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Modulation of the Spray Jet of a Swirl Injector

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Abstract

This document describes several mechanisms for modulating the geometry of the spray sheet emanating from the exit nozzle of a liquid swirl injector. In general a highly uniform spray sheet is desired, but in some circumstances the ability to have an intentionally non uniform spray sheet is advantageous. The possibility of directing the spray jet is especially attractive in the case of injectors located near the wall of the combustion chamber. In this paper, mechanisms are described to obtains several effects on the geometry of the exit spray sheet. By making one or more slots on the wall of the cylindrical wall of the exit throat, or cutting the exit of the cylindrical nozzle in a serrated pattern, the conic spray sheet is converted into one or more ruler sheets directed along different directions. By removing the non-wet portions of the nozzle with the slots and reversing the flow direction, the ruler sheets are converted to shell like sheets. By sectioning the exit cylindrical nozzle with a plane whose normal direction is not aligned with the axis of the cylindrical surface the circumferential mass distribution may be skewed to one side of the cylinder. As the angle between the axis of the cylindrical surface and the normal to the sectioning plane increases from 0 to the value of the the angle of the flow of the film inside the cylindrical nozzle the value of the mass fraction in two opposing sides of the cylindrical surface also change, increasing in one side and decreasing on the other side. If the angle between the axis of the cylindrical nozzle surface and the normal to sectioning plane is greater than the flow angle of the film inside the nozzle, the mass flow rate vanishes in an arc in the azimuth direction. Another possibility is cutting the exit section of the cylindrical surface in a wavy pattern. This pattern will produce a spray film with varying circumferential mass flow rate and opening angle along the circumference. Most of these effect can be combined to generate a myriad of patterns. Analytic expressions for the variations of the mass flow rate along the circumference of the exit section are developed for a number of cases. The analytic expressions can be obtained from simple geometrical considerations.

1. Introduction

In the ideal case, the spray jet at the exit of the swirl injector nozzle has the form of a hyperboloid of one sheet, Figure 1. The linear mass flow rate along the circumference of the revolution figure is uniform.

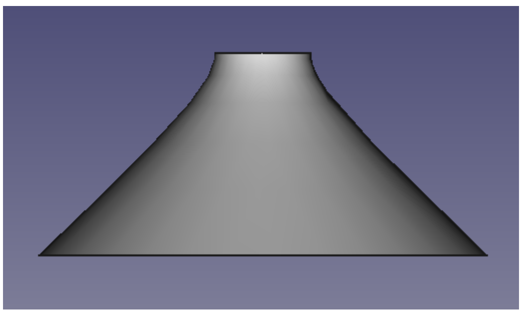

Figure 1: Hyperboloid Spray Sheet

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In the real case a number of phenomena cause distortions of the ideal hyperboloid surface:

Discrete entrance channels. In the ideal formulation, the entrance to the vortex chamber is a thin (infinitesimal) sheet homogeneously distributed around the circumference of the chamber. In the real case the entrance to the chamber is made through a number of discrete channels.

The entrance channels may have a circular or a rectangular cross section. In either case the angular momentum of the injected fluid varies with the radial position across the entrance channel section. This situation may be mitigated by locating the channel at a radial distance such that the average value of the angular momentum is equal to the design value.

The number of entrance channels The number of entrance channels is also important. If there is only one entrance channel, the cross section area of the entrance may be significant. Depending on the volume of the vortex chamber the perturbation of the discrete nature of the entrance channel may not be smoothed out inside the vortex chamber and will propagate all the way to exit nozzle, causing a non uniform exit cone.

Manufacturing inaccuracies. Manufacturing inaccuracies may be of several types; surface finish, lack of concentricity between the vortex chamber cross section area and the nozzle cross section area, etc. If the axis of the nozzle is not the same as axis of the vortex chamber, the thickness of the fluid film in the nozzle will vary along the circumference and therefore also the mass flow. The distance between the axis of the entrance channel and the axis of the vortex chamber may be different for different channels

Channel entrance disturbance. Even if the entrance channel is well aligned geometrically, non-uniformity of the flow conditions at the entrance of each channels may cause different flow conditions for each channel. A discussion on the effects construction and physical properties of the fluid on the circumferential distribution of the liquid jet is presented in.[1]

Viscosity and surface tension. The effects of viscosity show up mainly in the form of losses of total pressure in the entrance channels, vortex chamber and exit nozzle flow.

The effects of surface tension are usually more evident in distortions of the shape of the film sheet at the exit of the nozzle.

2. Summary of the formulas for the swirl injector

For the purpose of completeness, the main formulas describing the flow in a swirl injector are presented here. Full derivation of the formulas is presented by Bazarov et alii[2] and Bayvel.[1]

The geometrical characteristic, A, is a non-dimensional parameter defined by:

$$A = \frac{A_n R_{in}}{A_{in} R_n} = \frac{R_n R_{in}}{N R_{ch}^2} \tag{1}$$

where R_n is the nozzle radius, R_{in} is the radius location of the center of the entrance channels, R_{ch} is the radius of the entrance channel and N is the number of entrance channels.

The parameter φ is known as the coefficient of passage fullness of the nozzle throat, and is defined by:

$$\varphi = \frac{\pi(R_n^2 - r_{mn}^2)}{\pi R_n^2} = 1 - \frac{r_{mn}^2}{R_n^2} \tag{2}$$

where r_{mn} is the radius of the liquid film in the nozzle.

The mass flow coefficient, μ is defined by:

$$\mu = \frac{\rho U_{an} A_n \varphi}{\rho U_\Sigma A_N} = \frac{U_{an}\varphi}{U_\Sigma} = \varphi \sqrt{\frac{U_\Sigma^2 - U_{un}^2}{U_\Sigma^2}} \tag{3}$$

where $U_\Sigma = \sqrt{U_{un}^2 + U_{an}^2 + U_{rn}^2} = \sqrt{2(\Delta p)/\rho}$, and U_{un} is the swirl velocity in the nozzle, U_{an} is the axial velocity in the nozzle, U_{rn} is the radial velocity in the nozzle and Δp is the pressure drop of the entire injector.

The mass flow rate, $\dot{m}$, is given by:

$$\dot{m} = \mu A_n \sqrt{2(\Delta p)/\rho} = \mu A_n U_\Sigma \tag{4}$$

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The flow angle or the spreading angle of the flow in the nozzle, α, is given by:

$$\alpha = \tan^{-1}\frac{U_{un}}{U_{an}} = \sqrt{\frac{2(1-\varphi)}{\varphi}} \quad (5)$$

The thickness of the liquid film in the nozzle, h_n, is given by:

$$h_n = R_n - r_{mn} = R_n(1 - \sqrt{1-\varphi}) \quad (6)$$

3. The geometry of the transformed spray sheet

In this section the transformed spray sheet is shown from the geometric view point. In next section the algebraic formulation for some of the transformations is presented.

The visualization of the transformed spray sheet geometry becomes much more intuitive if we straighten the circular section of the exit nozzle. For each transformed geometry we show the straightened profile and the corresponding 3D geometry. In the straightened profile we show the path of the streamlines on the inside wall surface and also the streamlines of the sheet after it leaves the nozzle.

In all illustrations we will use the flow angle inside the nozzle $\alpha = 45°$.

3.1 The regular one sheet hyperboloid

The regular one sheet hyperboloid, Figure 2, is obtained from the nozzle with a circular exit section. The Figure shows the straightened view of the flow inside the nozzle and the initial section of the free flow film.

In Figure 2(a) The flattened view of nozzle is presented. The value of α is 45°. With this value of the angle the straightened section of the nozzle is a square (gray color). The dashed lines inside the square represent the streamline traces inside the nozzle, also straightened.

In Figure 2(b) we see the wrapped up profile. Note that each point on the 3D figure can be mapped to a point on the 2D figure. The transformations from one to the other can be obtained geometrically.

It must be noted that in all figures we are considering that the direction of the streamlines is unchanged as it leaves the nozzle exit section. In the real case the direction of the streamlines is slightly changed at the lip of the nozzle exit. As the excess centrifugal pressure inside the nozzle is converted to kinetic energy the component of the velocity normal to exit surface is increased which changes the direction of the streamline thereafter.

In Figure 2(c) the 2D and 3D profiles are superimposed.

3.2 The multiple rulers exit sheet

A ruler system exit film sheet, Figure 3, is obtained by cutting narrow slots tangent to the internal surface of the nozzle wall.

Figures 3(a) and 3(b) show the straightened nozzle and the 3D view sheet respectively. Figures 3(c) and 3(d) show the corresponding views for the 2 rulers sheet.

It must be noted that in the real case there will be some flow spilling across the stream lines due to the excess pressure (centrifugal) inside the nozzle.

Note that right-down running stream lines on the straightened section corresponds to a clockwise swirl rotation when viewed from the vortex chamber side.

3.3 The multiple shell spray sheet

If we section the nozzle exit along the path of anti-clockwise running streamline and reverse the flow direction to clockwise the exit stream is converted to a shell shaped sheet system.

Figures 4(a) and 4(b) show the straightened nozzle and the 3D view sheet respectively. Figures 4(c) and 4(d) show the corresponding views for the 2 shells sheet.

As in the ruler spray system the excess centrifugal pressure inside de nozzle will cause some spill transverse to streamlines at the edges of the cut. The edges of the shells will be distorted. The effects of surface tension will add to this distortion.

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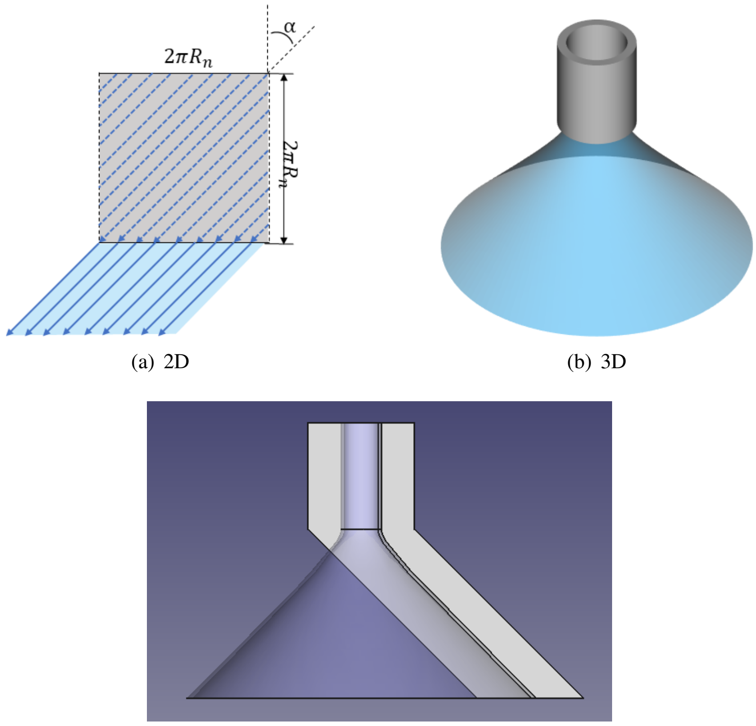
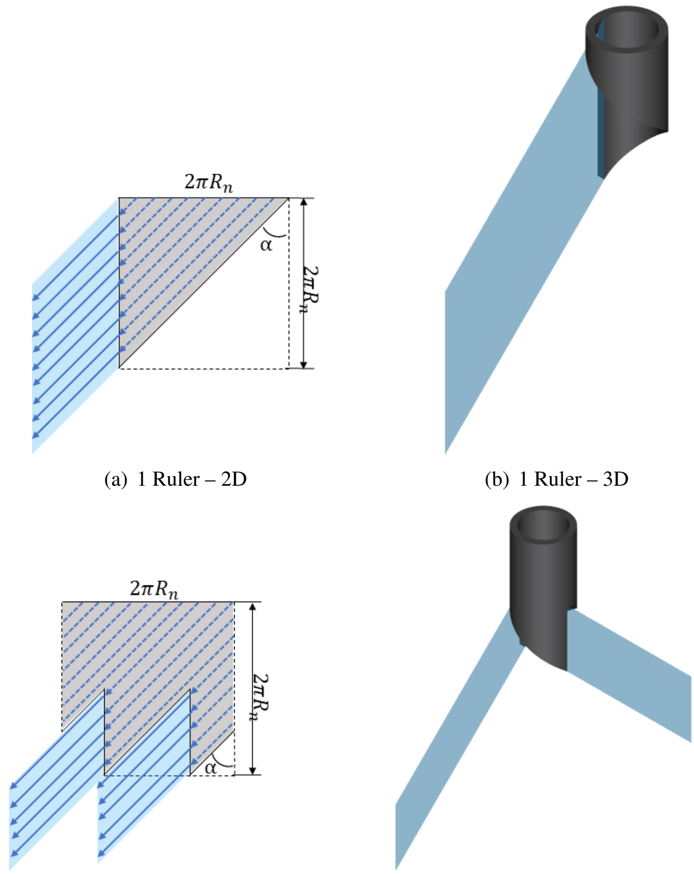


(a) 2D (b) 3D

(c) 2D-3D superimposed

Figure 2: The regular hyperboloid



(a) 1 Ruler – 2D (b) 1 Ruler – 3D

(c) 2 Rulers – 2D (d) 2 Rulers – 3D

Figure 3: The ruler system exit film

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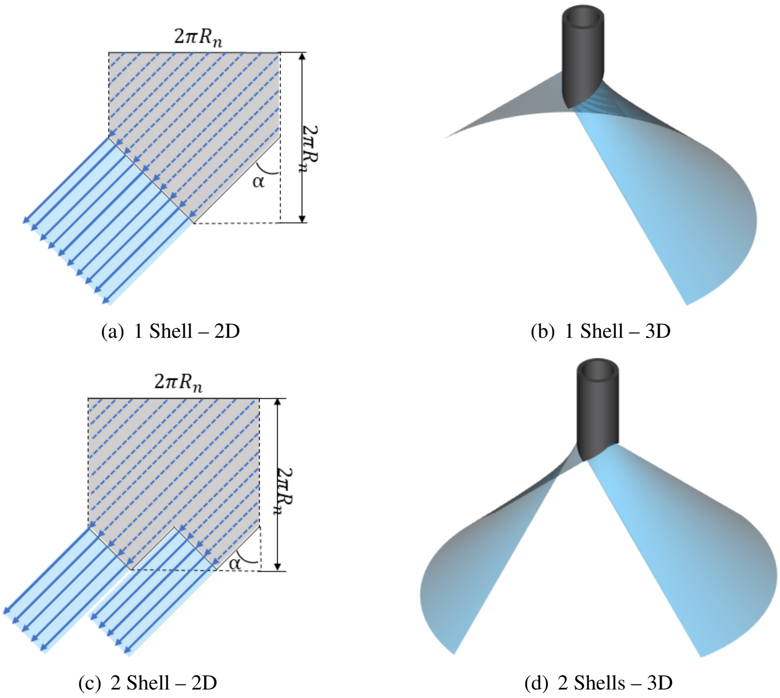


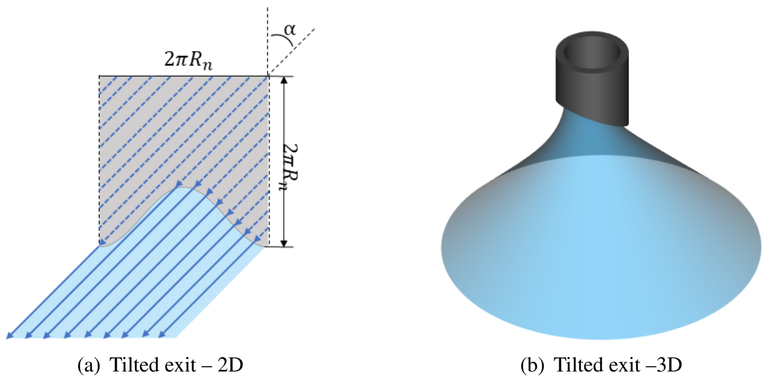
(a) 1 Shell – 2D (b) 1 Shell – 3D

(c) 2 Shell – 2D (d) 2 Shells – 3D

Figure 4: The open shell system exit film

3.4 The skewed one sheet hyperboloid

If the exit section of the nozzle is sectioned by a plane whose normal is not aligned with nozzle axis the one sheet hyperboloid gets skewed. Let's consider an angle β between the normal to the sectioning plane and the nozzle axis.



(a) Tilted exit – 2D (b) Tilted exit –3D

Figure 5: The skewed hyperboloid system exit film

For small values of the angle β the skewed hyperboloid sheet is full. As the value of the β angle increases a critical value is obtained. For values of the β greater than the critical value the hyperboloid sheet becomes discontinuous.

4. Mathematical formulation

In this section we present some of the mathematical formulation and transformation from straightened view to 3D views.

The height of the slot, h, that converts the liquid film into a ruler film is given by:

$$h = \frac{2\pi R}{\tan\alpha} \tag{7}$$

The angle of the ruler with the axial direction is α

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The width of the ruler depends on the flow angle and is given by:

$$w = 2\pi R \cos\alpha \tag{8}$$

According to this formula the maximum width of the ruler is for a value of α which corresponds to no rotation in the swirl chamber.

Even for a very small value of α when $\cos\alpha \approx 1$ the width of the ruler will collapse into a jet due to the action of the surface tension.

In practice the width of ruler will start as a jet, will open up into a ruler for small value of the angle α and will decrease thereafter, until it collapses again into a fluid fillet for very high values of the flow angle inside the nozzle.

It should be noted that the maximum value of the flow angle inside the nozzle is 90°.

The liquid film ruler may be divided in 2 or more rulers in different directions.

The angular separation of the slots depends on the relative width of the rulers. For two equal rulers of equal widths two slots with height $\dot{h}/2$ are π (radians) apart.

Consider the division in N rulers: $h_1,\ h_2, \ldots, n_N$ such that $\sum_{i=1}^{i=N} h_i = h$.

For $i = 1 to N - 1$ $\Delta h_i = h_{i+1} - h_i$.

The separation angles for the slots will be:

$$\phi_i = 2\pi \frac{\Delta h_i}{h} \tag{9}$$

4.1 Skewed hyperboloid sheet

The skewed hyperboloid sheet is obtained by sectioning the exit nozzle at an angle between the axis of the nozzle and the normal to the sectioning plane.

The non-dimensional helical length of the line along the circumference of nozzle exit is given by:

$$\dot{L} = \frac{2\pi}{\sin\alpha} \tag{10}$$

As the tilt angle increases the hyperboloid film is skewed with the mass flow being directed to the shorter side of the nozzle length.

Let α be the flow angle inside the nozzle and let β be the angle between the axis of the nozzle and the normal to the sectioning plane.

If β is less than α the skewed hyperboloid will be full but the linear mass flux along the periphery of the cone will vary.

If β is greater than α then there will be no flow in a arc along the exit section.

The abscissa is the distance along the azimuth angle in the nozzle cross section, $2\pi R$. The ordinate is the height of one full turn of the flow inside the nozzle, $\frac{2\pi R}{\tan\alpha}$.

In Figure 6 we present graphics for three different values of the angle β; 20°, 45° and 50°. The value of the flow angle inside the nozzle α is the same for the three cases; 45°.

In Figures 6(a), 6(c) and 6(e) we show the straightened section of the nozzle. The abscissa is normalized, divided by πR_n, where R_n is the radius of the nozzle. The ordinate is also divided by the same number. The function $g(x$ is the direction of the streamline inside de nozzle, the function $h(x)$ is the cut line of the tilted plan with the nozzle. Function $f(x)$ is a straight line parallel to the streamline passing through the maximum height of the tilted cut. It divides the left axis line in two parts, top and bottom. The ratio of the top to bottom parts is the ratio of the mass flow rate fraction directed towards the long and short sides of the cut.

In Figures 6(b), 6(d) and 6(f) we present the normilized linear mass flow rate along the circumference of exit section.

It is shown that in the interval $[-1, 0]$ the linear mass flow rate is higher than the average linear mass flow rate. In the interval $[0, 1]$ the linear mass flow rate is lower than the average. In 6(b), $\beta < \alpha$, there is mass flow around the perimeter of the exit section. In 6(d), $\beta = \alpha$, the mass flow rate becomes null for $x = 0.5$. In 6(f), $\beta > \alpha$, the mass flow rate becomes null along a the small arc the function becomes negative.

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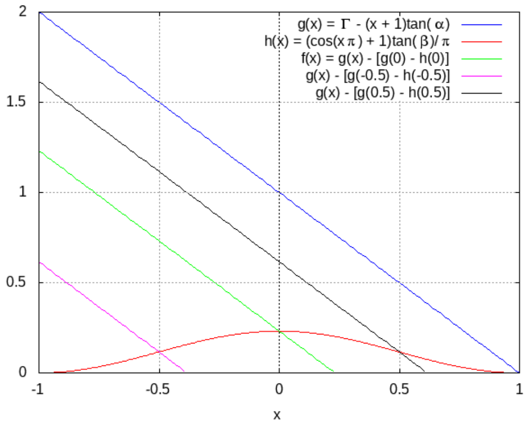
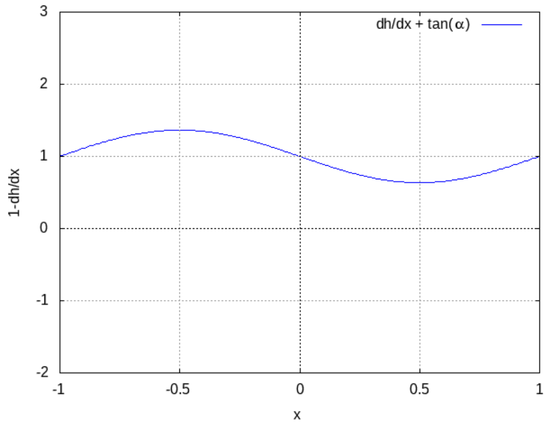
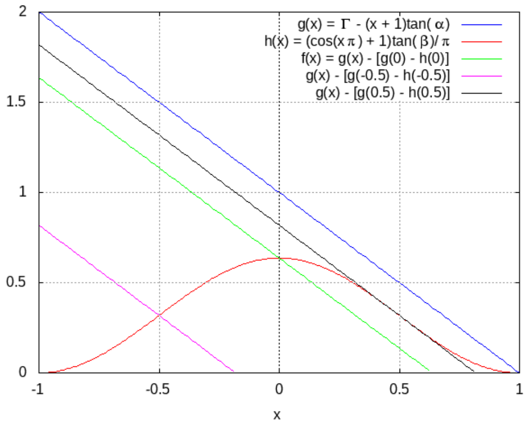


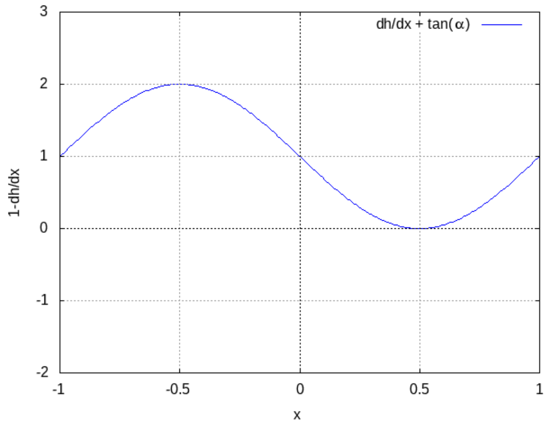
(a) 20° Flat



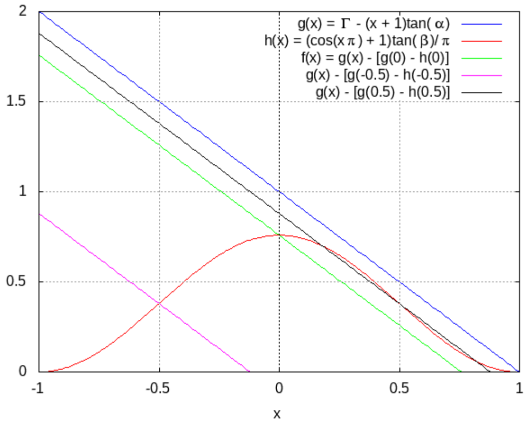
(b) 20° Non-dimensional Mass Flow Rate



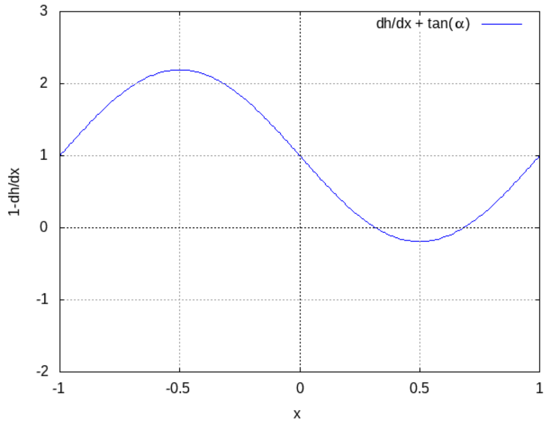
(c) 45° Flat



(d) 45° Non-dimensional Mass Flow Rate



(e) 50° Flat



(f) 50° Non-dimensional Mass Flow Rate

Figure 6: The tilted nozzle exit

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The unfolded cylinder is a rectangle. The height of the rectangle for one full turn of the fluid inside the cylinder is given by:

$$h = \frac{2\pi R}{\tan\alpha} \tag{11}$$

The amount of mass flow that is directed to front side part of the nozzle is given by:

$$F+ = \frac{1}{\tan\alpha} + \frac{2\tan\beta}{\pi} \tag{12}$$

The amount of mass flow that is directed to the back side part of the nozzle is given by:

$$F- = \frac{1}{\tan\alpha} - \frac{2\tan\beta}{\pi} \tag{13}$$

And therefore the ratio of mass flow rate to front and back side of the injector, τ is given by:

$$\tau = \frac{F+}{F-} = \frac{\frac{1}{\tan\alpha} + \frac{2\tan\beta}{\pi}}{\frac{1}{\tan\alpha} - \frac{2\tan\beta}{\pi}} \tag{14}$$

Solving 14 for β we obtain the tilt angle of the cut that is needed for a given ratio of mass flow rate between front and back side parts of the injector:

$$\beta = \tan^{-1}\left[\frac{\pi}{2\tan\alpha}\left(\frac{\tau-1}{\tau+1}\right)\right] \tag{15}$$

5. Acknowledgments

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