The Effect of Pre-swirl on the Discharge Coefficient of Rotating Axial Orifices

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Abstract

The characteristic of the flow through a set of rotating orifices for particular conditions is quantified in terms of a discharge coefficient which is the ratio of the actual flow divided by the flow for the ideal case. In the present study the pre-swirl was created by having Inlet Guide Vanes (IGVs) at the inlet of the rotating orifices. Pre-swirl changes the angle of attack to the orifice, and thus affects the incidence angle and the discharge coefficient. Pre-swirl improves the discharge coefficient in inclined orifices since it allows the incidence angle to reach zero at a much lower rotational speed than when there is no pre-swirl.

Introduction

Metering the right amount of cooling air is paramount to the overall performance of machines rotating at high speed, and a comprehensive understanding of discharge coefficient is essential to meet this requirement. The orifices covered in the standards (ISO 5167-1 and API 2530) are limited to square-edged concentric, and there are no correlations for orifices that rotate, Webster (1999) [9]. Thus, whenever a machine designer needs to establish which geometry will pass a desired flow in a rotating orifice system, this information may only be found in published papers. However, since the study of rotating orifices is relatively new compared to the work carried out on stationary orifices, there is much less information available in the public domain. In most cases, the information is simply not available. The present study seeks to add to the current level of knowledge by addressing how pre-swirls affect the discharge coefficient of rotating axial orifices.

The earliest study on rotating orifices was done by Meyfarth and Shine (1965) [8]. They represented the discharge coefficient in terms of the tangential-speed parameter *S*, which is the ratio of the tangential speed of the orifice and the axial velocity of flow into the orifice. Carlen (1965) [2] pursued Meyfarth and Shine's work and observed that the discharge coefficient was affected by the angle at which the fluid passes through the orifice but did not represent the discharge coefficient in terms of this angle, instead using the tangential speed parameter by Meyfarth and Shine.

Alexiou *et al.*(2000) [1] investigated discharge coefficients for flow through holes normal to a rotating shaft. The results of discharge coefficients were plotted against velocity head ratio, which is defined as the ratio of velocity head of the orifice jet to the velocity head in the main duct. Zimmermann *et al.* (1998) [10] proposed the representation of discharge coefficient in the relative frame of reference. This is because previous studies, which adopted the U/C_{ax} ratio, tend to have a range that would go to infinity, but, in the relative frame of reference, this range can be constrained between 0 and 1, and this allows different correlations to be compared on the same basis. The ratio in relative frame is written as $U/C_{ax,rel}$.

Dittmann *et al.* (2002) [3] investigated the discharge behaviour of rotating orifices with pre-swirl. The discharge coefficients were plotted against the velocity ratio $U/C_{ax,rel}$ in the relative frame of reference as described by Zimmermann *et al.* (1998) [9]. The results show that the discharge coefficient is strongly dependent on the velocity ratio with a distinct maximum at $U/C_{ax,rel} < 0$. The ratio of U/C_{ax} has always been used to represent the effect of rotation, but $U/C_{ax,rel}$ is gaining more usage because it allows discharge coefficients to be compared on the same basis. However, recently Idris and Pullen (2004) [4], proposed the incidence angle as the parameter to represent the discharge coefficient for rotating orifices. Besides taking into account the tangential speed and the incoming axial velocity, incidence angle goes a step further by embodying the angle of inclination of the orifice and any pre-swirl or cross-flows that exist at the entrance of the orifice. There are some studies in the past (McGreehan and Schotsch (1988) [7], Kutz and Speer (1994) [6]) that highlighted the effect of the incoming flow angle, but the term incidence angle was not singled out as the parameter that governs the discharge coefficient for rotating orifices.

The Test Rig and the Inlet Guide Vanes

Figure 1 shows the front views of the rig. The air flows into the inlet chamber, and then into the orifice holes within the rotating disc. The leakage between the rotating disc and the stationary inlet support plate is minimised by the labyrinth seal. The function of the inlet guide vanes (also called pre-swirl vanes) is to swirl the incoming flow at a desired angle. The vanes were screwed to an IGV disc by socket head screws, and its angle was varied by manually loosening the screws and changing the angle of inclination, Fig. 2. The points corresponding to the angle of inclination were marked out on the IGV disc, and the trailing edges of the vanes were positioned to be in line with these points.

The disc was manufactured from clear perspex for the points to be visible. Four different angle of inclinations were marked on the disc: 0^o, 30^0, 45^0 and 60^0, Fig. 3. The lengths of the inlet guide vanes (40 mm) were such that they would cover the entire circumference of the IGV disc when inclined at 90^0, i.e. cover the entire inlet for no air to enter. An inlet nose cone which was manufactured from nylon was also fitted to the IGV disc to guide the airflow into the inlet chamber after the flow has been swirled by the inlet guide vanes. The IGV disc was fitted at the front of inlet chamber.

The effect of pre-swirl on the discharge coefficient

The pre-swirl was created by having IGVs at the inlet of the rig, Fig. 4, located 128 mm upstream of the orifice inlet. Both positive and negative pre-swirl can be produced by changing the orientation of the 20 inlet guide vanes. Pre-swirl affects the discharge coefficient because it changes the angle of attack of the flow into the orifice. The results of the present study on pre-swirl were compared with those of Dittmann *et al*. (2002) [3] who represented the discharge coefficient in terms of the ratio $W_{1\theta,id}/C_{id,rel}$, where $W_{1\theta,id}$ is the ideal relative tangential velocity at the inlet of the orifice, and $C_{id,rel}$ is the ideal velocity of the orifice, Fig. 5b. Table 1 shows the parameters for Dittmann *et al.* and the present study. The pitch circle radius of the orifice used by Dittmann *et al*. is about 8 times larger than the present study. At 7000 rpm, which is the maximum speed in their study, the circumferential velocity of the orifice is U = 161 m/s. The present study has a maximum speed of 21000 rpm, and at r_h = 26.25 mm this translates to a circumferential velocity of U = 57.7 m/s, which is about three times lower than Dittmann *et al*.

In the study by Dittmann *et al*., the pre-swirl was established through nozzles located inside a pre-swirl plate, Fig. 5. The pre-swirl mechanism utilised by Dittmann *et al*. is called “direct transfer” where the nozzles are positioned at a large pitch radius similar or equal to the pitch radius of the receiver holes. The nozzles were oriented such that a jet following the extended nozzle centerline enters the receiver tangential to the pitch circle.

The free vortex theory[1] is used to relate the pre-swirl angle of the IGV and the flow angle that enters the inlet pipe.

$$\tan\alpha_{\text{pipe}} = \tan\alpha_{\text{IGV}}\left(\frac{\rho_2}{\rho_1}\right)\left(\frac{r_{h,\text{IGV plate}}}{r_{\text{pipe}}}\right)\left(\frac{A_{\text{pipe}}}{A_{\text{IGV gap}}}\right) \quad (1)$$

where,

α_{pipe}	flow angle enters the pipe
α_{IGV}	angle of the inlet guide vanes
$r_{h,\text{IGV}}$	pitch radius of the IGV
r_{pipe}	radius of the pipe
A_{pipe}	cross sectional area of the pipe
A_{IGV}	area of the gap (b) of the IGV blades ($2\pi r_{\text{IGV}} b$)

The diameter of the flow section is reduced from D (pipe diameter) to d (=βD, orifice diameter), which causes the axial momentum of flow to be increased by $\frac{1}{\beta^2}$, and since the angular momentum remains unchanged, the swirl angle entering the orifice opening would be reduced. Dittmann *et al*. represented the discharge coefficient in terms of the $W_{1\theta,id}/C_{id,rel}$ ratio. This ratio is related to the incidence angle as:

$$i = \tan^{-1}\left(\frac{W_{1\theta,id}}{C_{id,rel}}\right) - \beta_0 \quad (2)$$

[1] Free vortex theory – the product of tangential component of velocity and radii are maintained constant across any cross section.

For a straight orifice, β_o = 0, and equate ($W_{1\theta,id} = C_{1,id} \tan \alpha - U$, Fig. 5b), Eq. 2 can be written as:

$$i = \tan^{-1}\left(\frac{C_{1,id} \tan \alpha - U}{C_{id,rel}}\right) \qquad (3)$$

The results of Dittmann *et al*. have been translated to incidence angle using Eq. 3, and the discharge coefficient is plotted in Fig. 6. The highest incidence angle recorded for the present study is at $i = 0^o$, while for Dittmann *et al*. (2002) it is at about -20^o.

According to Dittmann *et al*. (2002), the discharge coefficient should decrease with increasing flow angle, and the results should have a symmetric progression relative to $W_{1\theta,id}/C_{id,rel} = 0$ (this is equivalent to $i = 0^o$ from Eq. 2). Their results did not exhibit this because according to them the value of C_1 is determined from the isentropic expansion through the pre-swirl nozzle (which gives an ideal velocity, $C_{1,id}$) and thus it is much higher than $C_{1,actual}$, and due to this, $W_{1\theta,id}$ overpredicts the real inlet velocity for the receiver holes. Thus, perpendicular inflow into the rotating receiver holes occurs at velocity $W_{1\theta,id}/C_{id,rel} < 0$.

Dittmann *et al.* used the angle of the nozzle as the pre-swirl angle to the orifice. This assumption is only correct if the total areas for both the nozzles and the orifices are the same, and the restrictors are located at the same pitch radius circle. Even though the total number of nozzles and orifices used are similar, the diameters are not the same ($d_{orifice}$ = 10 mm, d_{nozzle} = 8 mm). Using the free vortex equation, the pre-swirl angle is calculated as 75^o. This is much higher than the pre-swirl of 60^o used in their calculation. Figure 7 shows a velocity triangle with a negative tangential velocity, $W_{1\theta,id}$. When the pre-swirl angle is increased from α_1 to α_2, the tangential velocity is brought to zero. This example shows that the highest discharge coefficient for Dittmann *et al*. can be positioned at zero incidence angle (which refers to $W_{1\theta,id} = 0$) if a higher pre-swirl angle as calculated by the free vortex equation is used.

Changing the pre-swirl angle would not change the discharge coefficient but the graph of C_d vs. i would be shifted to either left or right depending on whether the pre-swirl angle is increased or decreased. The original graph of Dittmann *et al*. in Fig. 6, is shifted to the right so that the maximum C_d coincides at $i = 0^o$. The new graph is shown in Fig. 8. The pattern of the graph matches with the results given by the present study.

Due to the pre-swirl angle that enters the orifice for the present study ($\alpha_1 = 20^o$) being much lower than Dittmann *et al*. ($\alpha_1 = 60^o$), the incidence angle range is limited to $\pm 20^o$. In order to increase the range, the disc is rotated CCW, which allows the incidence angle to reach $+40^o$. There is a good agreement between the results of the present study and those of Dittmann *et al*.

Fig. 9 shows plots for inclined orifices at $\beta_o = 30^o$ with the IGVs positioned at different angles. For $\beta_o = 30^o$ and IGV = 0^o (symbol ⋇, no pre-swirl), the discharge coefficient increases with the rotational speed. This is because as the speed increases, the incidence angle improves from $i = +30^o$ at 0 rpm to $i = +1.5^o$ at 21000 rpm. Figure 10 shows the velocity vectors at the inlet of the orifice with pre-swirl angle positioned at $\alpha_1 = 0^o$, $\alpha_1 > 0^o$, and $\alpha_1 < 0^o$.

The inlet absolute velocity for zero pre-swirl is denoted by ${}^1C_{ax}$. For $U = 0$, the incidence angle is $+30^o$. However, as U increases, the angle (${}^1\beta_1$) of the relative inlet velocity ${}^1W_1$, starts to align with the orifice inclination angle, and at 21000 rpm, the incidence angle ($i = {}^1\beta_1 - \beta_o$) improves to $i = 1.5^o$. This explains why the discharge coefficient improves as the speed increases for orifice with angle of inclination of $\beta_o = 30^o$ and IGV = 0^o.

For $\beta_o = 30^o$, if the pre-swirl angle is positive, the discharge coefficient would be lower than the case where pre-swirl is zero. The reason is because for positive pre-swirl ($\alpha_1 > 0$, symbols ⊟ and △), the incidence angle for $U = 0$ is much higher ($i = +50^o$) than when pre-swirl is zero ($i = +30^o$). On Fig. 10, the positive pre-swirl angle ($\alpha_1 > 0$), gives the direction of the inlet absolute velocity of ${}^2C_{ax}$. As can be seen, for $\alpha_1 > 0$ there is a high incidence ($i = \alpha_1 - \beta_o$) when $U = 0$. [Note that by adhering to the sign convention (Japikse and Baines (1990) [5]), the inclination angle, β_o, is taken as negative because its direction is opposite to the direction of the rotation, ω]. With increasing U, the relative inlet velocity, ${}^2W_1$, would tend to align with the inclination angle. This improves the incidence angle, and the discharge coefficient. Figure 9 shows that the incidence angle, however, does not reach zero, even at 21000 rpm, due to the high positive pre-swirl angle. Due to the positive pre-swirl angle, the rotational speed required to give the same incidence angle as in $\alpha_1 = 0$, is much higher. A higher rotational speed means that a higher ideal mass flow rate is used to calculate the discharge coefficient. A higher mass flow rate for $\alpha_1 > 0$ means that the discharge coefficient is much lower than for $\alpha_1 = 0$.

The opposite scenario occurs when a negative pre-swirl is applied. As shown in Fig. 9 the discharge coefficient is much higher for the negative pre-swirl than when there is no pre-swirl. This is explained by the velocity vector in Fig. 10. For negative pre-swirl, the absolute velocity, ${}^3C_{ax}$, is oriented favourably on the same direction as the inclined orifice. At U = 0, the incidence angle for IGV = -60^o is i = 10^o, which is lower than the zero pre-swirl case (i = 20^o). The incidence reduces further as the speed increases. The highest C_d of 0.97 is recorded at 7000 rpm when the incidence is zero. Once the best incidence has been reached, increasing the speed further would cause the incidence and the discharge coefficient to decline. The incidence angle would be negative because the relative inlet velocity angle, $^3\beta_1$, is greater than the inclination angle (β_o), as shown in Fig. 10. The negative pre-swirl helps the inclined orifice to have a zero incidence angle at a much lower speed, 7000 rpm, compared to when there is no pre-swirl where the incidence angle is zero at 21000 rpm. Due to this, the discharge coefficient recorded is much higher compared to the inclined orifice with no pre-swirl.

CONCLUSION

For the straight orifice (β_o = 0^o), the effect of pre-swirl on the discharge coefficient is similar to rotating orifices (i.e. the slope of pre-swirl in the Cd vs. i is identical to the slope due to the rotation). However, for inclined orifices, pre-swirl tends to increase the discharge coefficient. This occurs because the pre-swirl alters the angle of attack of the flow and allows a zero incidence angle to form.

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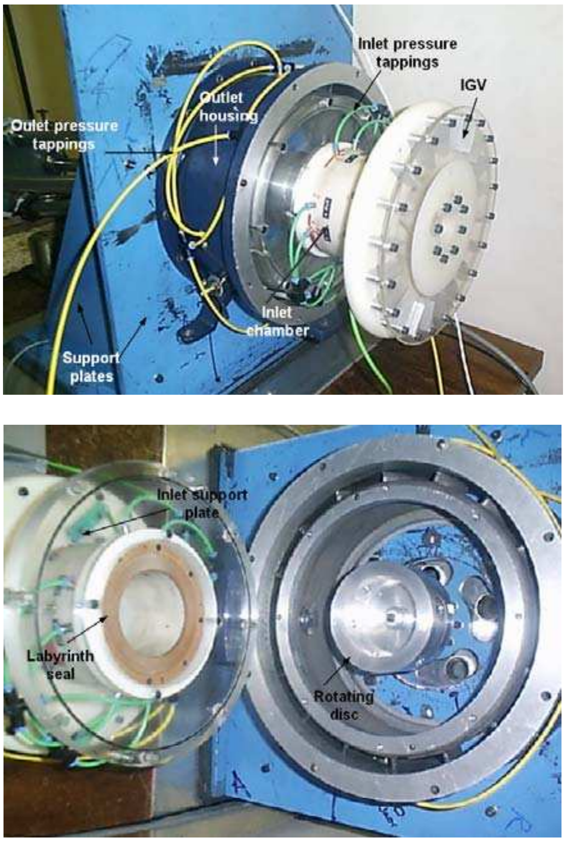

Figure 1: The assembly of the rotating orifices

Figure 2: Inlet guide vanes

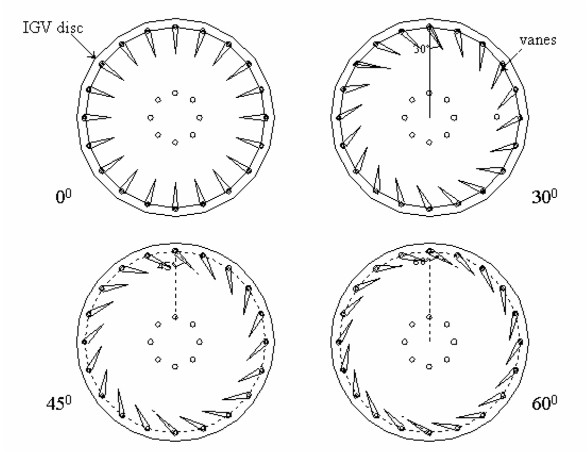

Figure 3: Illustration of the pre-swirl angles

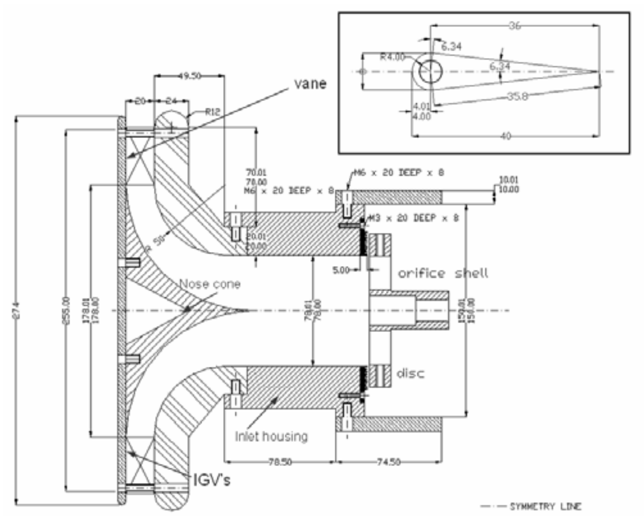

Figure 4: Inlet guide vanes (IGVs) of the present study are attached to the inlet housing. 20 vanes whose angle can be adjusted are arranged in circular array at ϕ250 mm.

Table 1: Dimensions of the present study and Dittman *et al.* (2002)

	Parameter		
Dimension		Present study	Dittmann *et al.* (2002)
Orifice hole diameter	d (mm)	10	10
Ratio of L/d	L/d	1.4	4.0
Pitch circle radius of orifice	r_h (mm)	26.3	220
Pressure ratio	Π	1.06	1.05-2.00
Number of IGVs or pre-swirl nozzles	-	20	12
IGVs or nozzles angle	α^1 (deg)	60^o	70^o
Number of orifices	n	6	12

[1] The angle is measured with respect to the meriodinal direction.

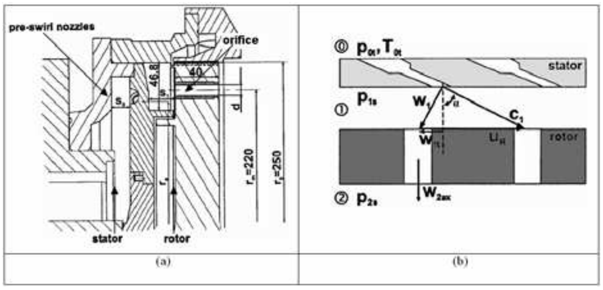

Figure 5: Dittmann *et al.* (2002) test rig (a) The position of the pre-swirl nozzles within the stator with a distance s_1 from the orifice. (b) The velocity vectors show the pre-swirl velocity (C_1), the inlet relative velocity (W_1), pre-swirl angle (α), relative inlet tangential velocity ($W_{1t} = W_{1\theta}$), and ideal velocity ($W_{2ax} = C_{id,rel}$) [Note: the notations (W_{1t}, W_{2ax}) used in Dittmann *et al.* (2002) are slightly different from the present study.]

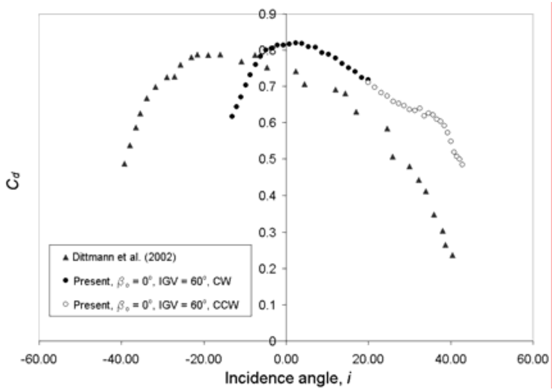

Figure 6: Variation of the discharge coefficient with the ratio of $U/C_{ax,id}$ for Dittmann *et al.* (2002) (β_o = 0°, pre-swirl nozzles angle = 70°, ω = 0 – 7000 rpm, r_h = 220 mm, Π = 1.05-2.00, L/d = 4.0, n = 12 holes), and the present study (β_o = 0°, IGV = 60°, ω = 0 – 21000 rpm, r_h = 26.25 mm, Π = 1.06, L/d = 1.4, n = 6 holes).

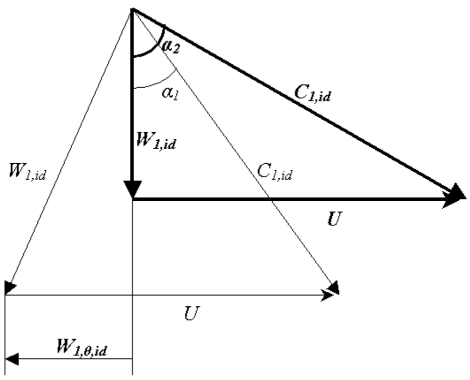

Figure 7: Velocity vectors describe how the tangential relative velocity ($W_{1\theta}$) changes for different values of pre-swirl angle (α_1 to α_2).

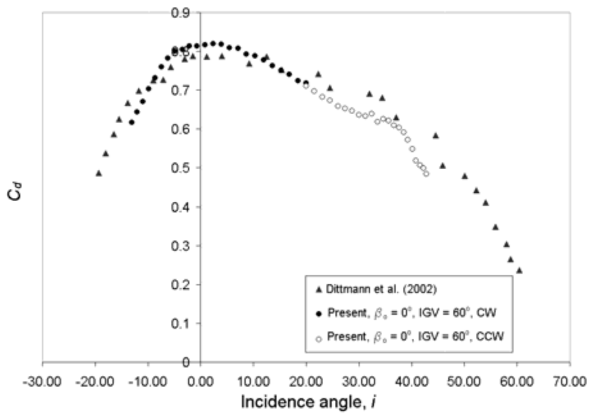

Figure 8: Variation of the discharge coefficient with the incidence angle, *i*, for Dittmann *et al.* (2002) (β_o = 0°, pre-swirl nozzles angle = 70°, ω = 0 – 7000 rpm, r_h = 220 mm, Π = 1.05-2.00, l/d = 4.0, n = 12 holes), and the present study (β_o = 0°, IGV = 60°, ω = 0 – 21000 rpm, r_h = 26.25 mm, Π = 1.06, L/d = 1.4, n = 6 holes).

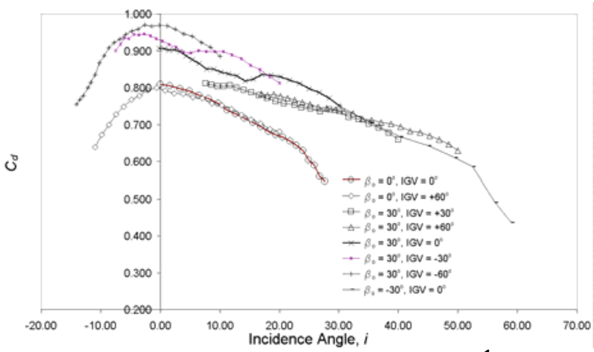

Figure 9: Velocity vectors at the inlet. $^1C_{ax}$ is inlet velocity with zero pre-swirl (α_1 = 0°), $^2C_{ax}$ is a +ve pre-swirl (α_1 > 0°), while $^3C_{ax}$ is a -ve pre-swirl (α_1 < 0°).

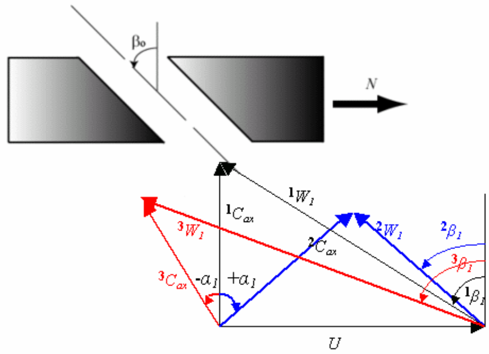

Figure 10: Velocity vectors at the inlet. $^1C_{ax}$ is inlet velocity with zero pre-swirl (α_1 = 0), $^2C_{ax}$ is a +ve pre-swirl (α_1 > 0°), while $^3C_{ax}$ is a -ve pre-swirl (α_1 < 0°).