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Effects of step in CFVN on Premature Unchoking Phenomena

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Abstract

CFVNs (Critical Flow Venturi Nozzles) are widely used as transfer standards and can realize the accurate measurement of the flow rate. However, previous research has reported that the pressure recovery effect of the diffuser deceases significantly in some CFVNs, and it has been called PUP (Premature Unchoking Phenomenon). In this study, we conducted experiments and investigated the CBPR (Critical Back Pressure Ratio) of the CFVNs. Additionally, in order to solve the PUP, we focused on the step in the diffuser and verified the its effect. As a result, although a backward facing step (causing increase of diameter) at the throat is effective for improving the CBPR at the Reynolds number of about 44000, it does not provide the improvement when the Reynolds number decreases to 11000. A forward facing step (causing decrease of diameter) in the diffuser delivers the desired pressure recovery even in the low Reynolds number of about 5000, and the CBPR can be improved. Therefore, the forward facing step in the diffuser is suggested to be a new countermeasure against the PUP in the low Reynolds number.

1. Introduction

Gas flow measurement is one of the most important industrial measurements, and CFVNs (Critical Flow Venturi Nozzles) are widely used as transfer standards. When the back pressure ratio (downstream pressure / upstream pressure) is lower than CBPR (Critical Back Pressure Ratio), flow velocity at the throat reaches the speed of sound, and the flow condition becomes stable. Therefore, the CFVNs can realize the accurate measurement of the flow rate. However, in the CFVNs, there is an essential problem where low back pressure ratio is required to produce choked flow. Assuming ideal gas and isentropic flow, the CBPR of the CFVNs without diffuser is about 0.528. In the subsonic flow after the transition occurred from the supersonic flow, the flow velocity decreases with the expansion of the flow path. Therefore, the diffuser plays a role as a pressure recovery system, and the its presence enable the CFVNs to choke at high back pressure ratio. However, previous research has reported that the pressure recovery effect of the diffuser deceases significantly in some CFVNs, and it is called Unchoking Phenomenon, the PUP (Premature Unchoking Phenomenon) or DPI (Diffuser Performance Inversion) [1] [2] [3] [4] [5]. In this study, we use the term “PUP”. The discharge coefficient usually shows a constant value up to a certain back pressure ratio and then decreases. When the PUP occurs, a decrease and a recover of the discharge coefficient are observed in a certain pressure ratio range (**Figure 1**). Many studies have been conducted on the relationship between the diffuser shape (length and angle) and the PUP. Cater et al. [5] [6] conducted experiments to verify the CBPR of the various CFVNs, and stated that a diffuser which was 10 times or more longer than the throat diameter was effective to suppress the PUP ($R_e > 14000$). Park et al. [7] concluded from the experimental results that the effect of the diffuser angle on the CBPR was small when it was in the range of 2° to 6°. Conversely, Asano et al. [8] claimed that the diffuser angle was optimal at around 3.5°, and their conclusions are conflicting. This may be attributed to different Reynolds numbers in the experiment. ISO 9300 [9] provides the relationship between the ratio of the diffuser exit area A_{ex} to the throat area A_{th} and the CBPR, assuming isentropic flow. However, the

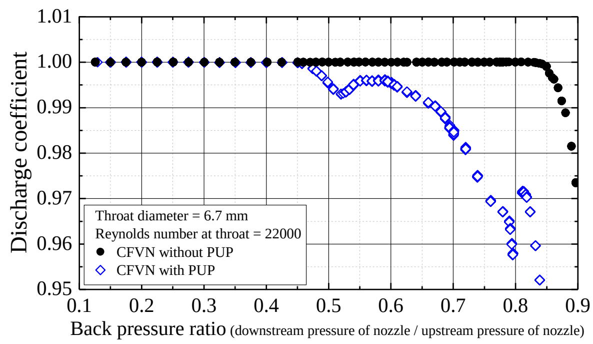


Figure 1: An example of PUP.

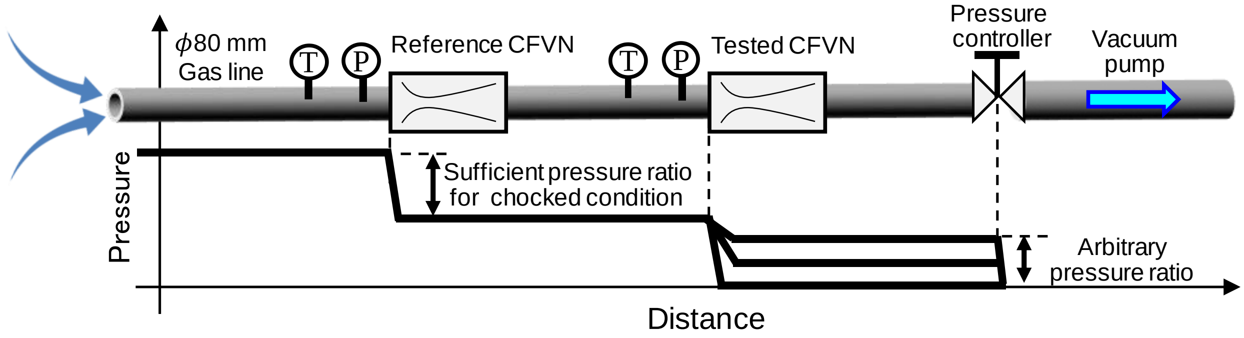


Figure 2: Schematic diagram of experiment.

relationship is applicable to Reynolds numbers greater than 2.0 × 10^5, and under low Reynolds number conditions, it is recommended in ISO 9300 [9] that the users maintain back pressure ratio of 0.25 or less. As seen in these studies, the PUP is a complex phenomenon, and the CBPR is different depending on Reynolds number and diffuser shape (length, angle, diffuser exit area). Especially in the low Reynolds number region, the discharge coefficient is strongly influenced by the PUP, and rational criteria for the CFVNs have not been established.

Since it is extremely difficult to uniquely determine the effective diffuser length and angle to suppress the PUP, a different approach in which a step is provided immediately after the throat has been proposed. von Lavante et al. [10] [11] indicated from experiments and numerical analyses that pressure fluctuation due to the oscillating shock in the diffuser leaded to unchoked condition, and by providing a backward facing step (causing increase of diameter) immediately after the throat, time variation of mass flow was suppressed. Cater et al. [6] verified the CBPR of the CFVNs with throat diameter d of 1.6 mm and diffuser length of 5.3d, and indicated that the CBPR was greatly increased by the backward facing step after the throat when Reynolds number was about 2.0 × 10^5. Therefore, although providing a step in the diffuser seems to be effective to suppress the PUP, the detailed verification of the Step Location and step size has not been conducted. In this study, we investigate the effect of the Step Location and step height on the CBPR. Especially, we report in detail the experimental results of a forward facing step (causing decrease of diameter) in the diffuser that is effective against the PUP.

2. Experimental setup

Figure 2 and **Figure 3** shows a schematic diagram of the experiment and measurement locations of the temperature and pressure respectively. On the upstream side of the test line, a reference CFVN whose discharge coefficient is known, and on the downstream side, a

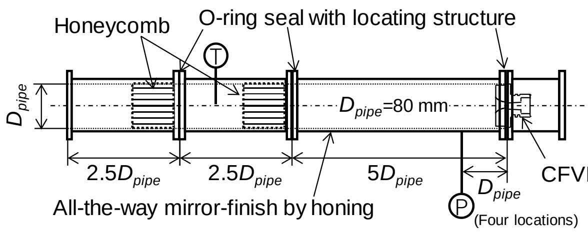


Figure 3: Measurement locations of temperature and pressure

tested CFVN are installed in series. Since the mass flow rate is constant in the test line, when the flow is steady, **Equation (1)** is derived as follows.

$$C_{d\_REF} Q_{theo\_REF} = C_{d\_DUT} Q_{theo\_DUT} \qquad (1)$$

where C_d is the discharge coefficient and Q_{theo} is the theoretical mass flow rate. The theoretical mass flow rate was derived by the same method as Ishibashi [12]. Additionally, the subscripts REF and DUT represent the values of the reference CFVN and tested CFVN respectively. During the experiment, a flow is generated in the test line by vacuum pumps, and C_{d_DUT} is calculated from **Equation (1)**. The discharge coefficient shows a constant value if it is less than the CBPR. The back pressure ratio of the tested CFVN is changed by the pressure controller, and the back pressure ratio where the discharge coefficient decreases by 0.2% is defined as the CBPR.

In this study, as the CFVNs for the countermeasure against the PUP, a step is provided immediately at the throat, at the end of the toroid and in the diffuser, and their locations are called Step Location A, Step Location B and Step Location C (**Figure 4**). The CFVNs with steps are not a one piece, and the diffusers are attached to each CFVN. **Table 1** shows the experimental cases. Large and small backward facing steps are provided at Step Location A (at the throat) for Case 3 to 6 and Step Location B (at the end of toroid) for Case 7 to 10. For Case 15 and 16, a forward facing step is provided at Step Location C (in the diffuser).

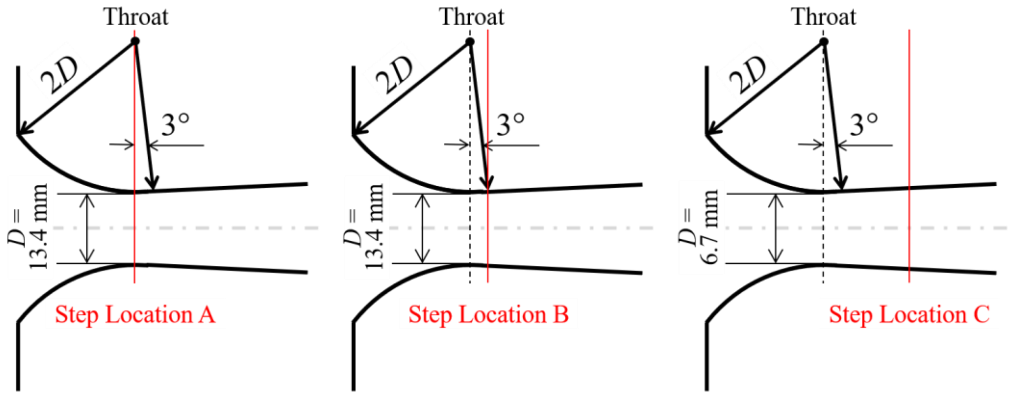


Figure 4: Outline of step location (Step Location A: at the throat, Step Location B: at the end of toroid and Step Location C: in the diffuser).

Table 1: Experimental Case.

Case	Throat Diameter d	Reynolds Number at throat Re	Diffuser Angle θ	Ratio of Diffuser Length to Throat Diameter L/d	Ratio of Diffuser Exit Area to Throat Area A_e/A_{th}	Step Location	Diameter change ratio before and after step $(d_{as}/d_{bs}$-1.0)*100
1	13.4 mm	44000	3.0	2.3	1.6		
2		11000					
3		44000				Step Location A (Step at the throat)	1.1
4		11000					
5		44000					3.0
6		11000					
7		44000		2.4		Step Location B (Step at end of toroid)	0.6
8		11000					
9		44000					2.4
10		11000					
11	6.7 mm	22000	3.0	2.4	1.6		
12		5500					
13		22000		8.7	3.7		
14		5500					
15		22000		10.5	4.0	Step Location C (Step in diffuser)	-8.5
16		5500					

3. Experimental results and discussion

3.1 Step at the throat and at the end of toroid (Step Location A and Step Location B)

Figure 5 shows the relationship between the back pressure ratio and the discharge coefficient for Case 1 to Case 10. Two types of large and small backward facing step (causing increase of diameter) are provided at Step Location A for Case 3 to 6 and Step Location B for Case 7 to 10. Additionally, in **Figure 5 (a)** (Case 1, 3, 5, 7 and 9), the Reynolds number at the throat is about 44000, and in **Figure 5 (b)** (Case 2, 4, 6, 8 and 10), it is about 11000.

In **Figure 5 (a)**, where the Reynolds number at the throat is about 44000, the CBPR of the CFVNs with steps (Case 3, 5, 7 and 9) is higher than that without a step (Case 1). This tendency is the same as previous studies [6] [13], and Wright et al. [13] discussed the improvement of the CBPR by the step at the throat from the following perspectives. A step 1) reduces the boundary layer thickness, 2) trips boundary layer from laminar to turbulent and 3) anchors a Prandtl-Meyer expansion fan and forces normal shocks further downstream, away from the throat. Comparing the CFVNs with a step, for Case 3 and 7 (small step height), the discharge coefficient decreases and recovers about 0.3% to 0.4% when the back pressure ratio is in the range of 0.6 to 0.65. Conversely, for Case 5 and 9 (large step height) the discharge coefficient is constant until the back pressure ratio reaches 0.75. Therefore, when the Reynolds number of is about 44000, step height is an important parameter for the CBPR. There is no significant difference in the CBPR depending on the step position (at the throat or at the end of the toroid).

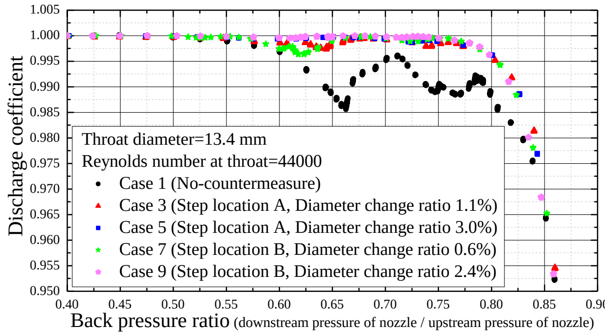
In **Figure 5 (b)**, where the Reynolds number at the throat is about 11000, the CBPR of the CFVNs with steps (Case 4, 6, 8 and 10) is equal to or less than that without a step (Case 2). This means that Although the steps at the throat or at the end of the toroid is effective for improving the CBPR at the Reynolds number of about 44000, it does not provide the improvement when the Reynolds number decreases to 11000. The behavior of the discharge coefficient to the back pressure ratio is similar in Case 4 and Case 6 (also, Case 8 and Case 10). In other words, when the Reynolds number is about 11000, the CBPR varies depending on the step position. This is different from the experimental results when the Reynolds number is about 44000. From the above results, the effect of the step at the throat or the step at the end of the toroid is largely dependent on the Reynolds number, and it is extremely important to verify whether the countermeasures are effective even in the low Reynolds numbers.

3.2 Step in the diffuser (Step Location C)

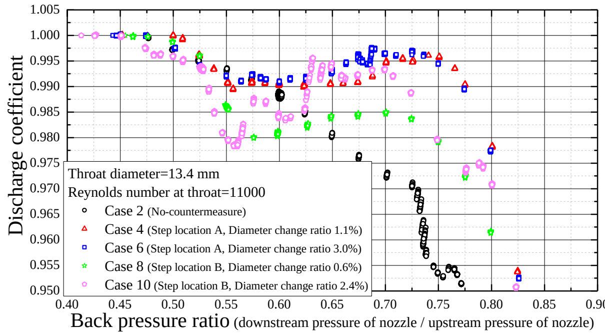
3.2.1 CBPR of a CFVN with the step in the diffuser

Figure 6 shows the relationship between the back pressure ratio and the discharge coefficient for Case 11 to Case 16. For Case 15 and 16, a forward facing step (causing decrease of diameter) is provided at Step Location C. When Reynolds number at the throat is about 22000, the CBPR for Case 11, Case 13 and Case 15 are about 0.48, 0.83, and 0.85, respectively. In Case 11 where the diffuser length is short, the CBPR is lower than in Case 13 and Case 15, and the short diffuser is not effective on pressure recovery. There is no significant difference in the behavior of the discharge coefficient to the back pressure ratio between Case 13 and Case 15.

When Reynolds number at the throat is about 5500, the CBPR for Case 12, Case 14 and Case 16 are about 0.60, 0.46, and 0.75, respectively. In Case 14, the CBPR is lower than in Case 12, and strong influence of the PUP can be seen. Cater et al. [5] [6] stated that at Reynolds numbers of 14,000 or more, the CFVNs with the long diffuser longer was effective for the PUP. Although this tendency is also confirmed in this experiment (Case 13), the effect of the long diffuser is small at low Reynolds numbers (Case 14). As described above, the PUP due to the interaction of shocks in the diffuser with the boundary layer is a very complicated phenomenon, and it is extremely difficult to derive a general rule from the experimental results. In Case 16, the CBPR is significantly increased compared to Case 14 having approximately the same diffuser length. From these results, it is clarified that a forward facing step in the diffuser delivers the desired pressure recovery even in the low Reynolds number of about 5000, and the CBPR can be improved. The above-mentioned methods of "using the long diffuser" and "providing a step at the throat or at the end of toroid" have small effects in the low Reynolds numbers. Therefore, the forward facing step in the diffuser is suggested to be a new countermeasure for the PUP in the low Reynolds number, and it is very useful finding in establishing rational and practical design guidelines for the CFVNs.



(a) Case 1, Case 3, Case 5, Case 7 and Case 9.



(b) Case 2, Case 4, Case 6, Case 8 and Case 10.

Figure 5: Relationship between back pressure ratio and discharge coefficient for Case 1~Case 10.

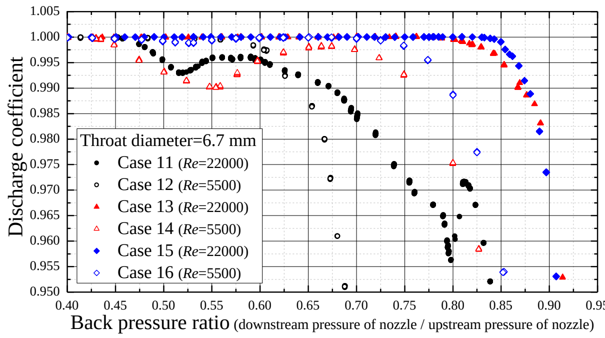


Figure 6: Relationship between back pressure ratio and discharge coefficient for Case 11~Case 16.

3.2.2 Pressure recovery effect and pressure distribution in the diffuser

Assuming isentropic flow, the relationship between the cross sectional area of the diffuser A and the pressure P is expressed by **Equation (2)**.

$$\frac{A}{A_{th}} = \sqrt{\frac{\gamma-1}{2\left\{\left(\frac{P_0}{P}\right)^{1-\frac{1}{\gamma}}-1\right\}}}\left\{\frac{2\left(\frac{P_0}{P}\right)^{1-\frac{1}{\gamma}}}{\gamma+1}\right\}^{\frac{\gamma+1}{2(\gamma-1)}} \quad (2)$$

where P_0 is the stagnation pressure and γ is specific heat ratio. The degree of pressure recovery is determined by the diffuser exit area from **Equation (2)**. Even in ISO 9300 [5], based on isentropic flow, the CBPR is estimated from the relationship between the ratio of the diffuser exit area of A_{ex} to the throat area A_{th}. However, the flow after the throat is supersonic, and a phenomenon with an increase in entropy due to shocks occurs in the diffuser.

Additionally, the shocks in the diffuser are also one of the causes of flow separation, and, therefore, the actual diffuser does not provide the expected pressure recovery. In order to estimate the CBPR, it is necessary to consider not only the diffuser shape but also the shocks in diffuser. The pressure ratio before and after the normal shock is expressed as follows from Rankine-Hugoniot equation. Using **Equation (3)** and the relationship between the cross-sectional area A and the Mach number M shown in **Equation (4)**, it is possible to calculate the downstream pressure of the normal shock generated at any position in the diffuser. **Figure 7** shows the relationship between the cross-sectional area A and the pressure P (**Equation (2)**) and the downstream pressure after the normal shock.

$$\frac{P_{as}}{P_0} = \frac{2\gamma M^2-\gamma+1}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}} \quad (3)$$

$$\frac{A}{A_{th}} = \frac{1}{M}\left\{\frac{(\gamma-1)M^2+2}{\gamma+1}\right\}^{\frac{\gamma+1}{2(\gamma-1)}} \quad (4)$$

where P_{as} is the downstream pressure of the shock. It is confirmed from **Figure 7** that the downstream pressure of the shock does not coincide with the pressure assuming transonic and isentropic flows. Assuming that, the pressure is recovered isentropically at the downstream of the normal shock, by determining the throat area, the diffuser exit area and the downstream pressure of CFVNs, it is possible to theoretically calculate the shock location and the amount of pressure recovery. **Figure 8** shows a value by subtracting the pressure in the supersonic flow from the downstream pressure after the normal shock. the value is derived assuming the diffuser angle of 3°, and the horizontal axis is the ratio of the throat diameter to the distance from the throat. From **Figure 8**, the amount of pressure recovery is different depending on the shock location. The amount

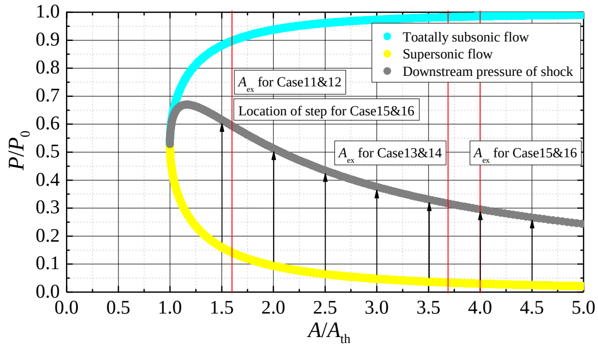


Figure 7: Relationship between cross-sectional area of diffuser and pressure.

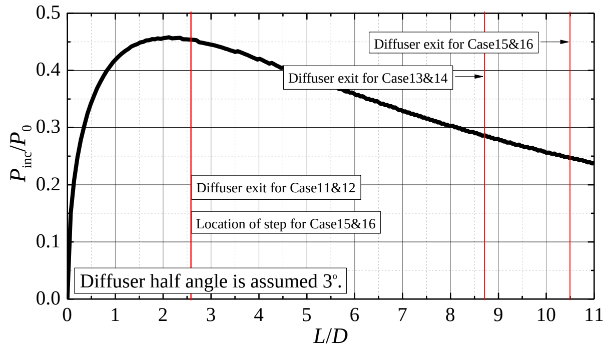


Figure 8: Relationship between shock location and amount of pressure recovery.

of pressure recovery becomes the maximum value of $P_{inc}/P_0 = 0.46$ when the normal shock occurs at $L/d = 2.1$. From the viewpoint of the pressure recovery, it is desirable that the amount obtained by the diffuser is large. However, the strong adverse pressure gradient due to the normal shock as shown in **Figure 8** causes flow separation. Since the forward facing step in the diffuser blocks the flow, an pressure increase is expected in vicinity of the step. This means that the forward facing step in the diffuser gives the same recompression as the normal shock with a different mechanism. From the reasons, we infer that the recompression, that is, the pressure gradient around the forward facing step is weaker than the that around the normal shock, and the CBPR increases by the suppressing flow separation.

4. Summary

In this study, we conducted experiments to investigate the CBPR (critical back pressure ratio) of CFVNs. In order to improve the CBPR, we focused on the step in the diffuser and verified the its effect. As a result, the following conclusions were obtained.

- The step at the throat and the step at the end of toroid are effective for improving the CBPR at the Reynolds number of about 44000. Conversely, they do not provide the improvement when the Reynolds number decreases to 11000.

- Since the effect of the step height on the CBPR depends on the Reynolds number, it is difficult to conclude the optimal step height (diameter change ratio before and after step). Therefore, it is extremely important to verify whether the countermeasures are effective even in the low Reynolds numbers.
- A forward facing step (causing decrease of diameter) in the diffuser delivers the desired pressure recovery even in the low Reynolds number. Although the CBPR is 0.46 without the forward facing step, it resulted the CBPR of 0.75 at the Reynolds number of 5000. Therefore, the forward facing step in the diffuser is suggested to be a new countermeasure against the PUP in the low Reynolds number.

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