LDA measurements of steady and unsteady flow through the induction system of a heavy duty diesel engine

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Yuanxian Zhu, Dick Evers,

Gerrit Huigen and Gerrit Hommersom
Eindhoven University of Technology

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Abstract

LDA technique was used to investigate valve exit flow and in-cylinder flow generated by a directed intake port of a heavy duty Diesel engine under steady and unsteady conditions.

The results obtained under both steady and unsteady show the flow patterns is very sensitive to the valve lift with this type of intake port. At small valve lift, flow profile around the valve periphery is relatively uniform, the corresponding in-cylinder flow is characteristic of double vortex. With valve lift increasing, the separating region appears near the valve seat in part of the valve periphery, therefore the flow pattern begins to depend on the position around the valve periphery. As a result, the valve exit flow is almost along the elongation of intake port at the maximum lift, the corresponding in-cylinder flow behaves as a solid body of rotation.

The motion of valve seems to have little effects on the valve exit flow pattern. However, the measuring results under unsteady condition show the temporal distribution of valve exit flow velocities and the mass flow rate during the induction process is affected by the volume of the stagnation chamber mounted between the intake port and the compressing air supply.

IN RECENT YEARS, more attention [1-7] has been paid on the flow behavior through the induction system of IC engine. The first reason is that such flows have much influence on the volumetric efficiency and in-cylinder flow characteristics, such as swirl and tumbling flow and turbulence, therefore the combustion process and the formation of pollutants. furthermore, the most of multi-dimensional model developed, which were for predicting the in-cylinder flow in engine, required the detail information of the valve exit flow as the boundary condition [8-9].

There are different types of intake ports for engines. The simplist one is the axisymmetric intake port, though this design is hardly used in the modern engines, the research results on which did give some basic and important information on developing the induction system of engines. For example, the dependent of discharge coefficient on the valve geometry [1], the effects of valve lift on in-cylinder flow [2].

The helical and directed port are two main types of intake ports in use. The former is widely used in automotive DI Diesel engines, because it tends to produce higher and more ordered swirl. References [2-5] have given the plenty of measured results on the related valve exit flow and induced in-cylinder flow, even the flow inside this type of port.

The latter- the directed intake port is mainly used in SI engine, IDI Diesel engine and heavy duty Diesel engines. The design of this type of intake port are diverse, depending on whether swirl is needed. References [6-7] gave the measured results of the valve exit flow for a typical directed port, [5] showed the measured results of the in-cylinder flow induced by another directed port. However, all of these results didn't show the relation between the valve exit flow and the induced in-cylinder swirl for this type of port.

Until now, most measurement works on such flows were done under steady condition. In this situation, a quasi-steady assumption was suggested. Apparently, steady flow measurements are attractive because of their some advantages, such as high quality of optical access for LDA and easiness of data acquisition and processing.

The validity of quasi-steady assumption has been examined by some researcher with unsteady measurement [1] [3] [7]. They found that the valve exit flow was insensitive to flow unsteadiness, piston confinement and valve movement in given speed range and given induction period. On the other hand, induced in-cylinder flow was strongly affected by transient effect.

This paper introduces a research work in Eindhoven University of Technology on the directed intake port of a DAF DKS1160 heavy duty Diesel engine. In this study, both the valve exit flow profiles and the induced in-cylinder flow profiles were measured. The similar measurements were done on both the steady flow-rig and the motored test assembly which takes account some real transient effects, resulting from valve motion and the intake stagnation chamber. In this way, we have not only the better understanding to the relation between the valve exit flow and the corresponding in-cylinder flow for this directed port, but also prove the validity of quasi-steady assumption in such situation.

Experimental system and measuring system

For steady measurement, the cylinder head of a DAF DKS1160 Diesel engine was mounted on a blow-up type steady flow rig and

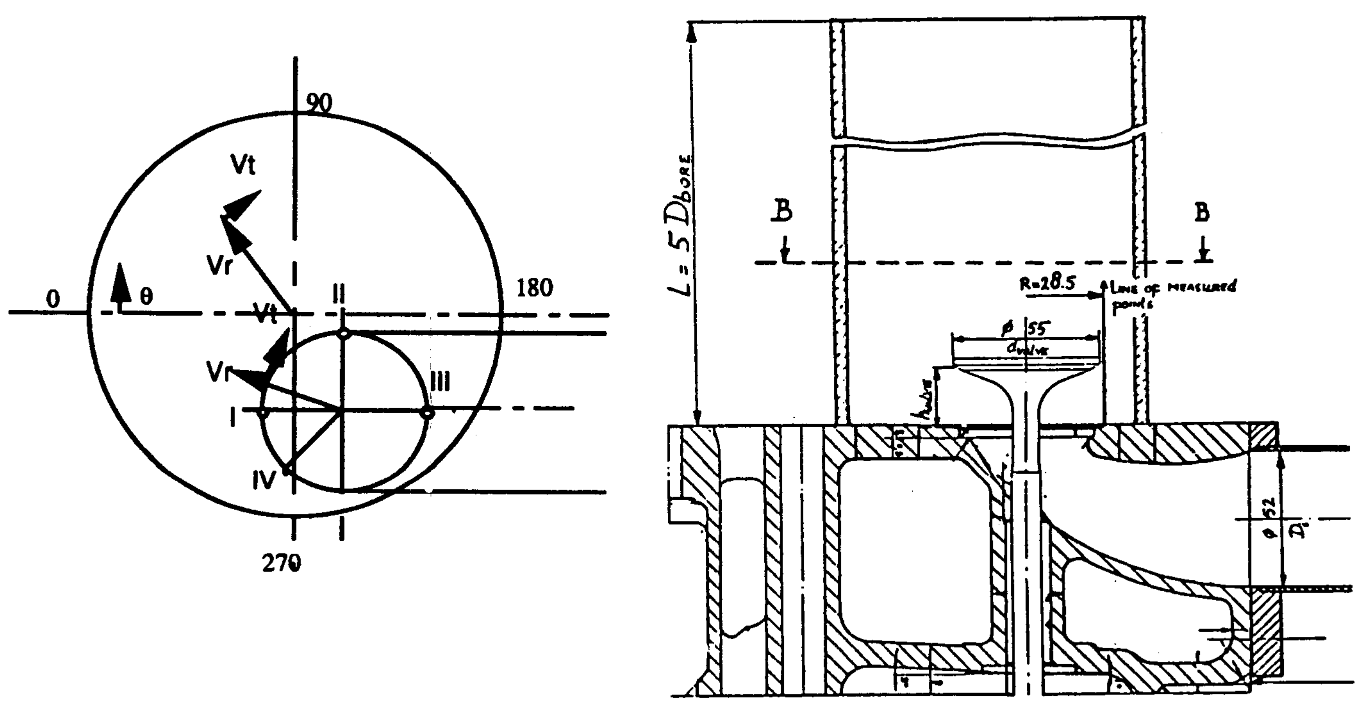


Fig. 1 The geometry of the intake port and valve

fitted with a pyrexglass open-ended thin wall cylinder of 130 mm bore. The geometry of intake port and valve was shown in Fig.1. Air was supplied from a compressed air supply. The cylinder head can be adjusted to rotate around the cylinder axis or valve axis, depending on whether valve exit flow or in-cylinder flow was measured.

For unsteady measurement, the same cylinder head and cylinder wall was used, but an intake valve driving system was installed on the cylinder head and a stagnation chamber was placed between the intake port and the compressed air supply, as shown in Fig.2.

The LDA system in this study operated in the dual-beam, off-axis forward-scattering mode and made use of a 5w Argon Ion laser and a rotating diffraction grating which split the beam and provided frequency preshift. Details of the optical access are given in Table.1.

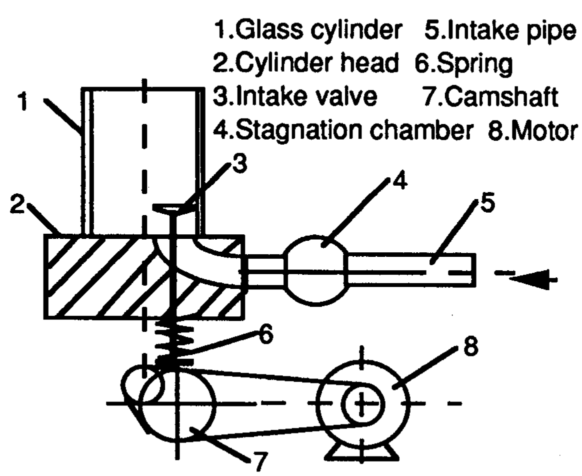


Fig.2 The Unsteady test assembly

The photon correlation was used as the signal processing technique. The signal from photomultiplier was sent to a digital photon correlator (Malvern K7023), which interface to an apple II micro-computer, a set of software [10] was developed to obtain the frequency (velocity) probability density function from autocorrelation function. An important

TABLE 1 Optical characteristics of LDA

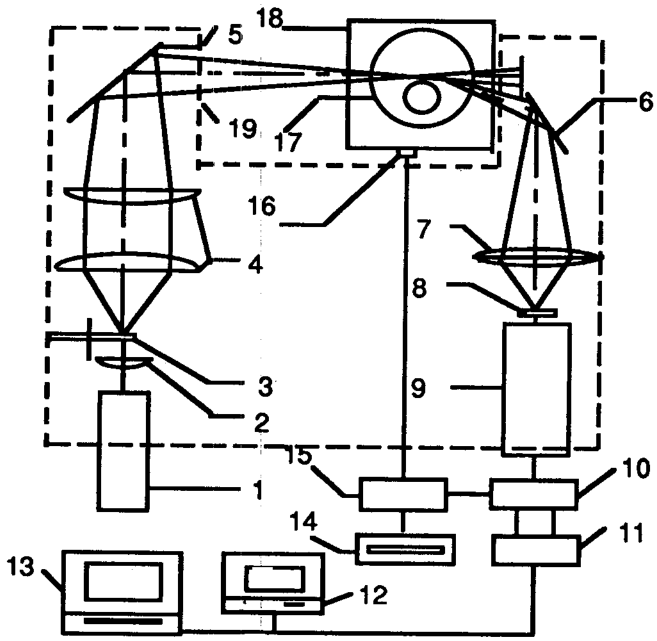
Angle of beam intersection, deg	4.46
Probe volume diameter, mm	0.475
Probe volume diameter, mm	12.2
	2 (off-axis)
Fringe spacing, µm	6.613

advantage of using photon correlation technique is that low scattering intensity is required and therefore no extra tracing particles are needed. For unsteady measurements, the window ensemble technique was used. A delay counter with a electro-magnetic detector mounted on the camshaft was linked to a strobe unit to enable that the signals were collected only within a preset camshaft angle window. The width of window may be adjusted to about 1 degree camshaft angle. Fig.3 shows the arrangement of the measuring system in unsteady condition.

In order to ensure the measuring precision, some measures were used. A theodolite was used to measure the angle between the laser beams at the measuring volume with an accuracy 0.1%. the measurement points were positioned with glass cylinder wall and the angles between the beams were corrected for refraction effects caused by the cylinder wall according the method in reference [11]. The velocity gradient broading was minimized by using very small probe volume dimension, the accuracy of signal processing software were proved to be within 2%.[11]

Results and discussion

Valve exit flow - The mean velocities were measured at valve lifts of 5, 9, and 12.7 mm and four orientations around the valve periphery (Fig.1). The reason that the orientation IV was placed at the current position is that too much scattering effect from wall on the opposite of the orientation II. Along axial direction, the distance between two measuring points is 1mm.Air flow rate was set



1. Ar-Ion laser
2. Lense
3. Rotating diffraction grating
4. Lense
5. 6. Flat mirror
7. Receiving zoom lense
8.Pinhole and filter
9. Photomultiplier
10. Strobe unit
11. MALVERN correlator
12. Oscilloscope
13. Computer
14. Timer
15. Delay unit
16. Magnetic detector
17. Glass cylinder
18. Cylinder head
19. X-Y-Z plateau

Fig.3 The arrangement of LDA system

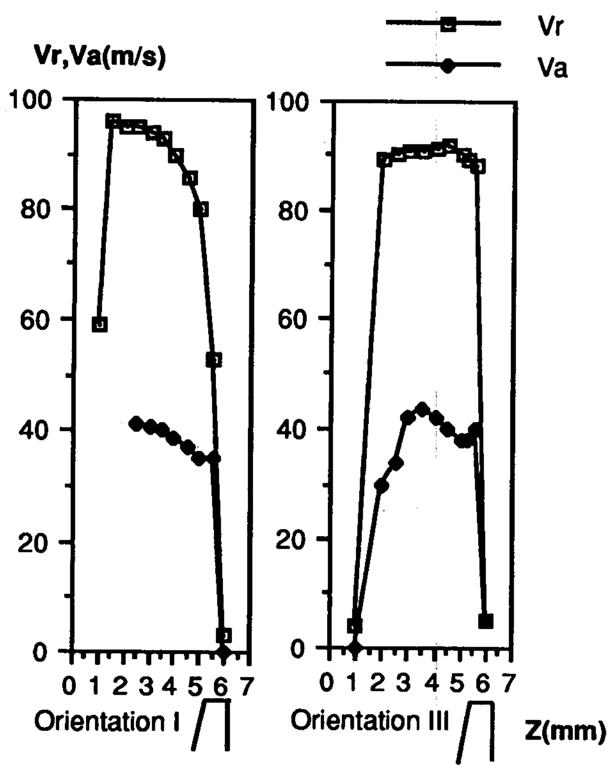


Fig 4 The valve exit flow profiles at 5mm lift (steady)

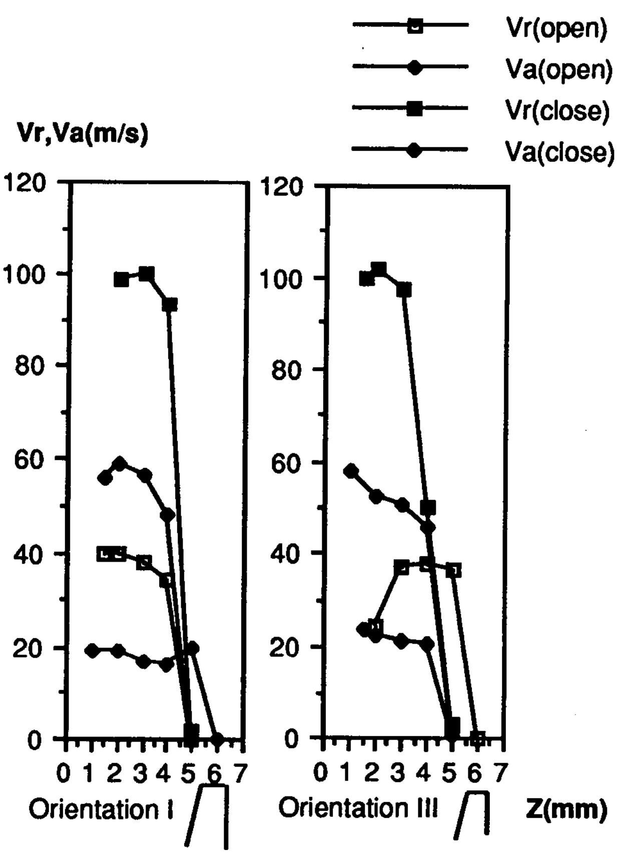


Fig.5 The valve exit flow profiles at 5mm lift (unsteady)

to 270 kg/h, corresponding to the mean flow rate of the unsteady flow for an engine speed of 1000 rpm, the corresponding piston mean speed is about 4.7 m/s. As tangential velocity components in this region is negligible, only axial and radial components were measured.

For unsteady condition, measuring timing were chosen as the valve lift of 5mm (open), 9mm (open), 12.7mm (maximum lift), 9mm (close), 5mm (close). Air flow rate was adjusted to 65 kg/h.

As shown in Fig.4, radial and axial mean velocity distribution are uniform around the valve periphery for the lift of 5 mm under steady flow condition. Furthermore, velocity components is uniformly distributed across the valve gap. The flow jet angle, with respect to the valve axis, is about 70 deg which is the same to the valve seat angle except small area near cylinder head where separating region is present. Fig.5 shows the mean velocities profile under unsteady condition at two timings which correspond the valve lift of 5mm, one is at valve opening process, another at valve closing process. It is found that mean flow patterns under unsteady condition are very similar with those under steady condition. However, the flow jet angle is smaller by 10% and the magnitude of mean velocity at the timing of valve opening is much lower than that got under steady condition. In fact, the valve exit flow velocity keeped increasing during whole induction process.

With the increase of the valve lift, the mean velocity profiles begin to be dependent on the position around the valve periphery. As shown in Fig.6, at the orientation I where the intake port direction elongates, high velocity and smaller separating region near the head can be found. On the contrary, the much larger separating region exists on the opposite position, the orientation III. The flow angle with respect to valve axis vary between the orientation I and the orientation III from 60 deg to 66 deg. The results obtained under unsteady condition show similar phenomena (Fig.7). However, it is found that the radial component almost keeps constant, but axial component increased when the valve opened from 5mm to 9mm therefore the flow angle decreased from

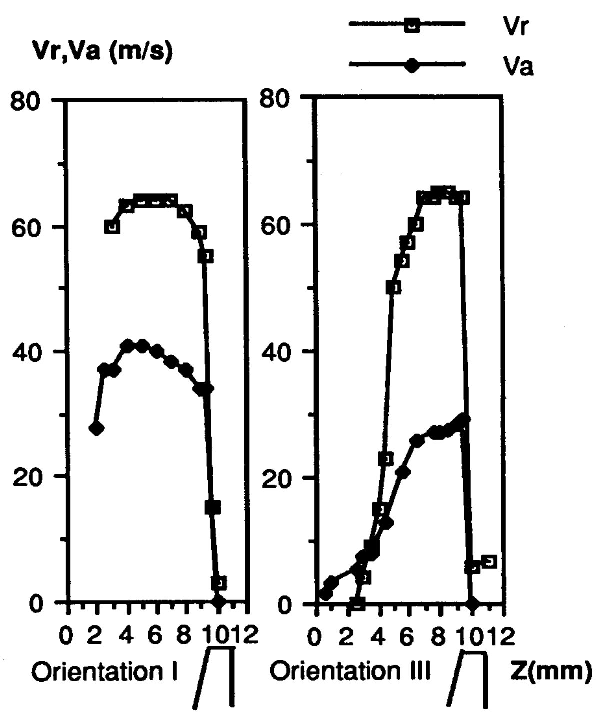


Fig.6 The valve exit flow profiles at 9 mm lift (Steady)

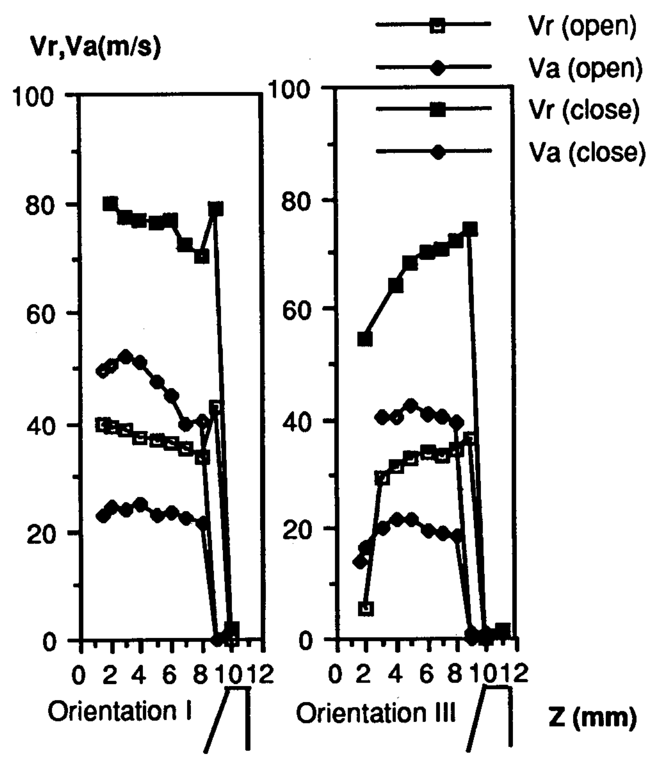


Fig.7 The valve exit flow profiles at 9mm lift (Unsteady)

70 deg to 60 deg. Similarly, the velocity value at the timing of the valve closing is agree with those at the same valve lift under steady condition.

When the maximum lift (12.7mm) is reached, the flow patterns are much different with those obtained at the valve lift of 5mm, the mean velocity profiles strongly depend on the position around the valve periphery (Fig.8). The flow jet is almost full of the valve gap at the orientation I. However, the separating region where the radial velocity component become negative occupy about 70% of the valve gap area and the flow angle vary considerably over the jet at the orientation III. The comparison of the steady flow results with those got at the same valve lift under unsteady conditions (Fig.9) showed that both cases had the same flow patterns and the values agree within 10-15%.

From previous results, it is clear that the valve exit flow patterns strongly depend on the valve lift and both steady and unsteady

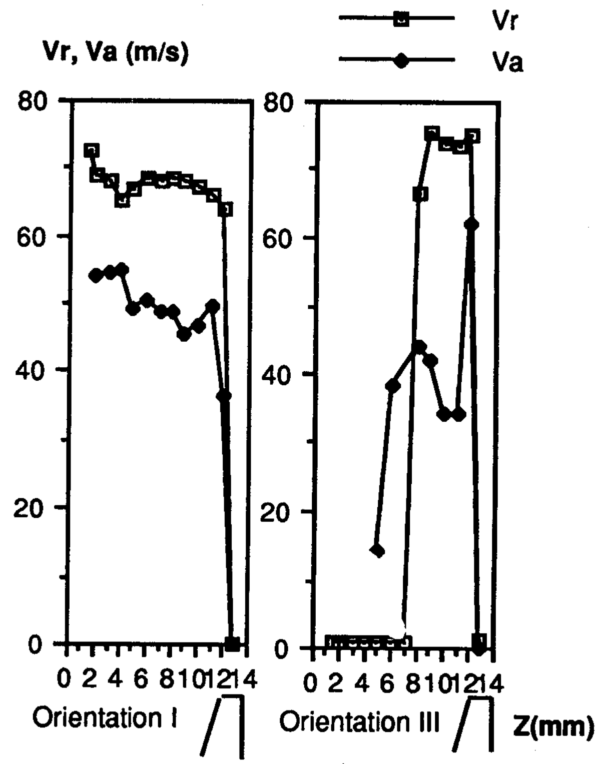


Fig.9 The valve exit flow profiles at 12.7 mm lift (Unsteady)

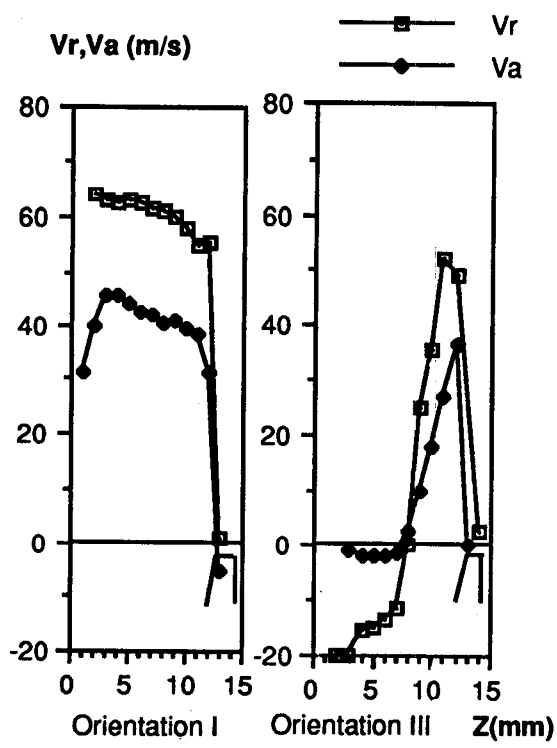


Fig.8 The valve exit flow profile at 12.7 mm lift (steady)

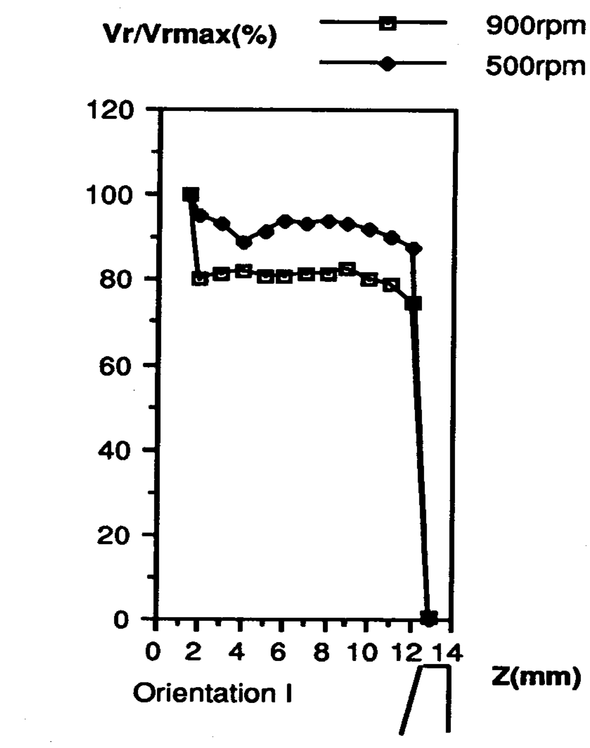


Fig.10 The valve exit flow profiles at 12.7 mm With different camshaft speed

measurements got similar results.

Unsteadieness from the valve motion seems to have little effect on the flow patterns. Fig.10 shows the valve exit flow patterns had little change when camshaft speed increased from 500 rpm to 900 rpm. So the assumption of quasi-steady is reasonable in such a condition.

On the other hand, the temporal distribution of valve exit flow velocity and transient mass flow rate under unsteady condition is much affected by the volume of the stagnation chamber placed between the intake port and compressed air supply. As shown in Fig.11 and Fig.12, with the chamber volume of 280L, the pressure in the chamber almost keeps constant (105 KPa) and the flow is accelerated during whole induction process. On the contrary, with the chamber volume of 20L, the pressure in the chamber changes dramatically (Pmax=110 KPa, Pmin=101KPa), and the flow is under decelerating condition (seeing Fig.13). It should be mentioned the pressure in the cylinder with the current test assembly was about constant, the results obtained in such a condition may be different from those in real engines. The determination of the transient mass flow rate at the valve exit should be based on the unsteady analysis to whole induction system.

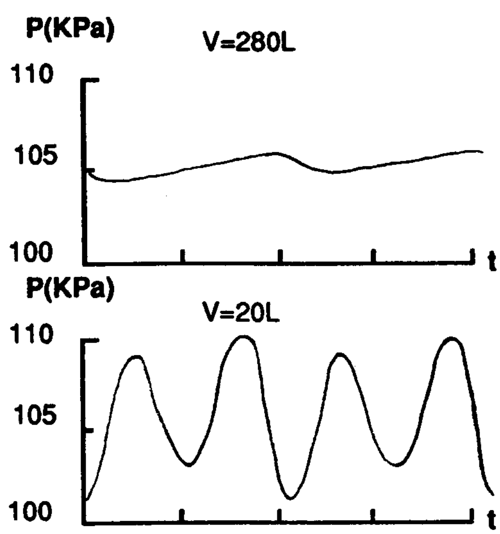


Fig.11 The pressure histories in the chambers

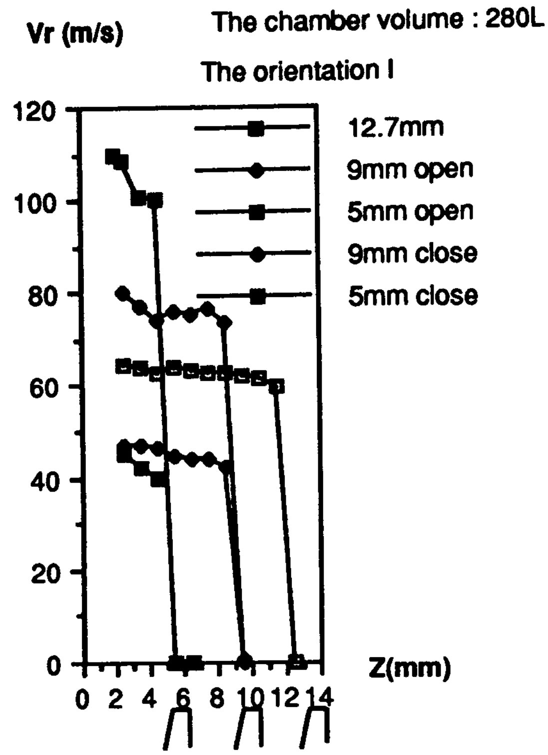


Fig. 12 The valve exit flow profiles with the chamber of 280 L

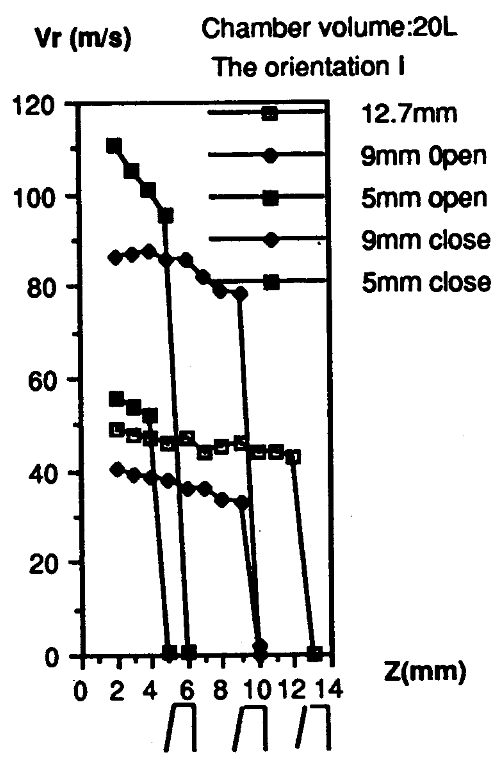


Fig. 13 The valve exit flow profiles with the chamber of 20 L

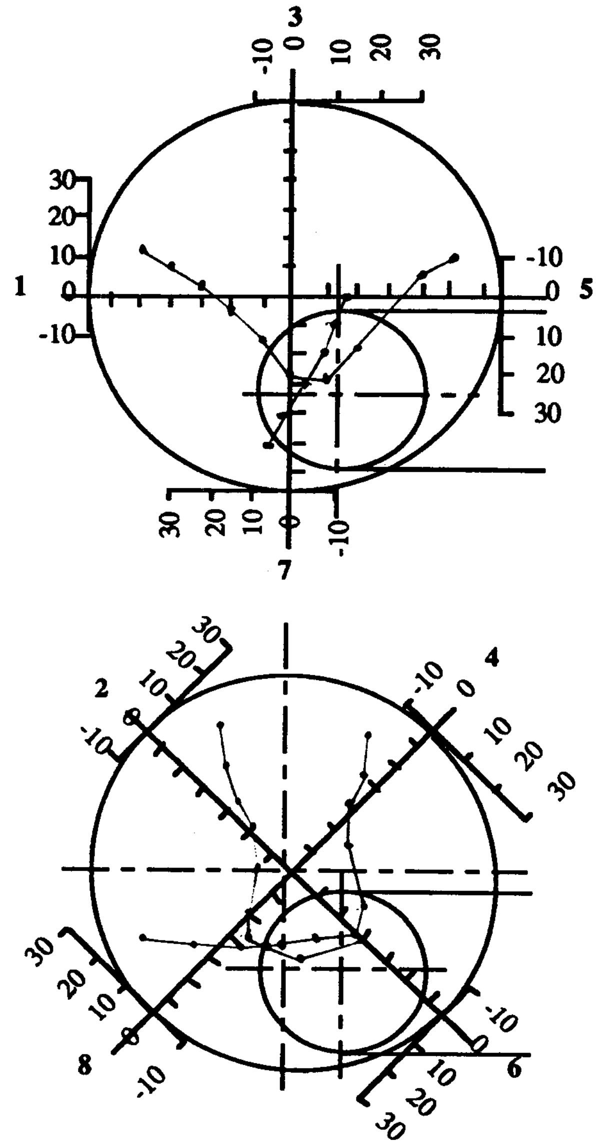
In-cylinder flow - Axial and tangential mean velocities at a down stream plane of a cylinder bore (Z=130 mm) were measured with 10mm distances along eight radii, spaced 45 deg intervals.

Fig.14, 15 shows the measured results at 5mm valve lift under steady condition. The tangential flow field is characteristic of double vortices which have almost equal sizes and intensities. The axis with which the two vortices distribute symmetrically is close to the line passing through the valve center and the cylinder center (θ=80 deg and θ=260 deg). The flow pattern in the axial plan (1-5) shows two revered flow regions which correspond the centers of two tangential vortices. High positive axial velocities are found in the cylinder center and the part of outer region (θ=45-90 deg).

At the valve lift of 9mm, the tangential flow pattern still keeps double vortex structure. However, the vortex which placed at the elongation of intake part expanded and covered more than half of the cylinder cross area, its strength is increased, too.

With the valve lift reaching maximum value, the flow pattern experiences much change and the double vortex disappears completely, instead the single swirl motion is established and it behaves as a solid body type of rotation. The velocity distribution in axial plane is uniform, comparing that at 5mm valve lift, no peak axial velocity at the central region, positive axial flow concentrates at the part of outer region (θ=45-180 deg), as shown in Fig.16,17.

Under unsteady condition, the flow velocities were measured at camshaft angle α=o, 90 deg, corresponding the, initial point of the valve opening and the valve lift of 5mm (the valve closing) respectively. As shown in Fig.18,19, when α= 90 deg the double vortex structure appears in the tangential velocity field, one dominating 80% of the cylinder cross area with the center near the cylinder center, the other one only occupying a very small area near the wall (θ =180-270 deg). Such a flow structure looks like those between the valve lif



5 mm lift

Fig. 14 The tangential velocity profiles at 5mm lift (steady)

lists of 12.7 mm and 9mm under steady condition. It seems that the effects from the valve exit flow at last timing corresponding the valve lift of 12.7mm-9mm just arrives at the downstream plane at the moment. Similarly positive axial flow happens in the half of the cross area (θ=45 - 180 deg). Fig.20,21 show a flow pattern at α=0 deg, which should attribute residual effect from last induction process, it seems that the flow field in the cylinder will

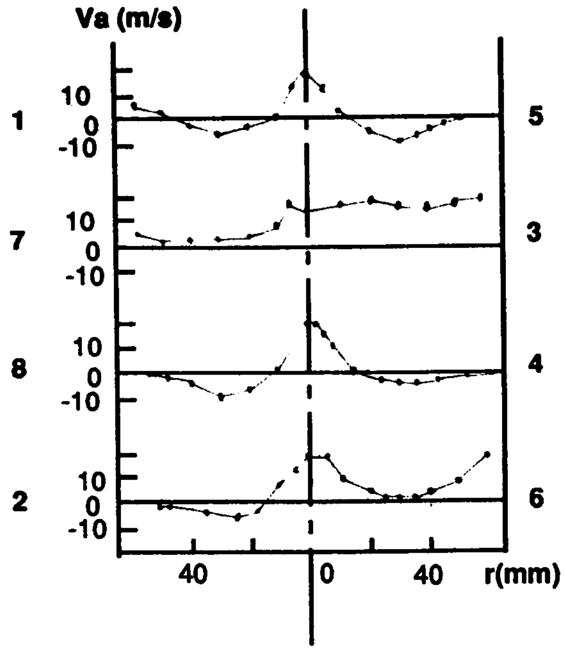


Fig.15 The axial velocity profiles at 5 mm lift (Steady)

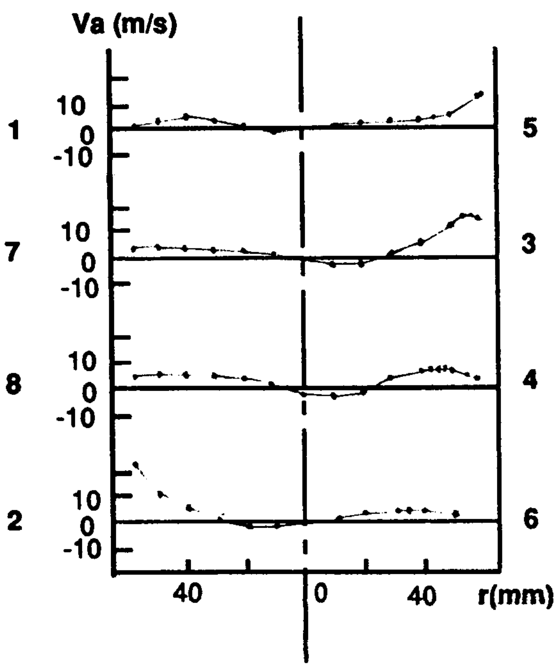


Fig.16 The axial velocity profiles at 12.7mm lift (Steady)

decay and become a steady solid type of rotation finally after valve closing, no matter how complicated process it experiences.

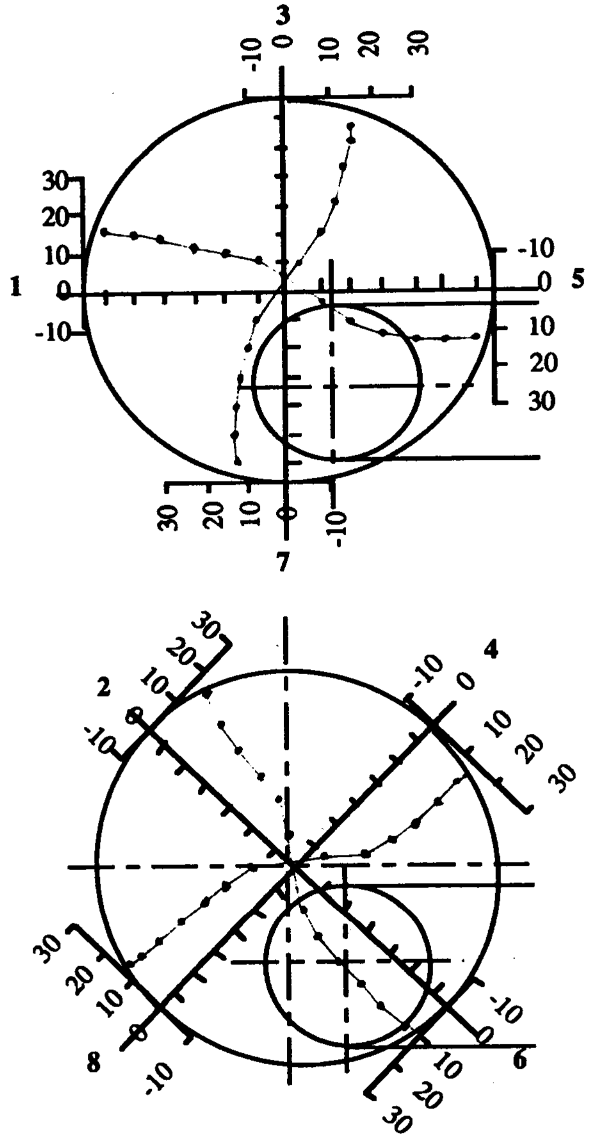


Fig.17 The tangential velocity profiles at 12.7mm lift (Steady)

From previous results, it is found that the ordered swirl can be generated with this type of directed port. As pointed in [3], such swirl is produced downstream of valve, and called post valve swirl. It is that the interaction of the valve exit flow and the cylinder wall causes the formation and development of swirl in the cylinder. This is the main reason that the induced in-cylinder flow pattern is very sensitive to the change of the valve exit flow.

A reasonable explaintation for the valve

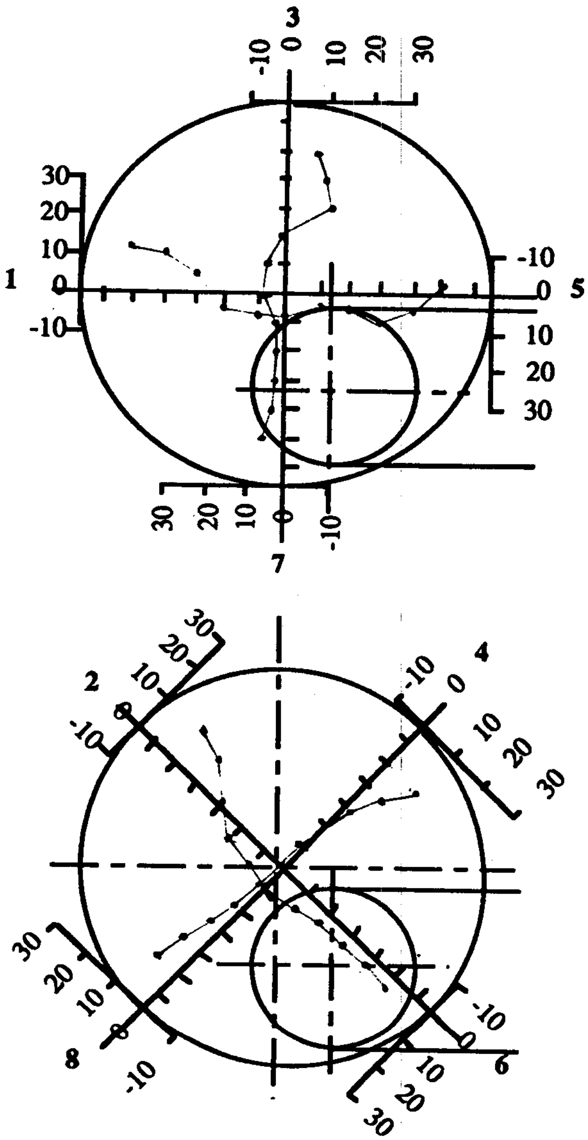


Fig-18 The tangential velocity profiles at θ = 90 deg (Unsteady):

exit flow changes dramatically at different valve lifts is based on a qualitative analysis to flow inside the port. At the part just upstream of the valve throat, the lower wall boundary become a 90 deg curve with a small radius, and the flow separation will happen there. When the valve lift is 5mm, the minimum cross area is at the valve exit plane; the flow, which can be treated as incompressible, will attach the boundary again at a downstream point to satisfy continuity condition. It is expected that the valve exit is full of flow and mass flow is

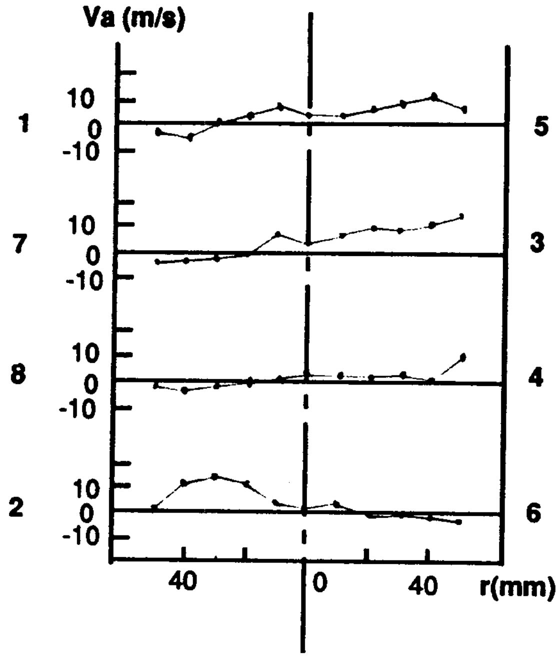


Fig. 19 The axial velocity profiles at θ=90 deg (Unsteady)

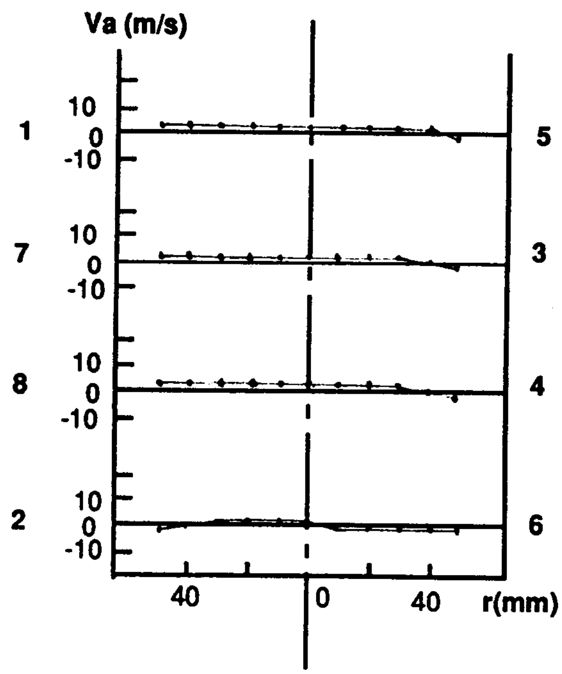


Fig. 20 The axial velocity profiles at θ = 0 deg (Unsteady)

uniformly distributed around the periphery of the valve. The jet at the orientation I will contribute to a clockwise vortex, and that at the orientation III will contribute to another

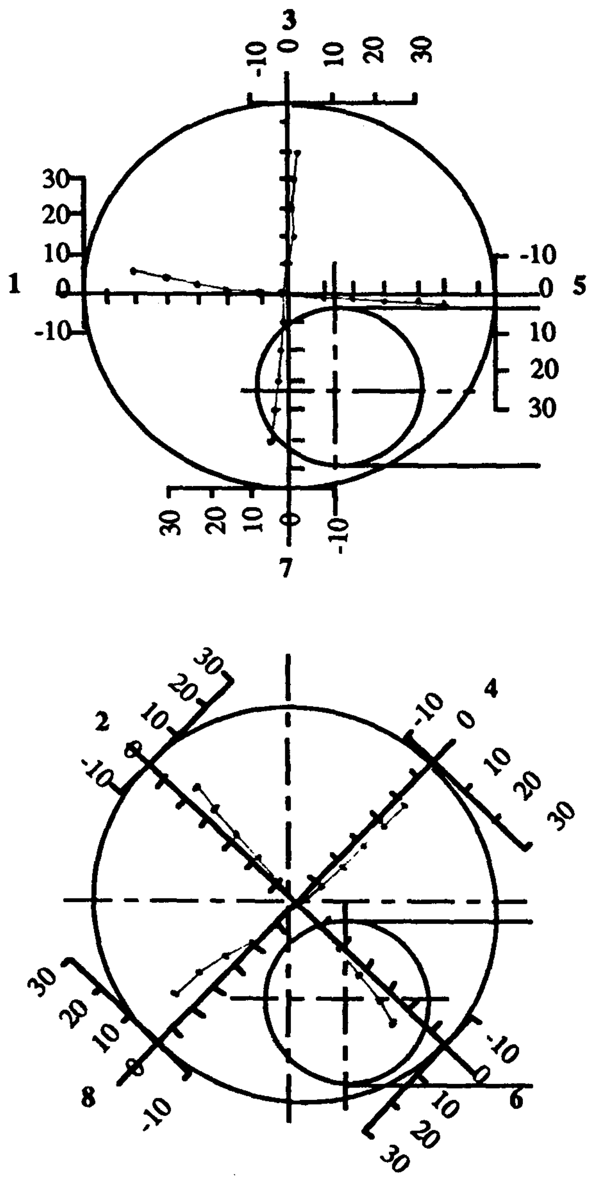


Fig. 21 The tangential velocity profiles at θ = 0 deg (unsteady)

counterclockwise vortex.

With the valve lift increasing, the minimum cross area will move upstream to the valve throat. In such situation, the separating region will expand until the valve exit with a positive pressure gradient. As a result, the mass flow at the orientation III is much lower than that at the orientation I, and the clockwise vortex will dominate over the whole cylinder cross area finally.

Conclusions

The valve exit flow pattern generated by a directed port strongly depends on the valve lift. At low valve lift, the flow around the valve periphery is uniform; with the valve lift increasing, separating region appear near the valve seat at the part of valve periphery, flow patterns become much less uniform.

The different valve exit flow patterns result in different in-cylinder flow patterns. With uniform valve exit flow, the in-cylinder flow pattern is characteristic of double vortices having the same size and strength. The flow pattern looks like a solid-body of rotation when the valve exit flow is almost toward the elongation of intake port.

The unsteadiness from valve motion has little effect on the valve exit flow pattern. Under this test condition, the assumption of quasi-steady is valid.

The temporal distribution of valve exit flow velocity and the transient mass flow rate during the induction process are heavily affected by the volume of inlet stagnation chamber.

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