

Flexible Asymmetric Shock Tube (FAST) Set-up

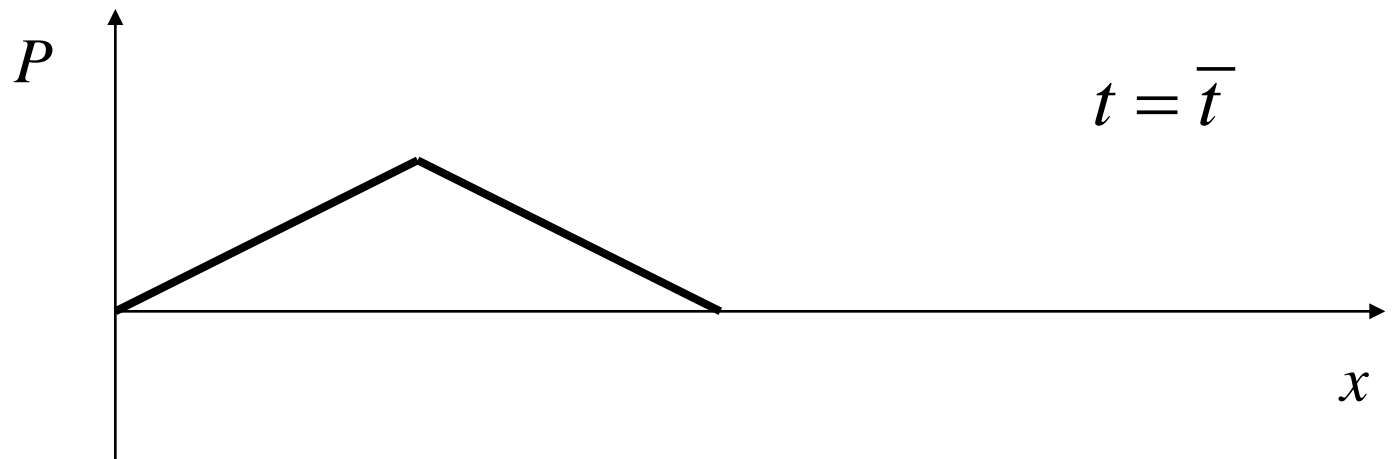
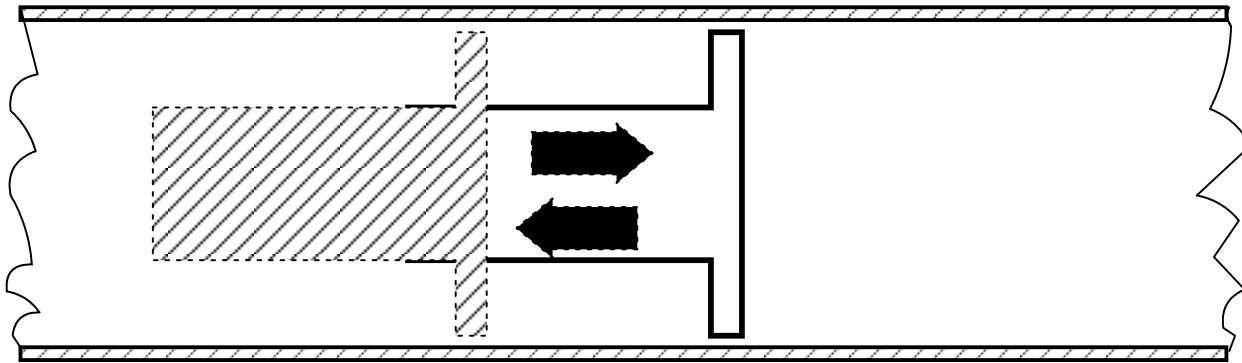
Status and first experiences

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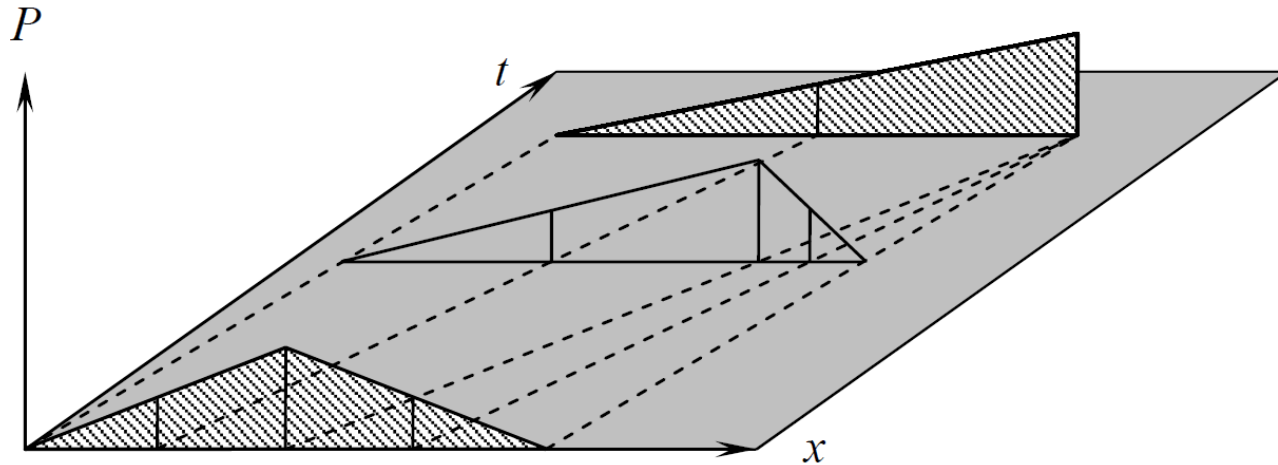
Outline

- Non-classical gasdynamics
- Flexible Asymmetric Shock Tube (FAST) setup
- Induced Breaking Diaphragm (IBD)
- Sound Speed measurements
- Future Work and Conclusions

Example: propagation of a weak pressure wave (piston)



Shock formation and the role of Γ



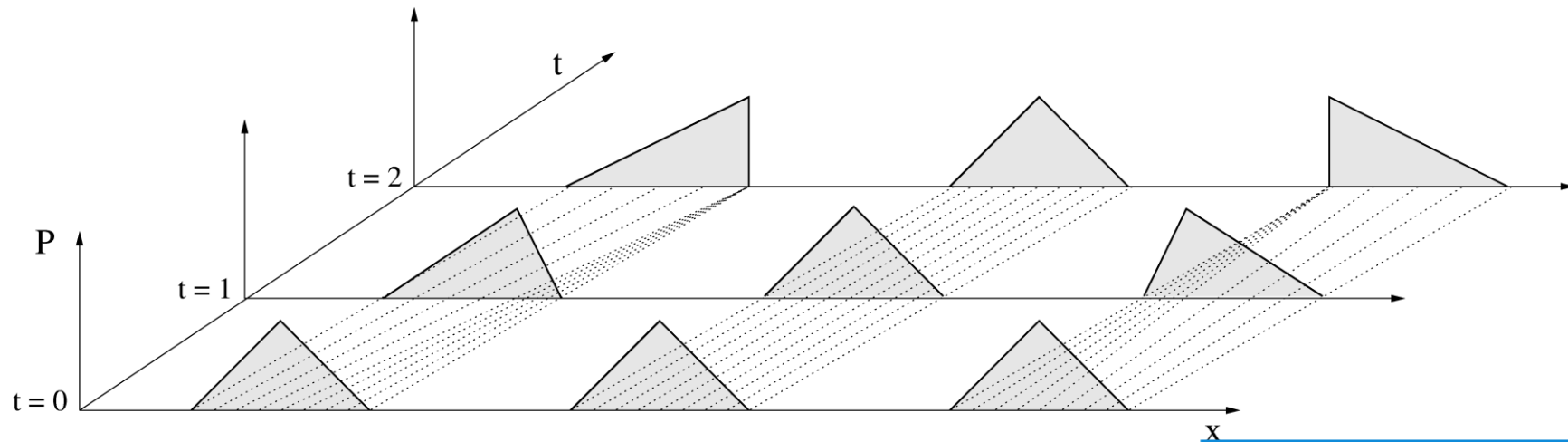
speed of the acoustic wave: $w = u + c$

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

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

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

Γ and shockwaves



$\Gamma > 0$

$\Gamma = 0$

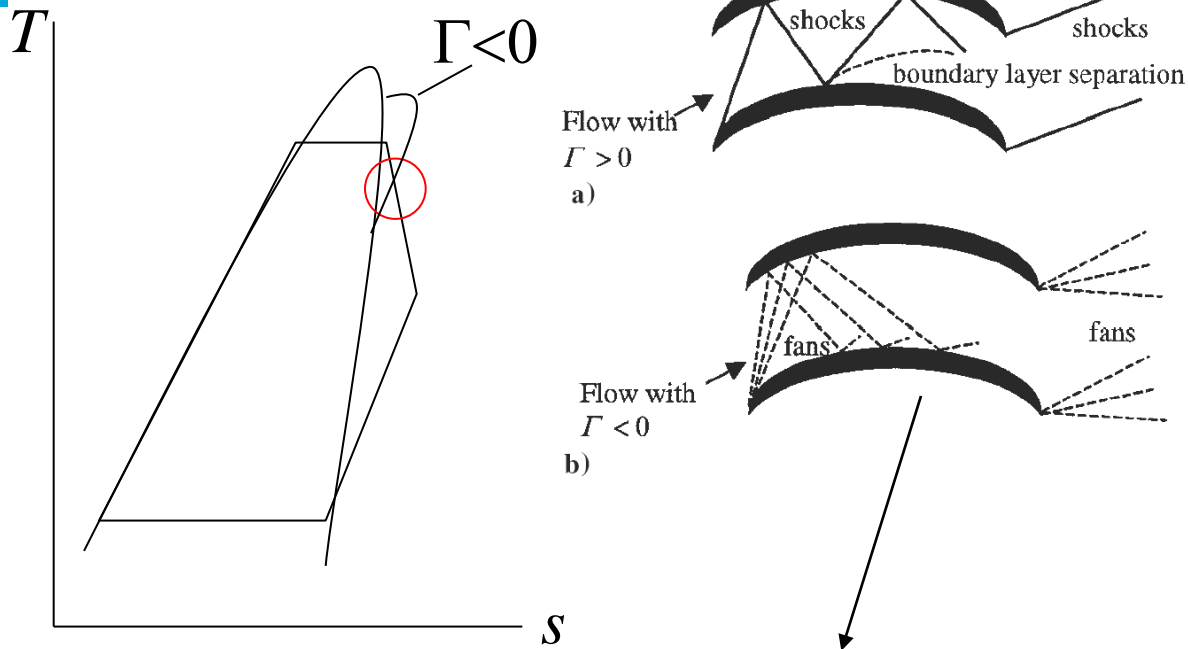
$\Gamma < 0$

$\Gamma > 0$	$dP > 0 \Rightarrow dw > 0$ $dP < 0 \Rightarrow dw < 0$	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

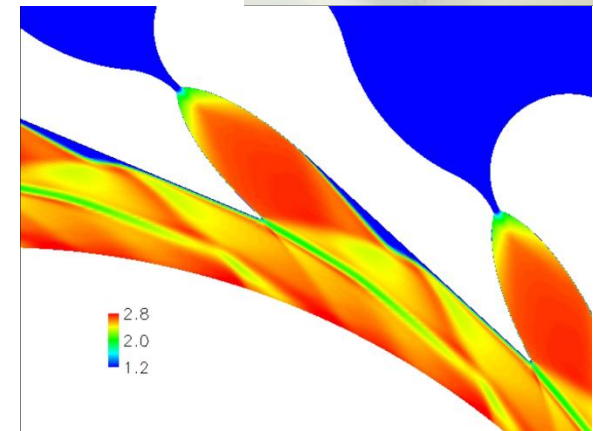
Shock-free ORC turbine: Compression fan!



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.



150 kW
ORC
turbine

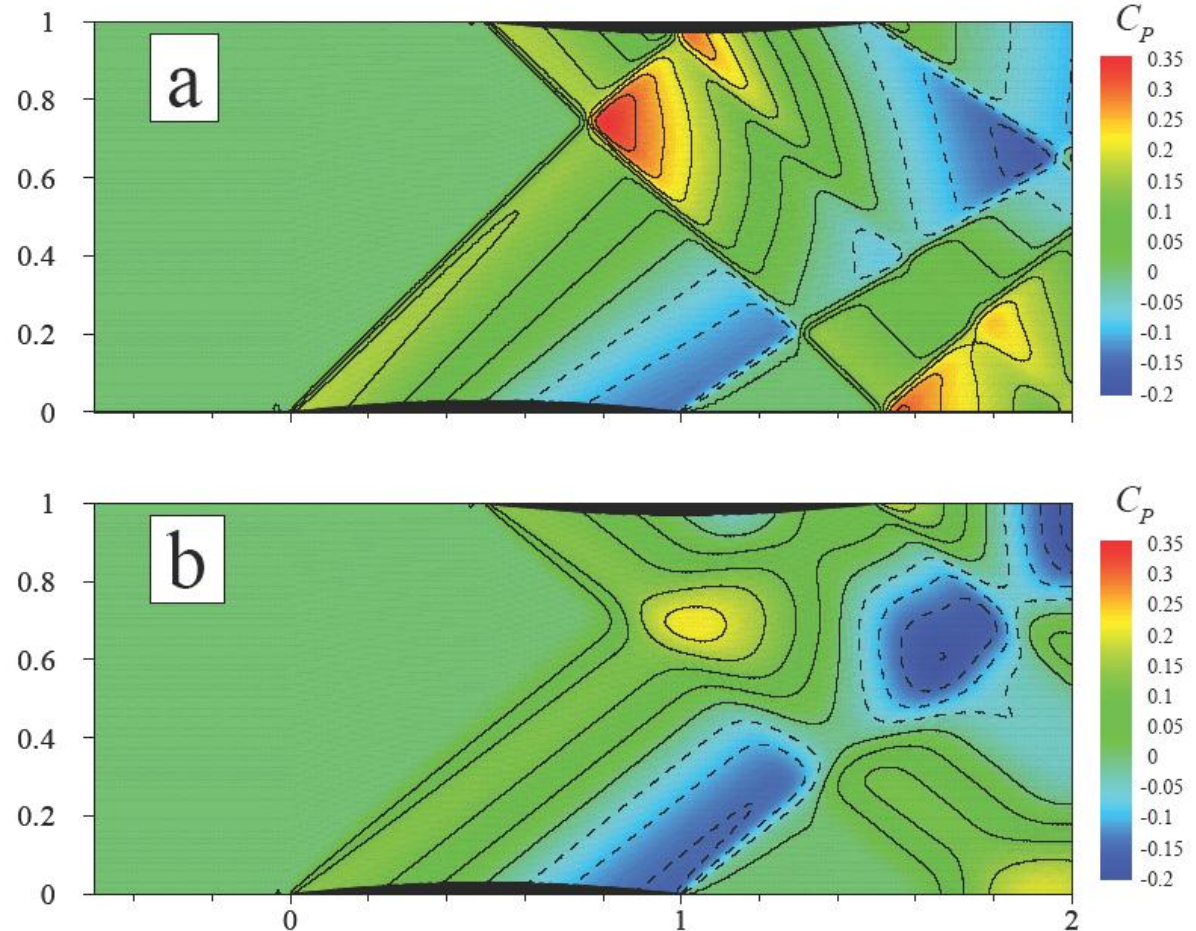


Non classical effect in a “simplified” turbine cascade

- a) Steam
- b) Siloxane

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.

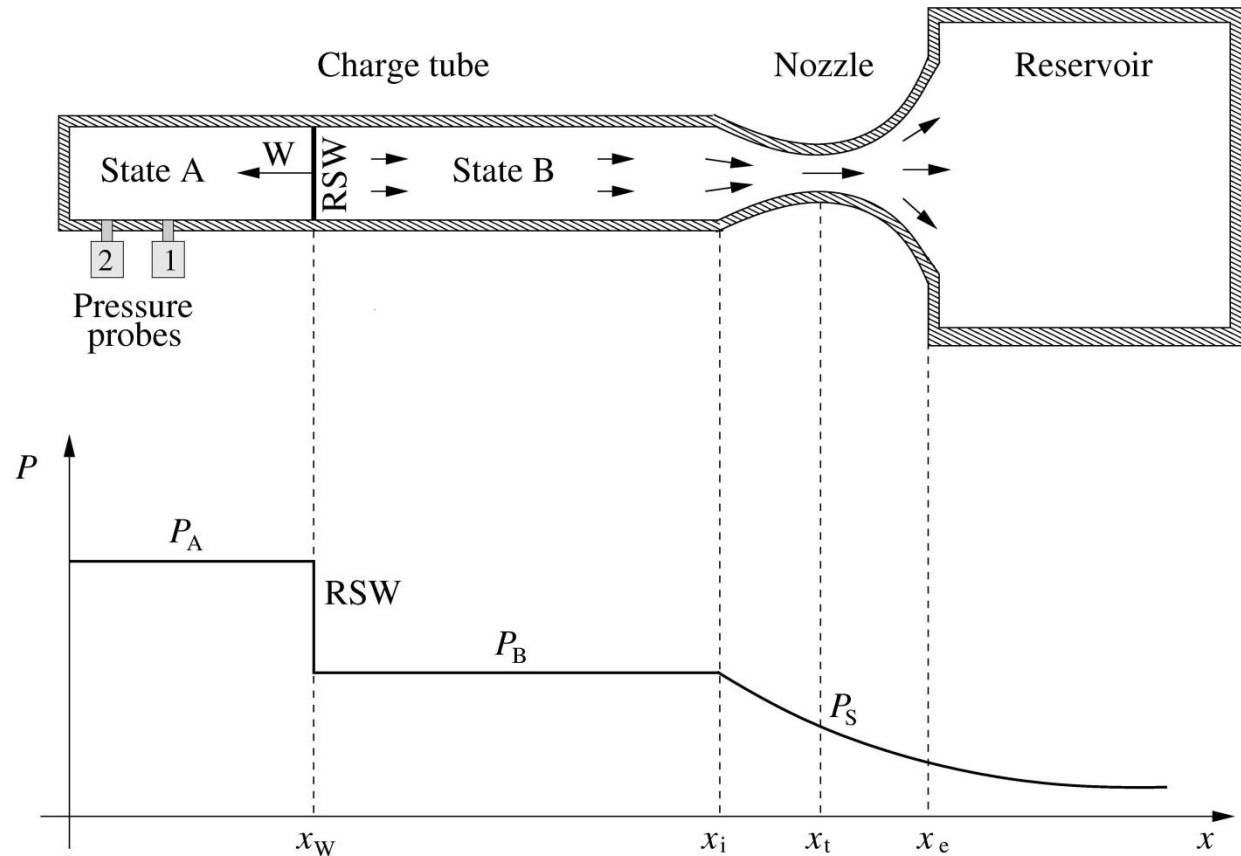
History non-classical gasdynamics experiments

- First experiment: Borisov (1983)
- Second experiment: Argrow (2000)

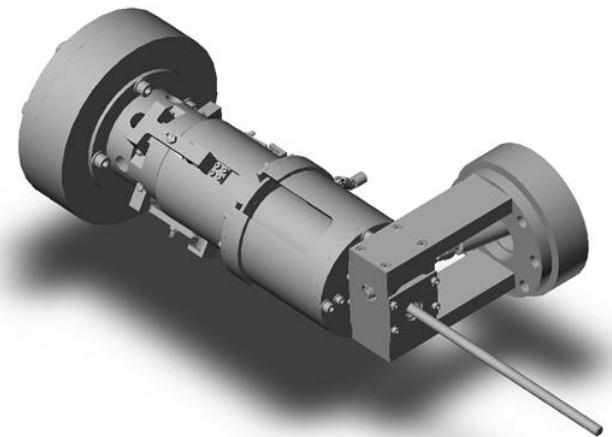
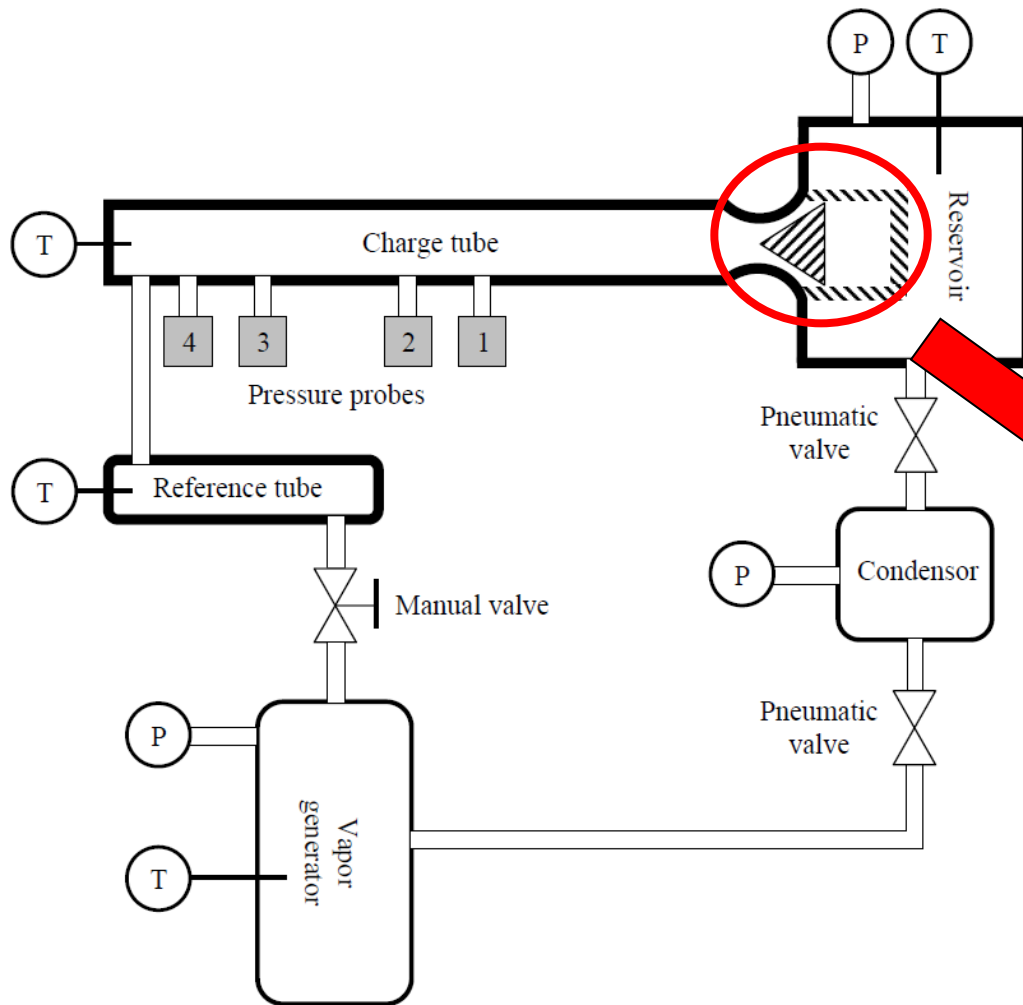
 Third experiment: TU Delft (2013/2014)

The FAST: the concept

- Ludwieg Tube
- Proof by speed-of-flight measurement of wave
- D6 Siloxane as working fluid
- Flexible: use as transonic wind tunnel (ORC blades)

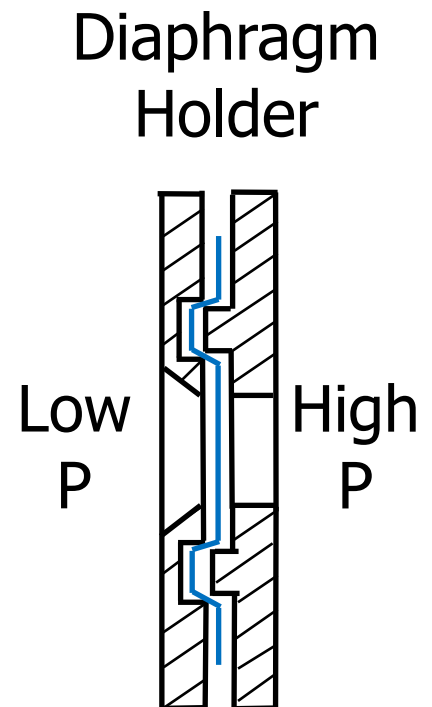
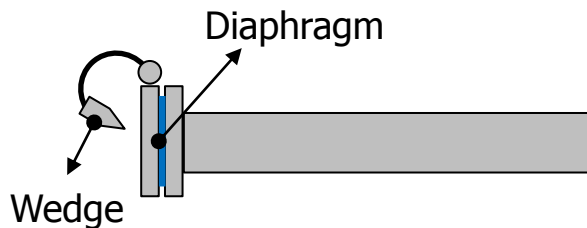


The FAST: realization

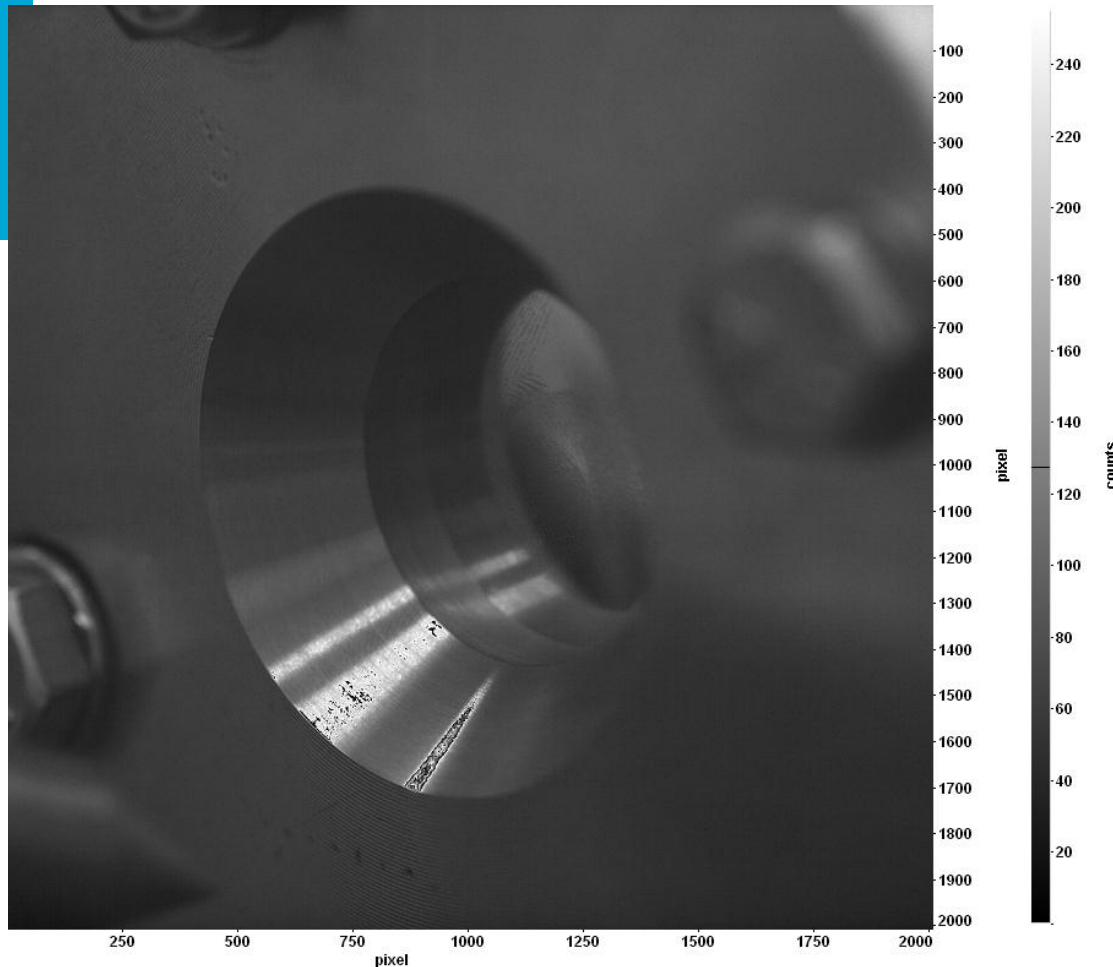


Alternative to FOV: Induced Breaking Diaphragm (IBD)

- Conventional diaphragms
 - Metal discs
 - Break @ $P_{\text{disc}} \approx P_{\text{exp}}$
 - Uncertainty high at low pressures
- Induced breaking diaphragm (IBD)
 - Resistant at $P_{\text{disc}} > P_{\text{exp}}$
 - Mechanical rupture



Induced Breaking Diaphragm (IBD)



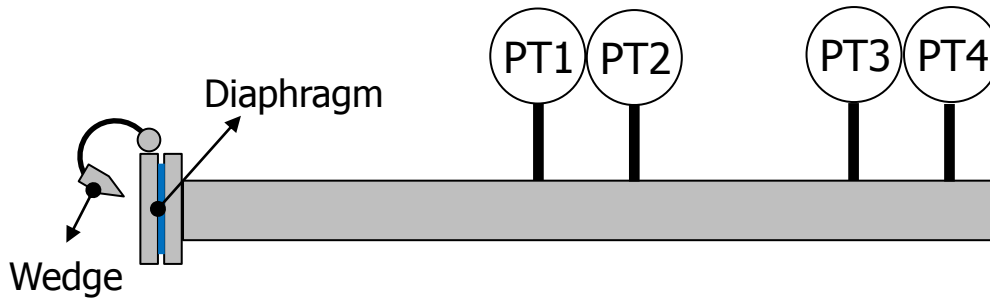
- Opening time $\approx 3,3\text{ms}$
- Tests at 250 °C with air and He
- With siloxanes?



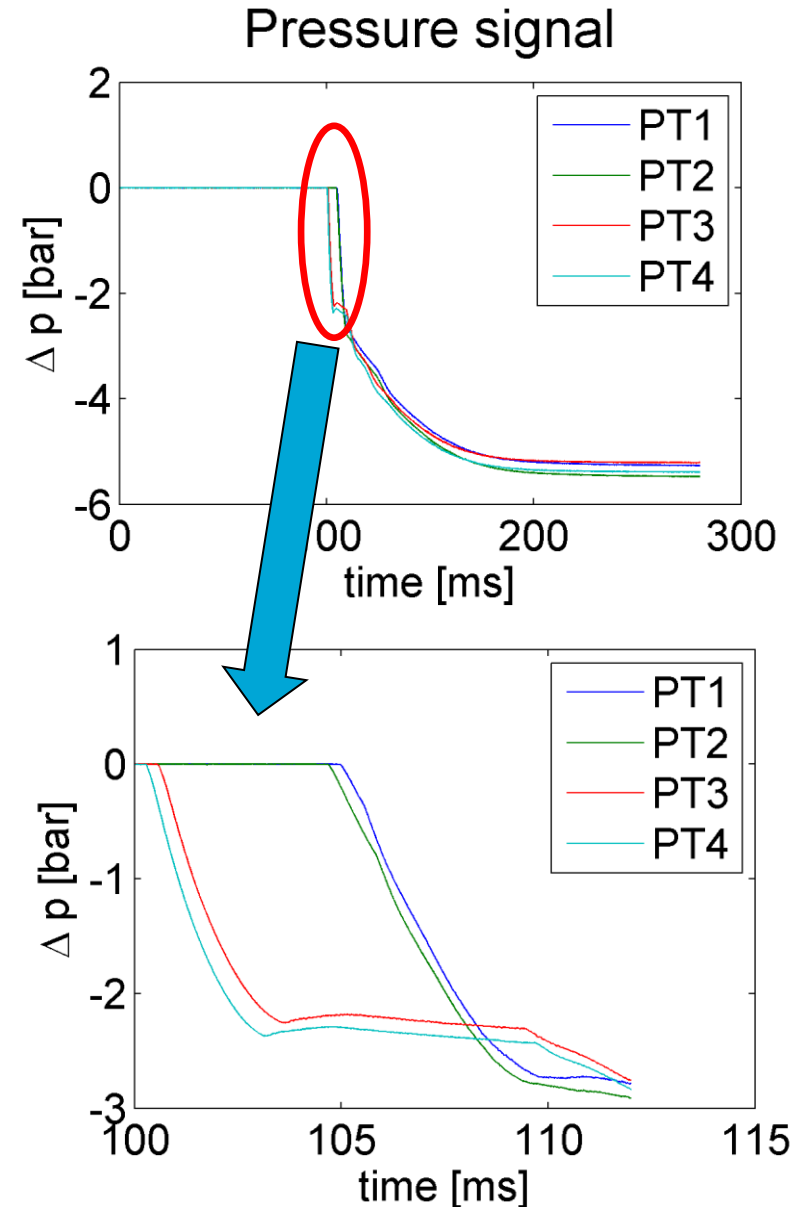
Sound speed

- Helium @ $p = 6$ bar, $T = 20 - 250$ °C
 - High speed of sound
 - Pure
- Pressure from 4x p-transducer at $f = 250$ kHz
- Δx fixed
- Δt by cross-correlation pressure-signals
- Signal manipulation needed

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



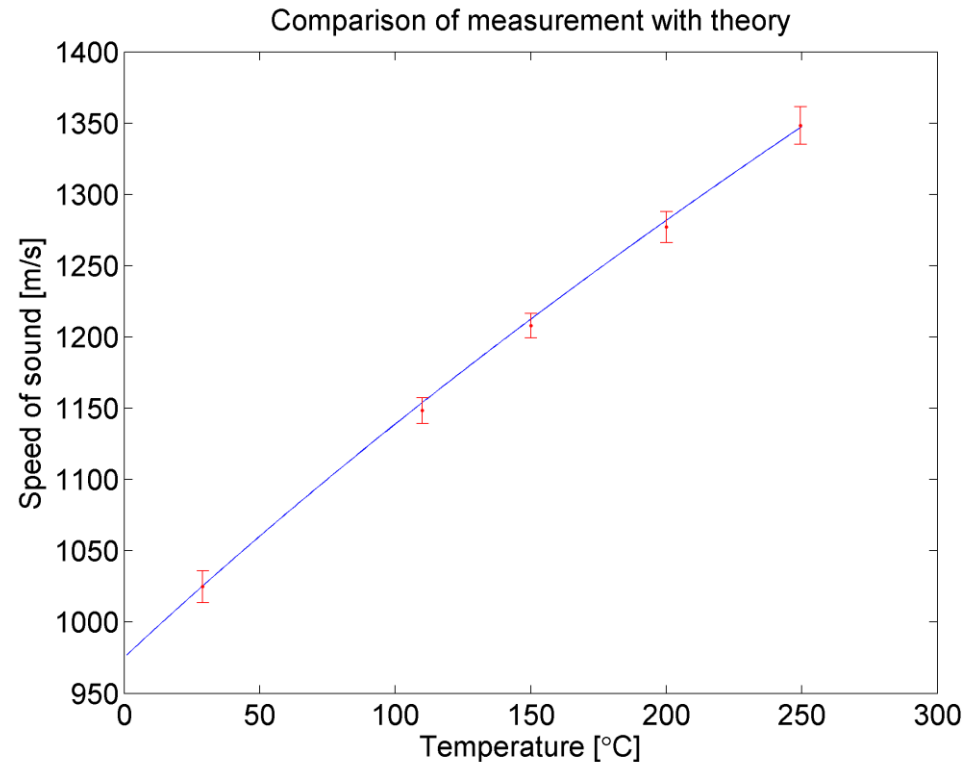
F.K. Lu, C.H. Kim, "Detection of wave propagation by cross correlation", Proc. 38th Aerospace Sciences Meeting & Exhibit, Jan 2000, Reno, Nevada



Sound speed results

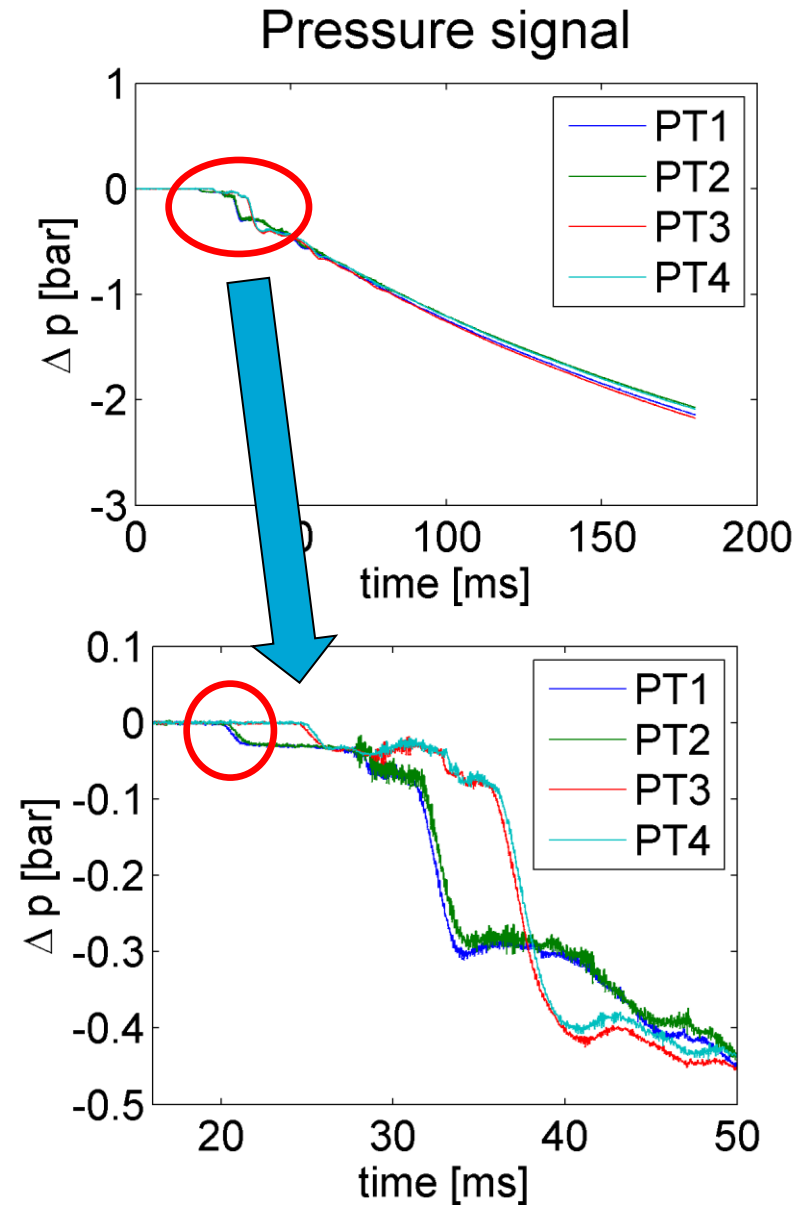
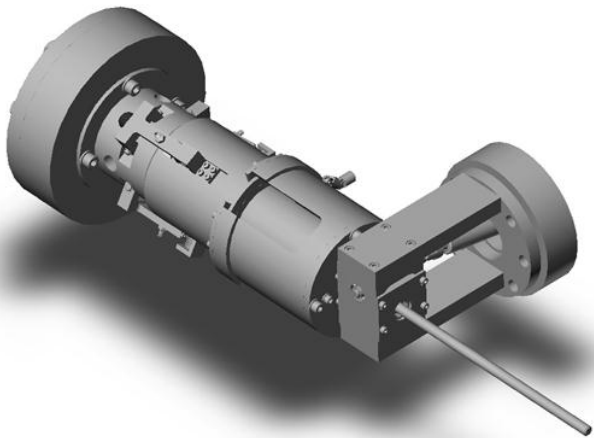
- Theoretical values from Refprop
 - Well known medium
 - Ideal gas regime
- Standard deviation < 1%

P [bar]	T [°C]	C _{th} [m/s]	C _{exp} [m/s]	Δc [m/s]	σ [m/s]
6,22	29	1025,5	1024,9	-0,6	11,3
5,92	110	1154,0	1148,4	-5,6	9,0
6,00	150	1212,5	1207,9	-4,6	8,5
6,70	200	1282,1	1277,1	-5,0	10,9
6,14	249,5	1347,0	1348,3	1,3	13,2



Sound speed

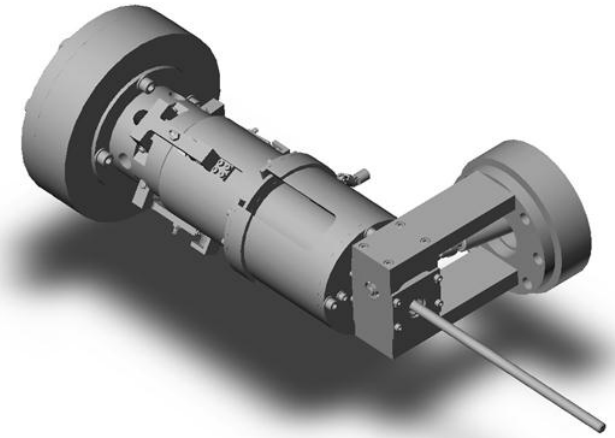
- IBD replaced by Fast Opening Valve
- More repeatable
- Consecutive tests
- Signal different due to valve opening sequence
- Cross-correlation possible



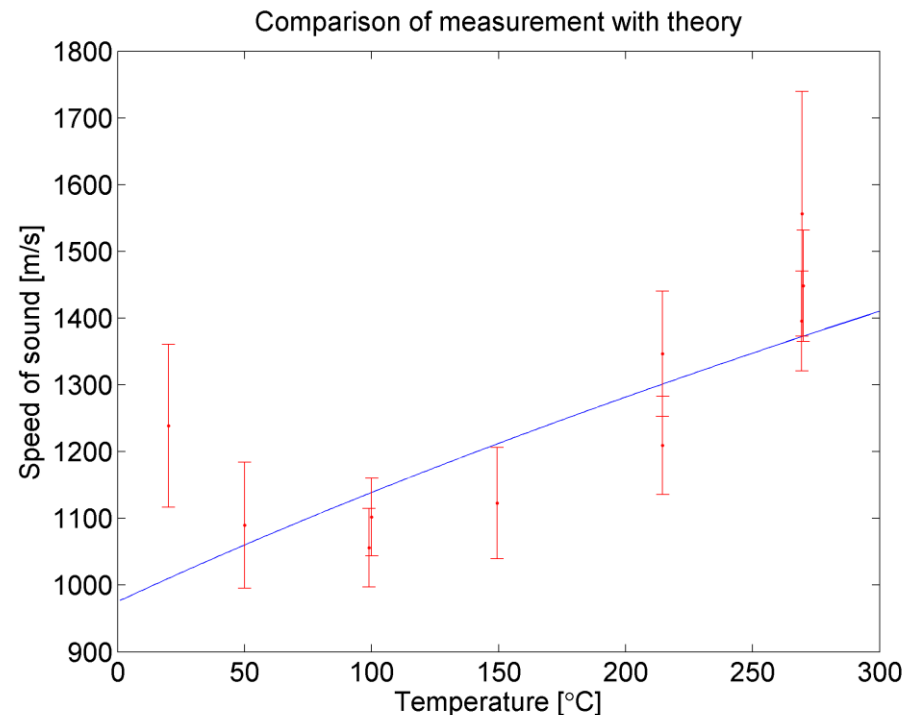
Sound speed results

Improvement necessary!

- But:
- 1st results
 - Very high speed of sound
 - Expansion fan \neq shock

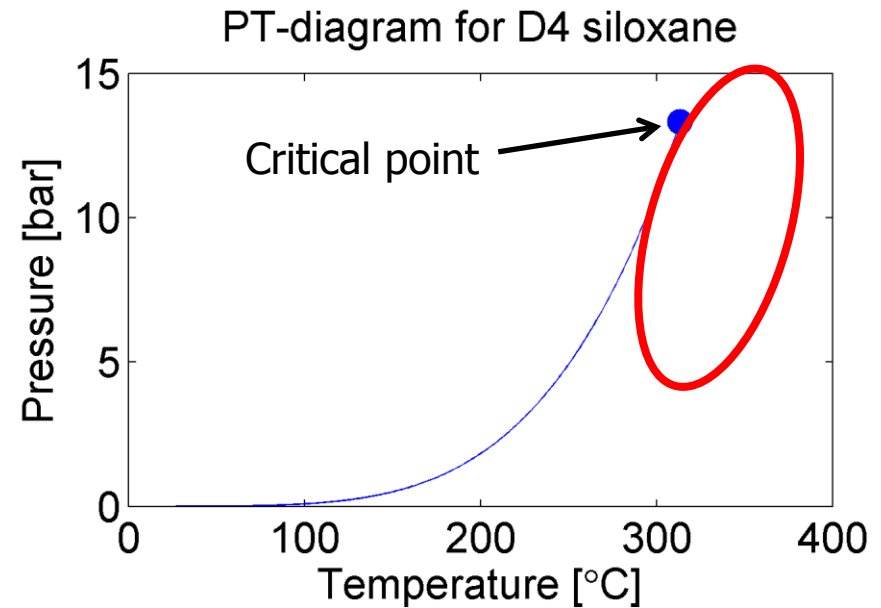


P [bar]	T [°C]	C_{th} [m/s]	C_{exp} [m/s]	Δc [m/s]	σ [m/s]
6,00	20,0	1010,1	1238,8	228,7029	121,9
6,50	50,0	1060,5	1089,7	29,2387	94,3
6,12	99,0	1137,4	1056,2	-81,2215	59,0
6,45	100,0	1139,1	1102,1	-36,9482	58,2
5,97	149,4	1211,6	1122,9	-88,7305	83,2
6,06	214,5	1301,3	1346,8	45,4879	93,8
6,04	214,6	1301,4	1209,4	-91,9796	73,6
7,29	269,3	1372,6	1395,7	23,0466	74,5
6,14	269,5	1372,4	1556,3	183,8931	183,5
8,47	269,9	1373,7	1448,5	74,7805	83,3



Future work

- Determination of opening time Fast Opening Valve
- Speed of sound measurements for ORC fluids
 - CFD code validation
 - Close to critical point measurements
- Rarefaction Shock wave measurements



Conclusion

- Flexible Asymmetric Shock Tube close to final commissioning
 - FOV works – maybe small adaptations
 - Low Pressure Plenum and Condenser sealed
- Induced Breaking Diaphragm tested with air & helium
- Speed of sound measurements in helium up to 250 °C
 - Successful
 - Standard deviation < 1%
 - Easier with lower speed of sound
- Interesting experiments within reach!!

Thank you for your attention!

Questions?

