Tadeusz J. Rychter, Andrzej Teodorczyk

Institute of Heat Engineering
Warsaw University of Technology

VARIABLE COMPRESSION RATIO ENGINE
– VR/LE CONCEPT

The state-of-art knowledge about the progress in the investigations of the VR/LE concept of the variable compression ratio engine is introduced. The engine kinematics, thermodynamic analysis, research engine design and application of the concept to the turbocharged diesel engine are reviewed.

INTRODUCTION

There is still a need for a practical method which would enable the compression ratio to be continuously varied during engine operation, to best suit its actual speed and load. Many ways of varying the compression ratio have been proposed, but only a few solutions to this problem appeared to be of practical use [1]. The most practically developed system is the BICERI concept [2], where the position of the piston crown with respect to the piston pin can be changed automatically in response to the level of the cylinder pressure. They have found so far limited application because they still have not proved their abilities in a mass production and a long-term use. Moreover, this type of an automatic compression ratio adjustment does not allow the compression ratio to be adjusted from outside the engine and this decreases the regulation system flexibility.

An alternate solution, known as the VR/LE concept (variable crank radius/ connecting rod length engine) has been developed at the Institute of Heat Engineering of Warsaw University of Technology. The solution allows the compression ratio to be controlled from outside the engine, but at the expense of increased mechanical complexity. However, other advantages are obtained

because of the particular thermodynamic cycle that VR/LE engine can follow. In some cases this would counterbalance the disadvantages created by the mechanical complexity.

The difference between the VR/LE engine and a conventional one results from the different crank mechanism kinematics. This type of the mechanism was already proposed long time ago by several designers, but the purpose of its use was, in general, not the same.

1. ENGINE KINEMATICS

1.1. General principle

The VR/LE crank mechanism (Fig. 1) consists of the piston (1), the connecting rod (2), the crankshaft (3) and the eccentric sleeve (barrel) (4) placed between the crank pin (5) and the connecting rod big-end. The compression ratio adjustment, coupled with the change of some other geometrical parameters of the engine, is obtained by the angular shift α_0 of the eccentric with respect to the crank pin. The α_0 phase angle is always measured at the position of crank throw parallel to the cylinder axis (at its longest distance from the crankshaft axis). The α_0 phase angle can be adjusted within the range of 0-360°, and this can be performed independently of the continuous rotational motion of the eccentric (ω_α).

1.2. Geometric relationships

The piston motion (Fig. 2) is described by the following general equation:

$$x = \left\{ \left[\left(1 + \frac{1}{2} + \sigma \right)^2 - \zeta^2 \right]^{\frac{1}{2}} \right\} +$$

$$-\frac{1}{\lambda} \sqrt{1 - \lambda^2 \left[\sin \Phi + \sigma \sin(\alpha_t + \Phi) - \zeta \right]^2} +$$

$$- \left[\cos \Phi + \sigma \cos(\alpha_t + \Phi) \right]$$

where: x — piston displacement from top dead centre (TDC), Φ — crank angle and λ, σ and ζ are the following dimensionless parameters:

$$\lambda = \frac{r}{L} \qquad \sigma = \frac{e}{r} \qquad \zeta = \frac{m}{r}$$

For zero cylinder axis offset ($m = 0$), equation (1) can be simplified as follows:

$$x = r\left\{\frac{1}{\lambda} - \sqrt{\frac{1}{\lambda^2} - \left[\sin\Phi + \sigma\sin(\alpha_t + \Phi)\right]^2} + \sigma\left[1 - \cos(\alpha_t + \Phi)\right] - \cos\Phi + 1\right\}$$

The actual eccentric angular displacement (α_t) is the sum of two angles:

$$\alpha_t = \alpha_0 + \alpha$$

where the angle α results from the turning motion of the eccentric with respect to the crank pin, with the angular velocity ω_α.
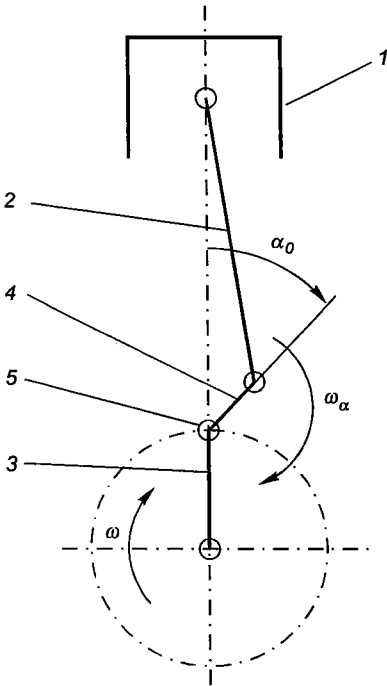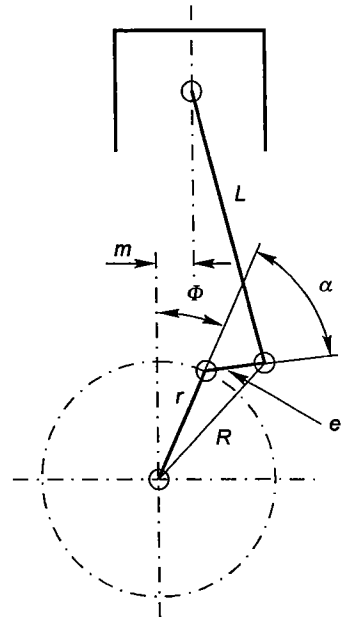

Fig. 1. VR/LE engine crank mechanism

Fig. 2. VR/LE engine general kinematics

1.3. Eccentric rotational speed

The three eccentric rotational speeds can be considered:

Case I: $\omega_\alpha = 0$, hence $\alpha = 0$, $\alpha_t = \alpha_0$

This is a trivial case, where the eccentric does not rotate, and the compression ratio can be adjusted in the way of changing the α_0 phase angle. Since in this case the eccentric does not rotate with respect to the crank pin except in the course of α_0 adjusting the application of this solution is not feasible because of the obvious lubrication and wear problems.

<u>Case II</u>: $\omega_\alpha = \pm 1/2\,\omega$

In this case eccentric rotates with respect to the crank pin with the angular velocity which is half of that of crankshaft. The signs plus and minus determine the eccentric rotation sense. The eccentric rotational motion causes the continuous change of the actual (instantaneous) crank radius being one of the basic geometrical engine parameters. This results in changing the TDC piston position and also — the length of every stroke of the piston. This implies that there will be differences in the engine thermodynamic cycles for various α_0 phase angle adjustments. This is illustrated in Fig. 3. The Case II seems to be the most interesting one and the greatest part of the research has been devoted to it.

<u>Case III</u>: $\omega_\alpha = \pm\,\omega$

This is the case where the eccentric rotates with respect to the crank pin with the angular velocity which is equal to that of the crankshaft. This case, although could be considered practical in application to slow running engines, at the high speed engines creates serious problems with designing the eccentric driving mechanism.

The extensive analysis of the VR/LE engine geometry for all three cases has been presented elsewhere [3].

2. THERMODYNAMIC STUDY

2.1. Standard air cycle analysis

The regulational parameter in the VR/LE engine is the α_0 phase angle which determines the eccentric axis position relative to the crank radius, and it is measured at the crank angle $\Phi = 0°$. The change of the α_0 brings about the compression ratio change along with the change of the displacement volume (Fig. 3). At the eccentric angular velocity equal to the half of the crankshaft angular velocity ($\omega_\alpha = \pm 1/2\,\omega$) the α_0 change results in a different length of each piston stroke within the cycle, continuously changing the engine cycle.

The fundamental thermodynamic analysis of the VR/LE engine cycle was performed [5]. The VR/LE engine theoretical cycle, supplemented by the charge exchange line, is introduced in Fig. 4. The variability of two parameters, the expansion extension ratio $\xi = V_5/V_1$ and the volumetric residual gas fraction $\beta = V_6/V_1$, cause the VR/LE engine cycles to differ from those of the conventional engine. The variability of these parameters as a function

of the compression ratio (defined as usual $\varepsilon = V_1/V_2$) is presented in Fig. 5 and 6 for the proportions of a small SI engine. The compression ratio values correspond to the respective values of α_0 phase angle. It has to be remembered, however, that in the VR/LE engine all the changes of the ε compression ratio are kinematically associated with the changes of other engine geometrical parameters.
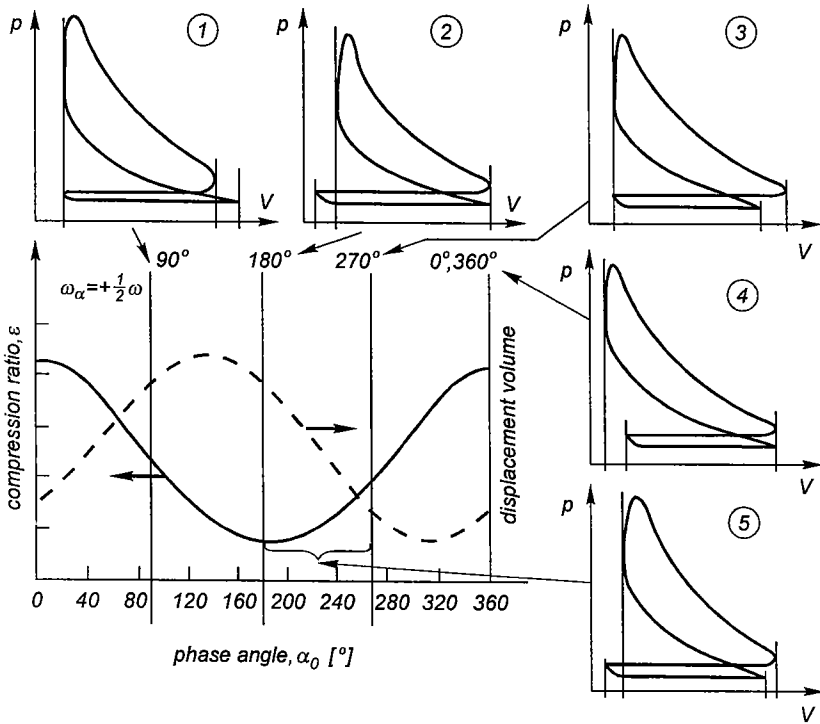

Fig. 3. Dependence of the compression ratio and the displacement volume on the α_0 phase angle (an example). The changes in engine cycle are also shown

The values of ξ, each of them for a different α_0 angle, correspond to different ε values. For $\xi > 1$ the expansion process is extended (Fig. 4a) and for $\xi < 1$ it is shortened (Fig. 4b). Also two β values correspond to the single ε value, but each of them is attained at a different α_0 angle. It is noticeable that the β values increase along with an increase of ε, which is in contrast to the conventional engine behaviour, where $\beta = 1/\varepsilon$ and therefore β decreases with ε increase. The difference in the ξ values between the VR/LE and the conventional engines affects the cycle thermal efficiency. The difference between β values has a remarkable influence on the total work of the cycle.
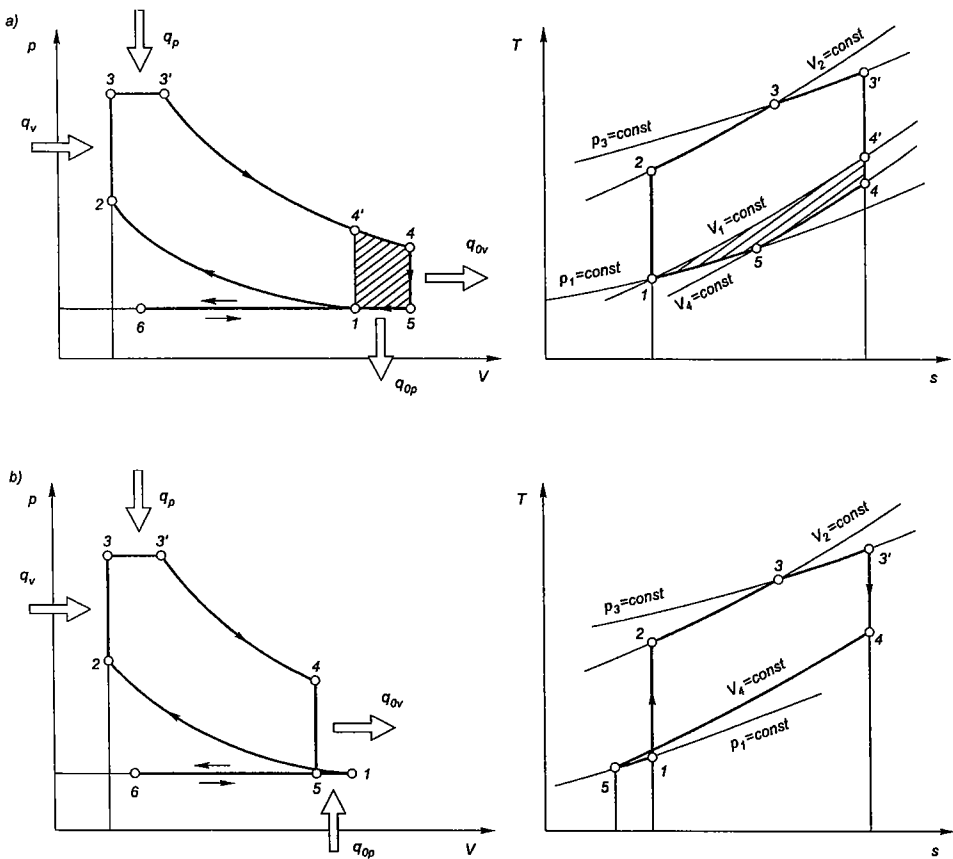
Fig. 4. Theoretical cycle of the VR/LE engine: a) — extended expansion, b) — shortened expansion
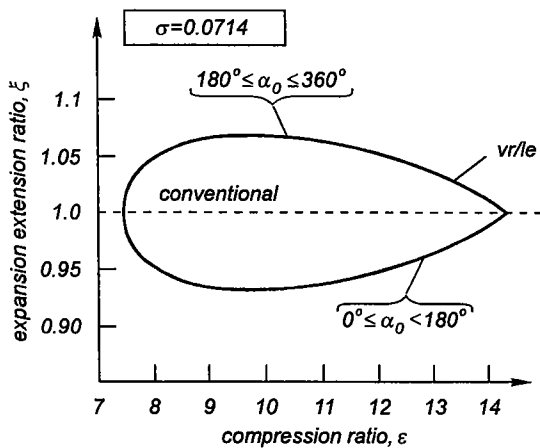

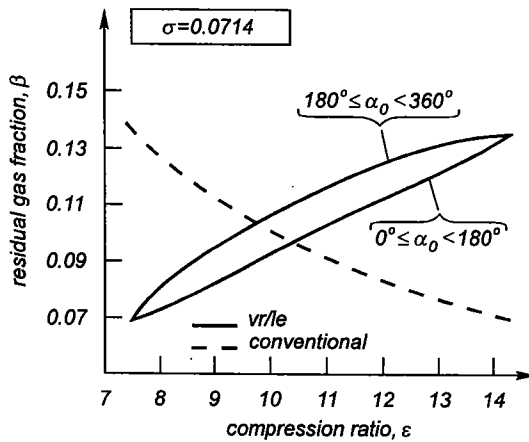Fig. 5. Dependence of the expansion extension ratio on compression ratio

Fig. 6. Dependence of the volumetric residual gas fraction on compression ratio

2.2. Cycle efficiency

By introducing definitions of a degree of isochoric pressure rise $\alpha = p_3/p_2$ and of a degree of isobaric volume rise $\varphi = V'_3/V_3$, relating the temperatures of each cycle point to the T_1 temperature and then simplifying, the following expression can be obtained for the theoretical efficiency of the dual cycle with extended ($\xi \geq 1$) expansion:

$$\eta_t = 1 - \frac{\xi(\alpha \varphi^k \xi^{-k} + k - 1) - k}{\varepsilon^{k-1}[k\alpha(\varphi - 1) + \alpha - 1]}$$

where k is the isentropic exponent. For the Otto cycle $\varphi = 1$ and for the Diesel cycle $\alpha = 1$.

2.3. Cycle work

The specific work of the cycle is:

$$l = \eta_t q$$

where q is the amount of energy delivered in the gaseous mixture into the cylinder. The general expression for the work of the extended expansion cycle has the form:

$$l = \frac{RT_1}{k-1} \left\{ \varepsilon^{k-1}[k\alpha(\varphi - 1) + \alpha - 1] - [\xi(\alpha \varphi^k \xi^{-k} + k - 1) - k] \right\}$$

The total work of the cycle comes out from the product of the specific work and the mole number of the fresh charge. The amount of the fresh charge can be, in turn, expressed as a function of both the parameters at the beginning of the compression and the residual gas fraction β:

$$L = l \, \frac{p_1 V_1}{RT_1} \, (1 - \beta)$$

For the conventional engine the β value depends only on the compression ratio, that is:

$$\beta = \frac{1}{\varepsilon}$$

In the engines with differentiated stroke lengths the β value changes and its magnitude results from the engine crank mechanism kinematics.

2.4. Thermodynamic analysis of VR/LE engine cycles

The thermodynamic evaluation of the cycles has been carried out for the case of $\omega_\alpha = +1/2\,\omega$, for the $\sigma = 0.0714$ and $\sigma = 0.045$ for the Otto or Diesel and dual cycles, respectively [5]. The ε ranges for both cycle groups has also been made different by the assumption of different ε_{min} values, that is the ε values at $\alpha_0 = 180°$.
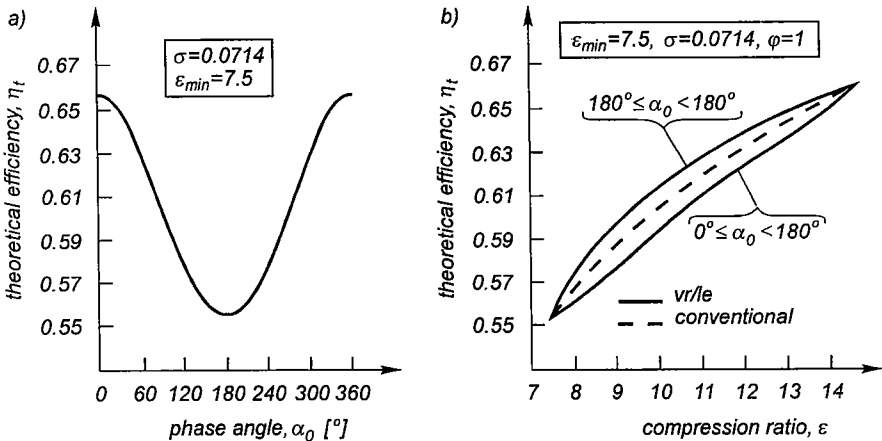

Fig. 7. Dependence of η_t on geometrical parameters of the VR/LE engine: a) on α_0 phase angle; b) on ε compression ratio

The $\eta_t = f(\alpha_0)$ profile is introduced in Fig. 7a; significant η_t changes result from the ε variations and from the different (at any α_0 angle) thermodynamic cycle of the engine.

The dependence of the theoretical efficiency on the ε compression ratio is introduced in Fig. 7b. The extension of the expansion process causes that the VR/LE-Otto engine cycle efficiency is greater than that of the conventional Otto cycle within the α_0 range $180° < \alpha_0 < 360°$ and it is lower when $0° < \alpha_0 < 180°$.

The dependence of the total cycle work of the VR/LE engine on the compression ratio is presented in Fig. 8 (solid line), where the cycle work, calculated with β as for a conventional engine, is represented by the dashed line.
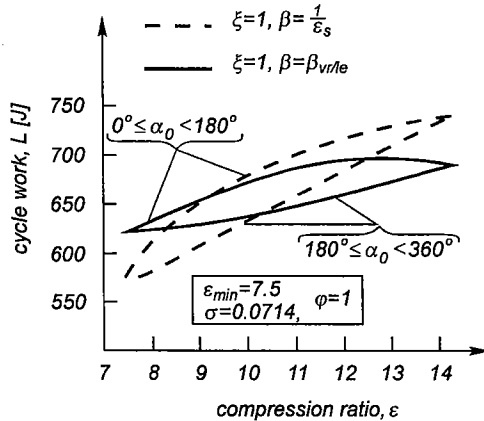

Fig. 8. Dependence of the L-cycle work on ε; the comparison with a conventional engine

3. ENGINE DESIGN

The small, 650 cu. cm displacement volume, two-cylinder car engine was used as a base engine and only one of the cylinders was utilised. It has been the engine still produced and used in cars. The main reason to apply the VR/LE concept to SI car engines is to gain the engine efficiency at partial loads by increasing the compression ratio up to that limited by the occurrence of the knock.

3.1. Crank mechanism

The basic engine dimensions are introduced in Table 1. The case where the eccentric rotates with respect to the crank pin with the rotational speed being half of that of the crankshaft was accepted. Moreover, the eccentric rotates in the opposite direction than the crankshaft does. Therefore, $\omega_\alpha = -1/2\,\omega$.

Table 1

Cylinder bore [m]	0.0770
Crank radius [m]	0.0353
Connecting-rod length [m]	0.1275
Eccentric size [m]	0.0024
Relative eccentric size $\sigma = \dfrac{e}{r}$	0.0684
Minimum compression ratio ε_{min}	6.13
Maximum compression ratio ε_{max}	9.61

The schematic of the eccentric drive mechanism used is presented in Fig. 9. The mechanism consists of two pairs of gears 2, 3 and 4 are half of the size of the eccentric gear 1. The gear 4 is coaxial with the crankshaft and it is fixed to the shaft which goes out of the engine. Since the gear ratio, defined as $i = r_m / r_c$ is equal to 2, the central gear does not rotate and it changes its angular position only to adjust the compression ratio by changing the phase angle.
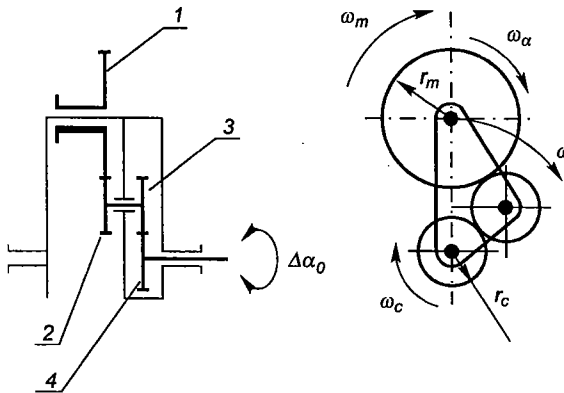

Fig. 9. Sketch of the eccentric drive mechanism

The dependence of the compression ratio upon the α_0 phase angle is introduced in Fig.10. It is important to notice that every value of the compression ratio corresponds to two different settings of the phase angle: one within the range of $0° < \alpha_0 < 180°$ and the second one in $180° < \alpha_0 < 360°$.

The change of the compression ratio brings about the simultaneous changes of the lengths of all the piston strokes (Fig.11). It is interesting that the induction stroke tends to decrease along with the increasing compression ratio. The engine displacement volume becomes therefore smaller at higher compression ratios which are supposed to be set at partial loads of the engine. This tendency is also advantageous.
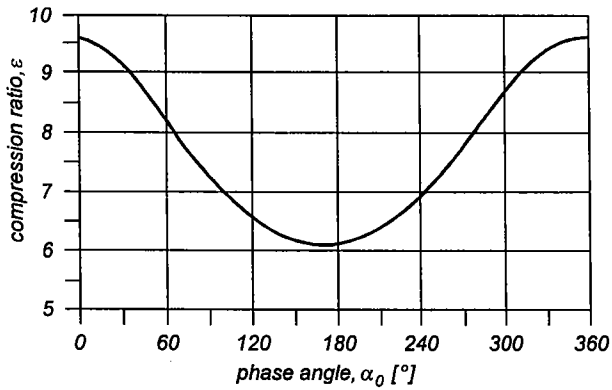
Fig. 10. Dependence of the compression ratio on the α_0 phase angle
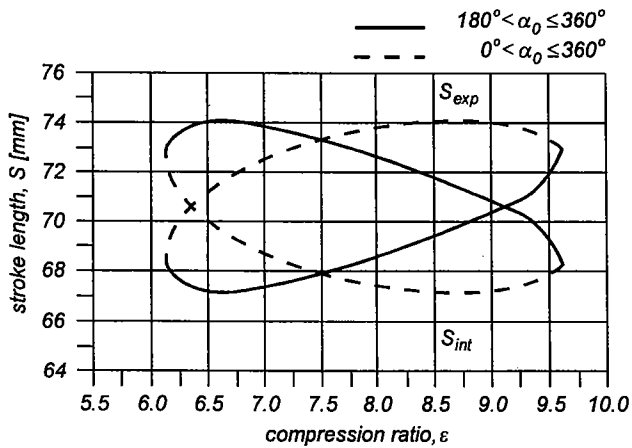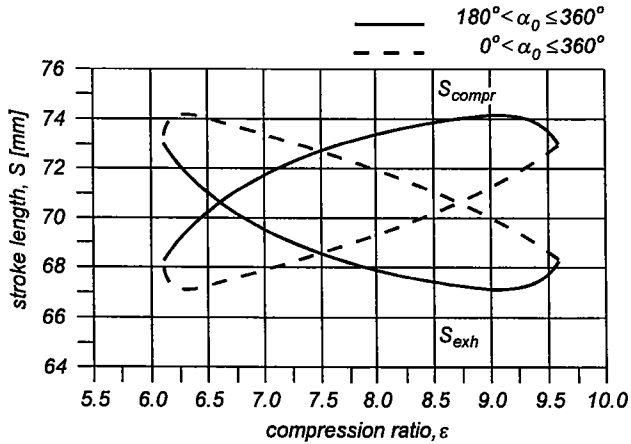

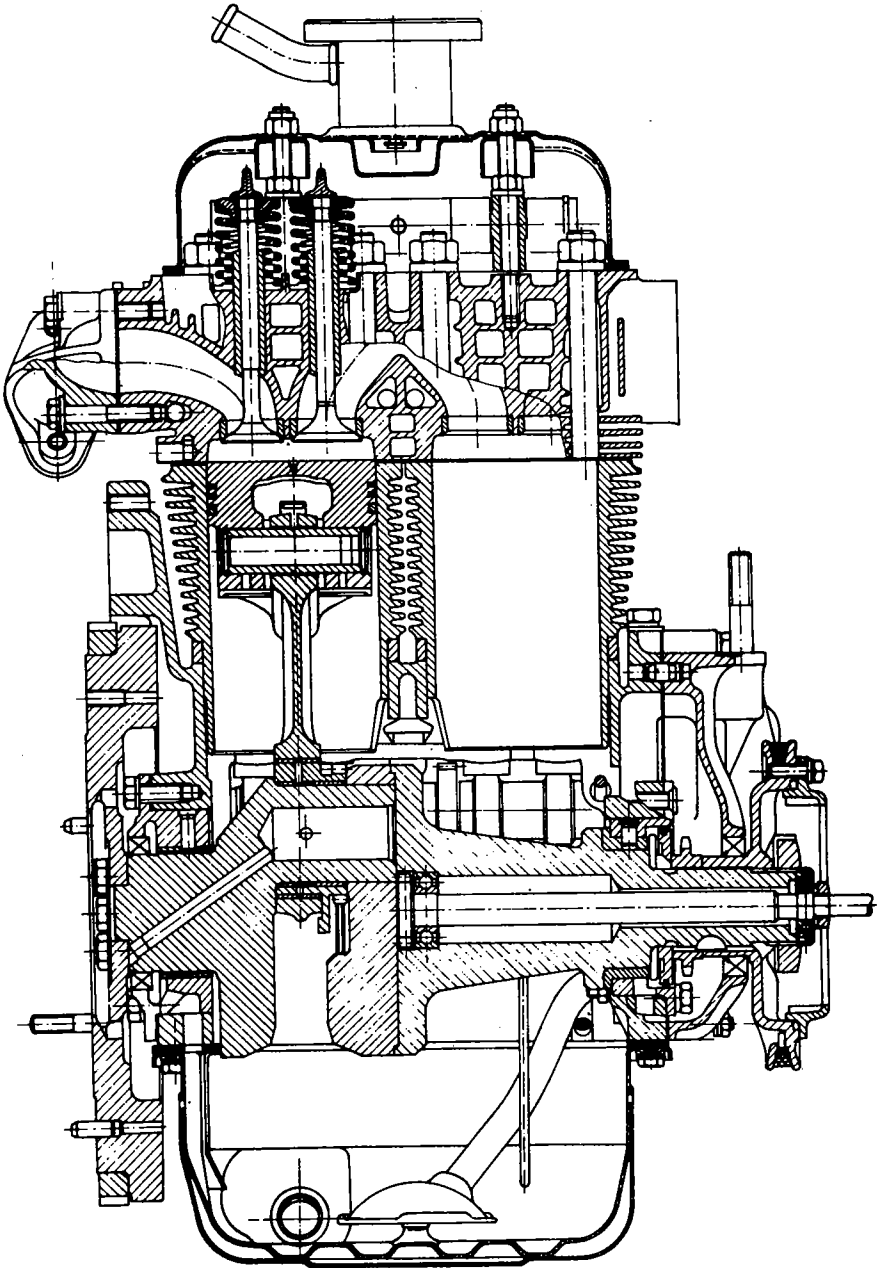Fig. 11. Dependence of the lengths of the individual strokes on compression ratio
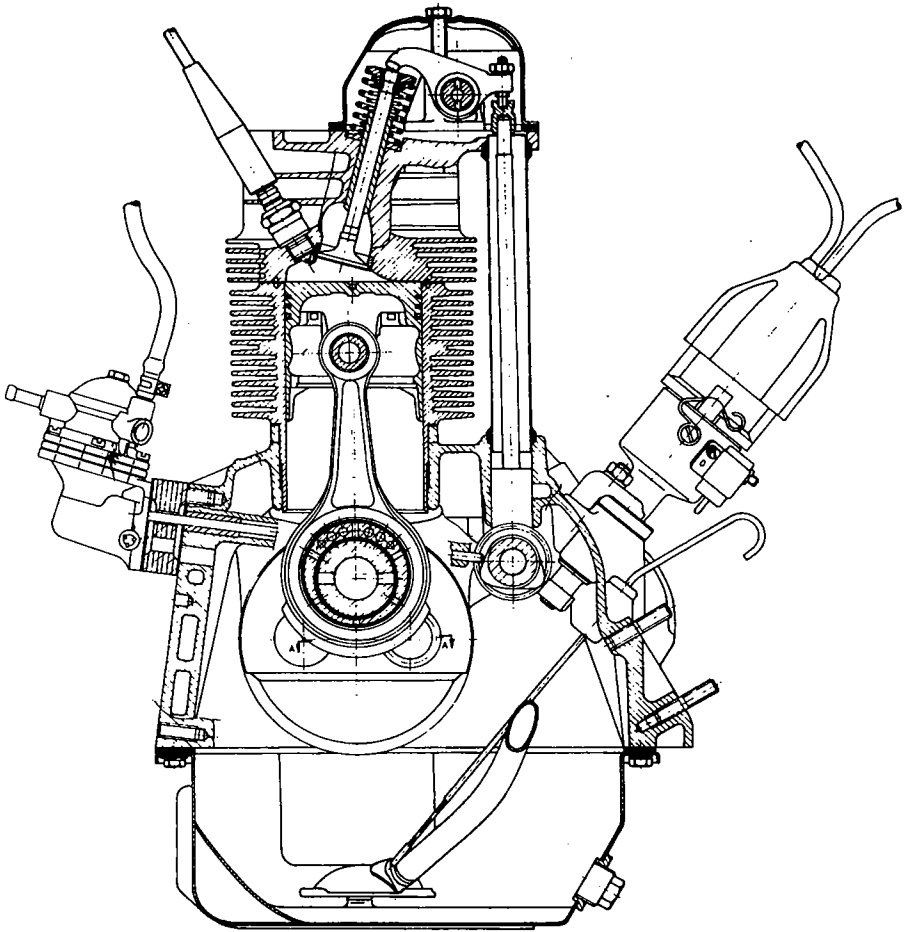
Fig. 12. Longitudinal section of the VR/LE engine

Fig. 13. VR/LE engine cross-section

3.2. Engine construction

The engine cross-sections are presented in Figs. 12 and 13. The single-cylinder crankshaft consists of three parts. Two of them are assembled together by pressing.

The hand-operated regulational mechanism is mounted on the front end of the crankshaft. It has allowed for the phase angle adjustment from outside of the engine during the engine operation. The appropriate lubrication system has been constructed.

The original wedge type combustion chamber has been used. It had to be lowered to increase the maximum compression ratio.

The engine was designed as the research engine and constructed for the investigations on a test rig only. The preliminary tests were assumed to be run at a constant engine speed. It made it possible to use the original carburetor which had been basically designed for the two-cylinder engine.

3.3. Preliminary investigations

The measured pressure-volume diagrams for four most characteristic phase angles are shown in Figs. 14 and 15. They illustrate the character of the changes of the engine cycle which take place at each different compression ratio.

The case presented in Fig. 16 is the most general one and it is typical for all the other α_0 values than presented in Figs.14 and 15. Here the length of each single stroke is different from any others and the relations among them are changing along with the phase angle adjustment.
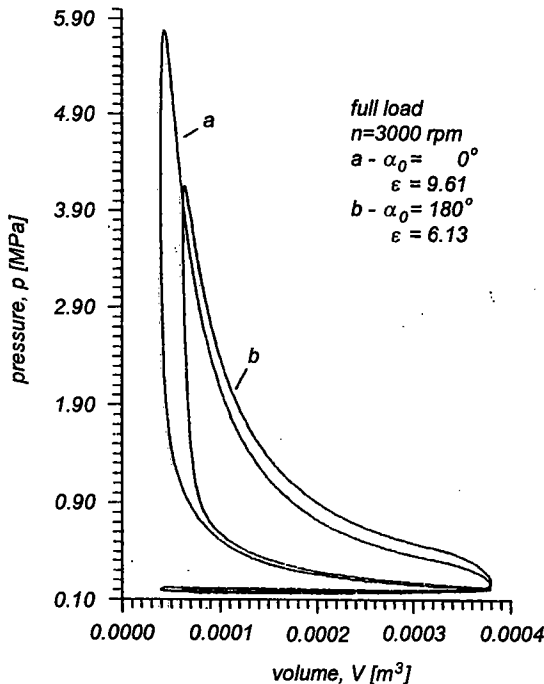

Fig. 14. Comparison of the p–V diagrams for the ε_{min} and ε_{max}
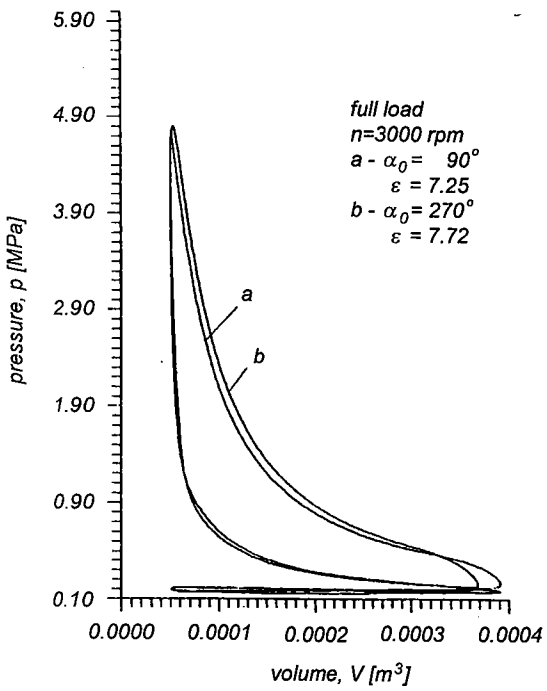
full load
n=3000 rpm
a - $\alpha_0 = 90°$
  $\varepsilon = 7.25$
b - $\alpha_0 = 270°$
  $\varepsilon = 7.72$

Fig. 15. Comparison of the $p-V$ diagrams for the ε_{90} and ε_{270}

full load
n=3000 rpm
$\alpha_0 = 270°$
$\varepsilon = 6.92$

exhaust

intake

compression

expansion
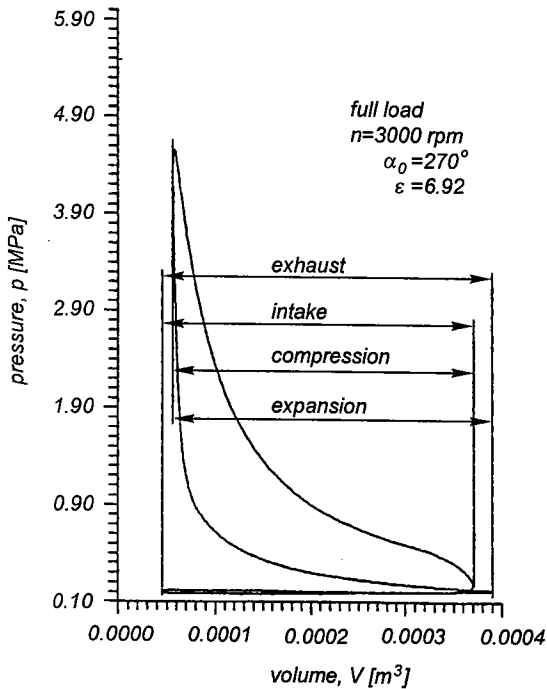
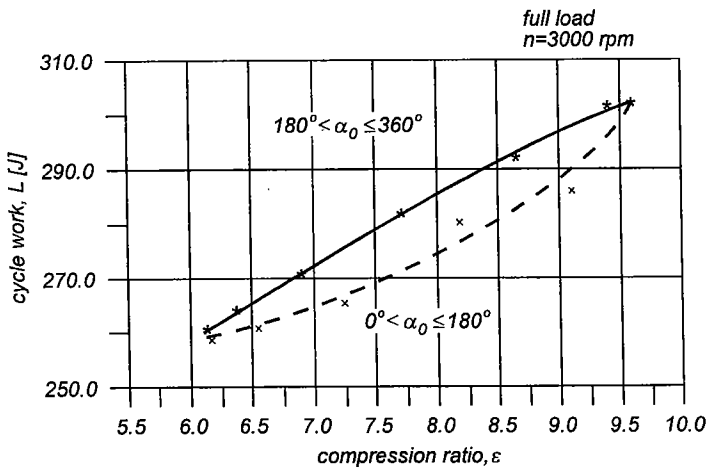Fig. 16. $p-V$ diagram for the $\varepsilon = 6.92$
($\alpha_0 = 240°$)

Fig. 17. Dependence of the work of the engine cycle on the ε

The work of the cycle as a function of compression ratio is shown in Fig. 17. The dependence of the cycle thermal efficiency on the compression ratio is presented in Fig. 18. The efficiency has been defined as the cycle work divided by the energy delivered with the fuel. The predicted by theory efficiency improvement at increased compression ratios is confirmed and it also gives the proof that the change of the cycle does not affect this tendency significantly. The slightly higher efficiency is obtained within the range $0° < \alpha_0 < 180°$.
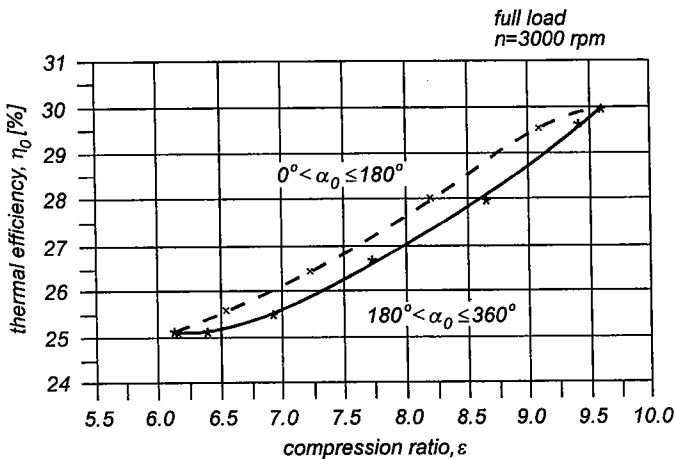

Fig. 18. Dependence of the thermal efficiency on the ε

The nitric oxide concentration in the exhaust gases was measured with the use of the chemiluminescent Beckman analyzer. The NO concentration at various compression ratios is presented in Fig. 19.
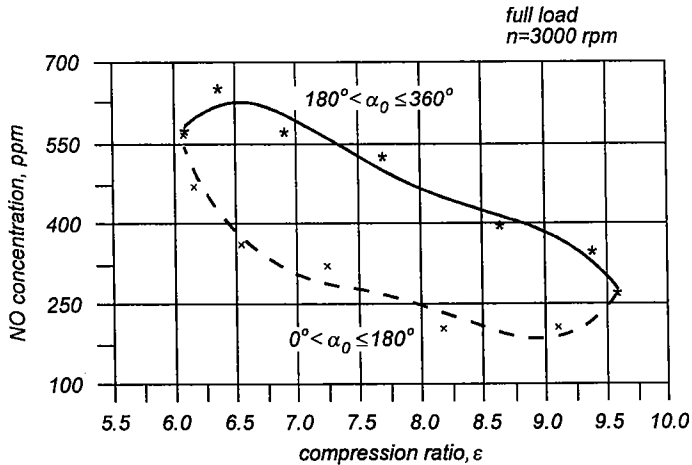

Fig. 19. Dependence of the NO concentration on the ε

More results and detailed discussion are presented in Ref. [6].

4. VR/LE FOR TURBOCHARGED DIESEL ENGINE

A variable compression ratio concept that can give different expansion ratio and the compression ratio has been evaluated by means of a simulation of a turbocharged diesel engine [7]. The inherent cost and complexity of diesel engines may be better suited to accommodating the VR/LE concept.

Table 2

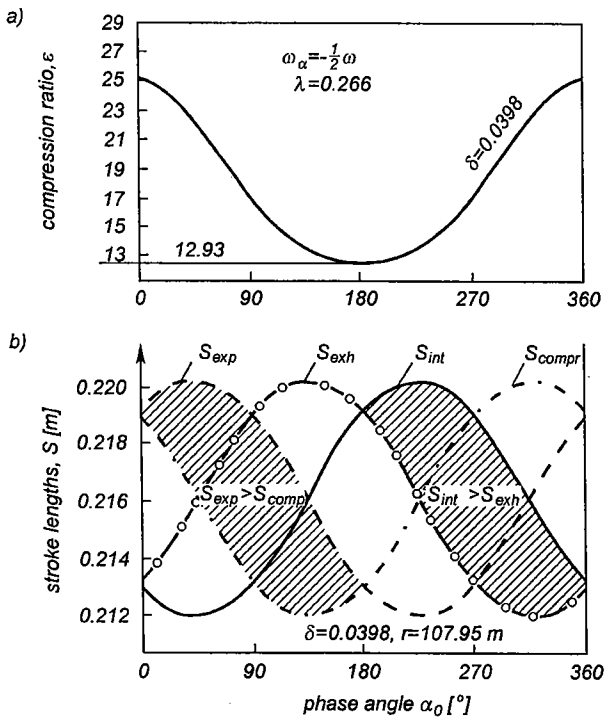| Bore	d	196.85 mm
Crank radius	R	107.95 mm
Connecting-rod length	L	406.40 mm
Eccentric size	c	4.30 mm
Relative eccentric size	σ	0.0398
Minimum compression ratio	ε_{min}	12.93
Maximum compression ratio	ε_{max}	25.20

Fig. 20. Dependence of (a) the compression ratio and (b) the stroke lengths upon the phase angle

The major engine dimensions are given in Table 2. Figure 20a illustrates the dependence of the compression ratio upon the phase angle. The assumed engine dimensions allow for the range of available compression ratios to be from 12.93 up to 25.20. Figure 20b presents the variations of the consecutive piston strokes along with α_0 changes. The different lengths of particular strokes during a single engine cycle causes qualitative modifications to the thermodynamic cycle of the engine. The thermodynamic analysis of the VR/LE engine cycle [6] has shown that within the range of α_0 angles, where the expansion stroke is extended with respect to the compression stroke, the cycle is similar to a turbocharged engine cycle. The difference is that in the VR/LE engine extraction of the „additional" energy from the exhaust gases is done directly inside the cylinder.

4.1. Mathematical model

The mathematical model used in the study describes the variation of the thermodynamic state of an engine system during the steady-state operation. The model makes use of the concept of thermodynamic control volume [8]. The equations that determine the behaviour of the system are derived from the

principles of mass and energy conservation for the thermodynamic control volume, and momentum conservation for the crank shaft and turbocharger rotor. The application of each conservation principle leads to a first-order ordinary differential equation (ODE). The complete set consists of 31 coupled ODEs.

4.2. Simulation results

The engine was modelled with the standard valve timing, for the whole range of the available compression ratios and fixed engine fuelling levels to give 25,
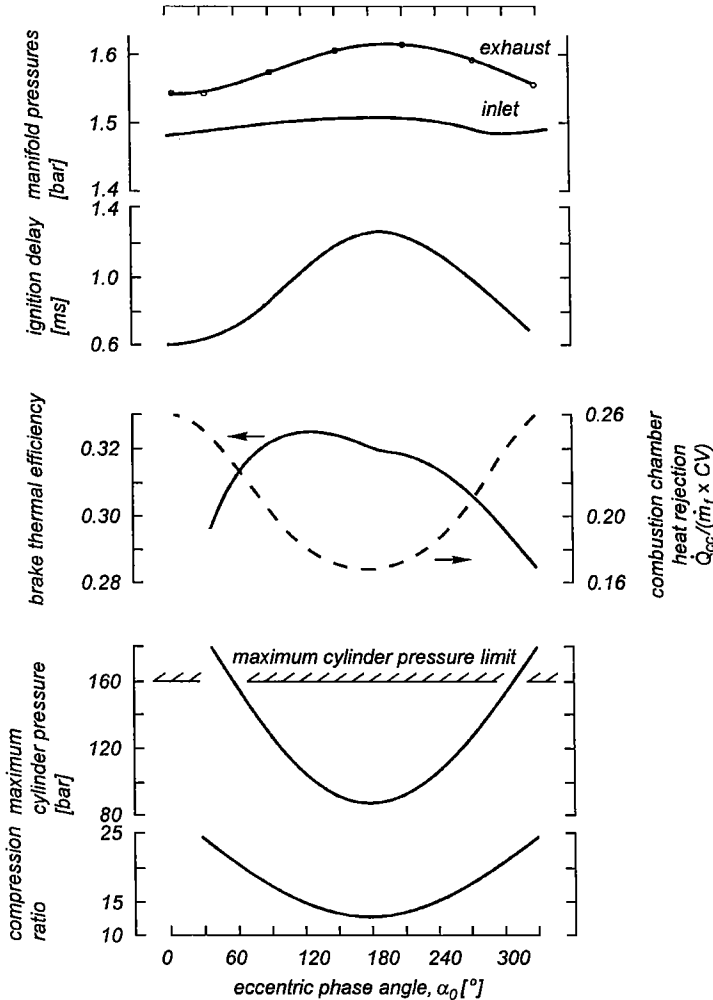

Fig. 21. Dependence of the gross performance parameters (compression ratio, maximum cylinder pressure, brake thermal efficiency, heat rejection from combustion chamber, ignition delay and manifold pressure) on the eccentric phase angle α_0 for the fuelling level corresponding to 50 per cent load in the standard engine

50, 75 and 100 per cent of maximum power. The objective of this study was to demonstrate how the VR/LE engine kinematics can affect the selected engine parameters: cylinder pressure and temperature, heat-release rate, heat flux to the walls, etc.

The way in which the phase angle affects the global performance parameters is shown in Fig. 21. When $\alpha_0 = 180°$ the compression and expansion ratios are the same as those of the standard engine. The fuelling level that gave 50 per cent of the maximum power with the standard engine was considered.

Firstly, as the compression ratio is increased, the peak pressure increases. For this engine a maximum cylinder pressure of 160 bar was imposed, so this limits the maximum compression ratio to just under 22 at 50 per cent fuelling.

Secondly, when the compression ratio is increased by decreasing the phase angle, there is an increase in the brake efficiency. Thirdly, Fig. 21 shows that raising the compression ratio leads to a reduction in ignition delay.

Finally, Fig. 21 shows that changing the compression and expansion ratios has only a slight effect on the turbocharger performance.

Similar results occur at other fuelling levels, except that above 75 per cent load, the limitation on the maximum cylinder pressure prevents the optimum compression ratio being attained.
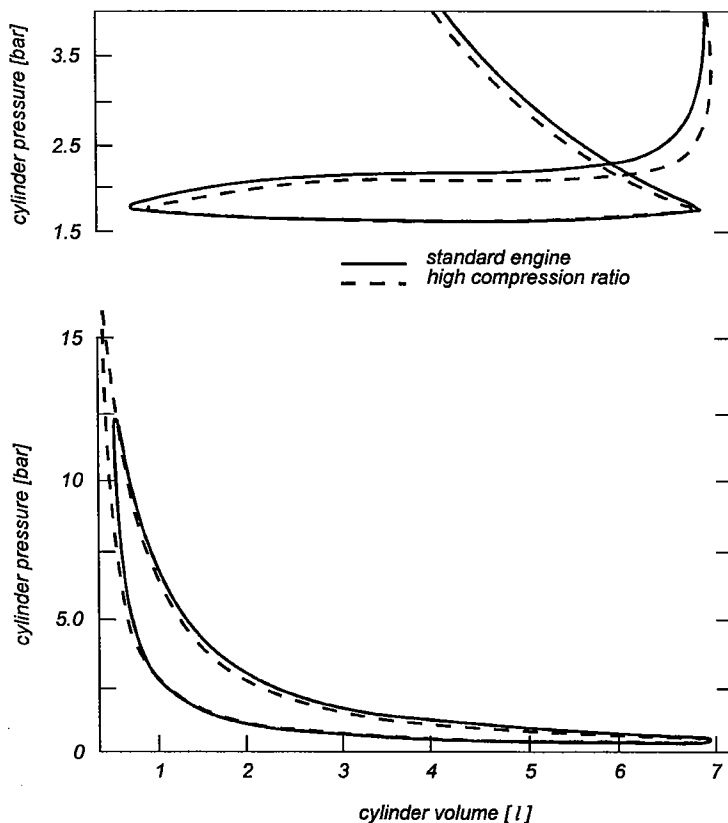

Fig. 22. A comparison of the cylinder pressure for the standard and VR/LE concept engine at a fuelling level of 75 per cent; the inset shows the pumping loop

The cylinder pressure diagram in Fig. 22 shows how the higher compression ratio (16.8) leads to a higher maximum cylinder pressure. The gas temperature in Fig. 23 is calculated on the basis of a single combustion zone. There is only a slight increase in the maximum temperature with the higher compression ratio, since there is a significant increase in heat transfer.

The simulation of the VR/LE concept applied to a highly turbocharged medium-speed diesel engine has shown that:

1. Above the 75 per cent load level the maximum cylinder pressure limits the compression to a lower-than-optimum-level.
2. Below the 75 per cent load level, the optimum compression ratio has been found to be lower than the compression ratio that would lead to the maximum cylinder pressure.
3. At the fuelling level that gave 75 per cent load in the standard engine (compression ratio of 12.9), it was found that a compression ratio of 16.8 caused:
   (a) about a 2 per cent reduction in fuel consumption,
   (b) a 0.35 ms reduction in ignition delay,
   (c) a predicted 6 dB reduction in combustion noise.
4. The computations of the in-cylinder conditions have shown that there are negligible changes in the peak gas temperature, but the higher in-cylinder pressures lead to increased heat transfer.

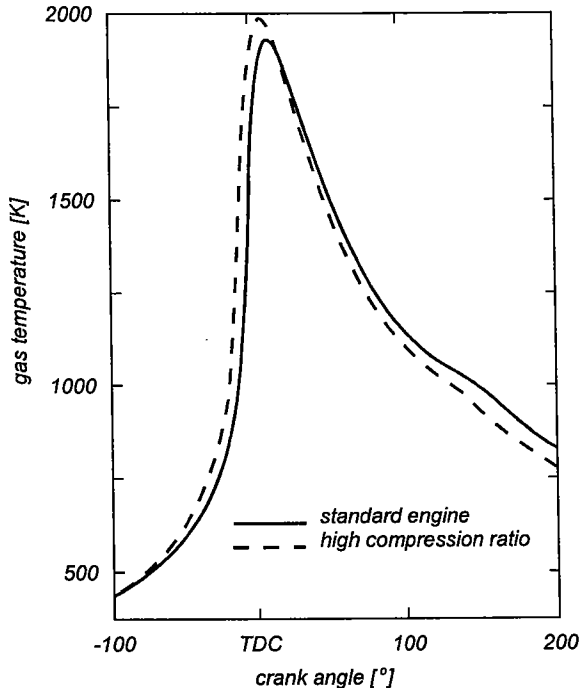The word „optimum" used has been related to the best engine efficiency.

Fig. 23. A comparison of the in-cylinder gas temperature for the standard and VR/LE concept engine at a fuelling level of 75 per cent

CONCLUSION

The engine has been proposed, called VR/LE, with unusual crank mechanism with continuous change of the ratio of the crank radius to the connecting-rod length. The relatively simple mechanism with no reciprocating parts makes it possible to adjust instantaneously and continuously the compression ratio within the range of values. The mechanism allows to achieve the required changes of fundamental geometrical engine parameters: compression ratio and displacement volume by appropriate selection of the mechanism kinematics and the range of the regulation of the phase angle.

The mechanism is versatile and it can be used for the engines irrespectively of their size and operational principle. The mechanism makes it also possible to change the engine cycle continuously and it shows the features advantageous for the improvement of the engine thermal efficiency.

The design of the research engine and its preliminary investigations have shown that there are not any serious design problems with the application of the VR/LE concept. The feasibility of constructing the real variable compression ratio engine according to the VR/LE principle has been proved. The results of the preliminary investigations confirmed the advantages of that concept.

The mechanism is able to differentiate the length of individual piston strokes during a single cycle which opens a new prospects for designers. The thermodynamical analysis of the theoretical cycle of an internal combustion piston engine, having different individual stroke lengths during a single cycle has been performed. The efficiency and work expressions for the cycle have been derived and used to compare the cycle to that of a conventional engine.

A variable compression ratio concept has also been evaluated by means of the simulation of a turbocharged diesel engine. The effect of compression ratio on the engine performance at fixed loads was presented. The principal benefits are a reduction in fuel consumption at part load and a reduction in ignition delay.

REFERENCES

[1] Ladommatos N., Balian R.A.: Combustion in a direct injection diesel engine with increased clearance volume. *Proc.Inst.Mech.Engrs*, Part D, 1990, 204(D3), pp.187-197.

[2] Mansfield W.P., Tryhorn D.W. and Thornycroft C.H.: Development of the turbocharged diesel engine to high mean effective pressures without mechanical and thermal loading. *CIMAC Conference*, Paper A6, 1965, pp.1-18.

[3] Rychter T.J., Teodorczyk A.: VR/LE Engine with a Variable R/L during a Single Cycle. *SAE Transactions*, Paper No. 850206, 1985, pp.2105-2123.

[4] Rychter T.J., Teodorczyk A., Bruno Bossio R. and Naso V.: Thermodynamic Analysis of a Variable-Cycle IC Piston Engine. *SAE*, Paper No. 859297, 1985.

[5] Rychter T.J., Teodorczyk A.: Economy and NO Emission Potential of a Variable R/L Engine, *SAE Transactions*, Paper No.850207, 1985, pp.2124-2137.

[6] Wardzyński W.F., Rychter T.J.: Variable R/L Research Engine — Design and Preliminary Investigations *SAE Transactions*, Paper No. 911773, 1991.

[7] Rychter T.J., Teodorczyk A., Stone C.R., Leonard H.J., Ladommatos N. and Charlton S.J.: A theoretical study of a variable compression ratio turbocharged diesel engine. *Proc.Inst. Mech.Engrs.* Vol.206, Part A: Journal of Power and Energy, 1992, pp.227-238.

[8] Charlton S.J.: Simulation program for internal combustion engines. *User Manual*, University of Bath, 1986.

SILNIK O ZMIENNYM STOPNIU SPRĘŻANIA – KONCEPCJA VR/LE

Streszczenie

W artykule przedstawiono wybrane, najistotniejsze wątki badań nad nową, zaproponowaną w Instytucie Techniki Cieplnej, metodą ciągłej, bieżącej regulacji stopnia sprężania w spalinowych silnikach tłokowych. Omówiono zasadę działania, zależności kinematyczne zmodyfikowanego mechanizmu korbowego oraz wyniki termodynamicznej analizy teoretycznego porównawczego obiegu takiego silnika. Realność koncepcji poparto wynikami badań jednocylindrowego silnika badawczego zbudowanego wg tej koncepcji. Przedstawiono również wyniki symulacji numerycznej metody VR/LE w zastosowaniu do turboładowanego silnika o zapłonie samoczynnym. Podsumowanie podkreśla oryginalność koncepcji oraz uwidocznia jej zalety i ograniczenia

ДВИГАТЕЛЬ С ИЗМЕНЧИВОЙ СТЕПЕНЬЮ СЖАТИЯ – КОНЦЕПЦИЯ VR/LE

Краткое содержание

В статье представлены избранные, наиболее существенные вопросы, связанные с исследованием предложенного в Институте теплотехники метода постоянного очередного регулирования степени сжатия в поршневых двигателях внутреннего сгорания. Обсуждены правила работы, кинематические зависимости модифицированного кривошипного механизма, а также результаты термодинамического анализа теоретического и идеального цикла такого двигателя. Реальность концепции подтвердили результаты испытаний одноцилиндрового двигателя, построенного согласно вышеуказанной концепции. Представлены также результаты числового моделирования метода VR/LE применительно к турбокомпрессорному двигателю с самовоспламенением. В резюме подчеркнута оригинальность концепции, описаны ее положительные стороны и ограничения.