Leibniz Institute for
Tropospheric Research

Aerosol Sampling and Inlet Systems
(on aircraft-borne platforms)

by Markus Hermann

Leibniz Institute for Tropospheric Research,
Leipzig, Germany

EUFAR Summer School on
Airborne Aerosol and Cloud Science

April, 2008

Contents

Aircraft-Borne (Aerosol) Inlets

Aircraft-borne aerosol inlets are needed:

- for transporting sampling air from outside the aircraft to the measurement instruments inside the aircraft,
- because some instruments are to large, heavy and/or complex to be mounted outside the aircraft, e.g., at a wing station

Major inlet characteristic:

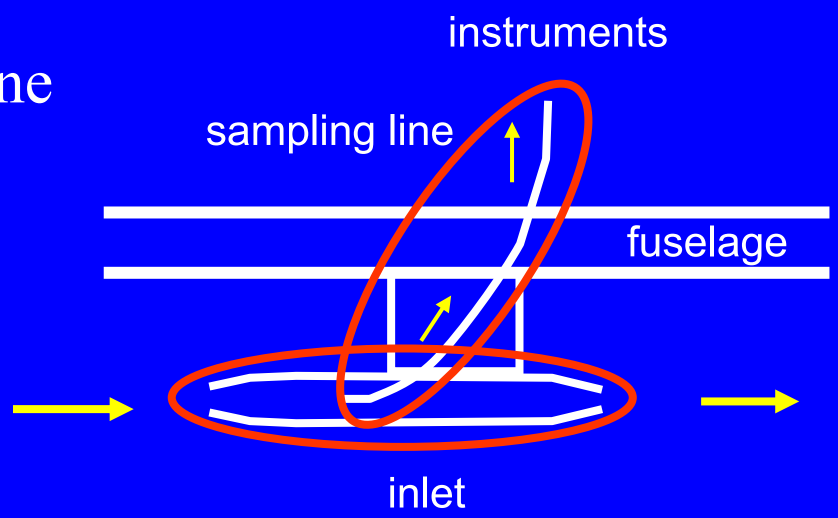
- **representative sampling of ambient aerosol particles**

Inlet Problems

- low pressure and temperatures: (p > 100 hPa, T > 200 K)
- high air velocities: True Air Speed (TAS) = 50 – 250 m/s
  but aerosol instruments need velocities of ~ 5 m/s
- measurement platform perturbs measurement
- measurement conditions are not constant
  (from take-off to cruise altitude)
- particles losses in the inlet system
- artifacts can occur, e.g., due to particle heating
  or sampling in clouds

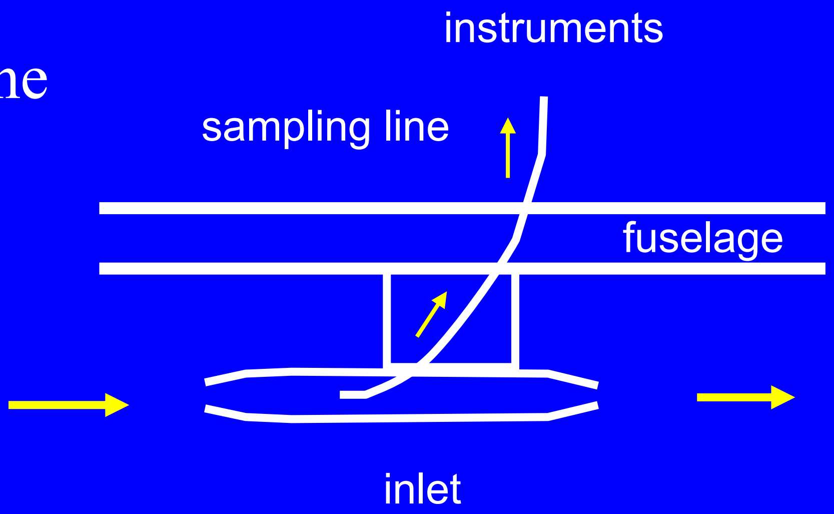
Definitions

- inlet system = inlet + sampling line

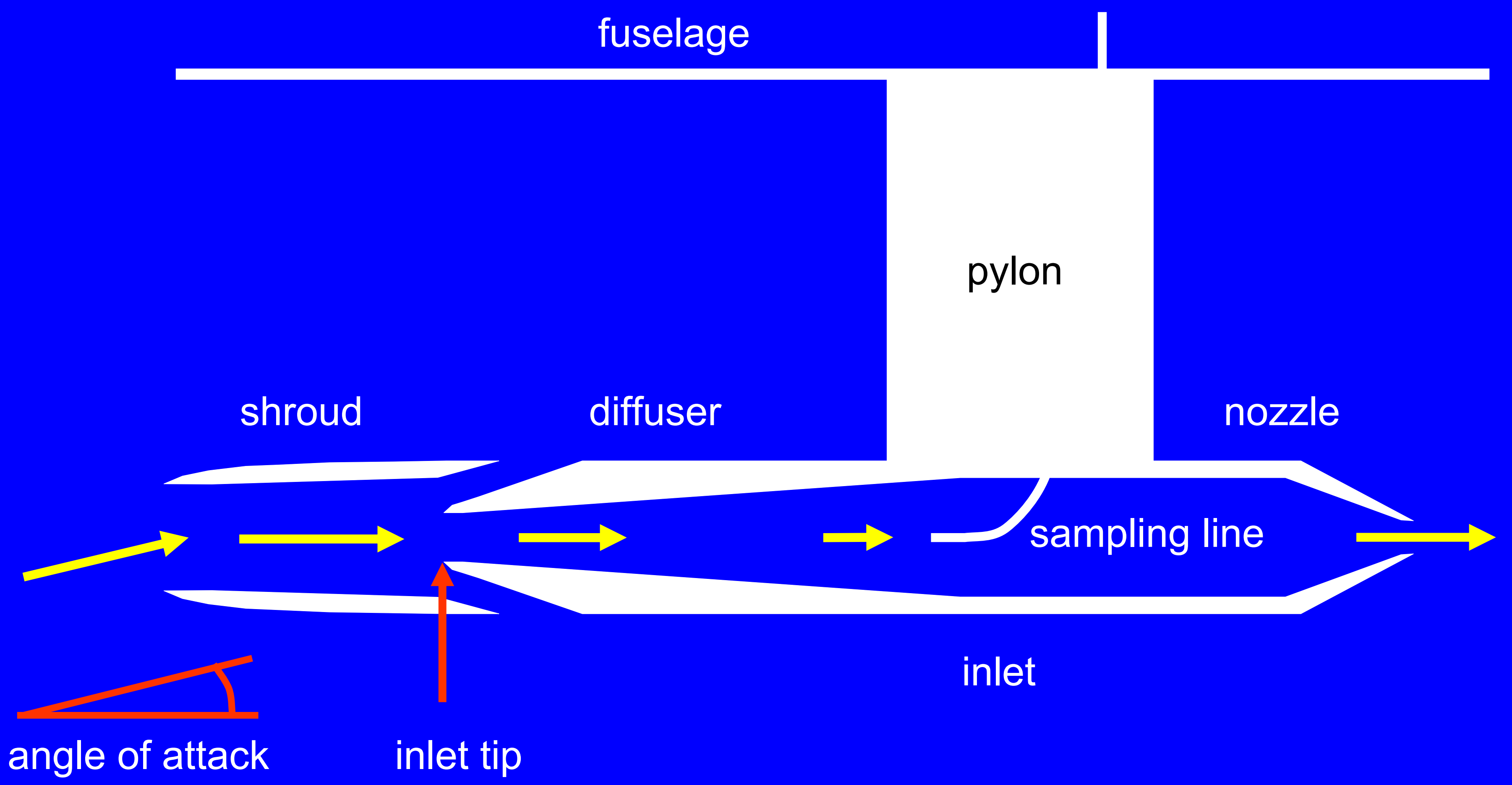


Definitions

- inlet system = inlet + sampling line



- **sampling efficiency** (inlet system) =
  inlet efficiency (inlet) + **transport efficiency** (sampling lines)
- inlet efficiency =
  aspiration efficiency + **transmission efficiency**


fuselage
pylon
shroud
diffuser
nozzle
sampling line
inlet
angle of attack
inlet tip

Aerosol Particles

- submicrometer particle = particle diameter < 1 µm
- supermicrometer particle = particle diameter > 1 µm
- nucleation mode ~ 1 – 10 nm diameter
  Aitken mode ~ 10 – 100 nm diameter
  accumulation mode ~ 100 – 1000 nm diameter
- particle relaxation time τ

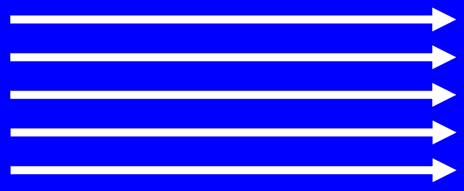
$$\tau = \frac{\rho_{\mathrm{P}} \cdot D_{\mathrm{P}}^{2} \cdot C_{\mathrm{C}}}{18\eta}$$

- particle Stokes number

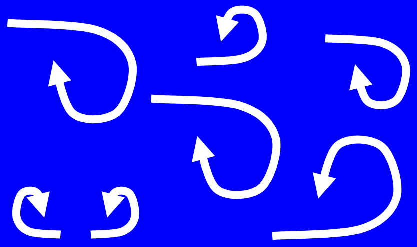
$$\mathrm{Stk} = \frac{\tau \cdot U_0}{d}$$

Fluid Dynamics

- laminar flow:
  - well-behaved
  - little particle losses



- turbulent flow:
  - contains eddies
  - large particle losses



- Mach number (Ma) = air velocity / sonic velocity (jet aircraft Ma ≈ 0.6 -0.85)

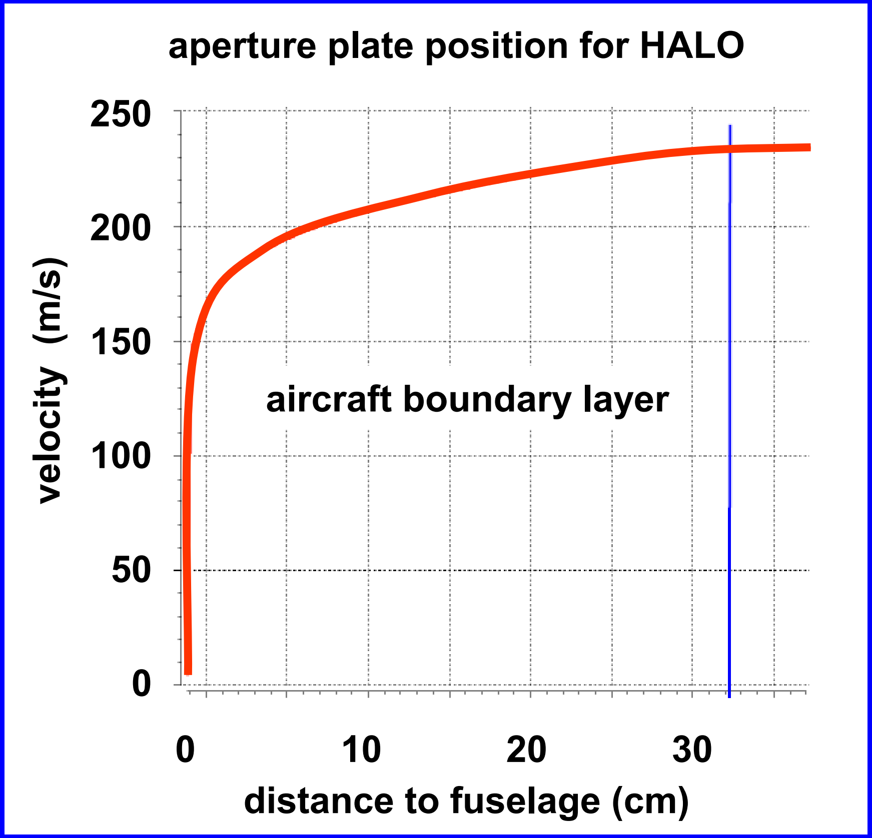
Leibniz Institute for Tropospheric Research

Computational Fluid Dynamics (CFD) modeling

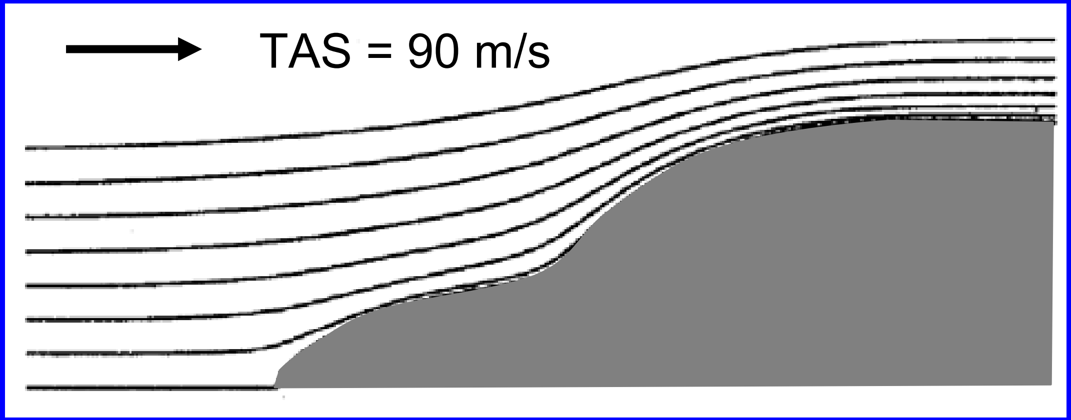
- modeling tool
- commercial computer codes (e.g., FLUENT, CFX)
- predict e.g., velocities, temperature, pressure, and turbulence intensity
- help to design and analyze geometries with fluid flows
- particle trajectories and inlet efficiencies can also be calculated!

Influence of the Measurement Platform

- aircraft influence the local flow field, in particular the velocity close to the fuselage (boundary layer)
- inside the boundary layer particle losses occur by deposition to the aircraft
- obstacles upstream the inlet can influence the flow field and particle concentrations

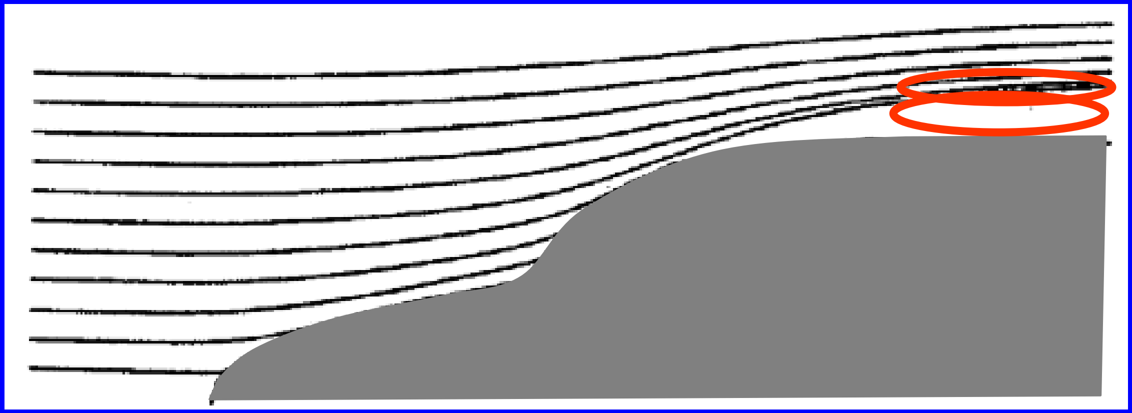


- even outside the boundary layer “shadow” and “enhancement” zones can occur for particles!



streamlines around a Fokker F-27

trajectories for 100 µm particles of unit density



King, JAOT, 1984

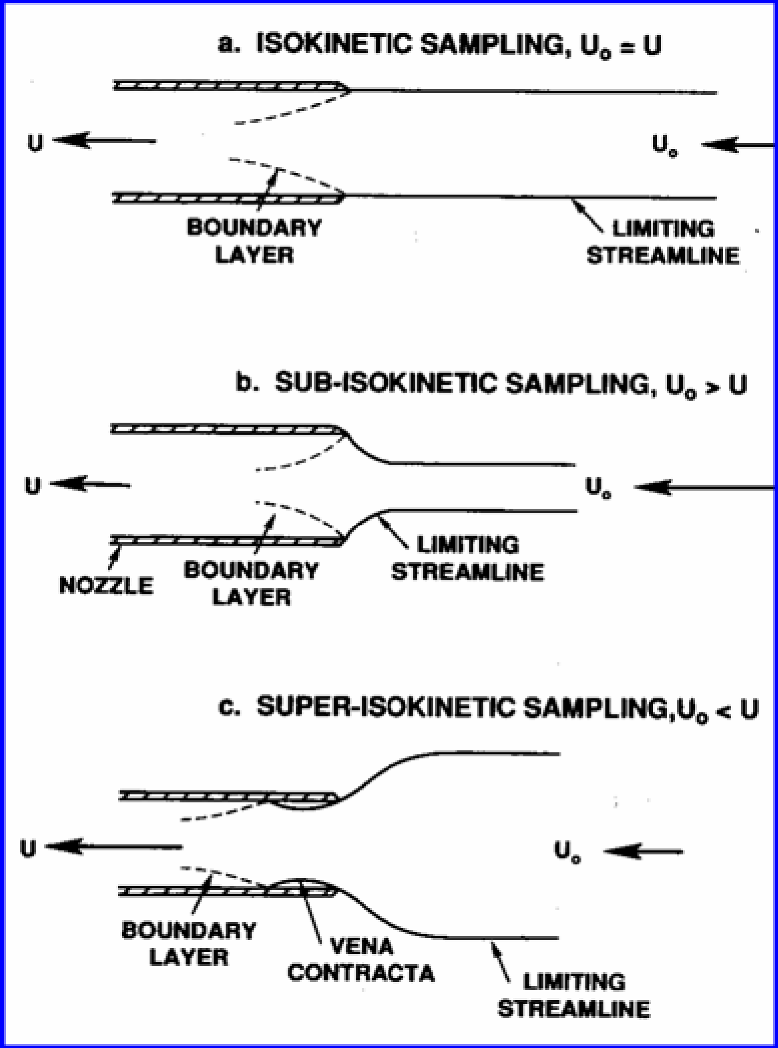
Inlet Issues and Efficiencies

particle losses in an inlet …

due to	occur	mainly for
• gravitational settling	always	supermicrometer particles
• inertial deposition	non-ideal sampling or turbulent flows	supermicrometer particles
• freestream turbulence effects	turbulent flows	supermicrometer particles
• laminar or turbulent diffusion	always	submicrometer particles

Aspiration Efficiency

- **isoaxial** sampling:
  direction of inlet is parallel to the streamlines ($\Theta = 0$).
- **isokinetic** sampling:
  isoaxial and sampling velocity in the inlet is equal to the wind velocity outside ($U = U_0$).
- **sub-isokinetic** sampling
- **super-isokinetic** sampling



Baron & Willeke, 2001

- inlet efficiency changes for ($U \neq U_0$) and ($\Theta \neq 0$) in dependence of the Stokes number
- example for Stk:
  TAS = U_0 = 150 m/s, p = 500 hPa, T = 265 K
  d_{in} (¼") = 4.57 mm, ρ_p = 1.5 g/cm^3

D_p = 0.5 µm $\Rightarrow$ Stk = 0.07

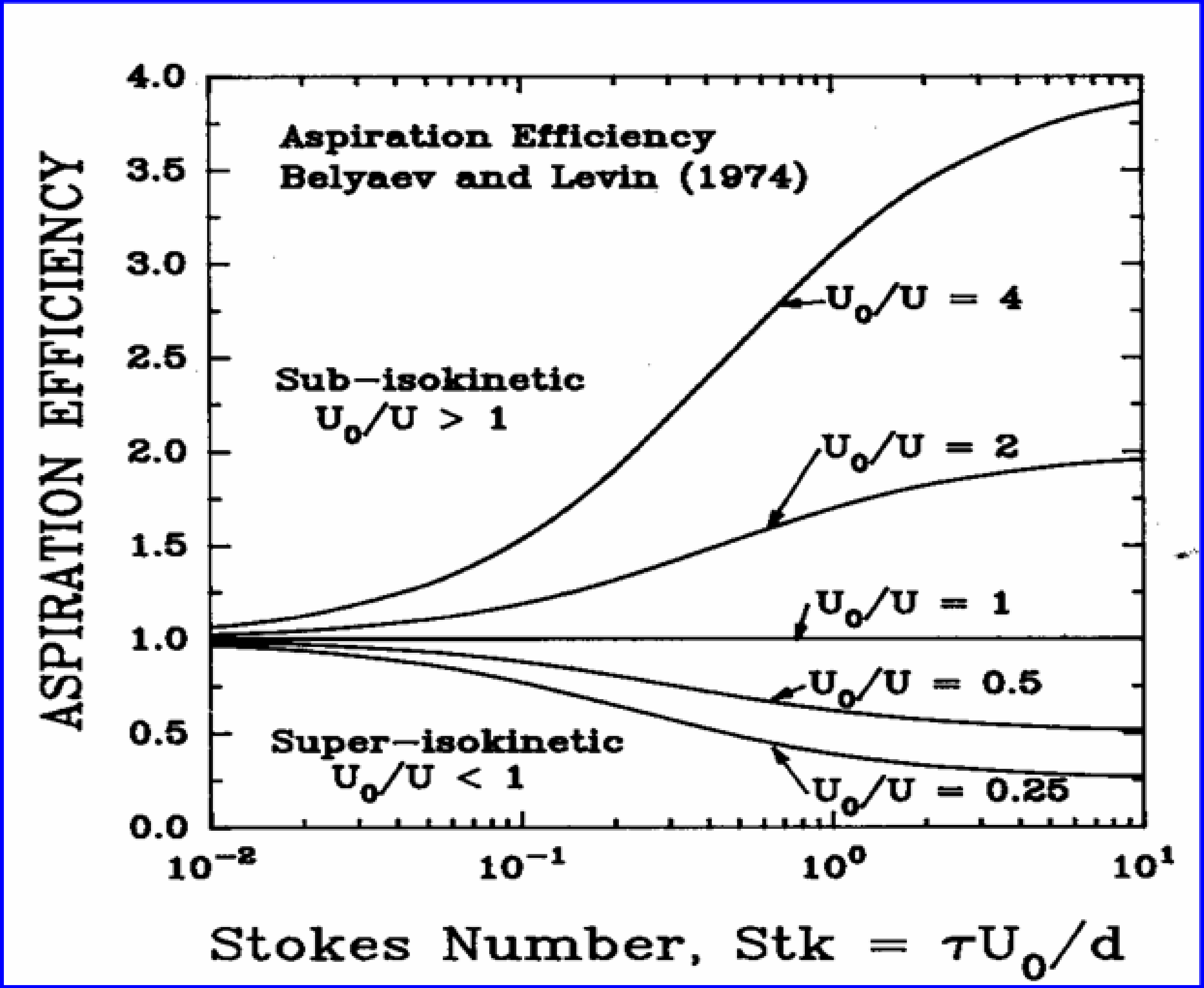
D_p = 2.0 µm $\Rightarrow$ Stk = 0.77

D_p = 5.0 µm $\Rightarrow$ Stk = 4.4

D_p = 10 µm $\Rightarrow$ Stk = 17

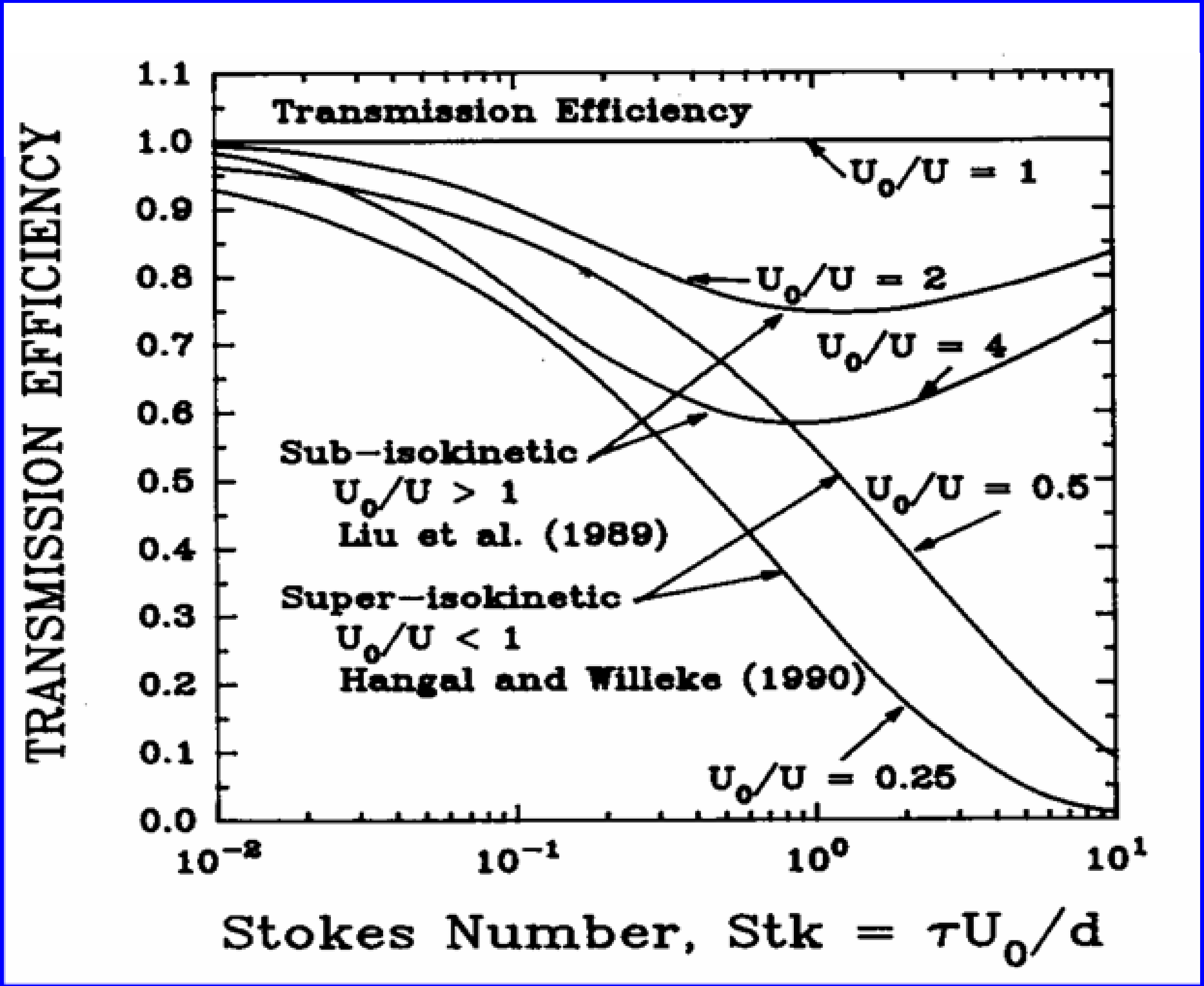
$$\tau = \frac{\rho_P \cdot D_P^2 \cdot C_C}{18\eta}$$

$$\mathrm{Stk} = \frac{\tau \cdot U_0}{d}$$

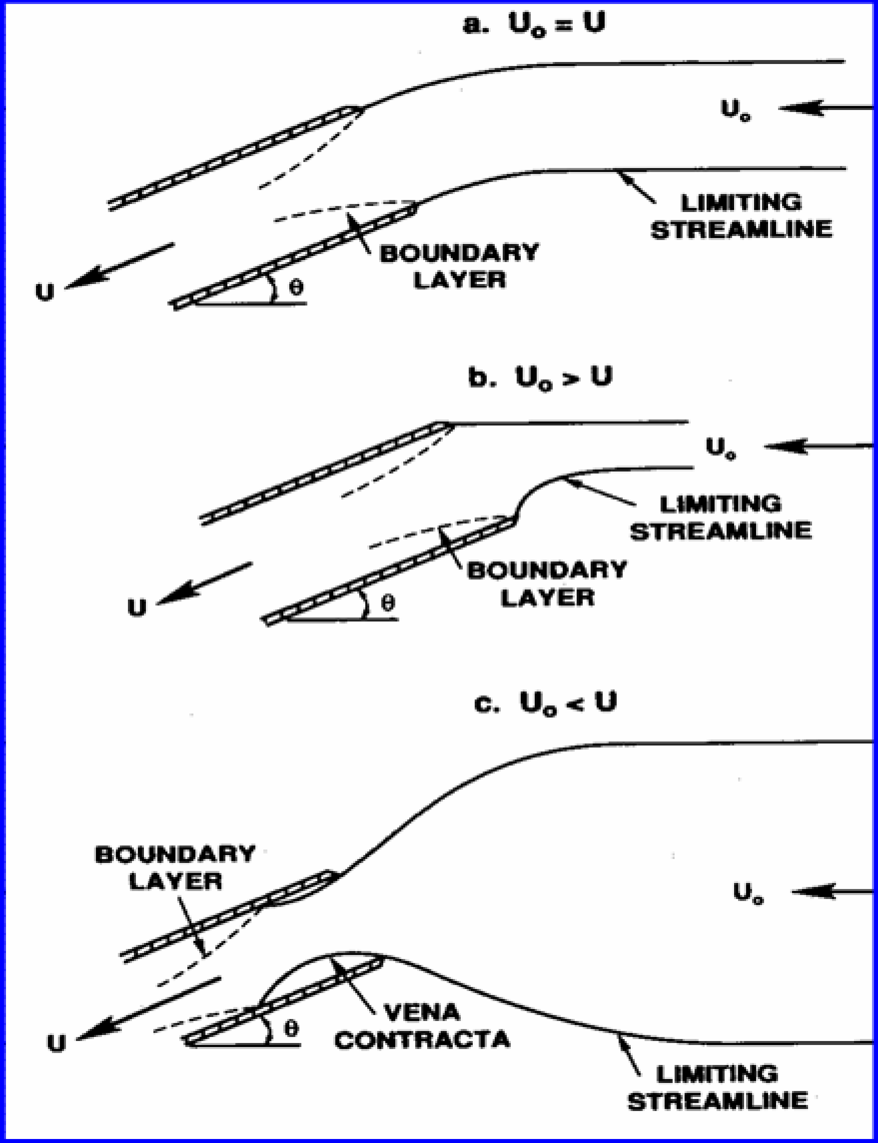


Baron & Willeke, 2001

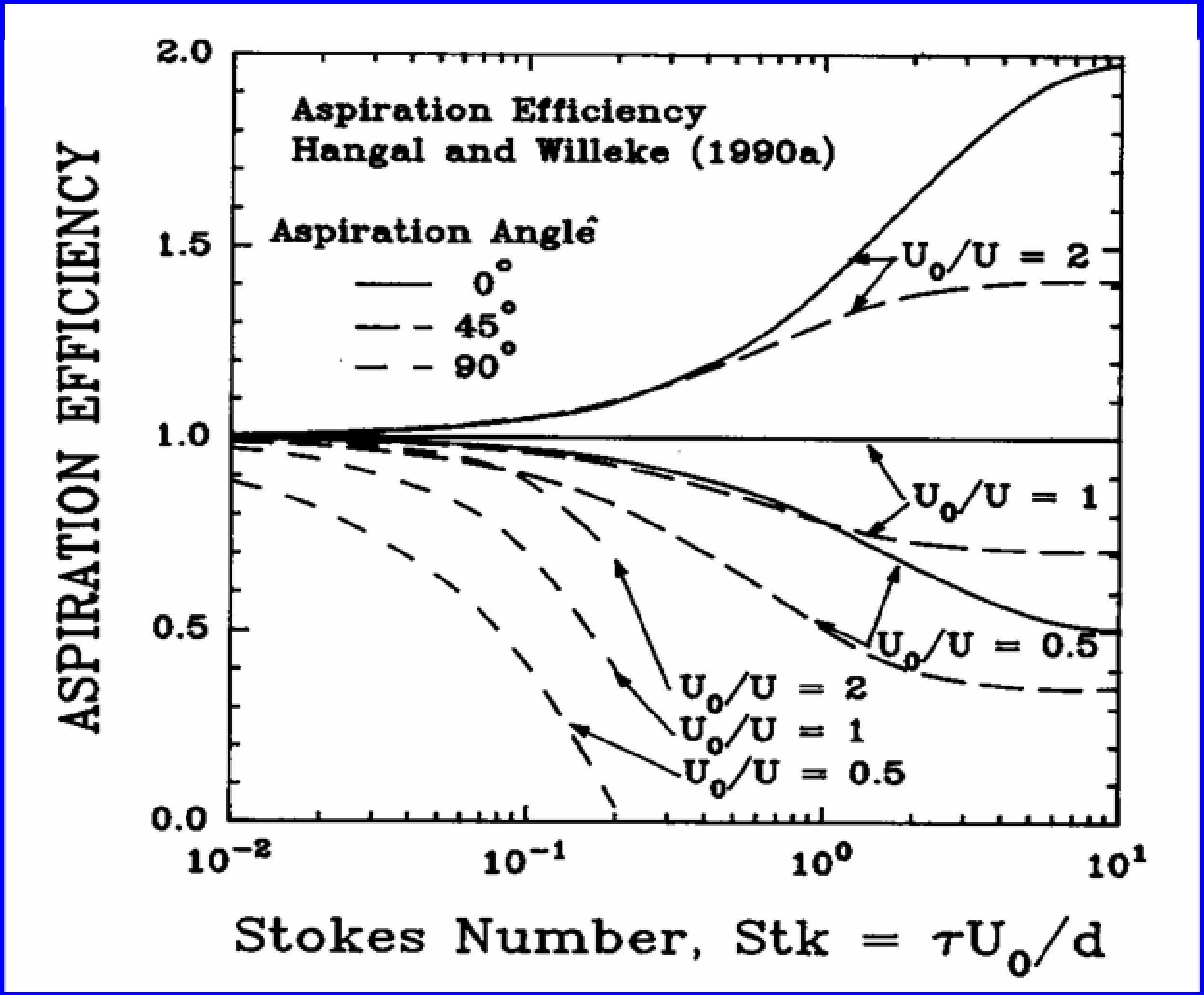
Leibniz Institute for Tropospheric Research



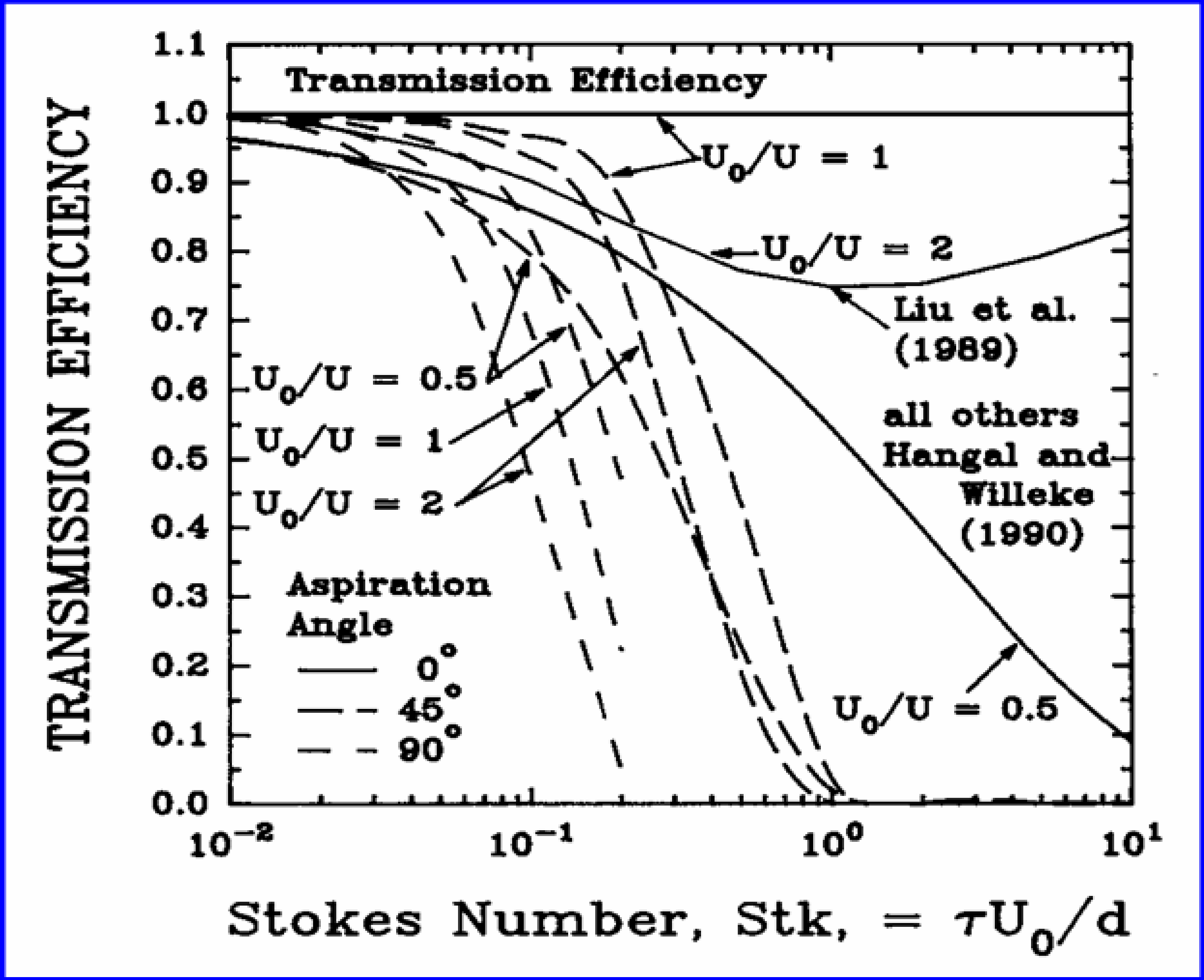
Baron & Willeke, 2001



Baron & Willeke, 2001



Baron & Willeke, 2001



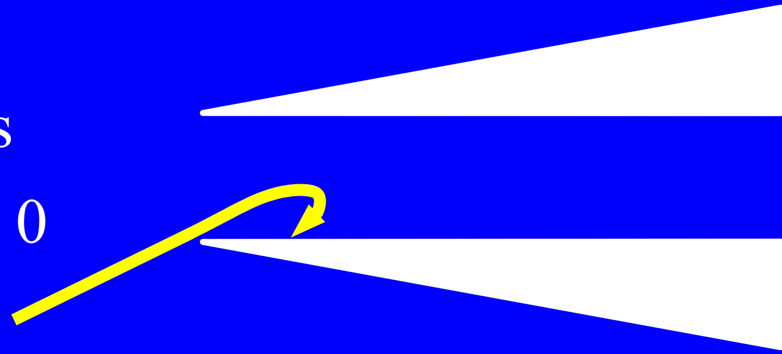
Baron & Willeke, 2001

- shape of the inlet tip strongly effects the aspiration efficiency!

- sharp inlet lips

  + small face area, little artifacts

  - flow separation occurs at $\theta \neq 0$

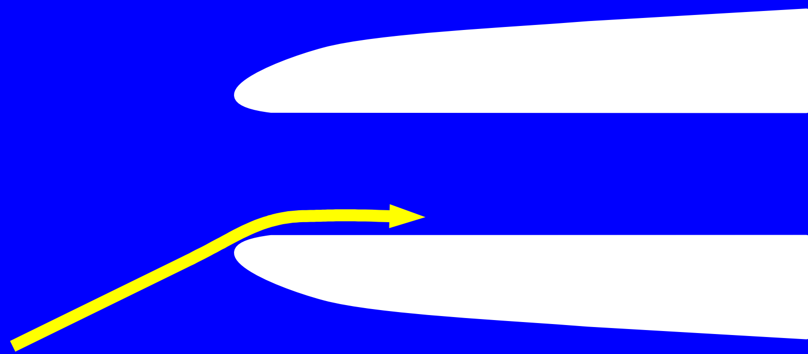


- blunt inlet lips

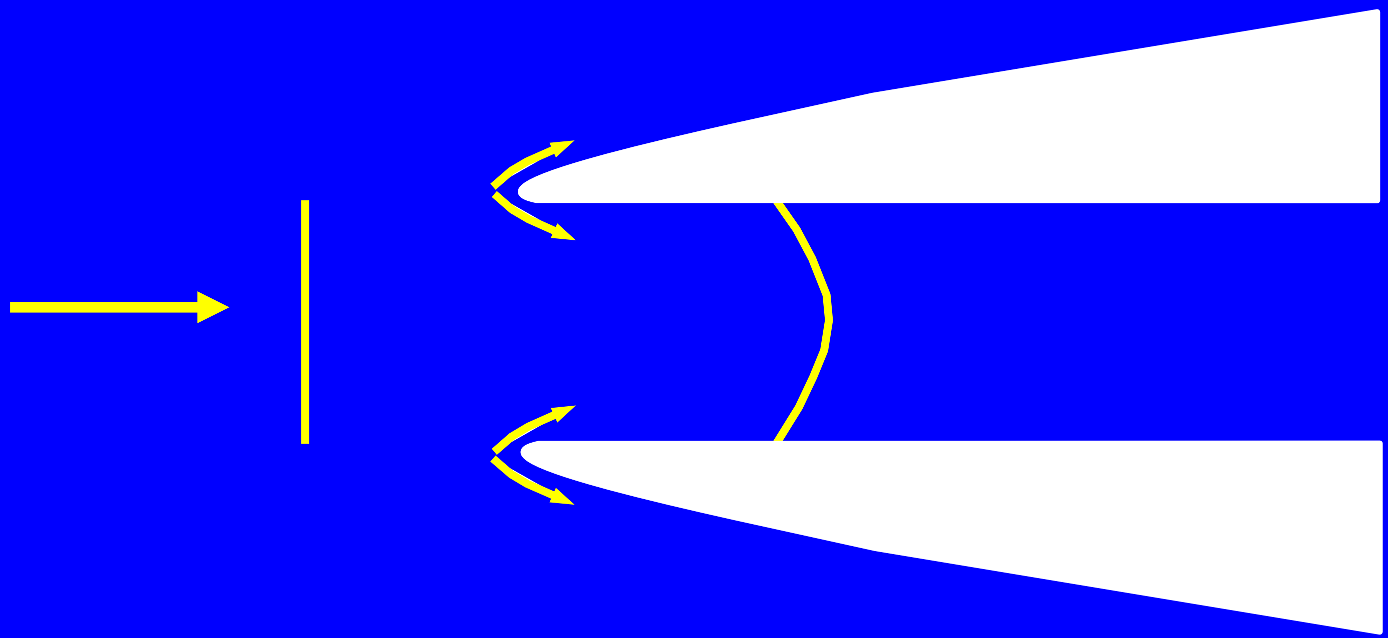
  + no flow separation

  - large face area, artifacts

  - shock wave may occur




1.67e+00
1.50e+00
1.34e+00
1.17e+00
1.01e+00
8.41e-01
6.76e-01
5.10e-01
3.44e-01
1.78e-01
1.27e-02
Y
Z
X
Contours of Mach Number
Sep 16, 2002
FLUENT 6.0 (3d, coupled imp, lam)

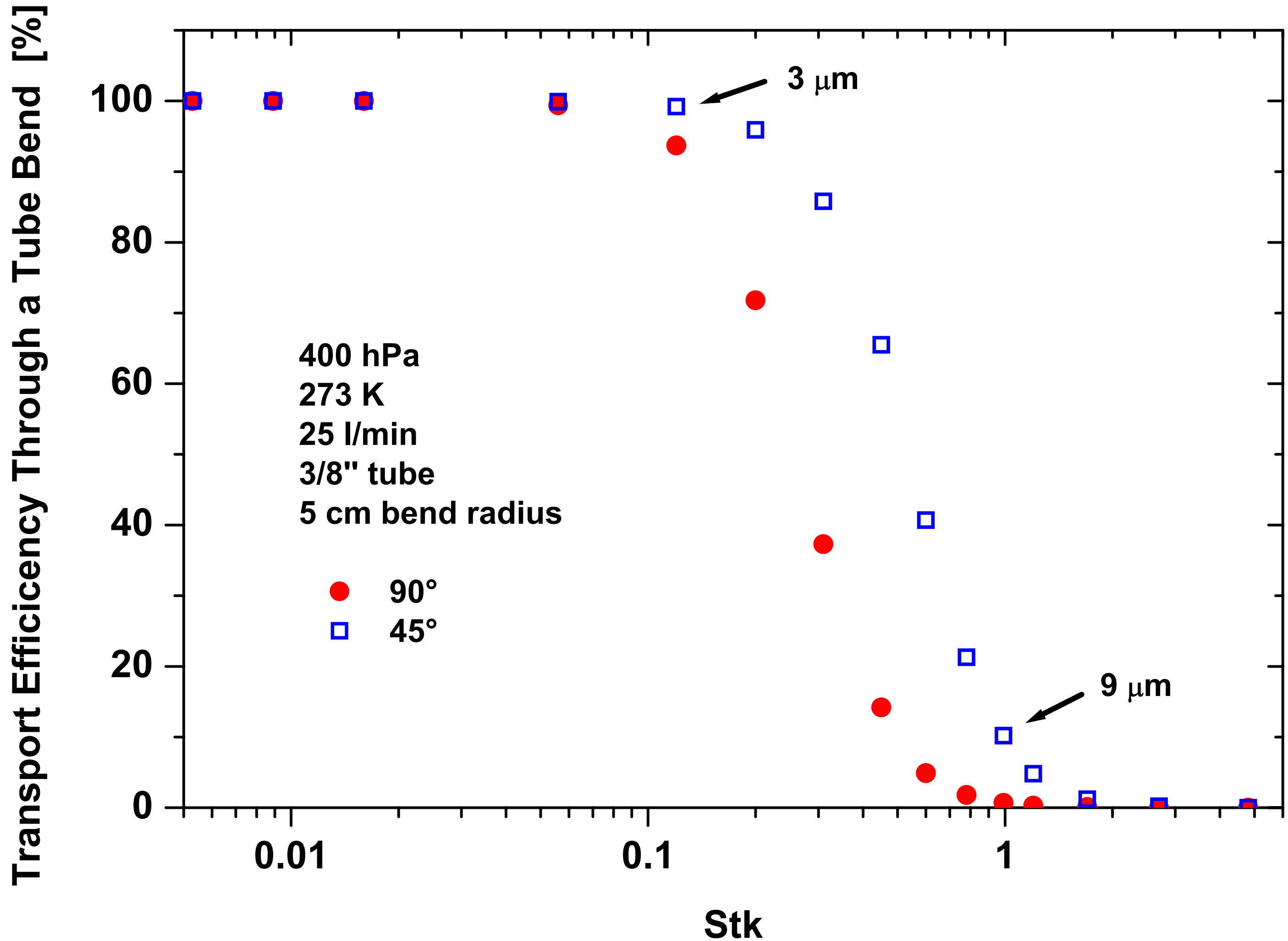


v = 0.86 Ma v > 1.0 Ma

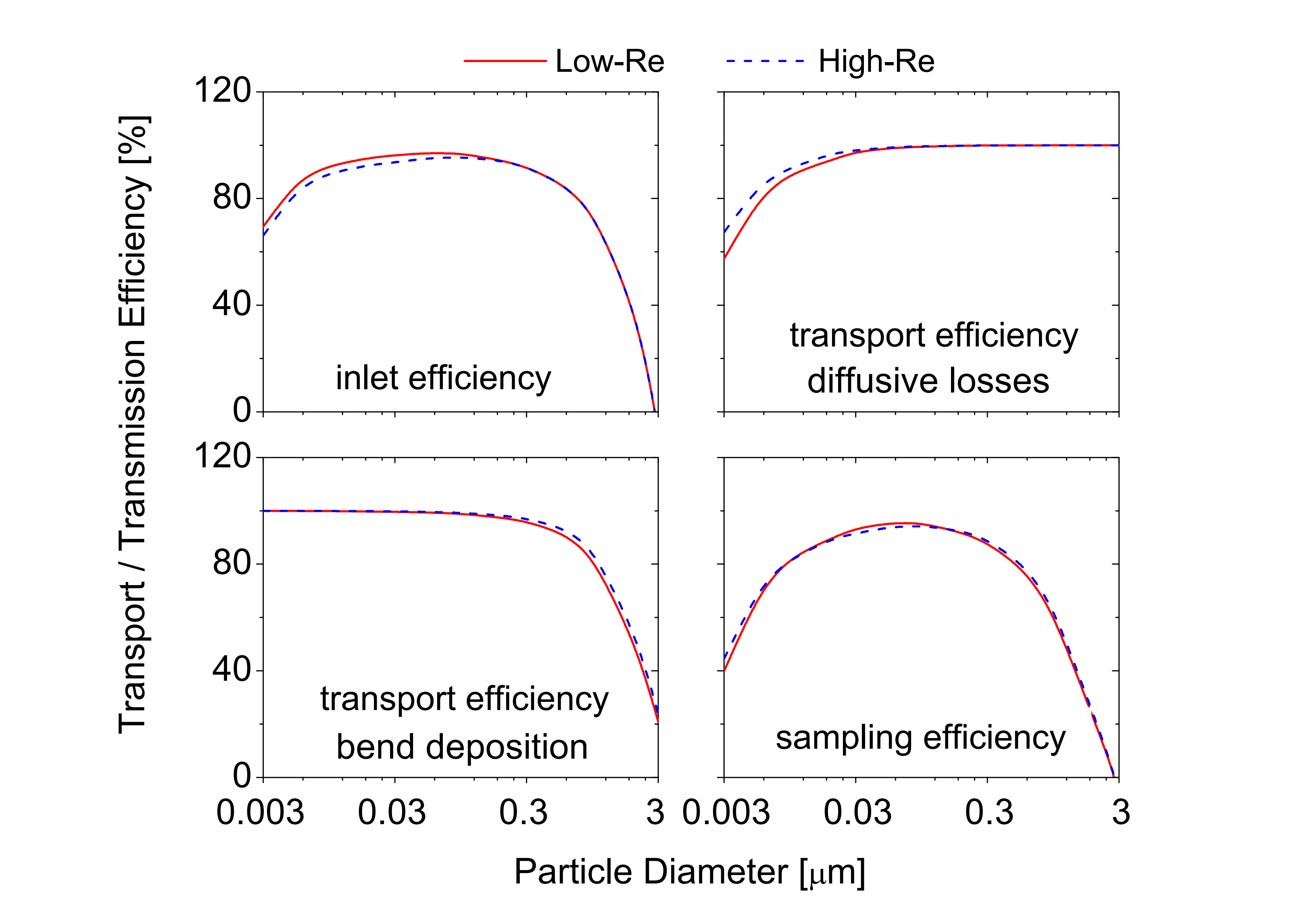
Transport Efficiency

particle losses in the sampling line …

due to	occur	mainly for
• gravitational settling	always	supermicrometer particles
• inertial deposition	in tube bends or turbulent flows	supermicrometer particles
• laminar or turbulent diffusion	always	submicrometer particles



e.g., Baron & Willeke, 2001

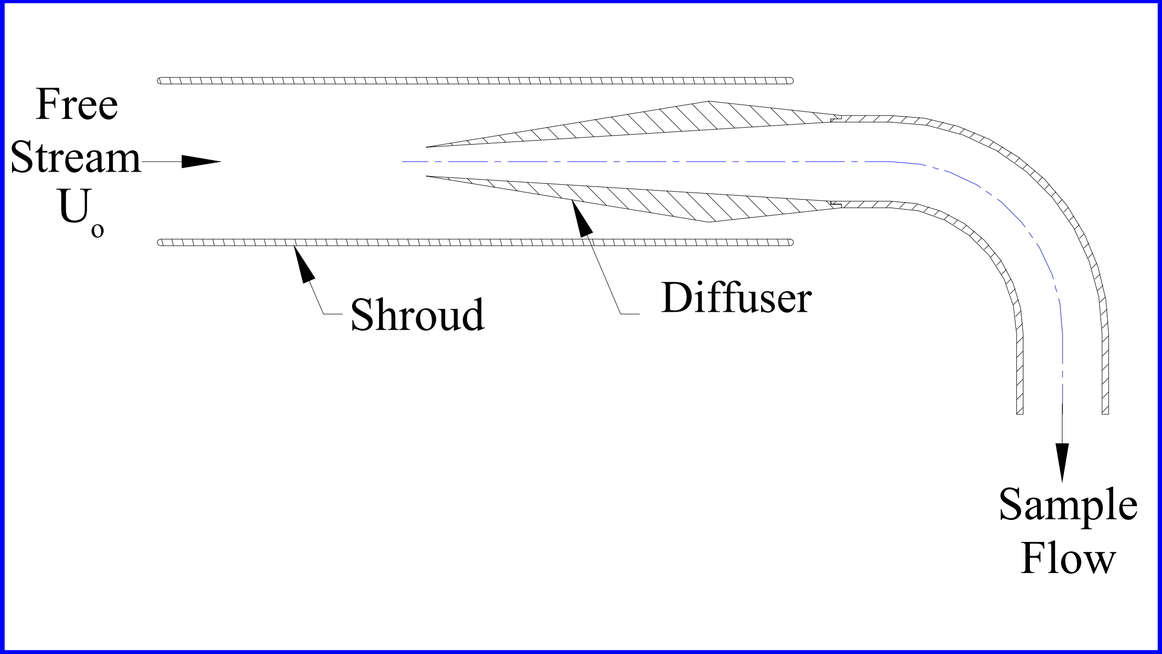


Hermann et al., JAOT, 2001

Real Inlets

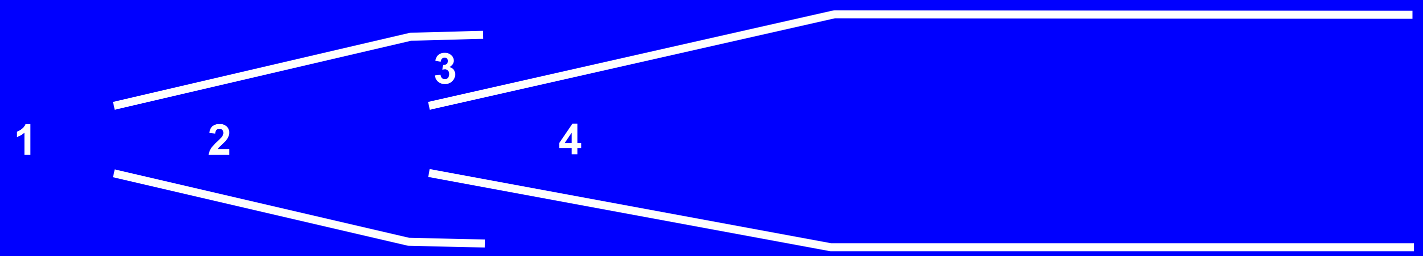
"Classical" aerosol inlet

- can consist of a shroud, one or two diffusers, and the sampling line
- small particle losses in the particle size range 10 nm – 500 nm

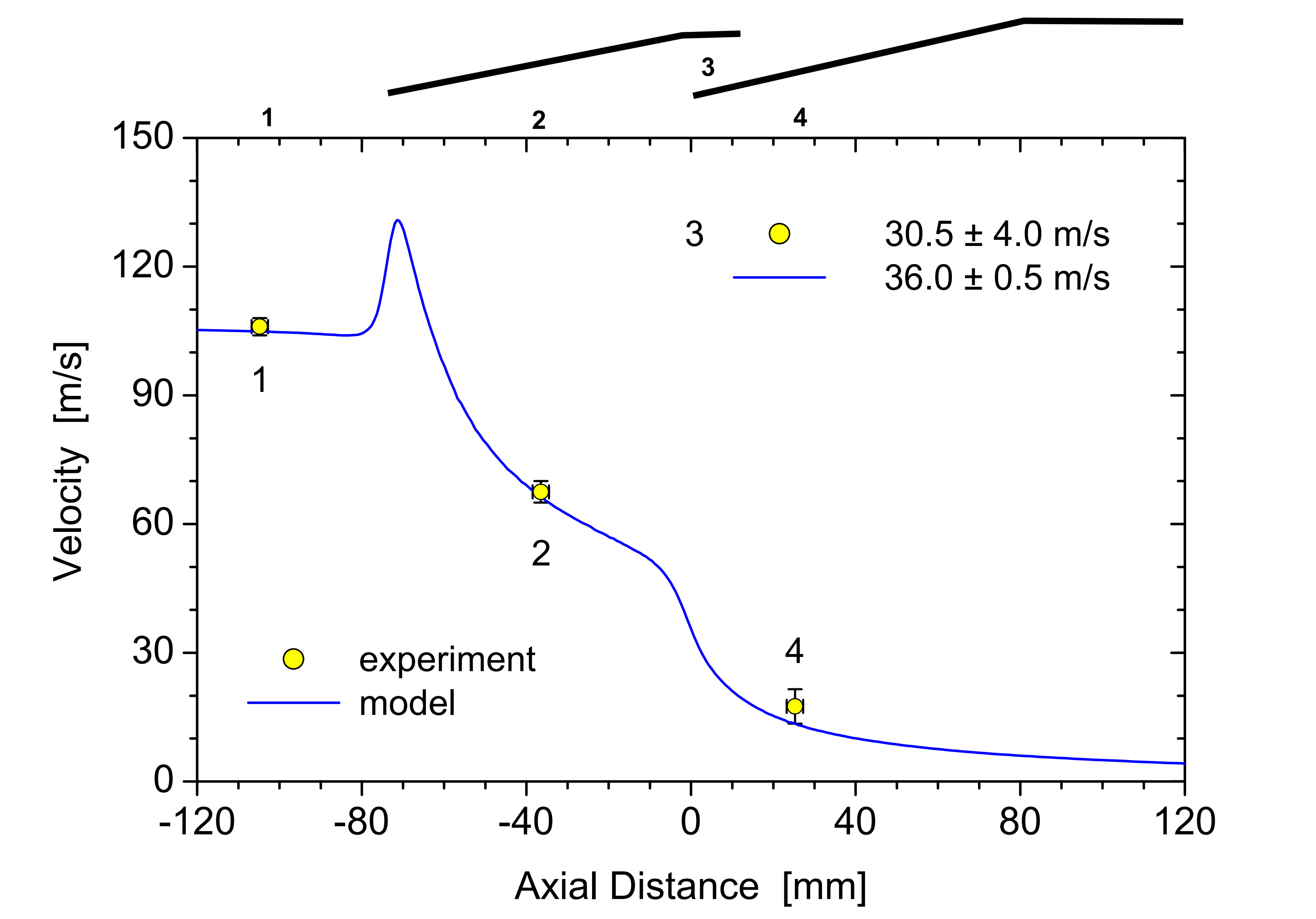


Baron & Willeke, 2001

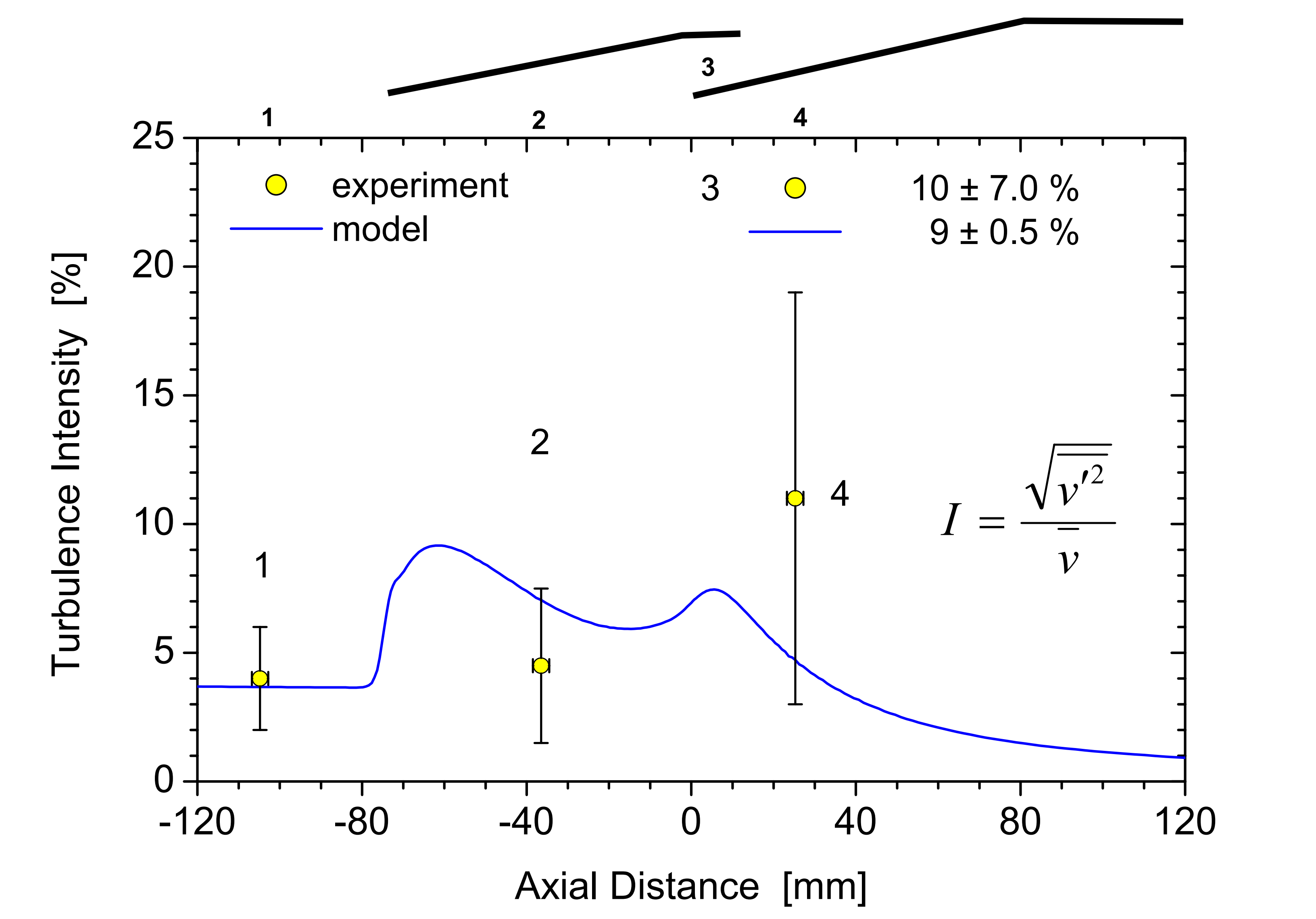
- aircraft: Gulfstream I, DOE, USA
- inlet: two-stage diffuser aerosol inlet with 5° half angle
- field experiment: July 9, 2002, Worcester, MA
  500-1000 m, 100-115 m/s, 0.3 M,
  977 hPa, 297 K
- instrumentation: 4x hot wire anemometers
  (Dantec Dynamics, Model 55P16)



- Fred Brechtel
  Brechtel Mfg. Inc.
  Hayward, CA, USA

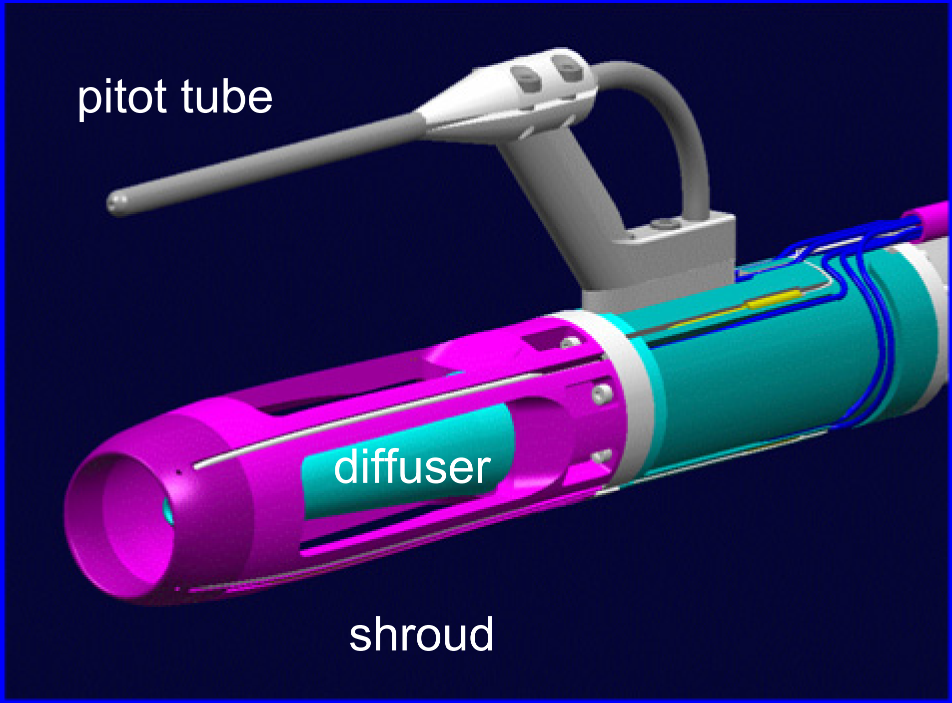


Leibniz Institute for Tropospheric Research

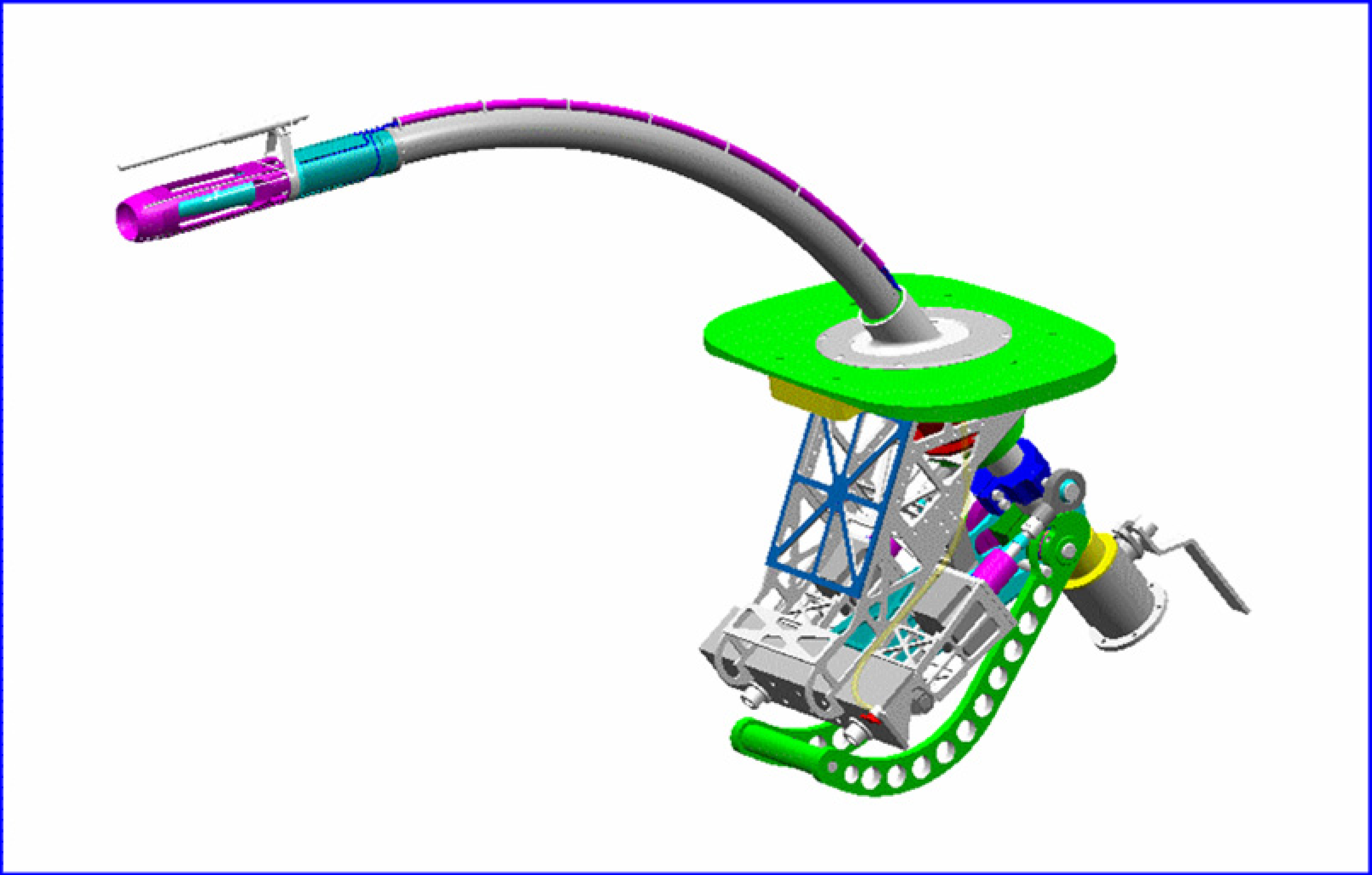

1
2
3
4
25
20
15
10
5
0
experiment
model
3
10 ± 7.0 %
9 ± 0.5 %
2
4
1
$I = \frac{\sqrt{\overline{v'^2}}}{\overline{v}}$
Turbulence Intensity [%]
-120
-80
-40
0
40
80
120
Axial Distance [mm]

Isokinetic Inlet (Météo France)

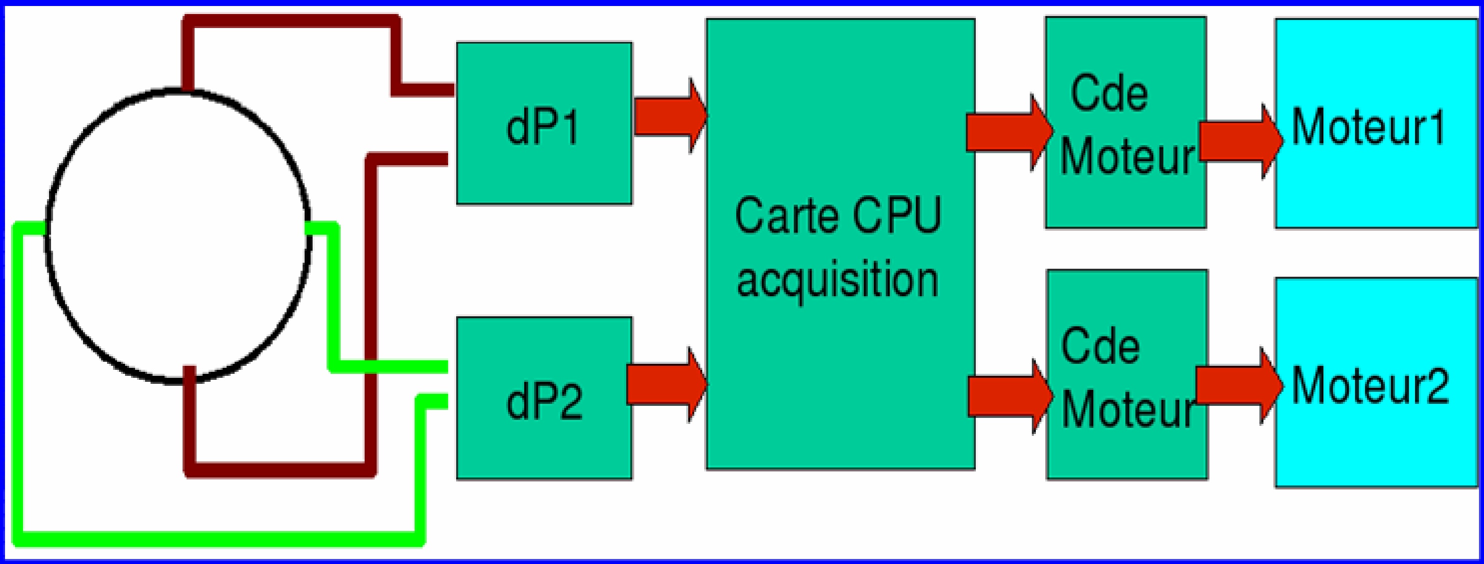
- shrouded diffuser-type inlet
- attitude of the inlet with respect to the aircraft is not fixed, but can be changed in flight
  ⇒
  isoaxial sampling
- volume flow is also adjusted
  ⇒
  isokinetic sampling



Bourrianne, 2008, pers. com.



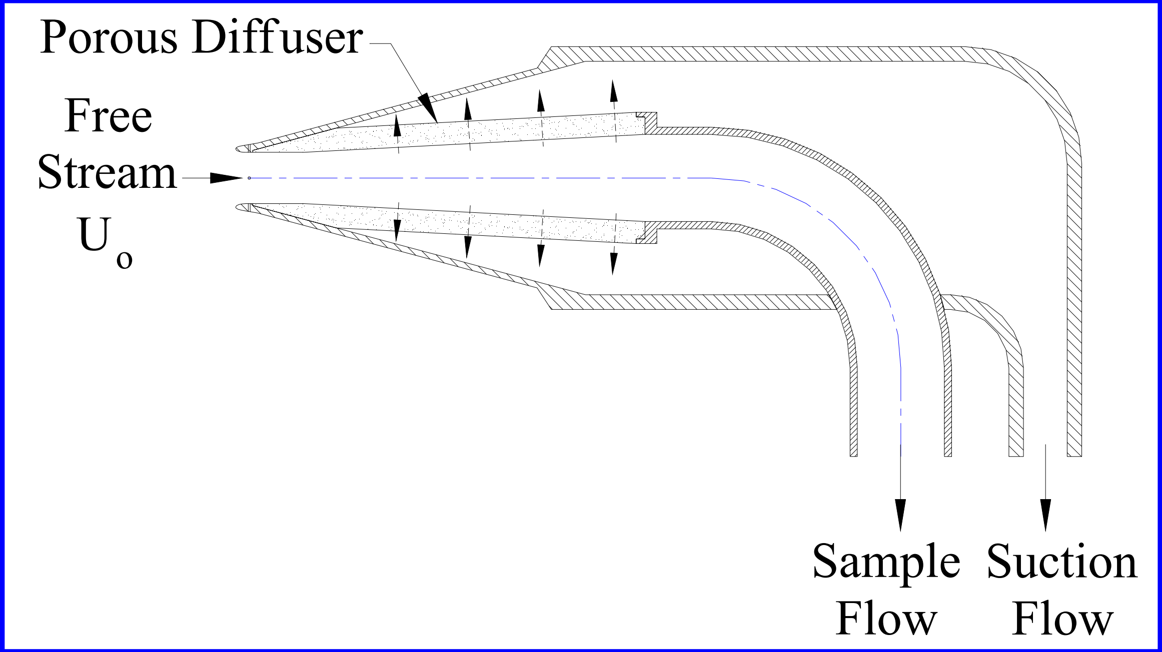
Bourrianne, 2008, pers. com.



Bourrianne, 2008, pers. com.

Low Turbulence Inlet (LTI)

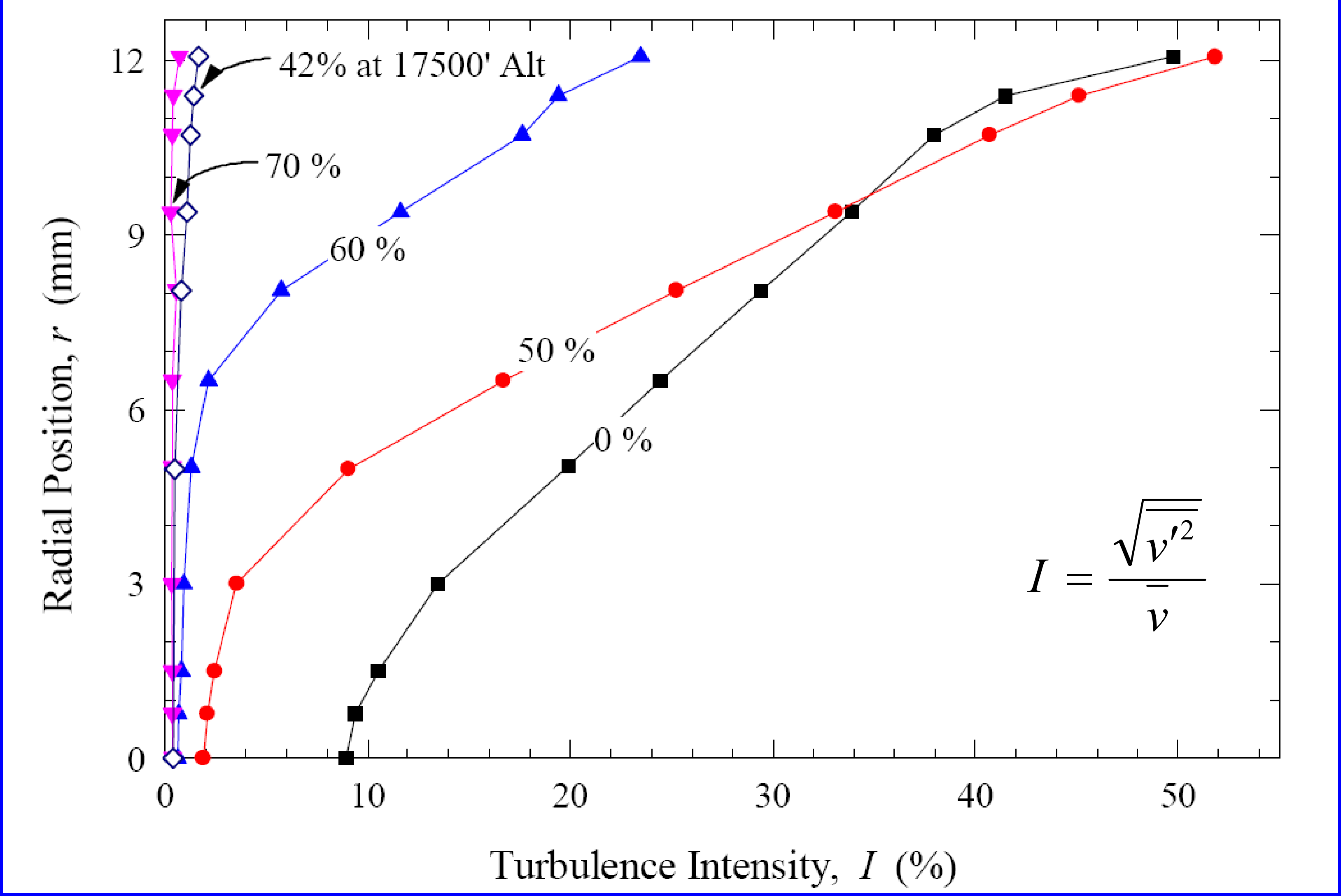
- inlet especially for particles larger than ~ 0.5 µm
- LTI uses boundary layer suction technique to get rid of turbulence and hence to reduce particle losses



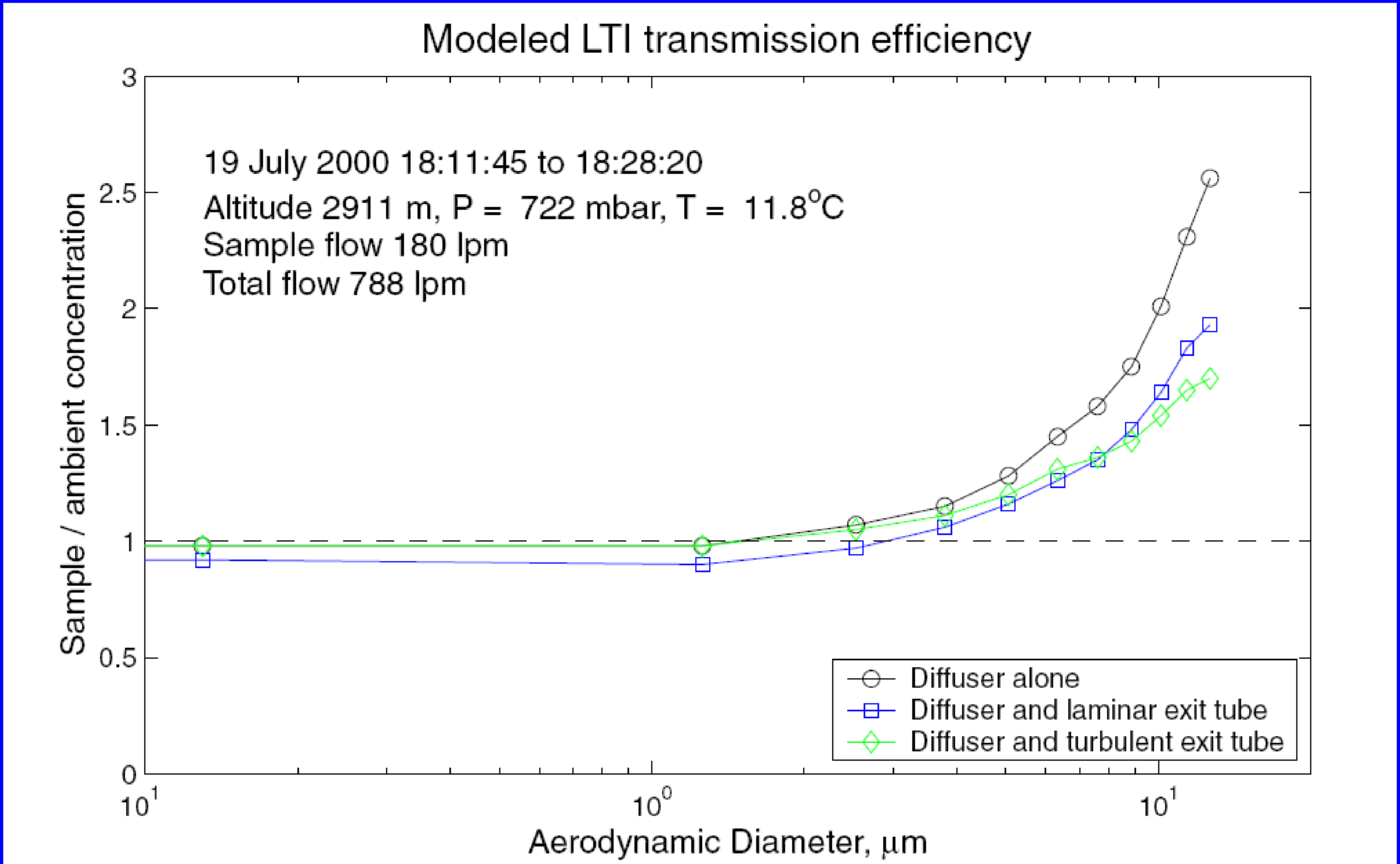
- University of Denver, Chuck Wilson et al.

Wilson et al., AST, 2004


35 cm
100 cm



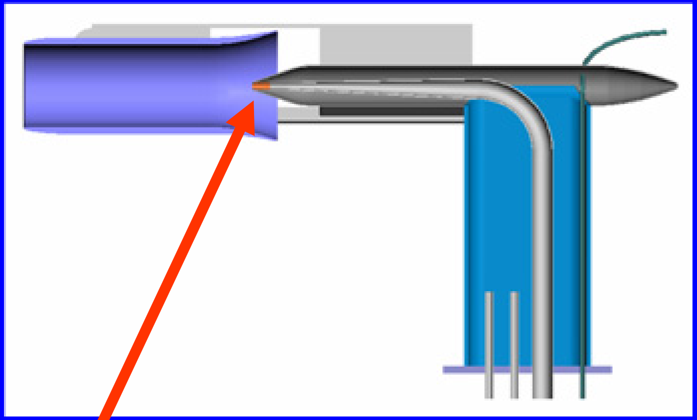
42% at 17500' Alt
70 %
60 %
50 %
0 %
$I = \frac{\sqrt{\overline{v'^2}}}{\overline{v}}$
Radial Position, r (mm)
Turbulence Intensity, I (%)
0
3
6
9
12
0
10
20
30
40
50

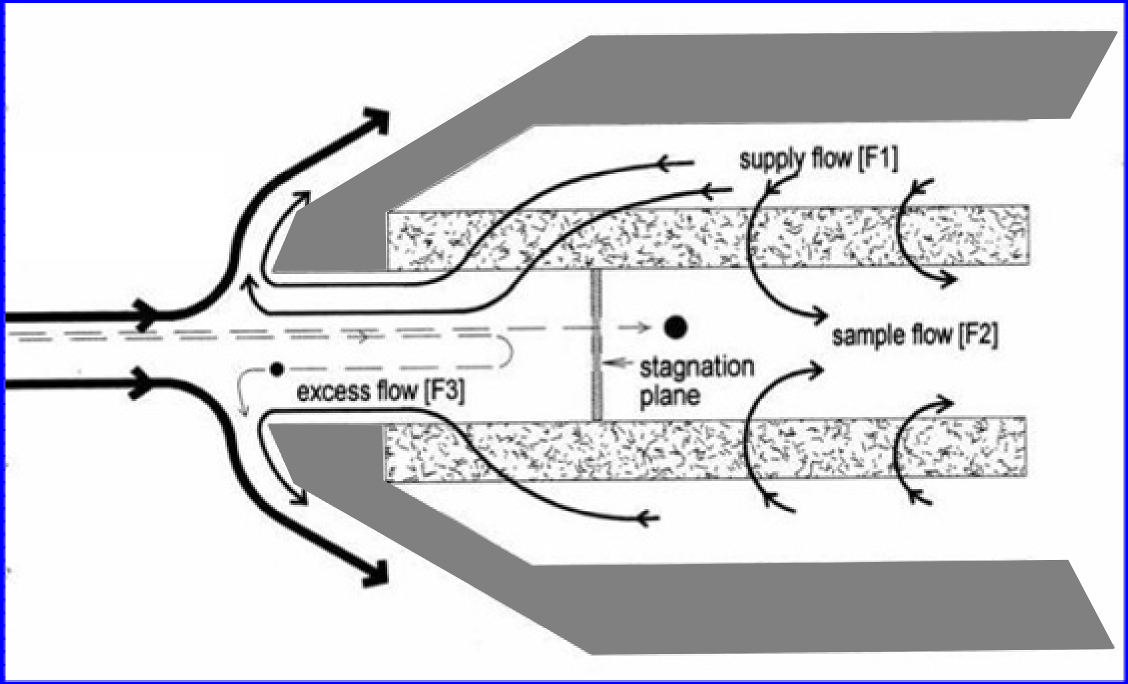


Modeled LTI transmission efficiency
19 July 2000 18:11:45 to 18:28:20
Altitude 2911 m, P = 722 mbar, T = 11.8°C
Sample flow 180 lpm
Total flow 788 lpm
Sample / ambient concentration
Aerodynamic Diameter, µm
Diffuser alone
Diffuser and laminar exit tube
Diffuser and turbulent exit tube
0
0.5
1
1.5
2
2.5
3
10^1
10^0
10^1

Counter flow Virtual Impactor (CVI)

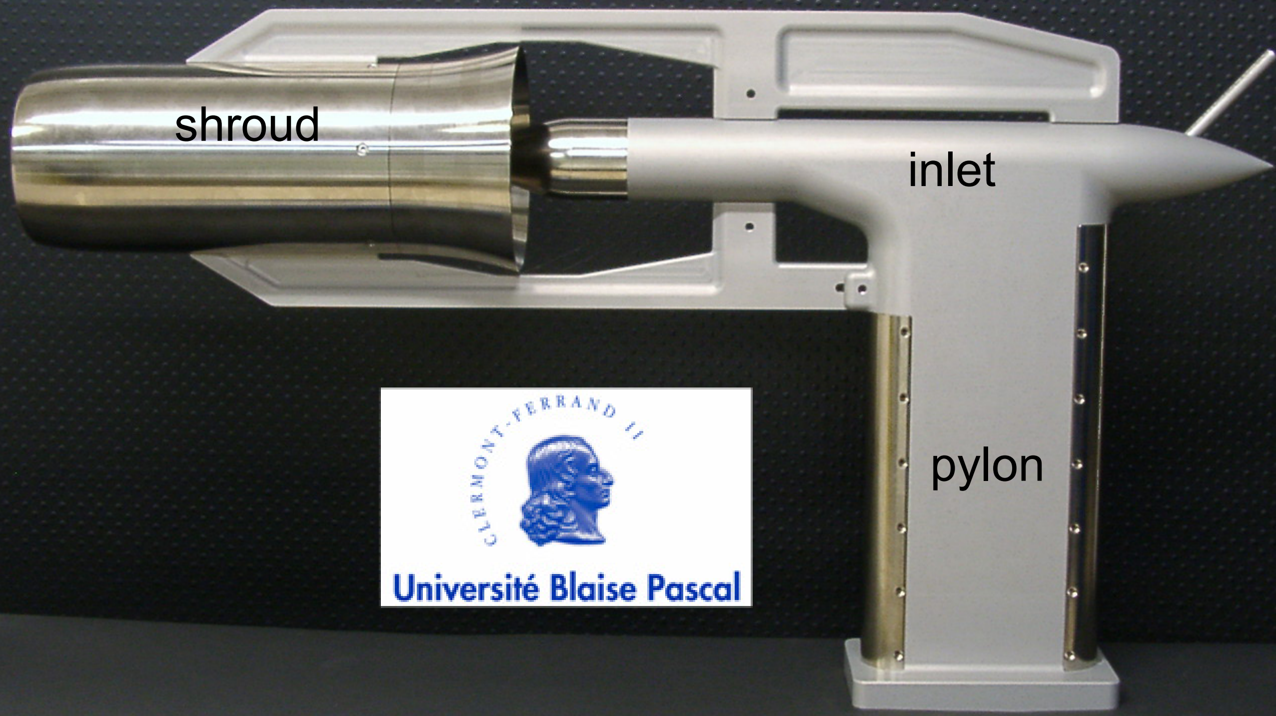
- inlet for measurements of ice and cloud condensation nuclei





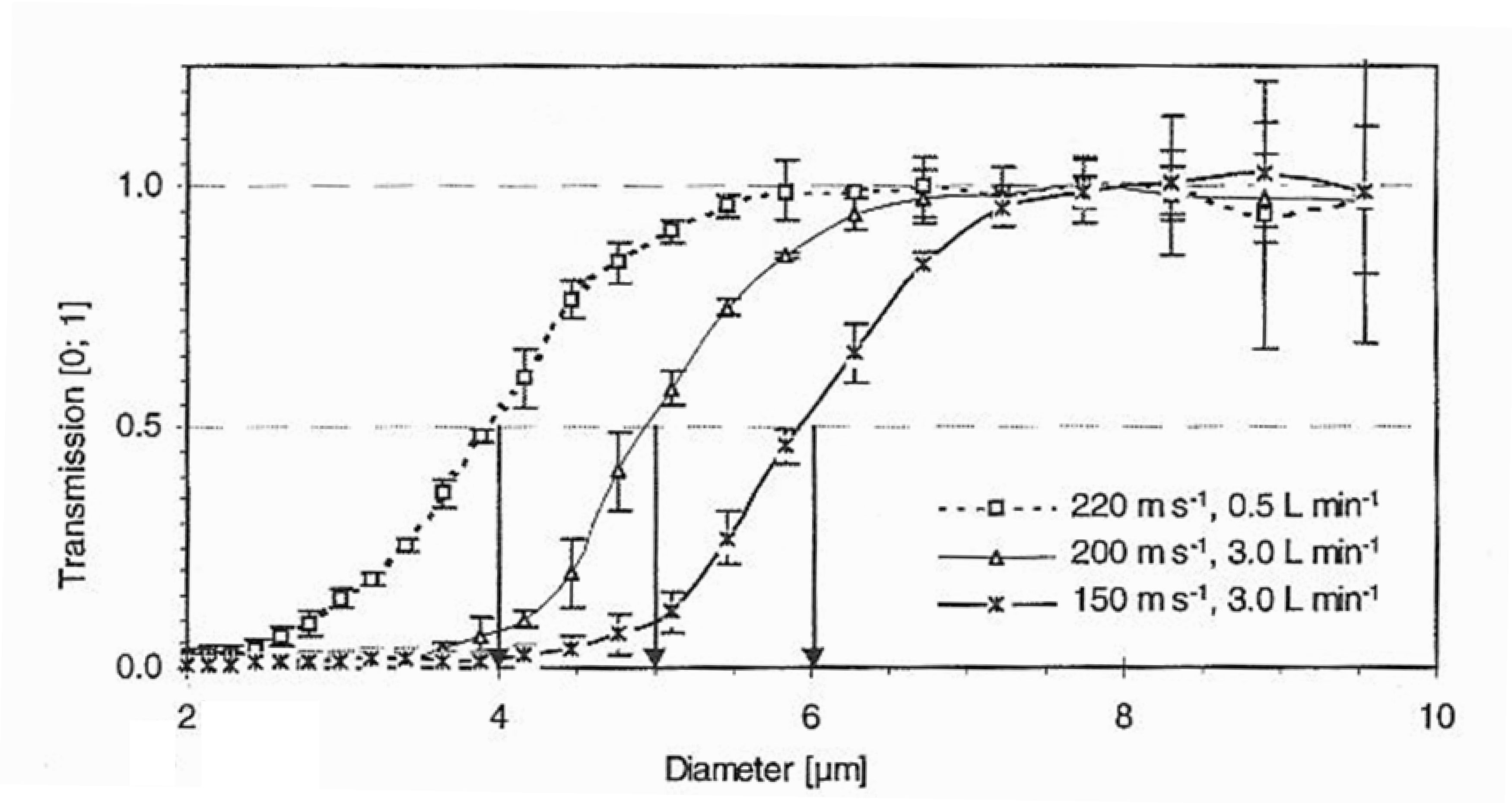
CVI Photo

- Alfons Schwarzenböck, LaMP, Clermont-Ferrand, France



Université Blaise Pascal

- French ATR-42 and Falcon aircraft

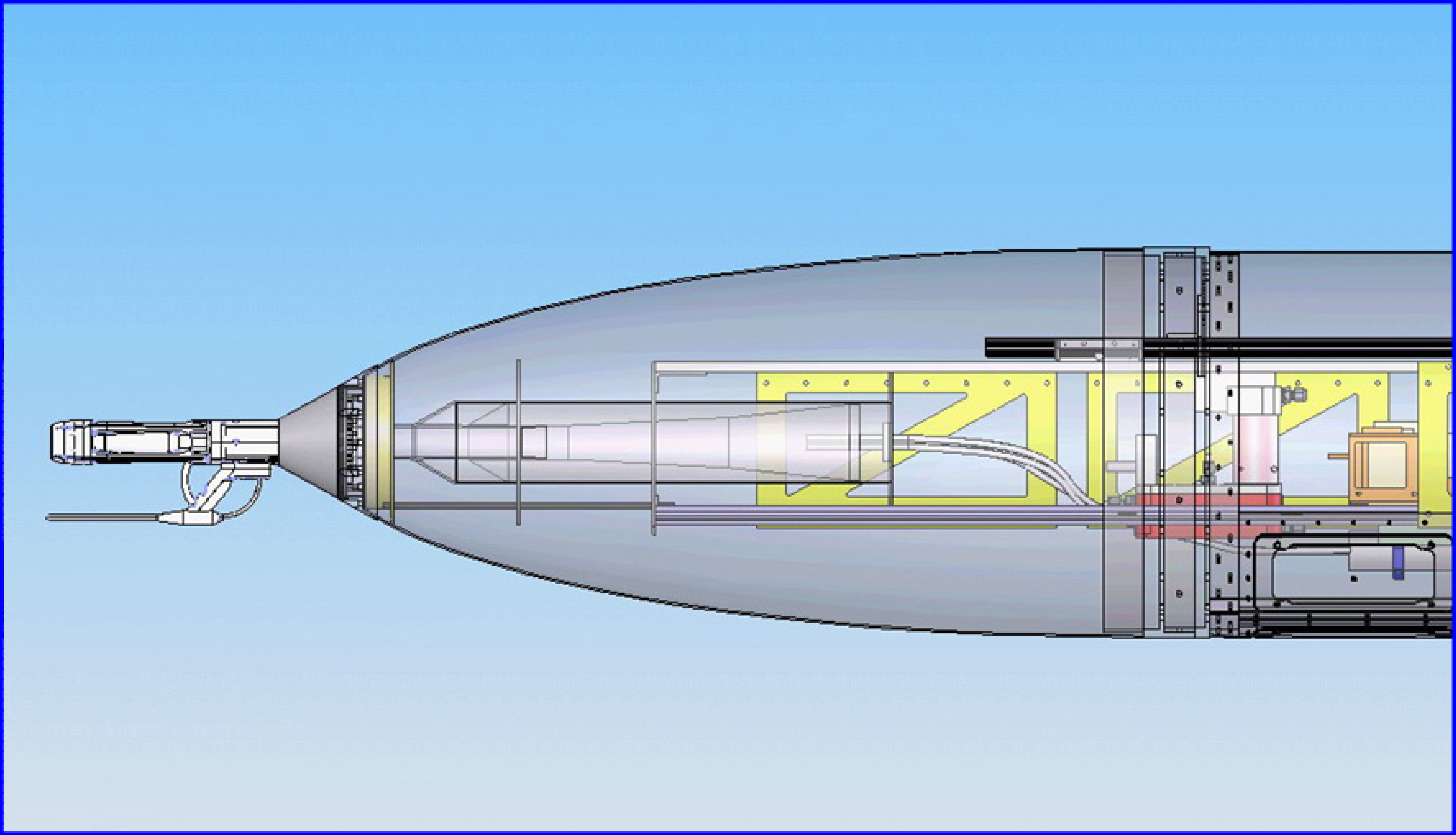


Schwarzenböck, PhD thesis, 1998

Airborne Aerosol Reference Pod (AARP)

- idea: to construct an aerosol measurement package with minimal and well known particle losses
- realization: as wing pod, developed in the framework of EUFAR

- advantages:
  - "no" aircraft influence
  - "no" tube bends
  - short sampling lines

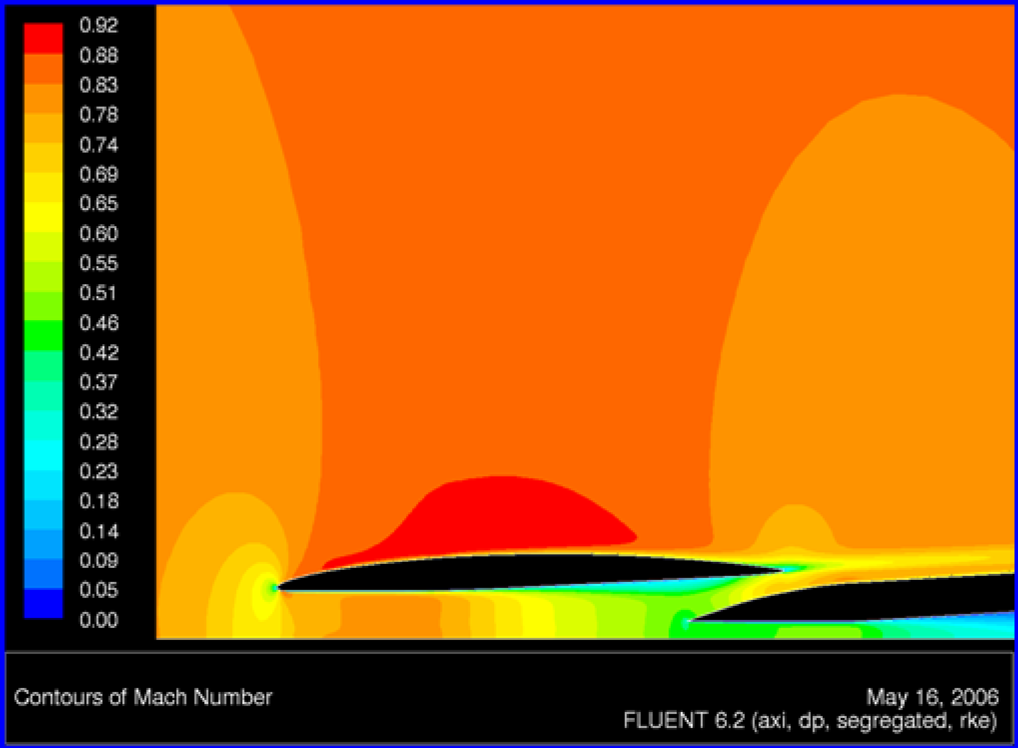


Real Inlets

enviscope GmbH, 2008

Leibniz Institute for
Tropospheric Research

- inlet:
  MF-inlet with two inlet heads is used:
  - low-speed inlet (turboprops)
  - high-speed inlet (jet aircraft)

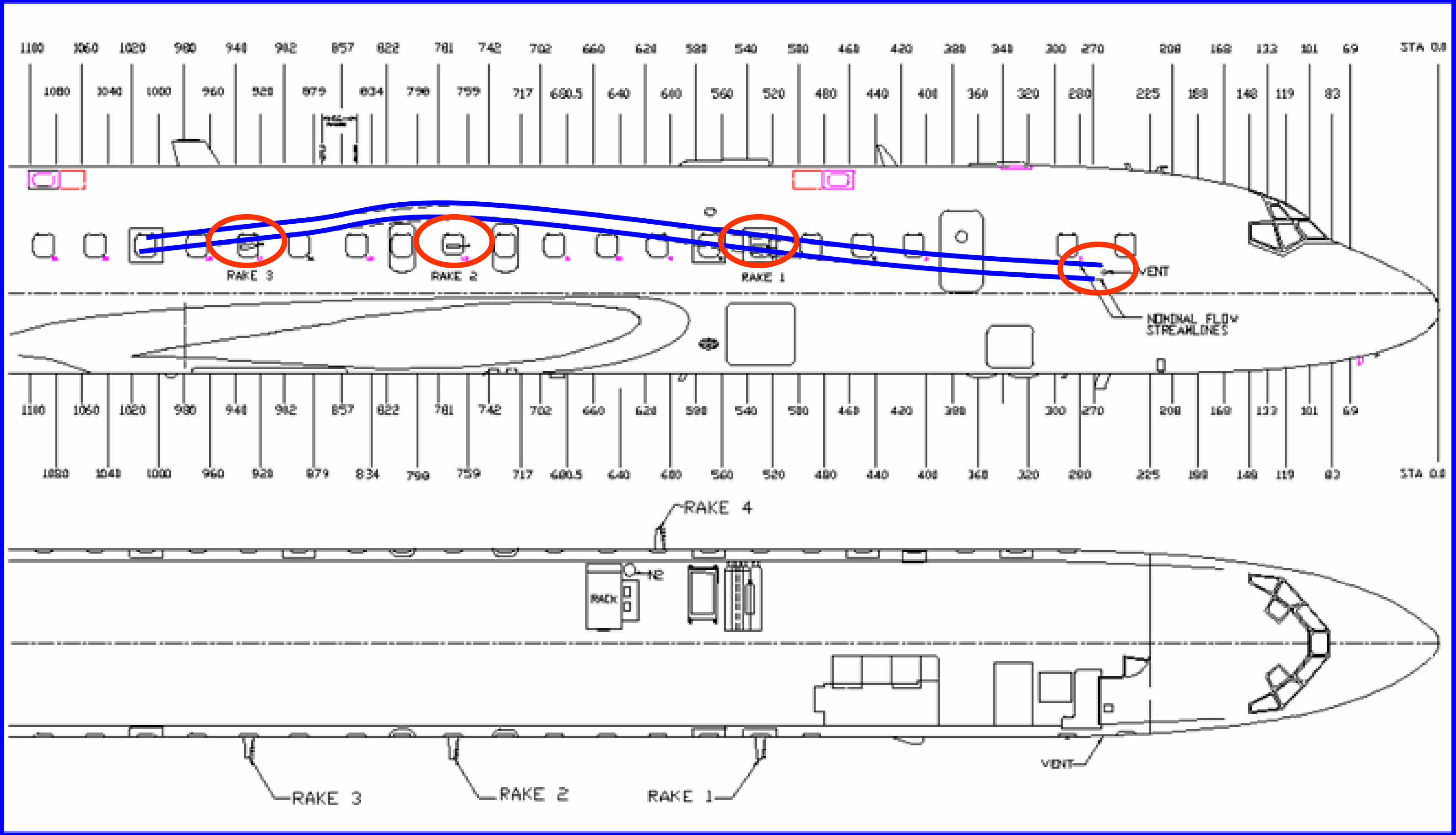


- application: AARP can be flown at the wing station of large research aircraft an thus can be used for intercalibration of aerosol measurement systems (inlet plus instruments)

Leibniz Institute for Tropospheric Research

Measurement Artifacts

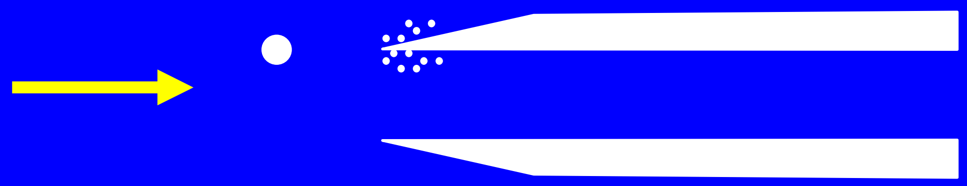
- "any perceived distortion or other data error caused by the instrument of observation"
- aircraft influence
- cloud droplet break-up (on surfaces or in shock waves)
- particle resuspension
- particle evaporation
- electrical effects
- …



Vay et al., JAOT, 2003

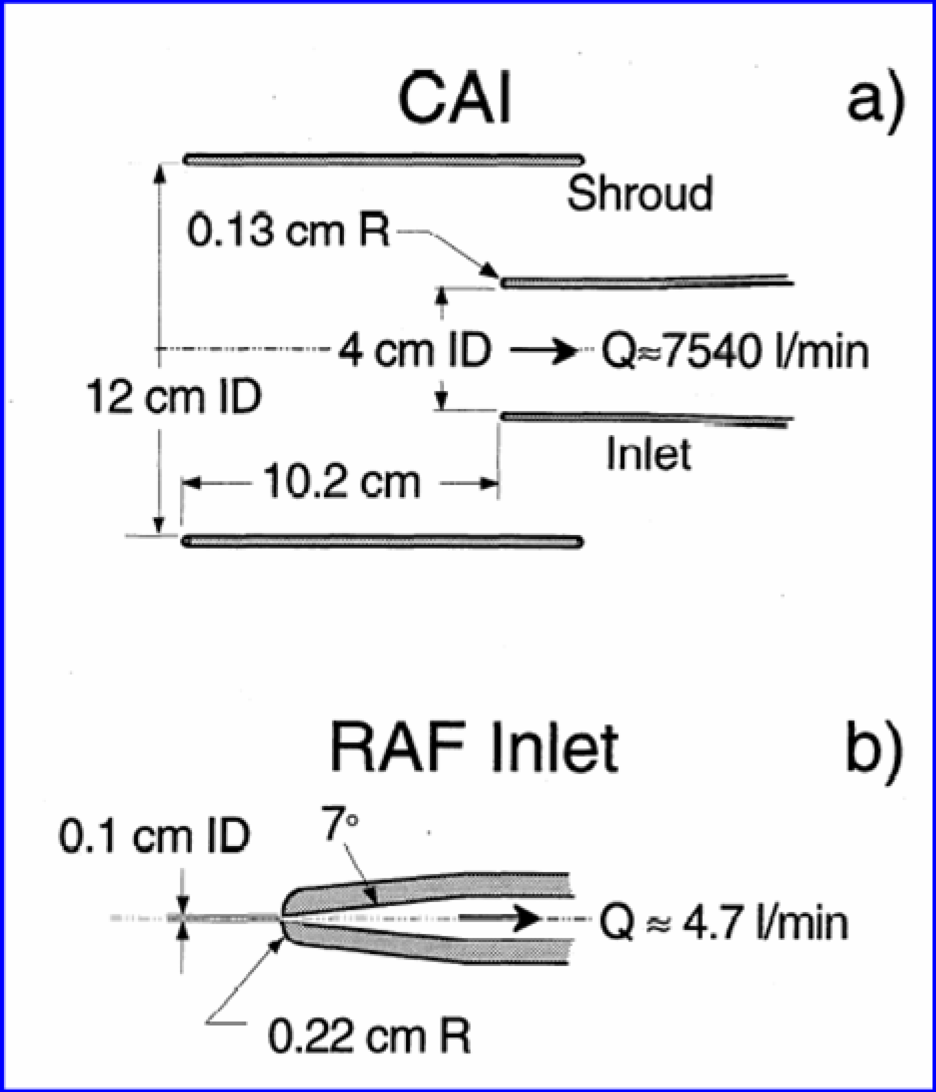
Sampling in Clouds

- cloud droplets or ice particles hit the inlet tip and might break-up into several hundred small particles (same for shock waves)
- especially blunt inlets are subject to this problem

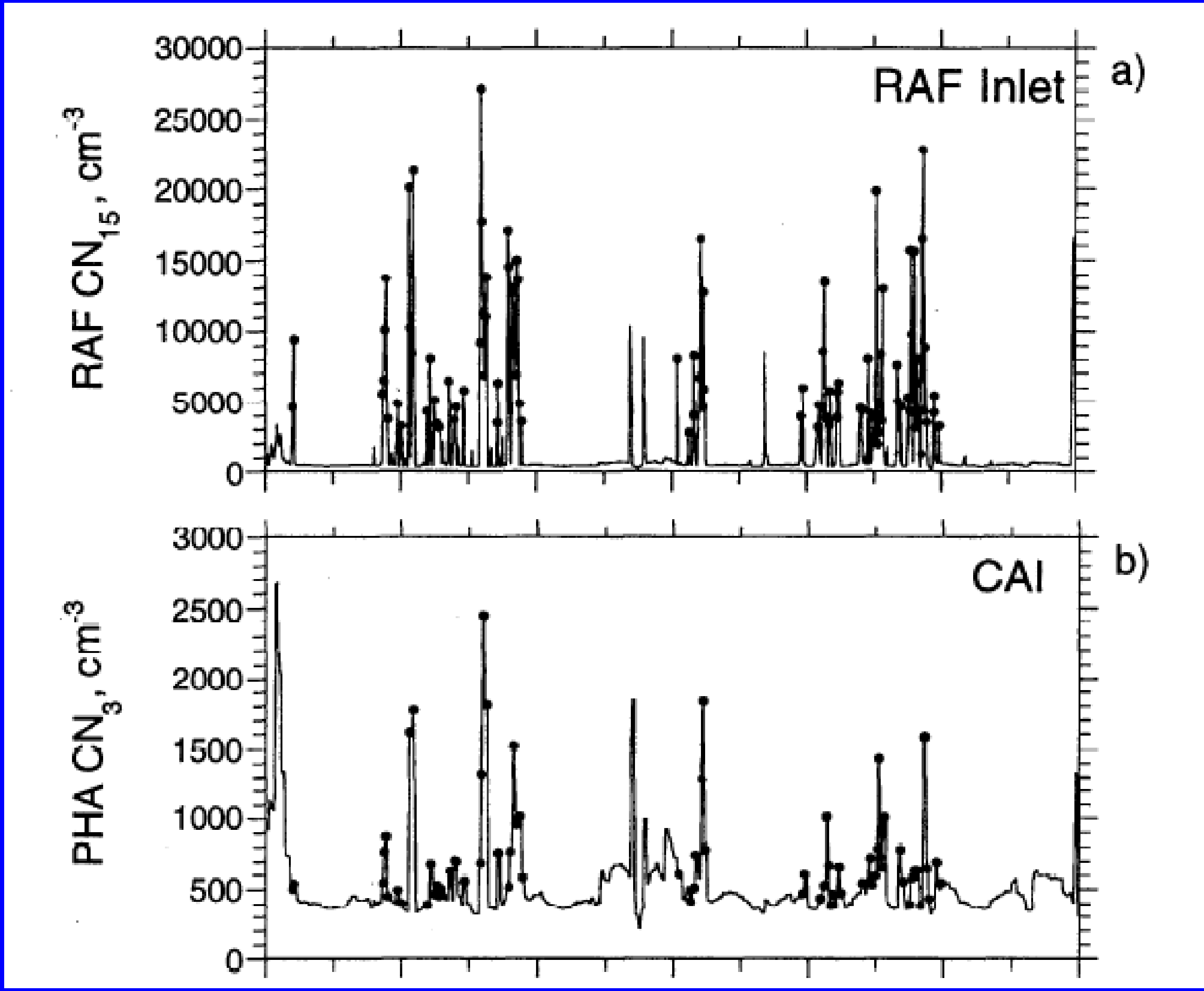


- even if particles don't break-up, there is the possibility that the liquid water film acts as aerosol spray generator

Leibniz Institute for Tropospheric Research

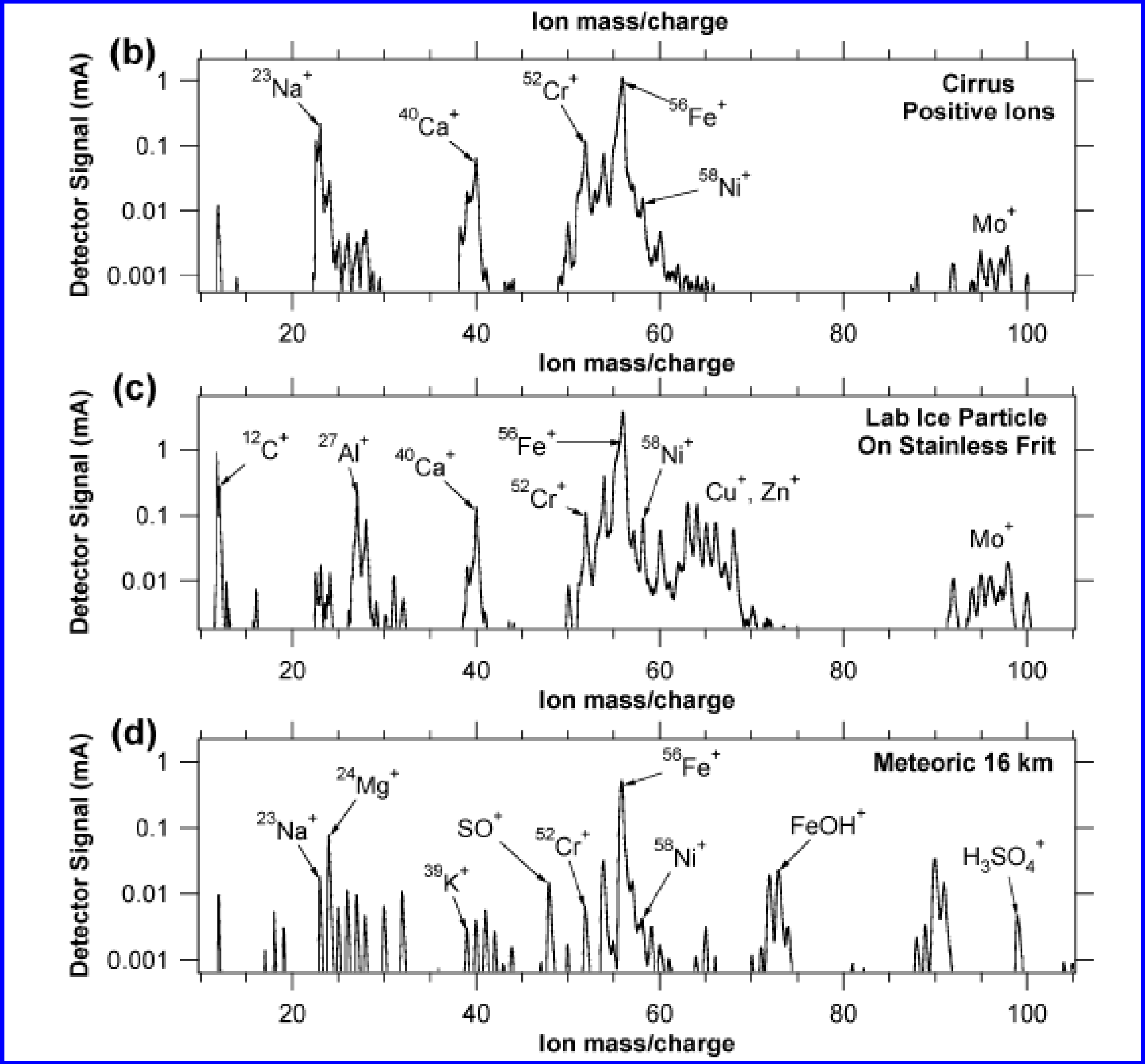


Weber et al., JGR, 1998

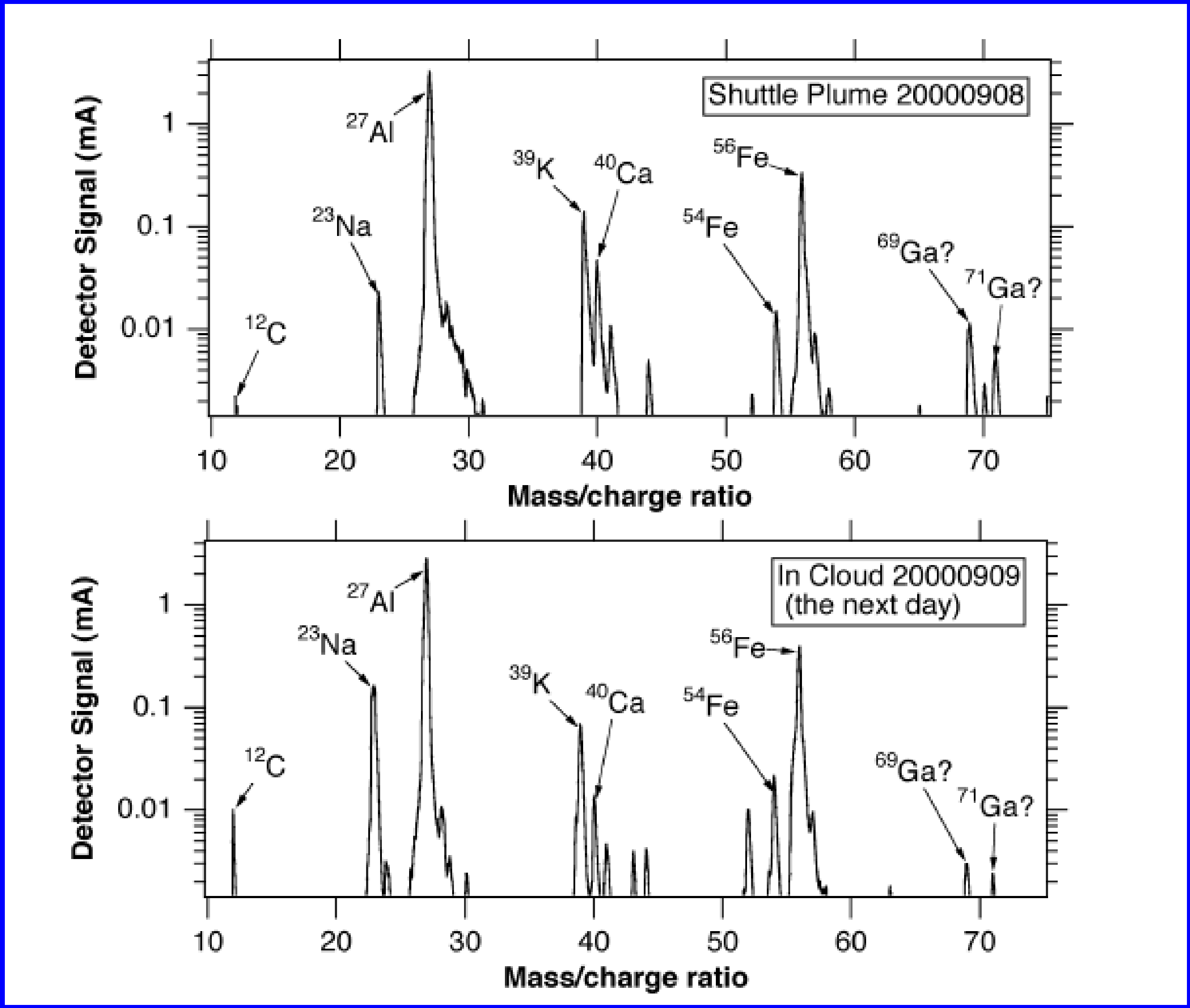


C-130, TAS = 100 m/s

Weber et al., JGR, 1998



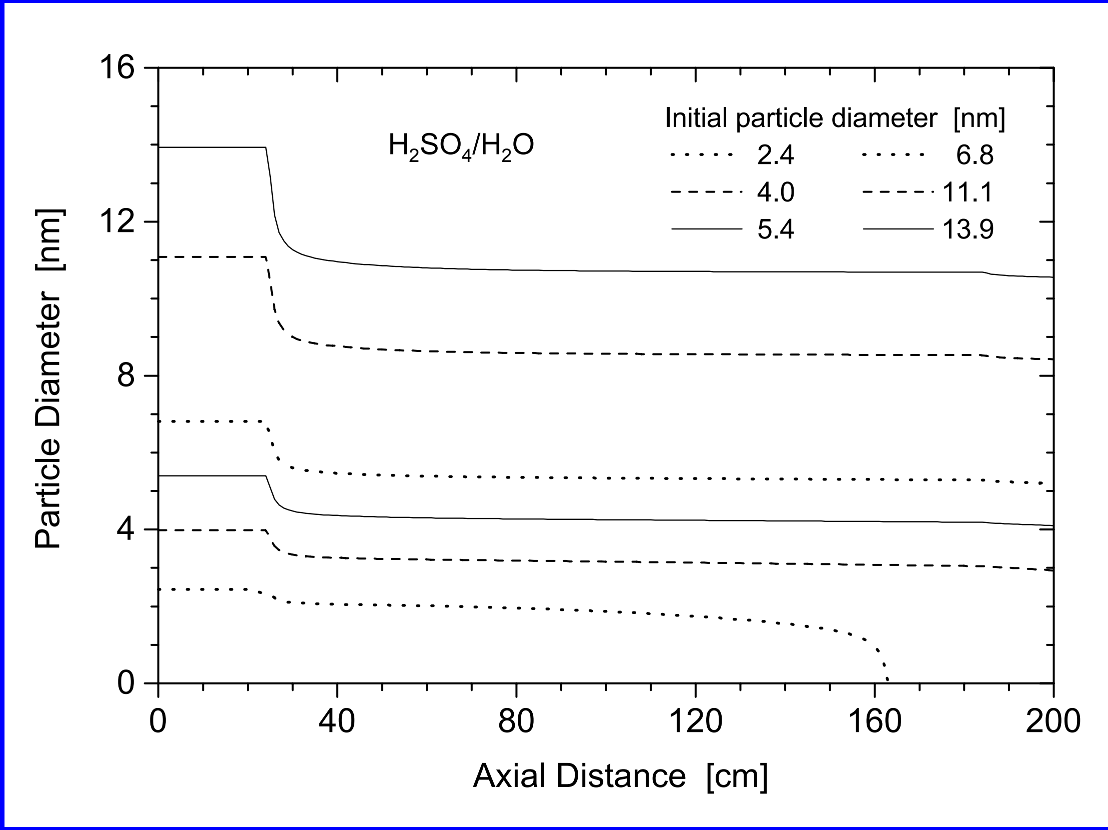
Murphy et al., AST, 2004



Murphy et al., AST, 2004

Particle Evaporation

- deceleration of sample air implies a “ram heating” of 5-30 K
- most measurement devices are operated at about 298 K (25°C)
- total heating from ambient temperatures to measurement conditions can reach up to 90 K!



Hermann et al., JAOT, 2001

Leibniz Institute for Tropospheric Research

Electrical Effects

- collisions with cloud droplets or ice particles charge the aircraft
- associated electrical fields and particle charging
  can change particle sampling efficiency
- concerning the electrical effects on aircraft-borne aerosol
  sampling nearly now literature available!
- recommendation:
  - avoid sharp tips (not always possible)
  - guarantee electric conductivity

Romay et al., AE, 1996

Summary

- aerosol measurements using aircraft platforms is not trivial!
- aircraft can strongly influence the measurement results
- particle losses in the inlet occur mainly for supermicrometer and nucleation mode particles
- for specific questions specific inlets were designed

Recommendations

- flow field and particle trajectories around the aircraft should be known when choosing a position for an aerosol inlet
- CFD modeling of the inlet should be carried out to know inlet sampling properties in advance
- inlet sampling efficiency should be determined either by
  - CFD modeling
  - wind tunnel experiments
  - in-flight intercomparison
  - using empirical equations

Thanks for your attention !