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MEASUREMENT ERRORS WITH PNEUMATIC PROBES BEHIND GUIDE VANES IN TRANSONIC FLOW-FIELDS

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ABSTRACT

Probe blockage effects are presented for transonic flow through a guide vane row in a three-stage low-pressure (LP) steam model turbine. Accurate experimental data from measurements in a transonic turbine are needed for the verification of CFD results. The accuracy of static pressure measurements in transonic turbine stages is severely affected by the pneumatic probe, which disturbs the surrounding flow-field. These disturbance effects are significantly present during measurements inbetween turbomachinery blade rows. Therefore, the phenomenon associated with this blockage effect must be investigated and determined.

The aim is to measure the blockage effects on the blade passage flow, which are produced by a pneumatic pressure probe immersed in the flow between two adjacent blade rows. In order to measure these effects, two stator blades are instrumented with static pressure taps along the blade chord, as well as along the blade span. During the investigations, the radial and circumferential positions of the probes relative to the blade channel are varied. Pressure probe readings of two four-hole wedge probes with different stem diameters and a five-hole cone probe are compared as well as correlated to the static pressure readings of the stator blade pressure taps. Finally, the apparent deviations of the different readings are discussed.

NOMENCLATURE

C_a	mm	axial chord	Ma	-	Mach number
d	mm	diameter of the probe stem	P,p	hPa	pressure
Q	mm	opening	xp	mm	axial probe position behind the trailing edge

subscripts	tot	total state	stat	static state
	1,2,3,4,5	No. of probe tapping	dyn	dynamic pressure

INTRODUCTION

Accurate experimental flow measurement data is needed for the verification of CFD results and for the improvement of the design of turbines. Pneumatic multi-hole probes represent a simple and proven measurement means for determination of the local flow vector and the thermodynamic state of the fluid, and are still in common use in cascades and turbomachines. The advantage of this measurement technique is that it can be used in two-phase flow also. Generally the repercussion free optical flow measurement technique, such as Laser Doppler Anemometry (LDA) and Laser 2 Focus (L2F), cannot be used in the wet steam turbine flow.

The disadvantages of the pneumatic multi-hole probe measurement technique is that the flow-field is disrupted by the probes. This disruption appears upstream of and at the probe head. However the comparison of experimental investigations using pneumatic multi-hole measurements with numerical results at the last stage agrees very well in the subsonic flow regions ahead and behind the LP-stage /1/. In contrast, in the transonic region between the blade rows there is a significant deviation between the measurements and the calculations of the static pressure. There are several investigations (/2/, /3/, /4/ and /11/) concerning the problems and accuracy of pressure measurement in transonic and supersonic flows with pneumatic multi-hole probes. In any case the presence of the probe has an effect on the flow. These difficulties with the pneumatic multi-hole measurement technique are influenced by the cross-section areas (blockage, relative cross-section area of the probe), by the jet characteristic of the flow-field (free-jet, closed tunnel) and by the probe structure (head and stem). The influence of the probe structure is significant (/3/ and /4/) on the flow-field upstream of and at the probe head. It is difficult to make a proper assessment of the direct influence of the probe on the measurement results.
The influence of these factors on the flow measurements as described before could be reduced by constructing a special probe (for example, to reduce the influence of a radial stem an axial stem should be used). This solution is not possible in the current investigation (real turbine) due to of the restricted mounting-area between the stator blade row and the rotor blades. To find out the most accurate way of measuring, it is necessary to first work out the influence of the probe on the flow through the blade passage. An estimation of the accuracy of the flow-field measurements can be given with this information. Presented in this paper are the probe blockage effects on the flow-field measurements inbetween the turbomachinery blade rows.

TEST FACILITY

At the University of Stuttgart - Institut für Thermische Strömungsmaschinen - a test rig for LP steam turbines is in operation. It is an efficient facility that enables various investigations on down-scaled last stages. The main research interests are: the efficiency of the last stage, the dynamic characteristics of the blading, and the flow-field in the last stage and the diffuser. A data acquisition system for stationary and non-stationary experimental data has been installed. Former publications (/5/, /6/) describe the test rig thoroughly.
The present investigations are carried out with a 1/4.2 scale three-stage LP steam turbine with curved guide vane designed by Siemens-KWU. The full scale facility has an exit area of 12.5m^2. Fig. 1 shows a longitudinal-section of the turbine. With the moveable diffuser ring and the probe traversing device it is possible to measure the thermodynamic conditions at any location behind the guide vane row of the last stage.

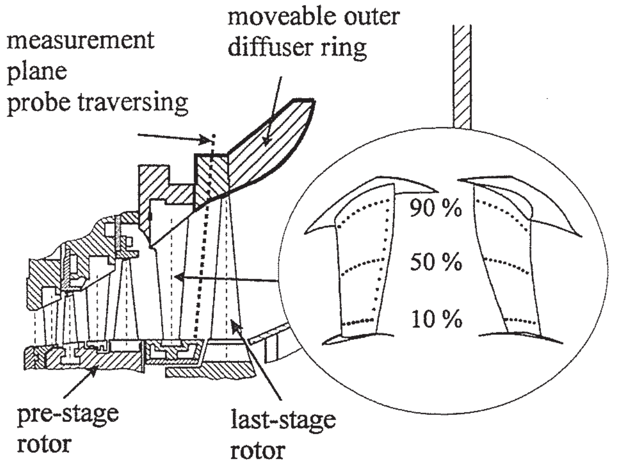

Fig. 1: Longitudinal-section of the LP steam turbine with the position of the static pressure taps and the probe traversing

MEASUREMENT TECHNIQUES

To record the influence of the pneumatic probes on the flow through the stator blade passage, adjacent blades are instrumented with static pressure taps. To measure the pressure distribution in one blade passage at 10%, 50% and 90% blade span, the suction and pressure surfaces are drilled with 10 static pressure taps along the blade chord. Fig. 1 shows the two blades with the locations of the static pressure taps. To get detailed information about the static pressure distribution along the blade span, equidistant

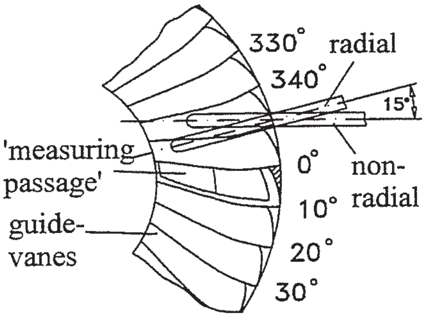

Fig. 2: Curved guide vane with the radial and non-radial probe traversing

static pressure taps are installed between the three tap rows in the chordwise direction near the trailing edge at the suction surface. These 13 static pressure taps along the blade span are named 'trailing-edge' static pressure taps in this paper. This instrumentation of one blade passage facilitates the measurement analysis of the interaction between the flow through the blade passage and the downstream mounted probes.

The traverse of the pneumatic probes in this plane is possible in both radial and non-radial directions. Fig. 2 shows the two set-ups for the probe traversing behind the trailing edges of the guide vane. The inclined angle of the non-radial probe traverse is 15°. This position of the pneumatic probes in relation to the blade passage is recommended in /7/ and /4/ for reducing the probe blockage effect. However, this recommended set-up can only be partly fulfilled in this modern bowed guide vane.

The probe blockage area behind the measuring blade passage can be varied on one hand by traversing the probes in the circumferential and radial direction, and on the other hand by positioning the probes radially and non-radially and by using stem diameters of 8 mm and 6 mm.

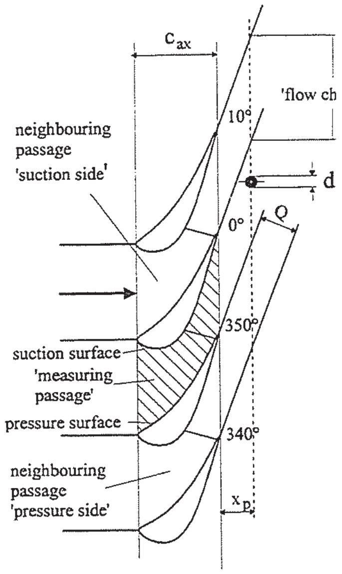

Fig. 3: Cross-section of the guide vane row and position of the pneumatic probe in the cylindrical coordinate system.

Fig. 3 shows the cross-section of the stator blade row and the probe mounted downstream with the dimensions important to calculate the probe blockage ratios. Table 1 lists the probe blockage ratios (stem (d) and probe head size (a) to opening (Q) in 10, 50 and 90% span).

Span [%]	x_p/c_a x	d_{probe}/Q, d = 8 mm	d_{probe}/Q, d = 6 mm	a_{wedge}/Q, a = 2.85 mm	a_{cone}/Q, a = 2.7 mm
10	0.37	0.51	0.38	0.1805	0.171
50	0.44	0.51	0.38	0.1805	0.171
90	0.51	0.54	0.40	0.1900	0.18

Table 1: Probe blockage ratios downstream of the guide vane row

PNEUMATIC MULTI-HOLE PROBE

The flow measurements are taken by means of two four-hole wedge probes (stemdiameter 8 mm and 6 mm) and a five-hole cone probe (stemdiameter 8 mm) shown in Fig. 4. The asymmetric shape of the wedge probes in the radial direction matches the special characteristics of the flow in the last stages. The sharp wedge makes it very sensitive to the flow direction and suitable for high Mach numbers. Fig. 4 shows the dimensions of the used probes (d_{probe} = 8 and 6 mm).

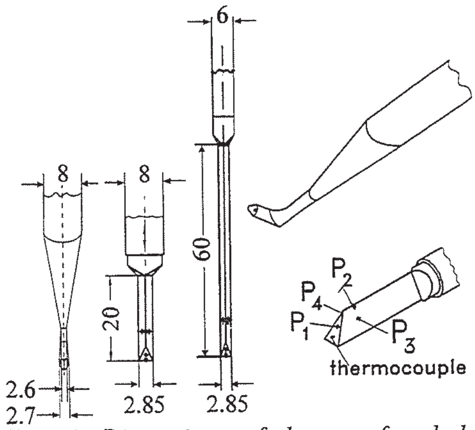

Fig. 4: Dimensions of the two four-hole wedge probes and the five-hole cone probe

EXPERIMENTAL RESULTS

1. Influence of the pneumatic probes on the blade passage flow

Near the 'trailing-edge', the Mach number distribution over the span is between 1.1 and 1.3 at this turbine load. Fig. 5 shows the deviation of the dynamic pressure distribution at the 'trailing-edge' as a function of the circumferential position of the probe. The deviation is calculated as a difference between the measured static pressure minus the undisturbed static pressure at the pressure taps divided by the undisturbed dynamic pressure (stagnation pressure in front of the guide vane minus the static pressure at the 'trailing-edge' static pressure taps). The losses through the blades are not included because the real losses over the span in the turbine are not accurately known. The insertion of the 6 mm wedge probe is at 90% of the span. The location of the probe head is shown in Fig. 5. The traversing is carried out on the non-radial measurement plane.

The used coordinate system is linked to the probe position on the outer casing, as depicted in Fig. 3 and 5. Relative to the coordinate system the location of the 'trailing-edge' static pressure taps varies from hub to tip between 355° and 5°. This variation is caused by the bow of the guide vane and by the changing direction of the flow over the span. It is therefore important to compare the position of the probe regarding the measured wakes in the 'flow channel'. One blade pitch of the guide vane corresponds to 10°.

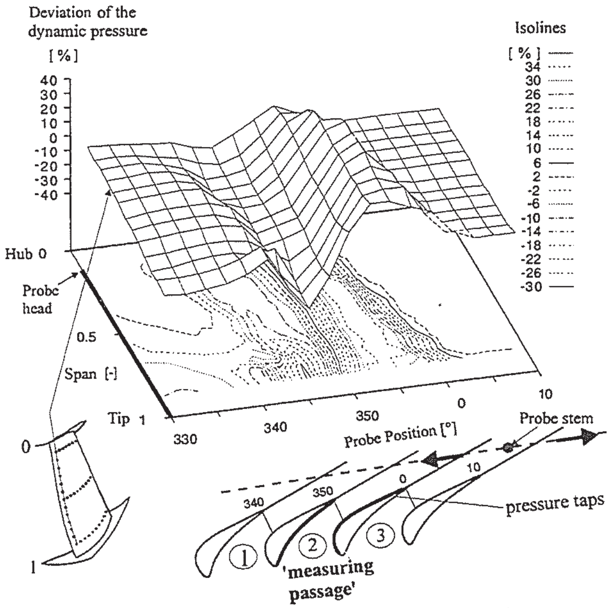

Fig. 5: Pressure deviation at the 'trailing-edge' static pressure taps obtained for different circumferential probe position with the 6 mm diameter non-radially traversed probe inserted at 90% of the span

There is no influence observed on the flow through the passage equipped with static pressure taps, when the probe is positioned in the neighbouring passage 'suction side' in Fig. 5 signed with the number ③ (position greater than 5°). However, when the probe reaches the wakes of the investigated passage named 'measuring passage' (number ②) in Fig. 5, there is a distinctive reduction of the measured dynamic pressure over the whole span visible. This effect results in an increasing deviation over the whole span (Fig. 5). At 90% of the span, the deviation reaches a maximum of 34%. At this point, the probe is located in the middle of the 'measuring passage' (354°) and the probe blockage effect reaches its maximum. If the probe is moved further in the direction of the pressure side of the blade passage ②, the deviation decreases. It reaches a minimum of 30% at 90% span if the probe is moved in the 'flow channel' of the neighbouring passage (① probe position between 340° and 350°).

The blockage of the neighbouring 'flow channel' leads to a strong acceleration of the flow in the blade passage where the pressure taps are installed. The deviation is negative. This result was also found in /4/. The reason for this effect is the different influence of the probe on the 'flow channel'. While the probe is traversing, in the measuring passage (②), the exit area of the nozzle is blocked and the Laval-ratio is getting smaller. This results in a decreasing pressure. If the probe is located in channel ①, the disturbances of the probe interact with the smallest cross section of the Laval nozzle (channel ②). The Laval-ratio increases and therefore the static pressure in the 'measuring passage' decreases.

These results are important for the traversing direction of the probes behind guide vanes. In order to reduce the blockage effects as much as possible, the probe stem should be passed through channel ③. Comparing the results of the radial and non-radial traversing this conclusion is confirmed. Radial mounted probes interfere more strongly with the flow-field even with a smaller blockage area in the investigated channel /11/. The relevant factor is the position of the traversed probe in relation to the 'flow channel'. The reason therefore is the curvature of the guide vanes. For this test set-up, the traversing of the radial mounted probe stem is through channel ①. The non-radial mounted probe stem blocks only the investigated passage or the neighbouring passage ③. Taking these results into account, further investigations concerned only the non-radially probe traversing.

Fig. 6 shows the resulting deviation with the 6 mm wedge probe traversed in 50% span. The diagrams describe the deviation of the static pressure at the different 'trailing-edge' pressure taps. At 90% span there is a deviation discernible up to 33% and over the whole blade pitch (350°-0°), as already shown in Fig. 5. A strong acceleration of the flow is detectable while the probe stem is traversed in the neighbouring passage. The similar curve with decreasing tendency is visible at the next static pressure tap. At 68% span the deviation is further decreasing, because of the transition region between probe stem and probe head. This deviation occurs at 70% of the blade pitch. The two black lines represent the blade pitch. In the height of the probe pressure taps at 50% span the deviation reaches up to 17% of the dynamic pressure. 40% of the blade pitch are affected by the deviation. Traversing the probe in the neighbouring channel there is no recognisable acceleration of the flow-field at this point in the investigated passage. The deviation of the pressure at the further pressure taps is small. At 30% span there is no influence of the probe ascertain on the flow through the guide vanes. Even with that strong reduction of the pressure deviation is in front of the probe head an influence of 17% existent. This interaction between the flow-field and the probe head leads to uncertainty in the pneumatic probe measurement results.

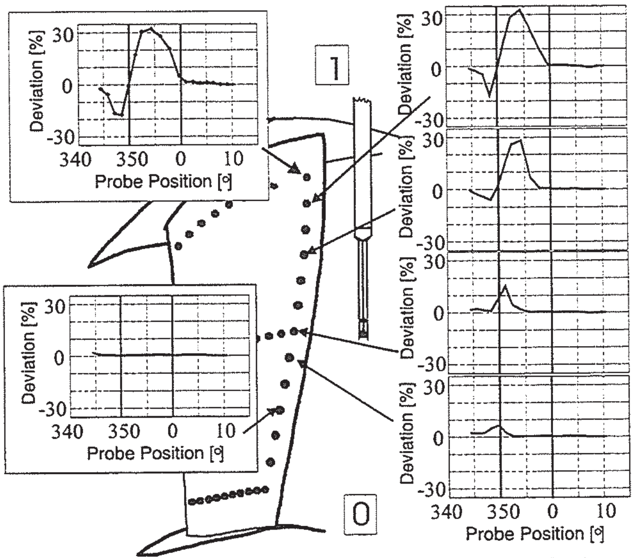

Fig. 6: Pressure deviation at different 'trailing-edge' pressure taps versus the probe position, with the 6 mm non-radially traversed wedge probe inserted at 50% of the span

2. Interaction between the pneumatic probe and the blade passage flow

Fig. 7 shows probe measurement results at 50% span compared to the upstream mounted pressure tap readings. The upper diagram shows the normalised static pressure distribution of the used probes. This is calculated by P_{static} Probe minus undisturbed static pressure at the 'trailing-edge' at 50% span, divided by the dynamic pressure at the undisturbed 'trailing-edge' pressure tap. In the diagram below, the deviation of the pressure at 50% span is visible. The repercussion of the different probe heads and stem-diameters on the flow-field is clearly visible. However, the largest deviation of the dynamic pressure is caused by the wedge probe with the diameter of 8 mm. The maximum reaches 21% and the whole flow passage (white area) is disturbed by the downstream mounted probe. The interference of the five-hole cone probe reaches up to 20% but covers only 60% of the blade pitch. The reason for this is the smaller probe head and the better separation of stem and probe head. The separation between probe head and stem of about 60 mm and the reduced stemdiameter are the main reasons for the smaller interference of the 6 mm wedge probe. The maximum deviation is 15% and the influence is at 40% of the blade pitch visible.

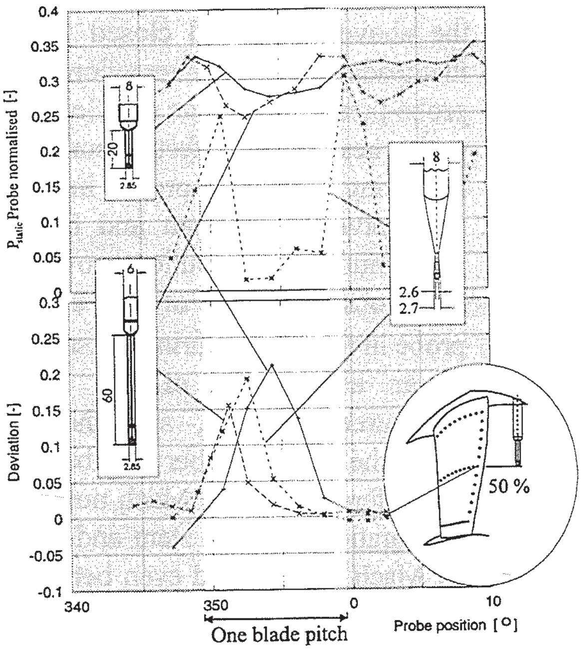

Fig. 7: Comparison of the normalised static pressure of the probe measurement at 50% span with the measured pressure deviation at the upstream mounted 'trailing edge' pressure tap versus probe position

In the upper diagram the results show a huge difference in magnitude of the normalised static pressure between the wedge probes and the cone probe. Comparing the magnitude of static pressure with the realistic value, the results of the wedge probes are more reliable. The curves of the two wedge probes differ only little in the static pressure level. The probe design with the smaller blockage ratio is lower in magnitude. Additionally this probe also can measure the wakes of the guide vanes better than the 8 mm wedge probe. Comparing the measured result with numerical results, the different slopes of the curve measured with the 6 mm wedge probe fit very well. The reasons for this behaviour of the 8 mm wedge probe are rooted in the huge deviation of the flow-field that makes a proper probe measurement impossible. It seems to be that the five-hole cone probe can detect the wakes and the slope of the static pressure, but the pressure level is too low. This result is caused by an acceleration of the flow around the probe head (closed tunnel characteristic) that causes a decrease in the measured static pressure.

3. Probe measurement results

Fig. 8 shows the distributions of the normalised Mach number at the 'trailing edge' static pressure taps (straight line at Ma = 1) and of the pneumatic probe measurement versus span. The traversings of the probes are in radial and non-radial direction. Each symbol on the curves of the probe measurement results represents a linear averaging of 13 circumferentially traversed measurement positions. For the final interpretation it must be taken into account that the behaviour of the fluid between the 'trailing-edge' and the probe head cannot be determined accurately. Furthermore, the axial distance between the position of the probe and the trailing edge of the guide vanes changes over the span, as shown in Table 1. The comparison of the different pneumatic probe heads shows a discrepancy between the wedge probes and the cone probe. The measured Mach number distribution of the cone probe is for both kinds of traversing higher, as already mentioned in Fig. 7. However, comparing the radially and non-radially traversing, the results of the wedge probes show a strong dependency on the kind of traversing, the cone probe seems to be independent by that. The reasons for this result can be found in the symmetric shape of the cone probe head and the better separation between stem and head. Another reason for this behaviour may be the above mentioned closed tunnel effect that leads to a larger interaction between the probe-pressure readings and flow around the probe head. This effect occurs also while traversing the wedge probes in radial direction between mid-span and hub, that the Mach number distribution proves. The bigger blockage effect of the 8 mm wedge probe in the neighbouring passage (①) leads to an acceleration of the flow in the 'measured passage', and therefore to a higher Mach number as the 6 mm wedge probe. The tendency of the Mach number distribution over the span (wedge probes) is the same by identical traversing. The differences in the Mach number by non-radial traversed wedge probes are directly attributed to the separation between stem and head and the smaller blockage area of the 6 mm wedge probe. The higher Mach number and even better agreement with the very static pressure distribution over the span of the 6 mm wedge probe, as already mentioned in Fig. 7, is caused by the probe geometry. The results of the non-radial mounted 6 mm wedge probe shows a decreasing Mach number near the hub. This tendency is even more realistic with the including losses of the boundary layers and the designed features of new last stages of LP-steam turbines. Also the shape of the curve fits best to the normalised Mach number distribution of the 'trailing-edge' pressure taps.

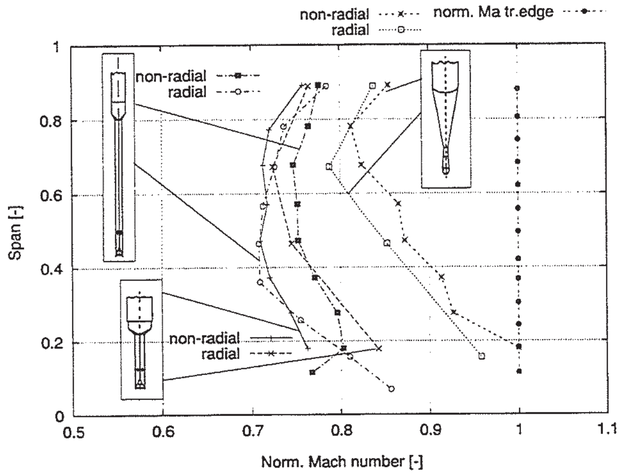

Fig. 8: Normalised Mach number distribution measured by different radially and non-radially traversed probes

SUMMARY

Two wedge probes with various stem diameters and a cone probe are inserted in the flow region downstream of the guide vane passage equipped with pressure measurement taps. Using this test configuration, it is possible to determine the direct influence of the probe on the flow in the guide vane passage. The influence of the blockage effect of the probe and of the stem on the flow around the probe head is shown, by comparing the results with different probes. Finally these differences are discussed, based on the measurement results in the 'flow channel' behind the guide vanes and the probe-pressure readings.
It has been proven that there is a strong influence of the probe on the flow of the guide vane passage. This influence is clearly measurable, even at probe head blockage ratios of less than 0.2. Radially and non-radially probe traversing showed a significant variation in the passage flow /11/ and in the readings of the wedge probes. In a more detailed investigation of the probe head influence on the guide vane passage flow, a significant reduction of the interference between probe and flow was observed due to the changed head design and the smaller stem diameter of the probe. In spite of the new designed 6 mm wedge probe, the difference between the disturbed and undisturbed dynamic pressure in the blade passage could not be reduced below 15% in maximum and the interference reduced below 40% of the blade pitch. The results of the 8 mm cone probe showed great discrepancy to the realistic Mach number distribution.
Due to the curvature of today's guide vane passages, the choice of the probe shape and the probe-measurement-plane inclination has a strong influence on the success of a measurement accuracy. The investigations showed that the probe should be mounted in such a way that the probe stem blocks the ‘suction side’ neighbouring passage (③) rather than the 'pressure side' neighbouring passage (①). This would disrupt the flow measurements considerably less, as shown in Fig. 5. However, the shape of the probe head has a great influence of the measurement results.
Further investigations aim to calculate the influence of the different probes on the flow. In addition, the remaining error factors are to be estimated. Guidelines for probe measurements in turbines are being developed from this investigation's conclusions.

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