# Possibility of Universal CFVN
# -- Forced Boundary Layer Transition in CFVNs --

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**Abstract**

A rough surface artificially created on the inlet contraction of critical-flow Venturi nozzles (CFVNs) lowers and fixes the transition Reynolds numbers with keeping the stability of their flow-rates in the same degree as those without the transition. The lowered transition Reynolds number results in the smaller jump of the discharge coefficient caused by the transition. Experimental results of the forced transitions in CFVNs of various shapes are shown in the paper and a possibility of the "Universal CFVN" that has a smooth curve of the discharge coefficient over the full range of the Reynolds number from the laminar to the turbulent boundary regimes are discussed.

## 1. Introduction

Critical flow Venturi nozzle (CFVN) is the most accurate and stable gas flow meter/generator. Its characteristics is well defined in literatures such as ISO 9300 [1], ASME PTC19.5 [2], and so on. However, it is well-known that the characteristics of CFVNs suddenly changes owing to the boundary layer transition (BLT) that mostly occurs at the Reynolds number of $1{\sim}2\times10^6$. This phenomena makes the literatures define two characteristics for a CFVN depending on the Reynolds number range. The users of CFVNs then have to avoid using CFVNs in the BLT range otherwise they can detect it, which is very difficult. ISO 9300 defines a single curve covering the whole Reynolds number range by loosening its uncertainty to include the both characteristics within its uncertainty, which was a breakthrough that made the users be not necessary to care about the BLT, but some of them may wish a smaller uncertainty. Of course, ISO 9300 defines a characteristics curve with a smaller uncertainty but it can be adopted only in the laminar boundary layer regime at the Reynolds number of up to $1.4\times10^6$.

It is commonly considered that BLT is unstable and sensitive to the flow condition so that it is difficult to predict its transition Reynolds number. It was however demonstrated that BLT in high precision nozzles (HPNs) (or the accurately machined nozzles by the terminology of ISO 9300) is rather stable and predictable although there found some small variations in the tendency of the characteristics changes during the BLT [3]. Since the variations are not so large in practice, it will be possible to define a single curve covering over the whole Reynolds number range [3] that will have a smaller uncertainty than that currently defined in ISO 9300. However, if the curve should be applied to many CFVNs including normally machined CFVNs of various surface finishes, some more verification may be needed.

Under these circumstances, the author proposed to adopt new geometries other than the modern standard ones to have smaller characteristic variation during the BLT [3]. This paper is to propose another possibility to overcome the BLT problem, that is, to fix the transition Reynolds number by a trip put on the inlet surface.

Forced BLT using a trip is also applied to one of the new geometry that has a potential to replace the current standard one, that is, $R$=1$D$ HPNs where $R$ is the inlet curvature and $D$ is the throat diameter. In $R$=1$D$ HPNs, BLT have not been observed at the Reynolds number up to about $2\times10^6$, but the forced transition revealed that they do have a BLT, however, the change of the characteristics caused by the BLT is small enough for practical applications so that it will be possible to define a single curve in a simple form as ISO 9300 does that represents the characteristics of the new CFVN over the whole Reynolds number range with a smaller uncertainty.

All the $C_d$ in the paper were measured by the middle-range air flow standard in Japan [4] [5] except for those in Figure 2 shown by void circles that were measured by a company [3].

## 2. BLT in CFVNs of standard geometries

Figure 1 shows the behaviours of the discharge coefficient, $C_d$, of 24 HPNs across the BLT. All the HPNs are complying with ISO 9300 toroidal throat CFVN with $D$ ranging from 13.4 to 18.9 mm. aCURVE and nCURVE are the $C_d$ curves defined in ISO 9300 [1] for accurately and normally machined CFVNs, respectively. sCURVE is defined in the reference [3] to trace aCURVE, nCURVE and the center of the $C_d$ changes caused by the BLT in HPNs. HPN is categorized in the accurately machined CFVN in the definitions of ISO 9300. The maximum deviation of the measured $C_d$ from sCURVE is smaller than $\pm$0.2% so that sCURVE will be a good standard curve for toroidal throat CFVNs complying with ISO 9300 as far as the figure shows. It is noted that all the points in the figure are plotted by void circles and there is no solid circle at all, so the circles apparently look solid were by illusions of superimposed void circles.

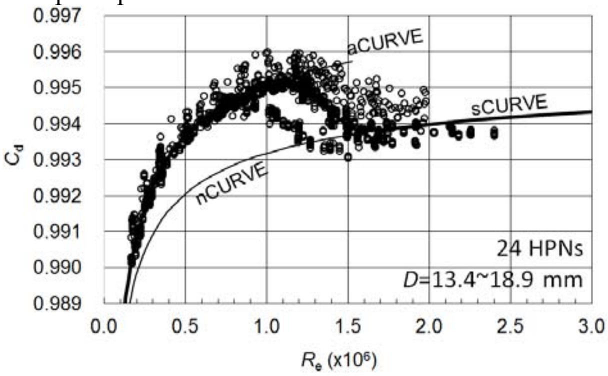



**Figure 1:** $C_d$ of 24 HPNs across BLT. All accurately machined ISO toroidal throat CFVNs (HPNs). All plotted by void circles.

Figure 2 shows the behaviours of $C_d$ of 8 normally machined CFVNs. Seven of them were carefully machined [3] so the geometry parameters were well defined but one of them had only a rough estimation of the throat diameter thus its $D$ value was modified to let its $C_d$ fit aCURVE in the laminar boundary layer regime. As far as the figure shows, normally machined CFVNs also behave almost the same as HPNs even in the BLT regime.

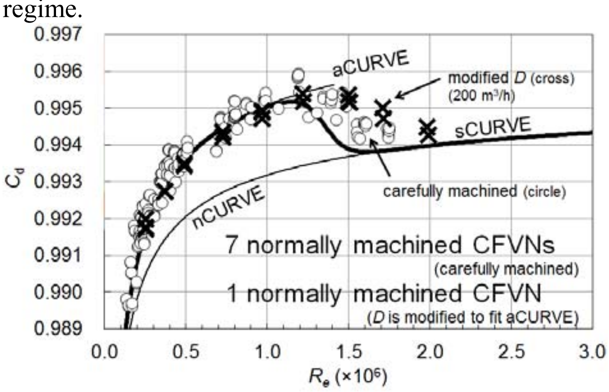



**Figure 2:** $C_d$ of 8 normally machined CFVNs across BLT.

## 3. Delayed BLT problem

Figure 3 shows $C_d$ of a HPN that has no clear BLT observed at the Reynolds number up to $2\times10^6$. It has somewhat special inlet geometry, that is, $D_{in}$=5$D$ but it is still complying with ISO 900, where $D_{in}$ is the inlet diameter (see Figure 6). The HPN has no sharp edge on the inlet contraction, so it may imply that the smooth inlet geometry delayed the BLT, however, the author found other HPNs with $D_{in}$=5$D$ that followed sCURVE, so there is no deterministic conclusion on the reason of the delayed BLT.

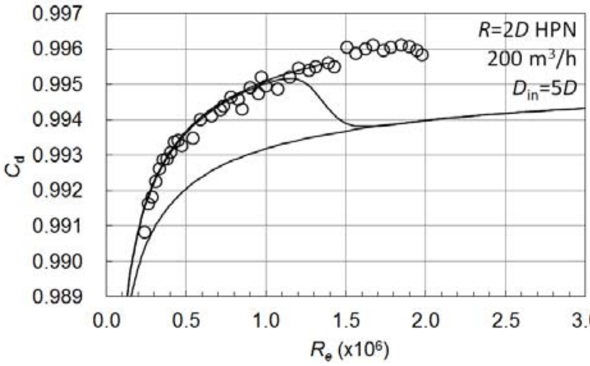


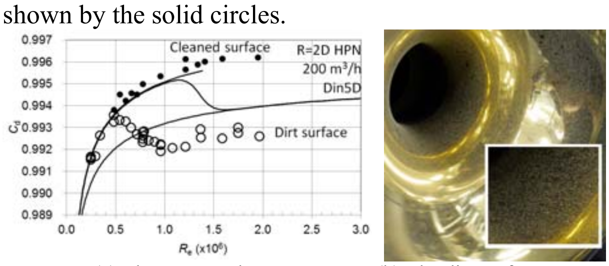

**Figure 3:** $C_d$ of a HPN with $R$=2$D$ ISO toroidal throat. Totally smooth inlet by $D_{in}$=5$D$.

## 4. Early BLT problem

The HPN discussed in 3. once had an unexpected BLT caused by dirt over its surface as shown in Figure 4. The surface was uniformly dotted at a low density by small particles of CaCl2 resulting in a surface that was felt like a rough sandpaper. This is an example that the surface roughness may cause unexpectedly large deviation from sCURVE. It is noted that the variation of the $C_d$ along the Reynolds number in the forced turbulent boundary layer regime is almost parallel to nCURVE. It is about -0.1% shifted, but the difference will be negligible in most practical uses, therefore, the dirt HPN could have used together with nCURVE rather than sCURVE to have a smaller error if the forced turbulent boundary layer has the same characteristics as the natural one at the higher Reynolds numbers.

It is also noted that the transition was very stable. The figure has 47 void circles that were obtained by calibrations performed over 10 days. There was no hysteresis observed as the figure clearly indicates.

Cleaned surface recovered the original characteristics as shown by the solid circles.




(a) The measured $C_d$. (b) The dirt surface.

**Figure 4:** $C_d$ of the HPN shown in Figure 3 when its surface had dirt.

## 5. Effect of the downstream geometry on the BLT

Figure 5 shows the $C_d$ variations during the BLT in HPNs that have (a) no diffuser, (b) a very short diffuser of 0.06$D$ length or (c) no diffuser but the throat is cylindrical for 0.5 mm as shown in Figure 6. All the HPNs have $D$=13.4 mm. It is confirmed that there is no affects on the BLT from the geometries at and downstream of the throat.

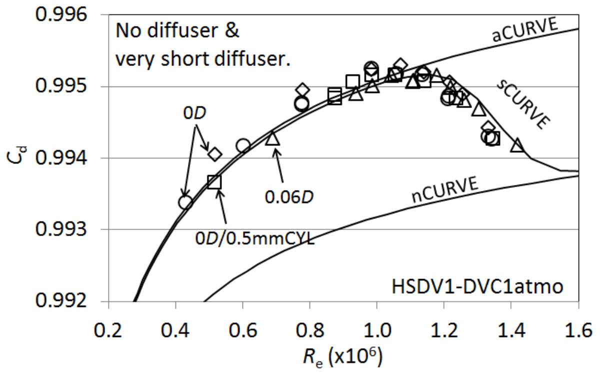
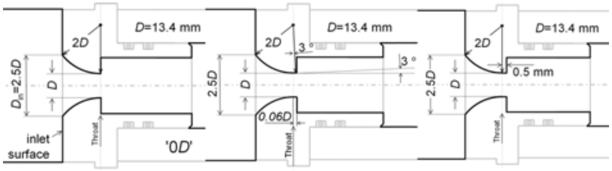



**Figure 5:** $C_d$ of HPNs with no or a very shot diffuser shown in Figure 6.




(a) No diffuser. (b) 0.06*D* diffuser. (c) 0.5mm cyl / no diffuser.
**Figure 6:** The no and very short diffuser HPNs.

## 6. Forced BLT in a *R*=1*D* HPN by DAUB paints

A paint containing fine particles that makes the surface certainly rough was hand-painted on the inlet surface of a HPN of *R*=1*D* where *D*=18.9 mm as shown in Figure 7. The HPN has a totally smooth inlet with $D_{in}$=3*D* and a long enough diffuser. The paint patterns are distinguished by the distance of the paint edge of the throat-side from the inlet surface, but the distances are not so accurate thus they are just for identification. As seen later, the paint location is not so critical. The paint height (thickness) is unknown, but a certain height could be recognized by visual check as may be seen in the figure. Recoating to change the height was also examined.

The paint was added towards the throat one by another from the '5 mm' paint. No care was paid onto the inlet-side edge and it was left unchanged in the recoats. The throat-side edge was carefully painted to make its edge as parallel to the throat as possible. Since the throat locates at a depth of 18.9 mm from the inlet surface, the deepest paint '13 mm' had its edge at about 6 mm upstream the throat. There were some more paint patterns made for the measurements but not shown in Figure 7.

Their $C_d$ are shown in Figure 8. Originally, the HPN did not have any BLT observed at the Reynolds number up to $2\times10^6$ as shown by the solid circles in the right figure. '5 mm' paint did not cause a clear BLT. '6 mm' to '11 mm' paints caused a clear BLT as shown in the right figure. '12 mm' and '13 mm' paints can be classified into another group by the lowered $C_d$. They can be disturbing the flow even in the laminar boundary layer regime, but to confirm it, further investigations will be needed. In any case, the BLT is not so sensitive to the paint quality, the edge quality or the edge location in a certain range since the rough paints in the group '6 mm' to '11 mm' and also '12 mm' and '13 mm' resulted in almost the same BLT in each group.

From the viewpoint of the purpose to fix the transition, the daub points can be less adequate than the band paints that will be introduced below because of the lack of the upstream edge.

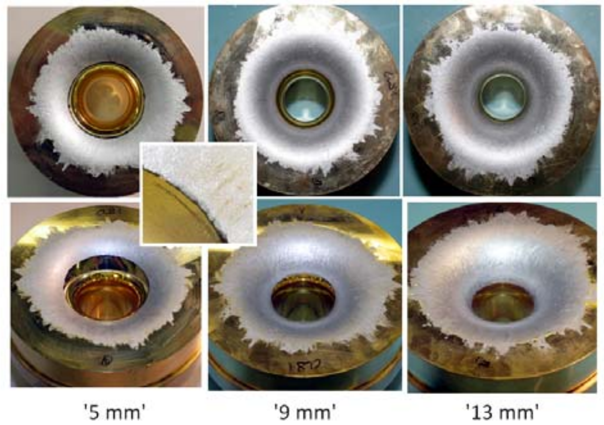
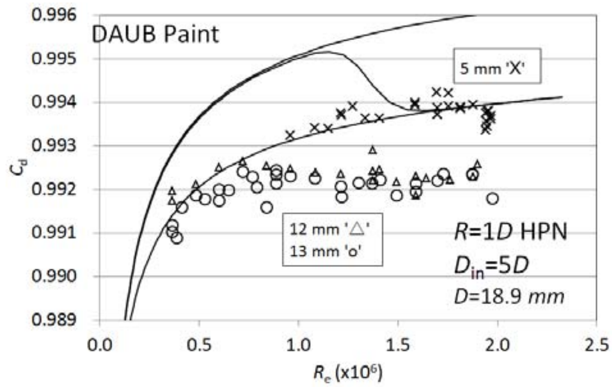
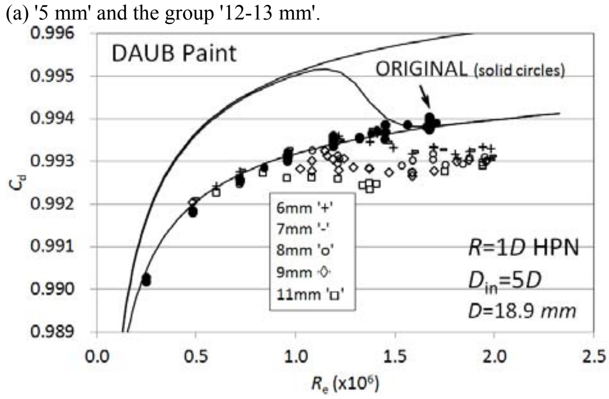



**Figure 7:** Daub paint on a HPN to force the BLT. *R*=1*D* and *D*=18.9 mm.




(a) '5 mm' and the group '12-13 mm'.




(b) Group '6-11 mm'.

**Figure 8:** $C_d$ of the daub painted HPN shown in Figure 7.

## 7. Forced BLT in a *R*=1*D* HPN by BAND paints

The forced BLT was then tried with the same *R*=1*D* HPN by 'band' paints shown in Figures 9 and 10. The two numbers in each band name indicate the rough distances from the inlet surface to the band edges of the throat-side and then the inlet-side. 'HIGHER' was a recoated one on the original band to make the band thickness higher, so as 'HIGHER#2' that was recoated again on the 'HIGHER' band. However, the 'HIGHER#2' was not just a higher band beyond the

'HIGHER' but actually a thicker and wider band owing to the low viscosity of the paint as can be recognized in the figures. Their $C_d$ are shown in Figure 11.

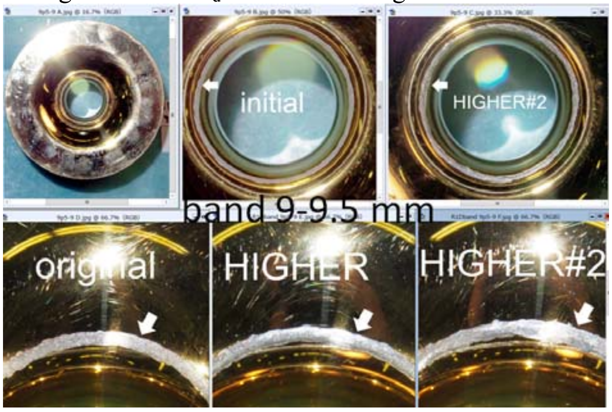



**Figure 9:** Band paints of '9-9.5 mm' on $R$=1$D$ HPN.

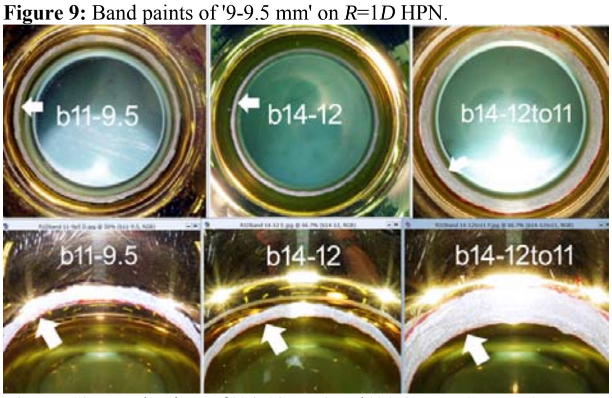



**Figure 10:** Band paints of '14-12 mm' and '11-9.5 mm' on $R$=1$D$ HPN.

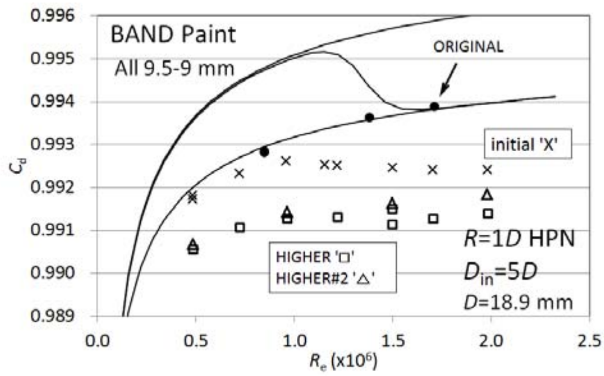
The initial '9.5-9 mm' band resulted in a 'good' BLT since the $C_d$ in the laminar boundary layer regime is still located on the original laminar boundary layer curve. The 'ORIGINAL' $C_d$ in the left figure were measured after a band had been chemically wiped away so that, by comparing with the original $C_d$ shown in Figure 8 that are really original one before being painted, it was confirmed that the paints did not give any damages on the nozzle quality.

The slightly thicker paint 'HIGHER' suddenly made $C_d$ considerably lower even in the laminar boundary layer regime, then the paint height did not affect the $C_d$ as those of 'HIGHER#2' show. This may imply that a bump of a certain height is not a good trip. Similar deduction can be obtained about edges on the inlet contraction [7].

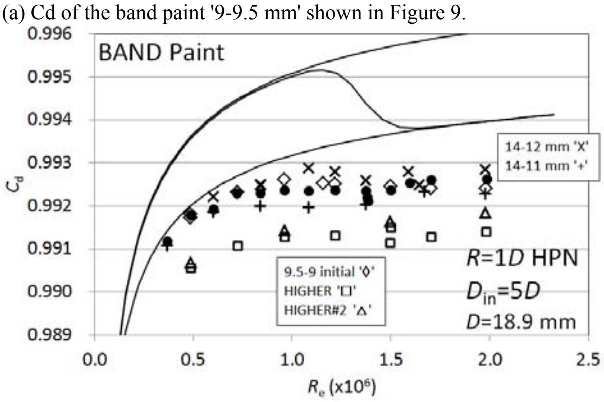
Interesting is that the paints '9.5-9 mm', '11-9.5 mm' and '14-12 mm' have almost the same $C_d$, therefore, the forced BLT is considered to be not sensitive to the trip location. The throat of the HPN locates at about 29.5 mm from the inlet surface so that their throat-side edges located in the range from about 5 mm to 20 mm upstream the throat.

The '14-12 mm' band was then recoated to have its inlet-side edge at about 11 mm, whose resultants are denoted by '14-12to11 mm'. It did not change the $C_d$ very much but the wider band resulted in slightly clearer BLT as shown in the right figure. It is interesting that the band near the throat needed a wider width than that located farer from the throat to have a clear BLT.

A vertical paint was also tried as shown in Figure 12, but it seems not to be an effective way to force the BLT.




(a) Cd of the band paint '9-9.5 mm' shown in Figure 9.




(b) '5 mm' and the group '12-13 mm'.

**Figure 11:** $C_d$ of the band painted HPN with $R$=1$D$ shown in Figures 9 and 10.

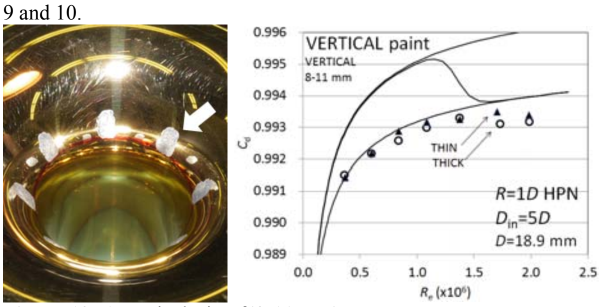



**Figure 12:** A vertical trip of '8-11 mm'.

### 8. Forced BLT in a *R*=2*D* HPN by BAND paint

The forced BLT by band paints was then examined in a $R$=2$D$ HPN that has $D$=13.4 mm and $D_{in}$=2.5$D$ so its inlet toroidal is cut of at about 1.6$D$ upstream of the throat It has a long enough diffuser.

*7.1 Various bands with the throat-side edge at 19.5 mm*

All the bands shown in Figure 13 have their throat-side edges at about 19.5 mm from the inlet surface. The band '19.5-19 mm' and '19.5-17 mm' were independent from each other, i.e., both were painted on the unpainted HPN in order to confirm the reproducibility of the forced BLT. Actually, the difference in the locations of the inlet-side edges were purely caused by the painting skill. The '19.5-17to16 mm' band was a recoat on the '19.5-17 mm' band. Their $C_d$ are shown in Figure 14.

The reproducibility of the forced BLT was OK as shown in the left figure since the differences are within 0.1%. The author who is the painter feels that the difference was caused mainly by the paint thicknesses rather than by their locations or widths of the bands. The difference of the paint qualities can be observed in the figures.

The extension of the band towards the inlet surface resulted in somewhat unexpected behaviour in $C_d$, i.e., the larger scattering was resulted in by the wider band as shown in the right figure. At some Reynolds numbers, e.g., at $1.4\times10^6$, $C_d$ was not stable so that the measurement was repeated several times. This can have been caused by the paint quality as described above. As seen in the lower right figure in Figure 13, an annular bump was created in the band center by the recoat. In any case, the scattering of $C_d$ are within 0.1%, so the differences are negligible in practical uses.

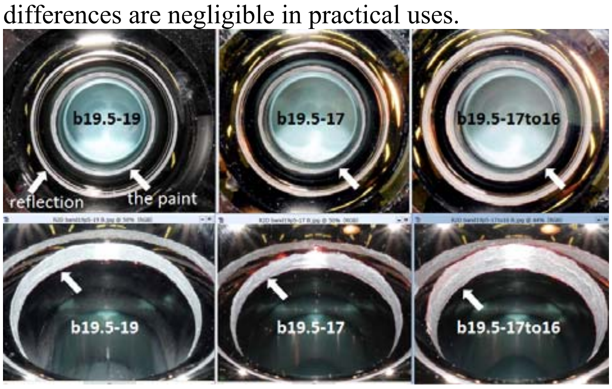
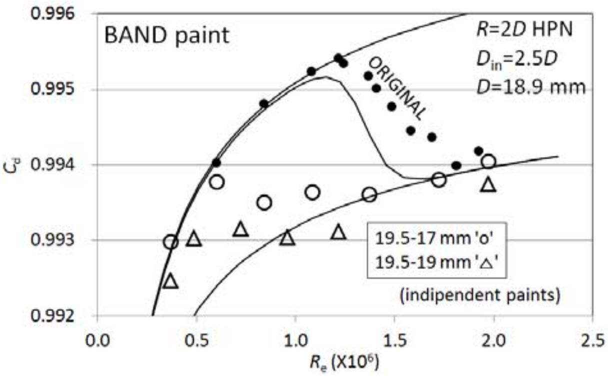
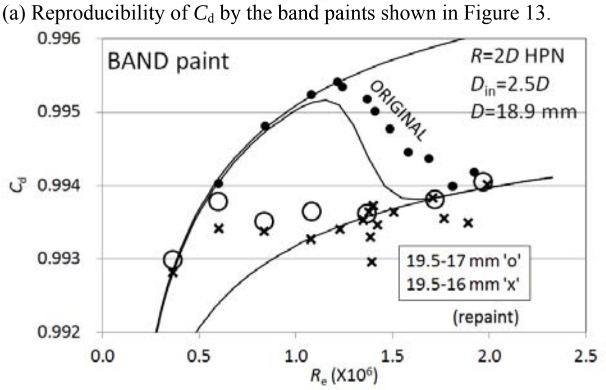


**Figure 13:** Band paints on the $R$=2$D$ HPN.



(a) Reproducibility of $C_d$ by the band paints shown in Figure 13.



(a) Extension of the band towards the inlet-side as shown in Figure 13.

**Figure 14:** $C_d$ of the band painted HPN shown in Figure 13.

*7.2 By bands of various locations and widths*

Forced BLTs were examined by various bands shown in Figure 15. At first '23-22 mm' band was painted then another one of '20-19 mm' band was added so that it was double banded, then the '23-22 mm' band was wiped away thus it was again single banded then finally the inlet-side edge of the remained band was recoated to be '20-17 mm' band. All of them resulted in almost the same $C_d$ as shown in Figure 16.

**Figure 15:** Bands on the $R$=2$D$ HPN.

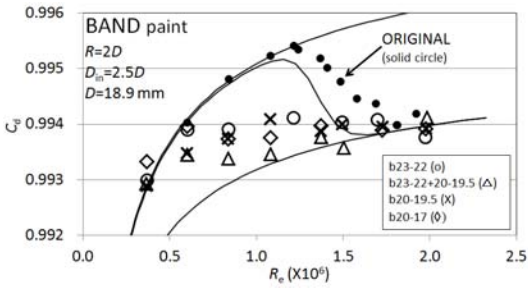


**Figure 16:** $C_d$ of the banded HPN shown in Figure 15.

*7.4 Forced BLT in various CFVNs*

The forced BLT in smaller HPNs of 100 $m^3$/h ($D$=13.4mm), 50 $m^3$/h ($D$=9.5 mm), 25 $m^3$/h ($D$=6.7 mm) were examined in the similar way as described above. All of them had a long enough diffuser and a $D_{in}$=2.5$D$ inlet. The HPN shown in Figure 6 (a), the no diffuser HPN, are also examined. Furthermore, the normal CFVN 'modified $D$' shown in Figure 2 is also included.

All of them behaved similar as shown in Figure 17. Even in the smallest HPN and also the no diffuser HPN, the forced BLT is succeeded.

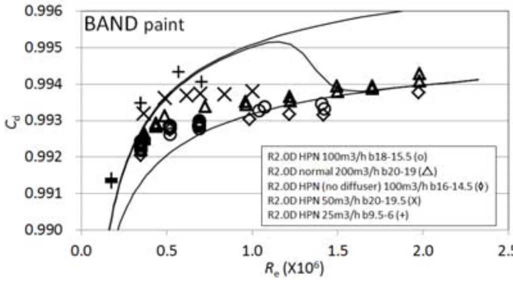
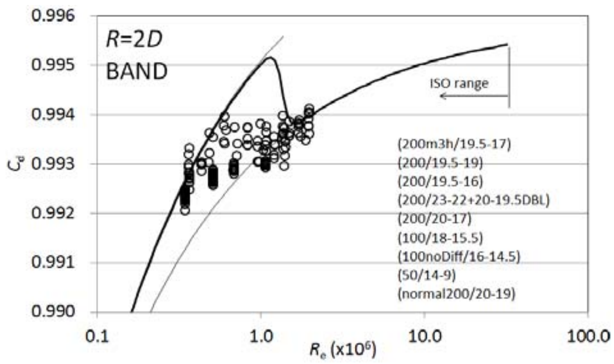


**Figure 17:** $C_d$ of various banded HP.

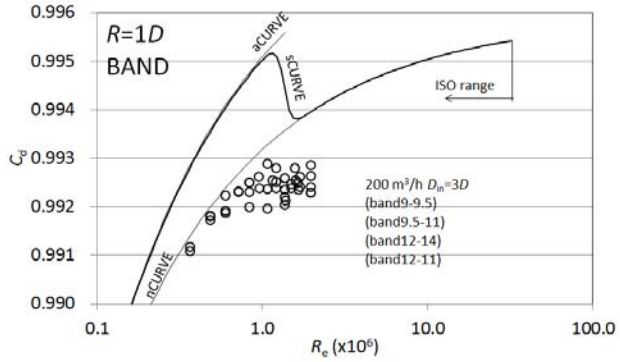
## 9. Summary

All the $C_d$ accompanied with a 'well-forced' BLT are gathered in Figure 18. These $C_d$ are not sensitive to the trip locations as many kinds of the band paints resulted in almost the same $C_d$, however, thick trips often resulted in considerable decreases of $C_d$. By comparing Figure 18 (b) with (c), it can be said that a well-painted band is a better trip than daub paints to force the BLT from a lower Reynolds number accompanied with more stable $C_d$ in the turbulent boundary layer regime. The $C_d$ of *R*=2*D* CFVNs in the forced turbulent boundary layer regimes seem to obey nCURVE. If it is correct, CFVNs with an adequate trip will have a smoother $C_d$ over the whole Reynolds number range without a large jump by a BLT at a higher Reynolds number. Such a CFVN fixing the BLT at a certain Reynolds number will have a large advantage because it will accept a certain range of surface finish to have the same $C_d$. It can be termed as the 'Universal CFVN' after the original name of one of the ISO 9300 curves, the 'Universal Curve''.

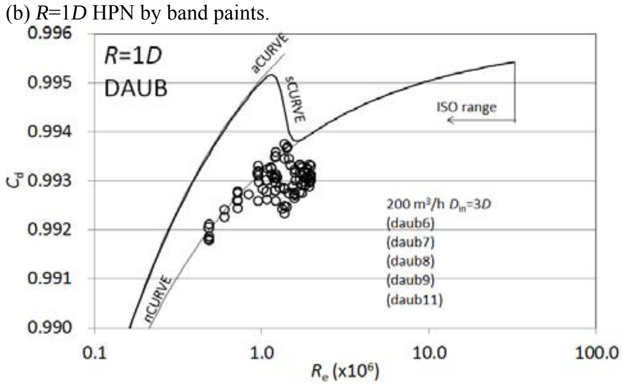
From the viewpoint of fixing the BLT or fixing the starting point of the BLT, daub paints may be less adequate than band ones because of the ambiguity of the inlet-side specific location. However, the point of transition seems to be fixed by the throat-side edge rather than the inlet-side one. It was shown that a certain width of the band is necessary to have a clear BLT. The BLT seems to have some 'resonance' on the band location; some bands near the throat needed wider width than the others located farer to have a 'well-forced' $C_d$. As far as examined, thick band or bump on the inlet surface is not adequate to let a CFVN be the Universal CFVN.




(a) *R*=2*D* HPN by band paints




(b) *R*=1*D* HPN by band paints.




(c) *R*=1*D* HPN by daub paints.

**Figure 18:** $C_d$ by the forced BLT.

**References**

[1] ISO 9300: *Measurement of gas flow by means of critical flow Venturi nozzles*, 2005.

[2] ASME PTC 19.5: *Flow Measurement*, 2004.

[3] Ishibashi M, "Discharge coefficient equation for critical-flow toroidal-throat venturi nozzles covering the boundary-layer transition regime", *Flow Measurement and Instrumentation*, **Vol 44**, pp. 107-121, 2015.

[4] Ishibashi M, Kato N, Harada H, "Dead-Volume Correction (DVC) for the Calibration of CFVNs - Differential Calibration and Optimum Estimation -", in Proc. FLOMEKO 2016.

[5] Ishibashi M and Morioka T, "The renewed airflow standard system in Japan for 5-1000 m$^3$/h", *Flow Measurement and Instrumentation*, **Vol 17**, pp. 153-161, 2006.