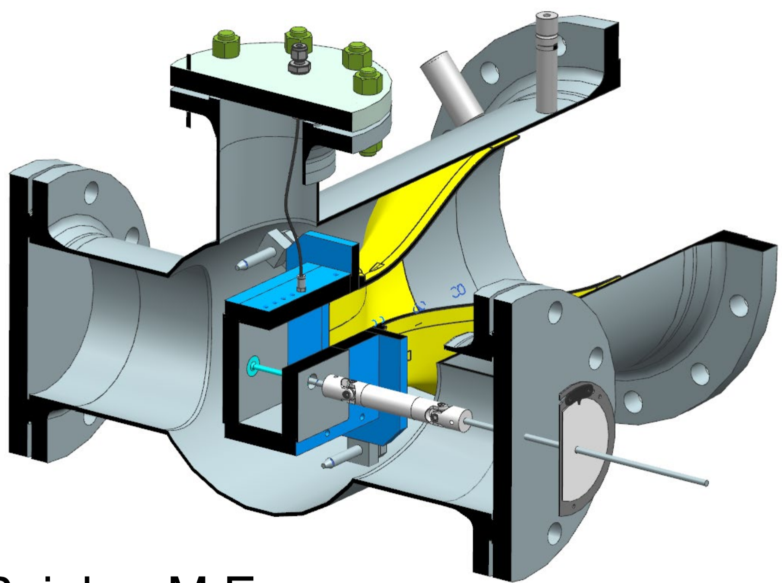
NICFD 2020

for Propulsion & Power

Performance of a Rotatable Cylinder Pitot Probe in High Subsonic Non-Ideal Gas Flows



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Paper ID: 8

Content

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Introduction & Motivation

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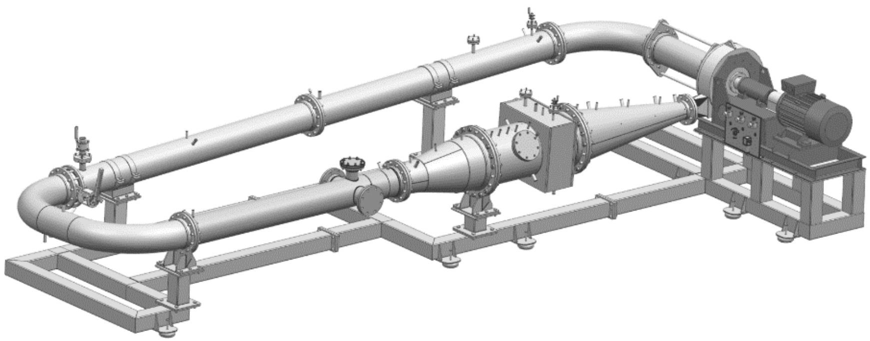
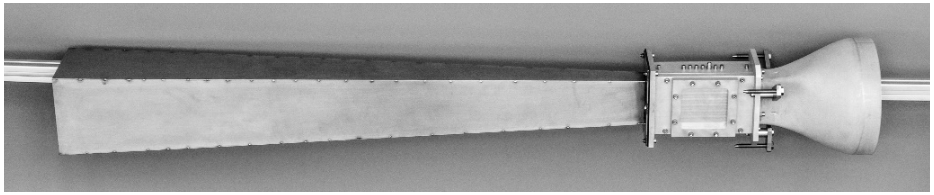
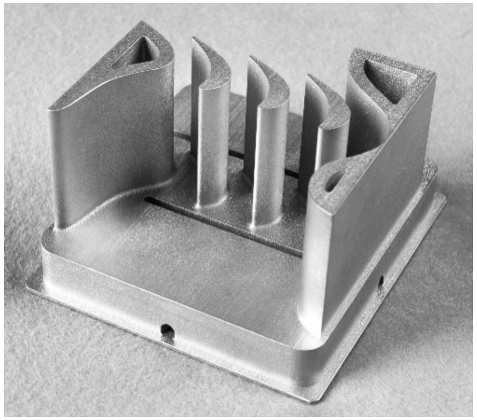


Closed Loop Organic vapor
Wind Tunnel (CLOWT)
Fluid: Novec™ 649



Modular High Speed Test Section
High Subsonic - Transonic



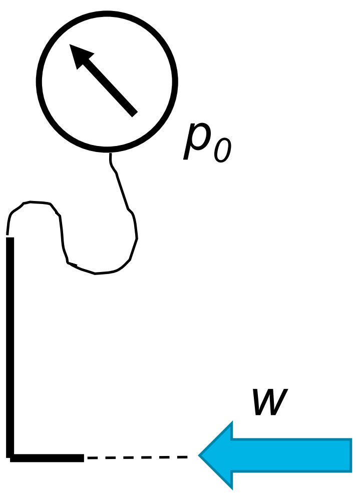
Printed turbine
guide vanes

Linear blade cascade
Mach number determination
→review of loss correlations
→affect of surface roughness

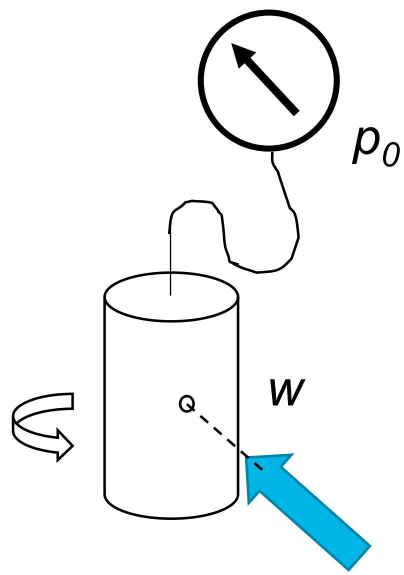
Pitot Probes: Basics

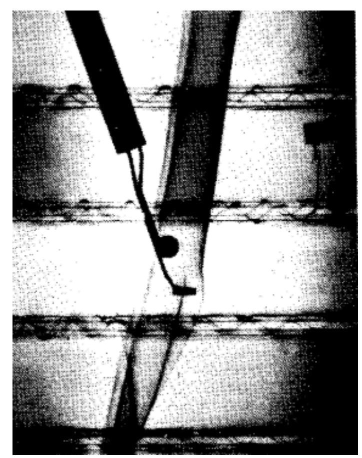
Definition: Device to measure stagnation (or total) pressure
Principle: Flow is brought isentropically to rest (stagnation)
Purpose: Determination of flow velocity (+free static pressure)
Invention: Henri Pitot (1732)

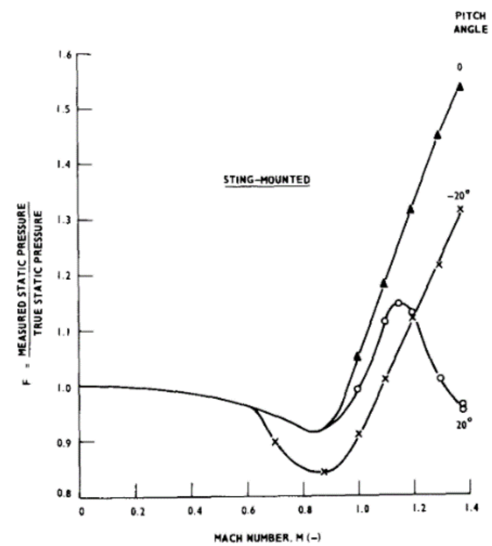
Classical L-Pitot Probe



Cylinder Pitot Probe







Langford et al. 1982
(issues for M>0.4 observed)

Pitot Probes: Gasdynamics

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Isentropic flow relations:

Perfect gas flows:

Subsonic:

$$M^2 = \frac{2}{\gamma-1}\left(\left(\frac{p_0}{p}\right)^{(\gamma-1)/\gamma} - 1\right)$$

Supersonic:

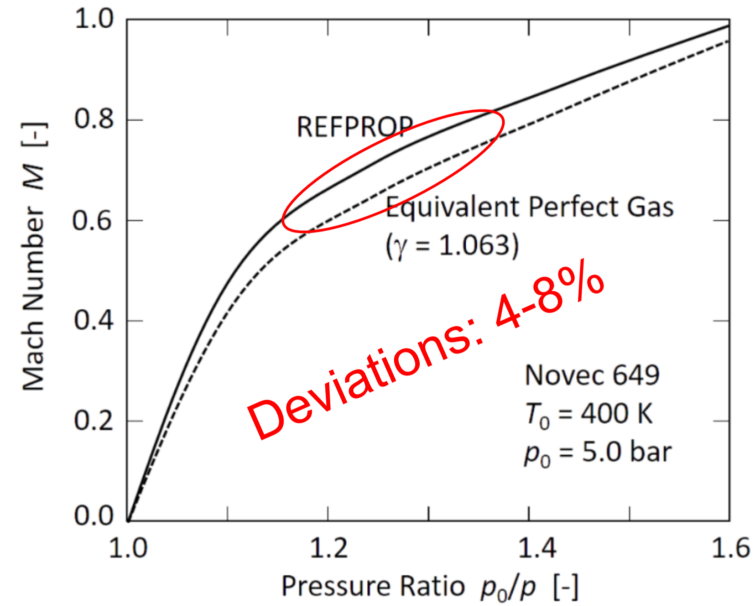
$$\frac{p_0}{p} = \frac{\gamma+1}{2} M^2 \left(\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)}\right)^{1/(\gamma-1)}$$

p: free-stream static pressure
p_0: Pitot probe total pressure (downstream of shock)
γ: Isentropic exponent

Non-ideal gas flows:

- Suitable equations of state
- Solving mass & energy balance equations

$$M = f(p, p_0, T_0)_s$$



Method: Passmann M. et al. – NICFD 2016

Experimental Setup

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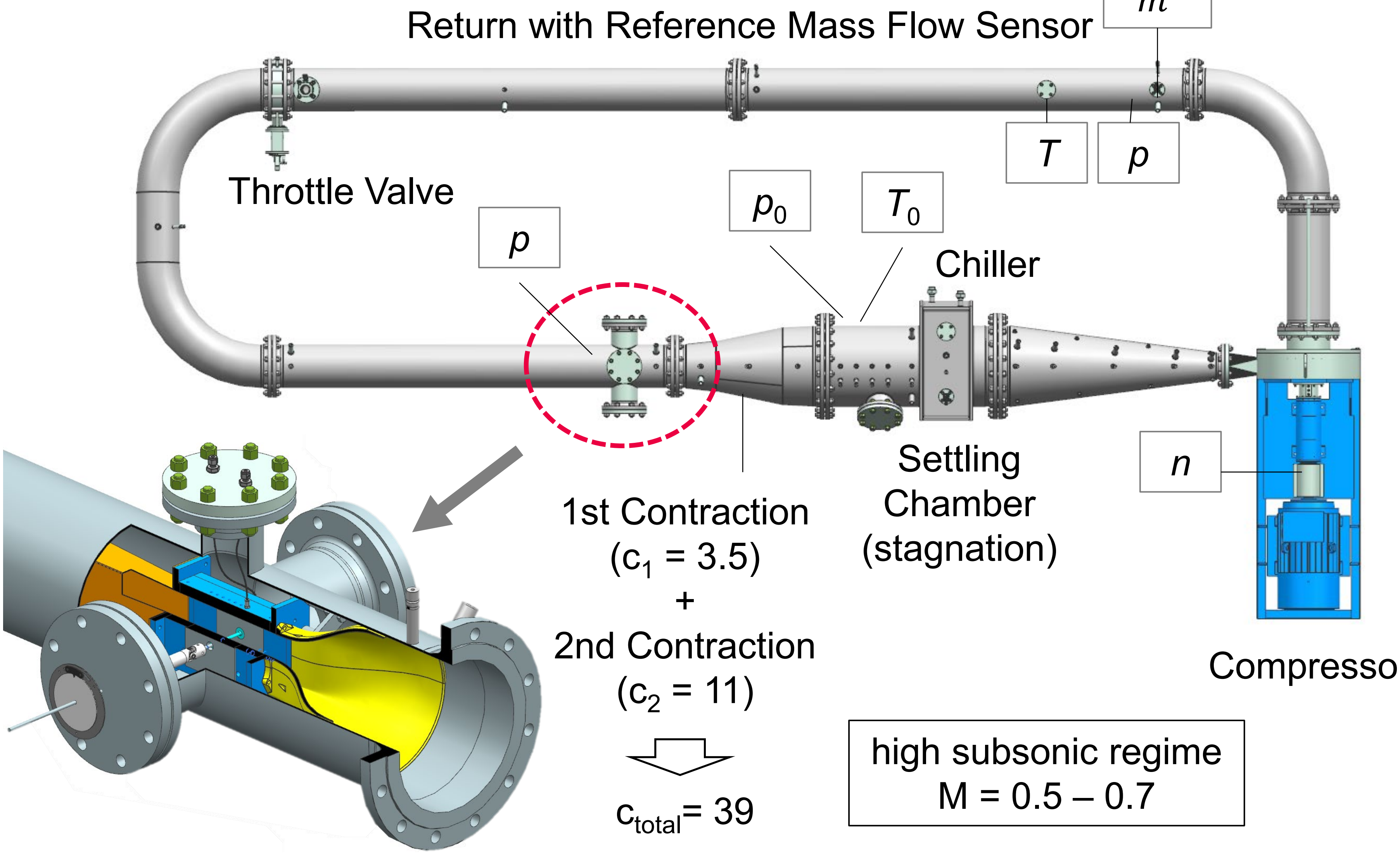
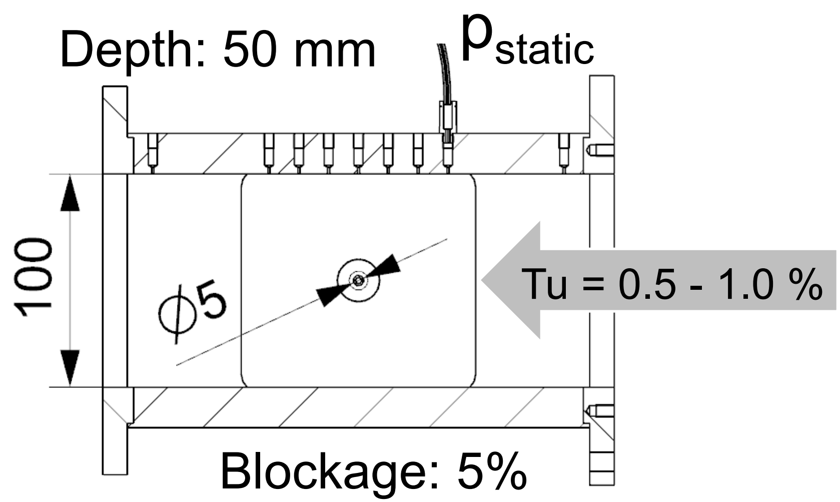
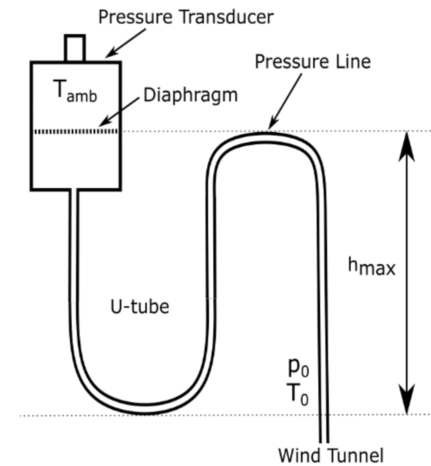
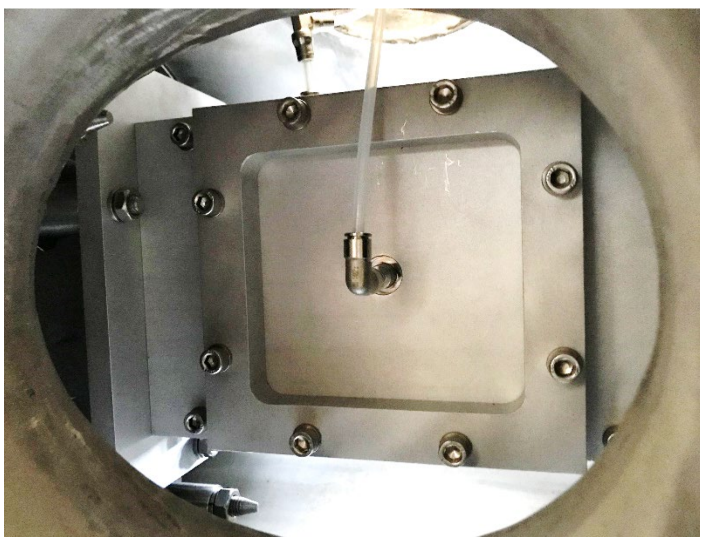


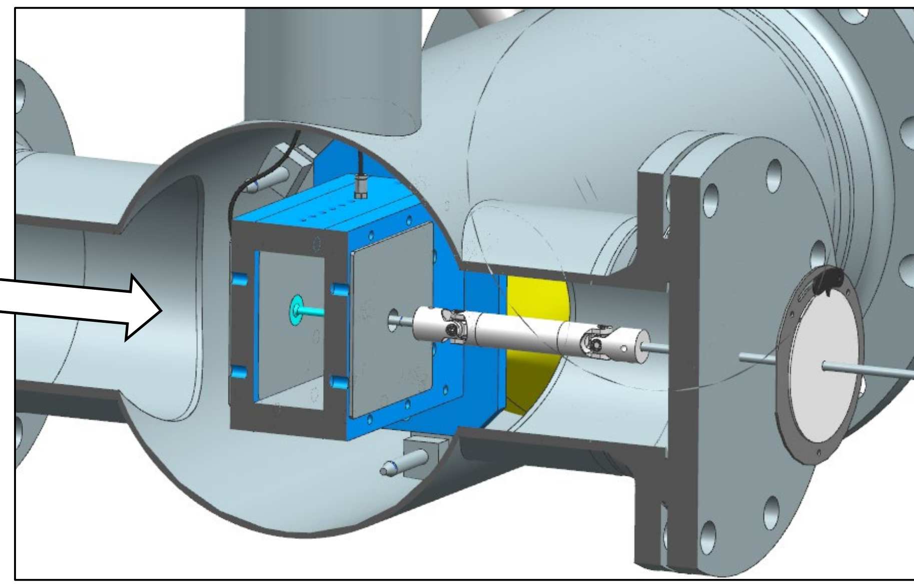
high subsonic regime
M = 0.5 – 0.7

Experimental Setup









Experimental Setup

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Cylinder Pitot Probe

Insert with flexible cardan shaft

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Experimental Setup

Process parameters & fluctuations

Process parameter	**Value**
Pressure level *p* [Mpa]	0.294 ± 0.017
Temperature level *T* [K]	368 ± 1.6
Density *ρ* [kg/m³]	34.5 ± 2.2
Compressibility factor *Z*	0.88 ± 0.01
Speed of Sound *a* [m/s]	88.2 ± 0.9
Isentropic exponent *κ* [-]	1.056
Dynamic viscosity *μ* [Pa·s]	$1.38 \cdot 10^{-5}$
Prandtl number Pr [-]	0.77
Reynolds number Re [-]	$1.8 \cdot 10^{5} – 6.1 \cdot 10^{5}$
Mach number M [-]	0.16 – 0.7

Measurement uncertainties

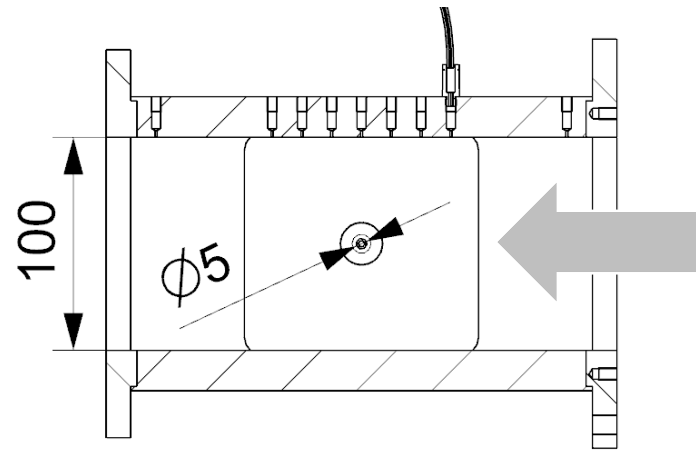
Process variable	**Uncertainty**
Pressure $\Delta p/p$	**0.6 - 1.5%**
Temperature $\Delta T/T$	< 0.1%
Mach number $\Delta M/M$	**1.0 - 3.0%**
Reynolds number ΔRe/Re	1.8 – 4.8%
Compressibility factor $\Delta Z/Z$	2.4%
Pressure Coefficient $\Delta C_p/C_p$	1.0%

Fluid: Novec™ 649 by 3M™

Blockage correction

Blockage factor d/H = 5 %

Perturbed velocity field affects:
Cp and w

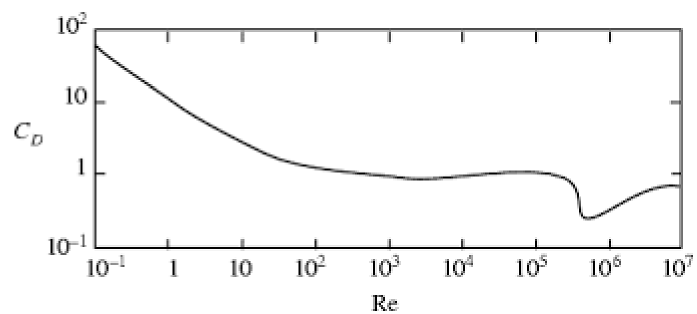


Blockage parameter ε (Wyler 1975)

$$\varepsilon = \frac{w - w_{Pitot}}{w_{Pitot}} = \frac{C_D}{2(1-M^2)}\frac{d}{H}$$

$$C_p - 1 = \left(\frac{w_{Pitot}}{w}\right)^2 \left(C_{p,Pitot} - 1\right)$$

$$C_p = \frac{p_{pitot} - p}{p_0 - p}$$



$$C_D = 1.15 + 0.75\,(M - 0.2)$$?

Wyler, J. S. (1975) Probe Blockage Effects in Free Jets and Closed Tunnels. ASME J. Eng. Gas Turbines Power, vol. 97(4), 509-514

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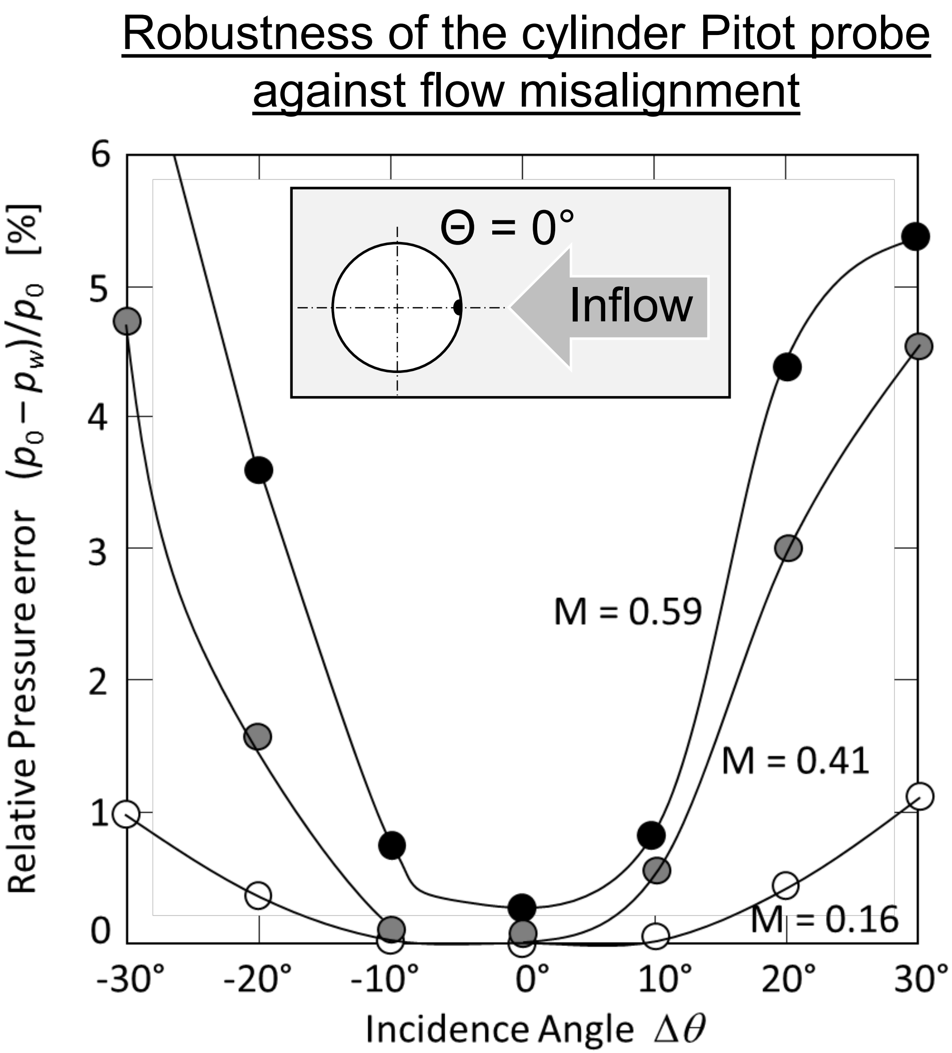
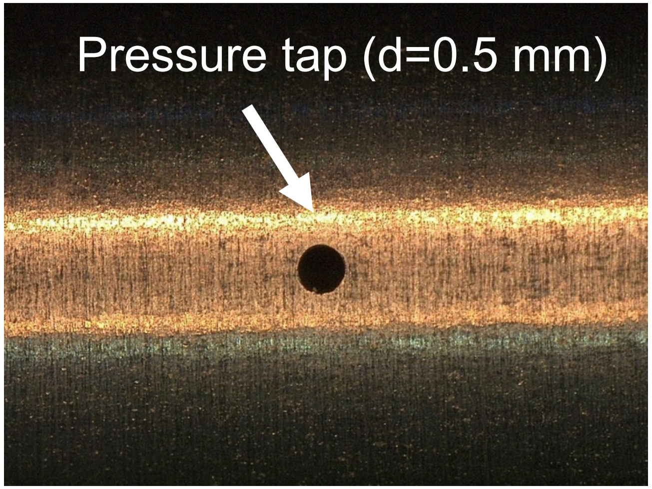
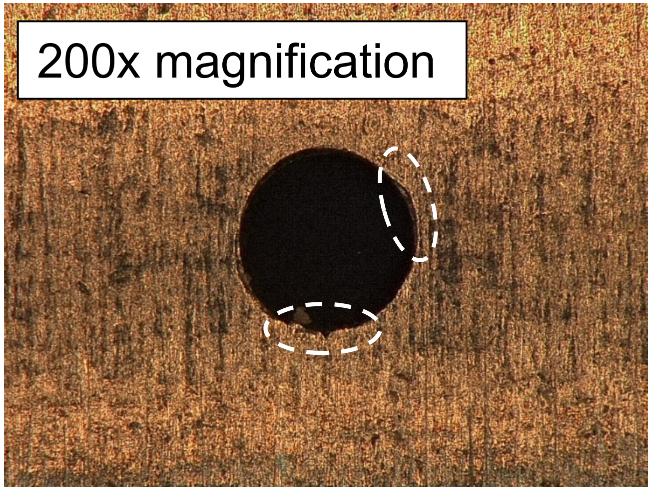
Experimental results

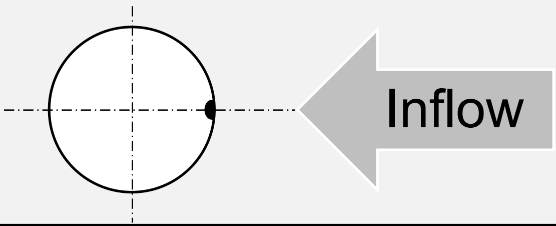






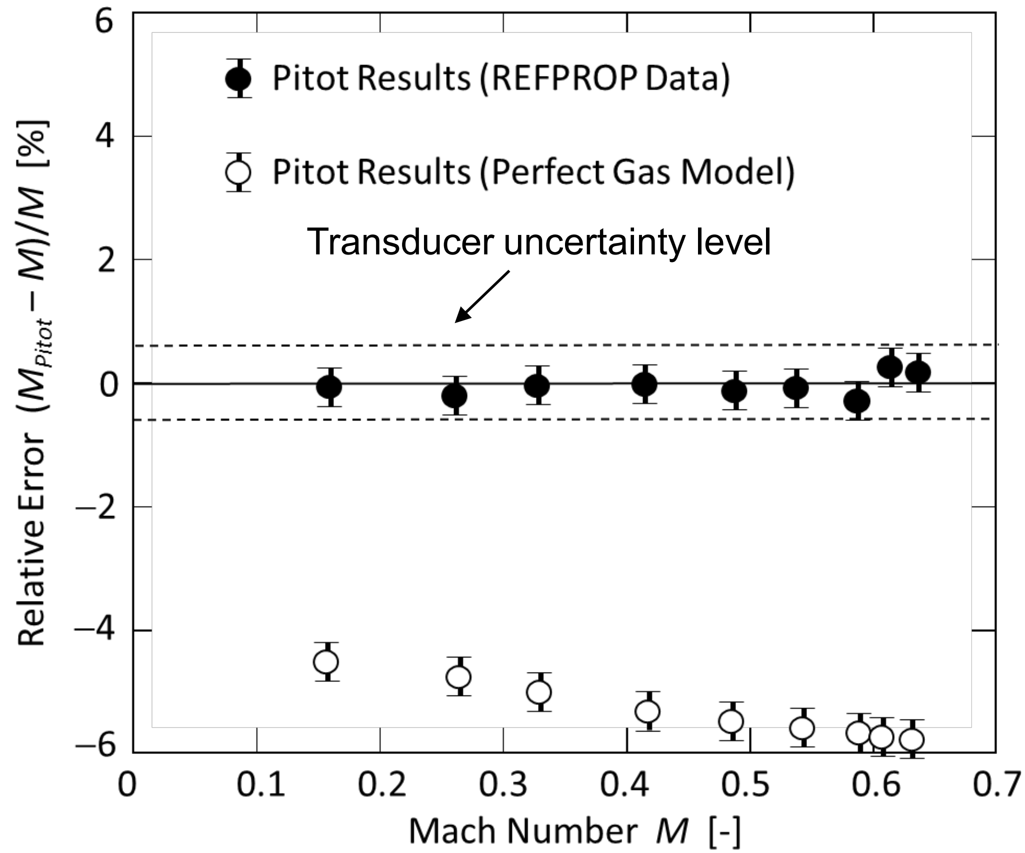
Experimental results

Aligned Pitot configuration: Θ = 0°



Reference

$$M = f(\dot{m}, p, p_0, T_0)_s$$



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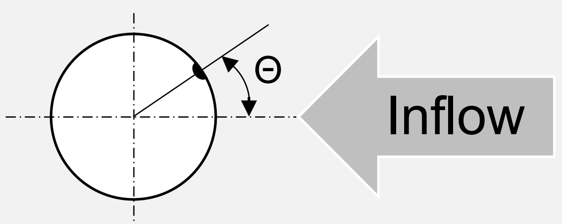
Experimental results

Variable
Circumferential Angle Θ



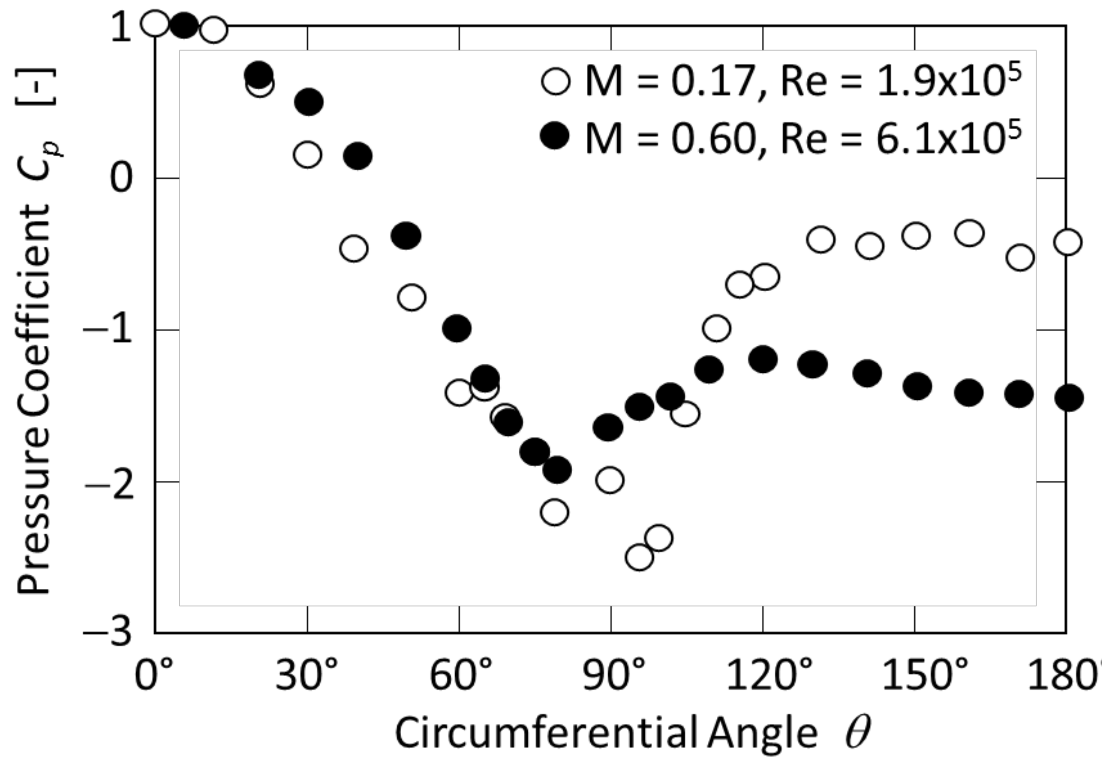
Pressure Coefficient C_p

$$C_p = \frac{p_{pitot} - p}{p_0 - p}$$

p: freestream static pressure

p_{pitot}: pitot pressure

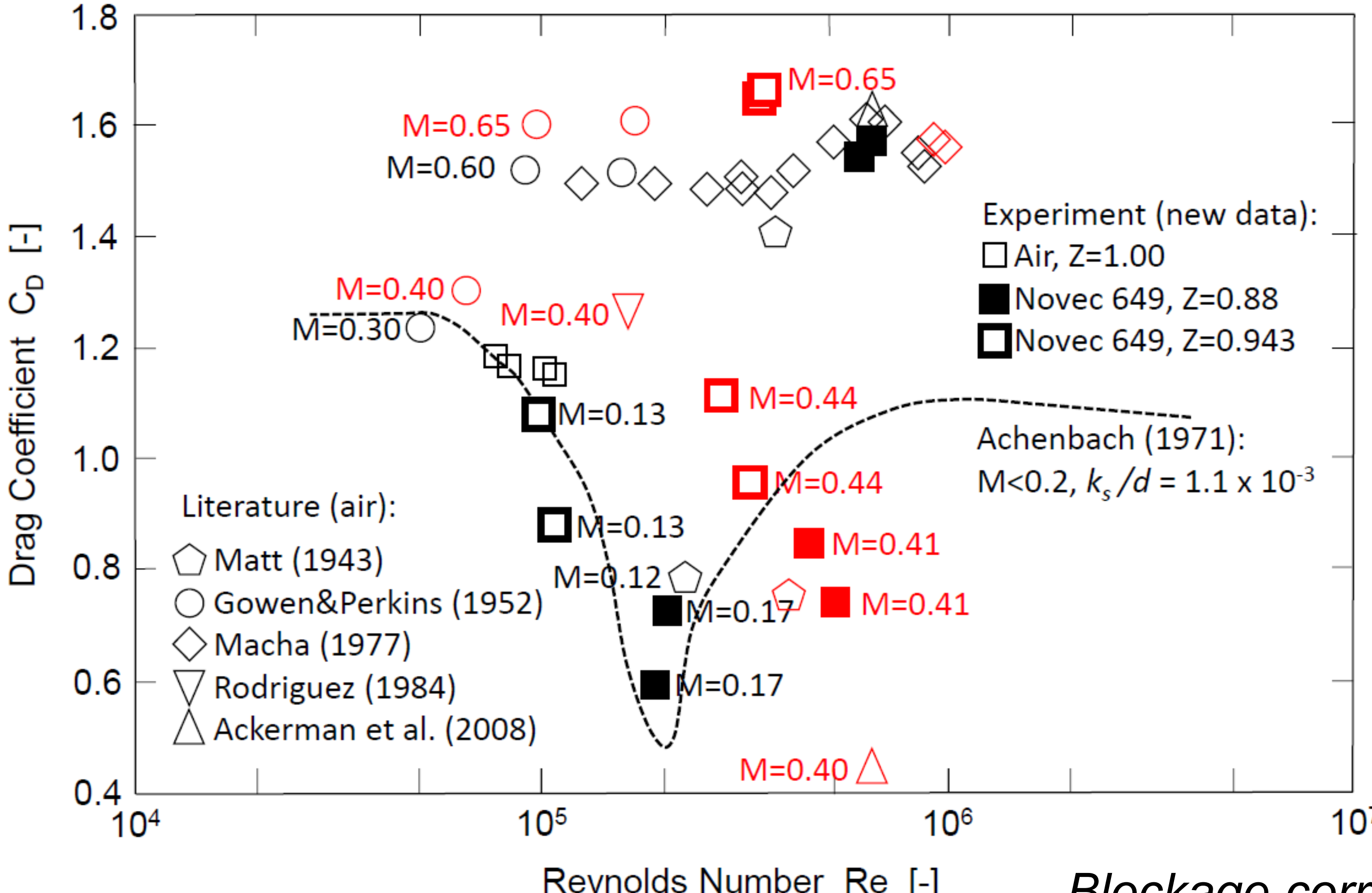
p_0: stagnation pressure



- ✓ M=0.17: Agreement with literature data
- ➢ M=0.6: Drag divergence → Transition

Experimental results

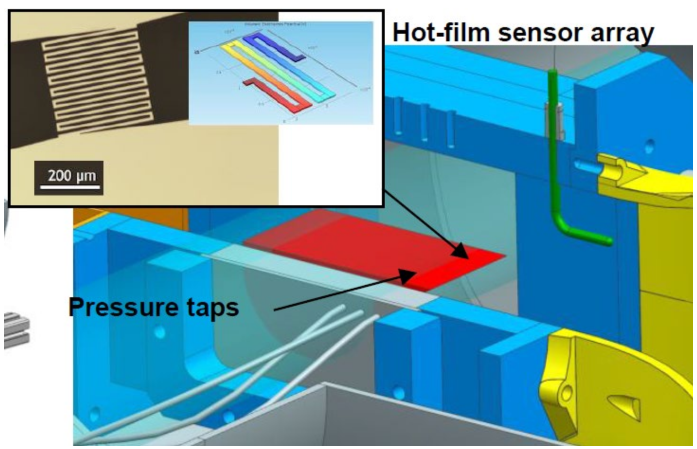
Drag coefficient for Blockage Correction
depends on Ma & Re (but not on Z)



Blockage correction x3 !

Conclusion & Outlook

- Mach number determination with Cylinder Pitot Probe was successful in high subsonic flow
- Probe Blockage effects have to be considered, especially for larger blockage factors (as usual in turbomachinery applications) to minimize uncertainties
- Drag divergence and locally supersonic flow phenomena were observed, which in turn affect probe blockage and should therefore be carefully considered
- Future research: see REGAL-ORC (2021-2024)



REGAL-ORC

Thanks for your attention ☺