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Evaluation of Cylinder Volume Estimation Methods for In–Cylinder Pressure Trace Analysis

In–cylinder pressure trace analysis is an important investigation tool frequently employed in the study of internal combustion engines. While technical data is usually available for experimental engines, in some cases measurements are performed on automotive engines for which only the most basic geometry features are available. Therefore, several authors aimed to determine the cylinder volume and length of the connecting rod by other methods than direct measurement. This study performs an evaluation of two such methods. The most appropriate way was found to be the estimation of connecting rod length based on general engine category as opposed to the use of an equation that predicts cylinder volume with good accuracy around top dead centre for most geometries.

***Keywords**: in–cylinder pressure trace analysis, piston engines, connecting rod length, cylinder volume*

1. Introduction

Correct evaluation of fluid properties and cylinder volume are paramount for the analysis of indicator diagram in internal combustion engines [1–3]. Even when complete information on engine geometry is available and cylinder volume can be correctly calculated, a sensor is employed to determine the exact moment when the piston reaches top dead centre (TDC). An error in the measurement of this position can have a significant influence on the calculated value for indicated fuel conversion efficiency.

Combustion investigations are usually carried out on experimental engines for which a complete set of technical specifications is available. Some calculations may however be performed for engines that do not feature such extensive information on their geometry. Basic dimensions are generally available even in general use literature such as the owner’s manual. Therefore, some interest was invested into methods that allow thermodynamic calculations to be performed even when limited information is available on engine geometry.

This study aims to investigate several such methods used for estimating cylinder volume when only bore, stroke and compression ratio data is available. Three such methods were compared to the case when connecting rod length is known, for six different engines. Relative error values were compared around TDC and a set of measurements in one of the engines fueled with hydrogen was analyzed using the cylinder volume given by the three estimation methods.

2. Materials and methods

Basic geometry is defined by bore (*B*), stroke (*S*), compression ratio (ε) and connecting rod length (*l*) for reciprocating engines. Typical values for the connecting rod to stroke ratio are 1.5 to 2 for small- and medium-size engines, increasing to 2.5 to 4.5 for large slow-speed CI engines [4], and cylinder volume (*V*) can be obtained as

$$V = \left\{ V_d / 2 \cdot \left[1 - cos(\theta) + 2 \cdot l/S \cdot \left(1 - \sqrt{1 - \left(S/(2 \cdot l) \right)^2 \cdot sin^2(\theta)} \right) \right] \right\} + V_c , \tag{1}$$

with V_d as displacement, θ crank angle rotation and V_c cylinder volume with the piston at TDC.

As combustion is the most complex process (as compared to intake, compression and exhaust), it is this part of the cycle that is generally investigated more thoroughly. Therefore, some authors have developed simple equations that can be used to estimate cylinder volume around TDC with good accuracy [5],

$$V = V_c + \left[1 + 0.896 \cdot (\varepsilon - 1) \cdot 10^{-4} \cdot (\theta - 360)^2 \right], \tag{2}$$

without the need for calculating the volume using equation (1) that requires the connecting rod length to be known. Equation (2) is claimed to ensure an accuracy of ±1% from 320 to 400 deg crank angle (CA) rotation (i.e. from 40 deg CA before to 40 deg CA after TDC).

Another way of dispensing with the requirement that connecting rod length be known is to assume that the root squared expression on the right side of equation (1) is negligible, thus resulting in

$$V = V_d / 2 \cdot \left[1 - cos(\theta) \right] + V_c , \tag{3}$$

an expression that is true only for an engine with very long connecting rod length (i.e. $l \to \infty$).

Six different engines, three spark ignition (SI) and three compression ignition (CI) power units were considered in this study. Specifications for these engines are listed in tables 1 and 2. These aggregates cover a wide range of engine type, operational parameters such as rotational speed, and should be representative for other cases as well.

Table 1. SI engines specifications

Engine	*B* [mm]	*S* [mm]	*l* [mm]	*ε* [–]	*l*/ *S* [–]
CFR [6]	82.55	114.2	254	7–10	2.224
GM [7]	105	95.25	158	8.56	1.659
Rover [7]	80	89	160	10	1.798

Table 2. CI engines specifications

Engine	*B* [mm]	*S* [mm]	*l* [mm]	*ε* [–]	*l*/ *S* [–]
Fairbanks – Morse [7]	79.4	101.6	190.5	14	1.875
Perkins [7]	98.4	127	228.6	16	1.8
BMC [8]	80.26	88.9	158	21.47	1.777

In order to evaluate the influence that the cylinder volume estimation method exerts on the accuracy of combustion investigations, a set of measurements performed on the cooperative fuel research (CFR) engine [6] fueled with hydrogen was investigated. The rate of heat release was calculated using a first law analysis. Considering the equation of state for ideal gases and the first law, the following formula can be written,

$$dQ = \frac{\gamma}{\gamma - 1} \cdot p \cdot dV + \frac{1}{\gamma - 1} \cdot V \cdot dp + \frac{1}{\gamma - 1} \cdot p \cdot V \cdot \frac{dM}{M}, \tag{4}$$

taking into account the variation of molecular weight during combustion. The ratio of specific heats (γ) was calculated for the overall fluid for every step (i.e. 0.5 deg CA rotation).

3. Results and discussion

In order to evaluate the capability of estimating cylinder volume using different methods when information on connecting rod length is not available, equations (2) and (3) were applied for an interval of 60 deg before and after TDC. Another situation investigated was the use of equation (1) with an estimated connecting rod length value of $l = 2 \cdot S$ for all six engines. Figure 1 shows calculated relative errors (i.e. (estimated volume – measured volume) / measured volume) for the three estimation methods. It is immediately evident that equation (2) does not ensure the accuracy of ±1% around TDC for all the engines. In particular, for the three diesel engines relative errors are even over ±3%. When confronted to the other two methods, the accuracy is comparable to the use of equation (1) with the estimated connecting rod length (*l* = 2 · *S*). Equation (3) features much higher errors within the 320..400 deg CA range, but compared to equation (2) it yields much better results, with an accuracy of up to ±10..16% for the rest of the interval (i.e. 0..320 and 400..720 deg CA). This is somewhat important, given that equation (2) can only describe volume variation only within a narrow CA interval.

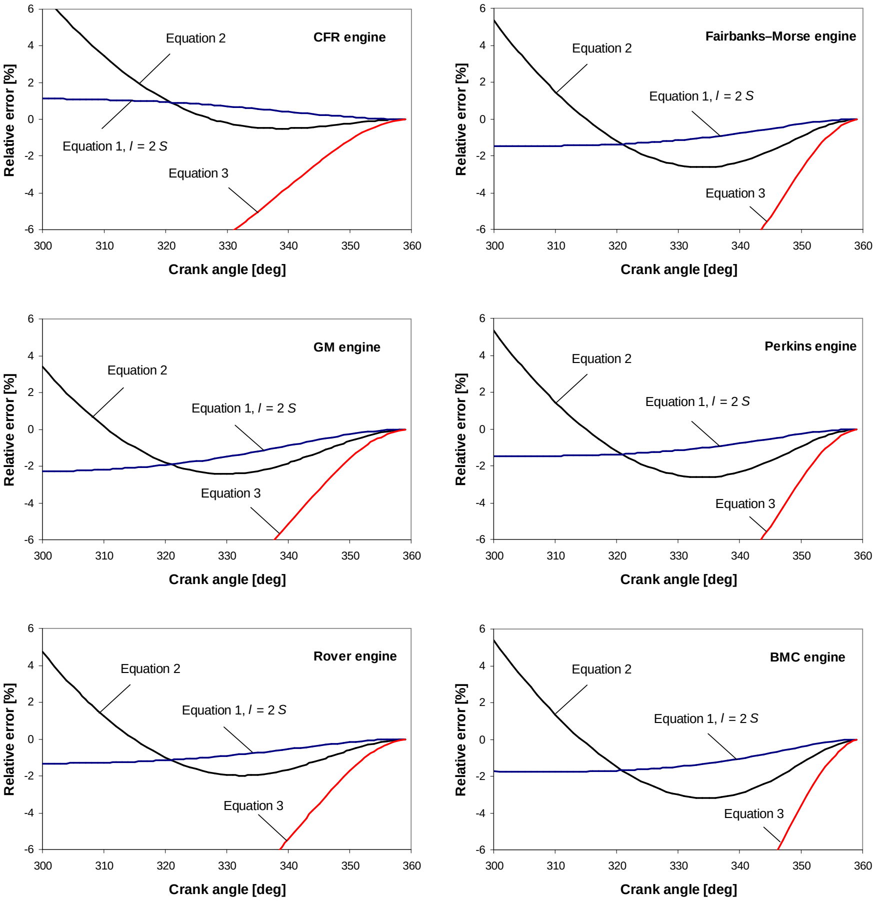

Figure 1. Relative error for calculated cylinder volume using different equations.

When comparing the three estimation methods, it became clear that estimating the length of the connecting rod combined with the use of equation (1) ensures good accuracy throughout the entire CA rotation range. Therefore, a combination of methods was investigated to find if this would represent an appropriate option for cylinder volume estimation. For all six engines, the cylinder volume was calculated with equation (2) for the 320..360 deg CA range, and using equation (1), an estimated connecting rod length could then be calculated. For most of the cases investigated (four out of six), the CA that ensured the closest estimated connecting rod length was around 315 deg CA (figure 2). For the remaining two engines however, this value showed large differences.

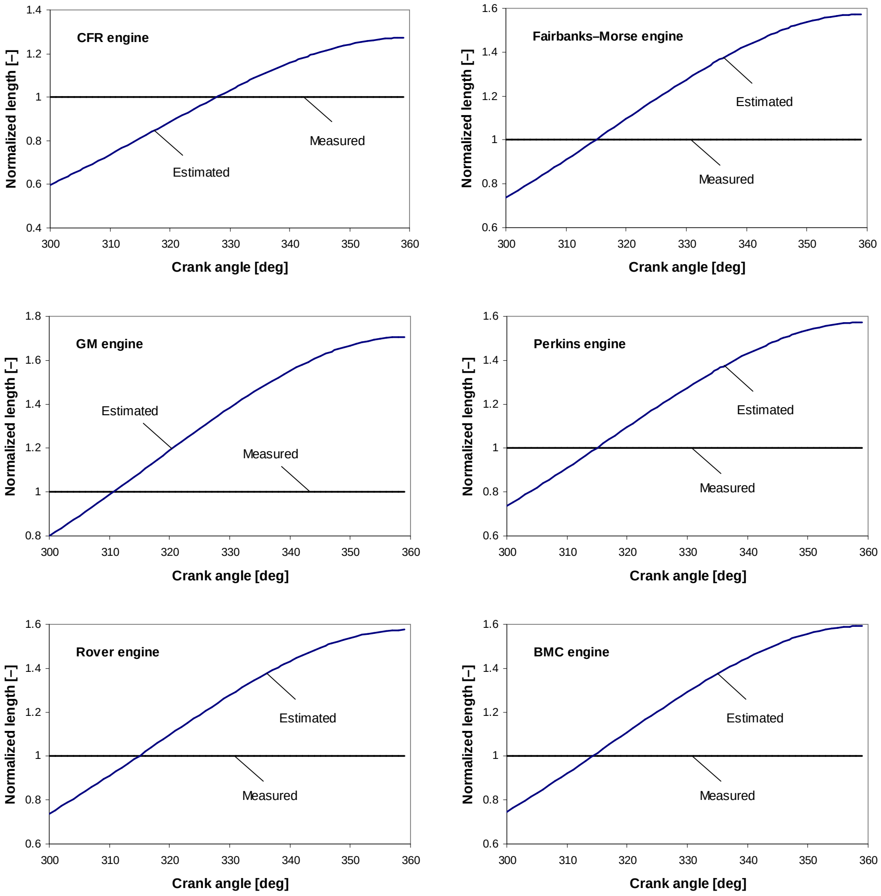

Figure 2. Estimated connecting rod length.

For the CFR engine this best fit value was close to 330 deg CA, while for the GM power unit, an angle close to 310 deg CA ensured the most accurate result. Given that even for such a reduced sample, no common trend could be established, this procedure was not pursued further, as it would not provide better results than simply estimating connecting rod length in an arbitrary manner.

As stated in the previous section, a set of measurements performed in the CFR engine featuring hydrogen fueling was investigated, in order to evaluate the influence that different cylinder volume estimation methods exert on the process of pressure trace analysis. Values for the calculated rate of heat release during combustion showed reduced variations from one method to the next and were very close to the ones obtained when using equation (1). Figure 3 shows the cumulative heat release calculated for the four cases with regard to cylinder volume estimation. Values obtained from the start of combustion (SOC) to its end are very close, with only the case of equation (3) showing a slightly increased difference at the end of combustion (EOC).

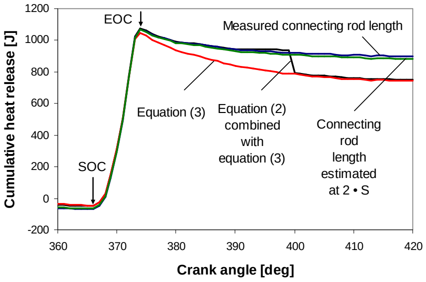

Figure 3. Influence of cylinder volume estimation method on the cumulative heat release analysis.

Given that equation (2) could not be used for CA larger than 400 deg, it was combined with equation (3) for the remaining CA interval. This is the reason for the large step observed in the trace obtained using this combination of the two methods. The best accuracy was obtained by estimating the connecting rod length at double the stroke. However, a very surprising result is that even a simple formula such as equation (3) has a reduced influence on the actual combustion analysis. Of course, hydrogen features high flame speed and combustion takes place within a few deg CA, thus reducing error levels. Other fuels such as gasoline or methane would most likely show a more pronounced influence. Equation (2) ensures an acceptable accuracy within the 320..400 deg CA range. This interval is sufficient for most combustion events. It should be noted however that for the CFR engine the relative error level for calculated cylinder volume was within ±1%, while for other engines this range was increased to up to ±3% (figure 1). Also, the inability to correctly predict volume variation for the rest of the CA interval is a significant disadvantage for equation (2). Therefore, it can be concluded that the estimation of connecting rod length at double the stroke combined with the use of equation (1) is the best method for evaluating cylinder volume when little data is available on engine geometry.

4. Conclusion

Three different cylinder volume estimation methods were compared to the case when the connecting rod length was known. Two methods featured an accuracy of ±2% around TDC, while the simplest equation featured relative errors of up to ±16%. One interesting conclusion of the study was that the method used has a reduced influence on combustion analysis, especially if this event is very short.

Of the three methods investigated, the estimation of the connecting rod length at double the stroke was found to feature the best accuracy. This procedure is bound to ensure the same level of relative errors for small- and medium-size engines. However, a correct choice of connecting rod length estimation can be made based on the category of the engine being investigated, thus making the proposed method usable even for large engines with comparable accuracy.

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