High Speed Pulsed Injection of Natural Gas

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ABSTRACT

The pulsed gas jet from an injector installed in the inlet port is directed through the annular gap of the open inlet valve so that its kinetic energy will create turbulence in the cylinder. The resulting velocity and turbulence were measured with hot-wire anemometry using a cylinder head with a glass cylinder and a fixed piston. The results show how the jet propagates into the cylinder, whereby its velocity is reduced as it entrains more and more air. The in-cylinder flow generated by the pulsed jet increases the rate and stability of combustion.

INTRODUCTION

The rate of combustion in SI engines is strongly influenced by turbulence and charge motion. Because of the much lower density of natural gas compared to gasoline, the flow through a gas injection nozzle attains the speed of sound with a few bar overpressure. With the "trans-valve-injection" combustion concept, the gas pulse from an injector in the inlet port is directed through the annular gap of the open inlet valve during the suction stroke [1]. Engine tests show that the rate of combustion can be increased by more than 50 % at lower RPM [1,2]. Optimum orientation and timing of the gas jet were initially found on the test bench [1].

In order to understand and explain the effect of the pulsed gas jet on combustion, its flow field was investigated with the help of hot-wire anemometry [3]. For these experiments, compressed air was used instead of gas and the piston was kept fixed in the cylinder. Therefore no suction flow existed and the action of the gas jet could be studied separately. This has to be taken into account when interpreting the results.

A free gas jet entrains the surrounding air and mixes with it because the two densities are nearly the same. The entrainment of air results from the instability of the shear

Fig. 1 Experimental set-up
surface between jet and surrounding air. During this process the average velocity of the jet consisting of gas and entrained air decreases while the total momentum remains practically constant [4,5]. Kinetic energy from the mean flow in forward direction is continuously transferred to large turbulent eddies. As these large eddies break down into smaller and smaller ones, their kinetic energy is cascaded down until it is dissipated by viscosity [6].

The best condition for ignition and subsequent flame propagation is small scale turbulence with a low mean velocity at the spark plug [7]. In modern gasoline engines with four valves this is obtained by means of tumble flow, which is effectively transformed into turbulence during the compression stroke through axial squeezing. The problem with the suction flow generated by the moving piston is that its velocity changes with RPM. This is often compensated by means of a flap in the inlet channel or by variable valve activation. “Trans-valve-injection” of a pulsed gas jet through the open inlet valve is an effective way to increase the rate of combustion by generating turbulence, especially at lower RPM [1]. At higher RPM the effect of the gas jet decreases but at the same time the suction flow becomes stronger. Therefore the two means for generating turbulence are complementary.

HOT-WIRE ANEMOMETRY EXPERIMENTAL SET-UP

For our experiments a plexiglass cylinder with a fixed piston was attached to the cylinder head of the original Volkswagen 1.8 L 4-cylinder engine [1,8] as shown in Fig. 1. Compressed air was used instead of natural gas for the following reasons: different hot-wire calibrations for gas and air and the safety hazard with gas. The velocity and turbulence of the jet were measured at different locations (Fig. 2) with hot-wire anemometry using the “Streamline” system from Dantec with a single wire probe of 1.2 mm length and 5 µm diameter. The injector, installed in the same position as for gasoline, was provided with an extension tube and a convergent nozzle with 1.5 mm diameter (Fig. 1). The direction of the extension tube was adapted so that the jet passed to the left side of the valve shaft directly through the valve gap [1]. The jet was pulsed with typical durations of 5 ms and 15 ms, using a Bosch EV 1.3 A gas injector, a pulse generator and an amplifier. The electric pulse also served to trigger the data acquisition in order to assure precise timing.

The different locations of the hot wire and its orientation were chosen under the following criteria: the probe positions were distributed along the main trajectory of the jet at increasing distance from the nozzle, they were displaced laterally until the maximum speed was measured and the direction of the hot wire was set perpendicular to the mean velocity vector. In the 6 mm gap of the open inlet valve, the hot wire had a direction tangential to the valve periphery (location A in Fig. 2), whereas in positions B C and D near the cylinder wall or the piston surface the wire was perpendicular to the wall at a distance of 1 mm. It should be noted that because the sensitivity of the hot wire decreases when the instantaneous direction of the velocity deviates from the perpendicular direction to the hot wire, the turbulent deviations from the mean velocity lead to errors at higher levels of turbulence. The hot-wire position near and perpendicular to the wall reduces this effect.

Because the level of turbulence in the free jet is rather high, the measured pulse signals were averaged in most of the cases in order to reduce the turbulent noise relative to the repetitive part of the signal [3]. This was obtained by making the sum of 10 pulses with identical timing (ensemble averaging), which decreased the noise superimposed on the signal by the square root of 10. The time scale for all measurements always starts with the electric pulse to the solenoid operated injector. The opening of the injector needle starts after a delay of 1 ms and takes 0.7 ms.

EXPERIMENTAL RESULTS

The objective of the hot-wire measurements was to understand the in-cylinder flow and turbulence caused by the pulsed jet and to explain its influence on combustion. For a better comparison, the pulses measured at different locations under different conditions are plotted together in groups.

From previous engine tests it was known that the best position of the nozzle is at a distance of about 60 mm from the inlet valve [1]. Fig. 3 shows a free jet at 60 mm from the nozzle in form of a 5 ms and a 15 ms pulse. The mean value of the jet speed is 71.8 m/s with compressed air of 5 bar overpressure. The 5 ms pulse is the ensemble average of 10 individual measurements, which reduces the turbulent noise by a factor of 3.16. For comparison the 15 ms pulse is a single measurement and shows the real magnitude of turbulence with a standard deviation of 17.7 m/s, corresponding to 25 %
Fig. 3 Velocity of free jet at 60 mm from nozzle (distance from nozzle to inlet valve): single pulse with 15 ms duration and ensemble average of 10 pulses with 5 ms duration

Fig. 4 Pulsed jet with 5 ms at locations A B C D (see Fig. 2): A in fully open inlet valve, B near cylinder wall, C and D near piston in upper and lower positions

of the mean. The front of the pulse is sharp, whereas the end occurs stepwise over about 5 ms, which is caused by multiple rebounds of the injector needle when impacting on the seat.

Fig. 4 shows the 5 ms pulse at the different locations A B C and D indicated in Fig. 2 under the condition of fully open inlet valve. In the inlet valve (curve A) the speed is the same as in the free jet (70 m/s). Near the cylinder wall (B) just after the impact of the jet and its deviation, the pulse arrives about 1 ms later and its average speed has fallen to 35 m/s. After a second deviation, the jet is shown at C just above the piston at 1/3 stroke length from TDC. It has an additional 5 ms of delay and a speed of only 16 m/s. In curve C one can see a turbulence free precursor of the pulse, indicating that the jet displaces the air ahead of it as it propagates. Curve D is for the piston in its lowest (LDC) position with 3.5 ms more delay and merely 12 m/s.

The 15 ms pulse under the condition of only 1/3 open inlet valve (2 mm gap) is shown in Fig. 5. At the inlet valve (A) the speed drops from initially 90 m/s to about 70 m/s for the cylinder closed with the piston. If for comparison the piston is removed, the speed increases to over 100 m/s. At the cylinder wall (B) the speed drops to 30 m/s after an initial peak of 40 m/s. Curves C and D at the piston in high and low positions

are similar to the 5 ms pulse. For a complete comparison, the 5 ms and 15 ms pulses at the piston in lowest position (D) are replotted in Fig. 6, for both full and 1/3 opening of the inlet valve. It can be seen that there is a steady decrease of both the peak and the duration of the pulse from 15 ms with fully open inlet to 5 ms with 1/3 open valve.

All curves in Figs. 4 to 6 represent ensemble averages over 10 individual pulses. As the pulsed jet propagates, the turbulent eddies become larger in size and at the same time slower. To illustrate this, Fig. 7 shows a single pulse and the 10 pulse average at the piston in higher position (C).

INTERPRETATION OF RESULTS

The objective of the hot-wire measurements was to understand how the pulsed gas jet generates in-cylinder flow and turbulence, in view of optimizing combustion with trans-valve-injection.

For the nozzle exit, a jet speed of 313 m/s was calculated assuming overcritical pressure ratio and a stagnation temperature of 20°C. From the measured flow rate of 1.51 g/s (continuous jet), a jet diameter of 2.09 mm after free expansion to ambient pressure was calculated. This allowed to confirm exactly the nozzle speed with an empirical equation for free jets [4] from the 71.8 m/s measured at 60 mm from the nozzle.

When the turbulent jet passes through the 6 mm gap of the open inlet valve (A in Fig. 4), its speed remains the same as with the free jet, which indicates that there is practically no interaction with the walls. When the inlet valve is only 1/3 open with a gap of 2 mm, the jet speed has an initial peak of 90 m/s (A in Fig. 5). This results from the lateral restriction of the jet with a similar effect as in a venturi nozzle. The top curve in Fig. 5 is the result of removing the piston from the cylinder. It shows that the speed of the 15 ms pulse gradually increases to over 100 m/s and is explained by a slow acceleration of the entrained air in the inlet channel. With the piston in place, the speed drops to about 70 m/s after 2 ms, which results from the pressure build-up in the closed cylinder and the partial back flow through the inlet valve to assure continuity. The speed oscillates with about 6 m/s, corresponding to the resonance of the cylinder volume with
during propagation in the cylinder. The original pulse duration of 15 ms decreases to about 12 ms (10 ms at location D) as a result of the pulse front being slower than the tail. This indicates that the pulsed jet is gradually transformed into a moving cloud. At the same time the turbulence as shown by the single pulses changes from higher to lower frequency and its relative standard deviation decreases slightly as the jet propagates. This is a result of the turbulent eddies becoming larger in size and it shows that the eddies do not contain back flow. When the jet is transformed into a moving cloud, its bulk motion remains stronger than the superimposed eddies.

CONCLUSIONS FOR TRANS-VALVE-INJECTION

The effect of trans-valve-injection on the rate of combustion is shown in Fig. 8., with results from the Volkswagen 1.8 L engine [9]. In comparison to injection before the suction stroke (A), trans-valve-injection with the best timing (B) has a 50 % higher combustion rate. Because of the high flow rate of a two-stage injector [2], the duration of the gas pulses was only 4 ms at 2/3 part load, which is short in comparison to the stroke time of 15 ms at 2000 RPM.

![Fig. 8 Rate of combustion with 3 different timings of pulsed gas jet: A before suction stroke, B early and C late during suction stroke (2/3 part load, 2000 RPM, spark timing 25°)](image)

There are two important differences between the conditions in our hot-wire measurements and in a real engine: first the moving piston changes the cylinder volume, generating a suction flow through the inlet valve, and secondly the natural gas jet has a lower density than air. Still the understanding gained from the hot-wire measurements can help to explain the flow phenomena in a real engine and their influence on combustion.

Formation of the flame kernel and flame propagation require small scale turbulence consisting of small eddies with not too high mean velocity at the time of ignition [7]. In trans-valve-injection the pulsed gas jet must at the same time
generate turbulence and mix with air. A large distance between the nozzle and the inlet valve allows the gas jet to entrain more air, which is an advantage for mixing. But at the same time the jet has a larger diameter when passing through the inlet valve and is therefore more restricted. Tests on the Volkswagen 1.8 L engine [1] have shown that when the nozzle is positioned directly in front of the inlet valve, the combustion rate decreases again. In tests with a small 0.35 L 2-cylinder Honda engine [10] the best results were obtained with a distance of 80 mm from the nozzle to the inlet valve. Here the inlet channel has a diameter of only 18 mm, which allows the gas jet to attach to the wall and spread laterally before reaching the inlet valve. This widening of the jet enhances mixing and makes the cross section of the jet well adapted to the narrow gap of the inlet valve.

The hot-wire measurements show that propagation and penetration of the pulsed jet are fast up to and along the cylinder wall but no further than the sharp corner at the piston surface (Figs. 4 and 5). Therefore the pulsed jet is not useful to generate a complete tumble flow. This also allows to answer the question about best timing of the gas pulse relative to the suction stroke. If the pulse is timed late during the suction stroke, it will lag behind the air which entered into the cylinder first and is near the piston. Ideally the pulse duration should coincide with the suction stroke, which is only possible for specific combinations of RPM and load. When at lower RPM the stroke lasts longer than the pulse, the best timing for the pulse was found to be such that it ends already before the the middle of the suction stroke [9]. This can be seen in Fig. 8, showing that the rate of combustion decreases again when the gas pulse ist timed late (C). Therefore short pulses should have early timing, the reason being that mixing is better in the small volume at the beginning of the stroke. At high RPM and load, the suction stroke becomes shorter than the gas pulse. Here it is important that the pulse end occurs before the the end of the suction stroke so that no gas remains in the inlet channel.

Because the density of natural gas is only 60 % of air, the deceleration of a natural gas jet in air will be faster and the penetration depth smaller than in our experiments with compressed air [5].

The flow rate of the jet, including the entrained air, can be estimated from the jet speed assuming momentum conservation. The speed ratio between the nozzle and a given position along the jet is therefore inversely proportional to the ratio of flow rates. At the inlet valve (A) the jet has about 70 m/s in its centre. Taking 35 m/s average speed over the cross section and 313 m/s at the nozzle, results in a total mass flow rate of nearly 9 times the value at the nozzle. The stoichiometric air/fuel mass ratio for natural gas is 16. It can be concluded that at the inlet valve the gas jet is already entraining half of the air needed for a stoichiometric mixture. The large amount of entrained air indicates efficient mixing between the gas jet and the surrounding air. Because of its lower density, a natural gas jet will be more decelerated at equal distance from the nozzle. Therefore it will entrain an even larger relative air mass than the air jet in our experiments.

The total volumetric flow rate of the jet at the inlet valve, calculated from 1.29 L/s measured at the nozzle times the factor of 9 from above, can be compared with the average suction flow rate generated by the moving piston in the 0.45 L cylinder. At 770 RPM the two flow rates are equal. At 2000 RPM the jet still covers 38 % of the average suction flow. At higher RPM the suction flow becomes much stronger than the jet. This can explain test results with the Volkswagen engine [1], in which the influence of trans-valve-injection on rate of combustion practically disappears at 4000 RPM.

The time delay of the pulse between the inlet valve (A) and the piston in lowest position (D) is about 10 ms (Figs. 4 and 5). This can be compared with the stroke time of 15 ms at 2000 RPM and shows that the two time scales are similar. The jet speed however is generally much higher than the piston velocity, which at 2000 RPM has an average value of just 6 m/s. The jet speed of 70 m/s at the inlet valve (A) is of the same order of magnitude as the air speed through the inlet valve at maximum RPM. At low RPM the suction flow becomes much weaker while the jet speed remains constant, which explains the strong effect of trans-valve-injection at low RPM, particularly at idle.

REFERENCES