Research Journal of Applied Sciences, Engineering and Technology 6(6): 1101-1105, 2013
DOI:10.19026/rjaset.6.4019
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: November 08, 2012 Accepted: December 22, 2012 Published: June 30, 2013

Research Article

Study of Top Dead Center Measurement and Correction Method in a Diesel Engine

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Abstract: The thermal loss angle error analysis and maximum pressure determination method analysis were conducted first. Then the polytropic exponent method, the inflection point analysis, the loss function method and the symmetry method were utilized under different rotating speed, load and cooling water temperature, to calculate TDC in D6114 diesel engine and the results were compared with TDC position measured under the same condition with direct method of measurement. The study proved that (1) thermal loss angle of the diesel engine ranges from -1.0 ~ -0.6°CA; (2) Thermal loss angle is mainly affected by rotating speed and is reducing when rotate speed increases;(3) the symmetry method is generally the optimum for calculating the thermal loss angle of automotive diesel engines, with an error within 0.2°CA.

Keywords: Top Dead Center, Thermal Loss Angle, Heat Transfer Loss

INTRODUCTION

In the studying procedure, the Top Dead Center (TDC) of an engine varies due to inertia force, bearing clearance variation and deformation of crank-link mechanism as well as pistons. Therefore, accurately determining the TDC position has a direct and important influence on the study of engine studying procedure and design calculation. Error in TDC positioning had a notable impact on the accuracy of transient volume calculation, thus influence the calculation of heat release rate, especially near TDC. Previous study (He and Li, 1990) has indicated that a ±1oCA error in TDC positioning will lead to an 5% error in peak value of heat release, an 10% error in accumulated heat release and an 5%～8% error in indicated mean effective pressure (IMEP).As the empirical formula (1) (Hribernik, 1998) tells, TDC position accuracy should reach 0.1 °CA (Kochanowski, 1976; Rocco, 1993) in order to make sure that IMEP has an accuracy of 0.1 kgf/cm2.

$$\frac{IMEP_{error}[\%]}{TDC_{error}[°CA]} \approx 9 \tag{1}$$

The measurement methods for TDC were mainly separated into two categories: direct and indirect methods. Direct measurement methods, which use position sensor to acquire position signal of TDC directly, are considered accurate but the installment of the sensor is complex. The results of indirect measurement methods are influenced by more variations and some of methods include empirical coefficients. However, with meticulously chosen coefficients, satisfactory results can also be acquired.

Table 1: Main technical parameters of D6114 diesel engine

Parameters	Indexes
Number and arrangement of cylinders	Straight 6-cylinder
Cylinder bore/mm	114
Stroke/mm	135
Displacement/L	8.26
Compression ratio	17.7:1
Rated power/kW	184
Rated rotate speed/r/min	2200
Maximum torque/N·m	955
Maximum torque speed/ r/min	1400
Static fuel supply advance angle/ ºCA	12
Type of the original supercharge	Garrett TBP4

In present study, the signal of piston position and cylinder pressure under motoring condition were acquired by cutting the individual fuel delivery. At different rotating speed and load, the thermal TDC was calculated according to the cylinder pressure. Then, error analysis was conducted based on the reference of TDC position measured by direct method.

Experimental: Our experiment was based mainly on D6114ZLQB direct injection (DI) diesel engine produced by Shanghai Diesel Engine Co., Ltd, whose parameters is shown in Table 1.

Considering accuracy and the dependence on empirical parameters of each TDC correction method, the polytropic exponent method, the inflection point analysis, the loss function method and the symmetry

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method were chosen as representatives. Here we briefly revisit these four indirect methods.

Polytropic exponent method (Deng, 1985; Engine Cycle Analysis Version 892, 1989): Due to the heat loss and mass leakage, the polytropic exponent will change dramatically near the TDC. The method utilizes the polytropic exponent based on an assumed thermal angle, in which the polytropic exponent is calculated by means of the following equation:

$$n(\theta_i) = \frac{\ln p_{cyl}(\theta_i) - \ln p_{cyl}(\theta_{i+1})}{\ln V_{cyl}(\theta_{i+1}) - \ln V_{cyl}(\theta_i)} \quad (2)$$

In the ideal condition, which means no heat loss and mass leakage exist, the polytropic exponent is irrelevant to the crank angle. When the polytropic exponent is negative before the assumed TDC position and becomes positive after it, it means the actual TDC is on the left side of the assumed TDC position and vice versa. The overturn of the polytropic exponent represents the correct TDC position. In the experiment, the assumed TDC position is gradually adjusted, ranging from -60 ~ -2°CA to 2 ~ 60°CA, then the mean-square deviations between the polytropic exponent and the ideal polytropic exponent are calculated. The TDC position corresponds to the minimum mean-square deviation.

Inflection point analysis (Stas, 1996): the inflection point means the crank angle where the second derivative of the pressure equals zero. Based on the assumption that the TDC coincides with the peak pressure location, the polytropic exponents at the inflection points are calculated with equation (2). The two exponents are denoted as m_1 and m_2. Thereafter, the assumed thermal loss angle is adjusted and another two polytropic exponents at the inflection points called m_1' and m_2' are calculated. When the assumed thermal loss angle is correct, the polytropic exponents should fulfill the equation below:

$$\frac{m_2' - m_1'}{m_2 - m_1} = 2.25 \quad (3)$$

The loss function method (Pipitone *et al*., 2007; Pipitone, 2008): The method considers the impact of heat loss as well as mass leakage and determines the TDC by establish the concept of loss function, which is defined as

$$\delta F = c_p \frac{\delta V}{V} + c_V \frac{\delta p}{p} \quad (4)$$

Near ±30°CA, the loss function is influenced hardly by thermal loss angle but only the structure of the engine. The loss function at pressure peak is directly related to the angular position θ_1 and θ_2 of the minimum and maximum δV/V,, so the relation between these two loss function can be built. Then the loss

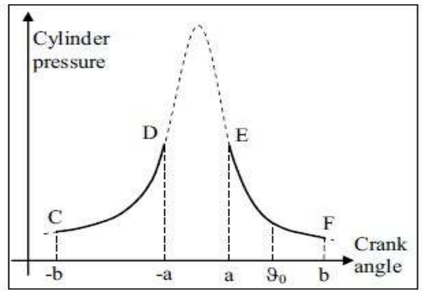

Fig. 1: Pressure curve in the calculation using symmetry method

function at peak pressure location can be determined and heat loss angle calculated. The formulae used are as follows:

$$\theta_{1,2} = \mp 76.307 \cdot \mu^{0.123} \cdot \rho^{-0.466} \quad (5)$$

$$\delta F_m = \frac{1}{2}(\delta F_1 + \delta F_2) \quad (6)$$

$$\delta F_{peak} = 1.95 \delta F_m \quad (7)$$

$$\theta_{loss} = \frac{2}{\rho - 1} \cdot \frac{\mu}{\mu + 1} \left[\frac{1}{c_p} \frac{\delta F}{\delta \theta} \right]_{peak} \quad (8)$$

where ρ is the engine compression ratio while μ is the rod to crank ratio.

The symmetry method (Nilsson and Eriksson, 2004): This method assumes that all heat loss occurs from –a to a°CA. The pressure during expansion process (curve EF) is lower than that during compression process (curve CD) due to heat loss (Fig. 1).

In the experiment, An offset of pressure Δ(θ) is added to the curve EF in order to realize the symmetry (Fig. 1). The offset Δ(θ) is:

$$\Delta(\theta) = (p(\theta_{TDC} - \theta_0) - p(\theta_{TDC} + \theta_0)) \cdot \left(\frac{V(\theta_{TDC} + \theta_0)}{V(\theta_{TDC} + \theta)} \right)^{\eta} \quad (9)$$

where θ_{TDC} is the estimated TDC position,θ_0 is the median of the region [a, b] and ηis an experiential constant which was set to be 1.9 in this experiment. The TDC position corresponds to the minimum of the following square deviation.

$$\sum_{a<\theta_i<b} \{p(\theta_{TDC} - \theta_i) - [p(\theta_{TDC} + \theta_i) + \Delta(\theta_{TDC} + \theta_i)]\}^2 \quad (10)$$

RESULTS AND DISCUSSION

Analysis of the Thermal Loss Angle: In this study, measurement error of the TDC position and maximum pressure position was first analyzed on D6114 diesel engine.

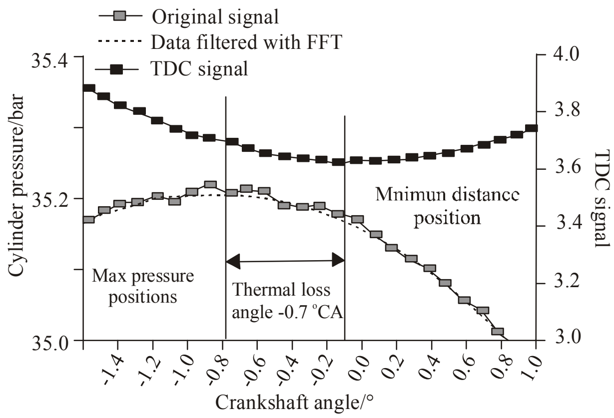

Fig. 2: The Calculating of Thermal Loss Angle of D6114 Diesel Engine

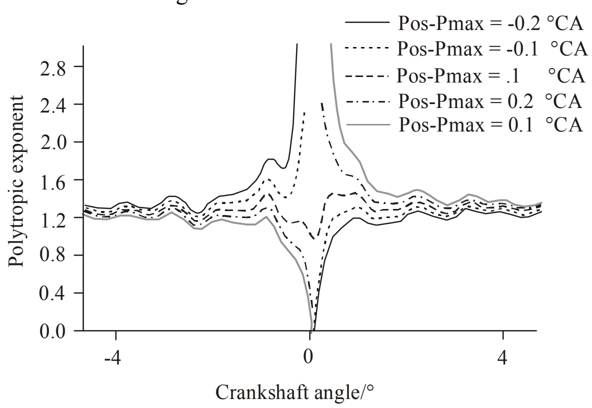

Fig. 3: The effect of Maximum Pressure Position Deviation on Polytropic Exponent

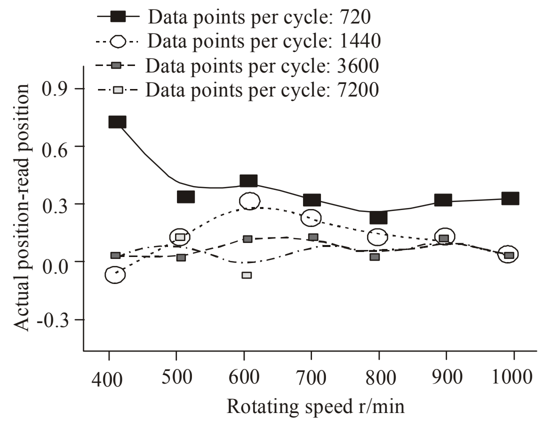

Fig. 4: The Relation Between Maximum Pressure Position Deviation and Sampling Rate

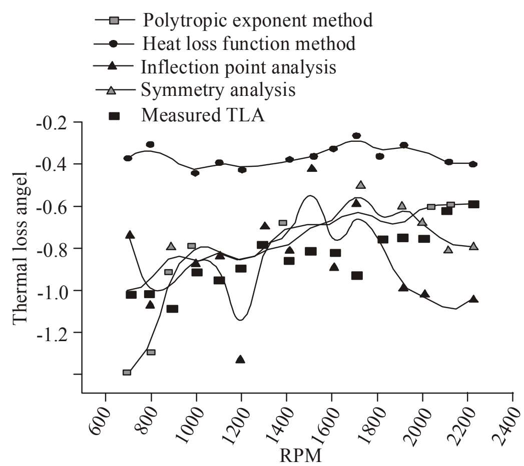

Fig. 5: Measured and Calculated Thermal Loss Angle of the DI Diesel Engine Under Different Rotating Speed

Figure 2 showed the cylinder pressure and TDC position measurement data of D6114 diesel engine under motored condition. The engine was operated under the rotating speed of 1000r/min. The maximum pressure point appears 0.7 °CA before the top dead center due to factors including heat loss and air leaking.

Analysis of the Method Determining the Maximum Pressure: Exact heat loss angle analysis requires accurate maximum cylinder pressure position. Because pressure changes slightly near TDC on the indicator diagram, sensor error and finite sampling rate can lead to deviation between actual maximum pressure position and position read from indicator diagram. So maximum pressure position can be either read from indicator diagram or calculated from polytropic exponent variation. Generally speaking, indicator diagram need to be smoothed before reading because smoothing of data helps to eliminate maximum pressure position error caused by pressure sensor fluctuation.

The polytropic exponent method uses the sensitivity of polytropic exponent to maximum pressure position, whose key steps are shown below:

- Acquire max pressure position by measurement
- In the range from -2°CA to+2°CA around max pressure position, shift pressure data with a step length of 0.1°CA. Then calculate the polytropic exponent between-10°CA to10°CA
- Calculate the sum of mean-square deviation of the average polytropic exponent
- The shifted step length corresponded with minimum deviation is the deviation between actual max pressure and position read from the indicator diagram

Figure 3 is the polytropic exponent curve of deviation between maximum pressure position read from indicator diagram and actual maximum pressure position. Polytropic exponent is sensitive to maximum pressure position and an error of 0.1°CA will cause the curve of polytropic exponent to change dramatically near the TDC.

Figure 4 shows the relation between maximum pressure position deviation and sampling rate. As the sampling rate increases, the deviation between the maximum pressure positions acquired by the polytropic exponent method and read from indicator diagram diminished. This suggests that when the sampling rate

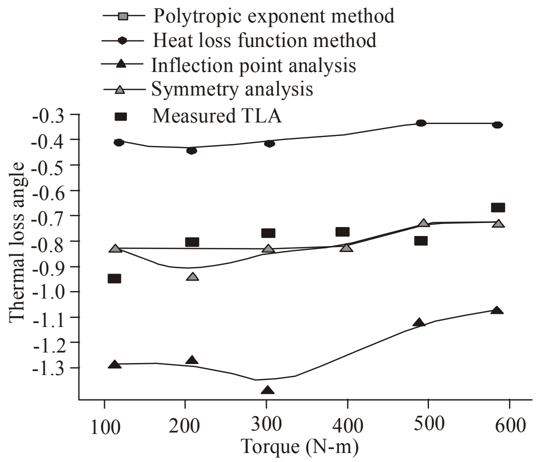

Fig. 6: Measured and Calculated Thermal Loss Angle of the DI Diesel Engine Under Different Torque

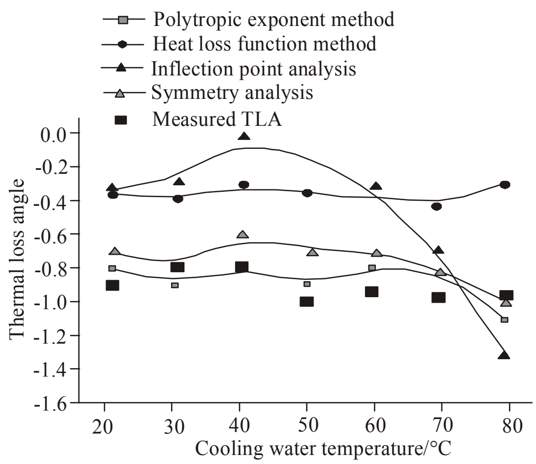

Fig. 7: Measured and Calculated Thermal Loss Angle of the DI Diesel Engine Under Different Cooling Water Temperature

goes high enough, the maximum pressure position read from indicator diagram is the actual maximum pressure position.

Experimental Results of Automotive D6114 Diesel Engine TDC Position: Figure 5 shows the comparison between the thermal loss angle calculated by the four methods and directly measured. It is obvious that the thermal loss angle decreases with an increasing rotating speed. When rotating speed increases, heat transfer time shortened, heat transfer reduced, so heat loss angle gradually decreases. With rotating speed varies from 700r/min to 2200r/min, heat loss angle decreases from -1.0°CA to -0.6°CA.

The figure also indicates that the thermal loss angle calculated with the loss function method deviated the most from the actual thermal loss angle, which mostly is more than 0.5°CA. The other three methods make less deviation. Thermal loss angle from the inflection point analysis fluctuates a lot and the error under certain rotating speed is great. The polytropic exponent method had greater error under low rotating speed. The symmetry method made a small error less than 0.2°CA under each rotating speed.

Figure 6 is the comparison between measured and calculated heat loss angle under different torque. Heat loss angle is hardly influenced by engine torque and almost remains static. The inflection point analysis and the loss function method lead to a larger error, while the polytropic exponent method and the symmetry method lead to a smaller error within 0.1°CA under different torque.

Figure 7 shows the comparison between measured and calculated thermal loss angle under different cooling water temperature. As cooling water temperature goes up, heat loss angle changes little. the loss function method leads to a greater error while the polytropic exponent method and the symmetry method leads to an error smaller than 0.2°CA under all conditions and the polytropic exponent method made the smallest error.

Concluding Remarks: The result showed that the thermal loss angle of vehicle diesel engines ranges from -1.0°CA to -0.6°CA, which well coincides with empirical data provided by AVL Corporation. This fact also proves the validity of the experiment and the calculating methods in this study. The methods of determining the peak pressure position were also analyzed. Though the peak pressure location needs correction at low rotating speed, the comparison between direct reading method and polytropic exponent method coincides when the rotating speed is high enough.

The thermal loss angle is largely influenced by the rotating speed. As the rotating speed increases, the heat loss angle decreases. As the engine speed rises up, the span for heat transfer decreases. Other variables like cooling water temperature and torque have little effect on thermal loss angle.

Four thermodynamic methods (The polytropic exponent method, the inflection point analysis, the loss function method and the symmetry method) were compared. For automotive DI diesel engine, loss function method generated obvious error, while the error of polytropic exponent method and the symmetry method is relatively low. In summary, the symmetry method is optimum for calculating the thermal loss angle of automotive diesel engine, with an error within 0.2°CA.

ACKNOWLEDGMENT

The study in this study was supported by the National Natural Science Foundation of China (Grant

No. 51106098). The authors are grateful to the colleagues at Shanghai Jiaotong University for their help with the experiment and preparation of the manuscript.

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