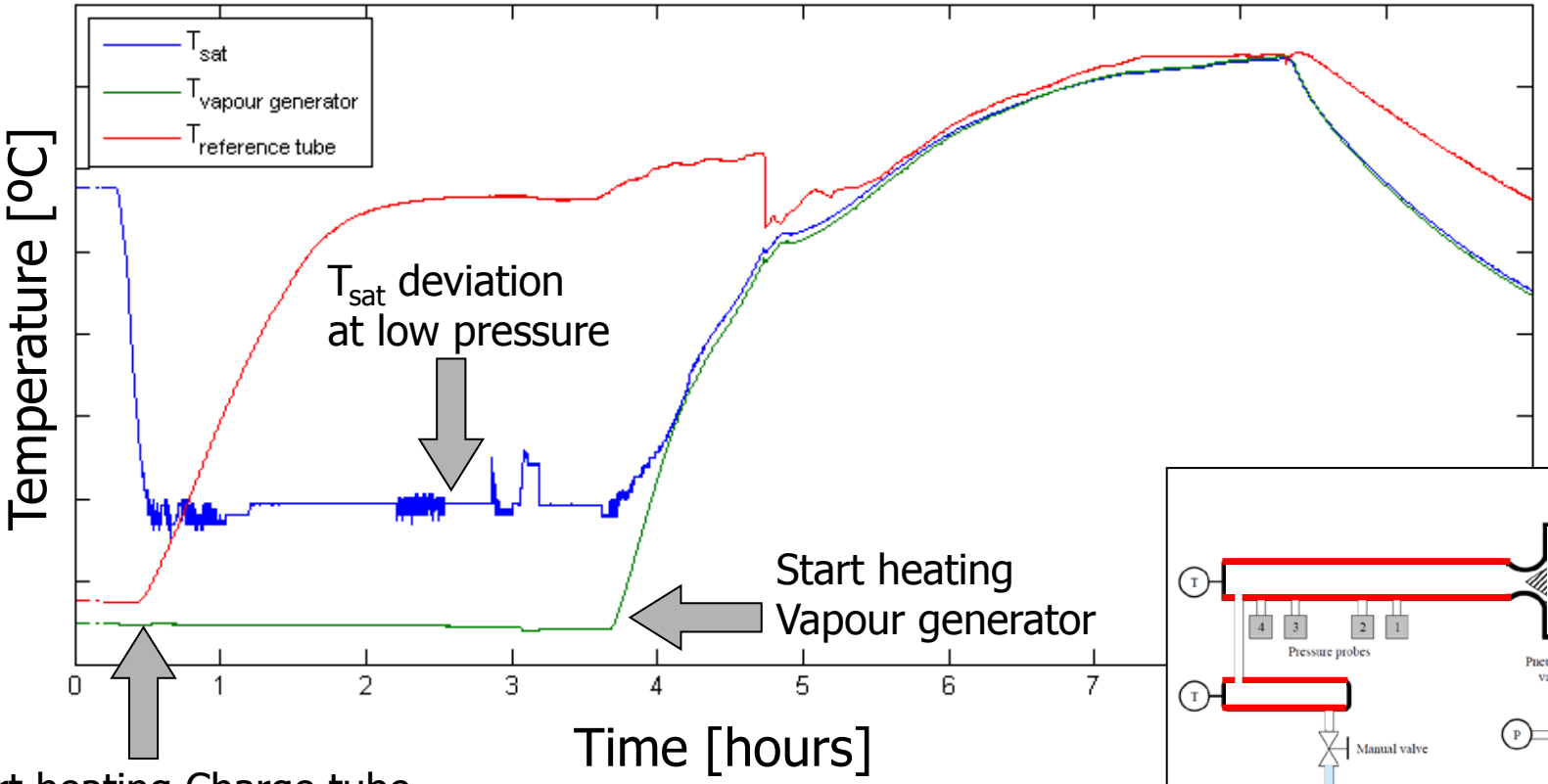

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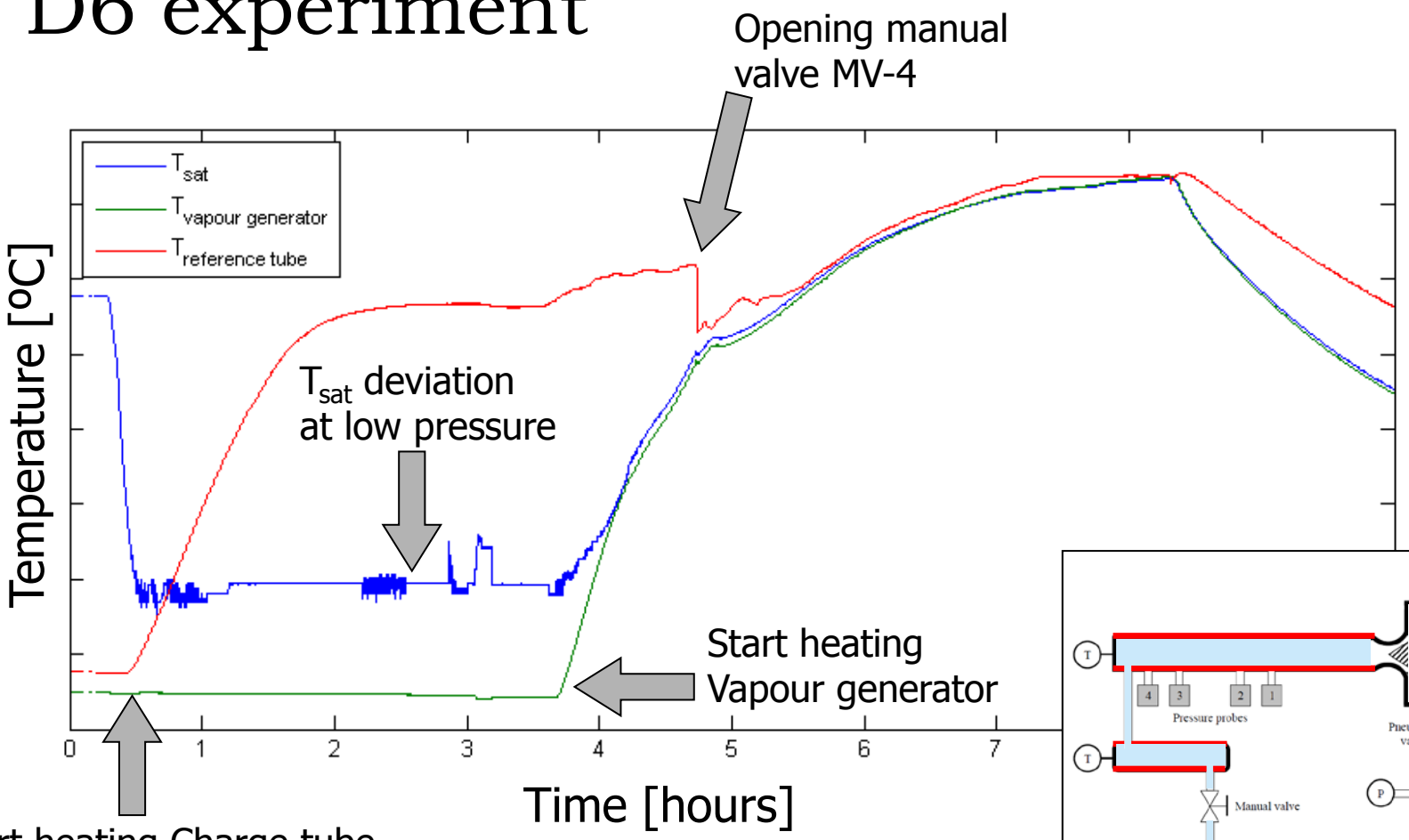

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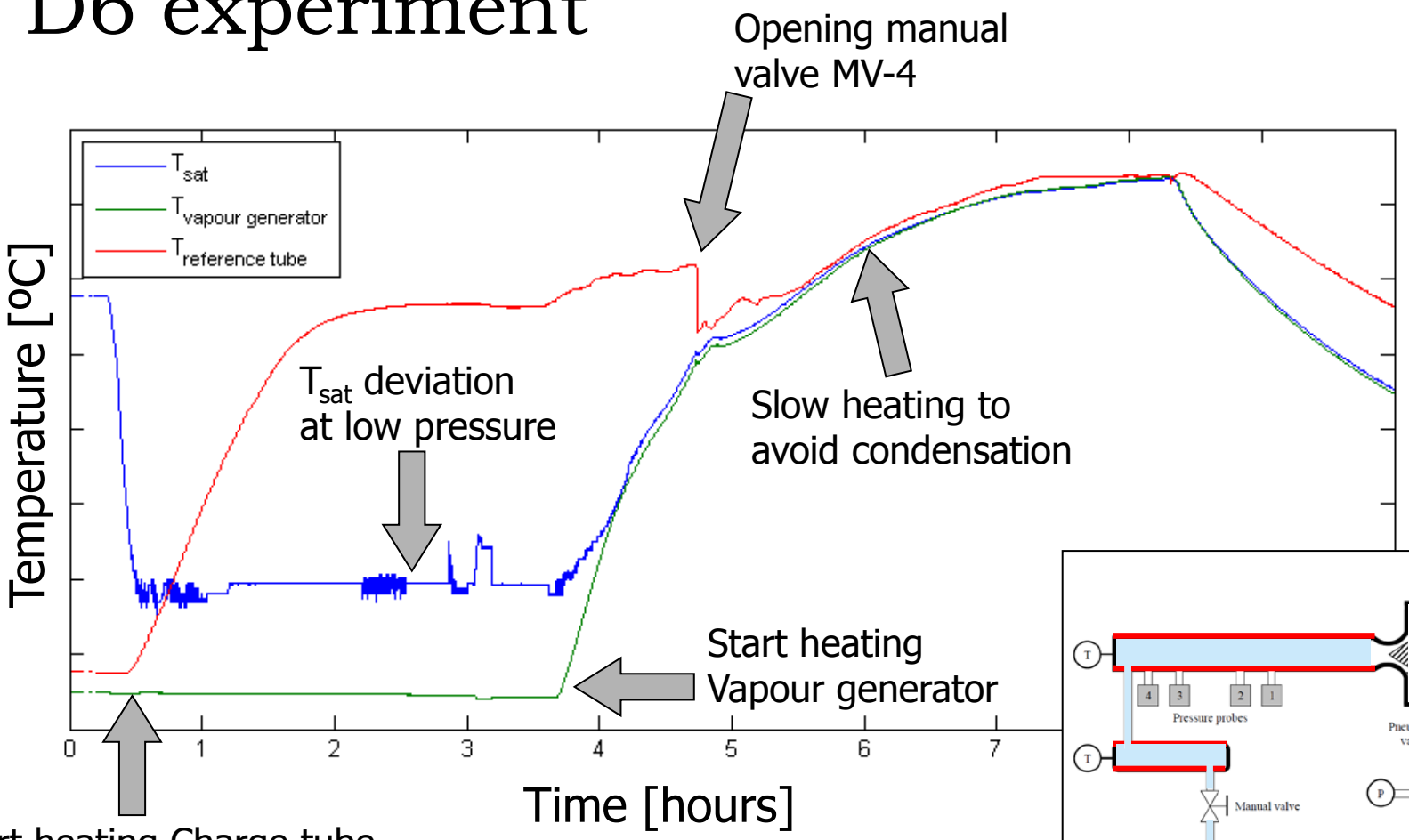

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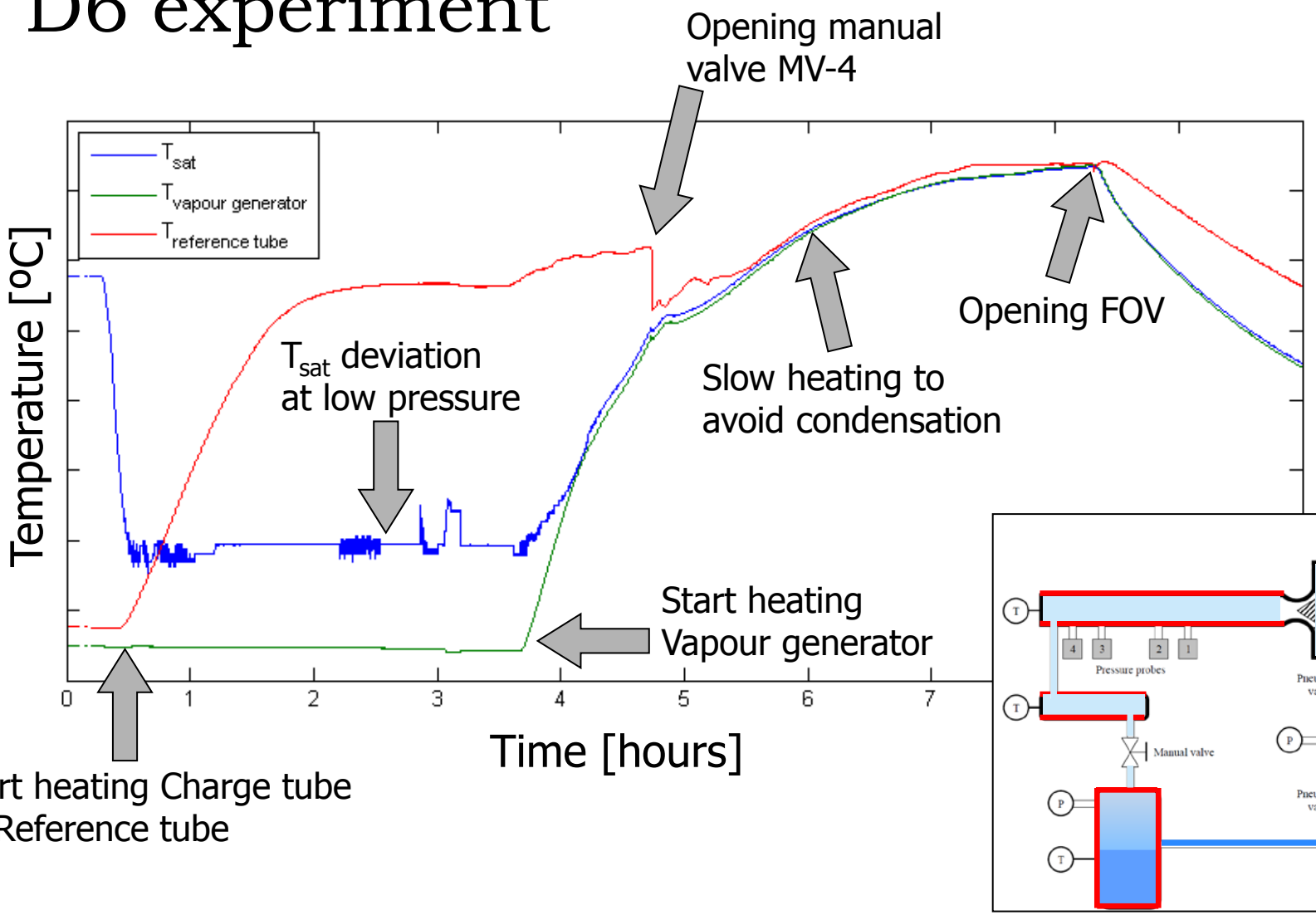
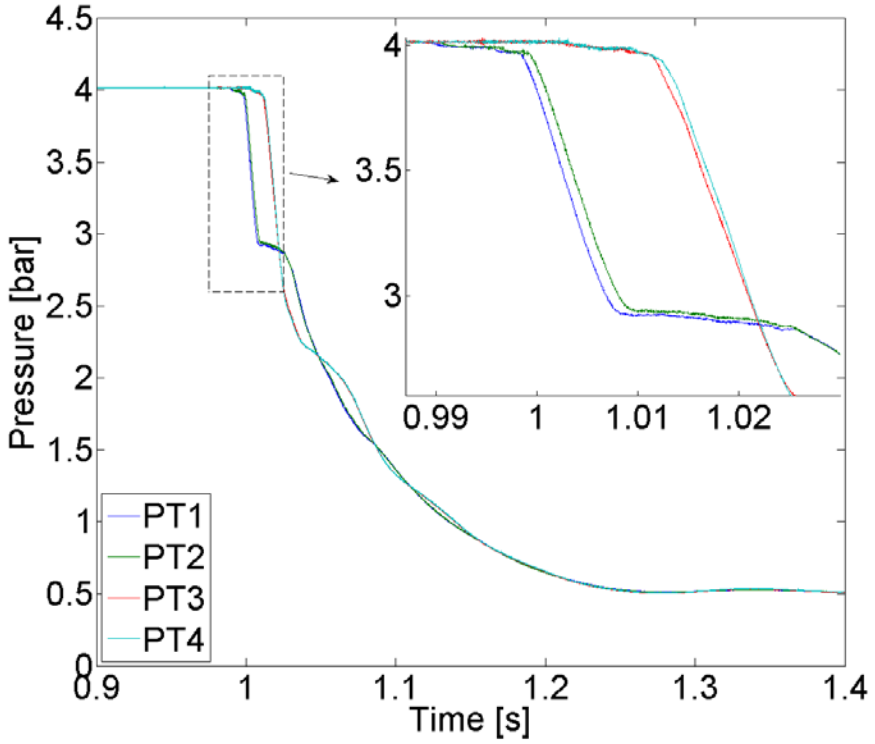


Nitrogen experiment

Pressure	4.01 bar
Temperature	25.8 °C
Γ	1.2

$$w = \frac{\Delta x}{\Delta t}$$

$\Delta x = 0.3\text{m}$



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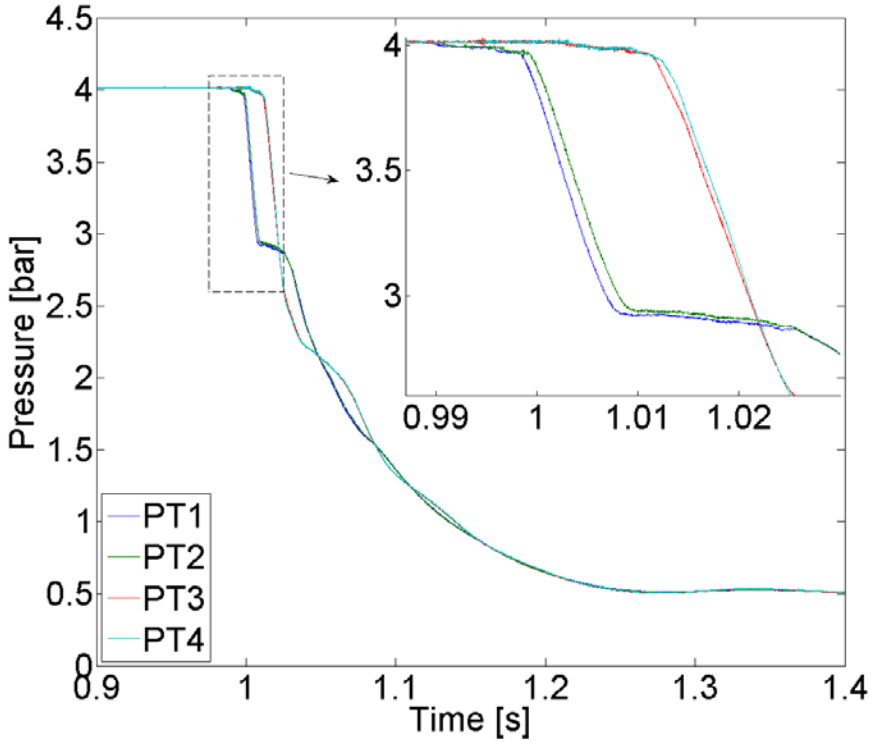

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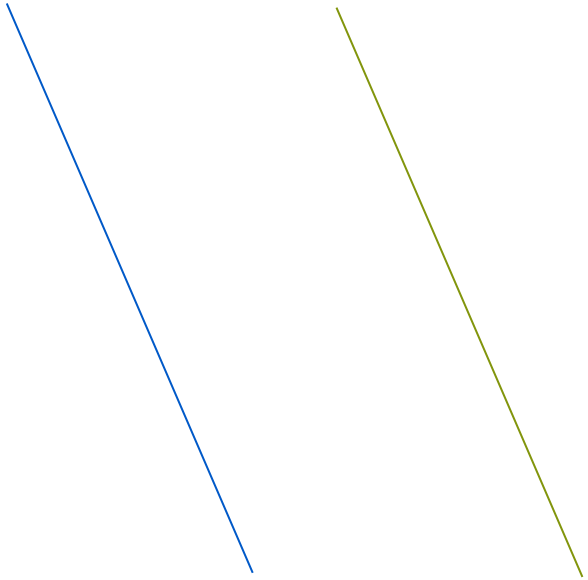
PT1 PT2



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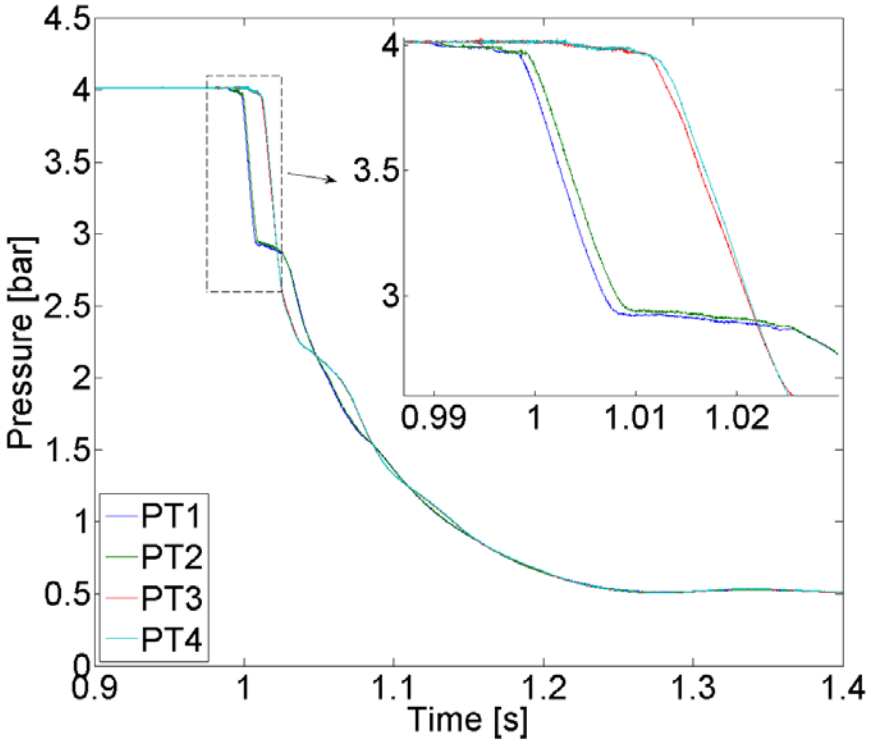

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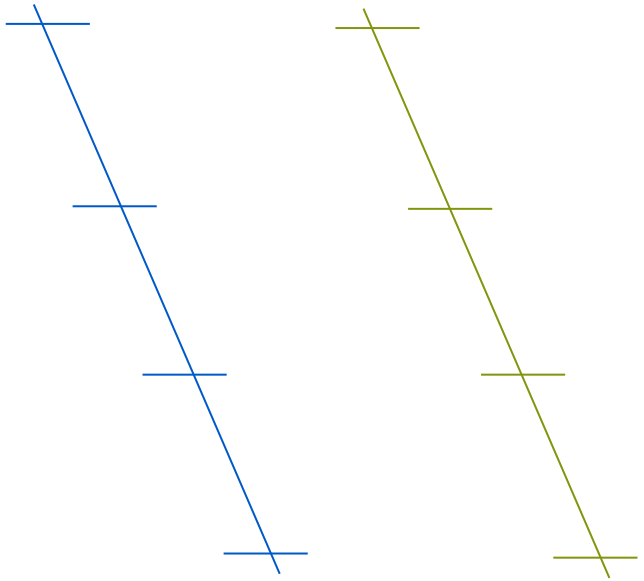

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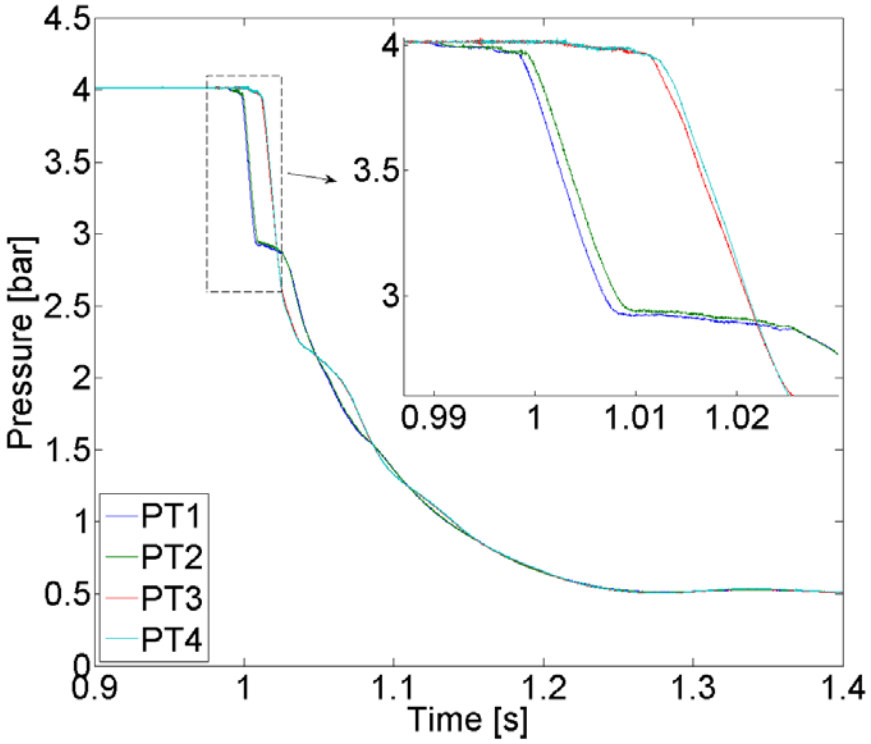
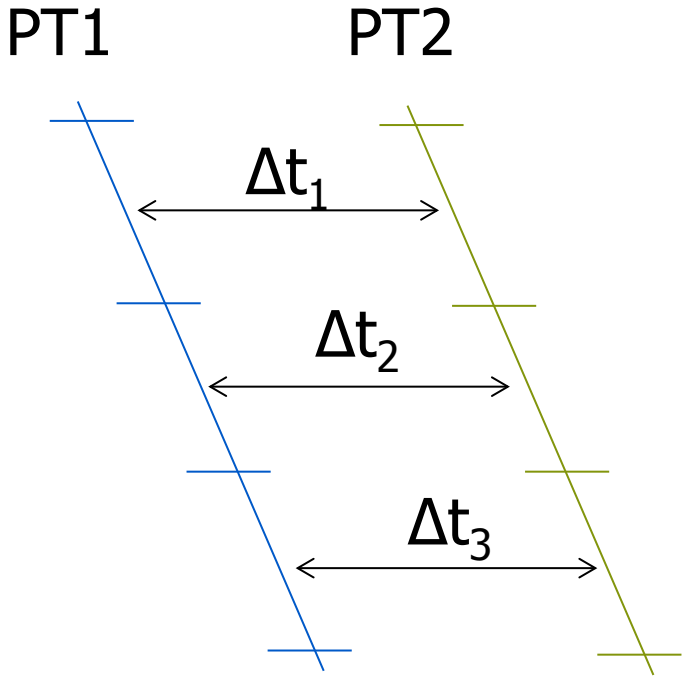
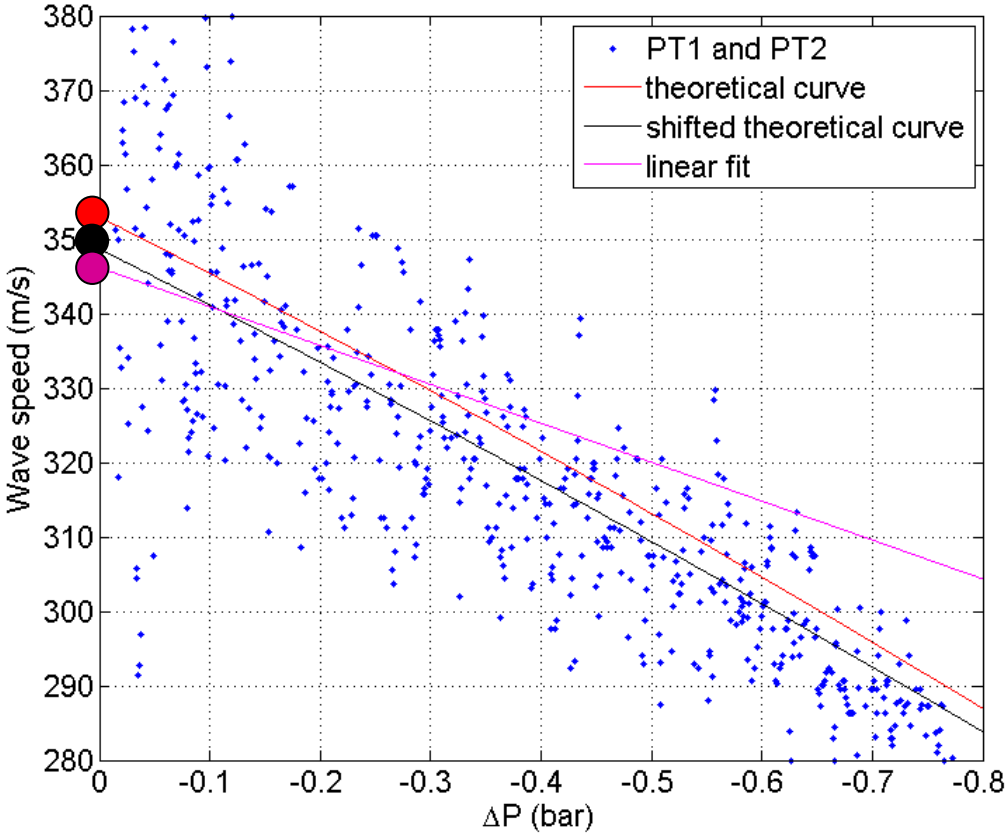




Nitrogen experiment

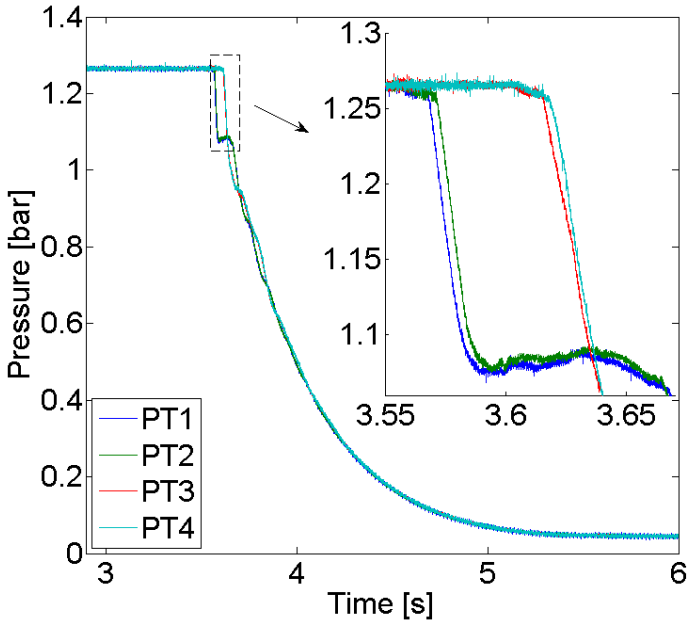
Speed of sound	
Theory	350 m/s
Shifted curve	349 m/s
Linear fit	346 m/s

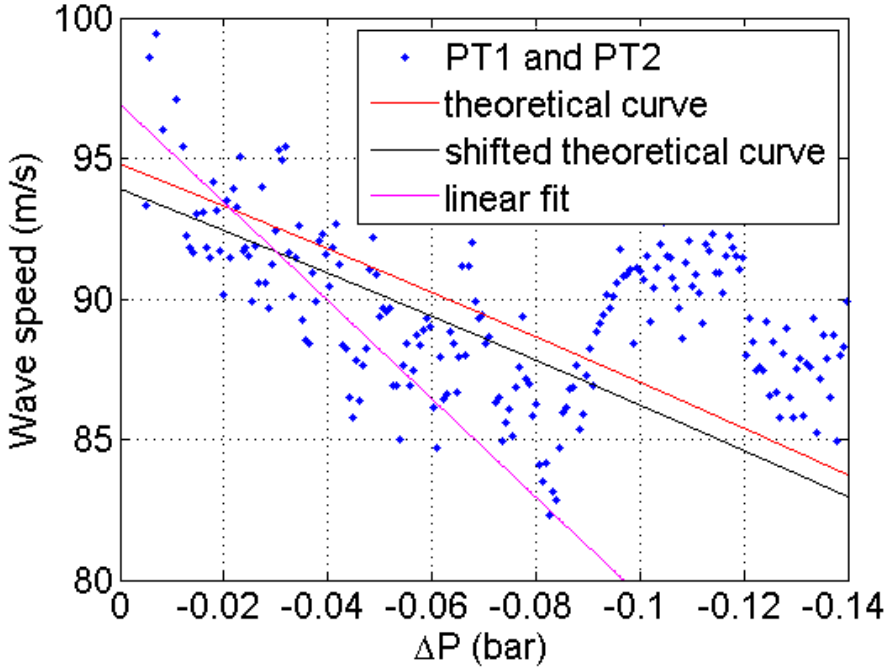


Average accuracy
5% wave speed
1-2% speed of sound

D6 siloxane experiment

Pressure	1.27 bar
Temperature	298 °C
Γ	0.91





Speed of sound	
Theory	94.8 m/s
Shifted curve	93.9 m/s
Linear fit	96.9 m/s

8% wave speed

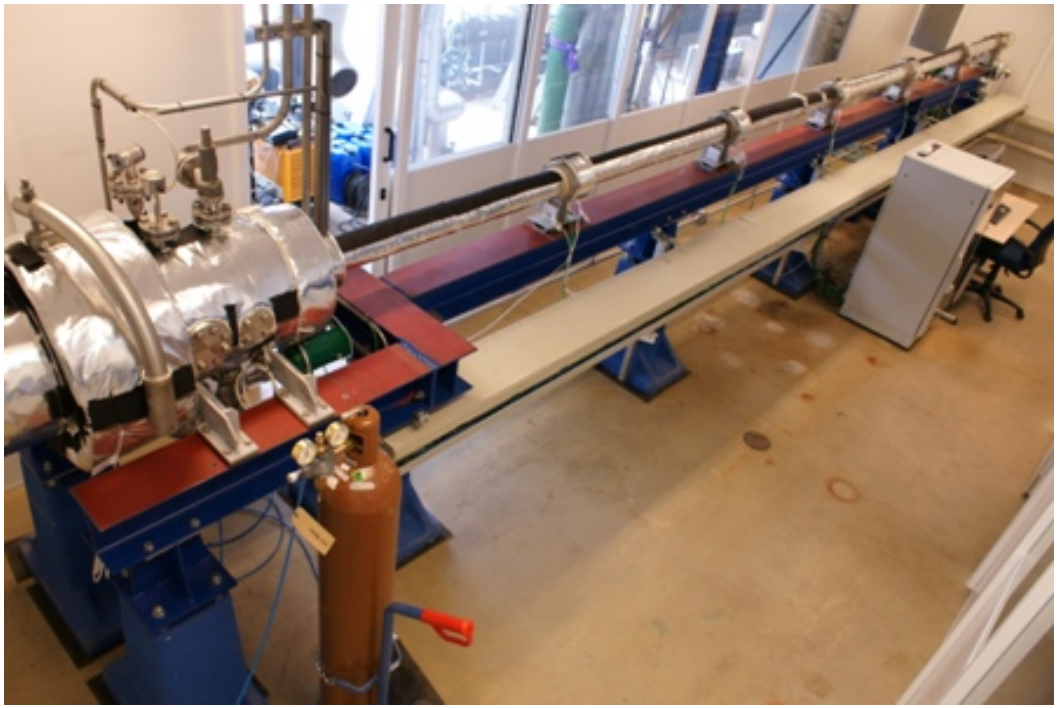
1.6% speed of sound

Conclusions & Future work

- Non-Ideal Compressible Fluid Dynamics
- FAST Ludwieg tube commissioned
- Pressure and Temperature regulated independently
- Measurements of Wave propagation speed
  - 5% - 8% accuracy
- Method to determine speed of sound
  - 1% - 2% accuracy
- Next: Measurements at lower Γ

Thank you for your attention!

Questions?



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