NUMERICAL INVESTIGATION OF TRANSITIONAL BEHAVIOR IN CRITICAL FLOW VENTURI NOZZLES

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*Abstract−*The flow fields in two toroidal Venturi nozzles operating at critical conditions have been investigated using numerical flow simulation. The present study focused on the transitional effects in the boundary layer, occuring in critical flow Venturi nozzles (CFVN) with shapes that might not confirm to the ISO 9300 standard. Two intake geometries were studied, with a well-tested transition criterium being applied. The nozzles displayed in most cases delayed transition at Reynolds numbers higher than indicated in the ISO 9300 standard

Keywords: critical nozzles, flow metering, laminar-turbulent transition

1. INTRODUCTION

The flow fields in two toroidal Venturi nozzles operating at critical conditions have been investigated using numerical flow simulation. The present study focused on the transitional effects in the boundary layer, occurring at Reynolds numbers of approximately one million and above, while concentrating on modified nozzle shapes as investigated experimentally by Ishibashi and Funaki [1]. In that publication, several modifications of the standard critical flow Venturi nozzles (CFVN) according to the ISO 9300 standard have been introduced. Depending on the shape of the nozzles, the discharge coefficient as a function of the nozzle Reynolds number diplayed behavior that was widely varying and, in contrast to the standard nozzle, not following the expected transitional dependency. Consequently, in [1], a consistant terminology has been introduced, see Fig. 1. In Fig. 1, D denotes the diameter of the nozzle at the throat.
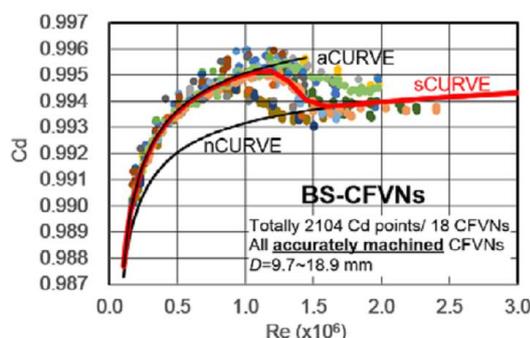

Fig.1. C_D coefficient as a function of the Re-number with the three characteristic, curves: a) laminar, n) extended turbulent and s) transitional, from [1]

However, even in view of the detailed experimental work, the apparent change in the transitional behavior could not be explained, as only global results (CD vs. Re-number) were available. Therefore, the authors of the present paper decided to carry out flow field analysis based on numerical flow simulations of two of the above modified nozzles. After the flow field with the corresponding conservative flow variables was obtained, the bypass transion of the boundary layer from laminar to turbulent could be predicted by applying the Abu Ghannam-Shaw (AGS) criterium [2], see Figure 2.

In the present investigation, only smooth inlet geometries were considered. These included standard shape with inlet radius of curvature $r_C = 2$ D, and a non-standard shape having smaller radius of curvature $r_C = 1$ D. The range of the Reynolds numbers considered in the present work was between 150,000 and 16 million. The Reynolds number was varied by changing the total pressure. The pressure ratio P_{out} / P_0 was changed between 0.2 and 0.7.

The predicted locations of the transition were mostly qualitatively consistant with the experimental findings by Ishibashi and Funaki [1]. However, their work extended to a maximum Reynolds number of 2 million, allowing only a statement that there was no obvious transition effect up to that Reynolds number. The present authors could show that in some configurations, the transition was predicted to occurre at Reynolds numbers over 4 million, well above the range investigated experimentally. At these high Reynolds numbers, the location of the transition was not affected by the outflow pressure ratios as long as the nozzle remained choked. These theoretical findings remain to be validated experimentally.

2. THEORETICAL BACKGROUND

The principle of determining bypass transition from laminar to turbulent boundary layer flow by a relatively simple procedure has been introduced by, among others, Abu-Ghannam and Shaw [2]. It has been first applied to CFVNs by von Lavante and Mickan [3]. As the procedure has been described in detail in [3], only its highlights will be given presently.

The method is based on the assumption that transition occures at a location, where the local momentum thickness of the boundary layer acceeds the critical boundary layer thickness given by the AGS formula:

$$Re_{\delta_2,crit} = 163 + \exp\left(F(K) - \left(\frac{F(K)}{6.91}Tu\right)\right)$$

$$F(K) = 6.91 + 12.75 \cdot K + 63.64 \cdot K^2 \; ; \; for K < 0$$

$$F(K) = 6.91 + 2.48 \cdot K - 12.27 \cdot K^2 \; ; \; for K > 0$$

This criterium , applied by the present authors, worked well, providing predicted locations of the transition from laminar to turbulent flow that were in qualitative agreement with experimental data given by other authors.

3. NUMERICAL RESULTS

The present numerical simulations were mostly carried out using the commercial program adapco Star CCM+ in its axisymmetric mode. Few selected cases were also simulated by the program ACHIEVE, developed by the first author and validated on multiple applications by experimental work. The results from CCM+ were consistent with those from ACHIEVE. As the commercial program CCM+ was easier to use, it was the program of choice for the present investigations. The results will be discussed for two cases. The geometries of these two cases were introduced by Ishibashi and Funaki [1]. Only geometries with smooth intake shapes (no edges) were selected, although the adges are explicitly admitted by ISO 9300. Each of the cases was simulated numerically for following set of parameters: outflow pressure ratios p_{out}/P_0 = 0.2 and 0.7; inflow turbulence level Tu = 10% and 4 %, Reynolds numbers 1.2×10^6 to up to 16×10^6.

3.1. Stepped CFVN with radius of curvature in the intake of $R_c = 2D$
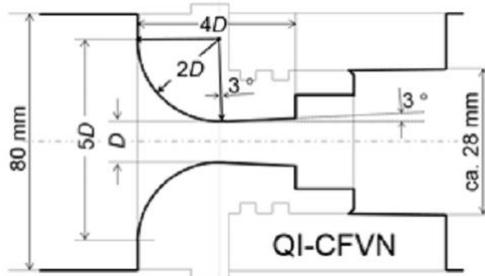

Fig.2. Geometry of cases Number 1, "2D nozzle", from [1]

The measurement of the discharge coefficient C_D, performed by [1], can be seen in Figure 3.:
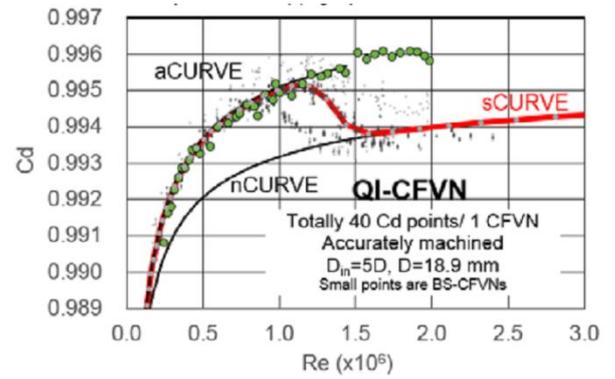

Fig. 3. Discharge coefficient C_D, "2D nozzle", from [1]

The green points (experimental data) display no sign of transition up to a Reynolds number of 2×10^6. The experiments were not carried out for higher Reynolds numbers.
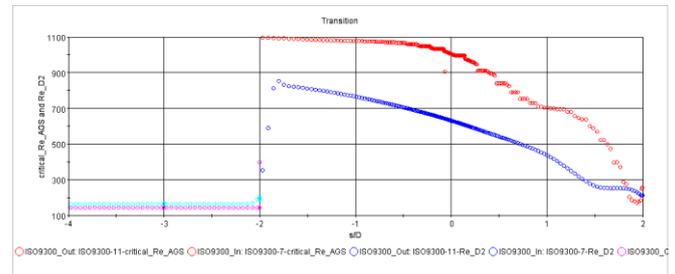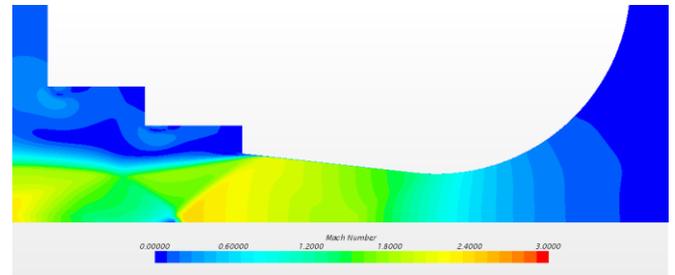

Fig. 4. Above: Flow field in the "2D nozzle", Mach number contours, p_{out}/P_0 = 0.2, Tu = 10%; Below: AGS transitional criterium applied to the flow field shown above

The flow field is shown in Figure 4 in terms of the Mach number contours for Re = 1.2×10^6 for Tu=10% and p_{out}/P_0 = 0.2. The medium (air) was flowing from right to left. Clearly visible is the oblique shock structure at the step in the outflow. The shock did not propagate to the throat, so that the nozzle remained choked at all times. Figure 4 right is demonstrating the application of the AGS-criterium; the red curve is the critical boundary layer thickness, the blue curve the local momentum boundary layer thickness. The slight overlaps in the intake part of the nozzle should be neglected, as these are close to the leading edge singularity where neither the AGS-criterium, nor the boundary layer thickness are defined. According to Figure 4 right, transition occurs in the exit shock.

An increase in outflow pressure causes the shock system to move toward the throat of the nozzle, as seen in Figure 5. The flow field displays massive separation due to the shock-

boundary layer interaction. The left picture indicates that the transition willaccure in the shock, as expected.
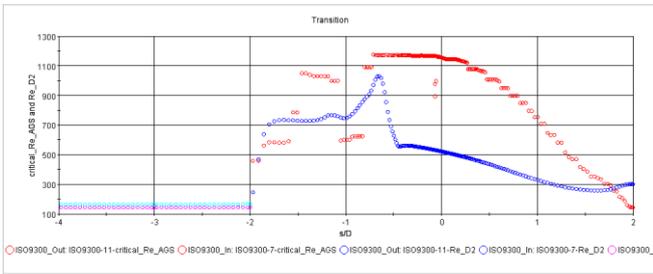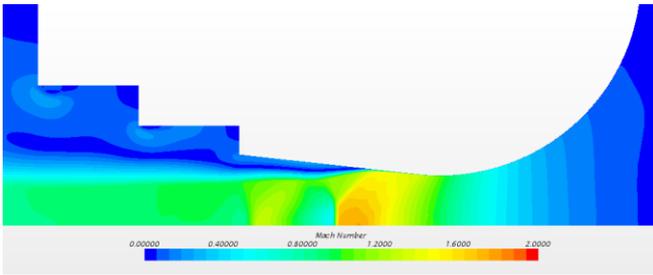

Fig. 5. Above: Flow field in the "2D nozzle" , Mach number contours, $p_{out}/P_0 = 0.7$, Tu = 10%; Re = 4.9×10^6; Below: AGS transitional criterium applied to the flow field shown above

At higher Reynolds number, Re = 4.9×10^6, the location of transition moves upstream to the throat. This is reflected by the corresponding Mach number contours as well as the AGS-curves, shown in Figure 6. Again, there was good agreement between the AGS-procedure and the expected effect of increasing the reanolds number. In the case of higher Reynolds number, however, the location of transition moved upstream to a distance along the wall of approximately s/D = -1.
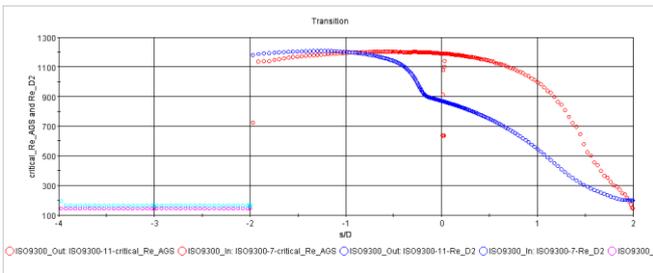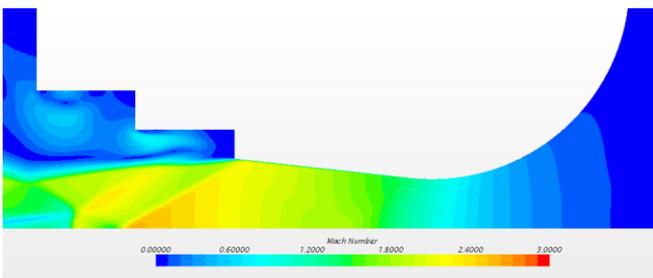

Fig. 6. Above: Flow field in the "2D nozzle" , Mach number contours, $p_{out}/P_0 = 0.2$, Tu = 10%; Re = 4.9×10^6; Below: AGS transitional criterium applied to the flow field shown above

In the case of higher outflow pressure ratio, the location of transition did not change significantly as compared to the lower Reynolds number, as the transition is induced by the shock. Still, the shock was located further downstream as compared to the lower Reynolds number due to the typical boundary layer behavior.
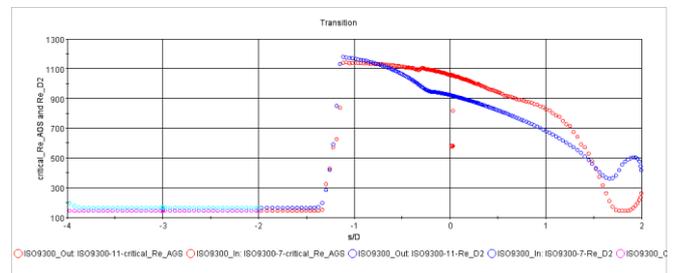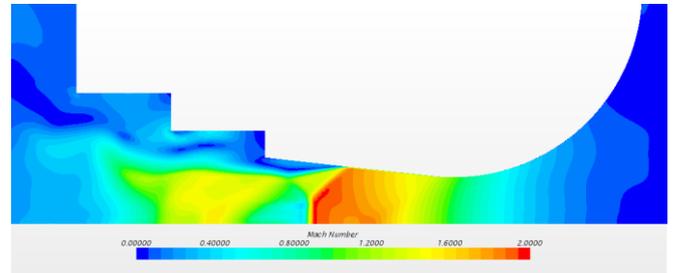

Fig. 7.Above: Flow field in the "2D nozzle" , Mach number contours, $p_{out}/P_0 = 0.7$, Tu = 10%; Re = 4.9×10^6; Below: AGS transitional criterium applied to the flow field shown above

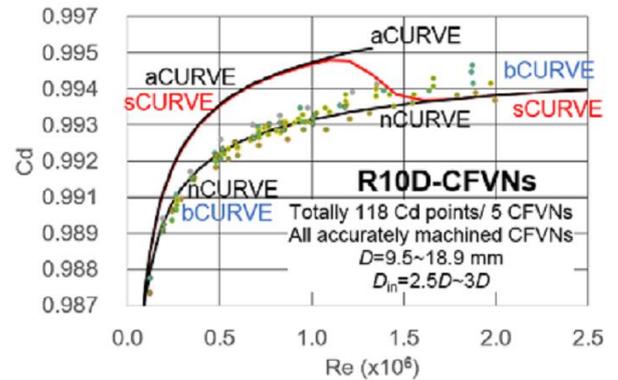### 3.2. Stepped CFVN with radius of curvature in the intake of $R_c = 1D$

Fig. 8. Discharge coefficient C_D, "1D nozzle", from [1]

The experimental data displayed in Figure 8 show no apparent transition up to a Reynolds number of Re = 2.5×10^6 as the C_d coefficient is following the so called n-curve. It was not obvious if the transition would occure at a higher Reynolds number yet or if it happend but did not affect the C_d coefficient. The subsequently shown results were supposed to shed some light on this issue.
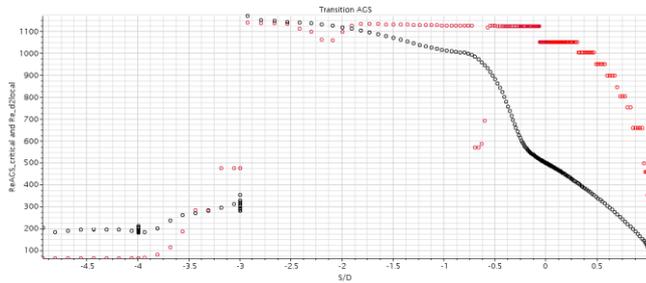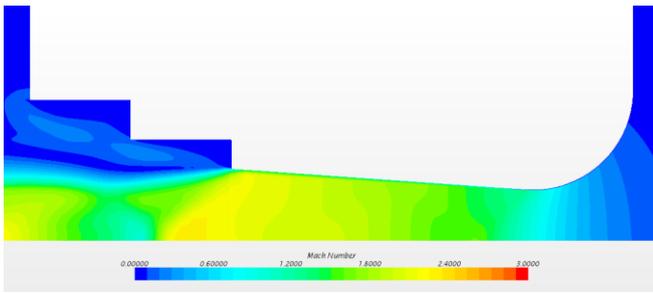
Fig. 9. Above: Flow field in the "1D nozzle", Mach number contours, $p_{out}/P_0 = 0.2$, Tu = 10%; Re = 1.2×10^6; Below: AGS transitional criterium applied to the flow field shown above

The discussion of the results will follow the above system used for the 2D nozzle. In Figure 9, we first see the results for the smaller Reynolds number of Re = 1.2×10^6 at free stream turbulence intensity of 10% and pressure ratio $p_{out}/P_0 = 0.2$. The location of the transition was predicted to be at the exit from the nozzle, not affecting the C_d coefficient.
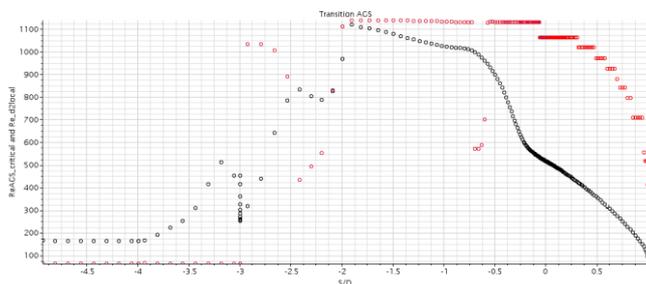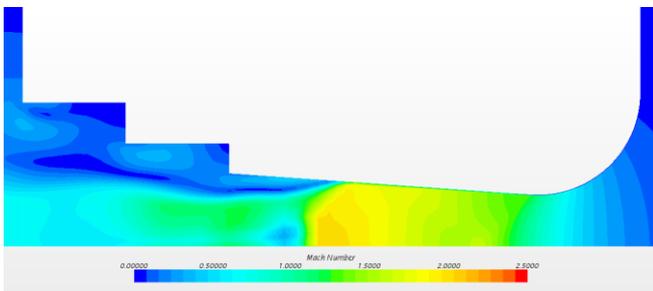

Fig. 10. Above: Flow field in the "1D nozzle" , Mach number contours, $p_{out}/P_0 = 0.7$, Tu = 10%; Re = 1.2×10^6; Left: AGS transitional criterium applied to the flow field shown above

At the higher pressure ratio $p_{out}/P_0 = 0.7$ the shock moved again upstream, but stayed at all times downstream of the throat. Consistantly with the results for the 2D nozzle, the transition was found at the shock location, as can be seen in

Figure 10. At the higher Reynolds number of Re = 4.9×10^6 , the location of transition moved upstream and just passed the throat, as can be observed in Figure 11.
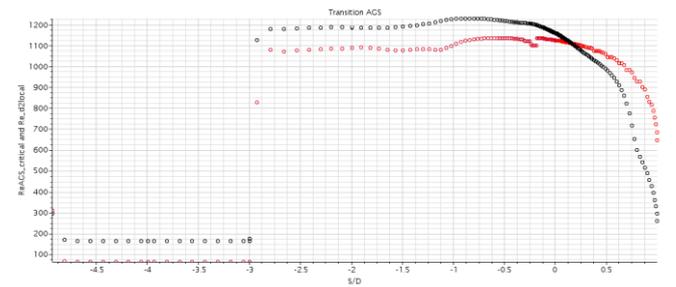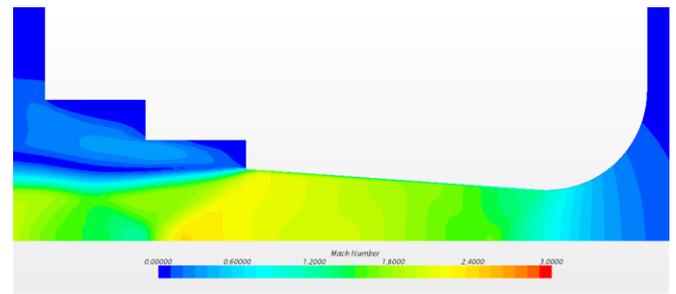

Fig. 11. Above: Flow field in the "1D nozzle" , Mach number contours, $p_{out}/P_0 = 0.7$, Tu = 10%; Re = 4.9×10^6; Below: AGS transitional criterium applied to the flow field shown above

The result is consistant with the experimental data given in [1], indicating that the transion was not apparent in Figure 8 because the experimental Reynolds number was not high enough.

4. CONCLUSIONS

The present method of estimating the location of transition gave results that were in good agreement with experimental data. In particular, the unusual behavior of the 1D nozzle was explained as delayed transition due to high local acceleration in the intake. Furthermore, in cases with relatively high back pressure, the transition was induced by a shock in the diffuser. Consequently, one has two kinds of transition in the CFVN: bypass transition, delayed by the typical flow acceleration and shock induced, with mostly unsteady shocks in the diffuser.

REFERENCES

[1] A. V. Oppenheim, R. W. Schaffer and J. R. Buck, *Discrete-Time Signal Processing*, Prentice Hall, New Jersey, 1999.
[2] M. Engin, A. Demirel, E. Engin and M. Fedakar, "Recent developments and trends in biomedical sensors", *Measurement,* vol. 37, nº. 2, pp. 173-188, March 2005.
[3] L. Van Biesen, T. Kemény and D. Röske, "Future development of IMEKO concerning non-governmental cooperation in measurement and instrumentation", *XVIII IMEKO World Congress*, pp. 1-5, Rio de Janeiro, Brazil, Sept. 2006.