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EFFECTS OF CYCLIC PRESSURE VARIATIONS ON COMBUSTION DEVELOPMENT IN A SPARK IGNITION ENGINE

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Abstract. An investigation of the engine cylinder pressure fluctuation has been conducted to find out the main problems it causes on engine power out. Several air fuel ratio experiments running the engine at 1800 rpm were carried out to get enough data to complete this study. A group of 30 cycles of pressure data, doing readings every ¼ of crank angle degree was used as a reference data for each experiment. The equivalence air fuel ratio was varied from 0.82 to 1.0, to investigate effects of mixture composition on engine cycle stability. The empirical Woschni's correlation was used to compute the amount of heat transferred by convection inside the engine combustion chamber. A computer program was set up to use the pressure data taking at a particular air fuel ratio and to work with equations for calculating the heat release profiles as a function of the crank angle degree. The heat release profiles inside the cylinder showed important variations, which correspond, to both the consumption of lean mixture and occurrence of too much pressure fluctuations. For each particular cycle maximum pressure data and its occurrence crank angle was plotted to show that engine cycles running on mixtures with air fuel ratios close to the stoichiometric air fuel ratio value develop the highest maximum cylinder pressure with the less crank angle variations near top dead center. A study of the coefficient of variation of the indicated mean effective pressure was performed to analyze the effect of the cyclic dispersion of combustion pressure on the indicated work per cycle.

Key Words: Pressure Fluctuations, Cyclic Dispersion of Combustion Pressure, Heat Release Rate, Indicated Mean Effective Pressure, Fuel-Air Equivalence Ratio.

1. Introduction

During gasoline engines operation it is known the existence of large pressure variation inside the cylinder when they run under lean conditions and it decreases if the engine work approaches the stoichiometric conditions. This phenomenon causes big instability on the engine performance (Heywood, 1988; Jovaj, 1982) and makes more troubles if combined with a poor distribution of air fuel mixture per engine cylinder. Other factors that contribute with it are the lack of control during mixture formation and the mixing process with exhaust residual gases from early cycles.

The problem with gasoline engines becomes crucial when the experiment main purpose is to get a maximum engine power by setting up the engine working conditions for an average cycle. Some spark adjustments need to be done to make the engine work properly in such case. Engine spark advanced regulations during the experiments need to be accounted to work far away from engine knocking conditions and therefore to avoid the appearance of combustion process with too high temperature cycles.

Janula (1983) shows how the combustion variability decreases the engine power out and deleterious the work economy, increases the level of toxic components in the exhaust gases, and demands higher fuel octane number. Therefore, to reduce the cyclic pressure variation during combustion requires making adjustments to the systems that control the air fuel supply and the spark advance angle. The flame propagation inside the combustion chamber is influenced by the characteristics of the mixture formation process, having the highest flame speed those cycles whit better homogeneous charge mixture. To accomplish this task some turbulence effects through the intake manifold ducts, cylinder heads, and pistons have to be promoted avoiding the unnecessary heat transfer to the walls.

Experimental work (Alkidas, 1982) related to heat transfer measurements in internal combustion engines has shown large variations of the heat transferred to the cylinder walls. Surface temperature measurements reveal an instability of the combustion process that modifies the temperature profile. Thus, the best control the engine can have on the fuel air supply system will ensure fewer shifts on the surface temperature. To study the experimental changes of the main combustion parameters is helpful to find an appropriate use of the fuel energy into the combustion chamber to get the best engine performance.

This study uses the results of cylinder pressure data taken from several air fuel ratio experiments working with a CFR engine. The engine was set up to run a road cycle simulation, which starts at 800 rpm and continues until it reaches 1800 rpm. After the engine having reached an stable condition an acquisition data system recorded all the surface temperature and cylinder pressure information. The engine was equipped with a metering fuel system connected to an electrical fuel injector. To provide constant air supply the engine manifold was attached to an air compressor system. To control the experiments a monitoring process was carried out, a computer displayed all information about the air fuel consumption required to keep the engine properly working, and an oscilloscope was used to continuously show the surface temperature and cylinder pressure traces.

The pressure data from each group of 30 cycles was reduced to analyze the engine cylinder work. A computer program uses the pressure data and information about the heat transfer coefficient obtained from the Woschni's correlation to calculate the gross heat release. The results from this simulation showed a large heat release variation that agrees with the cylinder pressure fluctuations and a consistent data behavior that characterizes engine lean operation. Later analysis showed great improvement in the energy release diagram when the engine ran on fuel air ratios closer to unity. These heat release trends are view on Heywood (1988) and Alkidas (1982) experiments with engines working similarly.

2. Theoretical Background

It is known that a gasoline engine develops its maximum power when it works with fuel-air mixtures slightly rich, it means using a value of ϕ approximately between 1.05 to 1.1.

Jovaj's (1982) and Heywood's (1988) works have shown the mixture richness as the main engine power output modifier. Therefore, all those parameters that influence the engine fuel air ratio are important on combustion analysis due to their relation with the cylinder pressure fluctuations. To get reliable experimental data from combustion processes in internal combustion engines some adjustments to its fuel air supply system and to the spark advance are required. Electronic fuel injection systems have shown better regulating function on the amounts of fuel and air feed to the engine cylinder compared to carbureted engines.

To have a good representative sample of pressure data (Patterson, 1966) it is important to decrease the cylinder pressure variability due to fuel air ratio changes. An experimental work presented by Araque (1995) shows that air supply fluctuations during the intake process produces suddenly surface temperature changes up to ten degrees. Therefore, the engine needs to work under stoichiometric or slightly rich conditions to provide engine working cycles with a secure, high and consistent cylinder pressure. However, some problems are pointed out in Janula's (1983) and Heywood's (1988) experiments related to fuel economy deleterious and rise of toxic components on the engine exhaust gas emissions under this working conditions.

An analysis of the pressure data showed a great cyclic pressure variation when the engine was running lean. According to Araque's investigation (1995) this unavoidable cylinder pressure variation combined with the lack of good air supply control decrease the engine power output. Therefore, the experiments should provide enough data to account for this problem. Some criterion should be considered to characterize how the pressure dispersion affects the progress of the combustion process in the engine cylinder. Janula's paper (1983) points out several parameters to study the engine cyclic pressure dispersion: combustion pressure, rate of pressure rise, maximum pressure and its corresponding angle with respect to the top dead center position. Besides, Heywood's book (1988) cites others parameters as the burn rate and flame front position to quantify the decrease in the released energy due to pressure fluctuation. Thus, the cylinder pressure fluctuation on gasoline engines is a problem that not only modifies the piston movement but also disturbs the combustion process.

3. Research method

Several air-fuel ratio experiments were designed to study their effects on the cylinder pressure variation. A four-stroke CFR spark ignition engine running with gasoline and with a compression ratio of 8.5 was used. An engine cycle simulation was carried out following real engine road working conditions. The data acquisition system was set up to record pressure data at 1800 rpm after reaching engine stability. To investigate the pressure and energy release variation from cycle-to-cycle the engine operation under lean condition was considered as a good choice since engine operation with fuel-air equivalence ratios close unity has shown less pressure variation (Heywood, 1988; Jovaj, 1982).

The pressure data was taken using a water-cooled AVL piezoelectric transducer mounted on the combustion chamber facing the spark plug location. An air compressor to maintain a constant air supply during the experiments was used to control the air pressure, as a result, to avoid changes in the correct fuel air ratio. Besides, the engine coolant and oil temperatures were kept around referenced values.

A typical sample of 30 cycles of pressure data was carefully reduced and analyzed, looking for bad and noisy data that modifies experimental cylinder pressure trends. The pressure profiles showed a little noise close to bottom dead center when the openings and closings valves events were in progress. A clearly defined combustion process showing a consistent growth of the cylinder pressure was observed, although, due to mixtures too lean or a misfire condition the pressure rise was delayed with respect to the top dead center.

4. Simulation Process

To investigate how the cylinder pressure fluctuation affects the development of the combustion process a simulation method with a computer program was done. Experimental pressure data for the close part of the engine cycle, geometrical engine parameters and the thermodynamics properties of the cylinder gases were used to calculate the average gas temperature in the cylinder using the ideal gas equation (Heywood, 1988). Several sets of pressure data corresponding to the experiments with different fuel-air equivalence ratio were studied using the computer code. The Woschni's correlation was utilized to compute the heat transfer coefficient to study the heat transfer by convection in the cylinder. Chemical equilibrium condition working with a ten-species model was used to calculate the variation of the thermal properties of the mixture with temperature. It allows the calculation of the gas constant, the constant volume and constant pressure specifics heats and its specific heat ratio.

To study the heat transfer by convection the computer program was used to obtain a surface temperature profile. A large amount of the transferred heat trough the piston is axially oriented, therefore, the surface temperature behavior was modeled using a one dimensional finite difference scheme. Alkidas's paper (1982) considers the axial heat penetration as the main heat component during engine combustion. This temperature profile was obtained from engine cylinder pressure data at steady state condition and without considering the inertial mass thermocouple effects. The accuracy (Araque, 1997) of these results was based on a mathematical analysis of the mean surface temperature and surface temperature growth during combustion by a contrast between theoretical values against experimental ones.

The heat gross simulation in the engine cylinder was completed without considering mass leakage or crevice effects. The application of the first law of thermodynamics and the ideal gas law allowed to study the heat transfer process inside the combustion chamber (Heywood, 1988) considering only a convection model. The control volume used to evaluate the heat transfer process in the engine cylinder is shown in Figure 1.

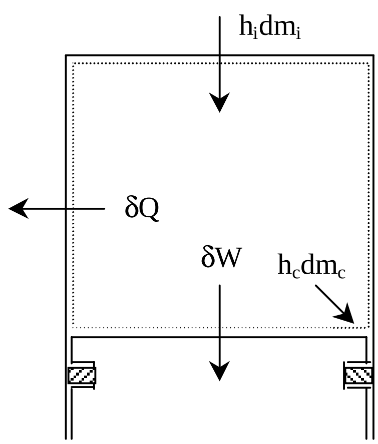


Figure 1- Open system boundary.

First law of thermodynamics for an open system.

$$\delta Q_{ch} = dU_s + \delta Q_{ht} + \delta W + \sum h_i dm_i \qquad (1)$$

Internal energy change.

$$dU_s = mc_v(T)dT + u(T)dm \quad (2)$$

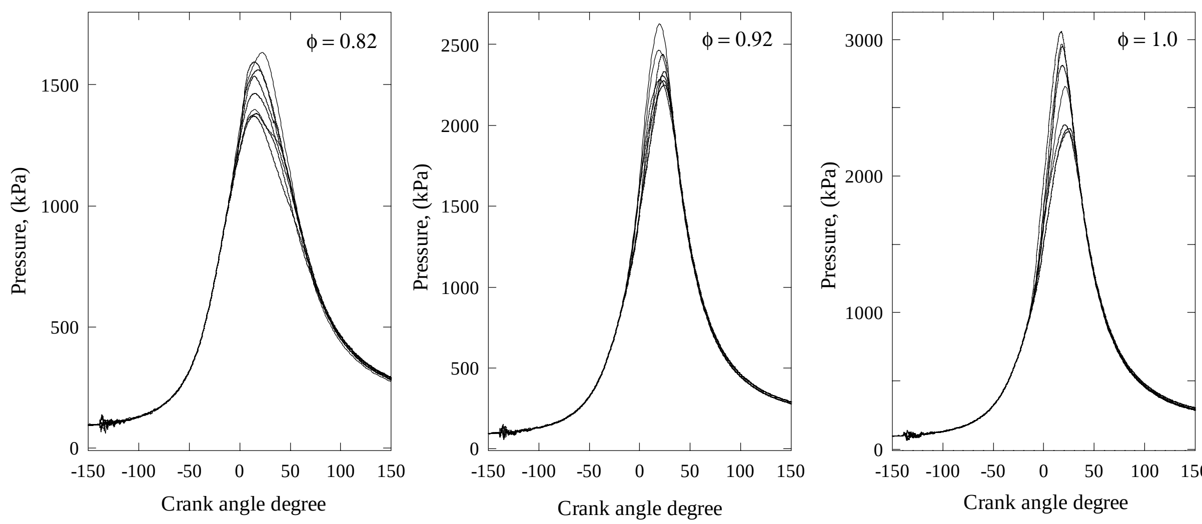
Heat transfer by convection using an averaged heat transfer coefficient

$$\frac{\delta Q_{ht}}{dt} = Ah_c(T - Tw) \quad (3)$$

Substituting Eq. (2), Eq. (3) and the ideal gas law into Eq. (1) let to get Eq. (4):

$$\frac{\delta Q_{ch}}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} + \frac{\delta Q_{ht}}{d\theta} \quad (4)$$

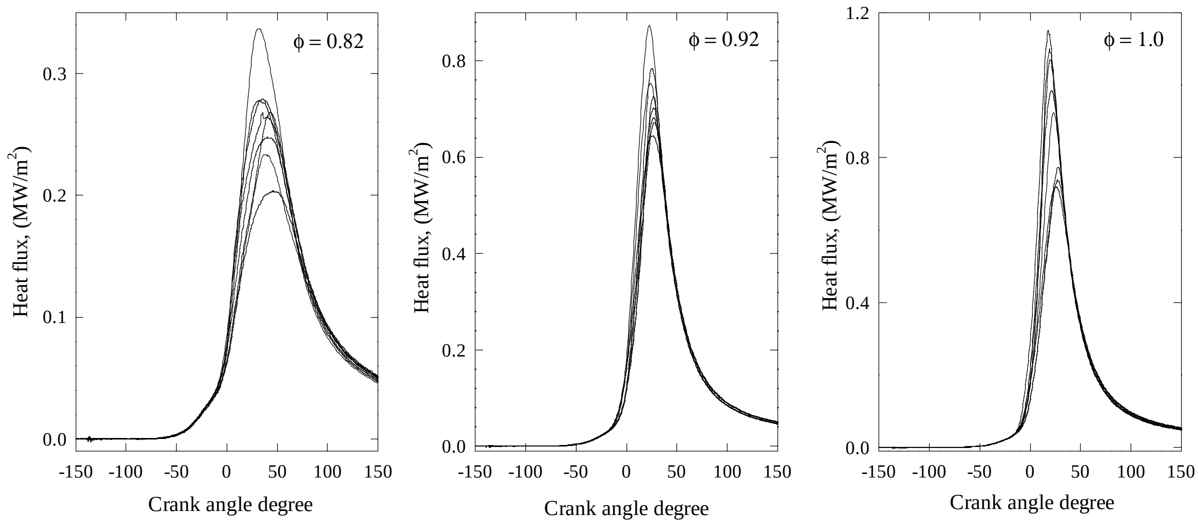
5. Results and Discussion



a) **b)** **c)**

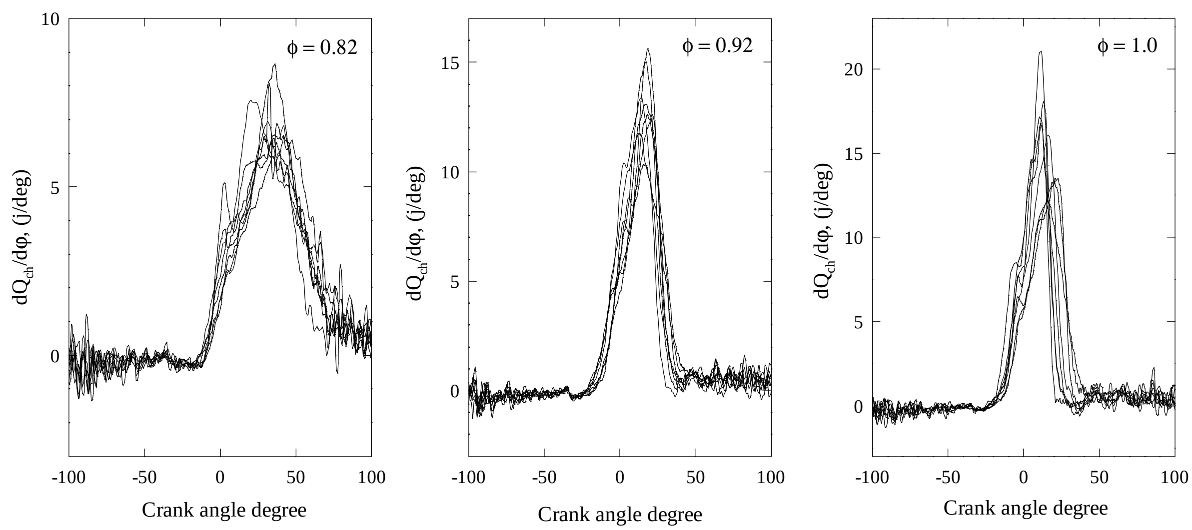
Figure 2- Cylinder pressure per crank angle degree: a) ϕ = 0.82, b) ϕ = 0.92, c) ϕ = 1.0

Figure 2 shows the cycle-to-cycle pressure variation obtained when the CFR engine was running at 1800 rpm using several air fuel ratios The experiments were designed for a variation of ϕ from 0.82 to 1.0. According to these experiments the less variation of the cylinder pressure is observed for engine operation with equivalence ratios, ϕ, closer to unity. The maximum pressure fluctuation for those experiments with ϕ = 0.82 showed lower maximum pressures with larger differences among them in comparison to the tests with ϕ = 1.0. A faster pressure rise, $dp/d\varphi$, together with a main combustion phase symmetrically distributed around top dead center is viewed in those cylinder pressure profiles obtained with the mixture richness is closer to 1.0. This cylinder pressure behavior is a good indication of cyclic robustness with high repeatability (Heywood, 1988). Thus, the fuel air ratios required to improve the engine power should be closer to its stoichiometric value. It will speed up the development of the combustion process after sparking due to better conditions of flame propagation. According to Janula’s work (1983), the flame velocity depends on many factors, the main ones are: the internal combustion chamber area, the amount of heat exchanged during flame propagation and the surrounding temperature. The higher the surface temperature, the faster the flame will move along it.



a) **b)** **c)**

Figure 3- Heat flux variation per crank angle degree: a) $\phi = 0.82$, b) $\phi = 0.92$, c) $\phi = 1.0$



a) **b)** **c)**

Figure 4- Gross heat release rate per crank angle degree: a) $\phi = 0.82$, b) $\phi = 0.92$, c) $\phi = 1.0$

Figures 3 and 4 show the heat flux variation and the gross heat release rate calculated from engine cylinder pressure data obtained with different fuel-air ratios. These trends point out that higher pressure variation will show more irregularity in the combustion process, thus, engine lean operation causes bigger changes in the heat release profiles. As an example, work the engine with $\phi = 0.82$ shows an important percentage of cycles with slow burning velocity and heat release rate too unpredictable. Besides, lean mixtures can be source of misfire, resulting in poor engine power development. This undesirable engine operation (Heywood, 1988) causes efficiency decay, high hydrocarbon emissions and torque variations increasing. These figures show the strong relationship between combustion development and mixture quality. An engine lean operation decreases the amount of heat released close to top dead center, however, if the mixture richness reach its stoichiometric value the heat release profiles show better development. The results show clear dependence among cyclic pressure variation, maximum amount of heat released and burning process duration. Studies of pressure fluctuation that considers the amount of heat released by the faster and slower cycles will allow getting better conclusions. Besides, enough pressure data is also required avoiding those running conditions too lean that cause too much cycle to cycle pressure variation. These experiments should be performed using a narrow scope of equivalence ratios, above and below 1.0.

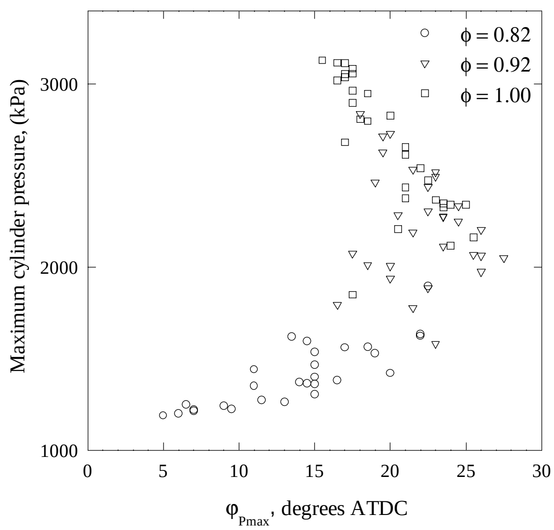


Figure 5- Maximum cylinder pressure as a function of its crank-angle degree.

Figure 5 shows the tendency of the data when maximum cylinder pressure values and its corresponding crank-angle degree are analyzed from cycle to cycle and for each fuel-air ratio. It shows a pressure distribution with the lean cycles at the bottom and the stoichiometric ones at the top part. This figure shows that even when the cycle-to-cycle variation exists the maximum pressures are closer distributed around top dead center when the mixture richness, ϕ, equals 1.0. Great pressure variability together with a wide crank-angle band is observed in those cycles that run on lean mixture. The experimental data shows that, the closer to the stoichiometric conditions the engine works, the faster the cylinder pressure growth, the higher the cylinder pressures and the lesser the heat release rate variation.

6. Conclusions

- The study of the cylinder pressure data from these combustion experiments show the engine fuel-air ratio variation as the main contributor to cyclic dispersion and unstable heat release behavior.

- Those experiments with less fuel air-ratio deviation around its stoichiometric value have the less cylinder pressure variation and the better combustion development.

- Engine handling under rich conditions should consider a balance among fuel economy, pollutant formation and power out.
- The less variation of the maximum cylinder pressure near top dead center, the more engine power development.

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