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DYNAMIC COMPRESSION RATIO ESTIMATION WITH CONSIDERATION OF DRIVE MECHANISM DEFORMATION ON INTERNAL COMBUSTION ENGINE

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ABSTRACT The common way to study the combustion process of internal combustion engines is to use of in-cylinder measured pressure data because the acquisition and analysis of engine data provides an important insight into the complex phenomenon of combustion. Thus, in predictive thermodynamic models of combustion process, parameters of engine must have precious values. The principal objective of this study is tried to determine the most important parameter of engine value at minimum errors by means of estimation parameters method and using the new compilation predictive thermodynamic model. In this paper, predictive thermodynamic model is first law of thermodynamic in zero heat release with considering of drive mechanism deformation to estimate dynamic compression ratio. It should mention that previous researchers did not pay attention to phenomenon of drive mechanism mechanical deformation. After presenting that new methodology in this work, the various calculation are carried out for its validation and it will be repeated in tree different engine speed (400 rpm, 600 rpm, and 900 rpm) to confirm values of parameters especially dynamic compression ratio, hence accuracy of dynamic compression ratio estimation and other estimated parameters are determined too. In addition, the comparative test aimed to characterize the precision of TDC determination in the new proposed method with value of TDC sensor.

Keywords in-cylinder pressure signal, polytropic model, parameters estimation, dynamic compression ratio, drive mechanism deformation.

INTRODUCTION

In the last century, the development of Internal Combustion (IC) engines has achieved a high level of success [11]. Study of combustion process by using of experimental pressure data is common method for evaluating of combustion process in internal combustion engine [8]. Most of made in factory engines did not have same dimensions preciously, so most of their parameters are varying from one cylinder to other cylinder even in one engine briefly [1]. These brief variations on engine dimension will cause remarkable errors to estimate values of heat release rate, start point of combustion, indicated power, indicated torque and in-cylinder temperature in heat release model [20]. Thus, precision estimation of engine parameters like clearance volume, TDC position, temperature of in-cylinder gas and especially compression ratio has special importance [14]. Afterward it tried to decrease errors of parameters estimation as well as possible. After calculation of TDC position, it is possible to estimate compression ratio. Accuracy of compression ratio has large effect on heat release and in-cylinder temperature. At near TDC it has high sensitivity and near BDC its sensitivity is low [14]. Since offset of crankshaft angle, degree affects on the TDC determination [7], for these mentioned reason in this paper is tried to define it exactly. Thus, it is necessary to use thermodynamics' model for parameters estimation. In order to define heat release energy, in-cylinder pressure measurement versus crank angle position should be measure. Whereas elimination of heat transfer in motoring condition is impossible, hence the peak compression pressure occurs earlier than minimum of cylinder volume this difference expressed in degrees of crank angle is called the "loss angle"[9]. However, TDC determination needs a precision method. It should be mention that accuracy of TDC determination affects on IMEP, mechanical and thermodynamical efficiency and heat release curve [20]. (Pinchon 1984) demonstrated the angular distance between the cylinder pressure maximum and the actual TDC, was described with a function including IMEP and the maximum cylinder pressure [22]. (Stas 1996) presented a method for determining of TDC base on difference of polytropic exponent in two inflexion points in pressure diagram on motoring condition. Two index points' positions have independency from pressure sensor offset and swept volume. Defect of this method is calculation of second derivation of cylinder volume because it causes numerical errors [24]. (Morishita and Kushiyama 1997) verified the effect of offset pressure sensor, TDC position, clearance volume and blow-by of gas on polytropic exponent in compression and expansion stroke. Whereas variation of TDC position and blow-by of gas affect on residual of polytropic exponent, they assumed that polytropic exponents have independency into other parameters then variations of each parameters on polytropic exponent are verified [17]. (Eriksson 1998) showed a systematic method to identify the parameters for first time base on heat release model in motoring condition and without encountering numerical errors. He estimated crank angle offset and compression ratio at Inlet Valve Close (IVC). In this study for shirking of over-parameterization, temperature of cylinder wall and heat release coloration assumed to be constant [7]. (Hribernik 1998) proposed a formulation giving the ratio between IMEP error and TDC position error, mentioned error is around 9% [10]. (Armas 1998) supposed mechanical deformations in very rigid elements like cylinder and crankcase are much smaller than those of piston, connecting rod and crank. Thus, he considered that deformations of cylinder and crankcase are waiver phenomenon then in order there are high pressure and high temperature on crown piston, connecting rod and crank especially near TDC then, he presented new formula for instantaneous volume mechanical deformation for first time [2, 21]. (Tazerout et al 1999a) presented a new thermodynamics method of TDC determination base on Temperature-Entropy in motoring condition if there is an error on TDC position, a small loop appear on Temperature-Entropy diagram. Endurances were done to eliminate of this loop then TDC position is determined [26]. on other study (Tazerout et al 1999b) estimated compression ratio by using Temperature-Entropy diagram and they determine the effect of compression ratio error on entropy diagram because this error affect on TDC position however they performed both calibrations, compression ratio and TDC position determination together [27]. (Stas 2000) in other study, used tertiary derivation of heat release rate to determine TDC in non-fire cylinder pressure too. Disadvantage of this method is precision determination of second and third derivations of pressure diagram [25]. (Chang et al 2004) presented dynamic method for TDC correction in combustion condition according correspond heat release diagram and polytropic exponent. They use polytropic exponent to correct TDC position in compression stroke condition [4]. (Klein et al 2006) presented four methods to estimate of compression ratio; whereas exact value compression ratio is unknown, they used two models, heat release model and polytropic model base on in-cylinder pressure simulation then they evaluated and compared it in motoring and combustion process [12]. (Payri et al 2006) verified the effect of deformation on compression ratio determination [20].

(Pipitone et al 2008) presented new method to determining of TDC position base on first and second thermodynamics' laws and they performed comparative test between results of termodynamical method and the data acquired with those obtained from a commercial available TDC sensor. They performed comparative tests aimed to describe the precision of their proposed method [23]. On mathematical viewpoint, since a physical system was simulated and its differential equations were founded this problem was solved according to initial and boundary conditions it is called "direct problem", but since needed parameters for solving equation was unknown and parameters estimation is the goal to achieve. Therefore, this problem interpreted to "inverse problem". It is remarkable that inverse problem becomes important when it is impossible to measure the unknown parameters directly. For this reason, we estimate clearance volume and dynamic compression ratio because direct measure of these parameters is very hard and impossible without very developed equipments in lab. On the other hand in previous studies [4, 7, 10,12, 26, 27, 24, 25, 19], researcher did not pay attention on effect of drive mechanism deformation phenomenon in compression ratio estimation, afterward a significant part of this paper was focused on this phenomenon that was occurred in reality to estimate compression ratio dynamically. Consequently, it assumes first law of thermodynamics which rate of heat release is zero i.e. first law of thermodynamics converts to polytropic model. Thenceforth drive mechanism mechanical deformation was considered in polytropic model and parameters were include of new model were estimated like pressure sensor offset, polytropic exponent, clearance volume, dynamic TDC position, constant value and an experimental coefficient. In next step, the most important factors on internal combustion engine- dynamic compression ratio- estimated too. The only estimated parameter of this new model that has possibility measured with sensor- dynamic TDC position- compared and validation with experimental value. Due to eliminate the effect of uncertainty associated with the combustion process [9] this study is done on motoring engine conditions (no fuel injection) in compression stroke [6,3] to estimate parameters. Since in combustion process the relation between volume and pressure did not worked as well as motoring conditions to estimate the parameters [12].

ESTIMATING PARAMETERS

By rewriting of first law of thermodynamics for controlled volume surrounded in piston space [28], it becomes as equation (1):

$$dU = \delta Q - \delta W \qquad (1)$$

Which U is internal energy of in-cylinder gas, Q rate of heat release and W is mechanical work on crown piston. Then, by considering Ideal gas law and energy variation of in-cylinder gas has relation on gas mass, heat specific at constant volume and temperature variations, hence difference relation C_v with C_p we will have following equation:

$$\delta Q = \frac{C_v}{R} V dP + \frac{C_p}{R} P dV \qquad (2)$$

Now we suppose pressure and temperature variations and gas velocity are low in compression stroke hence heat release consider being zero ($\delta Q = 0$) also, by replacement of Heat Capacities Ratio (HCR) and rearrange equation (2):

$$\frac{dP}{P} = -\gamma \frac{dV}{V} \tag{3}$$

With assumption $\gamma = const$, to integrate both side of equation (3) and using logarithmic function characteristic hence to multiply both side of relation, following equation will be get that is called "Isentropic" equation.

$$PV^{\gamma} = P_0 V_0^{\gamma} = const \tag{4}$$

The In-cylinder pressure measurements were carried out for various tree different speed 400 (rpm), 600(rpm), 900 (rpm) on engine TD43 by means of Kistler piezoelectric pressure sensor 6050B [5] (shown at figure (1)). Rate of sampling data is 0.4 degree of crank angle degree. In first step we have geometrical dimension of engine like volume displacement, length of connection rod,crank radius as shown as in table (1). Measured in-cylinder pressure is known too Now estimation of some parameters like offset pressure sensor, clearance volume, crankshaft angle offset, polytropic exponent and constant C will be done in polytropic model as following equation.

$$\left(p_m + \Delta p\right)\left(V_d(\theta) + V_C\right)^n = C \tag{5}$$

Table (1): Geometrical dimension of engine TD43

Property	Abbrev	Value/Unit
Bore	B	95(mm)
Stroke	L	82 (mm)
Crank radius	a=L /2	41 (mm)
Connecting rod	l	156(mm)
Displacement volume	V_{disp}	852(cm^3)

On the other hand, an important phenomenon must be taken into account on reciprocating mechanism parts of the engine. As a matter of fact, there is a mechanical deformation on shape of the crown piston, connecting rod and crank briefly that depend on two significant factors basically:
1- Due to the high In-cylinder pressure at compression stroke in the combustion chamber
2- Inertial force caused by piston mass [21].

As a result, its value is highest at near TDC because volume of cylinder is on minimum and in cylinder pressure is in maximum value [20]. So instantaneous mechanical deformation of drive mechanism depends on parameters like absolute pressure $\boldsymbol{P}$, acceleration $\boldsymbol{a_c}$, mass of drive mechanism $\boldsymbol{m}$ and engine geometry (connecting rod $\boldsymbol{l}$, distance of the axis of the piston pin to the

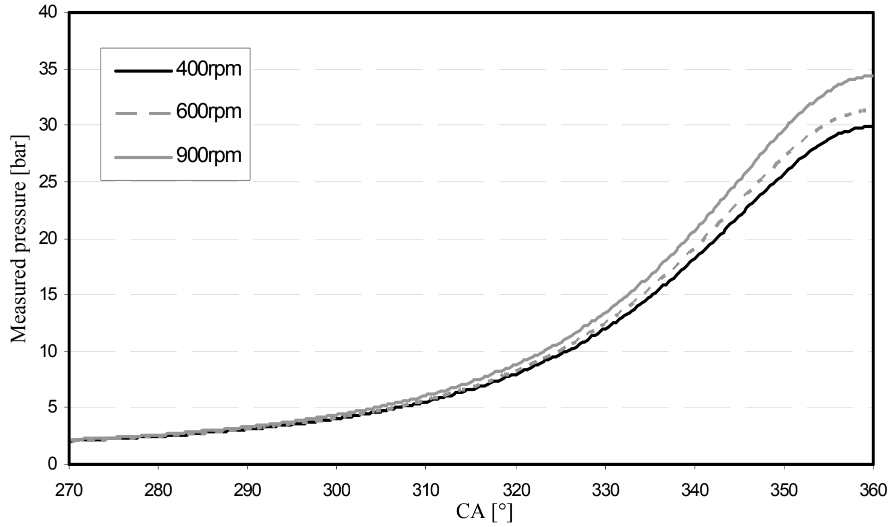

Figure 1: Measured in-cylinder pressure in tree engine speed (400,600, 900) rpm at motoring condition at compression stroke (data from [5])

piston surface L_{TP}, crank radius a ,diameters of cylinder B, diameters of piston pin D_{pin}, cross section of piston pin A_{pin}) plus K_{def} is experimentally adjusted coefficient [21].

$$\Delta y(\theta) = K_{def} \times \frac{1}{E_{steel}} (L_{TP} + l + a) \times \left[P \left(\frac{B}{D_{pin}} \right)^2 + \frac{m \times a_c(\theta)}{A_{pin}} \right] \tag{6}$$

As a matter of fact, this model assumes that the engines deformations are similar to that of an iron bar with a length equal to that of (length from piston pin to piston top + connecting rod + crank) and the diameter of the equivalent bar is assumed to be that of the piston pin for simplifying assumption. As the real geometry of the element involved is irregular, it rather to simplify and to adjust the real behavior by means of the value of K_{def}.
In fact by multiplication of drive mechanism strain on piston surface area, volume deformation is evaluated as latter equation. It necessary to express that volume deformation is a shrink volume therefore total volume of engine become a little larger with this assumption. Thus volume deformation has negative value, it means that K_{def} is reached negative.

$$\Delta V_{def,\theta} = \frac{\pi B^2}{4} \times K_{def} \times \frac{1}{E_{steel}} (L_{TP} + l + a) \times \left[P \left(\frac{B}{D_{pin}} \right)^2 + \frac{m \times a_c(\theta)}{A_{pin}} \right] \tag{7}$$

It is mentioned that m is mass of drive mechanism, this mechanism include of piston, pin of piston and $\left(\frac{1}{3}\right)$ connecting rod. The each mass of the alternative element have to be measured with a balance that is shown in table (2).

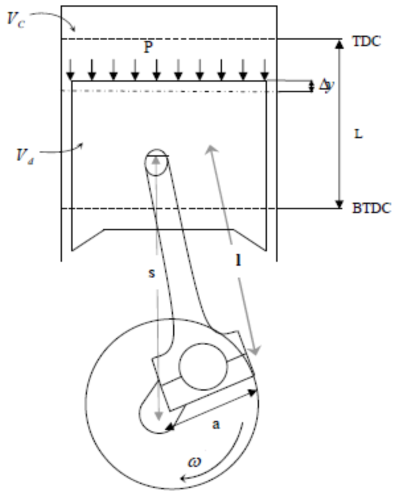

Figure 2: Schematic view of a reciprocating internal combustion engine with considering of deformation on drive mechanism

$$m = m_{piston} + m_{pin} + \frac{m_{conrod}}{3} \tag{8}$$

Table (2): Elements mass of TD43 engine

Mass of element	Abbrev	Value/Unit
Piston	m_{piston}	0.9255(Kg)
Connecting rod	m_{conrod}	0.7060(Kg)
Piston pin	m_{pin}	0.3867(Kg)

In order to evaluate piston linear acceleration, it should be derivate two times from vertical piston position respect to TDC versus crank angle, then piston linear acceleration equation is as following [13]:

$$a_c(\theta) = a \times \omega_e^2 \times \left(\cos(\theta) + \frac{a}{l} \times \cos(2\theta) \right) \tag{9}$$

Then, by substituting of volume deformation in polytropic model; our new methodology for parameters estimation will start to be present.

$$(p_m + \Delta p)\left(V_d(\theta + \Delta\theta) + V_C - \Delta V_{def,\theta}\right)^n = C \tag{10}$$

Since volume deformation is a shrink volume therefore its value is negative and to subtract the value of volume deformation from total engine cylinder volume shows that total volume of combustion chamber will be expanded.

As known cylinder volume is a function of crank angle degree that V_{disp} is volume displacement [8]. In despite of skipping fuel injection and finally lack of combustion process, at motoring condition heat transfer does not omit, thus the peak compression pressure occurs earlier than minimum of cylinder hence TDC position does not take place on minimum cylinder volume, this difference expressed in degrees of crank angle is called the "loss angle"[9], that erroneous determination of the TDC position is a major error source when calculating properties such as heat release etc [19]. For precision calculating cylinder volume versus crank angle degree, offset of crankshaft angle should be interfered in equation cylinder volume versus crank angle as shown in equation (11) because offset of crankshaft angle directly affect on TDC determination [7].

$$V_d\left(\theta+\Delta\theta\right)=\frac{V_{disp}}{2}\left(\left(\frac{l}{a}\right)+1-\cos\left(\theta+\Delta\theta\right)-\sqrt{\left(\frac{l}{a}\right)^2-\sin^2\left(\theta+\Delta\theta\right)}\right) \tag{11}$$

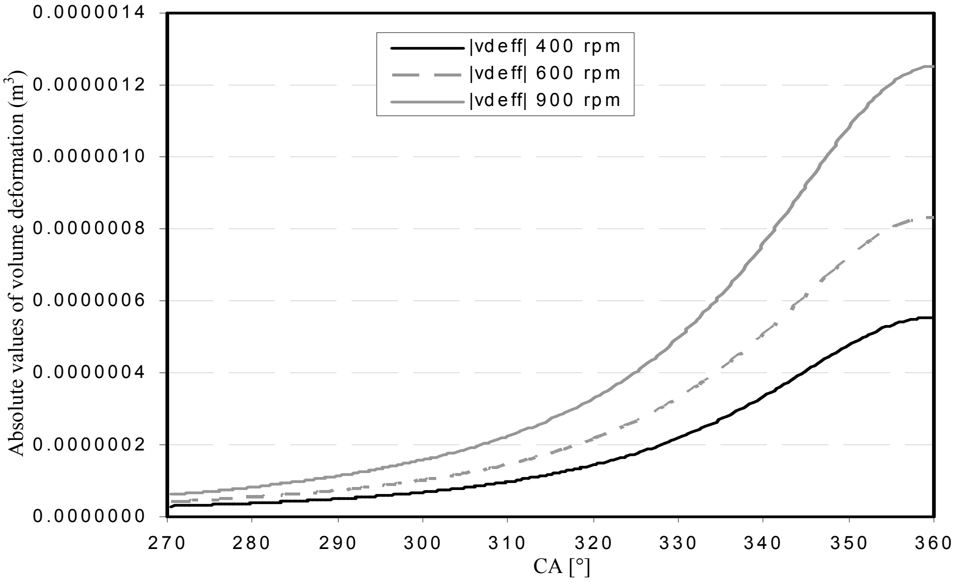

Figure 3: Absolute values of volume deformation ($\left|\Delta V_{deff,\theta}\right|$) in tree engine speed (400,600, 900) rpm at limited compression stroke in motoring condition

To link of equations (7) and (11) in polytropic model, finally equation (12) is reached. However, the internal combustion engine new thermodynamical compilation model appears, can estimate mentioned parameters like offset pressure sensor, clearance volume, dynamic TDC position, polytropic index, constant C and experimentally adjusted coefficient (K_{def}).

$$p_m=-\Delta p+C\times\left(\begin{array}{l}\frac{V_{disp}}{2}\left(\left(\frac{l}{a}\right)+1-\cos\left(\theta+\Delta\theta\right)-\sqrt{\left(\frac{l}{a}\right)^2-\sin^2\left(\theta+\Delta\theta\right)}\right)+V_C-\frac{\pi B^2}{4}\times\frac{K_{def}}{E_{steel}}\left(L_{TP}+l+a\right)\times\\ \left[P\times\left(\frac{B}{D_{pin}}\right)^2+\frac{m_{piston}+m_{pin}+\frac{m_{conrod}}{3}}{A_{pin}}\times a\times\omega_e^2\times\left(\cos\left(\theta+\Delta\theta\right)+\frac{a}{l}\times\cos\left(2\left(\theta+\Delta\theta\right)\right)\right)\right]\end{array}\right)^{-n} \tag{12}$$

We conclude that there is an improvement in the estimation parameters process because in previous common polytropic model (equation (5)) a lot of important parameters that are related to the engine mechanism properties and effect of in cylinder pressure on shape of alternative mechanism did not consider. It is necessary to understand the conditional works of engine affect on mechanisms properties and combustion chamber that they will have remarkable effect in compression ratio estimation finally.

In order to minimize residual between this new model and pressure data *Marquardt-Levenberg* [15-16] algorithm is used to solve this non linear equation in least square method. To coincident experimental in-cylinder measured pressure data on equation (12), parameters estimation is done and pressure sensor off set, clearance volume, dynamic TDC position, polytropic index, constant C, and K_{def} are estimated. After estimating of K_{def}, it will substitute in equation (7) and then volume deformation evaluates as shown as figure (3). Before fitting in-cylinder pressure data on new model (equation (12)), it is necessary to remove the noise of pressure signal because during recording pressure data, noises record is inevitable event [18]. So these noises cause remarkable error in parameters estimation. Consequently, the filtration process was carried out on measured pressure signal by means of a filter, since the used filter should not damage or change pressure phase. Thus, Net pressure signal is passed from smoothing algorithm that design especially for this work. It is mentioned that net pressure signal should be passed for several times (at least four times) as latter equation (13).

$$p_m(\theta_i) = \frac{1}{25}\begin{pmatrix} p_m(\theta_{i-4}) + 2p_m(\theta_{i-3}) + 3p_m(\theta_{i-2}) + 4p_m(\theta_{i-1}) + 5p_m(\theta_i) \\ +4p_m(\theta_{i+1}) + 3p_m(\theta_{i+2}) + 2p_m(\theta_{i+3}) + p_m(\theta_{i+4}) \end{pmatrix} \tag{13}$$

Being $\mathbf{p_m}$, $\boldsymbol{\theta}$ and **i** the pressure measurement, crank angle and number of data point respectively. The dynamic compression ratio is kind of compression ratio with considering volume mechanical deformation, is calculated base on equation (14). In fact CR_d is effective compression ratio that is lower than CR_d about 0.3-0.6 depending on in-cylinder pressure at TDC [20]. So inconsideration of volume deformation causes a remarkable error on compression ratio estimation and it confirms importance consideration of volume mechanical deformation. Now, knowing clearance volume, in-cylinder volume maximum, dynamic TDC position and volume deformation at near TDC are necessary, to estimate dynamic compression ratio.

$$CR_d = \frac{\max\left[V_d\left(\theta + \Delta\theta\right)\right] + V_C - \Delta V_{def,\theta=0}}{V_C - \Delta V_{def,\theta=0}} \tag{14}$$

In this study- for numerical calculations in parameters estimation- has used *MATLAB* and *SIGMAPLOT* softwares.

Results and discussions

The first difficulty encountered when doing numerical solution of equation (12), is define initial values parameters as starting points. This causes a problem to specify the best estimation whereas with different starting points different responses are achieved. It means that starting points have remarkable effect on residuals and finally on parameter estimation, but this problem should be removed. There are two ways to overcome this problem: The first is to add a

parameter for initial value and include it in the optimization. The second one is to set the initial value to zero and calculate a mean value [7]. The second procedure was chosen for its simplicity. Toward of initial clearance volume and pressure sensor offset, ploytropic index, dynamic TDC position, constant C and K_{def} put them to zero or even it is possible to put them a number very close to zero.
The second difficulty is to check the accuracy of the computations thus pressure data range should be restricted, then a pressure data limited to 90 degree of crank angle Before Peak Pressure (BPP) for compression stroke to do calculation of estimation. In fact tests procedure show that the crank angle degree length for compression stroke should be restricted from 180 degree but it should be sufficiently long to give consistent parameters estimation. So, both above strategies can be considered to provide the possibility of parameters estimation.
As shown as in table (3), to gave satisfactory results new presented method repeat for different speed of engine,400 (rpm),600 (rpm), 900(rpm),the nceforth it try to confirms the values of each parameters involved new model by averaging from tree almost similar estimated values of parameters in each engine speed. It is worthwhile to mention that the accuracy of each parameter is calculated too by means of standard deviation index.

Table (3): Result of parameters estimation for tree different speed of engine TD43

Engine speed(rpm)	**400**	**600**	**900**	**Mean**	**STD**
Δp	0.4783	0.4236	0.2609	0.3876	0.1130
$\mathbf{V_C}$	0.000052	0.000051	0.000049	0.000051	0.0000
$\Delta\theta$ **(BTDC)**	0.1122	0.2568	0.4236	0.2642	0.1555
C	0.000029	0.000055	0.000032	0.000038	0.0000
$\mathbf{K_{def}}$	-2.1262	-3.2412	-4.6235	-3.3303	1.2510
n	1.4107	1.333	1.2926	1.3456	0.0600
$\mathbf{CR_d}$	12.0596	12.2138	12.5663	12.2799	0.2597

Also, by means of a capacitive Kistler TDC sensor system 2629B placed in the spark plug hole of cylinder the mere measurable quantity of this model, TDC position, were evaluated 0.4101 (BTDC), However a satisfactory approximation for TDC position is equally reached.

Conclusions

Inasmuch precious estimate of the most engine parameter, compression ratio, is impossible even if we use professional, developed equipped laboratories hence it is indispensable to determine this parameter base on thermodynamical equations to recognize combustion process. In the present research, a numerical study according to experimental data is carried out on dynamic compression ratio estimation. This paper is presented one new thermodynamical method with considering drive mechanism deformation for motoring conditions to estimate compression ratio parameter dynamically.
To have consistent estimation of parameters without undulation in this new thermodynamical model, it should consider two strategies. To achieve this goal, it is necessary to consider suitable limit. Actually, the experiments show that if the 180-degree region for compression stroke has considered, it is impossible to have consistent estimation because parameters estimation did not

have independency from initial value, thus mentioned region should be limited until 90 degree of crank angle (BPP) for compression stroke

Finally according to table (3), values of pressure offset sensor, clearance volume, dynamic TDC position, constant C, polytropic exponent and K_{def} equal to 0.3879 (bar), 51 (cc), 0.2642 (degree BTDC), 0.000038 (bar.m^3), 1.3456, -3.3303 consequently, also error of clearance volume estimation and constant C are around to zero and especially K_{def} value errors are found to be higher than the other values errors. It is obvious that K_{def} coefficient error is higher than other parameters in order to it adjusted experimentally. In general, compared to experimentally measured value about estimation of TDC position by means of TDC sensor in this method demonstrates very good approximation. Moreover in this methodology dynamic compression ratio determines to 12.2799 too.

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