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Study of the Influence of Compression Ratio on the Rate of Heat Release in Small Displacement Diesel Engines

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Abstract

Background/Objectives: To make implementation of a thermodynamic diagnostic model to determine the rate of heat release in low displacement Diesel engines so that the performance of the combustion process can be quantified and sub-models of heat transfer can be adjusted; so that it can be applied in subsequent predictive modeling. **Methods:** With the pressure data in the combustion chamber and the set of variables composed of the pressure and temperature in the admission, fuel consumption, speed of rotation, injection pressure, compression ratio and environmental conditions, a thermodynamic model is defined. It allows quantifying how the heat release process occurs in the combustion process. **Findings:** The results allow verifying the influence of the compression ratio on the heat release process, finding that the rate of heat released increases with the increase of the variable under study. Likewise, it is verified that the most pronounced difference between the release rates for different compression ratios studied is in the premix combustion zone. **Application:** This methodology can be used for the process of optimization and redesign of thermal engines, to maximize the output power for the same fuel and operational conditions.

Keywords: Combustion, Compression Ratio, Diesel, Engine, Heat Released, Thermodynamic Model

1. Introduction

The thermodynamic diagnostic models applied to internal combustion engines use, as input data, among others, the values of the pressure in the combustion chamber and the position of the crankshaft. With these data and other measurements of average variables, the heat release rate (DFQL) is obtained as output, which is the basis of the combustion diagnosis. In the study of Diesel engines, different study techniques have been proposed, with the purpose of quantifying and controlling output parameters of these machines.

An experimental study profile is based on measurement results and direct visualization of the behavior of the processes in the engine in question. In these models, the adjustment of the data obtained from the rate of heat release to a mathematical combustion model is required. This is done through a semi-empirical approach, which can be observed in the works[1,2] or through a phenomenological (multi-dimensional) approach as observed in the works[3–5]. In the semi-empirical approaches, this adjustment is made through the form parameters of the Wiebe function, which are correlated with variables related to the operation of the engine[6,7]. It should be noted that the

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combustion model contains the largest amount of information regarding combustion, as well as the phenomena included in that process. That is why, by including a detailed sub-model of injection, satisfactory results are obtained in the adjustment process[8]. The above can be applied to the modeling of engines using different fuels, to verify the delivered performance[9,10].

Due to the load conditions experienced by the piston - connecting rod-crankshaft assembly, deformations occur that affect the calculation of the instantaneous volume in the thermodynamic cycle. These deformations vary in magnitude and direction throughout the process. The non-inclusion of these deformations in the modeling generates the appearance of fictitious quantities of heat in the results of the rate of heat release, particularly under trail conditions. For this reason,[11] developed a simplified model of deformations, which considers the effects of the pressure in the combustion chamber and the inertia of the mechanism, to express the variation of the instantaneous volume as a function of an adjustment constant, whose value is determined at from measurements undertow conditions.

For the thermodynamic modeling of Diesel engines, a characterization process is necessary as an initial step. When a combustion diagnosis model is applied, it is possible to define the parameters of the heat release rate, so that we can predict the behavior of the engine through predictive modeling. In the present work, the considerations and the calculation scheme for the combustion diagnosis will be presented, which will allow comparing the combustion performance in Diesel internal combustion engines and the influence of the compression ratio.

2. Methodology

The initial step for the diagnostic process characterizesthe engine using a technique called motored test. This test consists of forcing the engine to rotate at a certain angular speed, performing the processes of admission, compression, expansion and exhaust, but in the absence of combustion. For the complete characterization of the Diesel engine and guarantee correct modeling of the same, it is necessary to initially carry out a diagnostic process to adjust the experimental correlations and the rate of heat release.

2.1 Considerations of the Thermodynamic Model of Diagnosis

The following are the fundamental considerations taken into account for the formulation of the present diagnostic model:

- Uniform pressure throughout the combustion chamber. This assumption is valid because both the velocity of the fluid and the flame rate of combustion are less than the speed of sound, which allows uniformity in the measurement of the pressure in the chamber.
- Gases inside the combustion chamber behave like ideal gases. The validity of this assumption is because very small error margins are obtainedconcerning the real values.
- Specific heat of substances depends exclusively on the chemical composition of the gas and its temperature. This is a consequence of the previous assumption since for a mixture of ideal gases the calculation of their respective specific heat depends clearly on the composition of the same and its temperature.
- The calculated stoichiometric combustion products. This assumption is taken into account because usually in Diesel engines conventional combustion is used, where the combustion flame is located in the stoichiometric region of the air-fuel ratio during the controlled combustion phase.
- Thermodynamic properties such as internal energy and enthalpy are calculated based on the average temperature of the combustion chamber. The phenomena of diffusion and heat transfer present tend to stabilize the temperature uniformly in the combustion chamber, which decreases the error in the calculations.
- The transfer of heat through the walls is considered. This consideration is necessary to obtain more precise results and by the reality of the phenomenon. If not taken into account, this would lead to an engine work without heat transmission so that the apparent released heat would be calculated instead of the released heat.

- Deformations in the crank-connecting rod-piston mechanism are considered. When not considering the deformations of the mechanism, it affects the thermodynamic results of the model.

2.2 Fundamental Equations

The basis of the combustion diagnosis is the calculation of the rate of heat release caused by the combustion of fuel. It is necessary to take an energy balance taking the variables associated with the process (Figure 1), which leads to obtaining of Equation 1, which is consistent with the deduction of other authors[6,11]:

$$DFQL_{real} = \frac{P\cdot\frac{dV}{d\theta}+m_{cam}\cdot C_v\cdot\frac{\Delta T}{\Delta\theta}+\frac{dQ_r}{d\theta}-\frac{dm_{fuel}}{d\theta}\cdot[h_{fl(Tiny)}-u_f]+\frac{dm_{bb}}{d\theta}\cdot R_{gas}\cdot T}{m_{combtot}\cdot LHV} \quad (1)$$

From (1) there are the following terms:

$DFQL_{real}$: Real heat release rate.

$P\cdot\frac{dV}{d\theta}$: Boundary work carried out in the combustion chamber.

$m_{cam}\cdot C_v\cdot\frac{\Delta T}{\Delta\theta}$: Change of internal energy of the combustion chamber.

$\frac{dQ_r}{d\theta}$: Heat rejected by convection of the combustion chamber.

$\frac{dm_{fuel}}{d\theta}\cdot(h_{fl(Tiny)}-u_f)$: Energy associated with fuel injection and vaporization.

$\frac{dm_{bb}}{d\theta}\cdot R_{gas}\cdot T$: Flow work associated with losses due to leaks in the combustion chamber.

$m_{combtot}\cdot LHV$: It is the total energy released by the fuel injected during the cycle.

Temperature is related to the pressure using the ideal gas equation. The term $P\cdot\frac{dV}{d\theta}$ is related to the actual volume of the combustion chamber. This is determined with a kinetic analysis of the piston - connecting - journal mechanism, which allows to define how the instantaneous volume changes depending on the angle of rotation of the crankshaft, the force due to the pressure and the inertial force[11].

$$V(\theta)=V_c\cdot\left[1+\left(\frac{C_R-1}{2}\right)\cdot\left(R+1-cos\theta-\left(R^2-sen^2\theta\right)^{\frac{1}{2}}\right)\right] + A_P\left[\frac{K_{DEF}\cdot L_{CR}\cdot\left(P(\theta)\cdot A_P+m_i\cdot a\right)}{E_{STEEL}\cdot A_{CR}}\right] \quad (2)$$

Where

C_RCompression Ratio.

Vc:Clearance Volume.

R:Relation between connecting rod length and crank radius.

θ :Crankshaft angle.

K_{DEF}:Coefficient of deformation, adjusted experimentally.

L_{CR}:Length of the connecting rod.

A_P:Piston area.

$P(\theta)$:Pressure in-cylinder.

m_i:Mass Connecting rod, piston and pin.

a:Acceleration of connecting rod, piston, and pin.

E_{STEEL}:Young's module of steel.

A_{CR}:Cross section area of the connecting rod.

The value of $P(\theta)$ is measured with a chamber pressure sensor and an angular decoder, which is described in the next section. To optimize the calculation process, a software called DIAGNO-DIESEL has been developed, which takes the pressure signal in camera, together with the characteristics and operating data of the engine, and generates as output the heat rate released for that operation condition.

2.3 Experimental Equipment

For the acquisition of experimental data, the Diesel engine test bench illustrated in Figure 2 was used. This

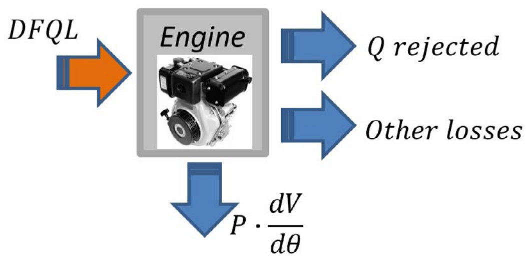

Figure 1. Energy balance applied to the study system.

bench has a single-cylinder engine installed whose technical characteristics are specified in Table 1. The engine is instrumented with a pressure sensor and an encoder, to acquire the variation of the pressure inside the combustion chamber along the crankshaft turn (Figure 3). This pressure signal as a function of the angle of the crankshaft (θ) is taken to a DAQ's, so that it serves as an input to the developed thermodynamic model of diagnosis. In addition to the above, a fuel and air measurement system is coupled to the engine, in order to quantify the dosage at the point of operation. For the verification of the output power, a dynamometer is coupled to the engine, so that resistive load is supplied and the torque delivered is quantified.

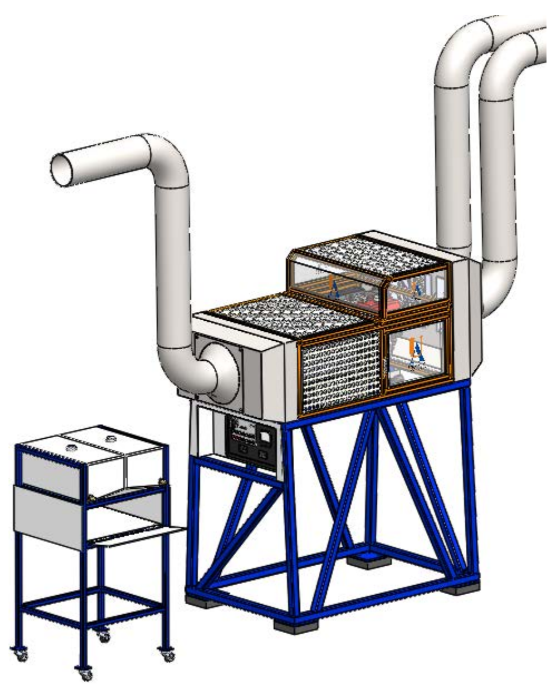

Figure 2. Schematic of the engine test bench used for the experimental study.

Table 1. Data engine used in the study

Engine	
Manufacturer	SOKAN
Model	SK-MDF300
Type	4T, Air Cooled
Displacement	299 CC
Maximum power	6.6 HP to 3600 RPM
Fuel	Diesel
Compression ratio range	14-16
Injection Angle	20° BTDC
Injection Pressure	220 bar
L_{CR}	7.1 cm
R	3.2
A_P	69 cm^2
K_{DEF}	1.31

3. Result and Discussion

Following the line of analysis exposed in the works of Armas[11], a sensitivity analysis is necessary in the diagnostic models, to verify which are the most influential variables on said model. In the present study, the influence on the heat released on the modification of the compression ratio is analyzed, taking advantage of the availability of an engine test bench that can vary this parameter.

3.1 Chamber Pressure Curves for Combustion Analysis

For the sensitivity analysis of the compression ratio on the released heat rate, the chamber pressure signals are acquired, which are observed in Figures 4 and 5 for an admission pressure of 1 and 1.05 bar respectively. These curves were obtained in a test condition of 75% of maximum engine power, a relative air/fuel ratio of 0.71 and using Diesel ($C_{18}H_{32}$). The influence of the increase of the intake pressure on the maximum pressure obtained is observed. As the intake pressure increases, the pressure inside the combustion chamber increases and therefore the output power of the engine increases.

The influence of the compression ratio (C_R) on the pressure in the combustion chamber is also evident. Increasing the C_R increases the maximum pressure peak inside the cylinder, which also leads to an increase in the

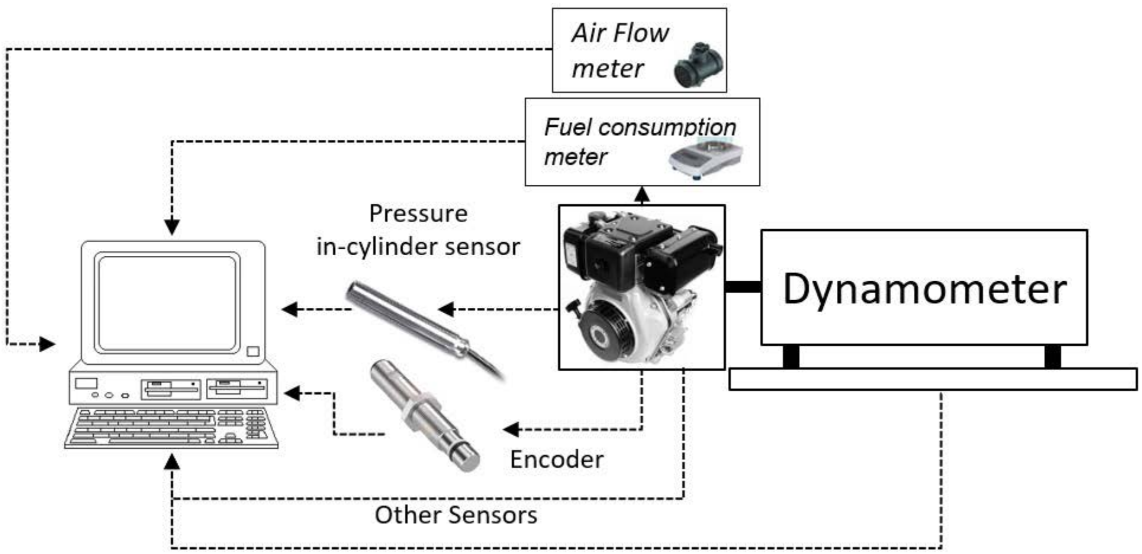

Figure 3. Instrumentation system used for data acquisition.

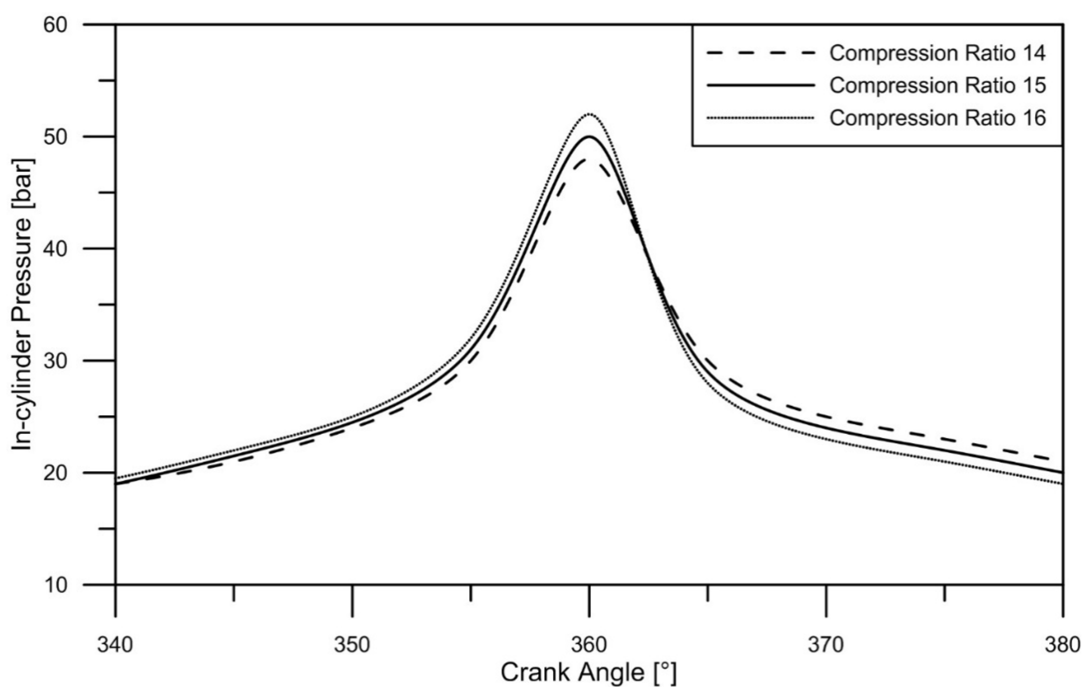

Figure 4. In-cylinder pressure as a function of crank angle . Intake pressure of 1 bar, relative air/fuel ratio 0.71 and 75% of the maximum power of the engine.

power delivered by the engine. For an intake pressure of 1.05 bar, a 7% increase in chamber pressure is observed, comparing the C_R of 15 and 16 (Figure 5). In the case of the intake pressure of 1 bar (Figure 4), it is less evident the increase (4%), but the same trend continues.

3.2 Rate of Heat Released as a Function of the Compression Ratio

By applying equations (1) and (2), which summarize the process of combustion diagnosis, the rate of heat release

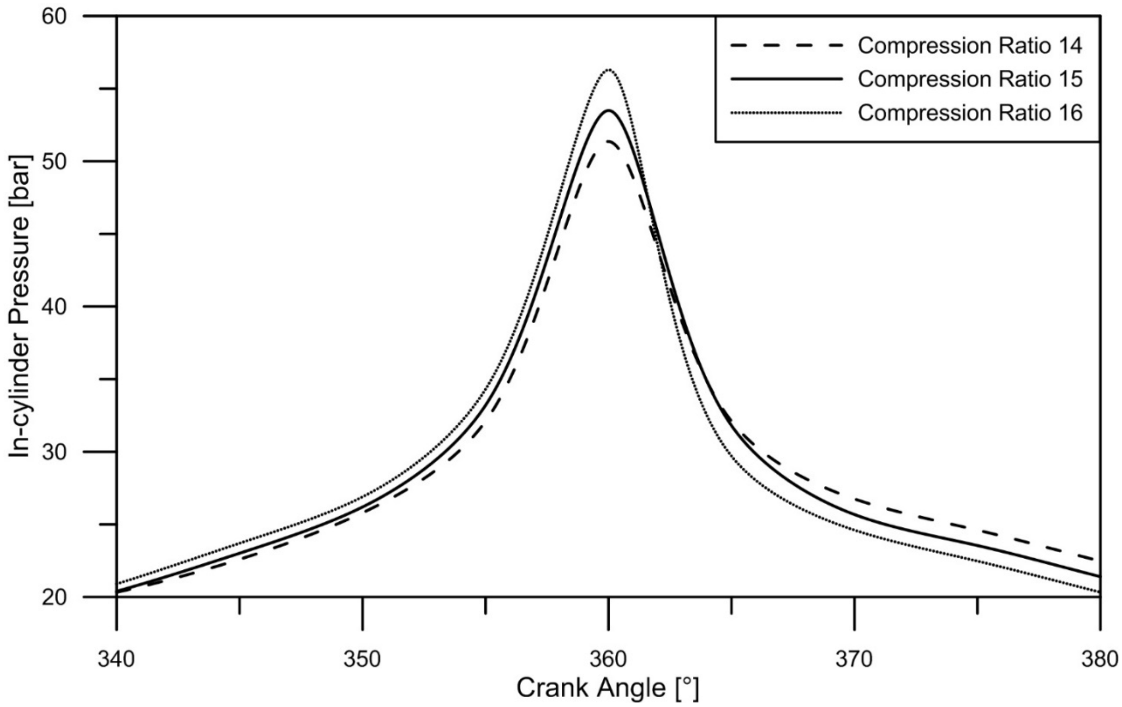

Figure 5. In-cylinder pressure as a function of crank angle . Intake pressure of 1.05 bar, relative air/fuel ratio 0.71 and 75% of the maximum power of the engine.

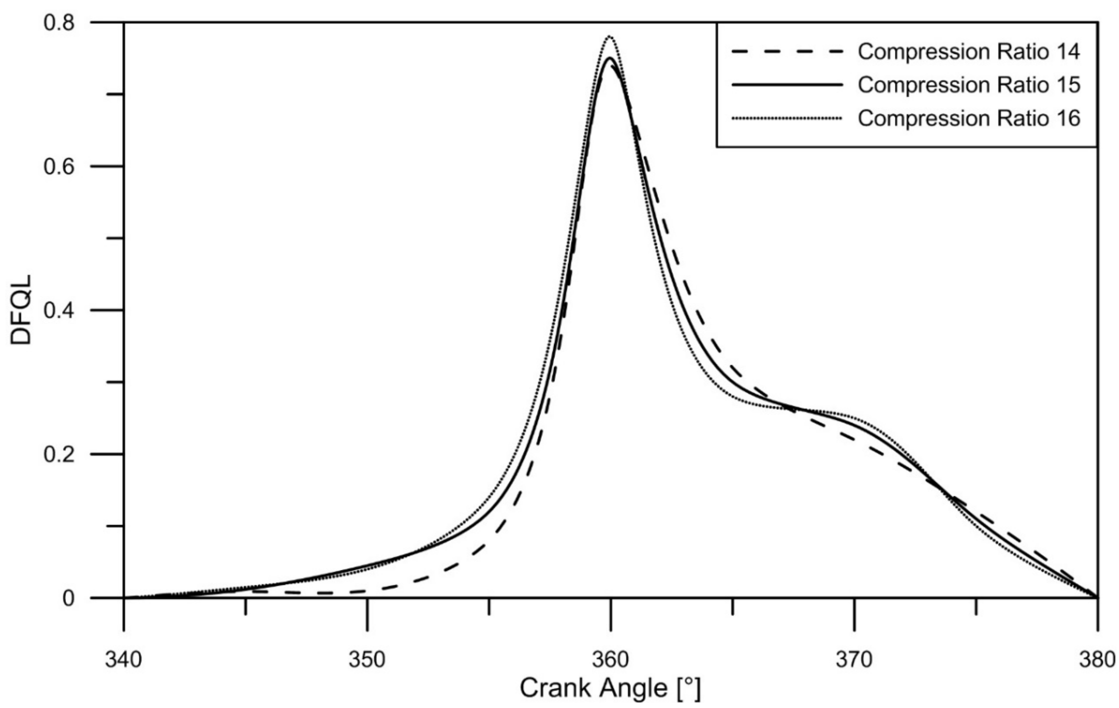

Figure 6. Rate of heat released (DFQL) as a function of crank angle . Intake pressure of 1 bar, relative air/fuel ratio 0.71 and 75% of the maximum power of the engine.

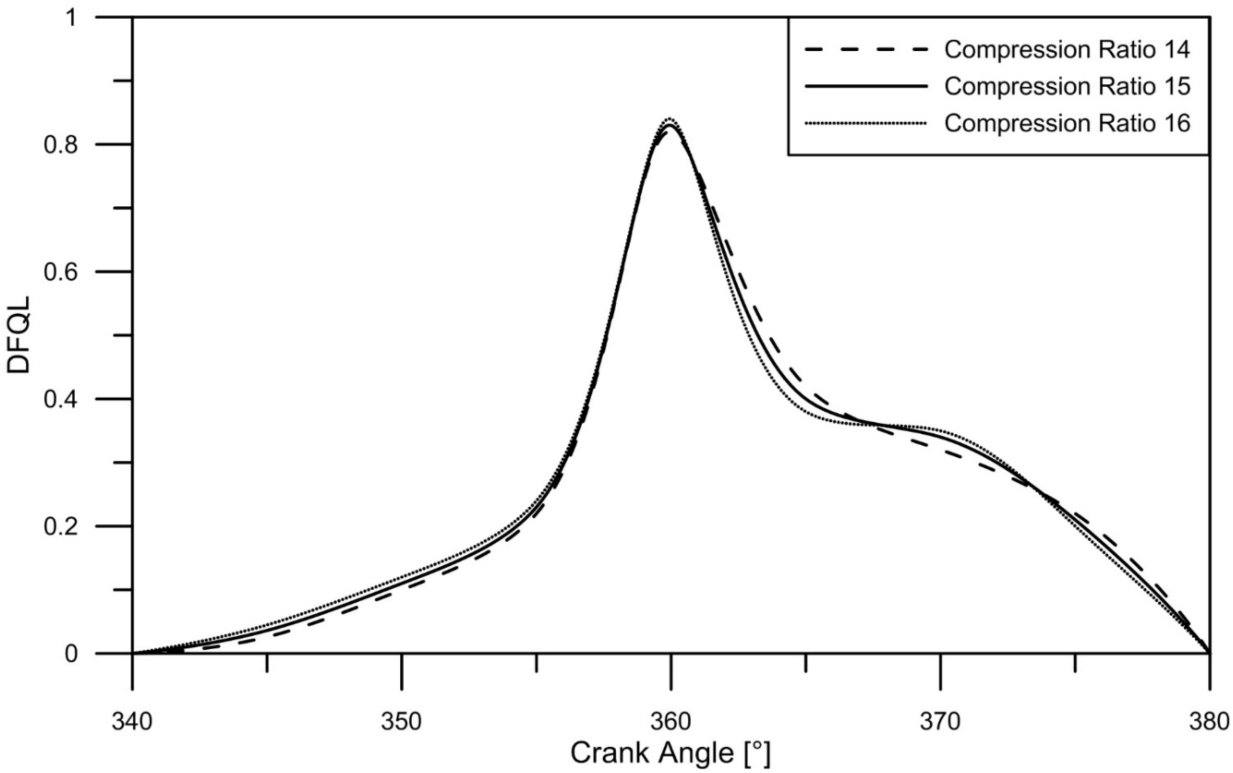

Figure 7. Rate of heat released (DFQL) as a function of crank angle . Intake pressure of 1.05 bar, relative air/fuel ratio 0.71 and 75% of the maximum power of the engine.

is determined. The most relevant input data are illustrated in Table 1. The strain coefficient K_{DEF} was adjusted experimentally through the motored test method, where a value of 1.31 was obtained.

With the pressure data of Figures 4 and 5, which served as input to the DIAGNO-DIESEL® software, Figures 6 and 7 were obtained. In these figures, it is observed how the heat release (DFQL) occurs during the process of combustion, where the premixed combustion stage (first stage) and the diffusion combustion stage (second stage) are observed. Comparing the figures, it is observed that the change of the compression ratio on the heat release rate is more accentuated for the case where the intake pressure is 1 bar (natural aspiration).

4. Conclusions

From this study, it is evident that the influence of the compression ratio on the rate of heat released during combustion is significant. When the engine operates with atmospheric admission pressure (without supercharging), the change in the rate of heat released (DFQL) due to the compression ratio is more noticeable, especially in the first stage of combustion (premixed combustion). Differences of up to 80% are observed in the first zone of combustion, mainly due to not having overfeeding, the movement of air in the admission limits the development of swirling motion, which affects the development of combustion. This allows to visualize that to increase the efficiency of the combustion process in Diesel engines with natural suction; it is important to increase the Compression Ratio (C_R) as much as possible.

Similarly, for the study case with an admission pressure of 1.05 bar, it is observed that the influence of the DFQL due to the compression ratio is less noticeable, although it is observed that the peak of the rate is higher in the case of the greater C_R, which is consistent with the previous works[11]. For this case, it is evident that in the diffusion combustion zone there is a considerable difference depending on the compression ratio, which is around 4%. From power delivered by the engine, the increase in the compression ratio by 1 cause an increase of 4% in the power output of the engine and the increase in the pressure at the intake by 0.05 bar causes an increase of 6% on the output power.

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