

# INFLUENCE OF SURFACE ROUGHNESS ON THE FLOWRATE BEHAVIOUR OF SMALL CRITICAL VENTURI NOZZLES

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*Abstract: The paper describes the results of experiments carried out with a set of 50 critical Venturi nozzles with diameters between 0.15 mm and 10 mm with special emphasis on small nozzles with diameters of less than 1 mm. All nozzles were shaped in accordance with the current ISO Standard 9300 [1], only the quality of surface finish having average roughness heights between 0.1  $\mu\text{m}$  and 1  $\mu\text{m}$  differed from the requirements of this standard.*

*The present investigations contain the determination of common relations used to characterize critical flow through Venturi nozzles and their dependence on surface quality. The paper also offers photographs of different inner nozzle surfaces and the results of mechanical throat scans of larger nozzles as well as the results of computational simulations of flow characteristics through a nozzle with comparable imitated surface perturbation.*

*All results of the investigations come to the same conclusion: No systematic or significant difference between the flowrate behaviour of small critical Venturi nozzles could be found when the surface roughness was changed between 0.1  $\mu\text{m}$  and 1  $\mu\text{m}$  (this range of surface roughness corresponds to the usual manufacturing surface qualities, from common lathe finish to well polished surface). Therefore, critical nozzles can be used without changes in their flowrate behaviour even in cases where the requirements of the valid standards [1,2] can not be strictly met.*

*Keywords: Critical Venturi nozzle, ISO standard 9300, discharge coefficient, critical pressure ratio, nozzle surface, CFD*

## 1 INTRODUCTION

The metrological application of critical Venturi nozzles extends increasingly to small flowrates and, therefore, small Reynolds numbers of less than 100,000, the minimum Reynolds number permitted by the still valid ISO standard 9300 [1] and the equivalent European and German standards DIN EN ISO 9300 [2].

In Germany, critical Venturi nozzles are already in use in legal metrology for flowrates down to few liters per hour (for instance for the  $Q_{\text{min}}$ -verification of diaphragm household gasmeters). Moreover, there is also a great demand for reliable and stable measuring techniques of small flowrates in the fields of medical applications, chemical and environmental analytics, or safety technologies. To realize such small flowrates, the required nozzles must have diameters much less than 1 mm, and the corresponding Reynolds numbers are found to be +several orders below the minimum of the ISO standard mentioned above.

The special requirements for an application of critical nozzles for legal measurement are layed down in a new PTB document [3], including also some the peculiarities of use of small critical nozzles. In this document, the minimum range of application was determined by the minimum gasmeter size to be proofed: A household gasmeter G 2.5, for instance, has a minimum verification flowrate of 25  $\text{dm}^3/\text{h}$ . For air at atmospheric conditions commonly used for the verification of such a meter, the required critical nozzle should have a diameter of 0.215 mm and the corresponding Reynolds number amounts to about 2.730.

Although practical experience with small critical nozzles already demonstrated their good suitabi-

lity as transfer and calibration standards, there is still a significant demand to investigate the real flow phenomena in more detail in order to understand it. In the case of small Reynolds numbers, boundary layer thickness increases relativ to the throat diameter, with flow rate changes in the nozzle to be expected.

For this reason, the present experiments were carried out to provide support for the satisfactory results obtained in the practical (industrial) gas meter calibration by corresponding theoretical treatment and numerical flow simulations. The PTB undertook an extensive investigation of small critical nozzles in a Reynolds number range below the minimum of 100,000 fixed by the current ISO standard 9300 [1]. University of Essen supported the main experimental data by complementary flow simulations using CFD code called ACHIEVE.

One of the crucial points of the present research program dealt with investigation of influence of the flow-channel's surface finish (surface roughness) since the corresponding requirements of the ISO standard 9300 can not be carried over to nozzles with diameters of only a few millimeters or even smaller due to, among other issues, manufacturing problems.

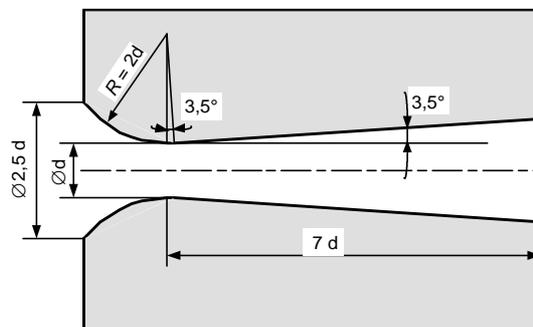
## 2 EXPERIMENTAL SETUP

*Critical nozzles to be investigated:*

In regarding to the shape of the inner contour, the critical nozzles were manufactured as recommended by the ISO standard 9300 – a convergent inlet with a radius of curvature of  $2 d$  ( $d$  - diameter of nozzle throat) is followed by a thoroidal throat and a divergent part (diffusor) of  $7 d$  length with a divergence wall angle of  $3.5$  deg. Only the quality of surface finish of the flow channel differed from the requirements of the ISO standard. To investigate the influence of different surface qualities on the main flowrate characteristics of the nozzles, their inner flow channels were manufactured with average roughness hights  $R_a$  between  $0.1 \mu\text{m}$  (well polished surface) and  $1 \mu\text{m}$  (common lathe without any special finish). This roughness range corresponds to the usual manufacturing surface qualities.

The minimum nozzle diameter used was  $0.15 \text{ mm}$ , the minimum flowrate amounted to about  $10 \text{ dm}^3/\text{h}$ . The Reynolds numbers realized covered an overall range from  $1,400$  till  $140,000$  including a wide region overlapping the present field of application of critical nozzles to give a reliable transition to the known standards.

Figure 1 shows the inner contour, Table 1 gives number and nominal throat diameter of all nozzles investigated within the framework of the current experimental program.



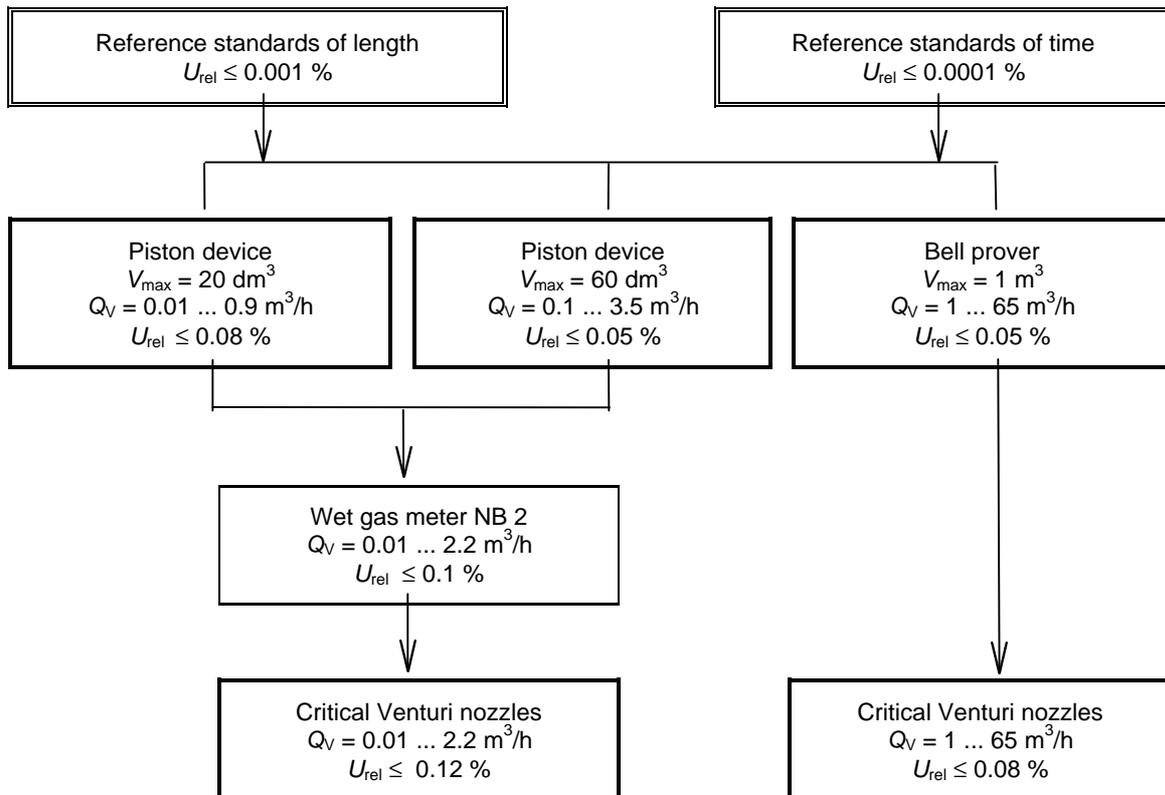
**Figure 1.** Inner contour of the nozzles investigated (confirming ISO standard 9300 [1])

*Standard facilities used for the flowrate measurements:*

All effects and dependencies of the nozzle characteristics were determined measuring the respective changes in actual flowrate realized under the specific conditions to be investigated. To get these effects with high accuracy and reliability, the primary volume and flowrate standards of PTB were used – a bell prover [4,5] with a volume capacity of about  $1 \text{ m}^3$  and an expanded uncertainty of  $0.05 \%$  for flowrates between  $1 \text{ m}^3/\text{h}$  and  $65 \text{ m}^3/\text{h}$ , and two piston devices [6] for the small flowrates down to  $10 \text{ dm}^3/\text{h}$ . Figure 2 gives an overview of these standard facilities, their main parameters and expanded uncertainties  $U_{\text{rel}}$  ( $k = 2$ ) calculated in accordance with the international ISO Guide to the expression of uncertainty [7]. As shown in this figure, the flowrates of the small nozzles could be measured only with the help of an intermediate wet gas meter because the piston devices are not able to generate the high pressure drop to realize critical flow through the nozzles.

**Table 1.** Number and nominal throat diameter of the nozzles investigated

Nominal throat diameter in mm	Number of nozzles		
	surface well polished $R_a = 0.1 \mu\text{m}$	surface polished $R_a = 0.4 \mu\text{m}$	surface common lathe $R_a = 1.0 \mu\text{m}$
0.15	8	1	1
0.20	9	1	1
0.25	2	1	1
0.30	2	1	1
0.40	1		
0.50	2	1	1
0.60	1		
0.80	1		
1.0	1		
2.0	1		
3.0	1		
4.0	1		
5.0	1	1	1
6.0	1		
7.5	1	1	1
10.0	1	1	1



**Figure 2.** The PTB's standards for gas volume and flowrate measurement used for investigation of flowrate behaviour of small critical Venturi nozzles

In this way, an expanded uncertainty of better than 0.12 % for flowrates less than 1 m<sup>3</sup>/h and better than 0.08 % for the larger ones was achievable. The reproducibility of all flowrate measurements could be kept within 0,03 % or better.

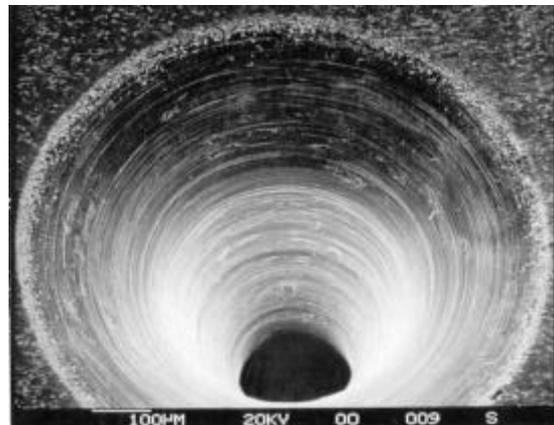
### 3 INVESTIGATION OF THE INNER FLOW CHANNEL OF THE NOZZLES

As already mentioned, the extremely high specifications of the valid standards concerning surface quality of the inner flow channel can not be realized for such small nozzle geometries as investigated in the current experiments. The best commonly practicable surface finish of the inner nozzle contour is the so-called well polished quality with an average roughness height  $R_a$  of about 0,1  $\mu\text{m}$ . For this case, a surface with  $R_a \leq 15 \cdot 10^{-6} d$  as required by the valid ISO standard 9300 could be achieved only for nozzles with throat diameters  $d$  greater than about 6.7 mm. For all smaller diameters, the nozzles already used in metrological (industrial) practice do not have surface qualities fulfilling ISO standard 9300.

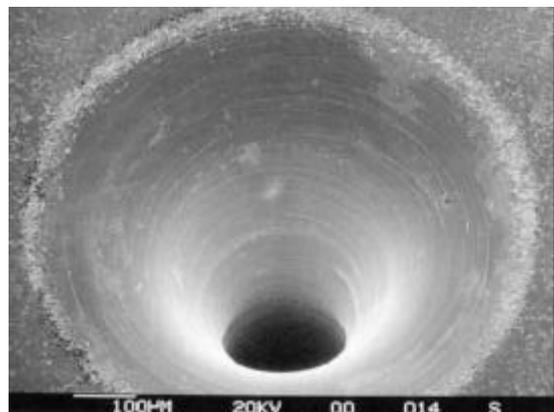
But the problem covers not only the manufacturing of the nozzles. In like manner, there do not exist suitable methods to proof the compliance of such strong requirements by direct measurements when the small nozzle geometry does not allow a mechanical access to the inner flow channel this is important especially for nozzles with throat diameters less than 1 mm. That's why the geometrical parameters of these small nozzles could be investigated only by contactless „remote“ methods – for the actual investigations, the throat diameters were determined by a special light microscope and the surface quality was estimated using photographs of a scanning electron microscope.

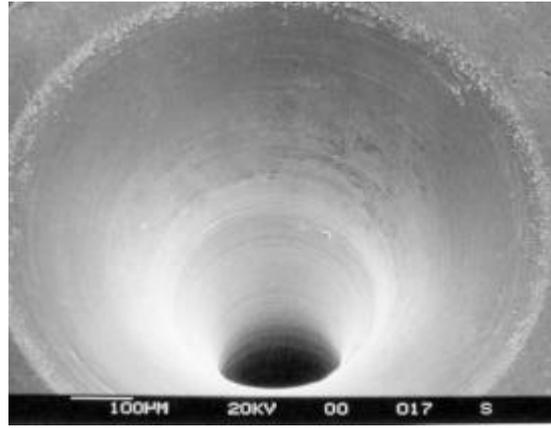
Figures 3-1 through 3-3 show a selection of photographs for three nozzles with the same throat diameter  $d$  of 0.2 mm, but different surface finish. It can be seen that the inner nozzle surface is dominated by the groove structure due to manufacturing, slowly disappearing at the following stages of finish. The entire series of pictures made by electron microscope contains all nozzles with throat diameters  $d \leq 0.5$  mm at several levels of enlargement between 1 : 100 and 1 : 2,500 (see also [8]). Although these photographs allow only a qualitative estimation of the geometrical surface parameters, they confirm the data used, for instance, for the average roughness heights.

**Figure 3-1.**  
Photograph of the inner surface of a toroidal Venturi nozzle with  $d = 0.2$  mm.  
Surface common lathe ( $R_a = 1 \mu\text{m}$ ).



**Figure 3-2.**  
Photograph of the inner surface of a toroidal Venturi nozzle with  $d = 0.2$  mm.  
Surface polished ( $R_a = 0.4 \mu\text{m}$ ).





**Figure 3-3.**  
Photograph of the inner surface of a toroidal Venturi nozzle with  $d = 0.2$  mm. Surface well polished ( $R_a = 0.1$   $\mu\text{m}$ ).

However, to get also some quantitative data describing the inner flow channel surface, a second set of nozzles was manufactured by using exactly the same machining technology to get the same surface quality. Only the throat diameters were chosen to be larger ( $d$  between 5 mm and 10 mm) to allow the application of mechanical methods for scanning the inner surface. For each nozzle size, again, three surface qualities were made – common lathe, polished and well polished surface finish (compare Table 1).

Some of the concrete mechanical throat scans of these larger nozzles are shown in Figures 4-1 through 4-3 for the 5-mm-nozzles and in Figures 5-1 through 5-3 for the 7.5-mm-nozzles. Each scan consists of 500 individual measurements per circumference. Based on these data, the average diameter as well as the deviation from roundness of each nozzle could be calculated. The respective values are also listed in Figures 4 and 5.

The scans show an interesting result: A subsequent finish of the flow channel surface can lead to serious changes in the surface shape as described, for example, by the picture series 4 for the 5-mm-nozzles. In this case, the nozzle with well polished surface got a deviation from roundness of more than 10  $\mu\text{m}$ . On one side, such a uncontrollable deviation seriously affects the flow behaviour in the throat region of the nozzles, on the other side, the uncertainty of diameter determination increases extremely. Therefore, there exists a certain danger to change the inner flow channel contour persistently when the surface is subject to a subsequent finishing to improve its quality.

Figure-series 5 shows another picture – in this case the subsequent polishing of the flow channel indeed improved the surface quality as well as the throat shape what is documented by the decreasing values for the deviation from roundness.

So, again the question arises: which influence has the surface roughness on the flowrate behaviour of (small) critical nozzles really? Is it necessary to meet the strong requirements of ISO 9300 or is it maybe more reliable to neglect these requirements, at least when the nozzles are manufactured and applied in large quantities and for a wide industrial use.

#### 4 INVESTIGATION OF THE MAIN FLOWRATE CHARACTERISTICS

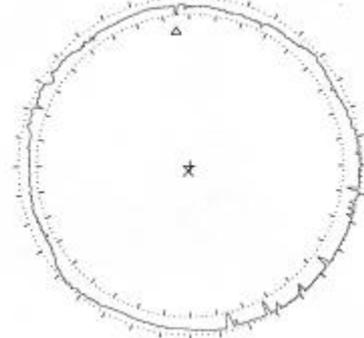
The main part of the investigations was, of course, directed to the flow characteristics of the nozzles. The respective experiments started with the determination of the dependency of the nozzle's discharge coefficient  $c_d$  on the Reynolds number  $Re_d$ .

Altogether, about 800 single measurements at more than 200 different measuring conditions were made to get this dependency  $c_d = f(Re_d)$  a part of which is shown in Figure 6 for the Reynolds number range between 1,000 and 10,000. This picture contains the experimental results for nozzles with throat diameters between 0.15 mm and 0.5 mm (compare Table 1). Each point is the mean of several measurements (3-5) at nearly identical conditions. The different surface qualities of the nozzles investigated are marked by different symbols – the black symbols characterize the results of nozzles with a surface not especially finished (normal lathe), the white symbols the slightly polished surfaces, and the coloured symbols the well polished surfaces.

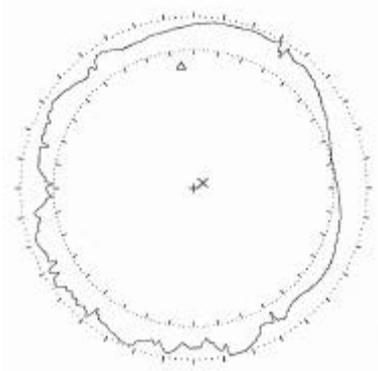
Scale: — 5.0  $\mu\text{m}$



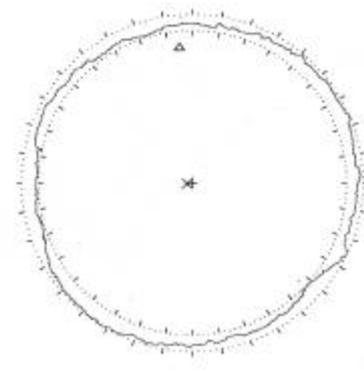
**Figure 4-1.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 5$  mm. Surface common lathe. Average throat diameter 4.974 mm. Deviation from roundness 2.60  $\mu\text{m}$ .



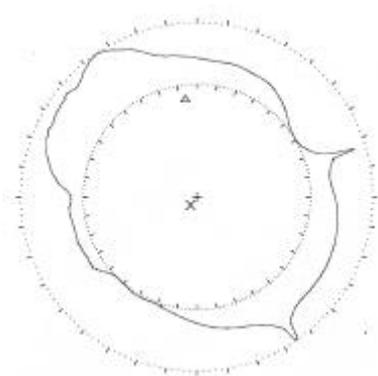
**Figure 5-1.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 7.5$  mm. Surface common lathe. Average throat diameter 7.465 mm. Deviation from roundness 2.73  $\mu\text{m}$ .



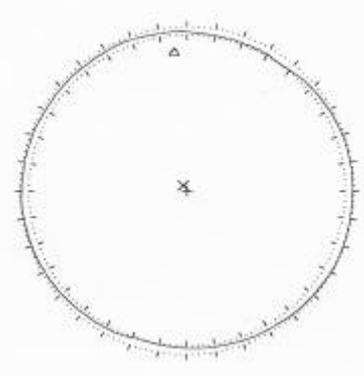
**Figure 4-2.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 5$  mm. Surface polished. Average throat diameter 5.058 mm. Deviation from roundness 5.27  $\mu\text{m}$ .



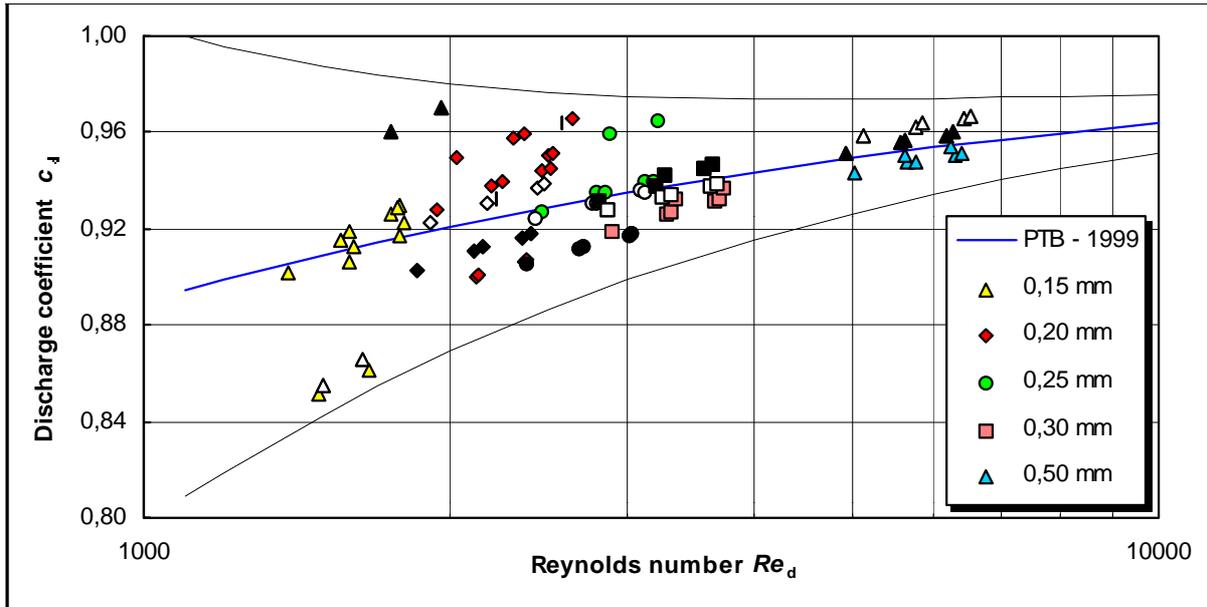
**Figure 5-2.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 7.5$  mm. Surface polished. Average throat diameter 7.540 mm. Deviation from roundness 2.51  $\mu\text{m}$ .



**Figure 4-3.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 5$  mm. Surface well polished. Average throat diameter 5.069 mm. Deviation from roundness 10.68  $\mu\text{m}$ .

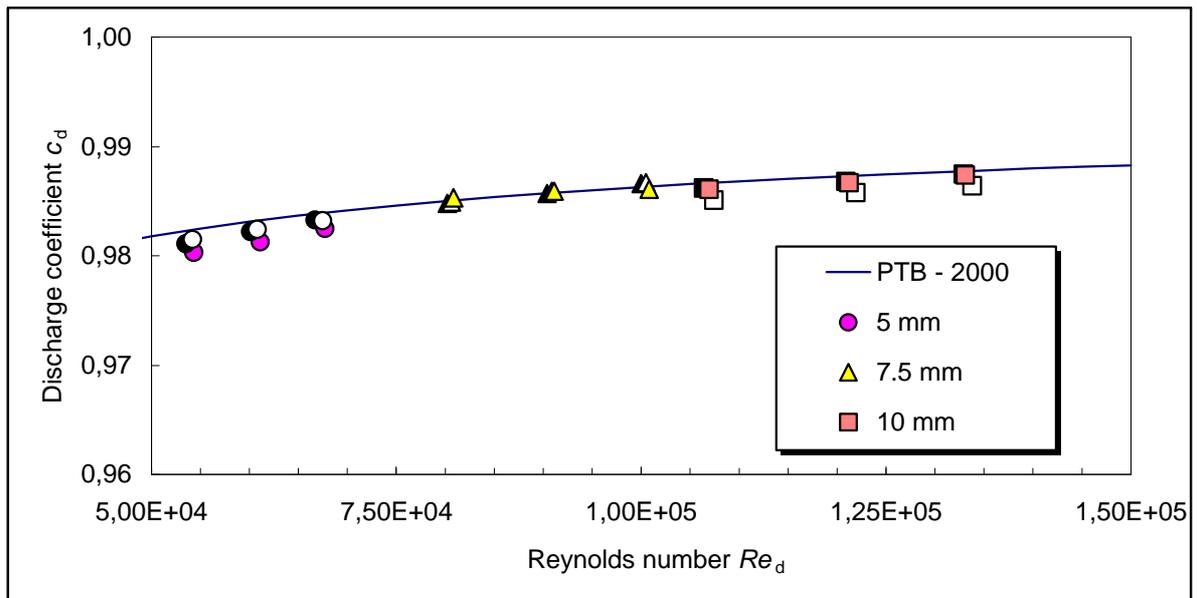


**Figure 5-3.**  
Mechanical throat scan of a toroidal Venturi nozzle with  $d = 7.5$  mm. Surface well polished. Average throat diameter 7.570 mm. Deviation from roundness 1.27  $\mu\text{m}$ .



**Figure 6:** Discharge coefficient  $c_d$  of small critical nozzles with diameters between 0,15 mm and 0,5 mm and different surface finish as a function of the Reynolds number  $Re_d$ .  
 The black symbols mark the measuring results of nozzles with a surface not especially finished (normal lathe), the white symbols – slightly polished surfaces, the coloured symbols – well polished surfaces.  
 The solid line characterizes the average  $c_d$ -curve of all nozzles used at PTB, the dashed line – the range of its uncertainty due to the uncertainty of diameter measurement of 10  $\mu$ m.

The same picture was obtained for the larger nozzles with diameters between 5 mm and 10 mm as shown in Figure 7.



**Figure 7.** Discharge coefficient  $c_d$  of critical nozzles with throat diameters between 5 mm and 10 mm and different surface finish as a function of the Reynolds number  $Re_d$ .

(For explanation of the symbols see Figure 6)

The main conclusion of these diagrams of Figures 6 and 7 is that there can not be found any systematic or significant difference between the flowrate behaviour of the critical Venturi nozzles investigated when the surface roughness was changed between the different qualities of average roughness heights between 0.1 µm and 1.0 µm

## 5 COMPARISON WITH THE RESULTS OF OTHER AUTHORS

The graphs in Figures 6 and 7 also contain the respective parts of the mean curve for  $c_d = f(Re_d)$  called „PTB – 2000“ and determined for all critical nozzles used and investigated at PTB covering the Reynolds number range until 1,000,000. The corresponding equation describing this curve is

$$c_d = 0.9982 - \frac{3.448}{\sqrt{Re_d}}$$

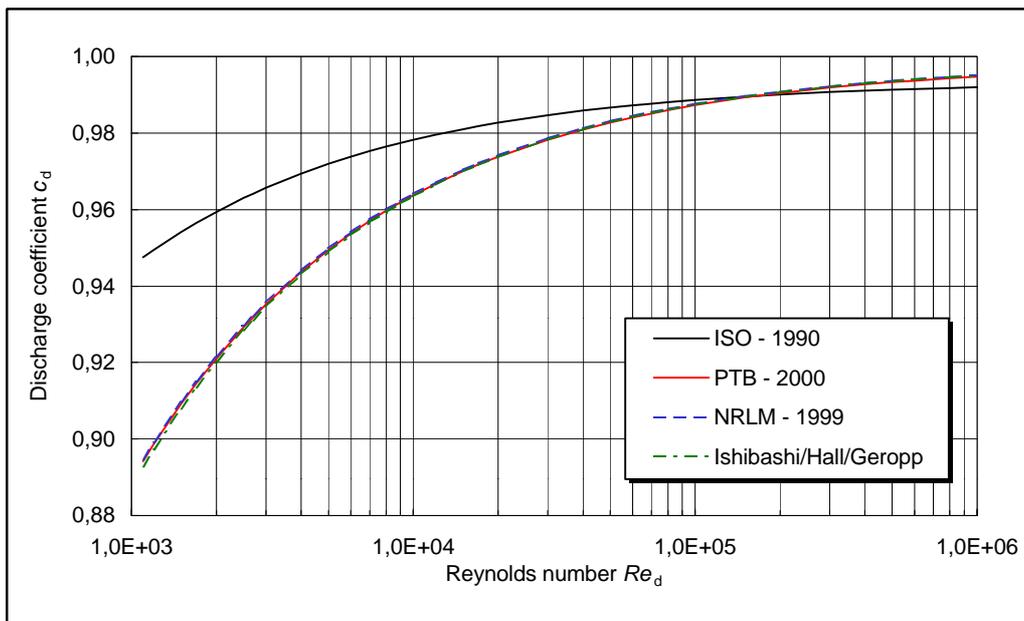
Figure 8 presents a comparison of this  $c_d$ -curve (which can be applied for all surface qualities in the roughness range investigated) with the function currently recommended by the valid ISO standard 9300 and with actual results of some other authors for the whole Reynolds number range between 1,000 and 1,000,000. The coefficients for the respective equations used for all applications in the form of

$$c_d = a - \frac{b}{\sqrt{Re_d}}$$

are shown in the following Table 2.

**Table 2.** Coefficients for the dependence  $c_d = f(Re_d)$  determined by several authors and sources

Author/Source	Coefficient <i>a</i>	Coefficient <i>b</i>
ISO – 1990 [1,2]	0.9935	1.525
PTB – 2000 [8]	0.9982	3.448
NRLM – 1999 [9,10]	0.9986	3.447
Ishibashi/Hall/Geropp [10]	0.99859	3.517



**Figure 8.** Comparison of the mean  $c_d$ -curve of PTB with actual results of other authors and sources

Although the equations shown are partly valid for different Reynolds number ranges, there is an excellent agreement between the curves of PTB, NRLM and a theoretical dependency obtained by Ishibashi [10] on the base of some older publications of Hall [11] (calculation of two-dimensional inviscid core flow field of the nozzle) and Geropp [12] (laminar boundary layer condition). It should be noted that both PTB and NRLM determined their dependencies experimentally, but at clearly different conditions:

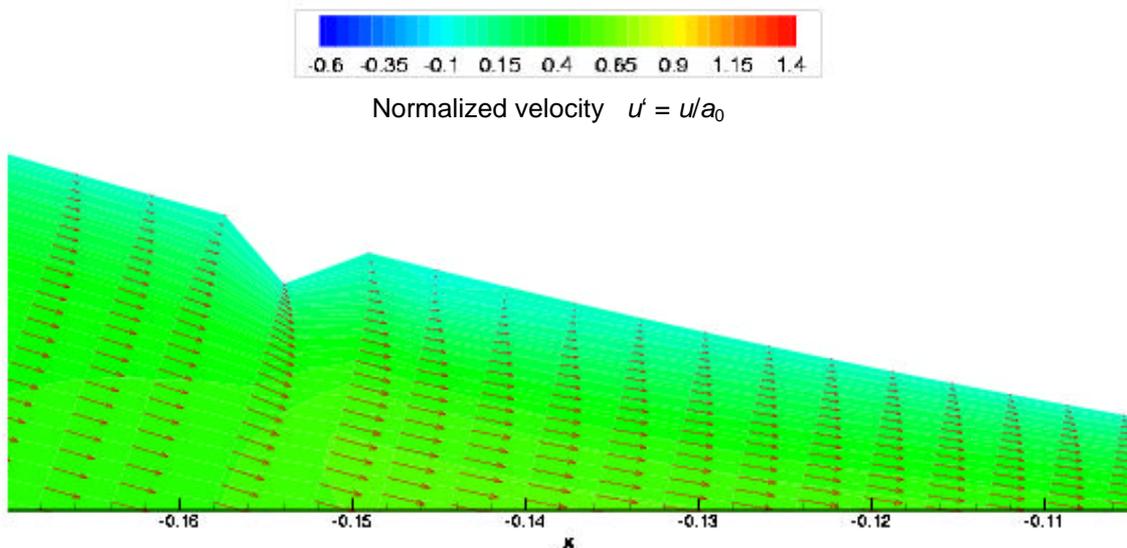
- PTB used nozzles of different surface qualities with average roughness heights between  $0.1 \mu\text{m}$  and  $1.0 \mu\text{m}$  mostly at atmospheric inlet conditions. The stagnation pressure changed at maximum between 820 mbar and 1020 mbar. The minimum nozzle diameter was 0.15 mm. The uncertainty of diameter determination amounts to about  $10 \mu\text{m}$  - for the small nozzles with  $d \leq 1 \text{ mm}$  because of the impossibility to use precise mechanical methods, for the larger ones partly because of changes of the throat shape due to a subsequent polishing of the flow channel.
- NRLM used so-called super-accurate nozzles with an average surface roughness less than  $0.03 \mu\text{m}$  and a machining error of usually less than  $\pm 1 \mu\text{m}$ . The minimum nozzle diameter was 3.4 mm. The Reynolds number range was realized by changing the stagnation pressures in a wide range.

On the other side it should be noted that all actual curves differ obviously from the current ISO-curve – not only in the range of small Reynolds numbers less than 100,000 where the standard is not valid (but is partly used for extrapolation). There are also discrepancies for the higher „valid“ Reynolds numbers where the curves cross and the differences change their sign.

## 6 NUMERICAL SIMULATION OF THE NOZZLE FLOWFIELD

To explain and support the experimental results, several numerical simulations were carried out. More detailed information can be found in [8,13]. Figure 9 shows only an example of a simulated velocity flow field in the vicinity of an imitated surface perturbation. The perturbation is located in the inlet of a toroidal Venturi nozzle with a throat diameter of 0.3 mm at a distance of about  $0.5 d$  before the throat. Its extension of  $6 \mu\text{m} \times 3 \mu\text{m}$  is much larger than the perturbations expected for a usual manufacturing surface.

Although the stream lines concentrate near the perturbation, they flow around the peak nearly undisturbed. Already at a distance of three times as much as the perturbation height, nearly no influence of the perturbation can be recognized.



**Figure 9.** Velocity flowfield in a critical Venturi nozzle of 0.3 mm throat diameter in the surrounding of a surface perturbation – strongly enlarged detail.

- Extension of the perturbation: Height x width:  $3 \mu\text{m} \times 6 \mu\text{m}$ .
- Length of the detail shown:  $65 \mu\text{m}$ .
- Distance to the nozzle throat:  $155 \mu\text{m}$ .

## 7 CONCLUSION

All results of the experimental as well as the numerical investigations show the same result: For usual manufacturing surface qualities with average roughness heights  $R_a \leq 1 \mu\text{m}$ , there could not be found any significant differences between the flowrate behaviour of the various critical Venturi nozzles. Therefore, critical nozzles can be used without any changes maintaining their characteristic flowrate even in cases when the requirements of the valid standards can not be strictly met. This is of particular importance especially for small nozzle geometries with throat diameters of only a few millimeters or less. Small critical Venturi nozzles of these sizes still possess the same advantages as the already established large ones.

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