ISSN:1687-1006

The Egyptian International Journal of Engineering Sciences and Technology

Vol. 26 (2018) 01–13

http://www.eijest.zu.edu.eg

Calibration Nozzle Performance-State of The Art

Mohammed R.Shaalan[a],Fatma A-M. Kassem[b] ,SaeedA.Ahmad[a],RehamS.Hagazy[c]

[a]Faculty of Engineering, Zagazig University, EGYPT
[b]Volume and Fluid Flow Metrology Laboratory,National Institute of Standards, Giza, EGYPT
[c] Force and Material Metrology Laboratory, National Institute of Standards, Giza ,EGYPT

ARTICLE INFO

Article history:
Received 1st Feb.,2018
Received in revised form 25th October 2018
Accepted 31st Oct.,2018
Available online: 15th November 2018

Keywords:
sonic nozzle
calibration
performance
characteristics

ABSTRACT

There has been deep interest by research workers in the metrology scope of sonic nozzle as measuring devices in certain engineering systems (e.g. calibration of gas flow meters, compressor discharge capacity testing and calibration of turbine engine gas passage). The main emphasis has been on how to enhance the accurate measurement of mass flow rate from such devices. Sonic nozzle one obvious solution in this case. Due to simple structure, high accuracy and stable performance.This paper gives an over view of up-to-date published research in the performance and characteristics of sonic nozzles used for calibrating gas flow meters. Some articles were reviewed and examined, covering various aspects of the subject, including the main illustrations and prominent results. The reviewed articles include those concentrating either on experimental, on numerical simulation, on theoretical investigation, or on combination. From discussion of articles there exist a great dependence on body temperature and geometry of sonic nozzle to get more accuratemeasurements .Beside that the back pressure effects on mass flow rate and normal shock in sonic nozzles used in calibration facilities should have more interest of study.Also there is still some room for further work, such as development the effect of geometry and kind of gases on discharge coefficient with deeper insight, to be carried out.

1. Introduction

The construction and testing of a facility incorporating a sonic nozzle as calibration device has attracted the interest of many researchers in the last two decades or so. Search in relevant literature indicates that works published in this respect may be classified into four distinct categories as follows:

(a) Experimental work
(b) Numerical simulation work
(c) Theoretical work
(d) Mixed work

In each of the above categories, emphasis has been on the characteristics and performance of the calibration device Fig (1)(sonic nozzle). Varying inlet conditions, area ratio, wall condition, and type of gashave been examined for their effects on the nozzle performance, particularly the nozzle discharge coefficient. In the following sections of the paper, summaries of published articles will be given, including a brief description ofthe test facility. Illustrations as appearing in eachreviewed paper will also be included for increasing the knowledge of the reader.

1.1. Definitions

Primary system:

The system that depends on the basic units in themeasurement process such as (Mass, Time, LengthandTemperature).

---

* Corresponding author: Tel: 01113952327
E-mail Address: Fatmakassem5@gmail.com

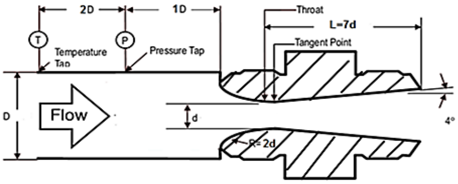

Fig.1.Longitudinal section through atypical sonic nozzle ISO9300 [18]

Transfer (Secondary) system:

The system that depends on the derived units in the measurement process such as (Area, Volume, Pressure and Velocity).

Standard uncertainty (u_x):

Estimation of the standard uncertainty of each input quantity of measurement process.

Combined standard uncertainty (u_c):

Standard measurement uncertainty that is obtained using the individual standard measurement uncertainties associated with the input quantities in a measurement model.

Expanded uncertainty (U):

Product of a combined standard measurement uncertainty multiplied by coverage factor.See table(1) explain the coverage factor at each confidence level.

$$U = k\times u_c$$

Table 1.Coverage factor versus coverage probability [40].

Coverage factor (k)	Coverage probability(p)
1.00	**68.27%**
1.65	**90%**
1.96	**95%**
2.00	**95.45%**
2.58	**99%**
3.00	**99.73%**

Traceability according to SIUnits:

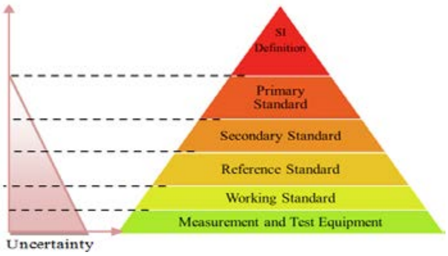

Fig.2. Pyramid traceability system withuncertainty [23].

Traceability is the chain of calibration, genealogy that establishes the value of a standard or measurement (see fig (2)).

Nomenclature

A	Area	m^2
a	Speed of sound	m/sec
C^*	Critical flow factor	-
C_d	Discharge coefficient	-
d	Throat diameter	m
f	Frequency of the unsteady flow	Hz
k	Coverage factor	-
L	Divergent length	m
l	Characteristic length	m
P	Pressure	pa
q_m	Mass flow rate	kg/sec
R	Gas constant	kj/kg.K
R_c	Radius of curvature at nozzle throat	m
Re_{th}	Reynolds number = $\rho\ v\ d/\mu_o$	-
T	Temperature	K
t	Time	sec
U	Expanded uncertainty	-
u_c	Combined standard uncertainty	-
u_x	Standard uncertainty	-
v	Air velocity	m/sec
xv	Water-Vapor mole fraction	-

Greek symbols

ρ	Density	kg/m^3
θ	Divergent angle	deg
μ_o	Dynamic viscosity at total conditions	Pa.s
γ	Specific heat ratio	-

Subscripts

b	Back condition
cr	Critical condition
m	Real mass flow
o	Stagnation condition
ref	Reference temperature
th	Throat

Abbreviations

NMIA	National Measurement Institute, Australia
KRISS	Korea Research Institute of Standard and Science
NIM	National Institute of Metrology, China
PTB	National Institute in Germany
PVTt	Pressure, Volume, Temperature and time
NIST	National Institute for Standard and Technology

1. Review of Published Works

1.1. Experimental Works

Park[3] (1995) investigated experimentally change coefficient of critical nozzles with upstream stagnation pressure by using a gravitational weighing system at KRISS. The calibration uncertainty of critical nozzle of 8mm throat diameter was about±0.08% and ±0.14% at upstream stagnation pressure 4Mpa and 1Mpa respectively.

Nakao et al [4] (1996) developed experimentally a calibration facilityas shown in fig(3) for a sonic nozzle based on the gravimetric method by using weight balance to calculatethe mass flow rate by accumulation the final mass minus initial mass with time .For small mass flow rates of gas up to about 5 g/min the authors show that the combined standard uncertainty for the primary system is ±0.105% while combined standard uncertainty for the transfer system is ±0.112% for a large sonic nozzle and ±0.089% for a smaller one.

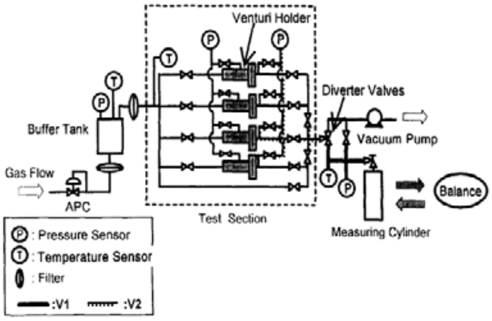

Fig.3.Schematic diagram of the calibration facility for small mass flow rate.(Nakao et al[4])

Choi et al [5] (1998) developed experimental study of the interface between seven bank toroidal sonic nozzles with throat diameter 4.3mm on discharge coefficient of measurement uncertainty(fig (4)).

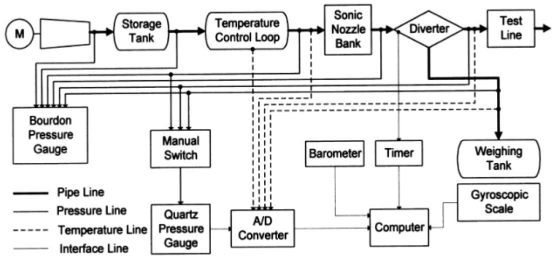

Fig.4.Layout of data acquisition and pressure monitoring system (Choi et al [5]).

The sonic nozzles were calibrated by primary system gas flow standard at KRISS within uncertainty ±0.25% at the stagnation pressure range from 0.5 to 2Mpa and throat Reynolds number range from 0.4×10^6 to 1.2×10^6. The results show that the average uncertainty from bank sonic nozzle measurement is ±0.05 % (fig (5)).

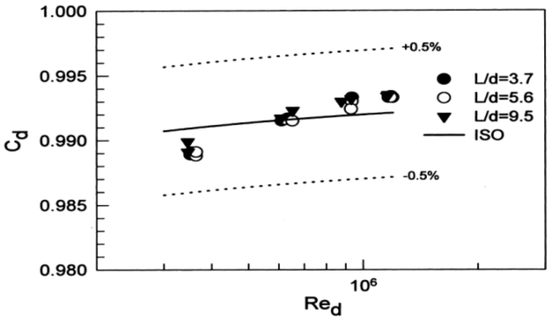

Fig. 5. Calibration data of the sonic nozzle bank for L/d=3.7, 5.6 and 9.5, (Choi et al [5]).

Choi et al [6](1999), investigated experimentally the effect of interference of sonic nozzles of different throat diameters on discharge coefficient of the same meter tube Fig (6). Super accurate sonic nozzles with three different throat diameters (4.3, 8.1, and 13.4 mm) were tested in a single meter tube. The discharge coefficient as functionofReynolds number and the uncertainties of the three nozzles were given in the table (2):

Table 2.Discharge coefficient and Uncertainty versus throat diameter obtained from the test facility used by Choi et al[6].

d	C_d	U
4.3	$C_d = 0.99702 - 4.1645/Re_d^{0.5}$	± 0.00081
8.1	$C_d = 0.99575 - 3.7026/Re_d^{0.5}$	± 0.00068
13.4	$C_d = 0.99662 - 6.0004/Re_d^{0.5}$	± 0.00063

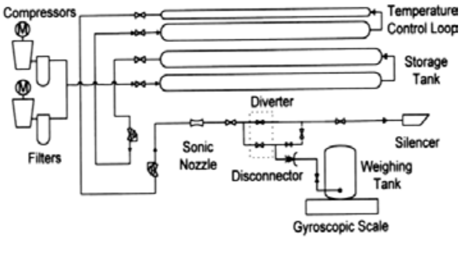

Fig.6. Schematic diagram of primary gas flow standard facility for KRISS (Choi et al [6] andPaik et al [10]).

Bignell[13] (2000) studied the case of using a sonic nozzlefig(7) as a secondary system to measure the gas flow rate by the volumetric method and calibrated by a standard system (primary system) for the effect of change in pressure, temperature and humidity. It should be taken into account when calculating the nozzle coefficient. The results showed that the inlet pressure affected the coefficient of sonic nozzle owing to change in the boundary layer thickness at throat, while the humidity effect on the density of air flow and specific heats is due to the contentof water vapor. These effects are important due to their direct effect on the coefficient ofthe sonic nozzle.

Paik et al [10] (2000) made two inter-laboratory comparisons of the discharge coefficient (C_d) for sonic nozzle at KRISS which has primary flow facility fig (6). The first comparison is the North American of the NOVA 10mm throat diameter nozzle. Agreement in deviation was within±0.2% of the mean of all laboratories. The second is inter-comparison of ISO 9300 toroidal throat ford nozzle. The ford nozzle package was calibrated against a KRISS master nozzle which has ±0.17% uncertainty at 0.74 MPa at medium and high Reynolds numbers .In this comparison values were near or below the ISO 9300 equation and deviation did not exceed 0.2% for KRISS results. Finally, the study indicated that the uncertainty of the primary gas flow standard facility of each laboratory was less than ±0.2%.

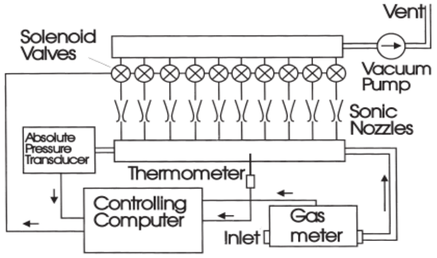

Fig.7. Schematic diagram for using sonic nozzle array to calibration gas meter(Bignell [13]).

Nakao and Takamoto[14] (2000) carried out an experimental investigation of the choking phenomena of sonic nozzles at the different Reynolds numbers ranging from 40 to 30 000 with nitrogen gas as the working fluidFig (8). Their results showed that the critical back pressure ratio has a relation to Reynolds number only. In ISO-type toroidal-throat convergent divergent nozzles, the lowest Reynolds number for achieving the choking condition was about 40 and the critical back pressure ratio was only about 0.05 at this Reynolds number. They concluded that the critical back pressure ratio had a topical minimum value around $Re_{th}=4\times 10^3$ and that the topical maximum value was about $Re_{th}=10^4$, the difference being due to the change in characteristics of the boundary layer in the divergent section of the nozzle.

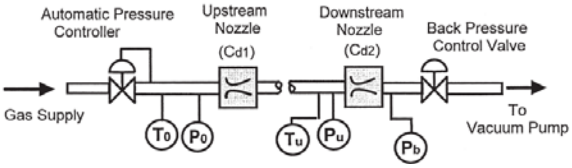

Fig.(8): Arrangement of sonic nozzlesin experimental test rig byNakao and Takamoto [14].

Hayakawa et al [12] (2000) developed an experimental sonic nozzle facility Fig (9) to calibrate a flow meter with a small flow rate (q) ranging from 10 mg/min to 100 g/min, using different diameter nozzles. They concluded that the expanded standard uncertainty (k=2) was less than 0.2% for nitrogen as working fluid.

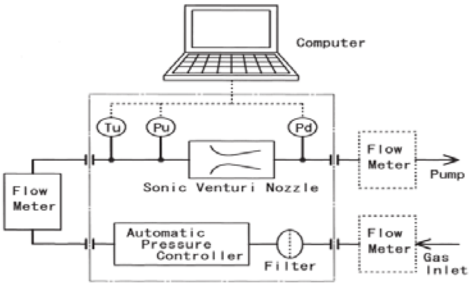

Fig.9. Experimental calibration facility for sonic nozzle with small flow rates. (Hayakawa et al [12])

Park et al [11] (2000) studied experimentally the parametric effect on discharge coefficient of sonic nozzle of diameter ranging from 0.28mm to 4.48mm .The study used a standard gas flow system at KRISS with uncertainty 0.37% at a Reynolds number of the range of ISO9300 Fig(10) , correcting the discharge coefficient with uncertainty 0.33% at high Reynolds numbers. The correcteddischarge coefficient was according to theoretical relation in Table (3).

Table 3. Corrected discharge coefficient for high Reynolds numbers (Park et al [11]).

C_d	U
$0.9995-3.6601R_{ed}^{-0.5}$	± 0.316%

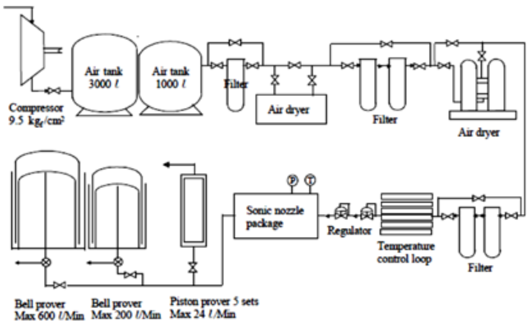

Fig.10. Schematic diagram for experimental setup.by Park et al [11].

Park et al [16] (2001) carried out a pure experimental workFig (11) to study the effect of the critical pressure ratio of sonic nozzles at low Reynolds numbers, for different divergence angles in the range from 2^o to 8^o. The test result for the angles of 2^o-6^o conformed toISO 9300 and the value of critical pressure ratio was 0.92. However, the critical pressure ratio for the nozzle of 8^o divergence angle was 0.85(less by 5.5% compared with ISO9300) . A correlation of the critical pressure ratio at low Reynolds numbers below $10^5$was given by Park et al [16] as:

$$P_{cr} = 0.9801 - 39.046(R_{ed}^{-0.5})$$

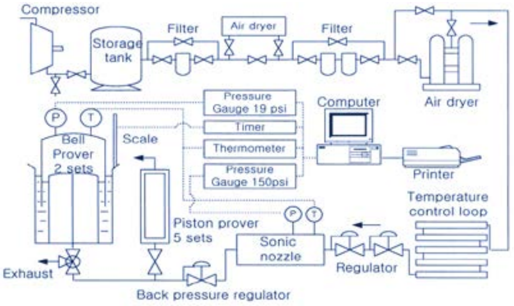

Fig.11.Schematic diagram for experimental setup by Park et al [16].

Bignell and Choi [17] (2002) studied the effect of temperature on the discharge coefficient of a sonic nozzle. Due to adiabatic cooling of the gas stream to -30 ^oC in the throat, the body of the nozzle was also cooled. The temperature drop of several bodies during operation was measured see Fig (12). The study used different throat diameters for measurement of air at environmental temperature and pressure. The results showed that with change of throat diameter from 0.715mm to 2.04 mm the percentage change of flow rate was 0.124% to 0.079%,respectively see Fig(13) and table(4).

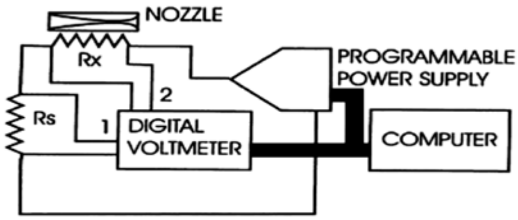

Fig. (12):Experimental setup.by Bignell and Choi [17].

Table 4. Effect of temperature difference between air and nozzle body on flow rates at different throat diameters. (Bignell and Choi, [17]).

d	Measured temperature drop(k^o)	Change in flow rate%
0.715	3.082	0.124
1.0	3.907	0.115
1.38	5.049	0.109
2.04	5.239	0.079

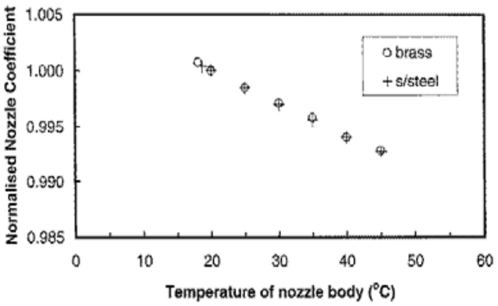

Fig.13.Effect of Temperatureon discharge coefficient. (Bignell and Choi [17]).

Lim et al [22] (2010) developed an experimental facility Fig(14) to study sonic nozzle calibration at low Reynolds numbers and pressures (below atmospheric pressure) in the pressure range 3 Kpa to 600 KPa . Therefore, calibration for a much wider range of flow-rates than thatwasexisting became possible. Calibration of flow meters in applications at lower pressures than the atmospheric pressure was then conducted.

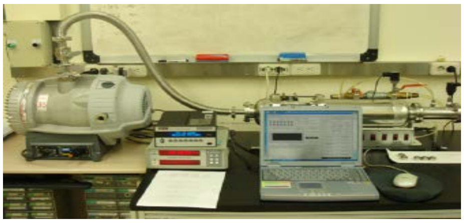

Fig.14. Photo of experimental setup by Lim et al[22].

The results showed that in the case of increasing the pressure, increase in speed occurs, leading to increased Reynolds number, this resulted in an increase in the discharge coefficient due to decrease in the thickness of boundary layer.

Chahine and Ballico[25] (2013) studied experimentally the effect of relative humidity on the discharge coefficient of sonic nozzle by using primary gas flow standard at NMIA to calibrate stainless steel sonic nozzles of diameters in the range from 0.1mm to 6.5mm at the volume flow rate range from 0.005 to 2.5 m^3/hrwith different air humidities. The results showed that the discharge coefficient of sonic nozzle decreased linearly with (x_v)between 0.07% to 0.12% in case of excessive humidity.

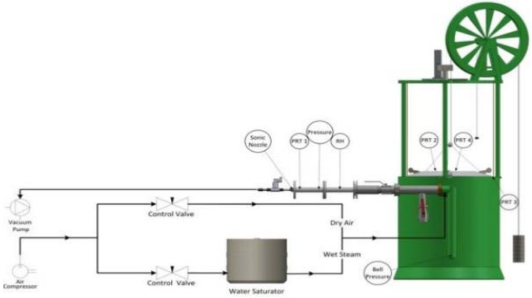

Fig.15. Photo of experimental setup byChahine and Ballico [25].

Wang et al [28] (2014) , using the setup shown in Fig(16) , carried out an experimental study of the effect of unsteady flow due to the condensation of water vapor on the flow rate of the sonic nozzle. They obtained correlation for frequency with φ_0 and w_0 as:

$$\bar{f} = \frac{fl}{a_{cr}} = \begin{Bmatrix} 4.007\varphi_o w_o^{0.53}, \varphi_o \geq 100\% \\ 2\sim10\varphi_o w_o^{0.53}, \varphi_o < 100\% \end{Bmatrix}$$

$$l = (R_c/d)^{½}$$

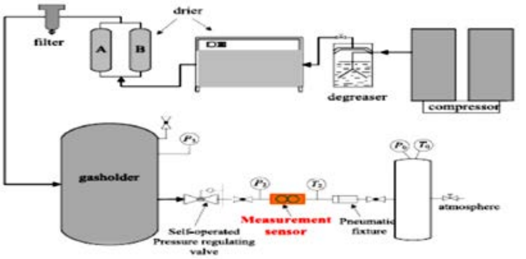

Fig.16. Schematic diagram for experimental setup by Wang et al [28].

Li and Mickan[33] (2015)studiedexperimentally the effect of humidity on discharge coefficient by using PVTt facility at NIM in China and comparedthe results with PTB in Germany (see table (5)) below.

Li et al [39], [2016] Comparing between uncertainty analysis by using PVTt facility Fig (17) and uncertainty analysis through sonic nozzle with (100 to 2500) Kpa. So, the uncertainty product from PVTt facility was 0.06%, while the uncertainty of the discharge coefficient of sonic nozzle was 0.08% at confidence level 95% (k=2).

Table 5.Comparison between PTB and NIM using PVTt facility (Li and Mickan [33]).

NIM results		PTB results		
C_d(NIM)	u_{cd} (NIM)	C_d (PTB)	u_{cd} (PTB)	En(%)
0.8982	0.13	0.8979	0.05	0.18
0.9497	0.13	0.9487	0.05	0.72
0.9629	0.13	0.9637	0.06	-0.57
0.9677	0.13	0.9674	0.06	0.21
0.9655	0.13	0.9653	0.06	0.14

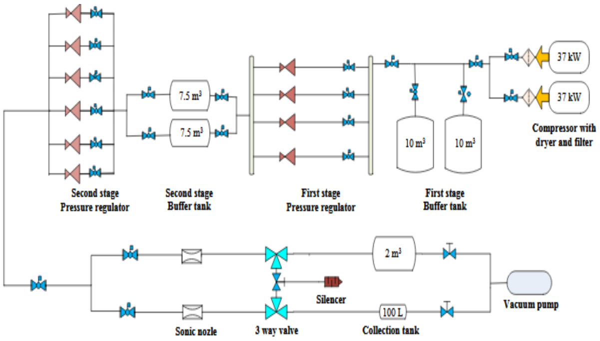

Fig.17.Schematic diagram for experimental setup by Li et al [39].

Li et al [43] (2018) developed experimentally the effect of throat diameter on flow of a sonic nozzle by using PVTt at NIM with throat diameter ranging from 1.921mm to 12.444mm and upstream stagnation pressure (160-2500)kpa. A correction of the discharge coefficient was gotten with the 2.39×10^4 to 2.89×10^6 Reynolds number and uncertainty ±0.2% as:

$$C_{d,NIM} = \left[0.99874 - \frac{4.01074}{\sqrt{Re}}\right] + \frac{0.00373 - \frac{1.28714}{\sqrt{Re}}}{1+exp(13.44507 - \frac{Re}{7*10^4})}$$

1.2. Compassion between experimental work

The difference between research experimental works from one to anther work is come from different environmental conditions, accuracy of measurement parameter devices, different parameter range and method of calibration test facilities of the sonic nozzle (e.g. In Choi et al[5] ,the sonic nozzles were calibrated by using primary system at KRISS depended on gravimetric method, while in Li et al [43] sonic nozzle calibration was by using PVTt system at NIM depended on volumetric method. They are works to get high accuracy in measurement with low uncertainty. The comparison divided to four terms depending on the parameters range of measurements:

a- For Reynolds number

Comparison between experimental results for Reynolds number shows that, when Reynolds number increases uncertainty decreases as in table (6).

Table6.Comparison between experimental works for effect of Reynolds number on measurement process.

Source	Reynolds number Range	Uncertainty%
ISO9300,[18]	2.1×10^4 to 2.3×10^7	±0.03
	2.1×10^4 to 1.4×10^6	±0.2
Choi et al,[5]	0.04×10^4 to 1.4×10^7	±0.05
Li et al,[43]	2.39×10^4 to 2.89×10^6	±0.2

b- For throat diameter

Comparison between experimental results for throat diameter shows that, when throat diameters increases uncertainty decreases as in table (7).

Table7.Comparison between experimental works for throat diameter on measurement process.

Source	Throat diameter Range	Uncertainty%
Choi et al,[6]	(4.3-13.4)mm	±0.00081-0.00063
Park et al,[11]	(0.28-4.48)mm	±0.316
Paik et al,[10]	10mm	±0.017

c- For mass flow rate range

Comparison between experimental results for equivalent mass flow rate shows that, when mass flow rate decreases uncertainty decreases as in table (8).

Table 8.Comparison between experimental works for effect of equivalent mass flow rate on measurement process.

Source	Mass flow rate Range	Uncertainty%
Nakao et al,[4]	Up to 5g/min	±0.112
Hayakawaet al,[12]	10mg/min-100g/min	±0.2

d- For upstream stagnation pressure

Comparison between experimental results for upstream stagnation pressure shows that, when upstream stagnation pressure increases uncertainty decreases as in table (9).

Table9.Comparison between experimental works for effect of upstream stagnation pressure on measurement process.

Source	stagnation pressure Range	Uncertainty%
Paik et al,[10]	740 Kpa	±0.17
Li et al,[39]	(100-2500)Kpa	±0.08
Choi et al,[6]	(500-2000)Kpa	±0.05

2.3 Numerical Simulation Works

Li et al [21] (2010) presented a numerical simulation of divergence angle effect on discharge coefficient of sonic nozzle for flow rate measurement at atmospheric condition with throat diameter ranging from 0.15 to 5mm and $2\times10^3 \leq Re_d \leq 6.6\times10^4$. They used a new parameter based on effective throat diameter (the deviation of effective throat diameter from the minimum effective diameter δ). They showed the effect of δ on discharge coefficient as follows.

i. For d>5mm the value of δ was very small .For the throat diameter the change of δ for nozzles with different divergence angles from 2.5º to 6.0º was also very small.
ii. For 1 mm ≤ d ≤ 5 mm, the effect of δ on discharge coefficient was non-linear. However, the change of δ for nozzles with the same throat diameters and different divergence angles from 2.5º to 6.0º is still very small.
iii. For d < 1 mm, the change of δ for nozzles with different divergence angles from 2.5º to 6.0º was comparable to the throat diameter. Therefore, a slow increase of the inviscid discharge coefficient with divergence angle occurred.

Ding et al [37] (2016), studied the thermal effect on mass flow rate of sonic nozzle, giving the following formulae:

$$1-3.800R_e^{-0.5}\,\Delta T/T_0 \qquad for \quad \gamma=1.33$$

$$C_t = \qquad 1-3.845R_e^{-0.5}\,\Delta T/T_0 \qquad for \quad \gamma=1.4$$

$$1-4.010R_e^{-0.5}\,\Delta T/T_0 \qquad for \quad \gamma=1.67$$

And therefore this should be taken into account when calculating thermal mass flow rate of the sonic nozzle and the relationship becomes as follows:

$$q_{m,Tw} = c_d + \frac{(c_t-1)c_\alpha\, c*\ A_{th}P_o}{\sqrt{R\,T_o}}$$

$$C_\alpha = \frac{A}{A_{ref}}$$

Alam et al [35] (2016) gave a numerical study of influence of nozzle geometry on the discharge coefficient with exit diameter =12.7mm. The discharge coefficient was significantly influenced by the radius of curvature, convergence and divergence angles. The sonic line moved towards nozzle exit as the radius of curvature was increased, while it trended towards the downstream region upon increase of the convergence angle.

Afroosheh et al [40] (2017) presented a numerical study of the effect of boundary layer growth on critical nozzle of hydrogen sonic jet through a 1mm diameter pipe connected to a high pressure tank (up to 70MPa). The simulation showed that the boundary layer caused a supersonic flow in the nozzle. The boundary layer effect on chocking and the mass flow rate was reduced compared to a sonic flow. Hence, the peak temperature in the axisymmetric flow was higher for inviscid simulations compared to viscous simulations. They concluded that inviscid simulations were less accurate but more conservative for safety studies since they predicted higher mass flow and higher temperatures.

1.3. Conclusion on numerical works.

The gas flow metering is mostly used in many fields, such as chemistry, industry and medicine. The sonic nozzle is used as master meter to test other types of gas flow meters and micro flow measurementhas been applied. Due to special geometry of critical flow venture nozzle, the gas expands and accelerates through the nozzle with different temperatures, the thermal effects influence on accuracy measurements.The performance of the nozzle entrance length, has explainedclearly, when inlet radius of entrancedecreases, discharge coefficient of sonic nozzle decreases. Whileeffects of entrance length areeffectively small, when inlet radius equal to four times throat diameter.

1.4. Theoretical Works

Stratford [1] (1964) gave a theoretical investigation of the calculation of the discharge coefficient of chocked nozzles with laminar and turbulent flow, based on the analysis. The relation between discharge coefficient and Reynolds number was obtained as shown in table(10).

Table (10): Corrected discharge coefficient for high Reynolds numbers (Stratford [1]).

Flow	C_d	Uncertainty
Laminar	$0.99844-3.0325\mathrm{Re}_{\mathrm{nt}}^{-0.5}$	±0.14%
Turbulent	$0.99844-0.0693\mathrm{Re}_{\mathrm{nt}}^{-0.2}$	±0.14%

Arnberget al [2] (1974) Studied theoretically the effect of Reynolds number on discharge coefficient form $4\times10^4$to 2.5×10^6 within uncertainty ±0.21%.Correlation formula as:

$$C_d = 0.99738-3.0358Re_{nt}^{-0.5}$$

IshibashiandTakamoto [9] (2000) the discharge coefficient of a critical sonic nozzle was derived theoretically by using super accurate nozzles at the Reynolds number range (5×10^4- 2.5×10^5) within uncertainty ±0.04%. A correlation of the discharge coefficient with Reynolds number was obtained as:

$$C_d = 0.99864\text{-}3.447Re_{nt}^{-0.5}$$

Ding et al [31] (2014) presented an algebraic study of divergence angle effect on flow rate and discharge coefficient of ISO-9300 for different Reynolds number range ($Re_d<1.1*10^4$). They showed that the discharge coefficient increased with divergence angle (Θ) (or the decrease of divergent section length (L)).

Ding et al [28] (2014) gave an analytical study of the effect of real gas (hydrogen) on discharge coefficient for a range of temperatures from 150Kto600K° and pressures up to 100 MPa. Massive detailed results of the effect of real gas state equation were obtained, showing that:

i. The stagnation pressure, stagnation temperature and nozzle throat diameter affected discharge coefficient of hydrogen gas.
ii. Under low temperature and pressure conditions, the effect of real gas can result in rise of the discharge coefficient. The discharge coefficient decreases with increase of pressure when T_o> 170 K.
iii. Under low pressure conditions, the discharge coefficient decreases at first and then rises with the increase of temperature. While under the high pressure zone, the discharge coefficient always rises with the temperature.
iv. The density decreases and velocity increases at nozzle throat by effect of the real gas.

1.5. Comparison between theoretical work

By linking the results obtained by experimental work with theoretical work, it was concluded that the greater the number of Reynoldsthe smaller the uncertainty obtained and the closer of charge coefficient to ISO9300 as indicated by table (11).

1.6. Mixed works

Johnson et al [7] (2000), gave a numerical simulation, theoretical and experimental investigation of vibration relaxation on the discharge coefficient for CO_2, N_2, He, O_2, Ar and air of a sonic nozzle for different water vapor contentsas shown in Fig(17). The variation of C_d with R_e for different percentages of water vapor is shown for a sonic nozzle with throat diameter range from 0.2950 mm to 2.3598mm and Reynolds number range from 2500 to 131000. The results indicated that all gases were unaffected by relaxation phenomena. Discharge increases with Reynolds number in laminar regime zone.

See Figure (18) shows the relationship between the Reynolds number and discharge coefficient calibration for different diameters and CO_2 being the working fluid.

Table (11): Comparison between theoretical works for various Reynolds number on measurement process.

Source	Re	Corrected (C_d)	Uncertainty
Ishibashi,Hall ,Geropp ,[9]	laminar	$0.99864\text{-}3.447Re_{nt}^{-0.5}$	±0.04%
Wendt , PTB,[15]	10^3 ~ 10^6	$0.9982\text{-}3.448Re_{nt}^{-0.5}$	±0.04%
	2.1×10^4~ 3.2×10^7	$0.9959\text{-}2.72Re_{nt}^{-0.5}$	±0.04%
Stratford ,uk,[1]	laminar	$0.99844\text{-}3.0325Re_{nt}^{-0.5}$	±0.14%
	Turbulent	$0.99844\text{-}0.0693Re_{nt}^{-0.2}$	±0.14%
Park, KRISS [11]	2.1×10^4~ 1.4×10^6	$0.99844\text{-}0.0693Re_{nt}^{-0.2}$	±0.32%
Cruz-Mava et al.,KRISS,[19]	1.4×10^6~ 2.6×10^6	$0.999\text{-}0.0997Re_{nt}^{-0.2}$	
Ishibashi, NRLM, [8]	5×10^4~ 2.5×10^5	$0.99864\text{-}3.447Re_{nt}^{-0.5}$	±0.04%
Anberg,ASME, [2]	4×10^4~ 2.5×10^6	$0.99738\text{-}3.0358Re_{nt}^{-0.5}$	±0. 21%

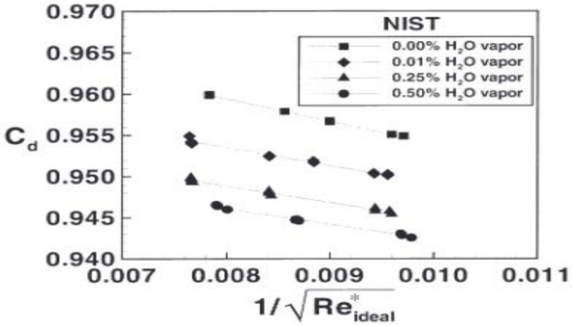

Fig. 17.Effect of water vapor on discharge coefficient of CO_2 by NIST (Johnson et al [7]).

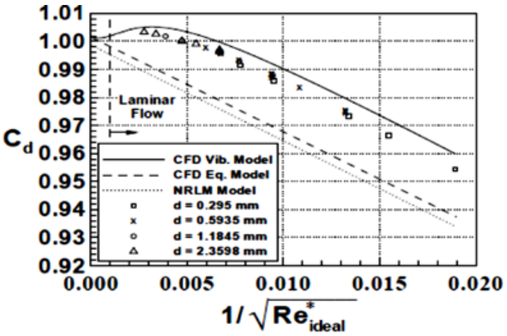

Fig.18.Experimental data of CO_2 calibration for different throat diameters.(Johnson et al [7]).

Cruz-Mayaet al [19] (2006) gave a numerical simulation study of the effect of turbulent boundary layer on mass flow rate and correcting the discharge coefficient accordingly so as to improve the accuracy of the measurement process and comparing withISO9300 and experimental work by KRISSsee Fig(19) and table(6) .The results show that the proposed discharge coefficient results are more accurate than the discharge coefficient that is stated according to ISO 9300.The deviation between the proposed method and the experimental method ranges from 0.138% to 0.111%for the Reynolds number range (1.4×10^6-2.6×10^6).A proposed discharge coefficient correlation (Numerical) was given as function in Reynolds number at throat diameter as shown in table (12).

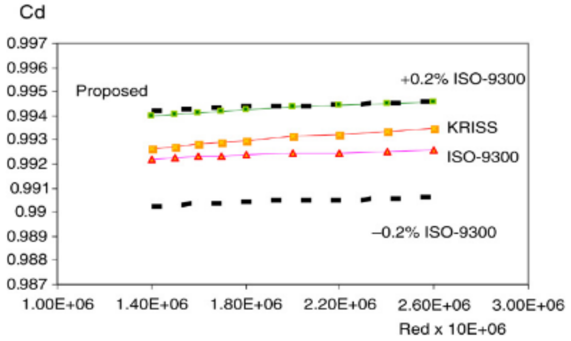

Fig.19. Comparisons between analytical and experimental correlations of the discharge coefficient (Cruz-Maya et al [19])

Wang et al [26] (2013) studied experimentally the true transient temperature distribution in the stagnation tank (length= 2.3m, D=0.55m, V=0.5m^3 and area 4m^2) and minimum temperature influence on flow measurement accuracy using thermodynamic model. They used a fluent software of mass and heat transfer and comparedit with experimental results on a sonic nozzle gas flow standard of diameter range from 3.8mm to 15.17mm with volume flow rate from 8to128 m^3/hr. The results clarified that the difference between experimental and numerical results was very small and the thermodynamic model proved the accuracy of the measurement.

Table (12): Comparison between numerical simulation and experimental results by Cruz-Maya et al [19].

Method	correlation	Uncertainty
Numerical simulation (proposed)	$C_d = 0.9990 -$ $0.09970\ /R_{ed}\text{-}^{0.2113564}$	±0.2%
Experimental (KRISS)	$C_d = 0.99575$ - $3.7026/R_{ed}^{0.5}$	±0.00068%

Ding et al [29] (2014) gave a numerical study of the non-equilibrium condensation of water vapor on discharge coefficient and compared results with experimental data. When the flow is homogeneous, there is considerable influence on discharge coefficient with high inlet relative humidity, which is related to thethermal choking notion. The discharge coefficient deviation reaches 0.275% when the inlet relative humidity isϕ_o=95%, which is comparable to the Lim et al [22] experimental data with accuracy of 0.15%.

Wang et al [27] (2014) gave a numerical simulation of wall roughness effect on discharge coefficient of sonic nozzle with throat diameter range from 0.5mm to 100mm , the Reynolds number range from 10^4 to 10^9 and relative roughness from 10^{-2} to 10^{-6}. Based on the simulation results and theoretical analysis, the relations between discharge coefficient and relative roughness were obtained. The authors state that when the manufacturing of a nozzle cannot satisfy the ISO 9300 requirement or the Reynolds numbers, exceed the upper limits of the ISO 9300 equation, the effect of roughness should be considered.

Yin et al [32] (2014) gave an experimental and numerical simulation study of characteristics for four small sonic nozzle range from 0.18mm to 0.96mm at the maximum flow rate 5m^3/hr with uncertainty 0.05%.The results clarified that the shape of sonic nozzle influenced the thickness of the boundary layer. Throat diameter effect on discharge coefficient showed that when increasing throat diameter, thedischarge coefficient increased. The results showed also that the discharge coefficient was maximumwhen thediameter of the inlet section was double the throat diameter and showedthat as the divergent section was made longerthe discharge coefficient increased.

Li and Mickan[33] (2015) carried out an experimental investigation in order to evaluate the effect of relative humidity of air on discharge coefficient of a sonic nozzle. Volumetric standard such as bell prover were used to calibrate critical flow nozzles at NMIA and comparison of experimental results with theoretical data was held. This experiment was carried out to calibrate the sonic nozzles of throat diameters from 0.1mm to 6.5mm at the volume flow rate 0.005 to 25 m^3/h and humidity of air equal ϕ_o=95%RH air. The measured change was up to 0.12% larger than predicted by theoretical calculation.

Ding et al [29] (2014) conducted an experimental/ numerical study of the effect of vapor condensation on the mass flow-rate of a sonic nozzle. The effect of condensation vapor on the flow rate of wet air outside the acoustic nozzle was also obtained. In addition, pressure fluctuation frequencies were also known with varying relative humidityϕ_o at input. The specific moisturew_o obtained from the thermal choking was during condensation. A correlation between numerical and experimental results was obtained.

Han et al [38] (2016) carried out a numerical simulation to study the internal flow field for a straight pipeline connected to a sonic nozzle for the influence on the discharge coefficient and gave comparison between numerical ,theoretical solution and experimental data with results shown in table(13).

Table (13): Comparison between numerical, theoretical and experimental discharge coefficient at different back pressure ratios. (Han et al [38]).

(p_b/p_o)	C_d (CFD)	C_d(Exp)	Relative Deviation (%)
0.507	0.98202	0.98062	0.14
0.573	0.98234	0.98124	0.11
0.638	0.98231	0.98101	0.13
0.750	0.98287	0.98197	0.09
0.799	0.98278	0.98207	0.08
0.838	0.98279	0.98199	0.08
0.849	0.98288	0.98218	0.07

Ding et al [36] (2016), gave an analytical investigation of the discharge coefficient of sonic nozzle with a relative equivalent surface roughness range from10^{-6} to 10^{-2} and different Reynolds number from 10^4 to 10^9. Comparison of analytic solution at the inlet pressure ranges from 1 to 70 bar with experimentaldata showed that the expanded uncertainty on C_d obtained by a primary calibration was estimated at 0.19% (k=2; 95% confidence). The experiment was operated in the pressure range 0.8bar to 50bar and temperature range from -2 C° to 23C° for air, nitrogen and natural gas. The throat diameter of sonic nozzle was 6.65 mm. The uncertainty of the flow rate was about 0.08 to 0.15%(see fig(20)).

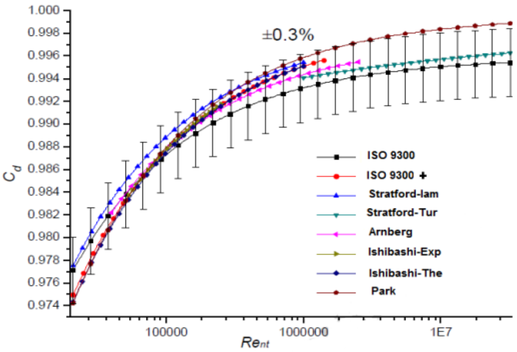

Fig.20. Comparisonbetween discharge coefficients at different conditions (Ding et al [36]).

Chang and Bai [41] (2017) carried out an experimental and numerical study,determining that the optimal structure of theexit velocity of a supersonic nozzle which is about five to six times the speed of the sound. This is used in the production of gas from the wellswhere the gas is usually loaded with a quantity of liquid, a situation that reduces the efficiency of gas extraction system. So the amount of liquid loaded must be eliminated by pushing the gas loaded with liquid through a supersonic nozzle. The latter is designed for a Mach number at exitof up to 6. Liquid droplets arethen fragmentedinto particles of size 10μm to 50μm. The droplets are thus extracted and the gas productivity is increased, hencethe production is more efficient. The results indicated that the higher the exit velocity from the jets, the less the volume of liquid droplets loaded with thegas.

2.7 Conclusion on mixed works.

The mixed works consist of experimental with numerical or numerical with theoretical where it purposes to validity of the numerical results. This part clarify some parameters that affect on sonic nozzles reading and discharge coefficient like, wall roughness, internal flow field for a straight pipeline connected to a sonic nozzles, thickness boundary layer and air contain with water vapor. So these parameters should be taken in consideration during calculation of discharge coefficient of sonic nozzle.

2. Comments and Necessity of Future Work

A review of the pertinent literature indicates that the discharge coefficient is directly proportional with Reynolds number, according to practical and numerical experiments. The sonic nozzle design can be adapted to improve discharge coefficient. Most related works have emphasized the length and angle of divergent section affected on performance of sonic nozzle. Further work should investigate the performance of a sonic nozzle at different operating conditions such as various types of gases, effect of geometry change and corrected to the discharge coefficient. Also the back pressure effects on mass flow rate and normal shock in sonic nozzles used in calibration facilities should have more interest of study.

3. Discussion and Evaluation of Current Status.

The above review indicates without any doubt the obvious interest by many research workers in the problems of sonic nozzle performance as a standard calibration device for many types of flow meters. However, it is generally felt that the individual authors concentrated on certain aspects of the subject. None of the above authors considered the problem comprehensively enough. For example, the effect of geometry and effect of kind of gases through the sonic nozzle requires further investigation. Also, work on sonic nozzle when a normal shock occurs is rather scanty or may be nonexistent and deserves consideration. Therefore, it true to say that there is still much room for investigation towards comprehensiveness. Nevertheless, the work summarized above should be considered of high value for this matter. The authors of the current review paper plan to study the problem with more and deeper insight, hoping to add something more to the art.

4. Conclusions

From the above review and discussion, one may draw the following conclusions:

a) Discharge coefficient depended on Reynold number and throat diameter.
b) Body temperature of sonic nozzle effected on accuracy of measurement, therefore should be considered in calculations.
c) The problem of sonic nozzle performance is an important one in the field of fluid dynamics.
d) There is still a lot of work to be done on the problem.Such as Effects of back pressure on mass flow rate and Normal shock occurrence in sonic nozzles used in calibration facilities.
e) Coverage of as much as possible the various aspects should be the main target by those who are to tackle the problem.

References

[1] B.S. Stratford, “The calculation of the discharge coefficient of profiled choked nozzles and the optimum profile for absolute air flow measurement”, The Aeronautical Journal Vol.68, No.640 pp.237-245,1964.

[2] B.T.Arnberg, C.L.Britton, and W.F.Seidl, “Discharge coefficient correlations for circular-arc venturiflow meters at critical (sonic) flow”, Journal of FluidsEngineering Vol. 96, No.2, pp.111-123,1974.

[3] K.A.Park, “Effects of inlet shapes of critical venturi nozzles on discharge coefficients”, Flow Measurement and Instrumentation Vol.6 , No.1, pp.15-19,1995.

[4] S.I.Nakao, Y.Yokoi and M.Takamoto, “Development of a calibration facility for small mass flow rates of gas and the uncertainty of a sonic venturi transfer standard”, Flow Measurement and Instrumentation Vol. 7, No.2, pp.77-83,1996.

[5] Y.M.Choi, K.Am Park, and S.O.Park, “Interference effect between sonic nozzles”, Flow Measurement and Instrumentation Vol. 8, No.2, pp.113-119, 1998.

[6] Y.M.Choi, K.Am Park, J.T.Park, H.M Choi and S.O Park, “Interference effects of three sonic nozzles of different throat diameters in the same meter tube”, Flow Measurement and Instrumentation Vol. 10, No.3, pp.175-181,1999.

[7] A.N.Johnson, J.D. Wright, S.I Nakao, C.L.Merkle, and M.R.Moldover, “The effect of vibrational relaxation on the discharge coefficient of critical flow venturis1”, Flow Measurement and Instrumentation Vol. 11,No., pp.315-327,2000.

[8] B.Bátyi, K.Kocsmar, A.S. Kun, and Z.Reményi, “Metrological and reliability features of a sonic nozzle prover system (SNPS)”, Flow Measurement and Instrumentation Vol. 11, No.4, pp.273-278, 2000.

[9] M.Ishibashi, and M.Takamoto, “Theoretical discharge coefficient of a critical circular-arc nozzle with laminar boundary layer and its verification by measurements using

super-accurate nozzles”, Flow Measurement and Instrumentation Vol. 11,No.4, pp.305-313,2000.

[10] J.S.Paik, K.Am Park, and J.T.Park, “Inter-laboratory comparison of sonic nozzles at KRISS”, Flow Measurement and Instrumentation Vol.11, No.4, pp.339-344, 2000.

[11] K.A. Park,Y.M.Choi, H.M. Choi,T.S. Cha,B.H. Yoon, "characteristic of small sonic nozzle",FLOWMEKO (2000).

[12] M.Hayakawa, Y.Ina, Y.Yokoi, M.Takamoto, and S.I.Nakao, “Development of a transfer standard with sonic Venturi nozzles for small mass flow rates of gases”,Flow Measurement and Instrumentation Vol.11, No.4, pp.279-283, 2000.

[13] N.Bignell, “Using small sonic nozzles as secondary flow standards”, Flow Measurement and Instrumentation Vol. 11, No.4, pp.329-337, 2000.

[14] S.I.Nakao, and M.Takamoto,” Choking phenomena of sonic nozzles at low Reynolds numbers” Flow measurement and Instrumentation Vol.11, No.4, pp.285-291, 2000.

[15] G.Wendt, and E.Lavante, “Influence of surface roughness on the flow rate behavior of small critical Venturi nozzles” In Proceedings of the 10th Int. Conference on Flow Measurement FLOMEKO, 2000.

[16] K.A.Park, Y.M.Choi, H.M.Choi, T.S. Cha, and B.H.Yoon, “The evaluation of critical pressure ratios of sonic nozzles at low Reynolds numbers”, Flow measurement and Instrumentation Vol.12, No.1, pp.37-41, 2001.

[17] N.Bignell, and Y.M.Choi, “Thermal effects in small sonic nozzles” Flow Measurement and Instrumentation Vol. 13, No.(1-2), pp.17-22, 2002.

[18] ISO9300 ,"Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles,2005.

[19] J.A.Cruz-Maya, F.Sanchez-Silva, andP.Quinto-Diez, “A new correlation to determine the discharge coefficient of a critical Venturi nozzle with turbulent boundary layer”, Flow Measurement and Instrumentation Vol.17, No.5, pp.258-266, 2006.

[20] A.Johnson, and J.Wright, “Comparison between theoretical CFV flow models and NIST’s primary flow data in the laminar, turbulent, and transition flow regimes”, Journal of Fluids Engineering Vol. 130, No.7, p.071202, 2008.

[21] C.H.Li, X.F. Peng, and C.Wang, “Influence of diffuser angle on discharge coefficient of sonic nozzles for flow-rate measurements”, Flow Measurement and Instrumentation Vol.21, No.4, pp.531-537, 2010.

[22] J.M.Lim, B.H.Yoon, S.Jang, H.M.Choi, and K.A.Park,“Step-down procedure of sonic nozzle calibration at low Reynolds numbers” Flow Measurement and Instrumentation Vol. 21, No.3, pp.340-346, 2010.

[23] S.Ducourtieux, and B.Poyet, “Development of a metrological atomic force microscope with minimized Abbe error and differential interferometer-based real-time position control”, Measurement Science and Technology Vol. 22, No.9, p.094010, 2011.

[24] C.C.Hu, W.T.Lin, and C.M.Su, “Flow characteristics of pyramidal shaped small sonic nozzles”, Flow Measurement and Instrumentation Vol. 22, No.1, pp.64-70, 2011.

[25] K.Chahine, and M.Ballico, “Evaluation of the effect of relative humidity of air on the coefficients of critical flow venturi nozzles”,Flomeko, Paris, France, pp.24-26, 2013.

[26] C.Wang, H.Ding, and H.Wang, “Thermodynamic model and dynamic temperature compensation in positive-pressure-based sonic nozzle gas flow standard”, IEEE Transactions on Instrumentation and Measurement Vol. 62, No.5, pp.1154-1165, 2013.

[27] C.Wang, H.Ding, and Y.Zhao, Influence of wall roughness on discharge coefficient of sonic nozzles. Flow Measurement and Instrumentation Vol. 35, pp.55-62, 2014.

[28] C.Wang, H.Ding, Y.Zhao, Y.Yan, and Y.Hu, “Sensor system for unsteady flow characteristics in a sonic nozzle with vapor condensation”, In Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, IEEE International (pp. 772-775). IEEE, 2014.

[29] H.Ding, C.Wang, and C.Chen, “Non-equilibrium condensation process of water vapor in moist air expansion through a sonic nozzle” Flow Measurement and Instrumentation Vol. 40, pp.238-246, 2014.

[30] H.Ding, C.Wang, and Y.Zhao, “Flow characteristics of hydrogen gas through a critical nozzle”, International journal of hydrogen energy Vol. 39, No.8, pp.3947-3955, 2014.

[31] H.Ding, C.Wang, and Y.Zhao, “Influence of divergent section on flow fields and discharge coefficient of ISO 9300 toroidal-throat sonic nozzle”, Flow Measurement and Instrumentation Vol. 40, pp.19-27, 2014.

[32] Z.Q.Yin, D.S.Li, J.L. Meng, and M.Lou, “Discharge coefficient of small sonic nozzles” Thermal Science Vol. 18, No.5, pp.1505-1510, 2014.

[33] C.Li, and B.Mickan, “Humidity effect on the calibration of discharge coefficients of critical flow Venturi nozzles in a pVTt facility” Flow Measurement and Instrumentation Vol. 46, pp.125-132, 2015.

[34] M.B.Shyamshankar,V.Sankar,"Investigation on Divergent Exit Curvature Effect on Nozzle Pressure Ratio of Supersonic Convergent Divergent Nozzle", Int. Journal of Engineering Research and Applications, Vol. 5, No. 5, , pp.164-172,2015.

[35] M.M.A.Alam, T.Setoguchi, S. Matsuo, and H.D.Kim, “Nozzle geometry variations on the discharge coefficient”,Propulsion and Power Research Vol.5, No.1, pp.22-33, 2016.

[36] H.Ding, C.Wang, and G.Wang, “Approximate solution for discharge coefficient of the sonic nozzle with surface roughness”, Flow Measurement and Instrumentation Vol 52, pp.227-232, 2016.

[37] H.B.Ding, C.Wang, and G.Wang, “Thermal effect on mass flow-rate of sonic nozzle”, Thermal Science, pp.146-146, 2016.

[38] K.Han, D.Luo, and Y.Shen, “Numerical simulation of the internal flow field for the straight pipeline after a sonic nozzle and its influence on the discharge coefficient” In Control Conference (CCC), 35th Chinese (pp. 9462-9465). IEEE, 2016.

[39] C.Li, L.Cui, and C.Wang, “The uncertainty analysis and capability verification for the high pressure pVTt gas flow facility of NIM, 2016.

[40] M.Afroosheh, F.Vakilimoghaddam, and M.Paraschivoiu, “Boundary layer effects on the critical nozzle of hydrogen sonic jet”, International Journal of Hydrogen Energy Vol. 42, No.11, pp.7440-7446, 2017.

[41] P.Chang, and B.Bai, “An improved method of gas well deliquification using supersonic nozzle”, International Journal of Heat and Mass Transfer Vol. 108, pp.2262-2272, 2017.

[42] http://www.oulu.fi/sites/default/files/content/OY%20ExpDesign%20Feb2013_Day1_070213.pdf

[43] C.Li, P.Cao, H.Zhang, and L.Cui, Throat diameter influence on the flow characteristics of a critical Venturi sonic nozzle. Flow Measurement and Instrumentation Vol. No. 60, pp.105-109, 2018.