Application of LDV and PIV techniques for flow measurements in the suction port of a screw compressor

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ABSTRACT

The application of LDV and PIV systems to measure the flow variation in the suction port of a new designed optical screw compressor has been found to be very successful. Time-resolved mean velocity measurements were made over a time window of 1° (∆θ) at a rotor speed of 1000 rpm, a pressure ratio of 1 and a gas temperature of 55°C. The LDV investigation on the suction port has shown a very stable and slow flow with almost no influence of the rotor motions everywhere except close to rotors at Z=10mm where the rotor motions start to show its influence and formed a more complex flow with a wavy axial flow profile. The PIV results confirmed flow trend measured by LDV and showed no influence of rotors’ movement on the mean flow structure. The PIV results within the vertical plane also showed relatively strong horizontal stream flow vectors upstream of the inlet suction port and became almost vertically downwards at the inlet port. Despite the current success, further improvements have been recommended to give better optical accessibility as close as possible to the rotors entrance.

1. INTRODUCTION

Screw compressors are well known for their simple design, low cost and high efficiency over a wide range of speeds and pressures, which make them suitable to be used in many industrial applications like air compression, refrigerant compression, food process, pharmaceutical, pneumatic transport and turbo charging [1-3]. Although the analytical methods for performance prediction of the screw compressors are well established and their design optimisations and basic operations are well known, there are limited information in the literature on the flow behaviour within compressors, from suction port to rotors’ chamber to discharge port, both experimentally and CFD simulation [4-10]. Obviously CFD flow simulation approach is the way forward for fully characterising the real time fluid flow (including multiphase), which would substantially reduce the times and costs of designs and production compared with an experimental based approach [1,6,7], however, the experimental approach by means of flow visualization, and flow velocity field measurement (using LDV and PIV techniques) is essential not only provide the real time flow dynamics but also to provide accurate data for validating CFD simulations [4,5,9,10]. Clearly, the flow process within the rotors’ working chambers depends greatly on the inflow structure coming from the suction port, the shape of the suction port and the flow trajectory as it enters into the rotos’ chambers [6]. Equally, The compressors performance is highly affected by flow behaviors within the suction port, rotors’ chamber and discharge port, particularly flow losses in the suction port that led to a decrease in compressors efficiency [7].

A number of the previous investigations have been carried out [4,5,8-12] to show the flow behavior within the rotors’ chambers, the discharge cavity and leakage flow using different experimental methods and CFD simulations. The flow within suction port of screw compressors remained fairly unexplored except those that showed the CFD can effectively be used for analysing the suction flow like that reported by [1] who also visualised the flow by high speed camera and compare them with the CFD predictions. Thus, the present report is an experimental investigation focusing on the flow measurements within the suction port of a screw compressor by designing a new optical suction port and applying LDV and PIV techniques to allow measurements of mean, rms and vector velocities as close as possible to the rotors. Time-resolved (clycled-resolved) velocity variation have been made in great details to be used for the validation of CFD codes. Details of the flow configuration will be given in the next section followed by the results and discussed section. Then, the report ends with a summary of the main findings.
2. FLOW CONFIGURATION AND INSTRUMENTATION
LDV and PIV measurements have been made at the inlet of an axial suction port of a standard screw compressor and their setups are shown in Figure 1. The compressor had ‘N’ type rotor profiles with a 5/6-lobe configuration, and was running at a rotor speed of 1000 rpm, a pressure ratio of 1 and a gas temperature of 55°C. Measurements at the suction port require a completely different setup than those used for rotors and discharge chambers by [5,9,10]. Also, the running conditions are quite different since there is no high pressure gradient, and therefore the motion of the rotors has little impact on the air flow except in its vicinity; in this study it is at Z=-10mm. To make the suction port optically accessible, the suction pipe has been replaced by a properly designed transparent cylinder that is fitted on the top of the machine inlet port with the same inner diameter, as shown in Figures 1 and 2, while the other end of the cylinder is fitted by a flat transparent window so that it would provide sufficient optical access into the suction port for both LDV and PIV measurements. The modified optical suction port with adopted coordinate system is shown in Figure 2 with the Z-axis is placed on the axis of the vertical cylinder and its zero is located at the entrance of the compressor inlet port on the top of the rotor chamber. The X-axis is aligned with the rotor’s shaft with its positive direction towards the main shaft, and the Y-axis is perpendicular to X and Z plane, and its direction goes from the female to the male rotor. The dark grey spots shown in Figure 2 correspond to LDV measuring points at three axial planes of Z=-10, 5 and 75mm with Z=-10mm being the nearest plane to the rotors. X- and Y-components velocity (referred to as axial velocity, V_x, and horizontal velocity, V_y, respectively) were easily measured from the top flat window, but the vertical velocity (Z-component, V_z) through the diagonal planes of the vertical cylinder, and was only measured at Z=75mm; V_z measurements at Z=5 and Z=-10mm was not possible because the laser beams were not able to access those locations due to the presence of the metallic compressor walls; this shortfall can be improved and it is recommended to modifying the inlet casing by inserting small optical windows on diagonal planes or replacing the inlet port wall upstream of the rotors entrance by an appropriate plexiglass pipe of the same internal diameter (to preserve its geometrical integrity), to allow closer optical access to the rotors for both LDV and PIV measurements.

The LDV and PIV systems were the same as those used by [4,13,14] who described the LDV and PIV systems fully and will not be repeated here. A conventional silicon oil atomizer with an average droplet size of 1-2 μm were used as the flow tracer. This is a most common air flow tracer to be used for LDV technique, and it has been shown to be suitable for PIV measurement by [4,13,14], which allowed good data processing when using the cross-correlation method. The seeding has been introduced into the suction port from the inlet feeding pipe, as shown in Figure 2. One of the disadvantages of using the silicon oil droplets is the fouling of optical windows, however, in the suction port it was found not to be a major issue mainly due to the uniform and stable flow nature of the suction port. It has been
shown by [15,16] that a better result can be obtained by using CO\textsubscript{2} solid particles blown through the suction port as seeding.

LDV measurements include angled-resolved mean velocities of, axial \(V_x\), \(V_y\) and \(V_z\) components along the diagonals X-plane (X-X') variations and Y-plane (Y-Y') variation, as shown in Figure 2, at different \(Z\) stations. Although LDV measurements provides very accurate information about mean and rms velocities, but it is a point measuring system and to describe the flow characteristics across the all fluid domain in full details would be a very time consuming task. Thus, PIV system is an alternative measuring technique that can capture instantaneous flow field velocity (2D or 3D) in a plane and provide useful information regarding spatial gradient and Reynolds stress everywhere within that measuring plane. Therefore, a 2-D PIV system has been employed to map the flow within the inlet suction port through horizontal and vertical planes as shown schematically in Figure 3. A comparison between LDV and PIV measurements has been made by current authors [17] and showed a very good agreement in mean velocities in a flow region of high velocity gradient and turbulent, which gives confidence in the accuracy of the measured PIV results. The transmitting PIV laser sheet was passed horizontally or vertically through the optical cylinder and top window directly or through a 45º mirror. As a consequence, all three velocity components can be measured but this requires different PIV setups. The arrangement of transmitting and receiving PIV system may differ for the above vertical and horizontal setups; some of these setups are difficult to arrange due to physical presence of the compressor unite, which may limit the range of measurements.

**Figure 2.** Optical compressor and suction port views with adopted coordinate system.

**Figure 3.** Schematic presentation of the PIV optical arrangement; (a) horizontal plane, (b) horizontal plane.

**RESULTS AND DISCUSSION**

Before going into details, a description of the inlet flow geometry is useful to help to understand the measured flow behaviour. Figure 4 shows a schematic description of the suction port from optical cylinder down to rotors. The details of the geometry of the suction port in Figure 4(a) shows that there is a bridge above the rotors that split the incoming flow towards the male and female rotors suggesting that the suction flow process takes place above the rotors around the bridge. With the present optical arrangement, unfortunately it is not possible to measure flow around the bridge; the closest location that measurement is possible is at \(Z=10\) mm which can still show the effect of rotors rotation on the suction flow. On the other hand, the inlet flow in the optical cylinder (Figure 4(b) is expected to be mainly vertically downwards towards the suction port. Considering above flow feature, it is expected that the flow within the optical cylinder to be of a uniform and stable nature except at \(Z=10\) mm where the flow would be exposed to the rotors’ rotation and be affected by their cyclic motion. Since there are five opening/closing of the discharge port operations during a full rotational cycle, the flow velocity measurements over one opening/closing cycle are presented (i.e. 72° of the main shaft rotation) with the
assumption that the flow over the other four are considered to be repeating and similar. It should be
noted that the opening of the discharge port corresponds to main shaft angle of $\theta=0^\circ$ and this is the same
for all LDV and PIV measurements. The following results present a small sample of data obtained in
this experiment with the main focus on the behaviour of the mean velocities as a function of the shaft
angular position, $\theta$, within the suction port; full set of results are presented in the thesis of [4], and it is
planned to publish them in a separate paper.

Figure 4. Schematic description of suction flow.

2.1. LDV Results
The velocity profiles presented in Figures 5 and 6 are cycle-averaged over one-degree time window
($\Delta \theta=1^\circ$) and are obtained from a continuous measurement with respect to shaft rotation over many 360°
till sufficient samples are collected to provide accurate (statically) mean velocity over 1° time window.
First the results of the mean vertical flow velocity, $V_z$, at $Z=+75\text{mm}$ are presented and discussed. Then
the mean velocity variations of axial ($V_x$) and horizontal ($V_y$) velocity components at $Z=-10\text{mm} +5\text{mm}$
would be presented, which are the main focus of the current study as $Z=+5\text{mm}$ represents the upstream
flow as it goes into the suction port, and $Z=-10\text{mm}$ represents flow within the suction port and as close
as to the rotors.

Figure 5. Variation of vertical ($V_z$) mean velocity as a function of rotor angle, $\theta$, at $Z=+75\text{mm}$
along: (a) $X-\text{X'}$ plane at $Y=0\text{mm}$, (b) $Y-\text{Y'}$ plane at $X=0\text{mm}$.
The variation of the mean vertical velocity component, $V_z$, at $Z=+75$mm along the X-X' and Y-Y' planes is presented in Figure 5. The results show uniform downflow (negative $V_z$ values towards the rotors) velocity profiles along both X-X' and Y-Y' planes at different X and Y locations, respectively, with no observable impact of rotors motion as would be expected at $Z=+75$mm. The downflow vertical velocity along X-X' plane, Figure 5(a), varies at different X locations so that it is around -0.7m/s at X=-45mm (near cylinder wall) and then increases gradually with X to a maximum value of around -1.4m/s at X=+15 and then drops to -1.2m/s at X=+45mm; note that this variation along X-X' is not due to rotors motion and it is due to the fact that the incoming flow from the top feeding pipe into the cylinder hasn’t yet developed fully at this Z location. Similar downflow can be seen along Y-Y' plane at different Y locations, Figure 5(b), with smaller variation in $V_z$ values with Y than that observed along X-X' plane, and no obvious trend with an overall average value of around -1m/s.

![Graph showing Axial and Horizontal Mean Velocities](image)

**Figure 6.** Variation of axial ($V_x$) and horizontal ($V_y$) mean velocities as a function of rotor angle, $\theta$, along the X-X' plane at $Y=0$mm, and at: (a) $Z=-10$mm, (b) $Z=+5$mm.

Figures 6 shows the mean axial, $V_x$, and horizontal, $V_y$, velocity profiles as a function of the shaft angular position along the X-X' plane at $Z=-10$mm (Figure 6(a)) and $Z=+5$mm (Figure 6(b)); the graphs on the left column of Figure 6 represent the axial velocity profiles, while those on the right column are the horizontal velocity profiles. Starting from $Z=+5$mm, Figure 6(b), upstream of the suction port entrance, the results show uniform axial and horizontal velocity profiles with $\theta$ suggesting little or no influence of rotors motion at this vertical plane. Also, the profiles at different X locations seem to be similar with the axial velocity tend to be positive up to 0.7m/s especially at negative X locations, while the horizontal velocity tend to be negative up -0.7m/s suggesting a slow reverse flow motion from male to female rotor along the X-X' plane at this vertical location. Further downstream at $Z=+10$mm within the suction port and closer to the rotors, Figure 6(a), both axial and horizontal velocities are influenced by the rotors motion and are changed with both X positions of the control volume and also the shaft angle, $\theta$. The latter was expected due to the close proximity of the measuring point with rotors where their movement interacts with the fluid motion and creating difference in pressure between the open rotors’ working chambers and the suction port. The axial velocities are mainly positive with the highest values up to 1.8m/s at X=-30 and +40mm, and that the profiles look like a wave, which may indicate that the flow is moving towards a working chamber that is opening and absorbing the fluid, but since there is more than one working chamber connected to the suction port for each single shaft angular position, the interpretation of the flow would more difficult. Unlike the axial velocity, the horizontal velocity has positive (towards male rotor) and negative (towards female rotor) values for +X and -X locations, respectively, with almost zero velocity at center, X=0; this is more pronounced for flow between shaft angle, $\theta$, of -30° to 10° with $V_y$ values up to +0.8m/s and -0.6m/s, respectively. The fact that the velocity changes from negative to positive values, suggests that there is a rotational flow movement with its centred close to the Z-axis. As mentioned before, measurements of main vertical velocity, $V_z$, was not possible at $Z=-10$mm +5mm and due to obstruction of the laser beams by the suction port wall.
Figure 7. Mean vector velocity variation of vertical ($V_z$) and horizontal ($V_y$) velocities within Y-Z plane at different shaft angles, $\theta$, and at X= 0mm.

The variations of the mean axial, $V_x$, and horizontal, $V_y$, velocities with shaft angle, $\theta$, along Y-Y' plane at Z= -10mm and +5mm, not presented here, showed similar results to that of Figure 6. Although, the trends were similar, there were differences and the results showed more dependency on rotor angle. Overall, the results near the rotors show the presence of a complex flow in the suction that includes an
axial component moving down towards the working chambers at the front of compressor, with the tendency of flow on the left of compressor pointing to the centre of the female rotor while the more flow on the right was pointing to the male rotor; similar to a simplified flow description presented in Figure 4. This is due to the geometry of the suction port that had been designed in such a way that the suction process takes place in front of the rotors.

2.2. PIV results
PIV setup are shown in Figures 1, 2 and 3 and measurements were recorded for different planes with respect to the shaft angle. Then, using purposely written special software, velocity results were averaged to acquire the mean vector velocity over a time window of 1° (Δθ); here 30 images were used to form the mean velocity vector field with an average standard deviation of 10% of the mean value in accordance with LDV results. As mentioned before, the suction port is more accessible with flow being stable with low mean velocities, and therefore less window fouling. Figure 3 presents the two measuring configurations used, first Figure 3(a) shows the arrangement for measuring the flow at the green laser plane (X-Y) localized at Z=75mm. This plane is the same used for LDV measurements. This position of 75mm is particularly chosen so to be far from the rotors. Figure 3(b) shows the vertical laser sheet, which is perpendicular to the rotors for measurements in the Y-Z plane. The sample results of eight selected PIV images at different main shaft angle, 0, are shown in Figure 7.

Figure 7 shows the distribution of mean vector velocity \( \sqrt{V_x^2 + V_y^2} \) of axial and vertical velocity components within Y-Z plane covering 40mm above the suction port entrance at eight different shaft angles, 0, and at X=0mm. The expectation was to see the flow to be vertical and uniform but the results show a more complex flow structure caused by the lack of flow development in the cylinder as explained with LDV results above. Again, similar flow structure can be seen at all, 0, with no influence of shaft movement. At the top of the graphs, there are relatively strong stream with almost horizontal vectors pointing to right, which suggests the flow is dominated by \( V_y \) velocity component. Then as the flow moves downwards, the velocities become more and more vertical. At the very bottom, near the suction port, flow is almost vertical. Due to the fact that PIV system needs two directions of operation, in this case the horizontal and vertical, it was not possible to obtain results nearer to the rotors than the ones shown at the bottom of each graph on Figure 11; such measurement is possible by LDV in back scattering mode. This shows how a one-point measurement system such as LDV is far more adaptable to an environment with limited optical access. On the other hand, if access is available, PIV exhibits an unbeatable solution with high spatial resolution, thus, it is recommended to modifying the suction port to provide more optical access for PIV measurements.

3. CONCLUSION
Mean flow velocities have been measured within the suction port of a standard optical screw compressor using laser LDV and PIV techniques. Time-resolved velocity measurements were made over a time window of 1° (Δθ) at a rotor speed of 1000 rpm, a pressure ratio of 1 and a gas temperature of 55°C. A summary of the main findings is presented below:

- The application of LDV and PIV systems to characterise the flow variation in the new designed optical screw compressor was found to be very successful. To improve the optical accessibility, it is recommended to modifying the inlet port casing by inserting small optical windows on diagonal planes or replacing the inlet port wall by an appropriate plexiglass pipe of the same internal diameter, to allow closer optical access to the rotors for both LDV and PIV measurements.
- The LDV mean vertical velocity component at Z=+75mm along the X- and Y-planes showed uniform downflow velocity profiles with values up to 1.4m/s and no impact of the rotors motion. Similarly, at Z=+5mm, the measurements of the mean axial and horizontal velocity components showed no influence of the shaft movement everywhere with low velocity values with uniform profiles.
- Close to rotors, Z=-10mm, the LDV mean axial and horizontal velocity components have been influenced by both the transverse locations along X- and Y-planes and also by the rotor motions due to the close proximity of the measuring point with rotors. Tracking of the measured axial and horizontal flows showed the presence of a complex flow in the suction port that includes an axial component moving down towards the working chambers with more air to flow towards the male rotor.
The PIV distribution of mean vector velocity of axial and vertical velocity components within Y-Z vertical plane revealed an unexpected complex flow structure due to lack of flow development in the inlet cylinder, as was also shown with LDV results. The results showed similar flow structure at all measured shaft angles with no influence of rotor motions, and that the flow consisted of relatively strong stream flows with almost horizontal vectors 40mm upstream of the inlet suction port. As the flow moves downwards, the velocities become more and more vertical so that at the inlet port the flow becomes almost vertical.

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