



# The upstream flow condition effect on the premature unchoking phenomena of the sonic nozzles

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## Abstract

With the atmospheric air as the working fluid, the premature unchoking phenomena were investigated with 18 sets of critical flow Venturi nozzles under 8 types of upstream flow conditions. Unlike the available research, there were no clear relationship between the upstream flow condition and the flow rate fluctuation and flow rate recovery for the premature unchoking phenomena. However, the diverse and unsteady characteristics of the premature unchoking phenomena were shown. With the comparison of upstream flow conditions, the new disturbance might be resulted from the “improper” upstream flow condition, which might influence the intensity and the position of the shock in the diffuser section of CFVN, and finally resulted in the diverse and unsteady characteristics of premature unchoking phenomena.

## 1. Introduction

The critical flow Venturi nozzle (CFVN) is kind of gas flow meter, which was widely used as the master standard to calibrate other kinds of gas flow meters directly related with the trade market, due to high accuracy and long term stability.

CFVN is operated at downstream-to-upstream pressure ratios sufficient to establish sonic velocities at the throat cross section. The maximum pressure ratio for sonic throat conditions is called the critical back pressure ratio (CBPR). CFVN must be operated at or below CBPR to reach the critical flow.

When the flow is assumed isentropic for the ideal gas, the CBPR can be expressed as,

$$CBPR = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (1)$$

When the working fluid is air,  $k = 1.4$ ,  $CBPR = 0.53$ . With the diffuser section, the CBPR of CFVN can be improved to 0.7, even 0.95. For the small CFVN or large CFVN working at low Reynolds number, the premature unchoking phenomena were founded by many researchers [2-7], which resulted in the decrease of CBPR. So, for CFVN operating at throat Reynolds numbers lower than  $2 \times 10^5$ , it was recommended that the users maintained a back pressure ratio of 0.25 or performed a simple unchoking test on their CFVNs [1].

In general, the premature unchoking phenomena were determined by the unsteady movement of shock resulted from the interaction between shock and the boundary layer, which was very complex and related with many factors [8].

Several different damping materials and configurations of upstream flow condition were investigated, and a clear correlation between the upstream pressure fluctuation and the level of

premature unchoking phenomena was gotten by Mikan et al., [9]. Moreover, On the base of Papamoschou's [10] research,  $Ha$ , Hagan number was presented to explain the premature unchoking phenomena, instead of Reynolds number,  $Re$ , presented by other researchers [2-7], which significantly reduced the scatter of the results.

Carter et al.'s [11,12] research showed that the occurrence of premature unchoking phenomena was affected by throat Reynolds number, diffuser angle, and strongly influenced by diffuser length, which was more likely to occur for the CFV when the diffuser angle was relatively large and/or the diffuser length was too short. With the optimized geometry with longer diffuser length, an empirical equation was presented to predict the CBPR down to the throat Reynolds number of  $1.2 \times 10^4$ .

With the atmospheric air, the impact of upstream flow conditions with different geometrical parameters was investigated within the Reynolds number of  $5.3 \times 10^4 \sim 1.81 \times 10^5$ . When the Reynolds number was higher than  $1.34 \times 10^5$ , the CBPR could reach the designed value according to ISO 9300 [1]. The CBPR was always higher than 0.48, even though the premature unchoking phenomena occurred. For the same throat diameter, the phenomena easier occurred for the sonic nozzle with larger diffuser angle. On the other hand, the “improper” upstream flow conditions resulted in the diverse and unsteady characteristics of the premature unchoking phenomena.

## 2. The experimental procedure

With 8 types of upstream flow conditions, the experiments were conducted with 18 sets of sonic nozzles.

### 2.1 The experimental system

The experimental system was shown in Fig.1. The orifice plate was used as the master meter to measure the flow rate of the sonic nozzle. There were several steps to make the measurement:

- 1) The valve 2 was open and turned on the vacuum pump. The standard tank was evacuated to 500 Pa, then the valve 2 was close;
- 2) The valve 1 was open, and the standard tank was filled to 100 kPa. The  $T_0$ ,  $p_0$ ,  $p_1$  and  $p_2$  were recorded during filling;
- 3) The experiments were repeated 9 times. The result was the average of 9 times' tests.

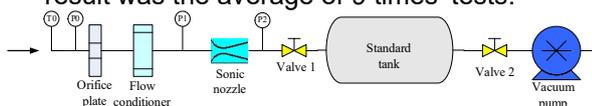


Figure 1. The experimental system

In principle, the mass flow through the orifice plate is expressed as,

$$Q = K' \sqrt{\Delta p \cdot \rho_0} = K \sqrt{\Delta p \cdot \frac{p_0}{T_0}} \quad (1)$$

To simply, the normalized flow rate,  $y$  was defined as,

$$y = \frac{Q - \bar{Q}}{\bar{Q}} \times 100\% \quad (2)$$

The CBPR was the back pressure ratio, when  $\left| \frac{y - \bar{y}}{u_y} \right| = 1$ . In practice, the increasing of back pressure was not continued, so the maximum back pressure ratio satisfied  $\left| \frac{y - \bar{y}}{u_y} \right| < 1$  was chosen as CBPR.

### 2.2 The sonic nozzles

With the reference of ISO 9300 [1], 3 types of sonic nozzles were designed.

- Type I: different diffuser angle;
- Type II: different diffuser length;
- Type III: different throat diameter.

The designed CBPR was 0.85 for type I and type III. The specifications of 18 sets of nozzles were shown in Table. 1.

Table 1. The specifications of sonic nozzles

No.	Type	SN	Throat diameter	Diffuser angle	Reynolds number	The length of diffuser section	
			$d$ [mm]	$[\circ]$			$[\ ] \times 10^4$
1	I	5-2.5	5.006	2.5	13.4	3.9	
2		5-4.0	5.038	4		2.4	
3		5-6.0	5.010	6		1.6	
4		10-2.5	10.018	2.5		3.9	
5		10-4.0	10.020	4		2.4	
6		10-6.0	10.021	6		1.6	
7	II	10-0d	9.988	4	13.4	0	
8		10-1d	9.993			1	
9		10-2.4d	10.039			2.4	
10	III	8601	4.025	4	13.4	5.3	
11		8602	5.909			7.8	2.4
12		8603	7.002			9.1	

13		8604	7.982		10.5
14		8605	9.086		11.9
15		8606	9.936		13.1
16		8607	11.032		14.6
17		8608	12.444		16.4
18		8609	13.674		18.1

### 2.3 The upstream flow conditions

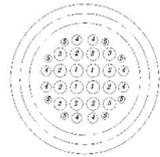
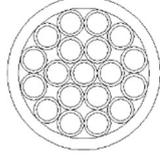
The orifice plate with throat diameter 18.218 mm was used as the master meter to measure the flow rate of the sonic nozzle of SN.5-2.5, SN.5-4.0, SN.5-6.0, SN.8601, SN.8602 and SN.8603, while another orifice plate with throat diameter 30.708mm was used to measure other sonic nozzles.

The flow conditioner was mounted between the orifice plate and the sonic nozzle and close to the downstream of orifice plate. 3 types of upstream flow conditions were designed.

- Type I: without flow conditioner;
- Type II: Zanker type flow conditioner;
- Type III: tube bundle type flow conditioner.

The specifications of 8 upstream flow conditions were shown in Table.2.

Table2. The specifications of upstream condition

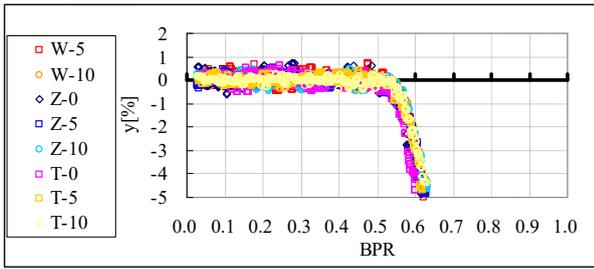
No.	Type	The distance between orifice plate and sonic nozzle	The abbreviation	Note
		$[\ ] \times D^*$		
1	I: Without	5	W-5	/
2		10	W-10	/
3	II: "Zanker"	0	Z-0	
4		5	Z-5	
5		10	Z-10	
6	III: Tube bundle	0	T-0	
7		5	T-5	
8		10	T-10	

Note:  $D$  is the diameter of pipeline, which is 50 mm in this paper.

## 3. The experimental results and uncertainty

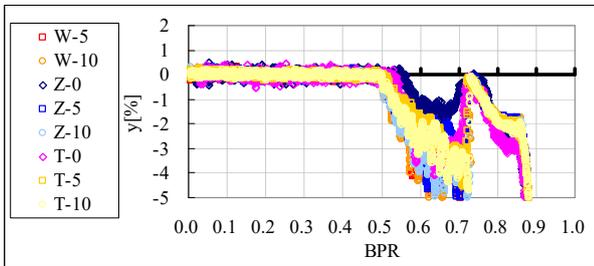
### 3.1 The experimental results

The typical relationship between nominal flow rate and back pressure ratio was shown in Fig.2. When the BPR exceeded CBPR, the nominal flow rate straight decreased with the BPR increasing.



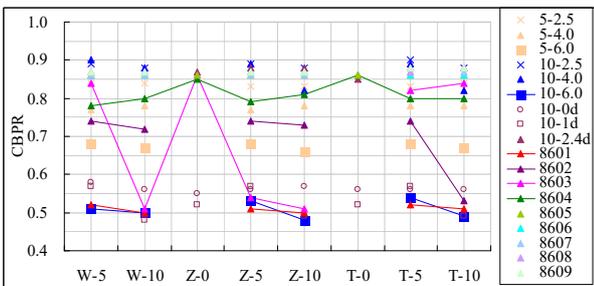
**Figure 2.** The test result of SN.10-0d

The premature unchoking phenomena occurred for SN.8603 as shown in Fig.3. When the BPR was over CBPR, the nominal flow rate decreased with increasing BPR firstly, then the nominal flow rate increased with increasing BPR until to the maximum nominal flow rate, finally decreased again. The similar phenomena occurred for SN.8601, SN.8602, SN.8604 and SN.10-6.0.



**Figure 3.** The test result of SN.8603

The test results of CBPR for total 18 sets of sonic nozzles were shown in Fig.4.



**Figure 4.** The test results of CBPR

From Fig.4, it was clear that:

- 1) The designed CBPR of 0.85 could be reached for the sonic nozzles satisfied with the requirement of ISO 9300 [1] when the throat diameter no smaller than 9.086mm, except for SN.10-6.0.
- 2) The occurrence of premature unchoking phenomena resulted in the obvious decrease of CBPR, which had strong relationship with the geometrical parameters and the upstream flow conditions.

■ **The geometrical effect**

- a) The phenomena occurred due to the existence of diffuser section. The small of CBPR for SN.10-0d was

resulted from the poor back pressure recovery due to short diffuser section as shown in Fig.2. The small of CBPR for SN.8601 was resulted from the phenomena, as shown in Fig.3.

- b) For the same throat diameter, the phenomena easier occurred for the sonic nozzle with larger diffuser angle. For the diffuser angle of 6.0, the phenomena o For the diffuser angle of 4.0, the phenomena occurred for the throat diameter of 7.982 mm; For the diffuser angle of 2.5, the phenomena did not occur.

■ **The upstream condition effect**

- a) For type III, the upstream condition had no influence when the throat diameter was no smaller than 9.086 mm or Reynolds number was larger  $1.24 \times 10^5$ ;
- b) With the different upstream flow conditioner, there were no clear correlation between the upstream pressure fluctuation and the level of premature unchoking phenomena.

**3.2 The uncertainty**

On the base of Eq. (1), the uncertainty of CBPR could be expressed as, with consideration of the measurement process,

$$u_Q = \sqrt{u_p^2 + u_{T_0}^2 + u_{step}^2 + u_{\Delta p}^2} \quad (3)$$

The meanings of each term were shown in Table.3,

**Table 3.** the uncertainty analyses

Symbol	Meaning	Quantity [%]
$u_p$	The differential pressure and stagnation pressure measurement	0.04
$u_{T_0}$	The temperature measurement	0.10
$u_{step}$	The pressure increasing step in the downstream of sonic nozzle, $p_2$	1.36
$u_{dp}$	The data processing method, on the base of Eq. (2)	0.39
		$u_Q = 1.42\%$ $U_Q = 2.8\% (k=2)$

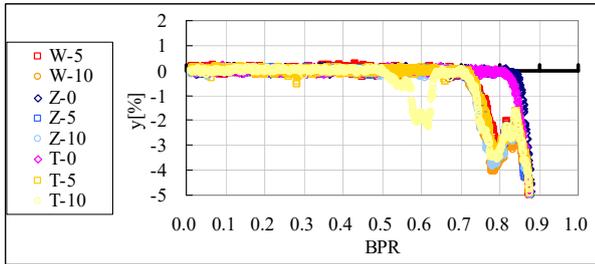
The detail explanation on the uncertainty could be found in Ref. [13].

**4. The premature unchoking phenomena**

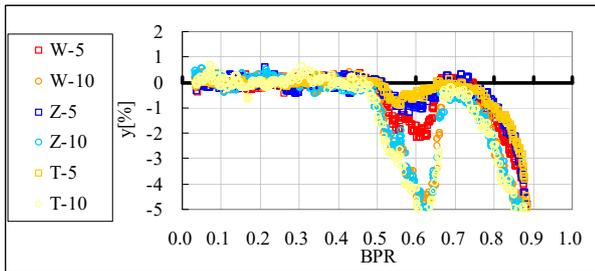
The premature unchoking phenomena occurred for SN.10-6.0, SN.8601, SN.8602, SN.8603, SN.8604. To investigate the phenomena, the experiments were repeated at least one more time for above each nozzle. The diverse and unsteady

characteristics of premature unchoking phenomena were displayed.

#### 4.1 The diverse characteristic



(a) SN.8602



(b) SN.10-6.0

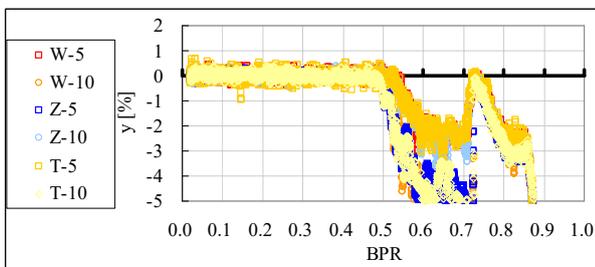
**Figure 5.** The diverse characteristic

With comparisons of Fig.3 and Fig.5, the diverse characteristics of premature unchoking phenomena were expressed.

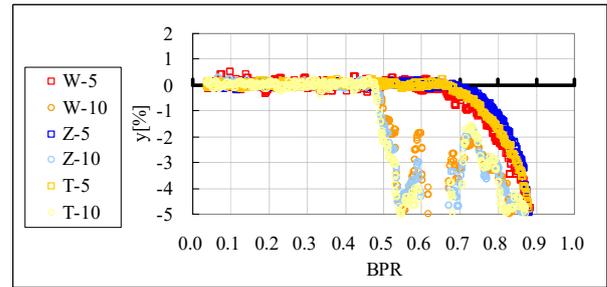
- The phenomena occurred for each upstream flow conditions, like SN.8601 and SN.10-6.0, or occur for partial upstream flow conditions, like SN.8602;
- For SN.8602, the phenomena occurred twice at different BPR when the upstream flow conditioner was tube bundle type with 10 D upstream pipeline.
- For SN.10-6.0, the flow conditioner did not result in the obviously flow rate recovery during the phenomena;

#### 4.2 The unsteady characteristic

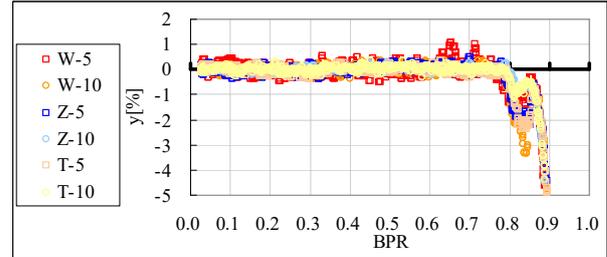
The unsteady characteristics of the phenomena were shown by the repeated experimental results.



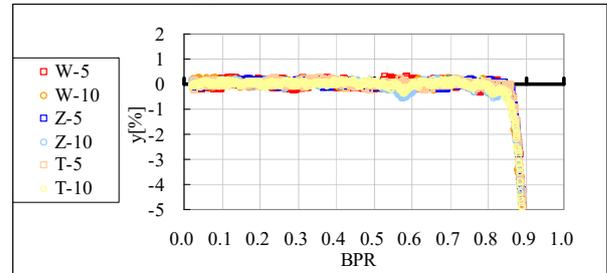
(a) SN.8601-The 2<sup>nd</sup> time



(b) SN.10-6.0-The 2<sup>nd</sup> time



(c) SN.8604-The 1<sup>st</sup> time



(d) SN.8604-The 2<sup>nd</sup> time

**Figure 6.** The unsteady characteristic

With comparison of Fig.3 and Fig.6(a), Fig.5(a) and Fig.6(b), Fig.6(c) and Fig.6(d):

- For SN.8601, the phenomena were almost repeated;
- For SN.10-6.0, the phenomena were repeated for the same upstream flow conditions with longer upstream pipeline, while they were disappeared for other upstream flow conditions. Within the phenomena, the characteristics of flow rate recovery were different for each time;
- For SN.8604, the phenomena were almost disappeared.

#### 4.3 The upstream flow condition effect

Mickan et al.,<sup>[8]</sup> research showed the phenomena could be depressed by the lower turbulent intensity resulted from the porous media of upstream flow condition, which did not occur in this paper. The experimental parameters of Mickan et al.,<sup>[8]</sup> and this paper were shown in Table.4,

**Table4.** The comparisons of experimental parameters

	Upstream flow conditioner			Orifice plate	Sonic nozzle
	Type	Diameter	Thickness	Diameter	$d$
	[/]	[mm]	[mm]	[mm]	[mm]



Mickan et al., [6]	Porous media	≤0.1	5 or 30	3	1
This paper	Zanker type	7.05 6.95 6.825 5.5 3.85	6.25		18.218 or 30.708
	tube bundle type	10	100		4.025~13.674

So, the relationship between the nominal (or effective) diameter of flow conditioner,  $d_{fc}$ , and the throat diameter of sonic nozzle,  $d$ , could be expressed the influence of upstream flow condition on the premature unchoking phenomena.

- The “proper” flow condition, if  $d_{fc} \ll d$   
In Mickan et al.’s work, the throat diameter of the sonic nozzle was 1 mm, and the nominal (or effective) diameter of porous media was no bigger than 0.1 mm, which mean  $d_{fc} \ll d$ . The turbulent intensity was dramatically depressed. The influence was almost linearly with the thickness of the flow conditioner.

- The “improper” flow condition, the  $d_{fc} \approx d$   
Besides SN.10-6.0, the premature unchoking phenomena occurred for SN.8601-8604 with throat diameter of 4.025 mm~7.982 mm, while the diameter of the flow conditioner was within 3.85 mm~10 mm. The existed turbulence intensity would not be depressed, and the new turbulence might be formed, which resulted in diverse and unsteady characteristics of the premature unchoking phenomena.

**5. Conclusions**

With the atmospheric air as the working fluid, the phenomena were investigated by 18 CFVNs with 8 upstream flow conditions in this paper. The premature unchoking phenomena occurred for 5 CFVNs. The experiments were repeated to investigate the phenomena.

The premature unchoking phenomena were resulted from the unsteady motion of the oblique shock by Ishibashi et al., [4] or  $\lambda$  shock by Mickan et al., [8] in the diffuser section of CFVN. The unsteady motion of the shock was related with the interaction of the shock and the boundary layer, which was influenced by the turbulent intensity. From this paper, the influence of upstream flow

condition on the turbulent intensity could be classified two kinds:

- The “proper” upstream flow condition ( $d_{fc} \ll d$ ):  
The turbulent intensity was depressed, which resulted in the bigger flow recovery during the premature unchoking phenomena.

The “improper” upstream flow condition ( $d_{fc} \approx d$ ):  
The new disturbance might be formed, which resulted in the diverse and unsteady characteristics of the premature unchoking phenomena.

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