Paper 23

12th Symposium on Measuring Techniques
for Transonic and Supersonic Flow in Cascades and Turbomachines

Prague, Czech Republic, September 12-13,1994

FLOW AND WETNESS MEASUREMENTS AT A TRANSONIC WIND TUNNEL WITH A SLOTTED NOZZLE

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Flow and Wetness Measurements at a Transonic Wind Tunnel with a Slotted Nozzle

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Abstract

In order to enable a precise calibration of pneumatic pressure probes, a wind tunnel was installed at the University of Stuttgart. Its peculiarity is a slotted nozzle with a circular cross–section. It facilitates a continuous variation of the Mach number in a range between Ma = 0. and 1.8; the point of operation is only depending on the pressure ratio at the nozzle. The tunnel can be operated either by air or by steam. Using steam as fluid, superheated as well as wet steam conditions can be realized. These conditions are determined with the help of a newly designed optical probe[a]*, based on the principle of light extinction. The paper contains a description of the tunnel design and a discussion of some measurement results.*

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[a] This probe is the result of a cooperation between the East China University of Technology (former SIME) and the University of Stuttgart

Nomenclature

L	mm	length of the nozzle	x	%	wetness
Ma	–	Mach number	y	mm	vertical probe position
$\dot{P}$	1/s	expansionrate	z	mm	axial probe position
Re	–	Reynolds number	κ	–	isentropic exponent
R	mm	radius of the nozzle	η	–	isentropic efficiency
T	K	temperature	subscripts		
b	mm	probe head diameter	tot	total state	
d	μm	droplet diameter	$stat$	static state	
p	Pa, kPa	pressure	n	nominal state	

1 Introduction

Some years ago, a wedge probe and a cone probe were calibrated in different European wind tunnels. The comparison of the probe calibration coefficients revealed wide discrepancies for the different tunnels. One of the likely causes were the different geometric setups of the test sections [1]. To distinguish errors related to the tunnel design from errors related to the fluid, the described test facility can be operated by steam as well as by air. Thus, the influence of the isentropic exponent with respect to the probe calibration coefficients can be investigated.

2 Tunnel design

The tunnel is integrated in a steam cycle connected to the heatpower station of the University of Stuttgart. Alternatively the tunnel can be fed by a compressor (P = 2.6 MW) to be operated by air.

Figure 2.1 shows the individual elements of the steam tunnel.

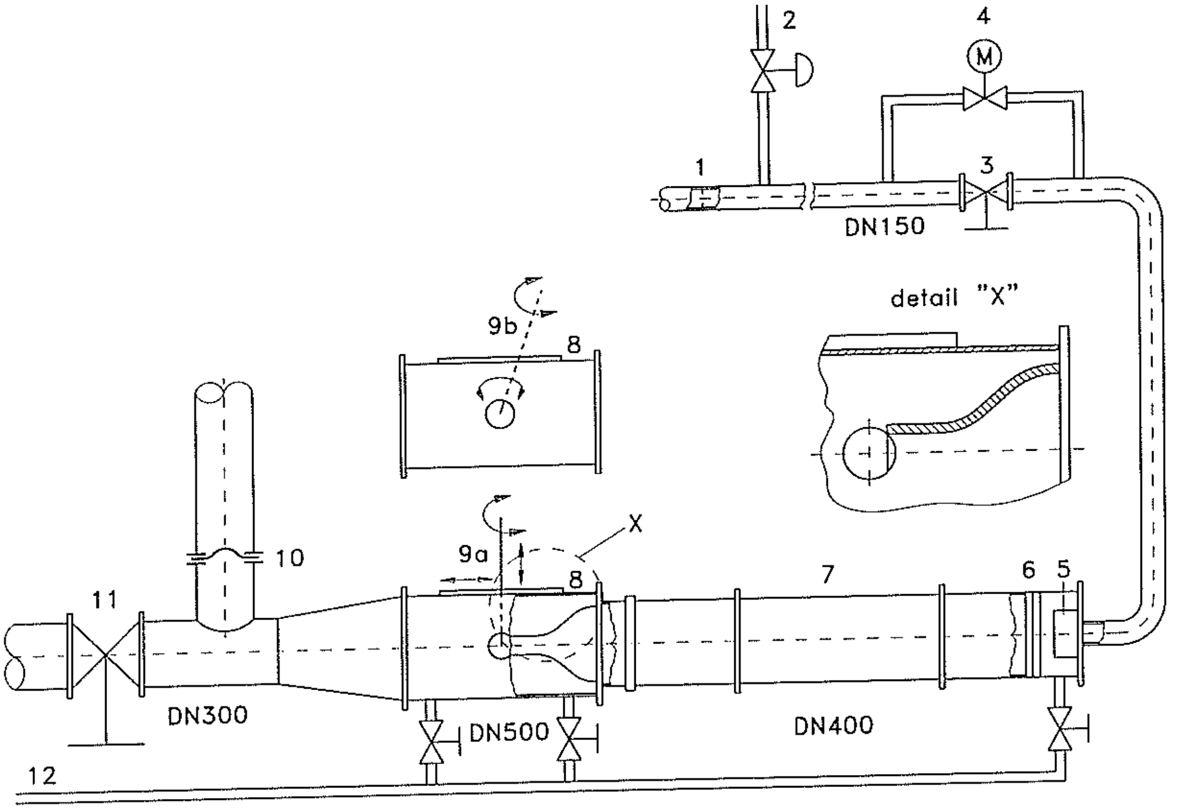

Figure 2.1: design of the steam tunnel

The mass-flow through the tunnel is determined with a blade orifice (1). The temperature and the pressure upstream of the nozzle are regulated by the injection of condensate (2) and tuning the valves (3) and (4). The flow conditioner (6) at the beginning of the settling chamber (7) consists of three perforated discs and two filters. Downstream of the nozzle (8), the probe support (9) for the flow probes is mounted. There are two possible configurations: either the axial position and the yaw angle of the probe are varied (the flow field downstream of the nozzle is determined) (9a) or alternatively, the probe head is fixed in an axial position and both, the yaw as well as the pitch angle are varied in order to carry out a three-dimensional calibration of the probe (9b). The rotation point of the probe support is located in the tunnel axis at distance of z = 40 mm to the outlet of the nozzle. To observe the flow and to use optical measurement systems, windows are installed in the axial location at the outlet of the nozzle (detail X). The diameter of the measurement chamber is 500 mm. Finally, the valve (11) behind the measurement chamber allows to alter the pressure level in the tunnel.

To accelerate the flow in the supersonic range, a slotted nozzle (Fig. 2.2) is used. This nozzle is designed according to the idea of J. Rosén [2], [3].

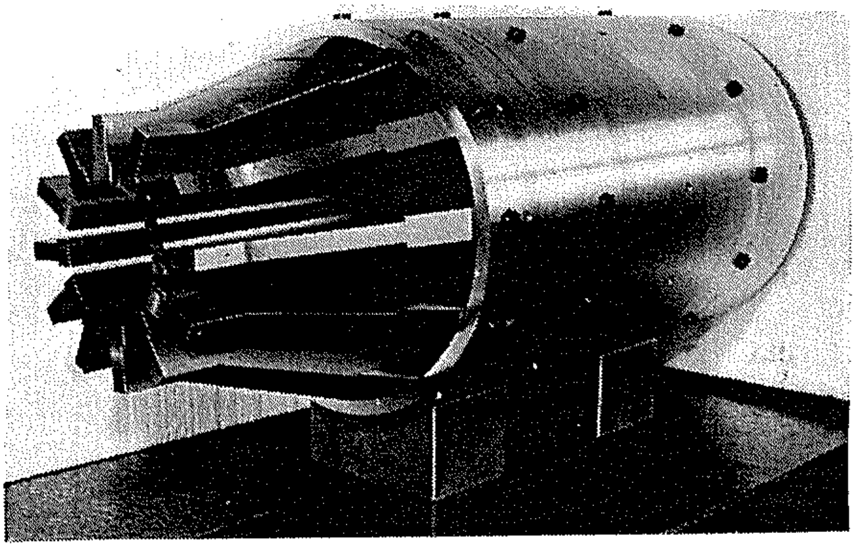

Figure 2.2: slotted nozzle

The length of the nozzle is 1270 mm, the minimum diameter is 125 mm. It allows a continuous variation of the Mach number in a range between $Ma = 0.$ and 1.8 according to the pressure ratio. The nozzle consists of a convergent and a cylindrical part. The cylindrical part has 12 identically tapered slots in radial direction with a axial length of 750 mm. At the outlet of the nozzle the width of the slots at the perimeter of the cylindrical part is 6 mm. The steam in the convergent part of the nozzle is accelerated up to sonic speed. Then, in the cylindrical part a certain amount of the steam spills over the slots into the surrounding chamber. The other portion of the steam remains in the nozzle and is expanded in axial direction. As a result, the same effect as with convergent/divergent nozzles is obtained.

The advantage of the slotted nozzle is that only by changing the pressure ratio the Mach number can be adjusted; a variation of the nozzle geometry is not required.

3 Data sampling

Figure 3.1 shows the location of data sampling in the calibration tunnel.

Upstream of the nozzle, the thermodynamic conditions are measured by the total state, total pressure and total temperature. Downstream, the static pressure at the wall of the chamber is measured and pneumatically averaged in five cross–sections (I ... V). In addition to that, there are ten tappings (1 ... 10) in seven cross–sections along the nozzle wall to determine the present pressure distribution. The reference conditions for probe calibration are obtained by the total state upstream of the nozzle and the static pressure at the outlet of the nozzle (tapping no. 7).

The water containers above the tappings are installed because the connected pressure transducers must not be contaminated by steam. Furthermore, the entry of steam into the measurement tubes is prevented by continuous air–purging. This principle is also used for probe measurements in steam turbines [4].

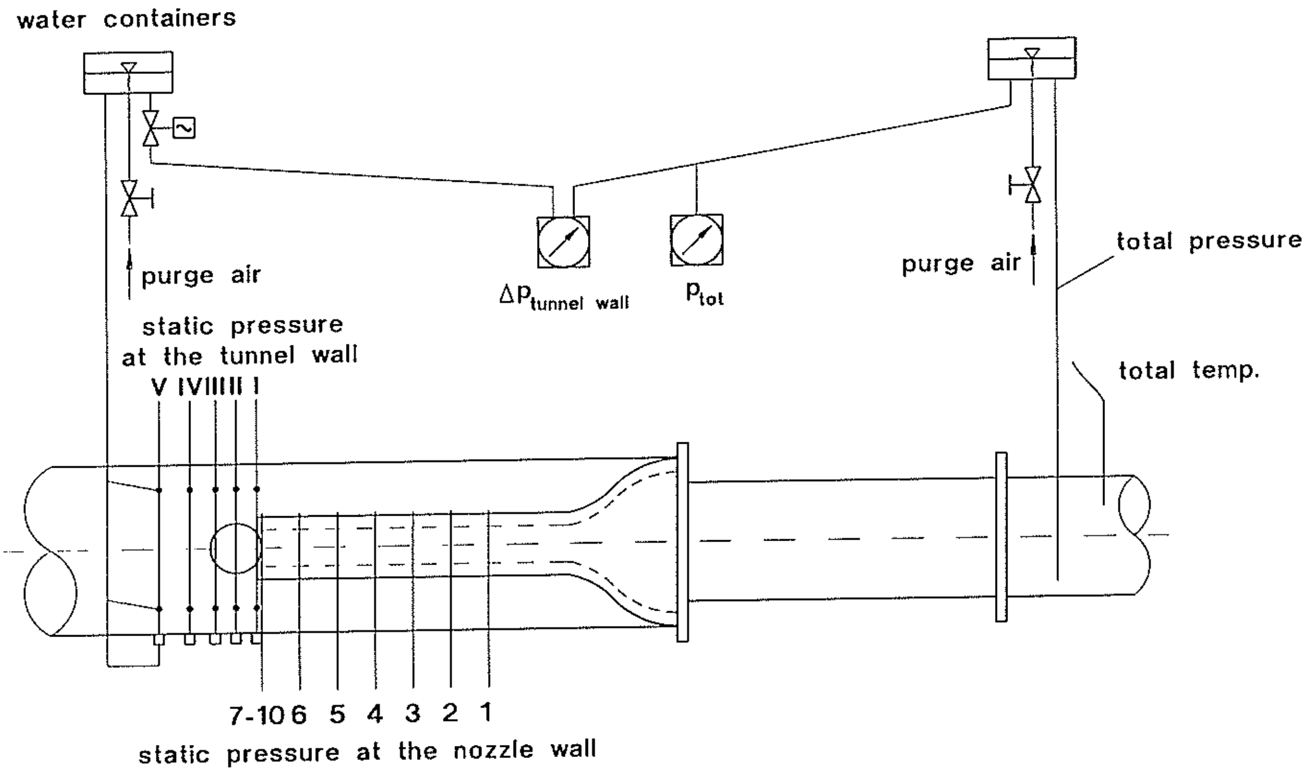

Figure 3.1: location of data sampling

The maximum total pressure upstream of the nozzle is about $p_{tot} = 160\,\text{kPa}$, the minimum static pressure downstream of the nozzle is $p_{stat} \leq 5\,\text{kPa}$, the minimum pressure ratio is about 0.1. The nominal conditions upstream of the nozzle are $p_{tot,n} = 40\,\text{kPa}$ and $T_{tot,n} = 453\,\text{K}$. The following controlling accuracies for the thermodynamic conditions upstream of the nozzle can be achieved: total pressure: $\pm 80\,\text{Pa}$ (about $\pm 0.2\,\%$ of $p_{tot,n}$), total temperature: $\pm 0.5\,\text{K}$ (about $\pm 0.11\,\%$ of $T_{tot,n}$). It is possible to vary the Reynolds number at sonic velocity upstream of the probe in a range between $Re = 1.3*10^4$ and $Re = 5.7*10^4$ (based upon a probe head diameter $b = 3\,\text{mm}$, fluid: superheated steam).

4 Wetness measurement

Because the tunnel can be operated with wet steam, it is necessary to determine also the wetness of the steam. To measure size, size distribution of the droplets, and wetness of the steam flow, an optical probe is used. The measurement principle of this probe is light extinction. The measurement range for the droplet size is $d = 0.02\,\mu\text{m}$ up to $d = 10.0\,\mu\text{m}$ [5], [6].

The principle, the parts of the measurement system, and the calculation of the wetness of a wet steam flow is described in the paper [7] presented in this symposium.

5 Measurement results

All the following results are achieved with steam. The tests with air as fluid will be carried out later on.

For this kind of nozzle, it is not possible to calculate the Mach number as a function of the pressure ratio on the assumption of isentropic expansion as at a Laval nozzle. Therefore it is necessary to calibrate the nozzle. For supersonic flows we used a Schlieren optical device to measure the Mach number. Its application required a static pressure at the outlet of the nozzle of $p \geq 10\,\mathrm{kPa}$, otherwise, the density of the steam would have been too small to observe the Mach angle. The maximum measurement error was about 4 %. In the case of subsonic flows, the static pressure was measured with a special pneumatic probe [8]. Figure 5.1 shows the resulting calibration curve: Mach number versus pressure ratio (curve 1). The pressure ratio is calculated with the static pressure at the outlet of the nozzle. At Mach number $Ma \geq 1.0$ the calibration curve is approximated by a polynom of third order:

$$Ma = a_0 + a_1(p/p_{tot}) + a_2(p/p_{tot})^2 + a_3(p/p_{tot})^3. \tag{1}$$

The calibration curve, depicted in the diagram, is only valid for the prevailing pressure level ($p \approx 12\,\mathrm{kPa}$) and the Reynolds number respectively, which were adjusted during the measurements. For other conditions, it is necessary to check the calibration [9]. In comparison to curve 1, curve 2 shows the function $Ma = f(p/p_{tot})$ for an isentropic expansion ($\kappa = 1.32$). A comparison of both curves indicates tremendous losses in the nozzle for supersonic flow conditions (isentropic efficiency $\eta \approx 0.85$ for $Ma \geq 1.2$), while there are no differences in the subsonic flow regime.

Figure 5.2 shows the Mach number distribution in the cross–section, where the probe calibration will be performed. The measurement position at the top of the nozzle is $y/R = +1$, at the bottom of the nozzle is $y/R = -1$ and the tunnel axis is according to $y/R = 0$. For supersonic flow conditions, the Mach number couldn't be recorded over the entire cross–section, due to the limited diameter of the windows in the measurement chamber. The deviations in this range are in the same order of the measurement uncertainity. The resulting minimum width of the undisturbed flow is $y/R = \pm 0.4$.

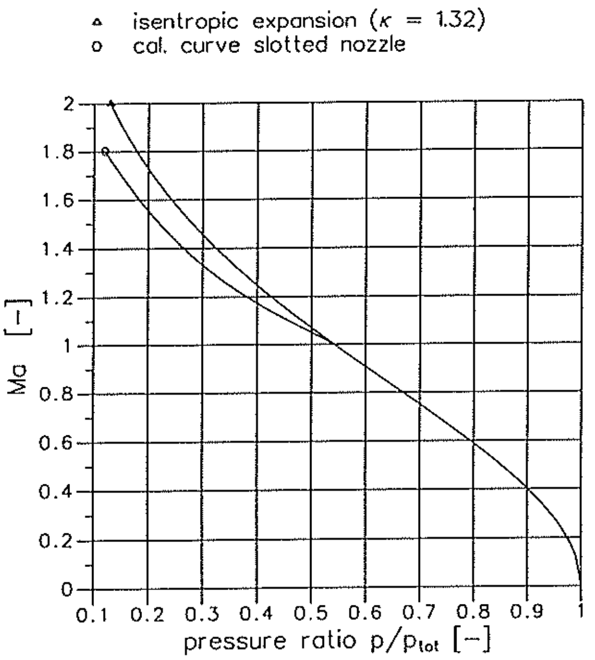

Figure 5.1: calibration curve and isentropic expansion for superheated steam

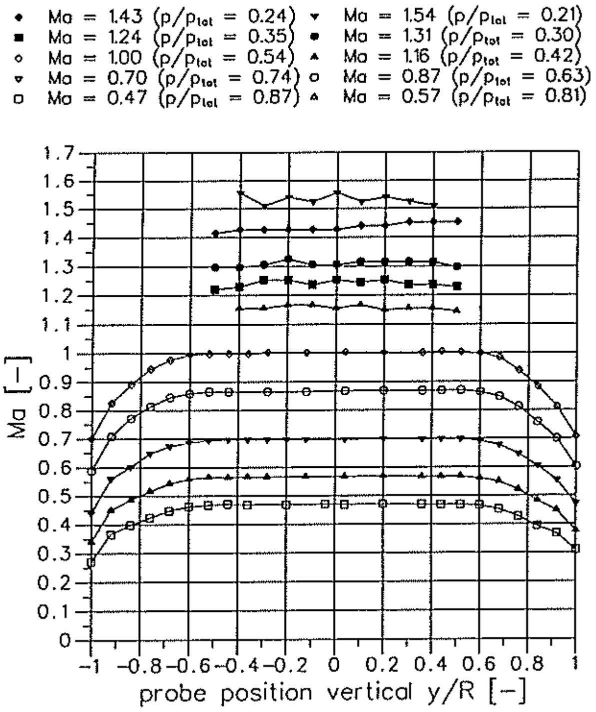

Figure 5.2: distribution of the Mach number in the later calibration cross–section

Figure 5.3 shows the distribution of the static pressure along the nozzle wall for different pressure ratios. The outlet of the nozzle is according to $z/L = 0$. The slotted part begins at $z/L = -0.6$. In the case of subsonic flows the static pressure along the cylindrical part of the nozzle is constant. When the pressure ratio is further decreased, the expansion to supersonic flow takes place right at the beginning of the slotted part. Reaching the value of the pressure ratio, the static pressure is constant all the way down to the outlet of the nozzle.

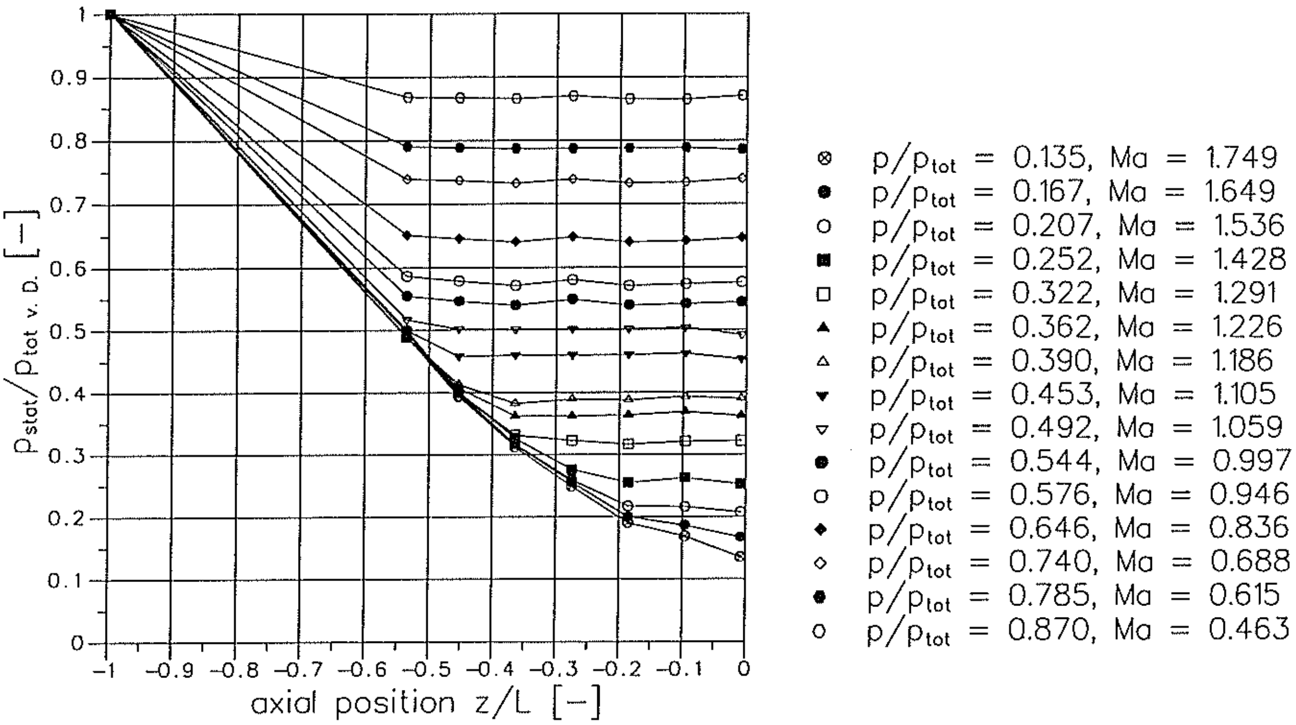

Figure 5.3: static pressure along the nozzle wall

Wetness measurements

Figures 5.4 and 5.5 show the results of wetness measurements with the optical probe. Besides the wetness and the Sauter mean diameter of the droplets the size distribution of the droplets for different measurement positions are depicted. The wetness and the mean diameter seem to be nearly constant for both Mach numbers (Fig. 5.4). The averaged droplet diameter with values of about $d = 1.13\,\mu m$ $(Ma = 0.9)$ and $d = 1.32\,\mu m$ $(Ma = 1.15)$ matches the expected data very well [10]. The expansionrate[1] of the supersonic flow is calculated to $\dot{P} \approx 315$ 1/s.

While the size distribution of the droplets is nearly monodisperse in the center of the jet, there is a wider spectrum at its bottom part (Fig. 5.5).

6 Conclusion

The slotted nozzle seems to be very convenient for probe calibration in transonic flows, because it is possible to calibrate at different Mach numbers without any modifications of the geometry. Furthermore the region of the undisturbed flow downstream of the nozzle is large enough to minimize probe blockage effects. The blockage factor φ [1] is calculated to $\varphi = 65.5$. This factor constitutes an average value related to the tested windtunnels at the workshop.

The tunnel can be operated either by air or by steam. Therefore it is possible to combine the results of probe calibration in both fluids with the same operating conditions.

The optical probe is well suited for wetness measurements at the steam tunnel.

We hope, that it is possible to improve the accuracy of pneumatic probe measurements in steam turbines with the results of this test facility.

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[1] expansionrate $\dot{P} = -\frac{1}{p}\frac{dp}{dt}$

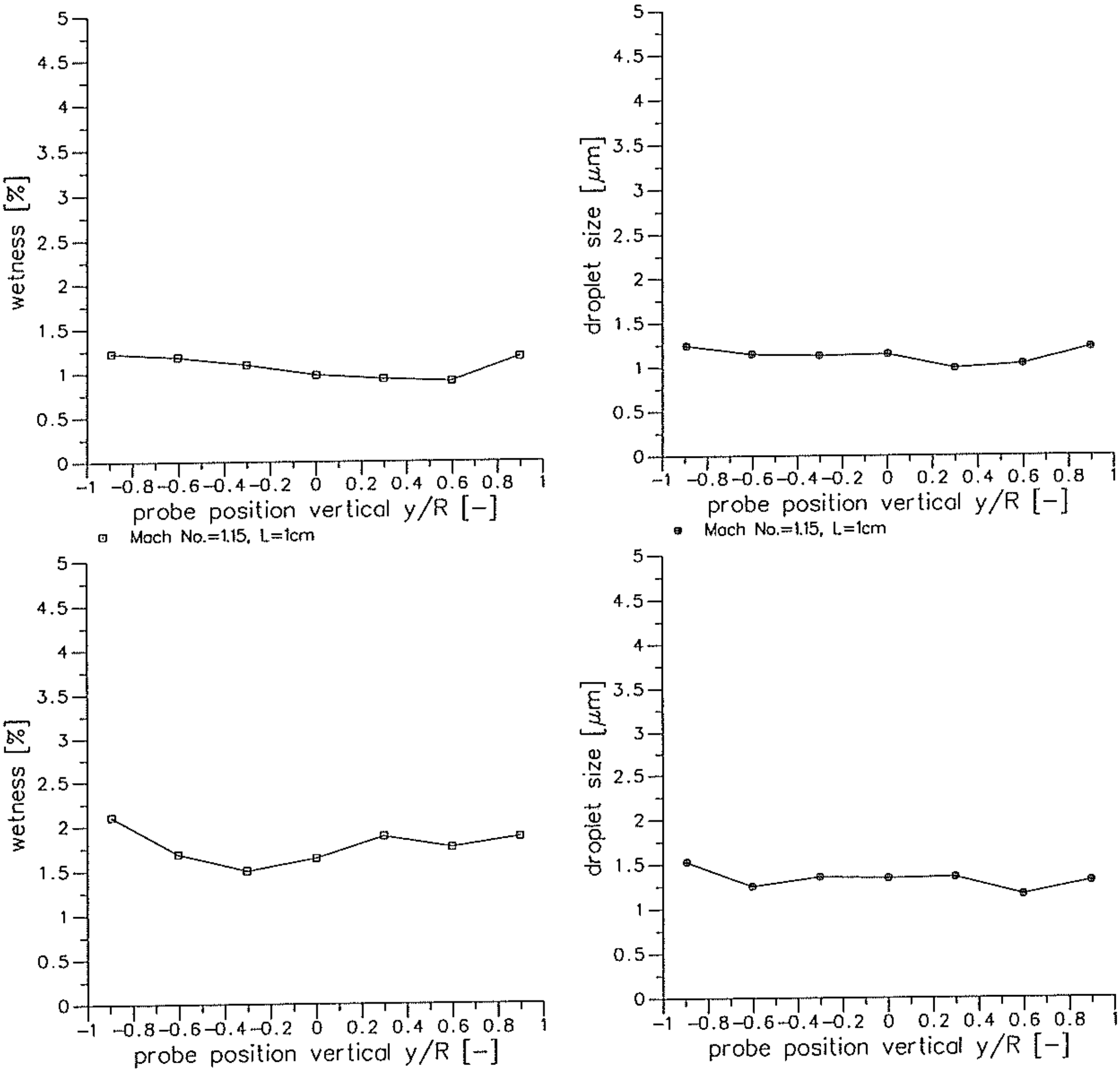

Figure 5.4: wetness and droplet size: Ma = 0.9 (above), Ma = 1.15 (below)

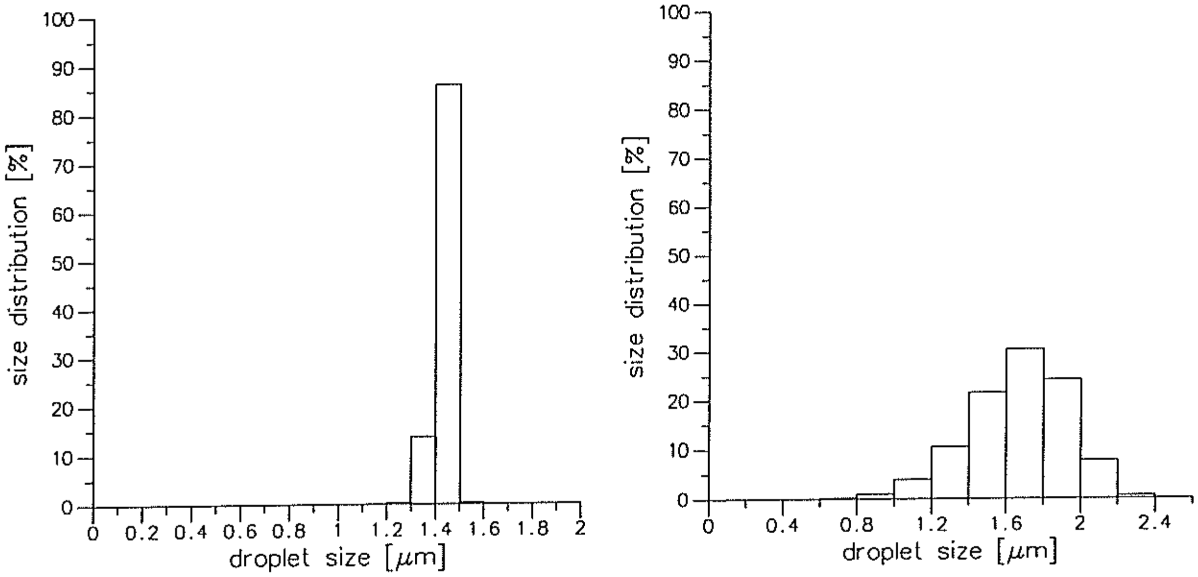

Figure 5.5: size distribution: center of the jet (left), bottom of the jet (right)

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Acknowledgement

We want to express our gratitude to the Siemens AG / KWU, for supporting the test facility and the satisfactory cooperating.