THE NINTH INTERNATIONAL PACIFIC CONFERENCE ON AUTOMOTIVE ENGINEERING
Bali, Indonesia, November 16-21, 1997

971300
(Abstract Code 115)

The Effects of Intake Port Design on Flame Propagation in a Lean Burn Spark-Ignition Engine

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ABSTRACT

Flame Propagation in an optical spark-ignition engine was visualized to see the effects of various shapes of intake ports on the combustion characteristics under lean burn conditions. The effects of tumble and swirl flows on the flame propagation were investigated experimentally in a 4-valve optical gasoline engine. The tumble flow patterns were generated by various intake ports of different entry angle; 25°, 20°, 15°. Inclined tumble(swirl) flows were induced by three different swirl control valves. The initial flame propagation was visualized by an image-intensified CCD camera. Flame images were processed to provide information on the flame size and convection correlated with tumble or inclined tumble flow characteristics.

It was found that there is a correlation between the stronger tumble during induction and turbulence levels at the time of ignition resulting in faster flame development. Inclined tumble was proved to be more beneficial than the pure tumble for faster and stable combustion under lean mixture conditions, which was confirmed by faster propagating flame images.

Keywords : Flame visualization, Shapes of Intake port, Lean burn

INTRODUCTION

It has long been recognized that the turbulent air motion in spark ignition engines controls combustion efficiency and formation of pollutants through large- and small-scale mass and heat transport. Significant process in both experimental investigations and numerical simulation has been made which has improved substantially understanding of in-cylinder flow process[1-5]. It has been known that changes in the combustion chamber shape and inlet geometry, both of which change the turbulent flow field, influence emissions, fuel economy and the lean operating limit of an engine.

Lean burn combustion has become one of the most promising concepts for improving fuel economy and reducing exhaust emissions[6]. However, lean combustion is associated with increased cycle-by-cycle combustion variations due to combustion instability[7]. The role of the turbulent mixture motion becomes critically important for lean operation of spark ignition engines where burning rates are much lower than that in stoichiometric engines. It has been known that burning rate in premixed mixtures is mainly determined by preflame turbulence level [8]. It has been reported [9-12] that the formation of a tumbling vortex sometimes with swirl in four-valve, pentroof combustion chambers represents the most effective method for enhancing turbulence levels at the time of ignition. There is some evidence of a strong correlation between tumble strength and turbulence levels at ignition [11] and a faster burn rate by stronger tumble made by modification of inlet ports[12, 13].

In the present study, the effects of tumble or inclined tumble flow generated by various intake ports on the lean burn characteristics in a four-vale engine are investigated.

The tumble flow characteristics with three intake ports with different entry angle (θ = 25°, 20° and 15°)were compared to see the effects of tumble flow. Three different shapes of swirl control valves were also applied to induce various inclined tumble(swirl) flows.

Visualization has been traditionally the most effective method for analyzing the flame behavior in reciprocating engines.[14, 15] The flame propagation was visualized with a CCD camera in the optical engine. Flame images were analyzed to compare the enflamed area and displacement of initial flames.

The research engine with experimental methods are described in the text section followed by results and conclusion, which shows the insight on the correlation between flow and combustion characteristics in a four-valve SI engine.

EXPERIMENTAL SYSTEMS

Table 1. Geometric/operational parameters of the pentroof-chambered 4-valve research engine

Displacement	1998cc
Bore x stroke	86.0 x 86.0
compression ratio	9.2 : 1
maximum valve lift (mm)	9
valve timing	IVO BTDC 10° IVC ABDC 55° EVO BBDC 55° EVC ATDC 10°

RESEARCH ENGINE - The four-valve research SI engine has pentroof combustion chamber and its geometric and operating characteristics are listed in Table 1. The effect of entry angle of inlet port on the tumble flow characteristics was tested with three inlet ports of different entry angles, i.e. a direction to the bottom surface of cylinder head, θ = 25°, 20° and 15° (see Fig. 1(a)).

Since the port of θ = 20° was found to be most effective in improving lean burn performance by enhancing tumble-generated turbulence[S-1], three different swril control valve were applied to this tumble port to see the effect of inclined tumble flows on the lean burn characteristics (see Fig. 1(b)). Flow capacities of each configuration was quantified by the steady flow that and LDV measurement under motoring conditions.

Fig. 1 (c) & (d) show the modifications of the engine which have allowed optical access to the combustion chamber for flame visualization as well as laser Doppler velocimetry(LDV) measurements.

FLAME VISUALIZATION - The flame propagation was visualization through the quartz piston window and a mirror(see Fig. 1(c)). The images of the flame were taken by a CCD camera

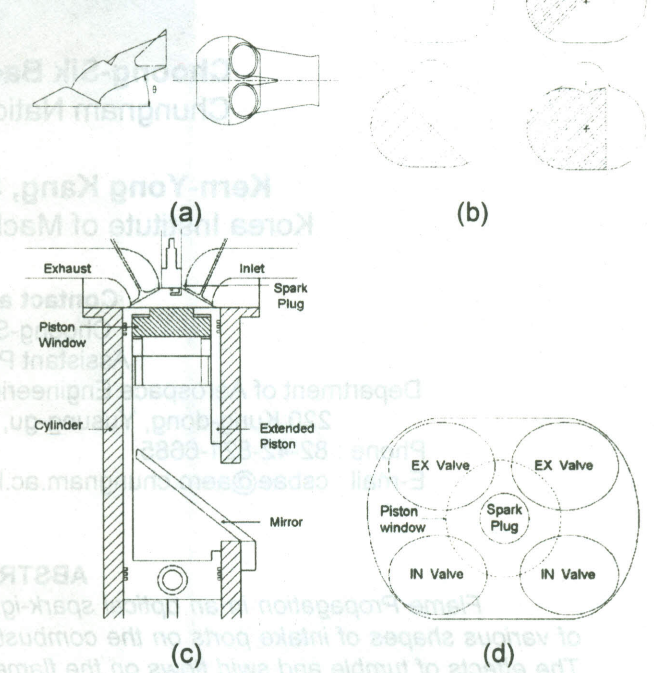

Fig. 1 The 4-valve research optical engine
(a) The shape of tumble ports
θ = entry angle;25
(b) Swirl control valves
(c) Side view of an optical single-cylinder engine
(d) Bottom view of an optical single-cylinder engine

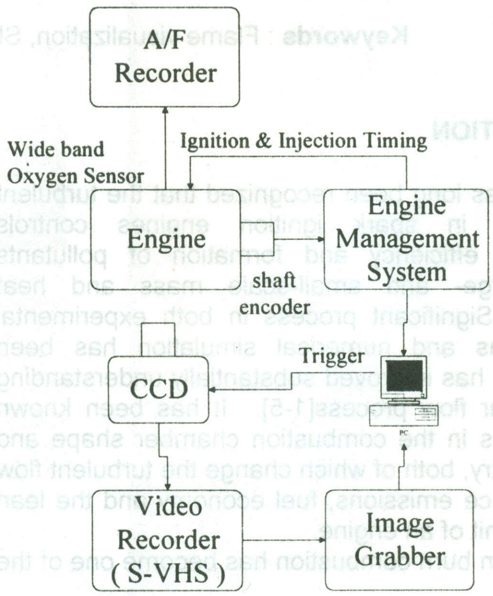

Fig. 2 The concept of flame visualization

(Hamamatsu C3077) with image intensifier (Hamamatsu C427314) which is highly sensitive to low light level so that the lean combustion behavior could be imaged. The shutter was triggered externally by the signal from the engine management system over successive cycles. Flame images were taken at 1250 rpm with exposure duration of 133 μsec (1°crank angle). During each cycle, flame images were frozen by gating the image intensifier at a given crank angle. The flame images were recorded by a S-VHS video recorder (JVC VICTOR HR-S10000) and digitized later on an image with an Hamamatsu image grabber(DVS-3000) to be stored in a computer. The inlet air and cooling water was heated and kept at 80°C to avoid liquid droplets enhancing evaporation of fuel droplets. Fig. 2 shows the experimental set-up of flame visualization.

The flame images were subsequently analyzed with a program capable of calculating the enflamed area, the gravitational center of this area and the distance between the spark plug and the flame center. This distance is very important during the early stages of flame development since a small flame can be more easily convected by the mean flow and is more susceptible to quenching.

RESULTS AND DISCUSSION

The detailed characteristics of tumble flows made by different intake ports of three entry angle[16].

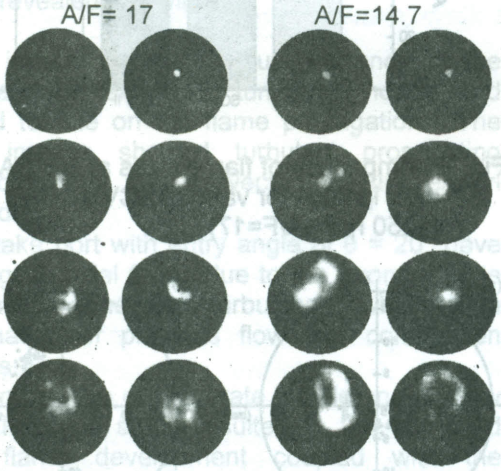

Fig. 3 Flame images obtained with 25° port for different mixture A/F=14.7 and 17 at 1250 rpm (ignited at 20° BTDC)

Fig. 3 shows images of propagating turbulent flames ignited at 20° BTDC for stoichiometric and lean mixtures at 1250 rpm. Flame kernel was made at the central area near spark plug and showed smooth development, since the port of θ = 25° gave relatively weak tumble flowfield. However, the initial developing flames were found to be convected away from the spark plug to exhaust valve side. This implies that the intake-generated tumble remained until the late stage of compression in pentroof-chambered engines, so that tumble velocity at the end of compression was found at leaner mixture(A/F = 17), which is due to inherent decrease of burning velocity in lean mixtures. The propagating flame is more deformed by the tumbling motion when the flame propagation is slower under lean mixture conditions.

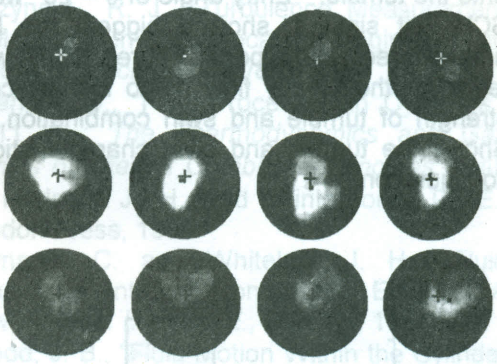

Fig. 4 Flame images obtained at 10° CA after ignition for 25°,20°and 15° tumble port under lean mixture condition (A/F=17) at 1250 rpm

The effect of tumble strength on the flame propagation was investigated by a comparison of flame images for three tumble ports of θ = 25°, 20° and 15°. Fig. 4 shows typical flame images at 10° CA after ignition with the lean mixture, A/F = 17, at 1250 rpm. The Quantitative comparison of these images was provided by flame image processing.

In order to identify and define the flame contour in the images obtained with direct flame imaging and the intensity data of each image generated by the image-intensified CCD video camera require several data processing steps. The basic element of a digitized image is the pixel or picture element and an image is composed of pixels distributed in a rectangular array. Each pixel in the image can have a value between 0(black) and 255(white), that is 256 different gray levels are defined as pixel values.

A threshold technique was applied to identify the flame contour which defines the flame region, thus allowing the calculation of the enflamed area and the gravitational center of the flame. It is clear that the identification of the flame front is accurate if the edges of the flame are sharp. Although in most cases, the flame front was optically sharp, some parts of it exhibited a gradual intensity variation from the core of the kernel towards the unburned gas, especially in the case of very early flame images. Nevertheless, changing the threshold level did not seem to have an appreciable effect on the flame region. The spark plug position is marked by a cross, while the calculated gravitational center is represented by a dot.

Fig. 5 shows the comparison of flame sizes at 10° CA after ignition which represents the enflamed area of flame images for more than 50 cycles in each case. This provides visual evidence of faster initial flame propagation with stronger tumble motion, since it was already found that θ = 20° port gave the strongest tumble with highest turbulence level resulting in the fastest combustion[16].

In addition to the tumble flow, swirl flow component could be beneficial in improving lean burn performances. Three different swirl control valves were selected to give the different strength of swirl onto the tumble. Entry angle of θ = 20° was used for SCV test since it showed biggest the best effect among three tumble ports. Three SCV's were at first tested in the steady flow rig to identify comparative strength of tumble and swirl combination. Table 2. Shows the tumble and swirl characteristics of each configuration.

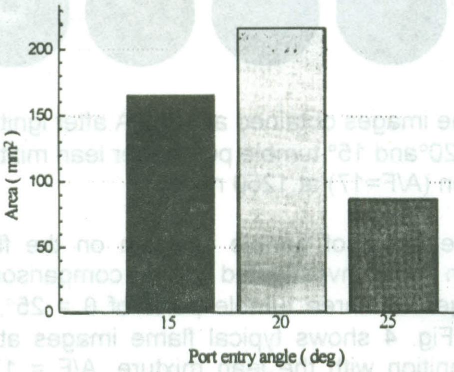

Fig. 5 Comparison of flame sizes at 10° CA after ignition for different tumble ports (1250 rpm, A/F=17)

Table 2. Flow characteristics of Swirl Control Valves

Configuration	Tumble ratio	Swirl ratio	Open ratio	Tumble angle
Tumble port θ = 20°	2.048	0.000	100%	90.0°
SCV I	3.363	0.594	55%	75.9°
SCV II	2.386	1.088	55%	65.5°
SCV III	1.540	0.837	37%	61.5°

The typical flame images of various SCV's are shown in Fig. 6. Initial flames are more convected away from the spark plug due to the existence of swirl as well as tumble component. More than 50 images of each configuration were also analyzes to give the size and displacement of flames. Fig. 7 shows the comparison of flame sizes of various SCV's SCV III of moderate combination of tumble and swirl showed the fastest flame propagation in the early stages.

The behavior of flame development of flame centers which is important in the initial stages of lean burn under strong flow field.

Fig. 8 shows the scattered data of flame centers of four configurations and averaged position of each case is compared in Fig. 9. It is found that SCV III resulted in the biggest convection. Convection by moderate combination of tumble and swirl is supposed to give the beneficial effect on the early flame growth rather than the quenching effect.

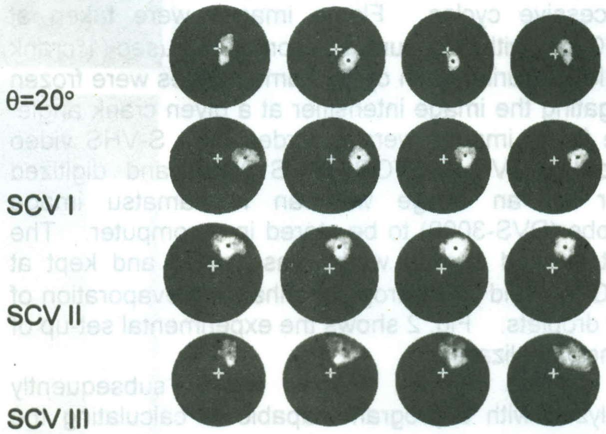

Fig. 6 Flame images obtained at 5° CA after ignition for various SCV's (1250 rpm, A/F=17)

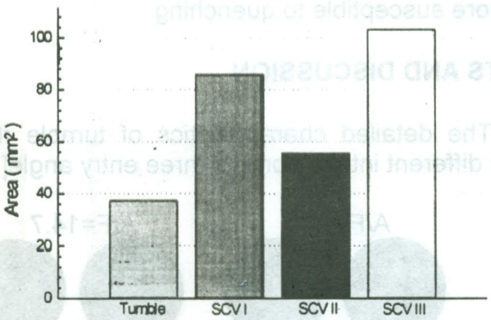

Fig. 7 Comparison of flame sizes at 10° CA after ignition for various SCV's (1250 rpm, A/F=17)

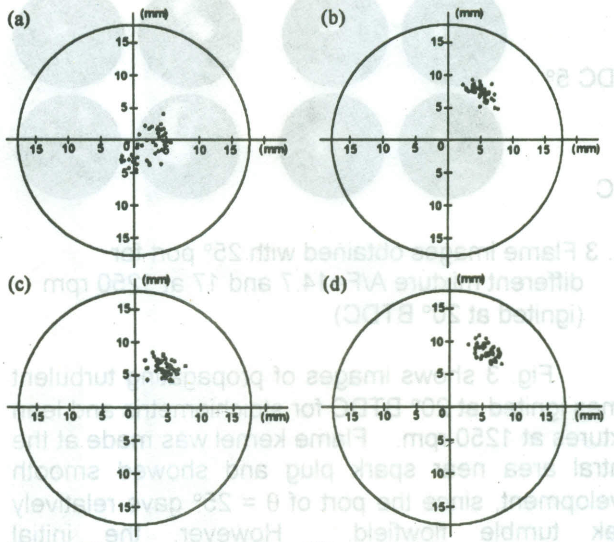

Fig. 8 Flame centers for different inlet ports (1250 rpm, A/F=17)
(a)Tumble, θ = 20° (b) SCV I
(c) SCV II (d) SCV III

The analysis of combustion performances combined with the flow measurement could give the tip for the selection of the optimal intake port design.

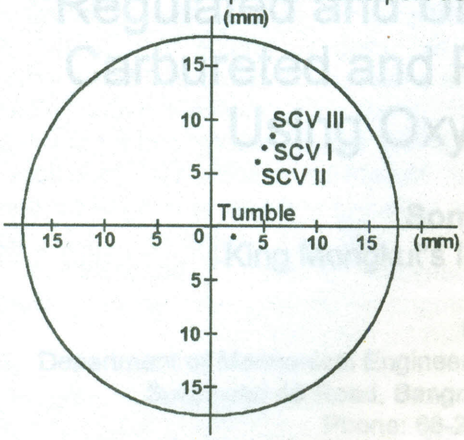

Fig. 9 Flame centers for different inlet ports averaged from Fig. 8 (1250 rpm, A/F=17)

CONCLUSIONS

The effects of tumble and swirl flow on early flame propagation were studied in a four-valve SI engine under lean mixture conditions with different inlet ports of various entry angle; 25°, 20°and 15° and of various swirl control valves. The propagating flames were visualized with image-intensified CCD camera and analyzed through image processing. The results revealed following:

(1) Flame images provided visual evidence of the advantageous effect of tumbling motion and inclined tumble on the flame propagation. The flame images showed turbulent propagating flame deformed and convected by tumble/swirl flowfield.

(2) The intake port with entry angle of $\theta = 20°$ gave the biggest initial flame due to the strong tumble and tumble-generated turbulence, which is a confirmation of previous flow and combustion analysis.

(3) The combination of moderate tumble and swirl by SCV III in this study resulted in the improved initial flame development coupled with the convection of flame.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided for this project by Korean Government, through the scheme of the National G7 Project.

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