SOME ERRORS OF GAS ENGINE INDICATION

Prof. Dr hab. Eng. Karol CUPIAL
Dr Eng. Adam DUŻYŃSKI
Dr Eng. Michał GRUCA
Dr Eng. Janusz GRZELKA
Institute of Internal Combustion Engines and Control Engineering
Technical University of Częstochowa

Abstract. The paper presents the effect of the accuracy of digital recording of indicated pressure variation on the results of the analysis of engine cycle indicated parameters, and particularly on the accuracy of calculation of indicated work, the heat release process, combustion angles, and working medium temperature in the combustion-gas zone and in the non-combusted charge zone. The analysis allows for the effect of sampling density, the effect of the accuracy of IDC (Inner Dead Centre) angle determination, the effect of A/C converter resolution and the accuracy of determination of engine compression ratio and cylinder pressure corresponding to the ambient pressure. The parameters of a system for recording high voltage variations in the ignition system have also been established.

1. Introduction

The results of engine indication, and particularly the results of the analysis of thermal processes occurring in the engine chamber are dependent, to a different extent, on the accuracy of measurements and the accuracy of determination of initial values assumed in the program analyzing them as known values. The study estimates the degree of sensitivity of engine cycle analysis results to the errors of determination of the numerical values of the following quantities: IDC angular position, compression ratio, the “zero” pressure (reference pressure) of the piezo-quartz pressure pickup, the sensitivity of the pressure measuring system, compression starting temperature, the resolution of the A/C converter, and the angular density of cylinder pressure sampling. The sensitivity analysis was based on the example of the results of indication of a ZI gas engine supplied with biogas and running without knocking. The measurements and recording of indicated pressure were carried out for 600 successive cycles of engine operation under a load of 1.26 MJ/m³; the pressure was recorded with a step of 0.35° c.r. (crankshaft rotation) using a 12-bit A/C converter.

The sensitivity analysis was performed using simulation methods by inputting to the program known deviations from the values assumed as correct ones. Only those parameters have been illustrated, which undergo significant changes as a result of simulation. Example results of recording and numerical analysis are shown in Figs. 1–4.

The analysis of indication results was carried out using the authors’ own software – the SILNIK32 program [3] – a zero-dimensional two-zone model of thermal processes accounting for the properties of ten semi-perfect gases [6], and LCT [1] and IND4 [2] – programs for recording and analysis.
2. Errors of determination of the “zero” pressure of pressure pickups

The basic element of the measurement system is a piezo-quartz pressure transducer. Piezo-quartz transducers enable fast-variable pressure increments to be measured with a good accuracy, but they do not provide a possibility of measuring the absolute value of pressure (or positive gauge pressure) in relation to the ambient pressure. Figures 5+9 show the effect of the error of determining this level on the basic thermodynamic parameters of the engine.
Changes in the reference pressure level do not have any effect on the indicated work and indicated efficiency of the engine. These changes, in the range from -10% to +10%, cause only slight changes in the engine cycle parameters, as follows: maximum combustion pressure changes do not exceed -0.25% to +0.25%; maximum heat release rate changes \( \frac{dQ}{dt} \) do not exceed +0.5% to -0.5%; 100% heat release angle changes are contained in the range -0.6 to 1.0%; medium heating efficiency changes are contained in the range -0.9 to 1.0%; compres-
sion polytropic exponent changes do not exceed $+2.0\%$ to $-2.0\%$; changes in the maximum temperature of the fresh charge zone and the combustion zone are contained in the range $+4.0$ to $-3.0\%$.

3. Effect of the error of determination of the piston inner dead centre

The error of determination of the IDC (inner dead centre) causes an incorrect assignment of the measured pressure value to the values of crankshaft rotation angle and cylinder capacity, which results in a considerable error of determination of engine parameters being dependent on the momentary cylinder capacity.

Figures 10–16 show the effect of the IDC determination error on the basic thermodynamic parameters of the engine.

![Fig. 10. Effect of the IDC determination error on the maximum combustion pressure angle and the angle of maximum combustion pressure occurrence](image1)

![Fig. 11. Effect of the IDC determination error on the indicated work and the charge exchange work](image2)

![Fig. 12. Effect of the IDC determination error on the maximum heat release rate and the angle of maximum heat release rate occurrence](image3)

![Fig. 13. Effect of the IDC determination error on the maximum combustion pressure increment and the angle of maximum combustion pressure increment occurrence](image4)
Changes in the IDC determination angle within the interval from -2.5° c.r. to +2.5° c.r. do not cause any significant changes in the following engine cycle parameters: maximum combustion pressure, and the 10% and 90% heat release angles.

Changes in the IDC determination angle within the interval from -2.5° c.r. to +2.5° c.r. cause little significant changes in engine cycle parameters, as follows: the maximum combustion pressure angle changes within the range from +0.8 to -0.6%, which corresponds to 3.2 and 2.4° c.r., respectively, as expressed in absolute units; the maximum pressure increment angle changes in the range from +0.8 to -0.7%; and the angle of maximum heat release rate changes in the range from +0.45 to -0.6%.

Changes in the IDC angle within the range from -2.5° c.r. to +2.5° c.r. cause significant changes in engine cycle parameters, as follows: the errors of determination of indicated efficiency, indicated power, and indicated work are contained in the range from +10% to -6%; the error of determination of fresh charge zone temperatures is contained in the range from -6% to +8%; the error of determination of combustion-gas zone temperatures is contained in the range from +8% to -6%; the error of charge exchange determination is contained in the range from -12% to +8%; and the error of determination of the maximum heat release rate is contained in the range from +14% to -10%. The error of determination of the 100% heat release angle, containing in the range of values from -2% to 9%, grows significantly.
4. Effect of pressure measurement density

Recording of all variations in the indication time takes place in real time using the crankshaft rotation angle transducer, which permits the time axis to be divided into segments corresponding to crankshaft rotation by a c.r. angle step equal to $\Delta \alpha$. Contemporary crankshaft rotation angle transducers enable the generation of, for example 3600 pulses per one crankshaft rotation, which allows obtaining the resolution $\Delta \alpha = 0.1$ c.r., while taking into account the possibility of activating the recording system with both the trailing edge and the leading edge, a resolution of $\Delta \alpha = 0.05$ c.r. can be achieved. Such a high resolution is obtained by means of electronic linear interpolation between successive characters (normally, there are 360 or 720 characters), which may result in the occurrence of unintentional errors of the measurement method.

Figures 17-23 show the effect of the frequency of recording of fast-variable pressures on the basic thermodynamic parameters of the gas engine running without knocking.

Fig. 17. Effect of pressure measurement density on the maximum combustion pressure and the angle of maximum combustion pressure occurrence

Fig. 18. Effect of pressure measurement density on indicated work and charge exchange work

Fig. 19. Effect of pressure measurement density on fuel dose combustion angles

Fig. 20. Effect of pressure measurement density on the maximum heat release rate and the angle of maximum heat release rate occurrence
Fig. 21. Effect of pressure measurement density on the maximum combustion pressure increment and the angle of maximum combustion pressure increment occurrence.

Fig. 22. Effect of pressure measurement density on the calculated temperatures.

Fig. 23. Effect of pressure measurement density on heating efficiency and indicated efficiency and on compression polytropic exponent.

Changes in the pressure sampling density within the range 0.1+10° c.r. do not have any significant effect on the maximum pressure, indicated work, charge exchange work, indicated efficiency, and medium heating efficiency. In a gas engine running without knocking, a sampling step of 1° c.r. is sufficient for the analysis of those parameters.

Pressure increments and heat release rate are cycle parameters, for which the differentiation of the recorded pressure signal is necessary. These parameters are sensitive to pressure sampling density, but this may be associated with the effect of non-filtered out internal noises of the apparatus and interfering signals received by the measuring system and then added to the pressure signal being measured. As the sampling density increases, the effect of measuring line noises on the derivative value of the numerically differentiated variation grows.

5. Effect of the error of geometrical compression ratio determination

Figures 24+27 show the effect of the error of determination of engine geometrical compression ratio on the basic thermodynamic parameters of the biogas engine running without knocking.
The value of compression ratio does not have any effect on indicated work and indicated efficiency. Geometric compression ratio changes in the range from −12% to +12% cause changes in determination, as follows: heat release rate changes from approx. +5% to −5%; the angle of occurrence of the maximum heat release rate changes in the range from −0.2% to +0.08%; the angles of 2, 10, 50 and 90% fuel dose combustion are contained in the range from −2% to +2%, whereas the angle of 100% heat release changes from −3% to +5%; heating efficiency changes are contained in the range from −2% to +2%; changes in fresh charge zone temperatures lie in the range +9% to −7%; and changes in compression polytropic exponent are in the range +3% to −5%.

6. Effect of the resolution of the A/C converter used in the recording apparatus

The numbers of bits of the A/C converter being an integral part of the digital recorder substantially affect the accuracy of representation of the variation being recorded. Thus, e.g., for a 12-bit converter with an operating range of 10V, the signal will be recorded with a resolution

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Fig. 24. Effect of geometrical compression ratio determination error on the calculated temperatures

Fig. 25. Effect of geometrical compression ratio determination error on the maximum heat release rate and the angle of maximum heat release rate occurrence

Fig. 26. Effect of geometrical compression ratio determination error on fuel dose combustion angles

Fig. 27. Effect of geometrical compression ratio determination error on heating efficiency and indicated efficiency, and on compression polytropic exponent
of approx. 2.44mV, while for a 16-bit converter this resolution increases up to approx. 0.153mV.

Figures 28+34 show the effect of the number of bits of the digital A/C converter on the basic thermodynamic parameters of the gas engine running without knocking.

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**Fig. 28.** Effect of the number of bits of the A/C converter on the maximum combustion pressure and the angle of maximum combustion pressure occurrence

**Fig. 29.** Effect of the number of bits of the A/C converter on indicated work and charge exchange work

**Fig. 30.** Effect of the number of bits of the A/C converter on heating efficiency and indicated efficiency, and on compression polytropic exponent

**Fig. 31.** Effect of the number of bits of the A/C converter on the maximum heat release rate and the angle of maximum heat release rate occurrence

**Fig. 32.** Effect of the number of bits of the A/C converter on the maximum combustion pressure increment and the angle of maximum combustion pressure increment occurrence

**Fig. 33.** Effect of the number of bits of the A/C converter on the calculated temperatures
In the case of recording fast-variable pressures in a ZI gas combustion engine, adequate accuracy is assured by an A/C converter with a resolution of 10 bits. In modern recorders, 12-bit converters are used as a standard, and their resolution is sufficient for indicating a combustion engine running without knocking.

7. Effect of measuring transducer sensitivity

Figures 35-41 show the effect of the sensitivity of the measuring transducer on the basic thermodynamic parameters of the gas engine running without knocking.

Fig. 34. Effect of the number of bits of the A/C converter on fuel dose combustion angles

Fig. 35. Effect of measuring transducer sensitivity on the maximum combustion pressure and the angle of maximum combustion pressure occurrence

Fig. 36. Effect of measuring transducer sensitivity on indicated work and charge exchange work
Fig. 37. Effect of measuring transducer sensitivity on fuel dose combustion angles

Fig. 38. Effect of measuring transducer sensitivity on the maximum heat release rate and the angle of maximum heat release rate occurrence

Fig. 39. Effect of measuring transducer sensitivity on the maximum combustion pressure increment and the angle of maximum combustion pressure increment occurrence

Fig. 40. Effect of measuring transducer sensitivity on the calculated temperatures

Fig. 41. Effect of measuring transducer sensitivity on heating efficiency and indicated efficiency, and on compression polytropic exponent

Change in measuring transducer sensitivity does not have any affect on the angle of the maximum combustion pressure, the angle of the maximum pressure increment, and the angle of the maximum heat release rate. Changes in the measuring transducer sensitivity from -12% to +18% cause changes in determination as follows: combustion pressure changes from ap-
prox. -12% to +22%; indicated work and charge exchange work change from -12% to +22%;
the angles of 2, 10, 50 and 90% fuel dose combustion change from +0.2% to -0.4%, whereas
the angle of 100% heat release changes from +0.5% to -0.8%; heat release rate changes are
contained in the range -12% to +18%; the changes of fresh fuel zone and combustion zone
temperatures are in the range -8% to +14%; and pressure increase rate changes are from -12%
to +22%.

8. Effect of compression starting temperature

The calculation of processes occurring in the cylinder after the closure of valves requires
the knowledge of the momentary chemical composition of the medium present in the cylinder
at the moment of closing the suction valve. Knowing the momentary cylinder capacity and the
pressure, the amount of the medium present in the cylinder can be estimated from the gas law,
if the temperature of the medium in the cylinder is calculated by another method, e.g. from the
balance of heat contained in the fresh charge and in the combustion gas remained from the
previous cycle. Figures 42–44 show the effect of the error of temperatures estimation on the
thermodynamic parameters of the gas engine running without knocking and fed with an air­
fuel mixture with a constant value of the excess air factor (λ=1.62).

![Fig. 42. Effect of the relative change of compression starting temperature on fuel dose combustion angles](image)

![Fig. 43. Effect of the relative change of compression starting temperature on the maximum heat release rate and the angle of maximum heat release rate occurrence](image)

![Fig. 44. Effect of the relative change of compression starting temperature on heating efficiency and indicated efficiency, and on compression polytropic exponent](image)

![Fig. 45. Effect of the relative change of compression starting temperature on the calculated temperatures](image)
Change in the compression starting temperature from -3% to +3.5% causes little significant changes in the angle of 2, 10, 50, 90 and 100% fuel dose combustion within +0.1% to -0.1%; changes in the angle of the maximum heat release rate from approx. -0.05% to +0%; and heating efficiency in the range -0.04% to +0.4%. No effect on the determination of polytropic exponent and indicated efficiency is observed.

Change of compression starting temperature within the range -3% to +3.5% causes significant changes in the determination of fresh fuel zone and combustion zone temperatures (-3% to +3%).

9. Effect of the error of fuel composition determination

Figures 46+49 show the effect of the error of determination of the gas fuel composition on the basic thermodynamic parameters of the biogas engine running without knocking.

Fuel composition change in the range -11% to +9.5% causes little significant changes in the angle of 2, 10, 50, 90 and 100% fuel dose combustion in the range -0.08% to +0.05%;
changes in the angle of the maximum heat release rate in the range from approx. 0.5% to -0.5%, and changes in combustion-gas zone temperature in the range -0.08% to 0.07%.

Fuel composition changes in the range -11% to +9.5% cause significant changes in the determination of indicated efficiency and heating efficiency in the range -10.3% to 8.5%.

No effect of fuel composition on the other analyzed thermodynamic parameters of the engine is observed.

10. Effect of the error of fuel consumption determination

Figures 50-53 show the effect of the error of determination of gas fuel consumption on the basic thermodynamic parameters of the biogas engine running without knocking.

The error of fuel consumption determination in the range 10% to -5% causes little significant changes of: the angles of 2, 10, 50, 90 and 100% fuel dose combustion in the range 0.2% to -0.05%; combustion-gas zone temperature in the range 0.14% to -0.01%; charge zone temperature in the range 0.03% to -0.02%; and heat release rate in the range -1.0% to 0.5%.
The error of fuel consumption determination in the range 10% to −5% cause significant changes in the determination of indicated efficiency and heating efficiency in the range 10% to −4.5%.

No effect of gas consumption error determination on the other analyzed thermodynamic parameters of the engine is observed.

11. Effect of the error of air consumption determination

Figures 54–57 show the effect of the error of determination of air consumption on the basic thermodynamic parameters of the biogas engine running without knocking.

The error of air consumption determination in the range 10% to −4.5% causes little significant changes of: the angles of 2, 10, 50, 90 and 100% fuel dose combustion in the range −0.2% to −0.08%; combustion-gas zone temperature in the range −0.15% to 0.06%; charge zone temperature in the range −0.03% to 0.01%; heat release rate in the range 1.1% to −0.4%; and heating efficiency in the range 0.65% to −0.25%.

No effect of air consumption determination error on the other analyzed thermodynamic parameters of the engine is observed.
12. Error of the frequency of sampling of high voltage variation in the ignition system

Figure 58 illustrating the effect of the frequency of sampling of high voltage variation in the ignition system indicates that the time of spark discharge, depending on the type of ignition system, is lies the range 0.3 ±2ms, thus being smaller by 1 ±3 orders of magnitudes than the duration of the working cycle of a four-stroke engine (n=1000 min⁻¹) which is 30ms.

![Graph showing effect of frequency of sampling]

Fig. 58. Effect the frequency of spark discharge variation recording on the accuracy of spark discharge variation representation (the values given in the legend of the diagram correspond to recording frequency expressed as Δα [° c.r.])

Decreasing the sampling frequency of the high-voltage signal below 0.82MHz (which, at an engine rotational speed of 1000 min⁻¹, corresponds to approx. 0.007° c.r.) causes significant qualitative changes in the recorded signal. Simultaneous recording of pressure variation in the cylinder and high voltage variation in the ignition system with this density and their further numerical processing pose difficulties of technical nature.

13. Summary

The susceptibility of particular engine thermodynamic parameters, Yᵢ, to the preset errors of determination of different constant values, Xⱼ, was evaluated by introducing the "susceptibility" factor defined by the following equation:
where: \( X_j \) denotes the value of the independent variable and \( Y_i \) denotes the value of the dependent variable assumed as correct. These results are summarized in Table 1 below, in which: \( e \) – denotes the effect of compression ratio on the parameters examined, \( CH_4 \) – effect of fuel composition, \( V_g \) – effect of gas fuel consumption determination, \( V_p \) – effect of air consumption determination, \( t_c \) – effect of compression starting temperature, \( k_c \) – effect of transducer sensitivity, \( BIT \) – effect of A/C converter resolution, \( p_0 \) – effect of the reference pressure of the pressure pickup, \( ZZP \) – effect of IDC determination error, and \( f_p \) – effect of pressure sampling density on particular parameters.

**Table 1. Values of the degree of susceptibility of indication results on the errors of determination of different initial data.** White colour denotes no susceptibility \((k=0)\), grey colour – little effect \((0<|k|<1)\), and the strong (bold) grey colour denotes great effect \((|k|>1)\).

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**Note:**
- for a number of bits not less than 10; the effect of the number of bits was assessed by relating the changes to A/C converter resolution in % of the change of the newest bit (LSB) [5].
- for sampling angles not greater than 1° c.r.
14. Conclusions

- An analog-to-digital converter having a resolution not smaller than 10 bit and enabling sampling of the pressure signal with a step not smaller than 1° c.r. (crankshaft rotation) assures the sufficient accuracy of recording of the variation of pressure occurring in the cylinder of a spark ignition supercharged gas engine running without knocking.
- For the accurate recording of high voltage variations in the ignition system of an engine running with a rotational speed of 1000 min⁻¹, an A/C converter is necessary, which will sample the signal with a step of at least 0.007° c.r. corresponding to a sampling frequency of approx. 0.86MHz.
- Indicated work and charge exchange work are, to a significant degree, sensitive to the error of measuring system sensitivity (averagely at 1.1%/°) and to the error of IDC (Inner Dear Centre) determination (averagely at 3.4%/°).
- The maximum pressure is significantly sensitive only to the error of measuring system sensitivity (averagely at 1.1%/°).
- The maximum combustion pressure increment is significantly sensitive to the error of measuring system sensitivity (averagely at 1.1%/°) and to the error of sampling density (-2.9%/°).
- The maximum heat flux of heating the medium in the cylinder is significantly sensitive to the error of measuring system sensitivity (averagely at 1.2%/°), the error of IDC determination (-4.3%/°) and the error of sampling density (-1.4%/°).
- The angle of 100% fuel dose combustion is significantly sensitive to the error of IDC determination (2.2%/°).
- Heat input efficiency shows high sensitivity to the error of IDC determination (2.8%/°).
- Indication efficiency exhibits high sensitivity to the error of gas fuel consumption determination (1.1%/°), measuring line sensitivity (1.1%/°) and the error of IDC determination (3.4%/°).
- The maximum temperatures in the combustion zone and in the non-combusted charge zone show high sensitivity to the errors of IDC determination (-3±1.6%). Only the errors of fuel consumption determination and air consumption determination do not have so significant effect on the evaluation of these parameters.

15. References

1. Gruca M.: Program komputerowy LCT.