# Flow Control of Annular Jet Expansion using Cross - flow Injection

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**Abstract.** This study focusses on the control of an annular jet that is issued from a stepped-conical expansion nozzle. The inner side of the annular channel consists of a central rod. Holes at the end of this central rod allow a cross - injection of 24 jets into the main flow. This cross - flow is equally distributed along the tangential direction. By varying the radial injection flow rate, the flow pattern of the main jet can be changed. A total of three different flow patterns exist, which are subject to hysteresis between an increase and subsequently decrease of radial injection flow rate.

**Key words:** flow control, annular jet, stepped - conical nozzle, cross - flow injection.

## 1. Introduction

Previous studies of the authors have shown the possibility of generating four different flow patterns within the same geometry by changing the swirl of the annular jet [3]. Important is the geometry of the nozzle, which has a large impact on the flow patterns and their transitions [2]. Also hysteresis is present between an increase and subsequently decrease of swirl. At zero swirl two different flow patterns can exist: the ‘Closed Jet Flow’ or *CJF* and the ‘Coanda Jet Flow’ or *CoJF*. The first one is an annular free jet and the second one is a wall jet. Transition between these flow patterns is only possible via the use of swirl.
Recently the authors discovered that the transition from a *CJF* to a *CoJF* is also possible without the use of swirl [1]. Some small modifications to the nozzle were enough to enable the transition with the aid of cross - flow injection. In this experiment, the radial injection flow rate fulfills the same role as the swirl number. In this paper an experimental study of the different flow patterns and the hysteresis in the transitions between them is made. The flow field is measured using a stereoscopic PIV system. Three different flow patterns exist and similar to the swirl number, hysteresis is present in an increase and subsequently decrease of the radial injection flow rate.

## 2. Experimental setup

A schematic view of the jet facility is shown in Fig. 1. A compressor generates compressed air which is stored in a buffer vessel after being dried and the compressor oil removed. The pressure inside the buffer vessel is 8 bar. This pressure is reduced to 5 bar using a pressure regulator. The flow is then separated into 2 parts: one part is called the main flow and the other one the secondary flow. Before going into the collector the main flow is seeded with particles of DEHS using an aerosol generator. In the collector the flow is divided into 6 different channels entering the settling chamber radially. In this settling chamber 12 vanes guide the main flow towards the annular channel with outer diameter $D_0 = 27\,\text{mm}$ (Fig. 1 on the left). The secondary flow rate enters the nozzle via the central rod. Along the central rod 24 holes with diameter $0.019\,D_0$ are equally distributed in the tangential direction near the end (Fig. 1 on the right). Through these holes the secondary flow is injected radially. The injection rate is regulated and measured using a mass flow controller. The range of the controller varies from 0 to $5\,\text{Nm}^3/\text{h}$ with an accuracy of $1\,\%$ and a repeatability of $0.2\,\%$ full scale. Since the radial injection has a large influence on the flow field, care was taken in the alignment of the nozzle and the central rod. Due to an in house designed positioning mechanism it is possible to centre the central rod within an eccentricity of less than $0.004\,D_0$.

## 3. Multiple flow patterns

In a cycle of increasing and subsequently decreasing radial injection three different flow patterns exist. These are labelled ‘Closed Jet Flow’ (*CJF*), ‘Open Jet Flow’ (*OJF*) and ‘Coanda Jet Flow’ (*CoJF*). A schematic view of these flow patterns is shown in figure 2. The starting flow pattern in a cycle of increasing and subsequently decreasing the injection flow rate is the *CJF* (Fig. 2*a*). At an increasing radial flow rate the *CJF* expands more radially and at an injection flow rate of 2 $\text{Nm}^3/\text{h}$ the *CJF* attaches to the divergent wall of the nozzle. This is the transition from a *CJF*

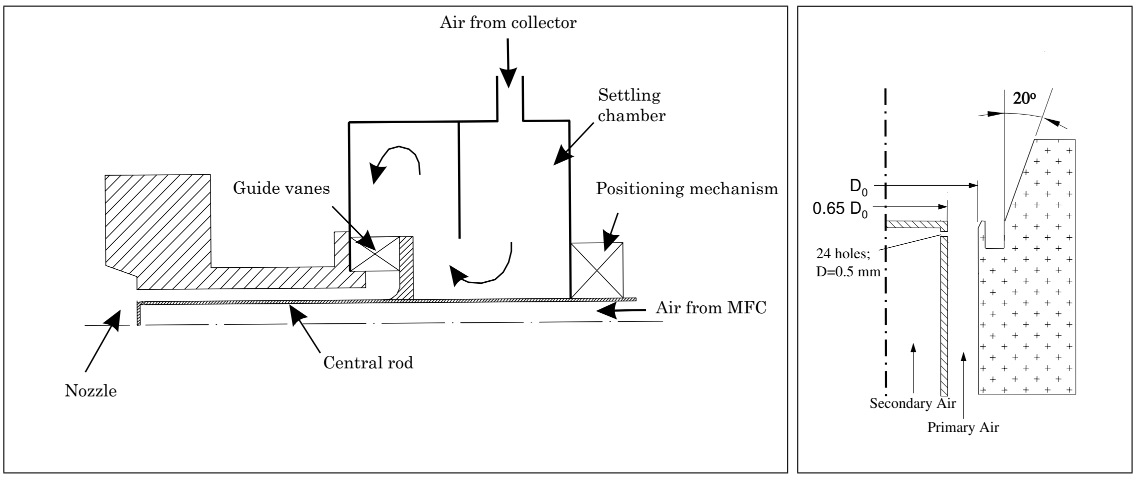


*Figure 1.* Schematic view of the experimental setup. Left: settling chamber and nozzle; Right: detailed view of the inside of the nozzle (not on scale).

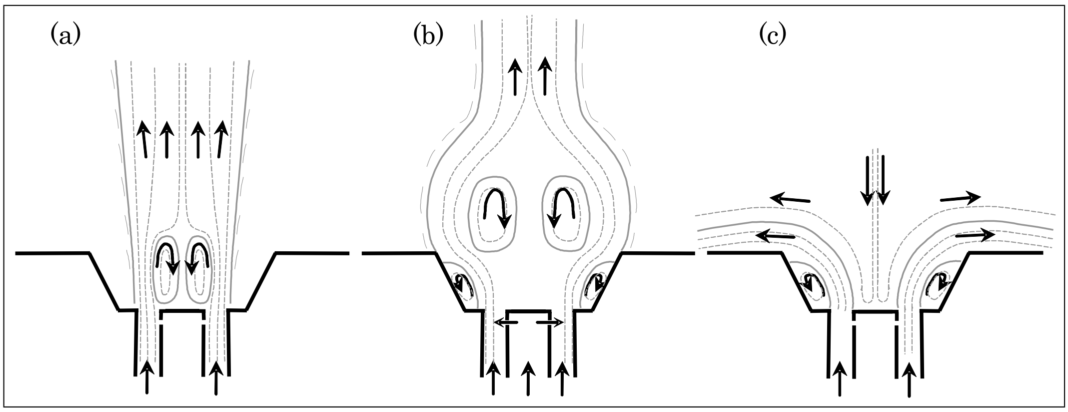


*Figure 2.* Schematic view of the different jets. ($a$): 'Closed Jet Flow' or *CJF*; ($b$): 'Open Jet Flow' or *OJF*; ($c$): 'Coanda Jet Flow' or *CoJF*. The arrows indicate the flow direction.

to an *OJF* (Fig. 2$b$). Decreasing the radial flow rate from this transition on results in an increased radial expansion of the *OJF*. At a flow rate of 1.7 $\mathrm{Nm^3/h}$ in the decrease the Coanda effect takes place at the nozzle outlet. This is the transition from an *OJF* to a *CoJF* (Fig. 2$c$). The *CoJF* remains till zero radial injection meaning hysteresis between increasing and subsequently decreasing the radial flow rate.

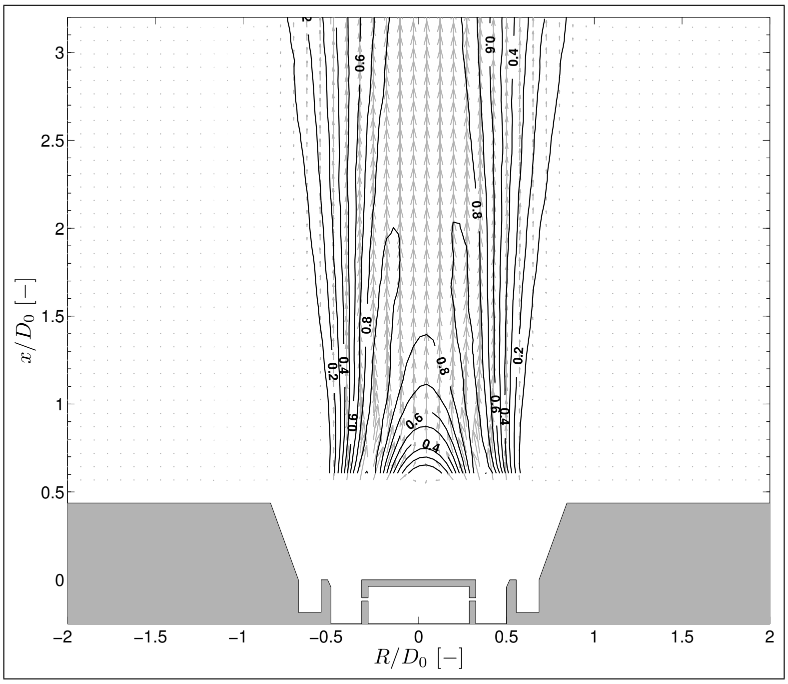


*Figure 3.* Contour plot of the normalised axial velocity $\overline{U}/U_0$ of a *CJF* at no radial injection. The grey arrows in the background are the measured velocity vectors. Only half of the vectors is shown to not overload the figure.

### 3.1. No radial injection (increase)

The first flow pattern at zero radial injection is the 'Closed Jet Flow' or *CJF* for which figure 3 shows the axial velocity contours measured. In the background of the figure the velocity vectors are plotted. Only half of these vectors is shown to not overload the figure. The PIV measurements are compared to LDA data reported by Vanierschot et al. [3] and the difference is within measurement accuracy. Behind the central rod the zero velocity point is situated at $x/D_0 = 0.51$. Further downstream the axial velocity recovers in the centre and at $x/D_0 > 2$ the maximum is again situated on-axis. Further downstream the *CJF* resembles a round jet and the flow field becomes self-similar.

### 3.2. 1.77 Nm$^3$/h radial injection (decrease)

With an increase of radial injection the injected jets penetrate more and more into the main flow and deflect the jet towards the divergent of the nozzle. At a certain radial flow rate the flow attaches to the nozzle. Figure 4 shows the axial velocity plots of an *OJF* for a radial injection flow rate of 1.77 Nm$^3$/h. The attachment to the nozzle creates a large toroidal vortex. The flow field is not symmetrical. The cause of this asymmetry is the radial injection. The radial flow rates vary from 0 to 5 Nm$^3$/h which yields a maximum exit velocity of 295 Nm/s. This is near sonic injection. The exit velocity through a hole with diameter $D$ is roughly proportional to $D^2$. A variation of 0.1 mm on 0.5 mm yields a velocity difference of $\pm 40\,\%$. Therefore slight asymmetries in the injection holes cause an asymmetry in the flow field.

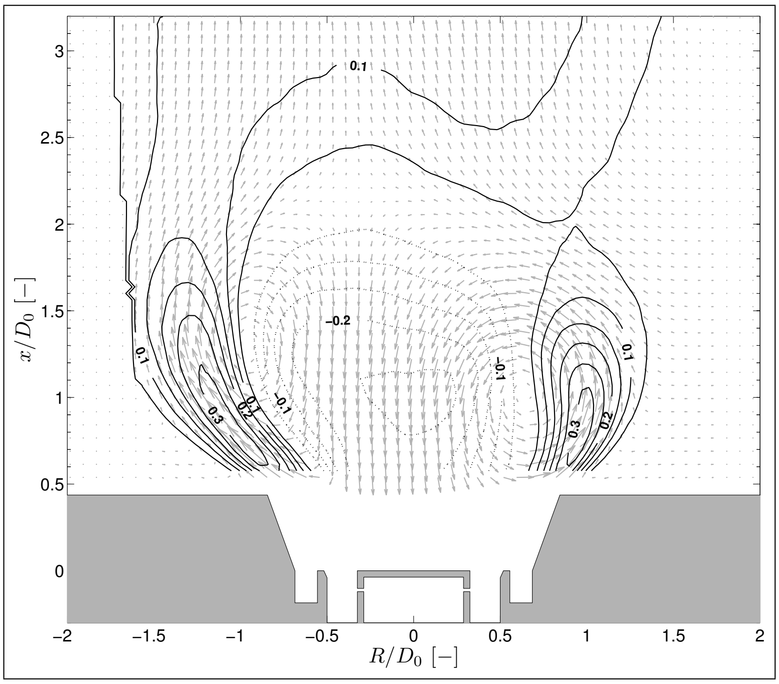


*Figure 4.* Contourplot of the normalised axial velocity $\overline{U}/U_0$ of a *OJF* at 1.77 Nm$^3$/h radial injection. The grey arrows in the background are the measured velocity vectors. Only half of the vectors is shown in order to not overload the figure.

### 3.3. No radial injection (decrease)

It is shown in a theoretical analysis by Vanierschot [1] that the reattachment length of the *OJF* to the nozzle determines the position of the eye of the central toroidal vortex. A decrease of radial injection causes an increase in reattachment length. As a consequence the eye of the toroidal vortex moves downstream and radially outward and the *OJF* expands more radially. At the nozzle outlet the sub - pressure increases. At a certain injection flow rate in the decrease, the radial expansion is large enough for the *OJF* to attach to the outlet of the divergent. This attachment is the transition from an *OJF* to a *CoJF*. Fig. 5 shows the axial velocity contours of a *CoJF* at zero radial injection. The *CoJF* remains till zero swirl and comparison with Fig. 3 shows the hysteresis in a cycle of increasing and subsequently decreasing the radial flow rate.

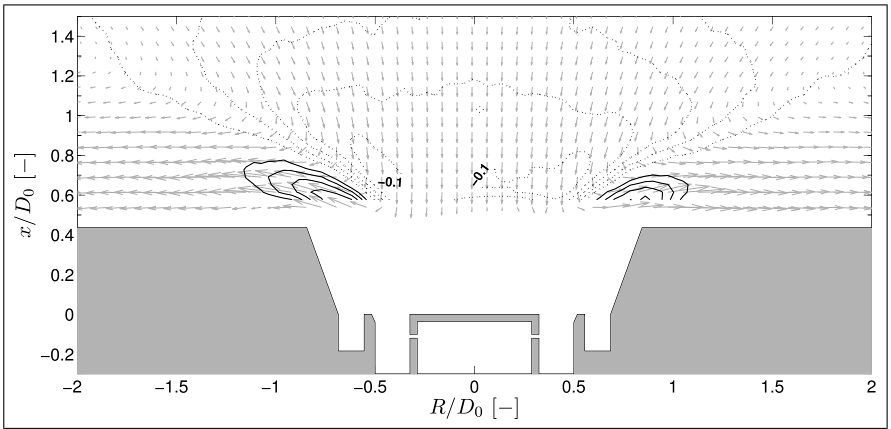


*Figure 5.* Contourplot of the normalised axial velocity $\overline{U}/U_0$ of a *CoJF* at no radial injection. The grey arrows in the background are the measured velocity vectors. Only half of the vectors is shown in order to not overload the figure.

## 4. Conclusions

In this paper an experimental PIV study is made of the control of an annular jet that is issued from a stepped - conical expansion nozzle. It is shown that a cycle of increasing and subsequently decreasing the radial flow rate can produce three different flow patterns within the same geometry. These flow patterns are subject to hysteresis between an increase and subsequently decrease of radial injection flow rate.

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