High-speed wind tunnel exercise

Ferry Schrijer
f.f.j.schrijer@tudelft.nl
room 0.39

Woutijn Baars
w.j.baars@tudelft.nl
room 0.36

Alessandro D’Aguanno
a.daguanno@tudelft.nl
room 0.37

Aerodynamics lab, Building 64

Exercise objective

- Comparison between theory and experiments related to quasi 1D compressible flows

- Validity of the assumptions related to quasi 1D flows

- Experimental techniques for compressible flows

Exercise content

1. Water channel demonstration

2. Wind tunnel measurements (group of 6 students)

3. Exercise report (performed directly after the practical in groups of 3 students)

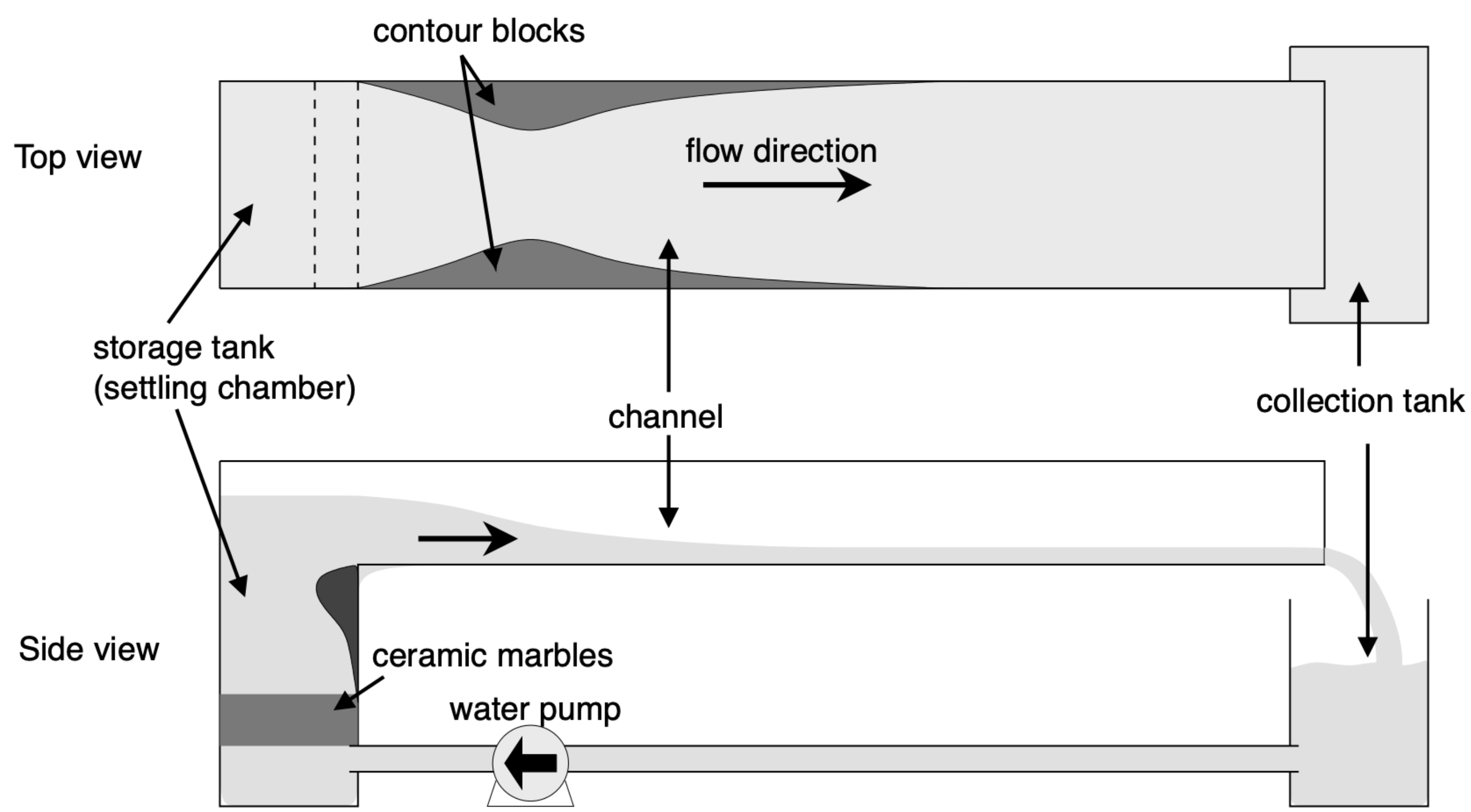
Water channel analogy

❖ Analogy between shallow water flows and supersonic flows

	air	water
continuity:	$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$	$\frac{\partial h}{\partial t} + \nabla \cdot (h \mathbf{u}) = 0$
momentum:	$\frac{D\mathbf{u}}{Dt} + \frac{\gamma p_t}{\rho_t^\gamma} \rho^{\boxed{\gamma - 2}} \nabla \rho = 0$	$\frac{D\mathbf{u}}{Dt} + g \nabla h = 0$

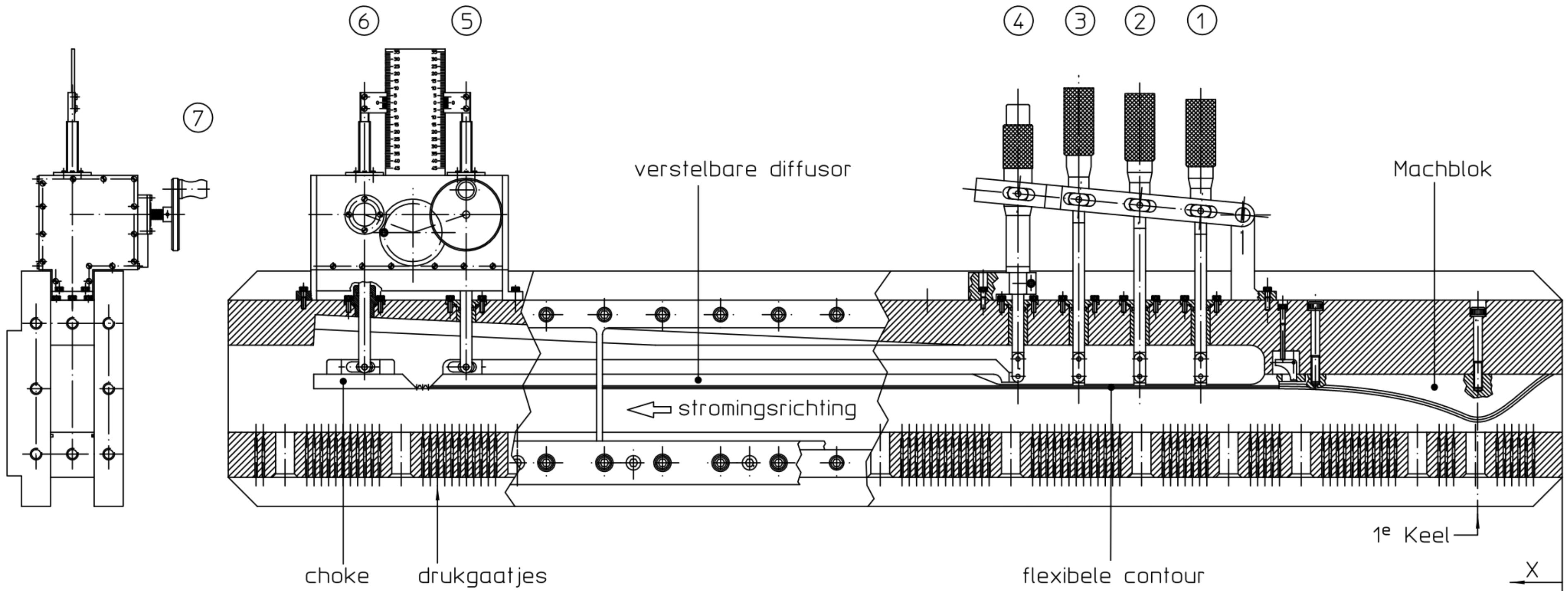
For $\boxed{\gamma=2}$:

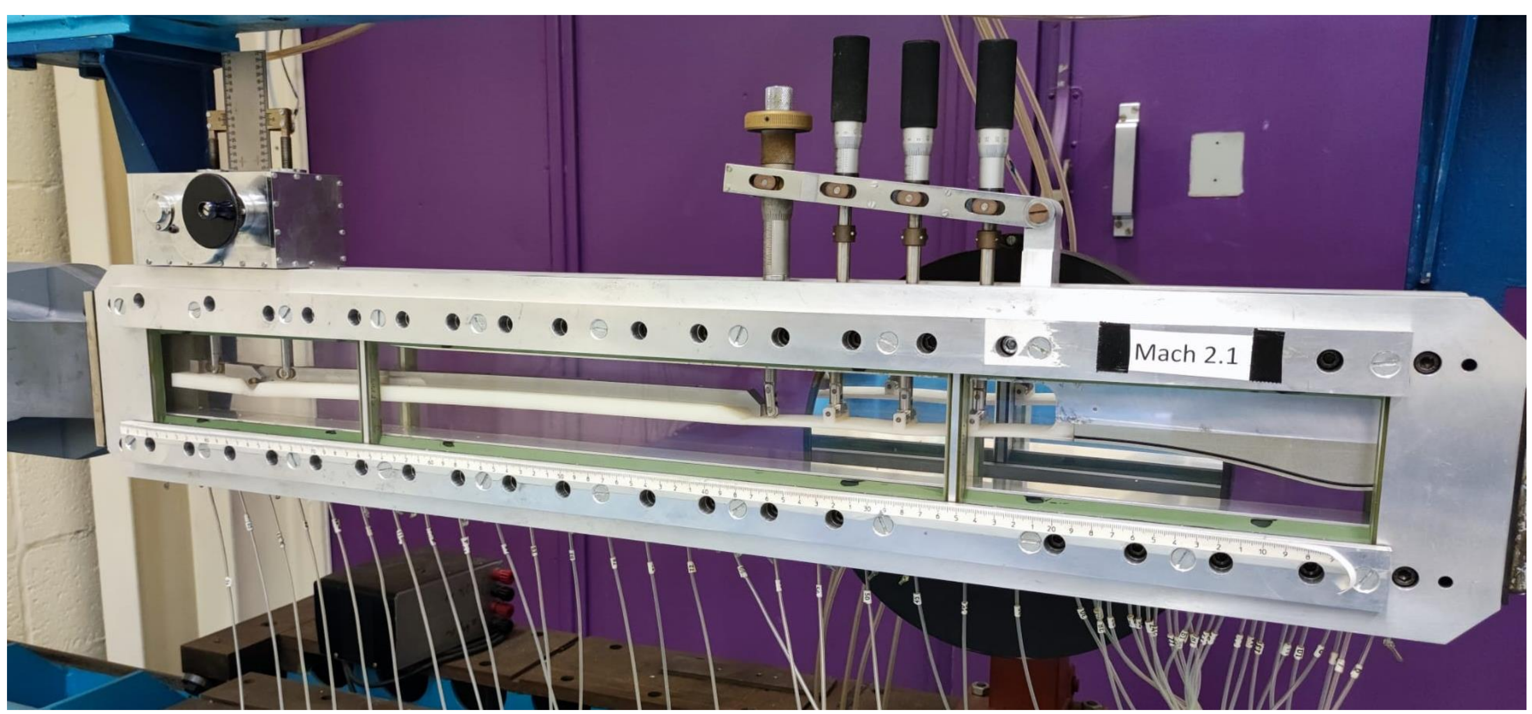
- $\rho \Leftrightarrow h$
- $p \Leftrightarrow h^2$
- $T \Leftrightarrow h$



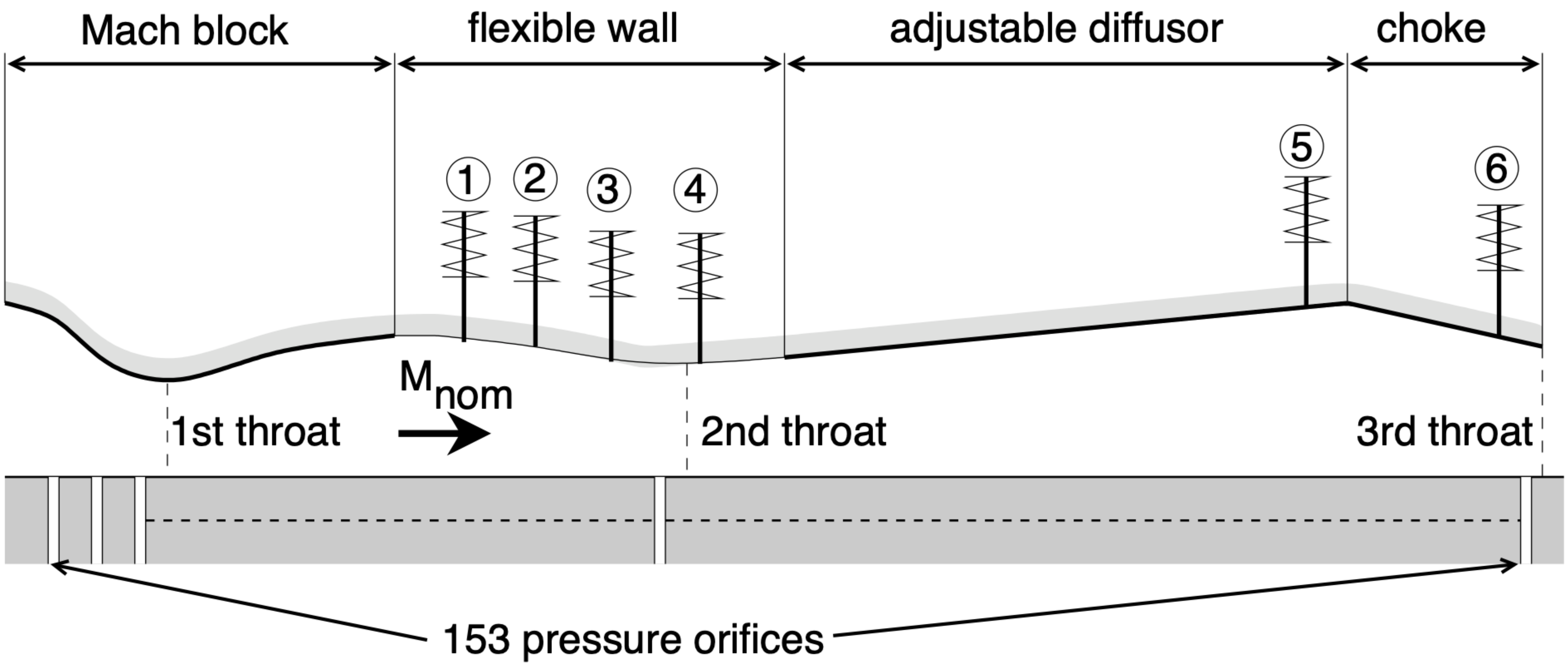
ST3 wind tunnel

① - ④ : micrometers voor instelling 2^e keel
⑤ : schroefspindel diffusor
⑥ : schroefspindel choke
⑦ : handwiel voor instelling diffusor + choke





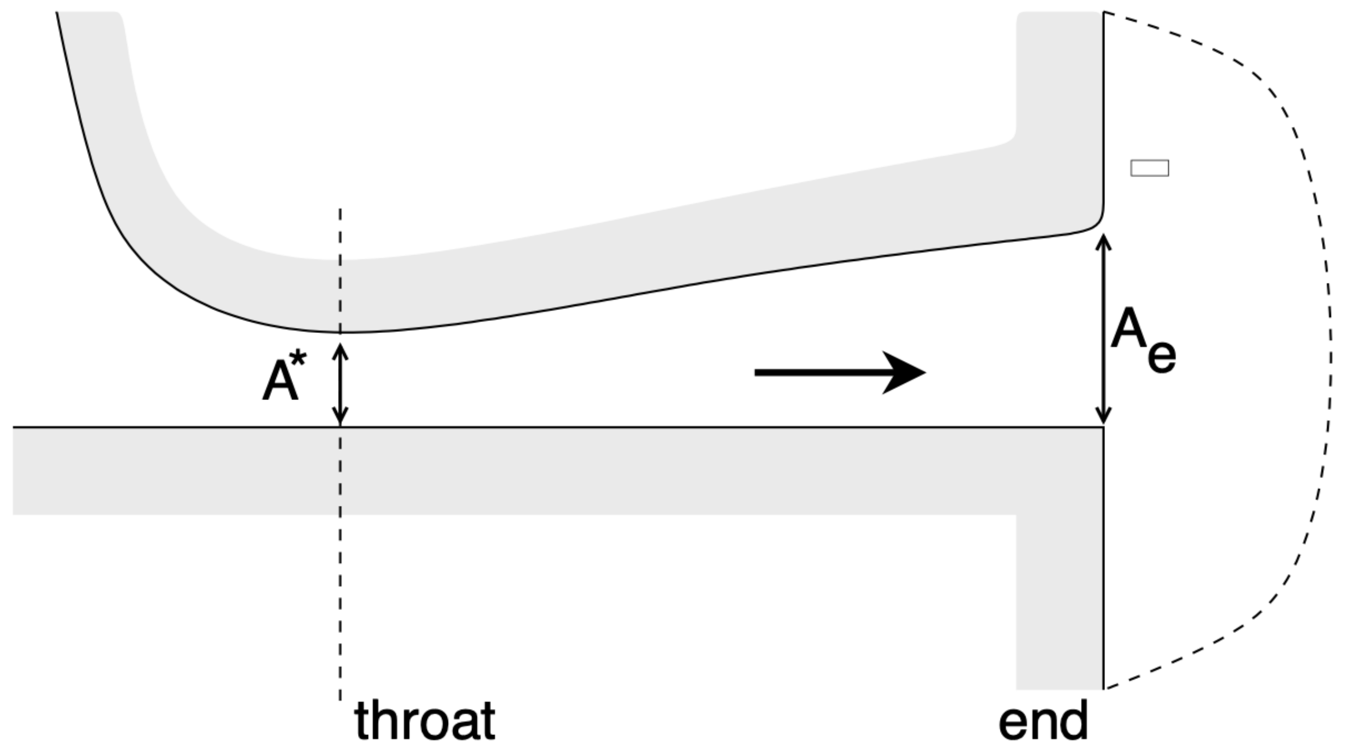
Wind tunnel tests



Two measurement series:

1. Subsonic and supersonic flow in the first throat
2. Normal shock wave in the adjustable diffusor

Flow through a convergent-divergent channel



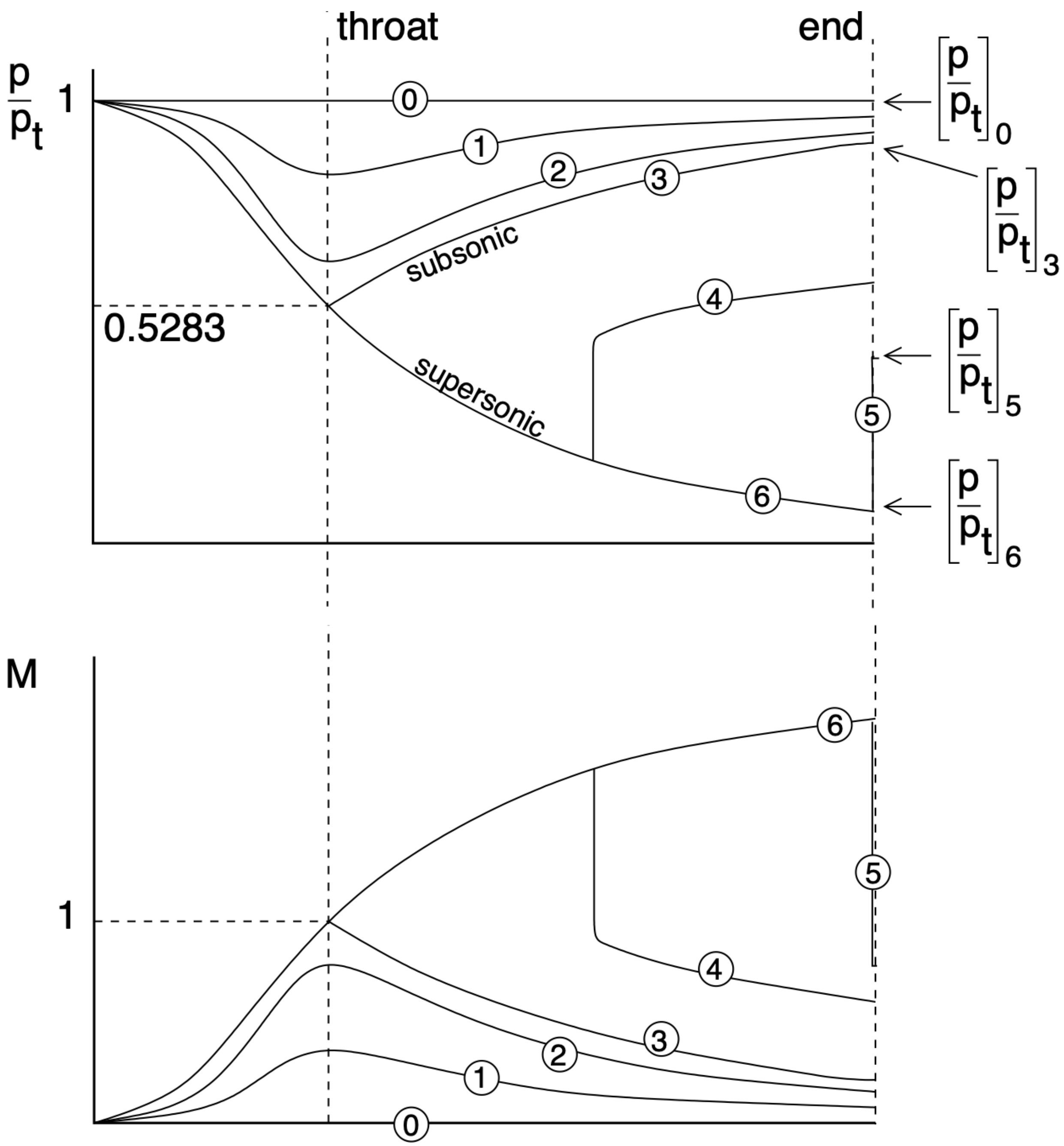
$$\frac{A}{A^*} = \frac{1}{M^2}\left(\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Two solutions depending on the boundary conditions:

1. M<1, subsonic solution
2. M>1, supersonic solution

Flow through a convergent-divergent channel

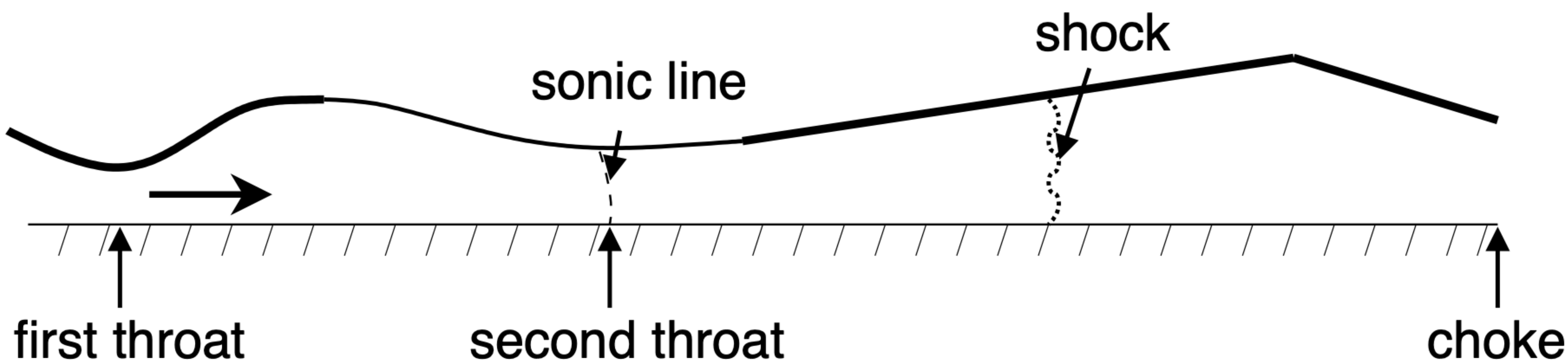
$$\frac{p}{p_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma - 1}}$$



Effect of decreasing exit pressure:

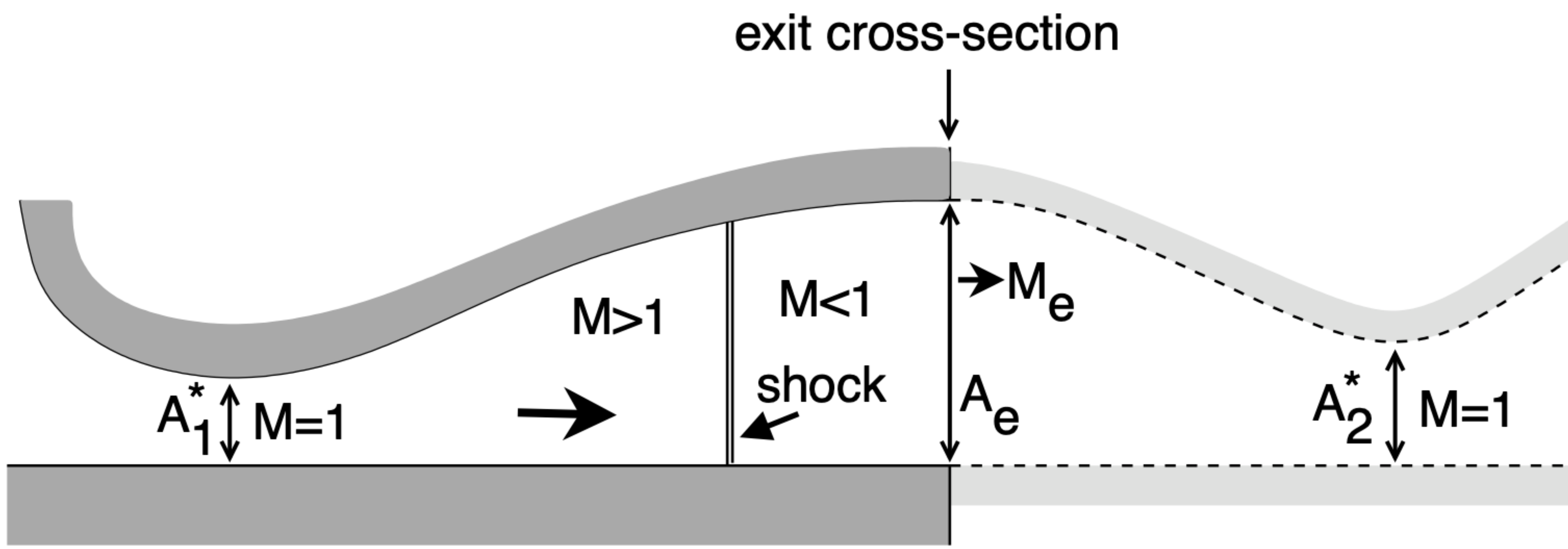
- $p > p_3$ subsonic flow (isentropic)
- $p = p_3$ throat is choked (isentropic)
- $p_5 < p < p_3$ locally supersonic (non-isentropic, shock-wave)
- $p < p_5$ supersonic downstream of throat (isentropic)

Shock in adjustable diffusor



Using the downstream choke, a normal shock wave can be positioned in the diverging part of the nozzle

Control of Shock position with second throat



Sonic condition in both throats: $\rho_1^* u_1^* A_1^* = \rho_2^* u_2^* A_2^*$

Rewriting the equations: $$\frac{A_2^*}{A_1^*} = \frac{p_{t,1}}{p_{t,2}} \sqrt{\frac{T_{t,1}}{T_{t,2}}}$$

Adiabatic flow: $$\frac{A_2^*}{A_1^*} = \underbrace{\frac{p_{t_1}}{p_{t_2}}}_{>1} \Rightarrow A_2{}^* > A_1{}^*$$

Measurement equipment

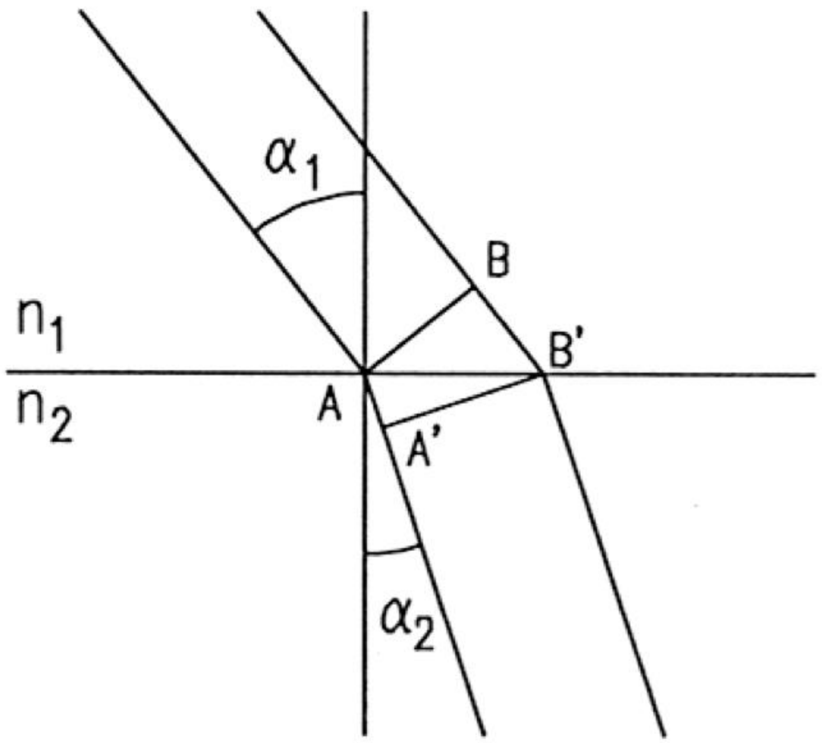
1. **Pressure measurements**

   To be used for the report to calculate Mach number and for comparison with the theoretical values

2. **Schlieren visualisation**

   Visualisation of the flow field (shock waves) which enables to better understand the pressure measurements

Schlieren visualization technique



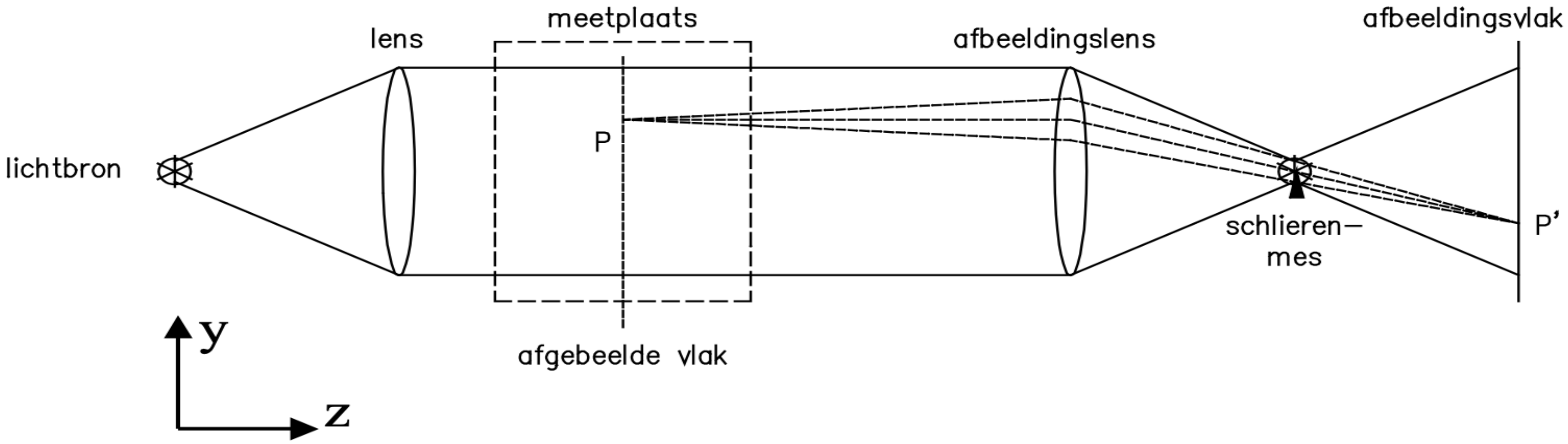
❖ Snell's law:

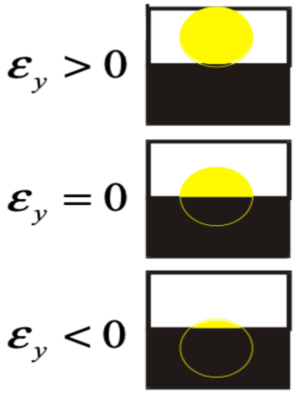
$$n_1 \sin(\alpha_1) = n_2 \sin(\alpha_2)$$

❖ Gladstone-Dale relation:

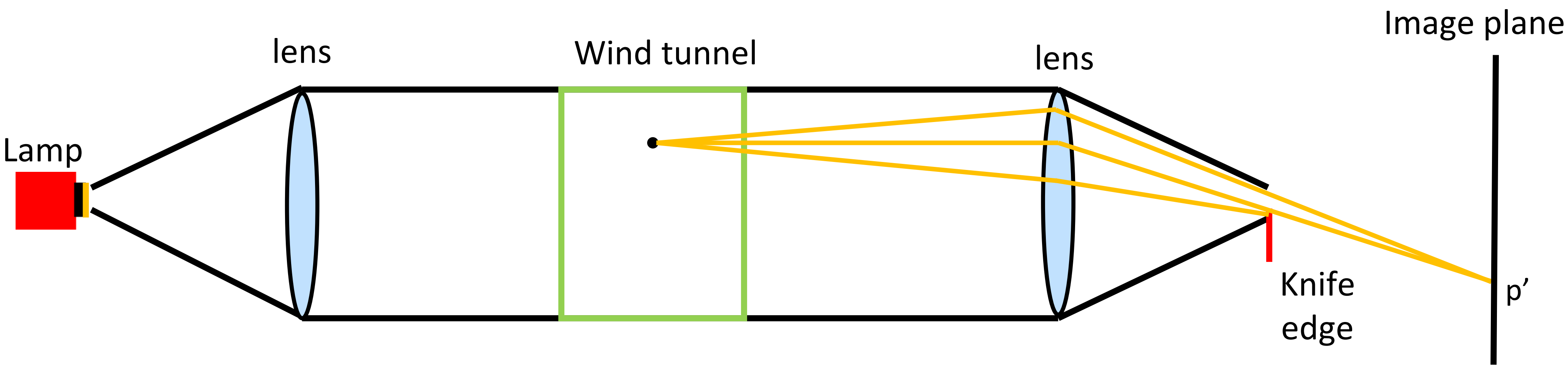
$$n = 1 + K\rho$$

The light-rays bend toward the high density

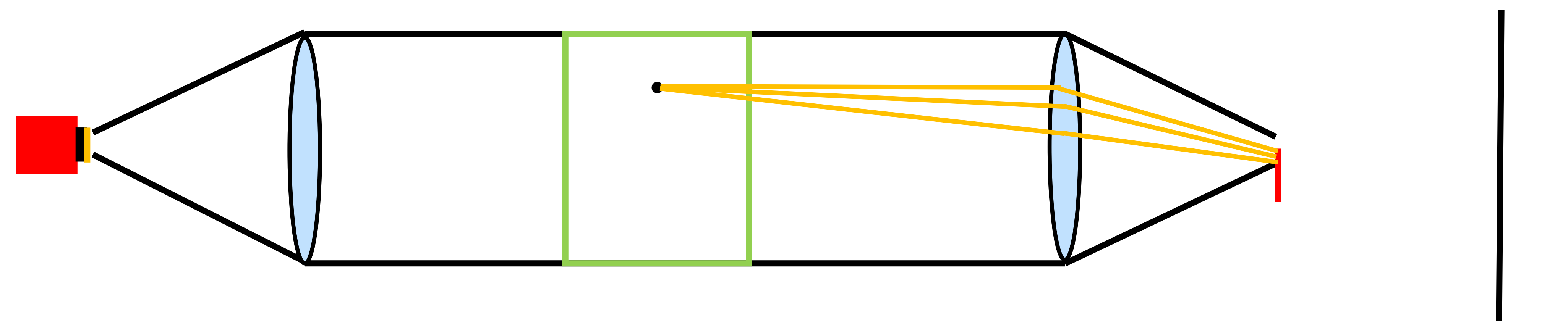




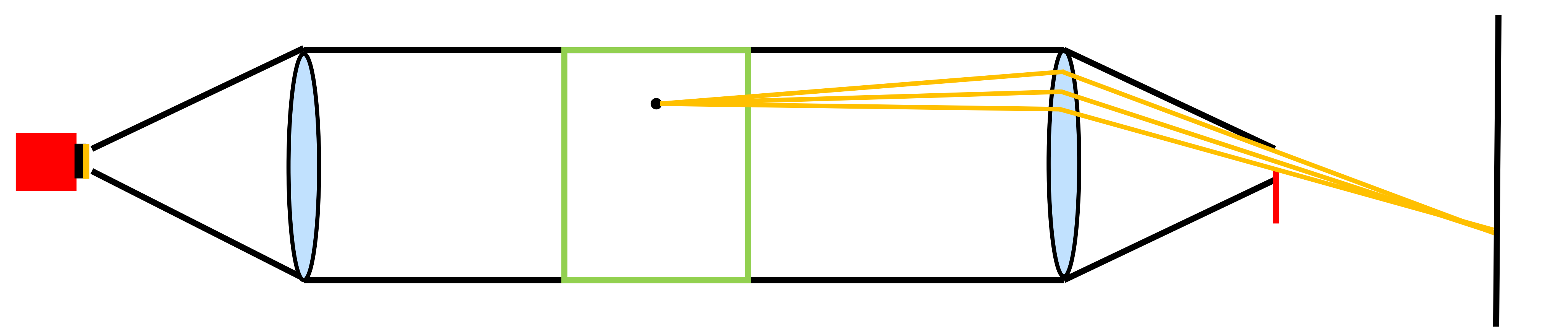
Schlieren visualization technique



❖ No density variations

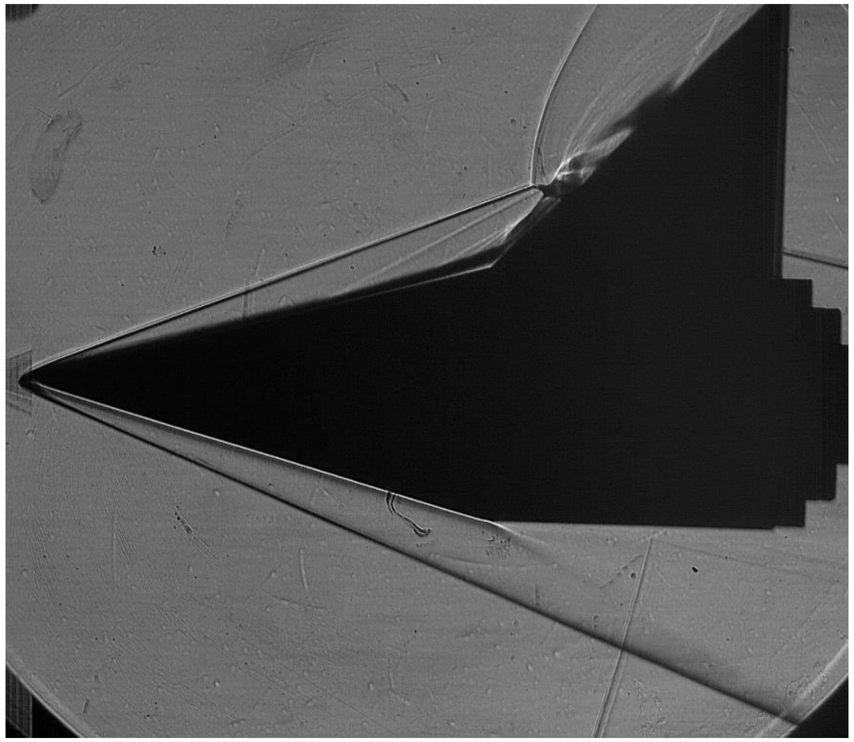


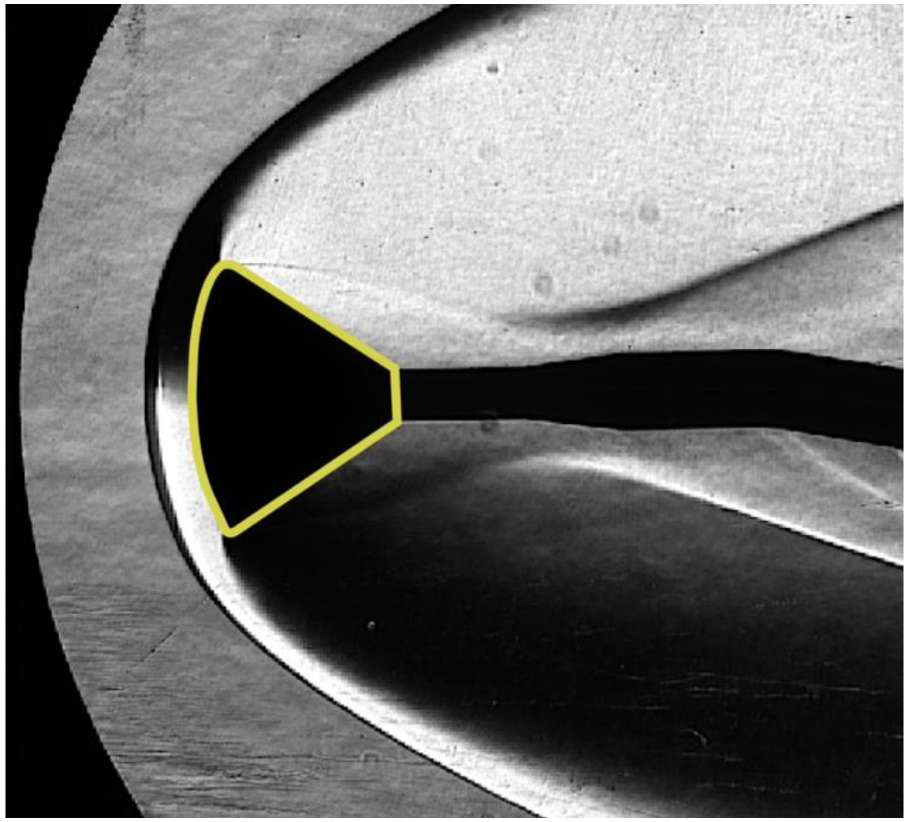
❖ Increase of density

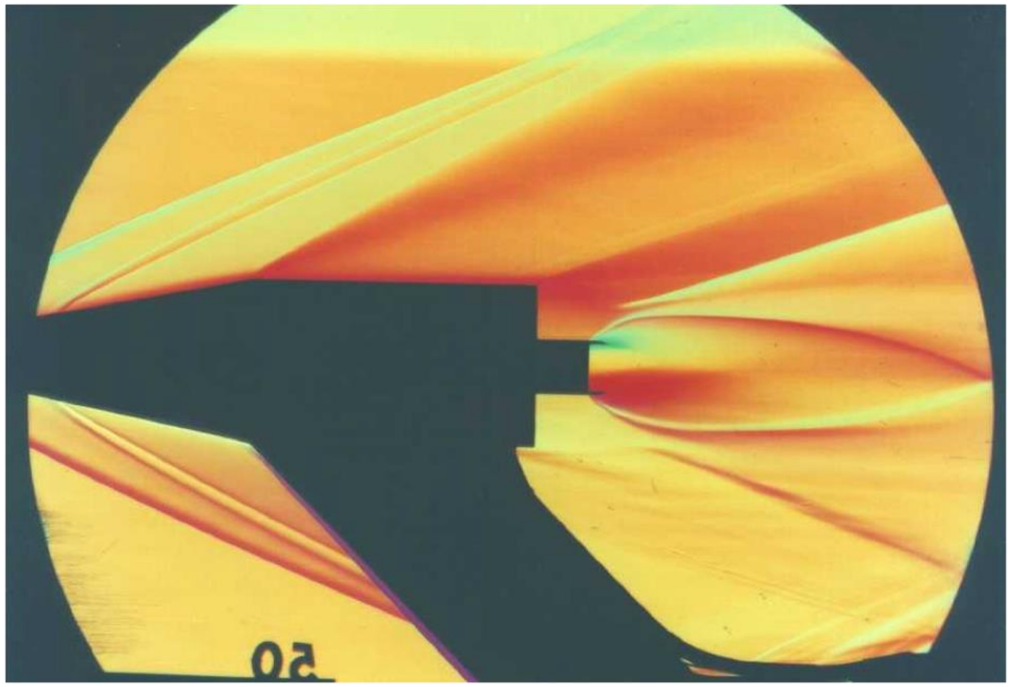


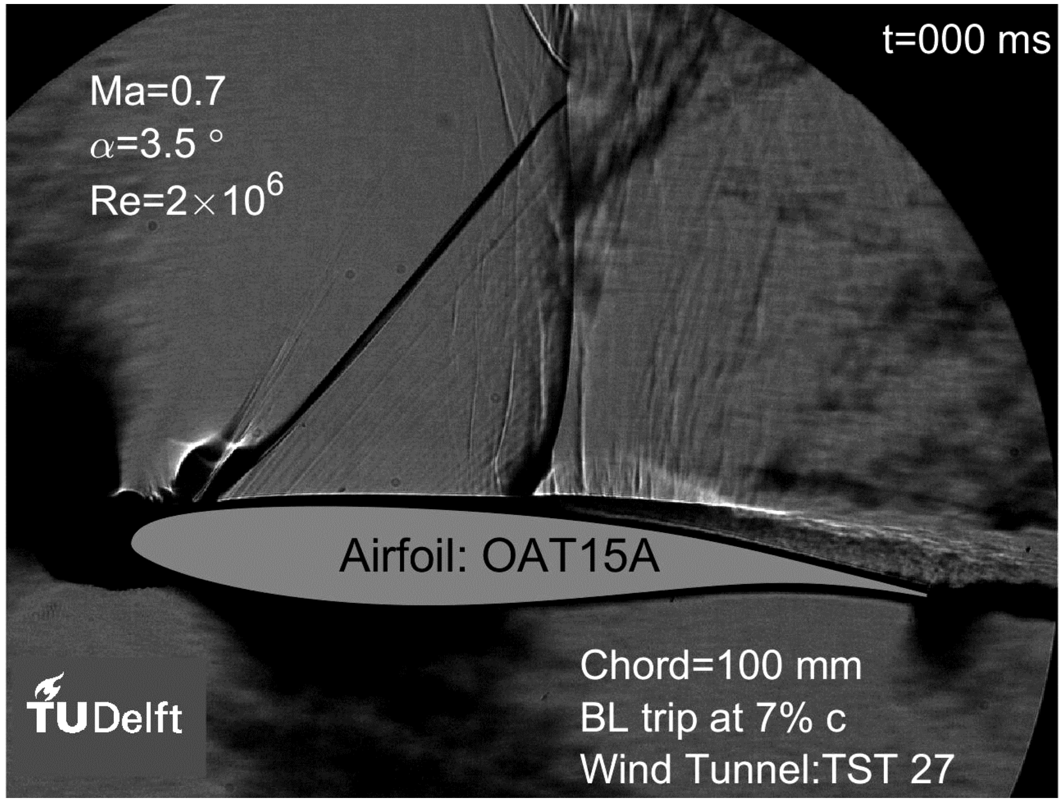
❖ Decrease of density

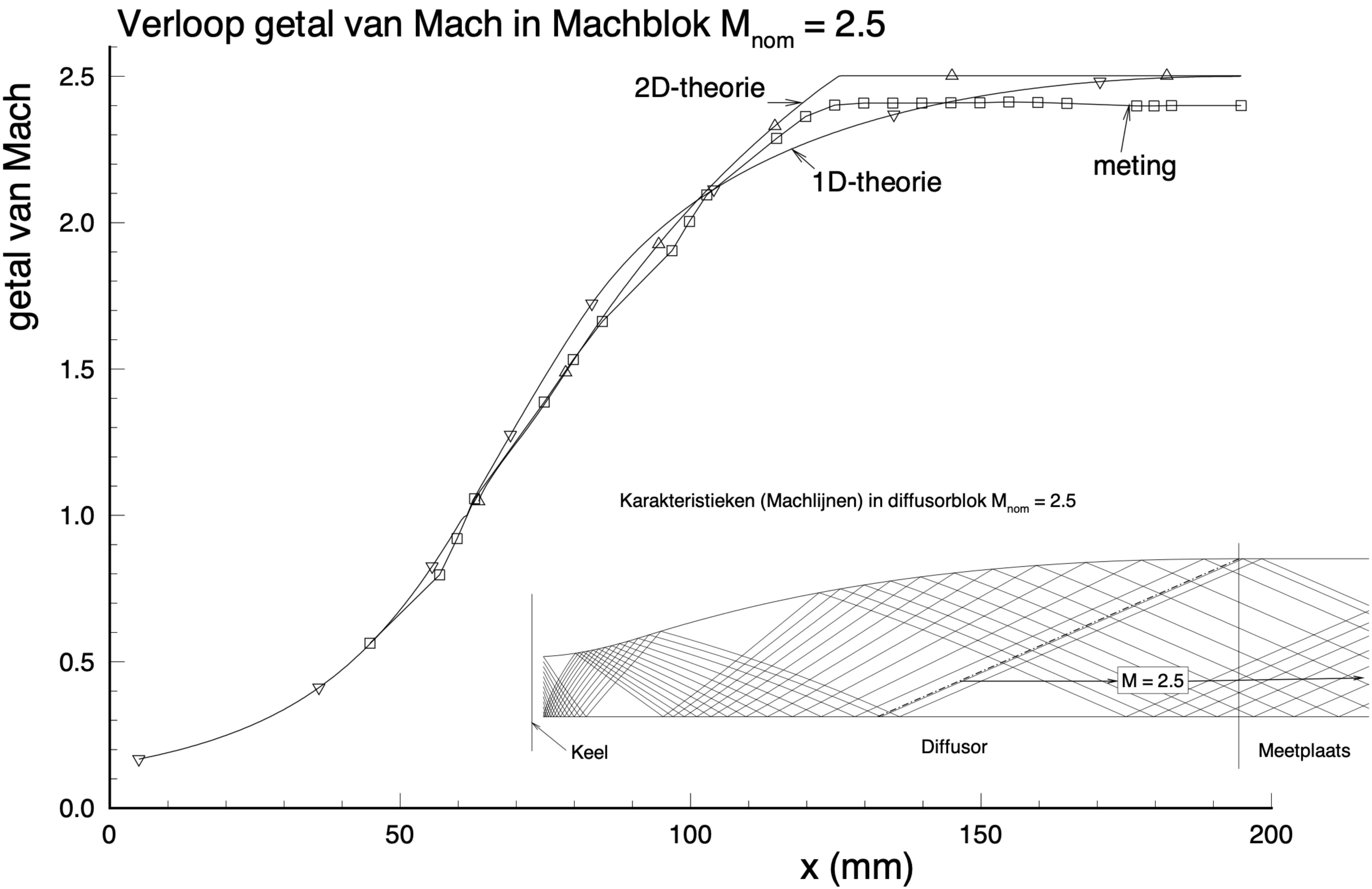
Schlieren image examples



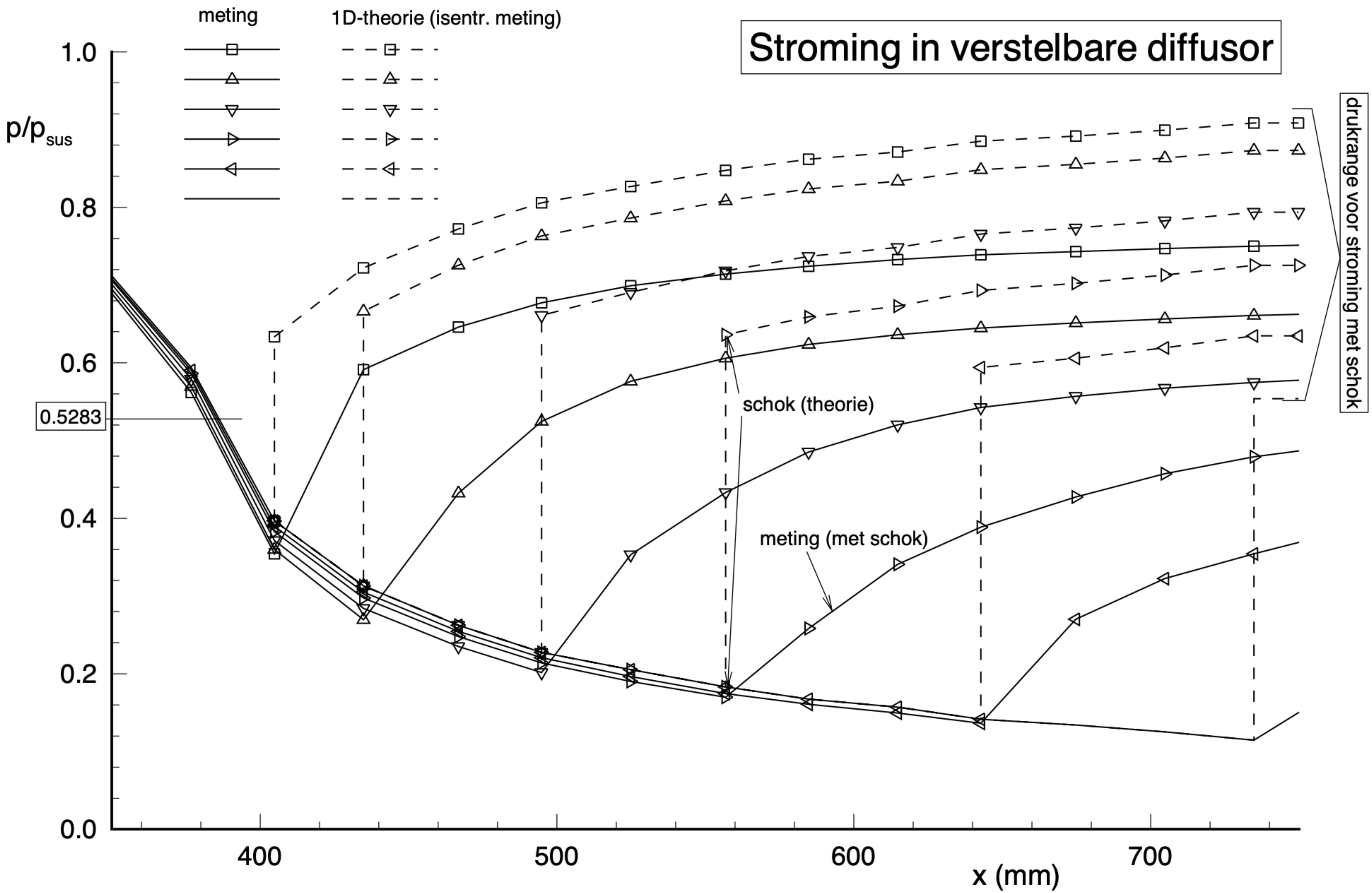


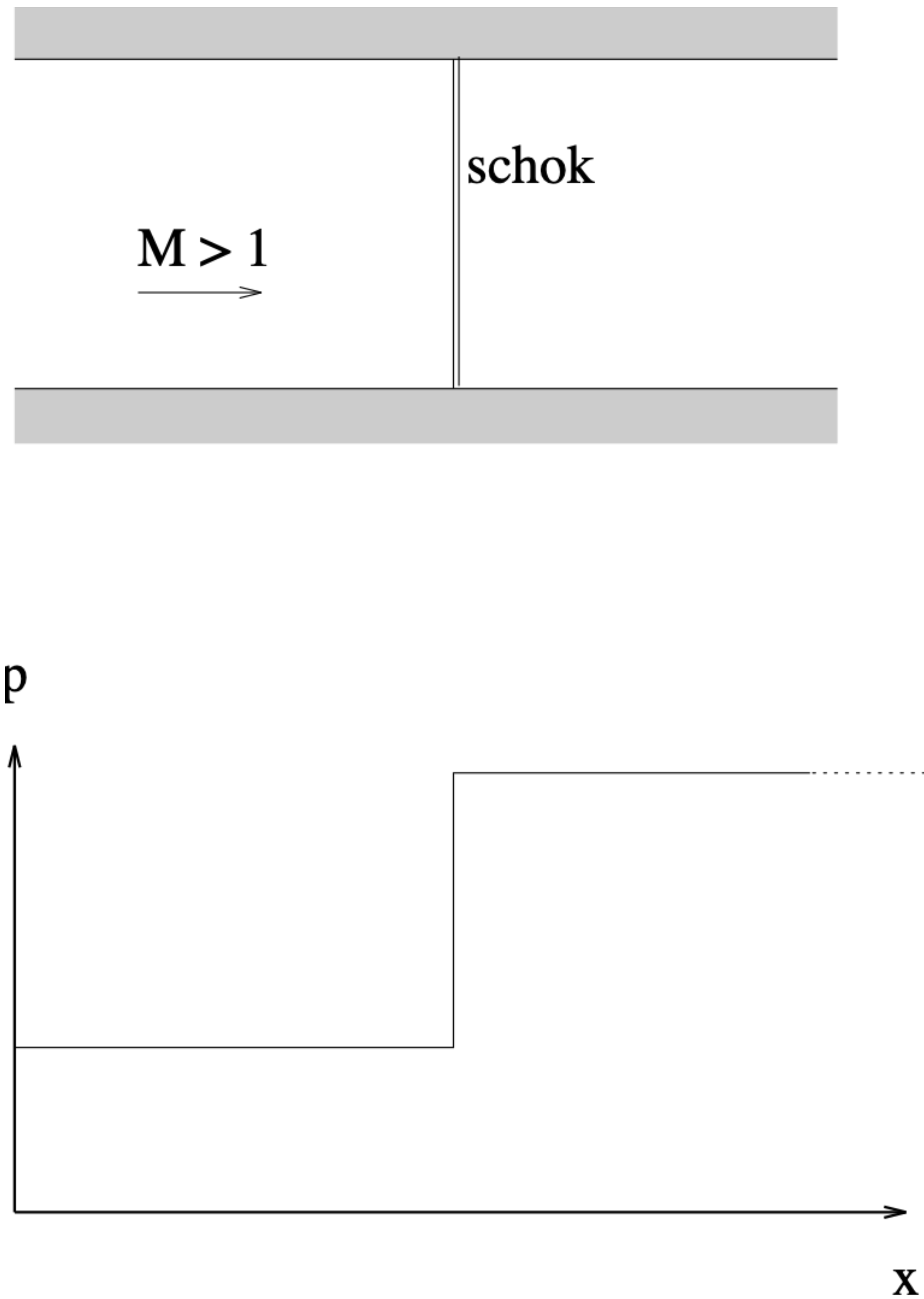




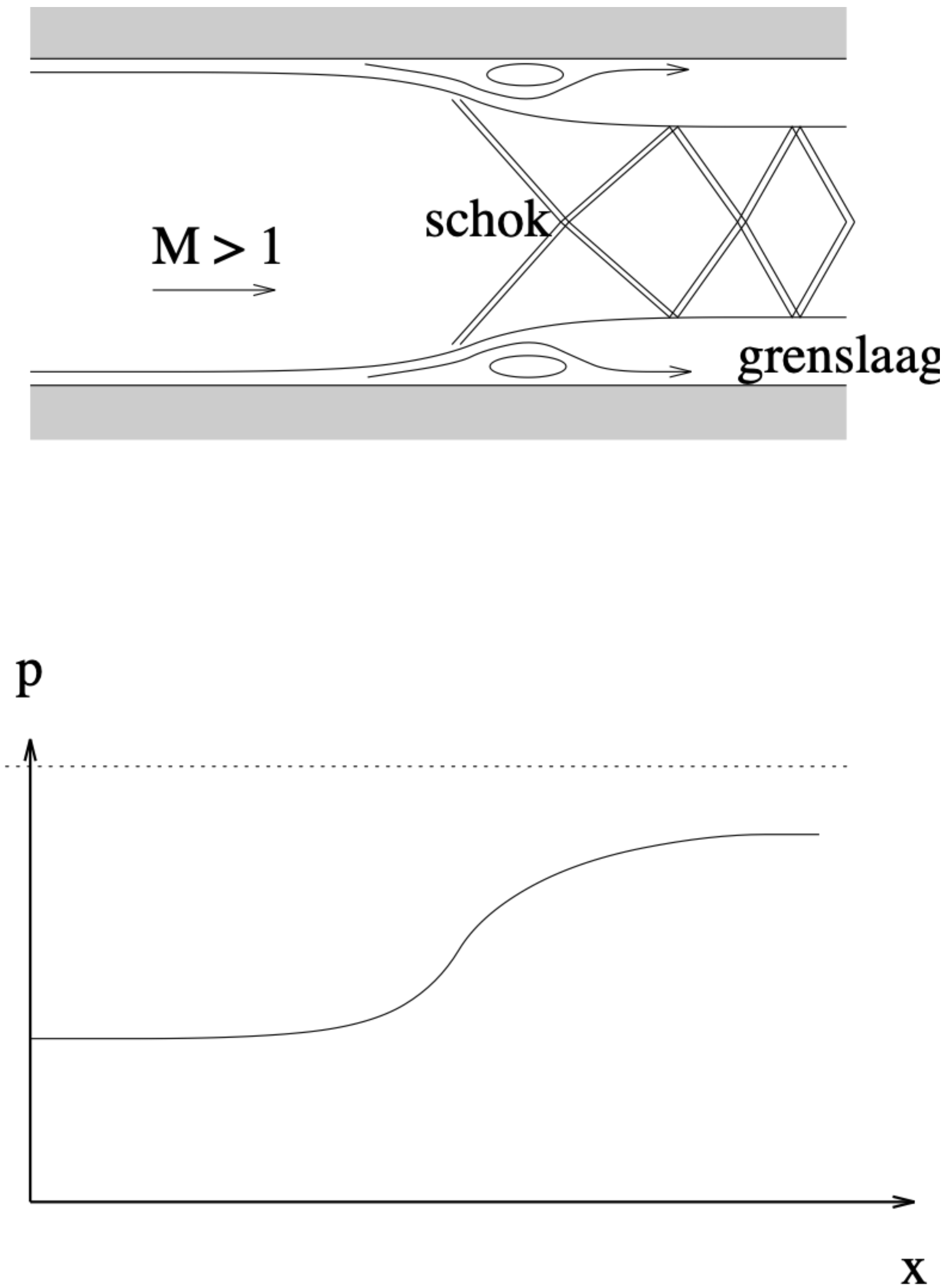


Verloop getal van Mach in Machblok M_{nom} = 2.5
getal van Mach
x (mm)
2D-theorie
1D-theorie
meting
Karakteristieken (Machlijnen) in diffusorblok M_{nom} = 2.5
M = 2.5
Keel
Diffusor
Meetplaats
0.0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200


Stroming in verstelbare diffusor
meting
1D-theorie (isentr. meting)
p/p_sus
1.0
0.8
0.6
0.5283
0.4
0.2
0.0
400
500
600
700
x (mm)
schok (theorie)
meting (met schok)
drukrange voor stroming met schok



1D, Inviscid



Viscous

Activity during wind tunnel measurements

- Operate the wind tunnel
- Acquire pressures through computer
- Sketch the schlieren image
- Take notes

Doing the report

- Bring a laptop with either Python or Matlab installed and a USB drive
- Answer all questions listed in the manual (ch. 3)
- Available time: 2 hours
- Send report by email to your practical-supervisor
- Report will be performed in groups of max 3 students

Evaluation report

- Your report will be graded (0, 5 or 10 points), it will not be possible to do a supplement
- The bonus points are only awarded when you score 50 points or higher at the exam
- When doing the report you are allowed to use notes and Anderson
- The bonus-points earned are only valid for the exam at the end of this period (<u>not</u> for the resit)

During the practical you are working in a lab, some basic rules:

Do not drink or eat during the practical

Keep your voice at a normal level

Do not wear ear phones

No skateboarding

Inform you practical supervisor immediately when you see something out of the ordinary

Practical information

Exercise will run from 10 to 27 January

5 groups per day:

9:00 10:30 12:00 13:30 15:00

Practical information

Before the exercise:

I. Register on exercise calendar (opens on 16 December at 13:00 and closes on 30 December at 23:59)
   Enrol in a group on Brightspace

II. Carefully study the exercise manual and chapter 10 of Anderson

III. Make sure you can read the example file ‘testfile.txt’ into Matlab or Python (to be uploaded to Brightspace)

<u>Exercise manual will become available on Brightspace as a downloadable .pdf</u>

Location: Aerodynamics Lab, building 64

Make sure your campus card is properly activated or else you will not be able to enter or exit the building.

In case it is not working please ask the service desk to activate it.

Arrive on time and wait the practical supervisor at the entrance of the building