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PIV Study of the Effect of Piston Motion on the Confined Swirling Flow in the Scavenging Process in 2-Stroke Marine Diesel Engines

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Abstract: The effect of piston motion on the in-cylinder swirling flow for a low speed, large two-stroke marine diesel engine is studied using the stereoscopic PIV technique. The measurements are conducted at 5 cross sectional planes along the cylinder length and at piston positions covering the air intake ports by 0%, 25%, 50% and 75%. The resulting swirling flow decays downstream the bulk flow direction and variation in Reynolds number has only effect in terms of magnitude. When the piston translates towards the top-dead-centre, it gradually starts closing the intake ports. The tangential velocity profile changes from Rankine/ Burgers vortex to forced vortex and axial velocity profile changes from wake-like to jet-like and then again to wake-like profile.

INTRODUCTION

Large two-stroke diesel engines, specifically the low speed engine (LSE) type, use air, swirling inside engine cylinder for scavenging process. Near the end of power stroke, fresh air enters the cylinder through in-take ports on the cylinder liner close to the bottom dead centre (BDC) and the in-cylinder rising air column removes the exhaust gases through single exhaust port fitted in the cylinder cover. Efficient scavenging improves the combustion performance of the 2-stroke diesel engines [1]. The scavenging method defined as 'uniflow scavenging' accounts for higher engine thermal efficiency due to better air/ gas exchange [2]. The scavenging ports, depending on different designs, are at an angle (15°- 25°) with the cylind er radius to impart tangential velocities producing a swirling air column. The resulting in-cylinder confined swirling flow removes the exhaust gases from cylinder, provides fresh air charge for the next cycle and introduces swirl to enhance mixing of injected fuel and its consequent combustion. Moreover, it also has a cooling effect on the cylinder liner and in case of a non-axis symmetric swirl, can result in an uneven temperature distribution at the walls. Thus investigation and optimization of scavenging process is very crucial for the performance and development of fuel efficient and environmental benign marine engine technology.

Experimental results available in scientific literature, focused on studying the uni-flow scavenging process in large marine LSE, are very few compared to small two stroke diesel engines. The authors could only find the results of experiments conducted on investigating the influence of inlet angles of the inlet ports on the scavenging efficiency by using liquids on a 1:4 scaled engine model instead of gases [3] and LDV measurements on a large, low speed engine model with bore 145mm and stroke 435 mm [1].

Large physical size of LSE and the engine operation make it very difficult and expensive to conduct direct experimental investigations. The scavenging process is very transient and complex in nature. In terms of variation in geometry of the flow domain, piston and exhaust valve are in continuous and simultaneous motion during the scavenging process. This will change the shape of air intake ports, exhaust port and cylinder length. Also regarding the flow physics, mixing and stratification of exhaust gases with fresh air charge occurs while in-cylinder mass flow rate changes between opening and closing of scavenging ports. This simultaneous variation in flow domain and flow physics consequently affect the in-cylinder swirl characteristics and the type of the vortex generated by that swirl.

In order to simplify the problem, an experimental down-scale and simplified model of the engine cylinder is developed, which is analogous to a straight cylinder/ pipe connected to a swirl generator but having features like movable piston, cylinder head and guide vanes to divert the flow entering the cylinder at a desired angle etc. The focus in this study is on the characterization of the effect of piston motion on the confined swirling flow and at different Reynolds number. The experimental results can thus be useful for interested readers within areas of large two stroke LSE and fundamental studies in turbulent swirling flows.

In this experiment, air at room temperature and pressure is used as the fluid and the cylinder length is kept at 4D i.e. equal to stroke-to-bore ratio for LSE. Stereoscopic PIV measurements are carried out to study the in-cylinder confined swirling flow without mixing and stratification, cylinder exhaust fully open and without any exhaust valve. The measurements are conducted at 4 fixed piston positions in translational direction i.e. piston partially covers intake ports by 0% (fully open ports), 25%, 50% and 75% but constant flow rate. PIV data acquisition is performed by keeping the piston at any aforementioned fixed position and then taking measurements at different cross-sectional planes along the length of the cylinder. The piston is then moved to next position and the same procedure is repeated. This makes the measurements to be conducted in a quasi-steady state because in real engine scavenging process, in addition to stratified flow, the piston accelerates or decelerates continuously (covering and uncovering the intake ports), exhaust valve opens and closes and the in-cylinder flow rate and Re change accordingly. In order to study the effect of variation in flow rate and Re on the in-cylinder swirling flow, for each given piston position, the measurements are conducted at two different flow Reynolds numbers (Re_A= $0.6x10^5$ and Re_B=$1.2x10^5$) based on the average velocity calculated from volumetric flow rate (Figure 1). In a real engine, the flow rate changes as the piston movement closes ports. The flow rate is also influenced by other parts of the engine and is therefore unknown. For simplicity, the flow rate has been kept constant for different port openings, but by using two different flow rates, we can demonstrate the effect of a changing flow rate. The experimental results can be useful for the computational modelling where, at first, the performance of a given model is validated against the experimental results at different quasi-steady state piston positions and a given Re and then a transient simulation of swirling flow during scavenging process is performed using computationally dynamic/ moving mesh techniques for piston and exhaust valve motions.

EXPERIMENTAL APPARATUS

An overview of the experimental setup is shown in (Figure 1). The scavenging flow test rig is connected with a fan with speed controller and an orifice meter to measure the volumetric flow rate through the setup.

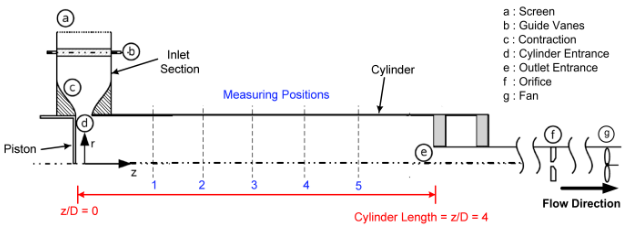

Figure 1 — Scavenging Flow Test rig

<u>Cylinder</u>

A transparent acrylic cylinder (produced using casting process to give good optical properties) is used. The total length of the cylinder is (L=760 mm) with internal diameter (D_i= 190 mm). One end of the cylinder is fitted inside the inlet section and at the other end an outlet section is fitted.

<u>Inlet-Section</u>

The inlet section (Figure 2) consists of two transparent ring-shaped acrylic plates with outer diameter (D_o= 600mm). The plates are fitted in parallel by mounting 60 guide vanes in between them thus serving as walls. The distance between the internal walls of the plates/ height of individual blade is 100 mm. A screen with 51% open area ratio is glued around the outer periphery of the inlet section as shown in (Figure 1). Flow enters the inlet section in radial direction and diverts at an angle by the guide vanes.

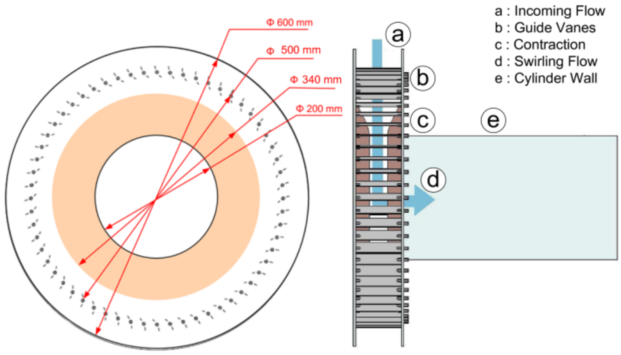

Figure 2 — Inlet Section

The guide vanes are adjusted in a way that one end is aligned in radial direction with the inlet. The flow enters the guide vane in radial direction and diverts at an angle. The guide vanes are mounted at a large radial distance from the geometric centre of the cylinder and close to the inlet (Figure 2). This will give some time to the flow after the vanes to settle thereby minimizing the wake effects. Further, before entering in to the cylinder, the flow enters a bell-mouth shape contraction section which will accelerate the flow and reduce the velocity fluctuations. The acrylic cylinder is entered in to the inlet section from one side and from other side, a transparent piston is mounted. The piston can slide inside the cylinder thus partially/ fully closing the cylinder inlet section, similar to real engine where the piston uncovers and covers the scavenging ports during the scavenging process.

<u>Outlet Section</u>

The outlet section (Figure 1) consists of a smaller internal diameter pipe (d_i=110 mm) and length (l=1415mm). Large length of the pipe will minimize any possible effect on the nature of the swirling flow inside the cylinder due to bending in connecting pipes to orifice plate and fan. The shape of the outlet provides a flat-bottom head to the cylinder.

STEREOSCOPIC PIV SETUP

An overview of the Stereoscopic PIV setup is given in figure 3.

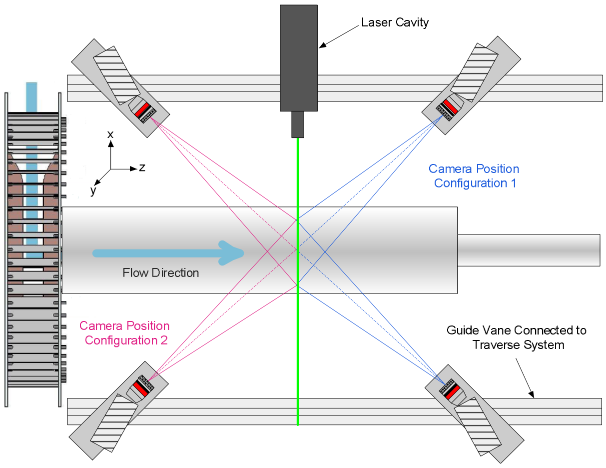

Figure 3 — Stereoscopic PIV Setup

The test rig is mounted horizontally on a table which is aligned in parallel with a traverse system. The laser cavity and two cameras are fitted on the traverse system. The traverse system is controlled using software installed on PC and provides motion in axial direction only i.e. along the length of the test cylinder. Laser cavity and cameras are mounted on the same traverse with their positions fixed relative to each other. Thus the traverse moves only laser and the cameras at the required measuring planes in axial direction (Z-axis).

Alignment and Calibration

The NewWave® Solo Nd:Yag pulse laser device (120 mJ pulses @ 15 Hz, Wavelength 532 nm) is mounted on the traverse in a way that the laser sheet is perpendicular to the cylinder. The laser sheet is aligned with the laser light reflected from the cylinder wall. This ensures that the laser sheet is perpendicular to the cylinder. Two Dantec HiSense cameras with 1344x1024 pixels and pixel size of 6.45µm are equipped with 60 mm focal length lenses and green light filters. Both cameras, mounted on the same traverse, are at one side of the laser sheet and while the cylinder is placed between the two cameras (Figure 3). The calibration target is attached on a disc of same diameter as the internal diameter of the cylinder and is slided inside the test cylinder. The calibration target is kept aligned with the laser sheet at only one of the measuring cross-sectional position and considering the test cylinder being axially aligned; same calibration is used for all the other measuring cross-sections. The cameras were focused on a rectangular target plane within the pipe diameter, avoiding measurements close to the cylinder wall due to strong reflections of the laser light. In order to capture all the measuring positions, two position configurations for the cameras are used (Figure 4). Due to angle of view, for the measuring positions near the outlet in camera configuration 1, camera view is blocked by the cylinder outlet wall and thus configuration 2 is used. For each configuration, calibration is performed at single measuring position. Dantec DynamicStudio® software is used for PIV measurements and data processing. Calibration was performed using 3rd Order XYZ-Polynomial Imaging model which is capable of handling distortion caused by the lens or curved windows [4]. In order to account for the possible misalignment of the calibration target with the laser sheet, disparity error correction is performed. For configuration 2, calibration and calibration refinement processes are repeated and is used only for the positions near the outlet.

One half of the test cylinder wall behaves like a concave reflecting surface and laser light reflections from the internal walls make a very bright spot near the concave wall facing the laser light (Figure 4). The F-number is set to 8 for the camera receiving the forward scatter and for the camera receiving the backward scatter, F-number is set to 4.

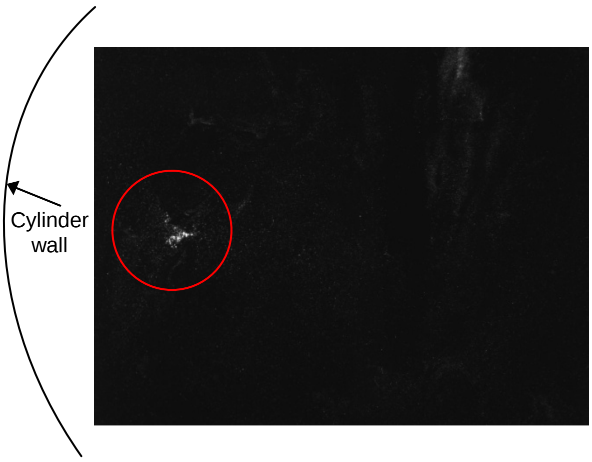

Figure 4 — Wall Reflections view from backward scatter camera (Cylinder wall location is an illustration and not in true scale)

Seeding

The seed generator contains 75/25 % by volume glycerol-water solution and size distribution of seeding droplets is in range of 1-3 µm. For a uniform and adequate seeding, the particles should mix properly with the incoming air entering the inlet section. For this purpose a metal frame, diameter 860 mm and width 150 mm, is mounted around the inlet section (Figure 5).

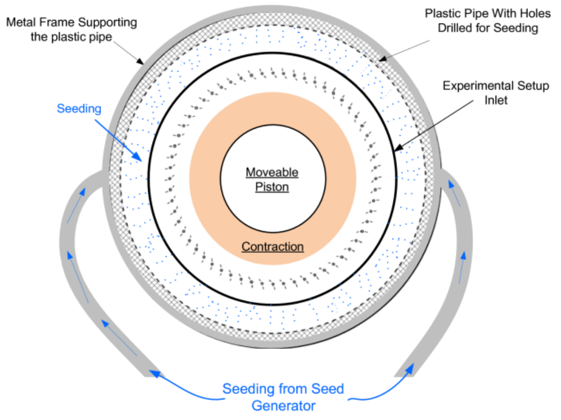

Figure 5 — Seeding Setup

A plastic pipe (diameter 40mm) is tied with the internal periphery of the metal frame in a helical shape so as to cover the whole breadth of the metal frame and consequently the inlet surface. A lot of small holes are drilled in the pipe wall facing the inlet of the experimental setup and the two ends of the pipe are connected to the seed generator. The radial distance of the pipe wall from the inlet surface is sufficient enough not to affect the incoming flow and provides a uniform seeding across the inlet surface.

Data Acquisition

For each Re, measurements are conducted at different cross sectional planes along the length of the cylinder, with their distances measured from the piston surface as reference (Figure 1). Both the cameras are focused in a way that their rectangular frames capture maximum area of the given cross-section but without capturing the near wall regions. At every position and a given Re, minimum 994 PIV snapshots are taken. Data processing and analysis of the PIV images is performed using multi-pass ‘Adaptive Correlation’ algorithm in Dantec DynamicStudio® software. The initial interrogation window size is 128 x 128 pixels with two refinement steps to a final interrogation area of size 32 x 32 pixels and 50% overlap of the side of the interrogation area.

RESULTS

Table 1 provides the detail for the axial position of the five cross-sectional planes where measurements are conducted. The axial distance ‘z’ is measured from cylinder bottom-dead-centre (BDC) i.e. piston surface when the port is fully open (Figure 1).

Table 1 — Axial Position of Measuring Planes

Axial Position	1	2	3	4	5
z/D	0.963	1.489	2.016	2.542	3.068

Average 3D Flow Field

The in-cylinder swirling flow results in a high velocity region at an intermediate radial position between the cylinder wall and geometric centre when the intake port is fully open (Figure 5). Contour colour represents axial velocity (out of the plane component) V_z normalized by bulk flow velocity V_b.

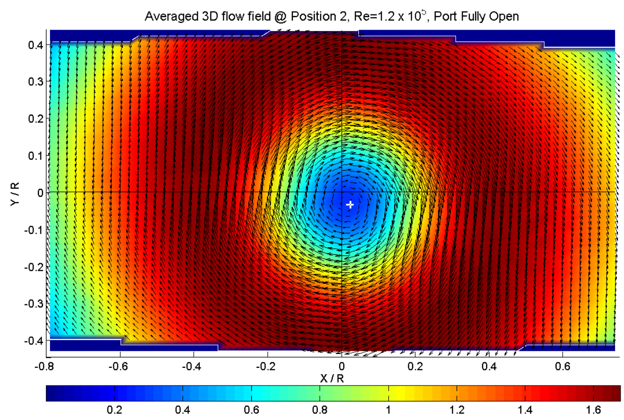

Figure 5 — Normalized average velocity Field, Fully open port

Although great care has been taken to make the experimental setup geometrically symmetric, the recirculating vortex core is asymmetric i.e. mean vortex position is not coinciding with the geometric centre of cylinder. Where ‘R’ is the radius of the cylinder and the ‘white’ mark represents the mean vortex position at the given cross-sectional plane.

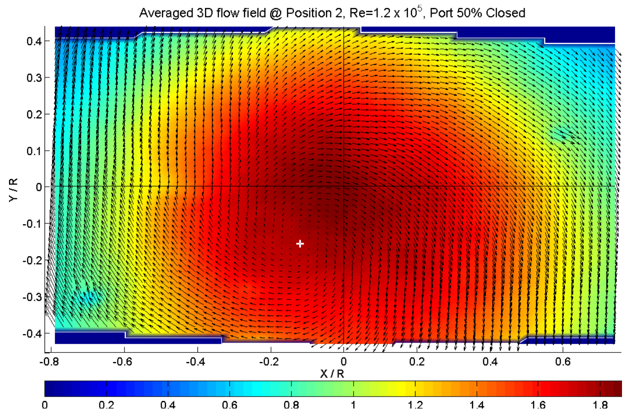

Figure 6 — Normalized average velocity Field, port 50% closed)

As the piston is gradually translated to the positions partially covering the intake port, the in-cylinder flow becomes comparatively more chaotic. The possible reason is that the piston behaves like a bluff body with a sharp edge to the flow entering the cylinder and the port area also reduces. This produces increased velocity fluctuations at the inlet compared to when the port is fully open and affects the in-cylinder velocity distribution (Figure 6). This required taking larger instantaneous PIV data samples to obtain a stable average.

Figures (7-14) give an overview of the tangential V_t and axial V_z velocity profiles at the 5 measuring planes and for each piston position. The presented profiles are obtained along X-axis and at Y=0. Both the velocity components are normalized by V_b based on the volumetric flow rate measured by the orifice meter.

<u>Fully Open port</u>

When the intake port is fully open, the tangential velocity V_t profile is similar to the Rankine/ Burgers vortex (Figure 7) which is comprised of a forced vortex core region and a free vortex outer region.

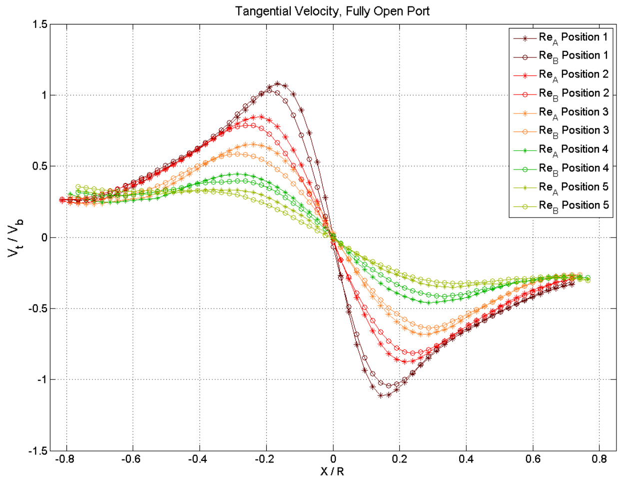

Figure 7 — Non-dimensionalized V_t at fully open port

Higher velocities are observed in the radial position where the inner forced and outer free vortices meet. The vortex core has the lowest velocity magnitude compared to other regions of the cylinder (except near cylinder wall region as in the current experiment the near wall measurements have not been taken).

The axial velocity V_z has a wake-like profile and has overall magnitude higher than V_t. This shows that flow has low swirl intensity. The vortex core size increases downstream as both the tangential and axial velocities gradually decay downstream the cylinder and the velocity peaks become fuller.

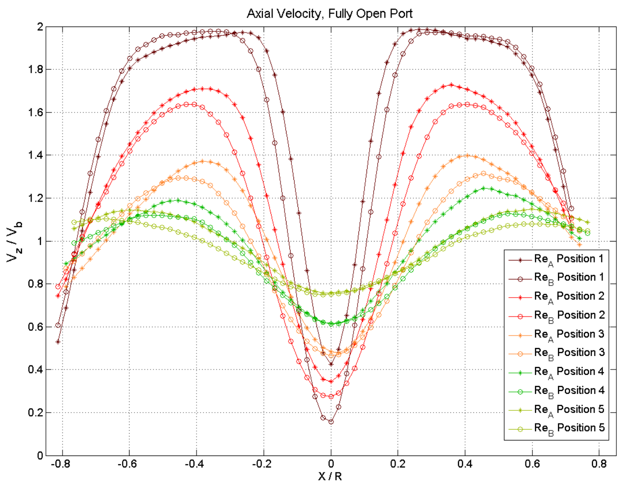

Figure 8 — Non-dimensionalized V_z at fully open port

Port Closed by 25%

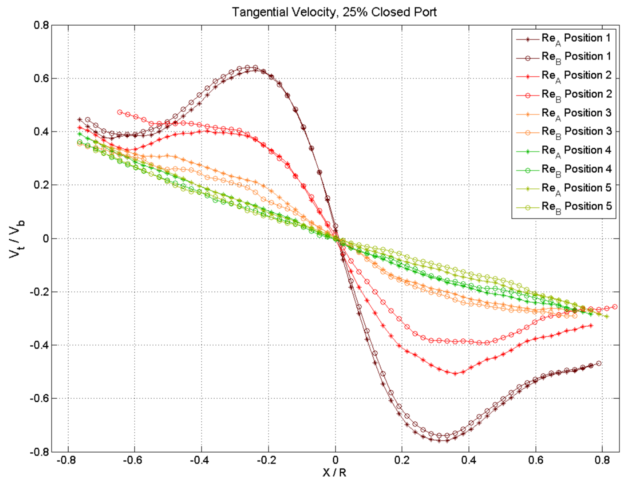

Figure 9 – Non-dimensionalized V_t at 25% closed port

At 25% partially closed port, overall V_t profile at downstream positions 4 and 5 changes to a forced vortex i.e. the high V_t region shifts to near wall position and eliminating the free vortex region. However the positions close to the cylinder inlet still have the forced and free vortex regions. The overall V_t magnitude decreases at all measuring positions compared to when the port was fully open (Figure 9).

The V_z at near outlet positions changes from wake-like profile to a more uniform distribution (Figure 10). At position 1 near the inlet, the peak values of V_z magnitude is higher than its value at open port position of the piston.

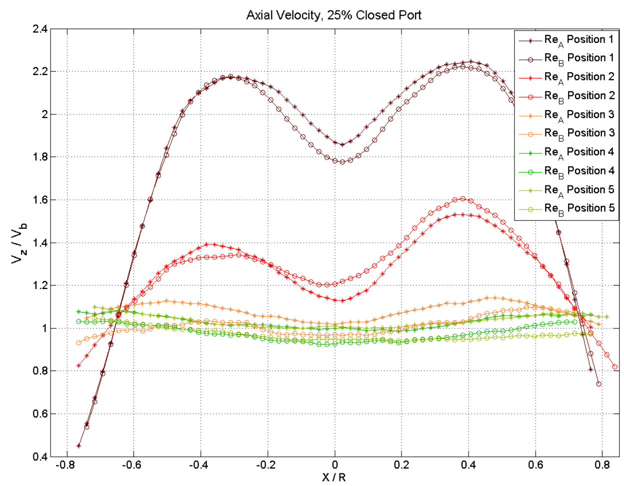

Figure 10 – Non-dimensionalized V_z at 25% closed port

Port Closed by 50%

With the piston covering 50% of the intake port, the shift in the peak V_t position to near wall region is now observed at further upstream positions (Figure 11). The profile lines are less smooth showing a non-uniform spatial distribution of the velocities.

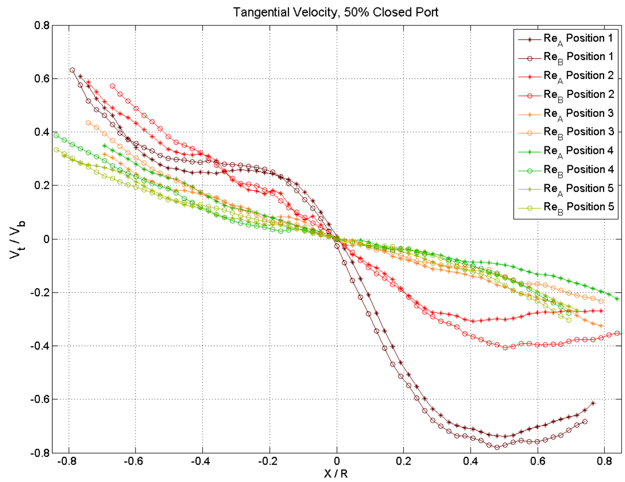

Figure 11 – Non-dimensionalized V_t at 50% closed port

A significant change is observed at the positions close to cylinder inlet where the V_z changes from wake to jet-like profile i.e. peak velocity magnitude is at the centre of the cylinder and decreases radially towards the wall. However, there is a rapid decay in the velocity peaks from position 1 to 3 and again at position 4 and 5 a uniform distribution of V_z is observed.

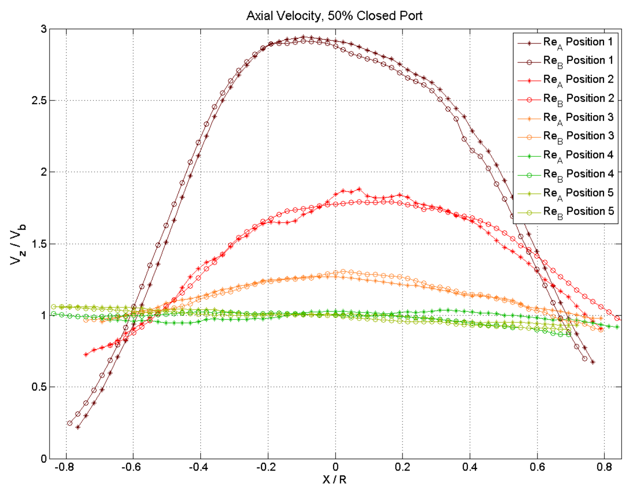

Figure 12 – Non-dimensionalized V_z at 50% closed port

Port Closed by 75%

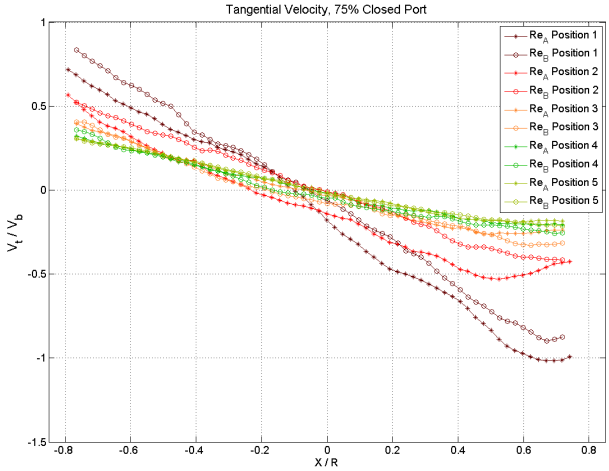

Figure 13 – Non-dimensionalized V_t at 75% closed port

The peak V_t in the entire cylinder is shifted to the near wall positions (Figure 13) and overall tangent velocity magnitude decays downstream the flow.

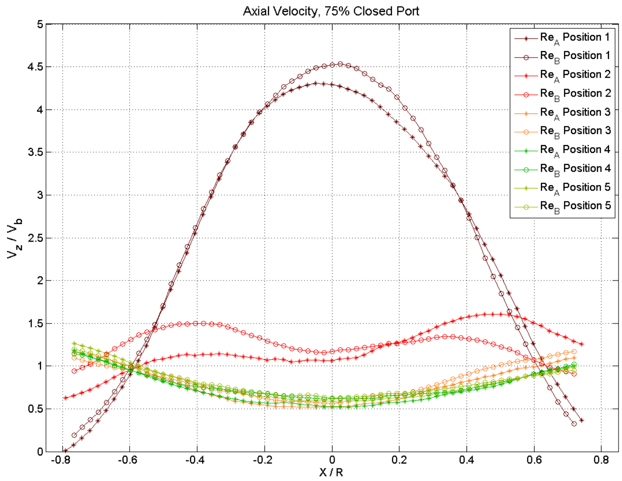

Figure 14 – Non-dimensionalized V_z at 75% closed port

Between position 1 and 2 the V_z changes back from jet like to wake like profile and remains the same at downstream positions. This indicates a vortex breakdown between these two measuring positions (Figure 14).

CONCLUSIONS AND DISCUSSION

Despite the axis symmetric geometry of the setup, the resulting in-cylinder swirling flow has a recirculating core with mean core position being asymmetric at all measuring positions i.e. from position close to intake port to cylinder outlet. At any given piston position and measuring cross-sectional plane, the variation in Reynolds number has no overall significant effect on the non-dimensional velocity distribution at that plane. The magnitudes of tangential and axial velocities decay downstream the flow due to internal wall. The introduction of piston, while partially closing the intake port, results in higher velocity fluctuations which require larger instantaneous data samples in order to obtain a good average compared to when the port is fully open. Further, the averaged tangential and axial velocity profiles/ distributions are not as smooth as when the port is fully open. The tangential velocity profile, at fully open port, is similar to a Rankine/ Burgers vortex .i.e. an inner forced vortex core and free vortex outer region. The higher velocities are observed at some intermediate radial position between cylinder wall and geometric centre where force and free vortex regions meet. At piston positions partially closing the port, the tangential velocity profile starts changing to a forced vortex .i.e. higher velocities are observed near the cylinder walls. This change in velocity profile begins from positions near the cylinder outlet and moves to upstream positions as the piston gradually closes the port. Fully open port results in axial velocity with wake-like profile at all measuring planes. However, no reverse flow at the vortex core has been observed. As the piston starts closing the ports, the axial velocity profile changes from wake-like to jet-like and again back to wake-like at higher percentage closure of intake port or vice versa.

The experimental results, from the test model, presented in this paper can help in understanding of the possible nature of in-cylinder confined swirling flow during the scavenging process. With the piston motion the change in the tangential and axial velocity profiles, both at different piston position and at different cross-sectional planes in the cylinder at a given piston position, represent a specific type of vortex and by studying the characteristics associated with that type of vortex a better understanding can be developed regarding real engine scavenging issues for example mixing of fresh charge with exhaust gases and stratified flow etc. Moreover, with swirling flow still being challenging for CFD, comparatively reliable results should be expected from a CFD model that is first validated against the experimental results for each piston position and then used to simulate the scavenging process using dynamic/ moving mesh techniques.

In order to study the stability and sensitiveness of the in cylinder swirling flows, further experiments will be conducted in future for different positions of the guide vanes, creating an asymmetry to the flow by positioning some of the guide vanes to block the flow etc.

ACKNOWLEDGEMENTS

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