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THE WORKING CYCLE OF THE MOTORING INTERNAL COMBUSTION ENGINE BY A NEW METHOD WITH CYLINDER PRESSURES AS IN REAL ENGINE OPERATION

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Abstract: The current standard methods of determining the mechanical losses of the ICE by motoring do not correspond to the low pressures in the cylinders of real engine operation. The new tried and tested method of determining passive resistances by motoring ICE with high working pressures in the cylinders is based on blowing doses of compressed air into the cylinders around BDC with special self-acting valves. When motoring with the new method, the same course of pressures in the cylinders and the same load on the crank mechanism, including the piston group, is achieved during combustion. The measurement proved the problem-free functionality of the self-acting valves, and the conducted experiments provided data on the dependence of mechanical and heat losses in the ICE on the working pressures in the cylinder.

KEYWORDS: internal combustion engine (ICE), motoring without combustion, mechanical losses, thermodynamic analysis, experiment

1 Introduction

Currently, in the development of ICE, there is an increasingly urgent need, from the point of view of the need to reduce exhaust emissions to increase the engine's overall efficiency. The overall engine efficiency is the result of thermal efficiency and mechanical efficiency. If we want to increase the engine's mechanical efficiency, it is necessary to reduce the mechanical losses of the engine. These mechanical engine losses need to be analyzed correctly. It is very often used in determining the effects of various measures on individual functional groups of the engine leading to the reduction of ICE mechanical losses, measuring passive resistances by motoring the ICE on an engine test bench with a dynamometer. The main shortcoming of the current method of measuring the mechanical losses of the engine by motoring is the large difference between the pressures in the cylinders during the motoring of the engine without combustion and the pressures in the cylinders during the standard operation of the engine with combustion. This problem is eliminated by the implemented variant of determining mechanical losses by motoring the ICE with increased pressures in the cylinders when the same working pressures as in real operation with combustion are achieved. This new method of measuring ICE mechanical losses by motoring requires permanent deactivation of the valve train (disengagement of valve actuation) on all cylinders. The intake and exhaust valves are permanently closed. Instead of spark plugs, multifunctional screws with self-acting one-way valves controlled by compressed air supply to individual cylinders, pressure sensors and decompression screws are screwed into the cylinder head. Fig. 1 shows the cylinder head section when motoring by the new method with screwed multi-function screws and compressed air supply [1].

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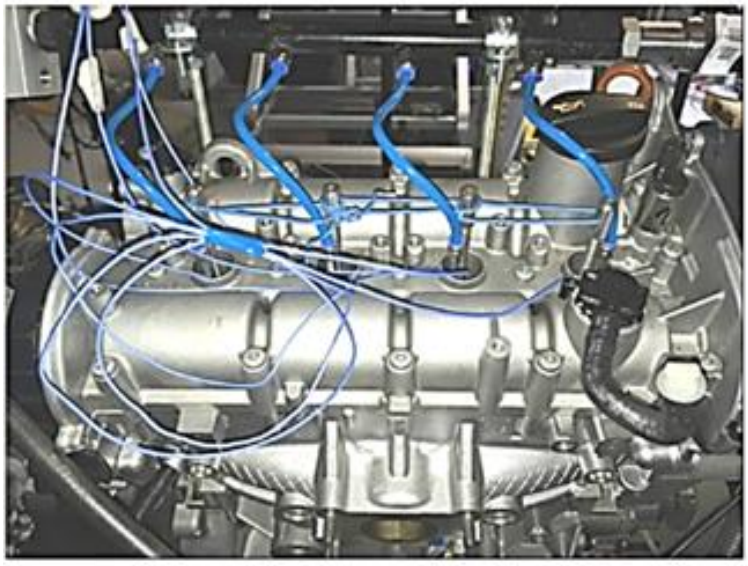
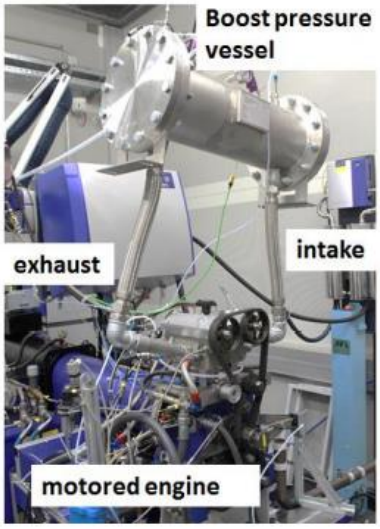


Fig. 1 View the cylinder head section with compressed air connections to the one-way self-acting valves when motoring with the new method.

The same type of measurement of mechanical losses by motoring the ICE with increased pressure in the cylinder with a controlled supply of compressed air directly to the individual cylinders has not been published in the literature. Variants of determining mechanical losses by motoring the ICE with increased pressure in the cylinder with a closed working circuit were published, where the exhaust was connected to the intake and the supply of compressed air to the intake manifold was controlled. This issue is described in the publication [2]. Fig. 2 shows the measuring station and some of the results achieved. A similar experimental design as in the case of [2] can be found in the literature [3] and [4]. However, pulsations of the compressed air occur with these closed-circuit ICE motoring methods. The pulses are caused by intermittent air inflows from the exhaust side and intermittent air withdrawals from the intake side. This problem fundamentally affects the reliability of the measurement of the indicated engine parameters and, thus, the reliability of the determination of the mechanical losses in the cranked engine.



a)

rpm	IMEP [bar] equivalent	Pmax [bar]	boost pressure absolute [bar]
1000	8	39	2
1200	6,5	33	1,8
1750	3	21	1,05
1750	5	31	1,53
1750	8	41	1,96
1750	10	51	2,4
2500	8	38	1,77

b)

Fig. 2 Test assembly for the boosted – motored friction test with examples of boost pressure levels adjusted to achieve target compression pressure [2].

The processing of the results of the performed measurements provides almost complete information about the thermodynamics of the working cycle when motoring the engine with the valves permanently closed. However, the standard procedure cannot be used to determine the course of the cylinder filling temperature during ICE motoring. The simplified calculation is based on a combination of a model calculation of the ICE working cycle with permanently closed valves and a streamlined calculation estimate of the point supply of compressed air doses in the BDC to the engine cylinder. It turned out that after setting the motoring mode (engine speed and air pressure to the self-acting valves), the state of cylinder filling stabilizes after about 200 work cycles. The calculated pressure values p_{max}, and p_{BDC} coincide with the measurement after stabilization. In the same way, the calculated values of doses [mg.cycle^{-1}] of compressed air into the cylinder coincide with the recalculated values of the measured drafts (i.e. the weight of the cylinder filling stabilizes). The values of measured and calculated thermodynamic losses [J.cycle^{-1}] are also comparable.

The injection of a dose of compressed air into the cylinder was treated as an outflow of a compressible fluid. The calculation was based on the set pressure p_{PAR} in the reservoir, taking into account the pressure losses in the system between the pressure reservoir and the self-acting valve. The pressure in front of the valve was reduced to half the p_{PAR}. Compressed air flow from the self-acting valve was into the cylinder space with the measured actual pressure p_{BDC}. The measuring cross-section at the outlet of the self-acting valve, which is determined by the geometry of the outlet cross-section and the contraction coefficient of the flow, was estimated. The blowing time was determined according to the course of the volume change exponent of the measured pressure course in the closed volume in the cylinder, calculated according to the known relationship for polytropic change:

$$n = \frac{ln\frac{p_i}{p_{i+1}}}{ln\frac{v_{i+1}}{v_i}} \tag{1}$$

The calculated polytropic exponent shows heat transfer between the cylinder filling and the walls. Still, its course is also affected by changes in the weight of the filling in the cylinder in both blow-by in and blow-by out. An example of such a view of changes in the cylinder is shown in Fig. 3.

From the course of the exponent of the volume change in the p-α diagram, it appears that the end of the exhaust is in a position approx. 90° CA before TDC (even after that, however, there are minor signs of changes), however, in the expansion area up to 90° CA after TDC, the course is "polytropic" exponent calm. Then the differences begin, which gradually increase, and at a position 30° before BDC, a significant effect of compressed air supply to the cylinder begins.

Concerning the dynamics of the self-acting valve plate's movement, the valve's opening to the whole measuring cross-section in the model calculation was reduced to ≈ 2/3 of the marked CA rotation area (according to the above-explained analysis of the measured pressure curve).

A simple model calculation showed that during the settling (stabilization) of all the observed values of the working cycle of a motoring engine with permanently closed valves, the importance of the calculated and measured pressures gradually approached. Regarding the cylinder charge temperature, the model calculation of the T_{BDC} temperature showed a trend where after an initial decrease and subsequent increase in the T_{BDC} temperature during the first 30 cycles, the T_{BDC} temperature started to decrease slightly. After about 200 cycles (i.e. stabilization of the mode), it approached the value of 272 K (12 K lower than the initial state).

The result is influenced in a certain way by the setting of the heat exchange between the cylinder filling, and the walls in the cylinder (especially by estimating the mean temperature of the walls) - a more detailed explanation can be found in [5, 6, 7].

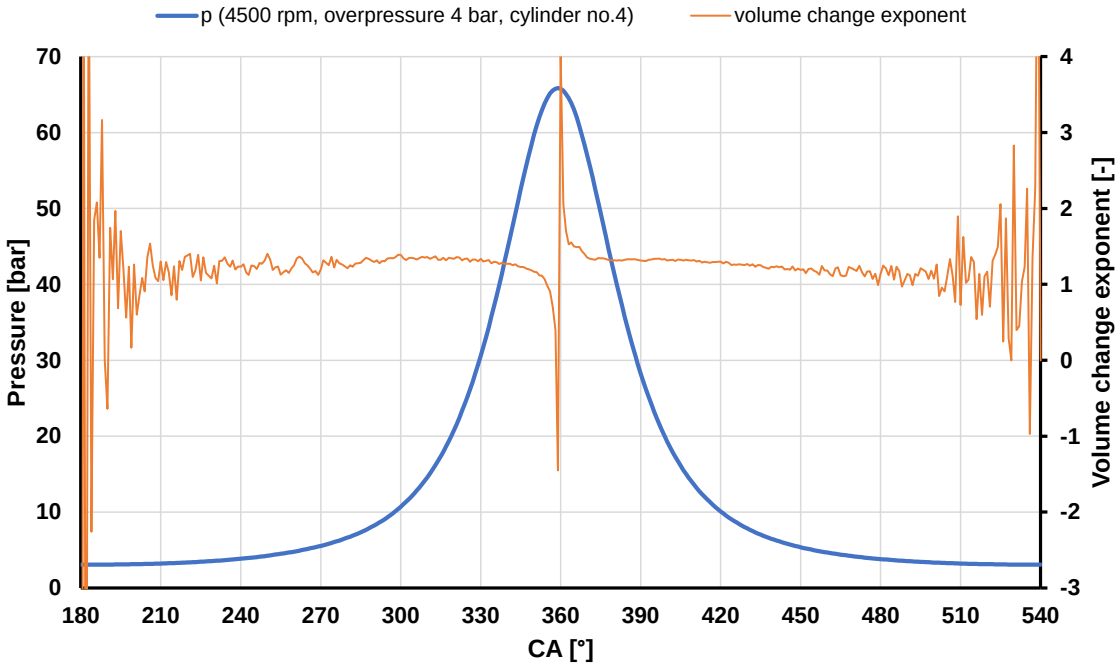


Fig. 3 The course of the volume change exponent in the p-α diagram.

Computational modelling of the working cycle of a motored mock-up of the engine without changing the cylinder's contents under different test modes, performed in the environment of modern simulation tools, will, however, require a more detailed description of the properties of individual events. In our case, it is also about the flow properties of the self-acting valve.

2 Automatic valve for blowing compressed air into the engine cylinder

The self-acting valve is built into the multi-function screw, located in the cylinder head instead of the spark plug. The structural arrangement is shown in Fig. 4: multifunctional screw (1), compressed air supply pipe (2) to the sealing surface of the self-acting one-way valve, decompression screw (4), sealing plate (7), spring (8) and guide sleeve (9).

The flow of compressed air in the system from the PAR (pressured air reservoir) to the cylinder occurs along a complicated path both directionally and cross-sectionally (see the blue line in the drawing). Almost sudden changes in cross-sections and flow direction cause intense swirling in the compressed air stream. During the flow of air from volume V2 to volume V3 (see to Fig.5), losses due to friction against the walls (slits of a rectangular cross-section with a height in the measuring cross-section S3 of up to 0.45 mm at total airflow) and turbulence losses occur in the decisive part of the path. Along the way, the pressure drops permanently, ensuring airflow. Internal losses heat the flowing air practically simultaneously along the entire route from volume V2 to volume V3. The flow in such a case is polytropic (adiabatic with internal losses). The polytropic expansion of air at the discharge is determined by the relation in which (in general) the value of the polytropic exponent can vary in the range $\kappa > n > 1$.

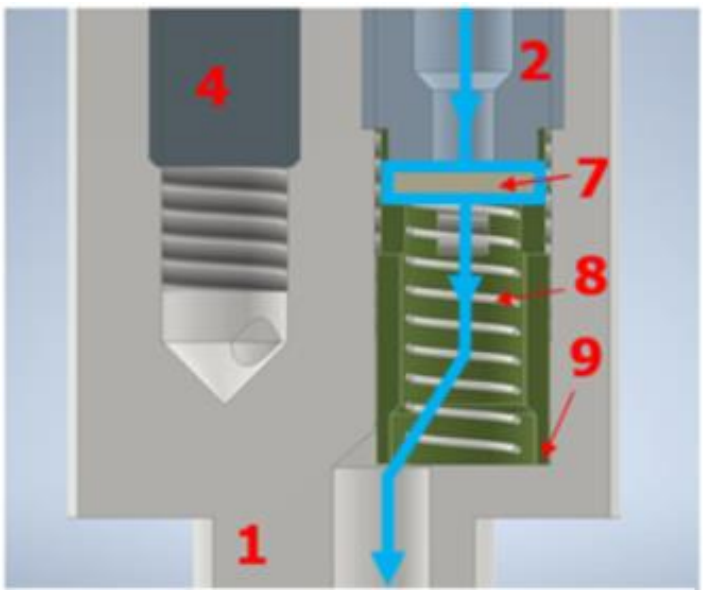


Fig. 4 A view into the internal structure of a self-acting one-way valve.

The flow of compressed air is determined by the measuring cross-section S3, which is created by the circular edge (Ø3.1 mm) of the hole in the sealing surface of the supply pipe and the lift of the sealing plate. The plate is stored in a guide sleeve, and the maximum stroke of the container is 0.45±0.05 mm. The whole flow cross-section of S3 is 4.9 mm2. The plate is pressed against the sealing surface in the rest state by a spring with a preload of 0.6 N (spring stiffness is 0.45 $N.mm^{-1}$). The air from the measuring cross-section S3 flows radially to the outer edge of the plate, where four cross-sections in the housing surround the plate and radially returns to the central part of the housing, from where it exits through the hole in the multi-function screw into the volume of the engine cylinder. The flow cross-section in this part of the flow path is comparable to the flow cross-section S3 at the full stroke of the plate in the self-acting valve.

Only a part of the total pressure drop ($p_{v2} - p_{v3}$) is used on the measuring cross-section S3, or pressure ratio p_{v3}/p_{v2}. The rest of the pressure drop maintains the air flow rate as it bypasses the valve plate to the outlet port from the multi-function screw to the cylinder.

The internal losses behind the measuring cross-section S3 during the flow in a complex path with the distribution of the total pressure drop determine that the outflow velocity c_{vS3} in the measuring cross-section S3 will be subcritical. The results of the measurements show that the effect of internal losses is that the flow of compressed air from volume V2 through the self-acting valve to volume V3 is practically isothermal (adiabatic, with heat input through internal losses during the entire flow path).

3 Experimental investigation of compressed air flow through an automatic valve

The entire system for the supply of compressed air to the self-acting valve and its connection to the assembly for measuring the flow properties of the valve with the marking of the measuring points of individual quantities is shown in Fig. 5 (the blue lines show the compressed air flow from the self-acting valve to the pipe that replaces the cylinder). All system parts are identical to the installation on the motored engine. The compressed air is in the pressured air reservoir (PAR), where the quick hose couplings are fixed. The air is led through the hose into the supply pipe set in a multifunctional screw with a self-acting valve. The multifunctional screw is fixed in the pipe mentioned above, at the end of which there is a throttle valve for adjusting the back pressure. Air from the throttle valve is routed to the Blow-By Meter to measure airflow through the reed valve. There is a fundamental difference

in the described measurement compared to the airflow conditions through the self-acting valve when measuring the engine. The flow of compressed air on the engine is a very dynamic process. The measurement of the flow characteristics of the valve in the assembly, according to Fig. 5, is in stable modes. Despite this difference, it was possible to obtain important information about the flow properties of the valve.

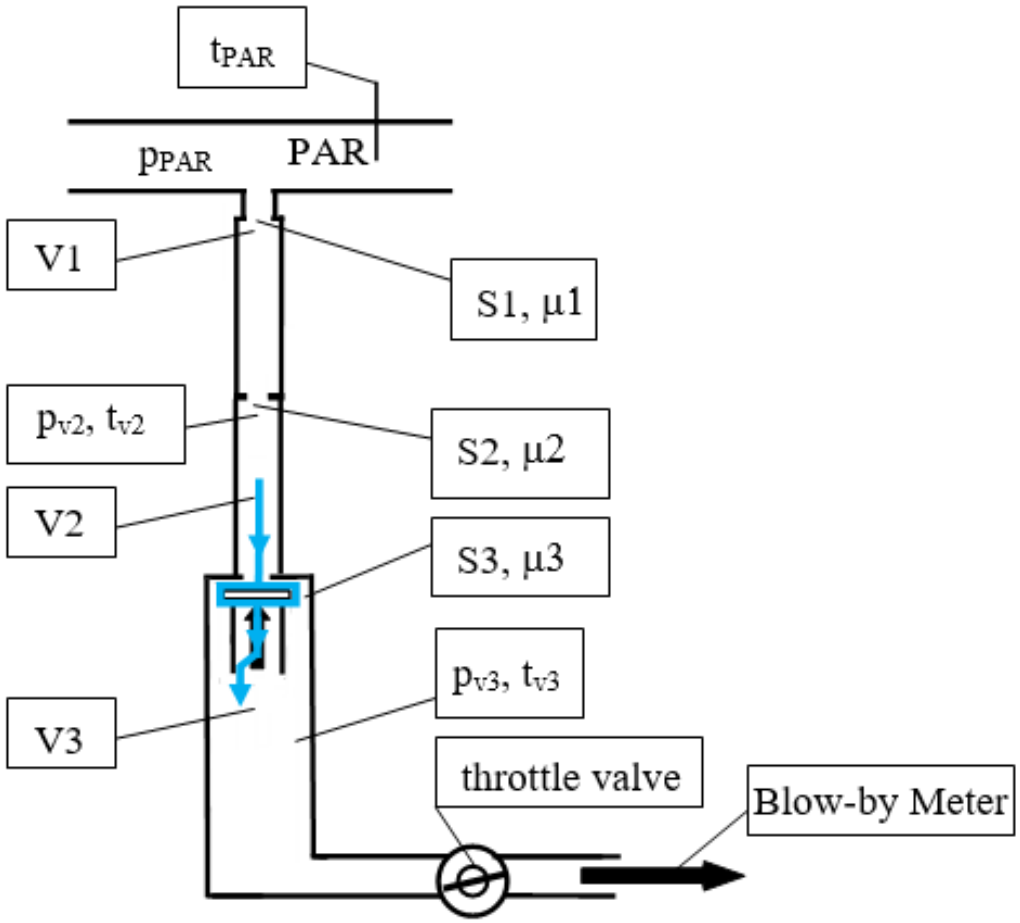


Fig. 5 Diagram of the entire system for supplying compressed air to the self-acting valve and connecting it to the assembly to measure the valve's flow properties.

The measurement was carried out in the area of the engine test box using the standard measuring equipment of the test room for the mean values of the pressures p_{PAR}, p_{v2}, p_{v3} and Blow-by drafts. The temperatures t_{PAR} and t_{v3} were measured using micro thermocouples (K). During the entire measurement, there were constant conditions in the test box (ambient pressure p_{amb} = 96.5 kPa, ambient temperature t_{amb} = 20.9°C and relative air humidity φ = 41.5%). During the measurement, the p_{v2} pressure was gradually increased, the flow rate was gradually adjusted by the throttle valve (which was measured by the Blow-by Meter), and after a short stabilization of all the values, their values were recorded.

An essential result of the performed measurements is the confirmation of the previously mentioned opinion about the significant influence of internal losses in the flowing air behind the self-acting valve. Compressed air flow through the self-acting valve into the volume of the engine cylinder is practically isothermal. During the measurement, the temperatures of t_{PAR} and t_{v3} were in the range of 22 ÷ 23°C.

Note: The air gradually expands from the inlet to the valve to the outlet in the cylinder volume to ensure the flow rate - in no case is it a case of throttling.

The flow of compressed air from space V2 to space V3 is solved as the outflow of compressed air through the outlet cross-section S3 on the plate, in front of which the pressure is p_{v2} and behind it is the pressure p_{vS3}, determined by the relation $p_{vS3}= [p_{v3} + (p_{v2} – p_{v3})/2]$.

The mass outflow quantity through the measuring section S3 is determined by equation (2).

$$\dot{m}_{v/S3} = \mu_{S3} \cdot S_{S3} \cdot c_{v/S3} \cdot \rho_{v/S3} \tag{2}$$

The effective cross-section $\mu_{S3} \cdot S_{S3}$ depends mainly on the stroke of the plate in the self-acting valve. Its size will be determined according to the measured airflow.

The subcritical speed $c_{v/S3}$ is expressed by equation (3).

$$c_{v/S3} = \sqrt{2 \cdot r_v \cdot T_{v/V2} \cdot \frac{n}{n-1} \cdot \left[1 - \left(\frac{p_{vS3}}{p_{v2}}\right)^{\frac{n-1}{n}}\right]} \tag{3}$$

The air density $\rho_{v/S3}$ in the measuring cross-section S3 at the outlet is determined by relation (4).

$$\rho_{v/S3} = \rho_{v/V2} \cdot \left(\frac{p_{vS3}}{p_{v2}}\right)^{\frac{1}{n}} \tag{4}$$

The density of compressed air in the volume V2 is determined by the equation (5).

$$\rho_{v/V2} = \frac{p_{v2}}{r_v \cdot T_{v2}} \tag{5}$$

After substituting into the equation for calculating the mass flow $m_{v/S3}$, we get the modified equation (6). This equation expresses the mass flow of compressed air through cross-section S3 during polytropic subcritical expansion (heating of the flowing air by internal losses leads to isothermal expansion with n = 1.01) [8]:

$$\dot{m}_{v/S3} = \mu_{S3} \cdot S_{S3} \cdot \sqrt{\frac{2 \cdot n}{n-1} \cdot \frac{p_{v2}^2}{r_v \cdot T_{v2}} \cdot \left(\frac{p_{vS3}}{p_{v2}}\right)^{\frac{2}{n}} \left[1 - \left(\frac{p_{vS3}}{p_{v2}}\right)^{\frac{n-1}{n}}\right]} \tag{6}$$

4 Measurement results

From the point of view of investigating the flow properties of the self-acting valve, the pressures p_{v2}, p_{v3} and the Blow-by flow are the determining variables. The graph in Fig. 6 shows the mutual relations between these quantities.

The result of the computational analysis of the flow of compressed air from the pressure reservoir to the engine cylinder, shown in Table 1, is based on the measured pressures p_{v2}, p_{v3}, the Blow-by flow and the assumed use of half of the total pressure drop for the flow through the measuring cross-section S3. Without more comprehensive verification, such an assumption cannot be generally valid for the entire range of flow rates. However, the procedure shown in Table 1 may be the key to further experiments and some automation of the processing of the results, aimed at refining the description of the flow properties of the self-acting valve.

The values of the individual quantities shown in the table were determined by calculation in the Excel environment. The result of the performed analysis is the values of the effective cross-section $\mu_{S3} \cdot S_{S3}$, which logically increase with increasing airflow due to increasing the lift of the plate in the self-acting valve. Logically, the flow (contraction) coefficient μ_{S3} also seems to grow. However, for a more precise description of the meaning of both items of the effective cross-section μ_{S3} and S_{S3}, more specific data (e.g. valve lift) are missing.

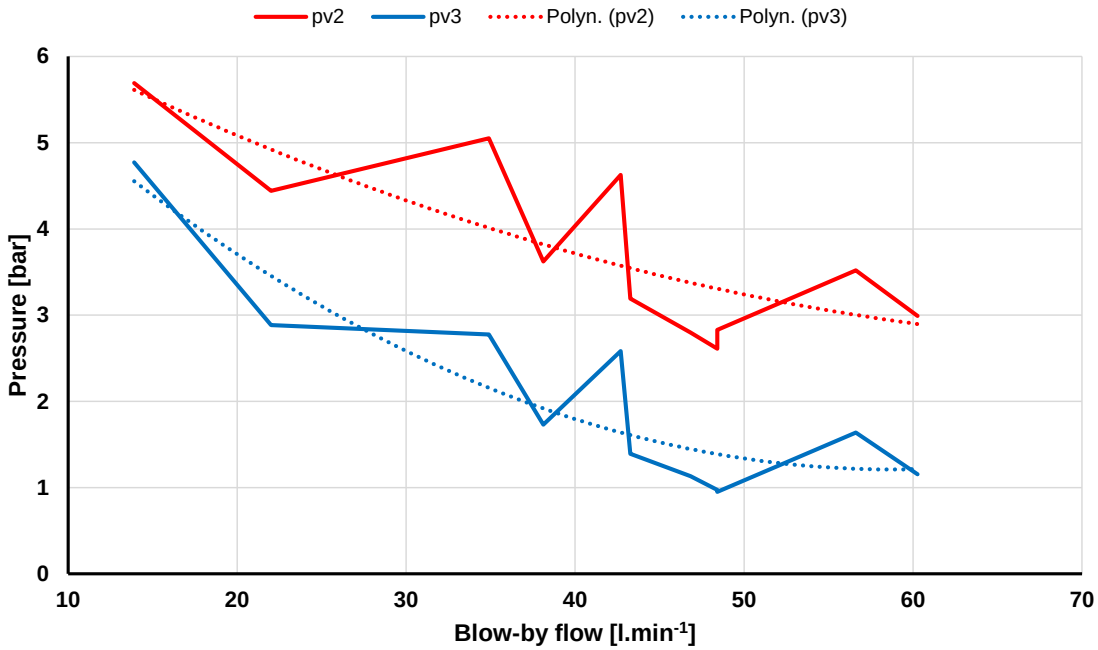


Fig. 6 Pressure progression before and after the valve depends on the Blow-by draft.

The point curves of all the quantities shown in the graph above are apparently marked by measurement errors (inaccuracies in the adjustment of the test mode), which, after mathematical correction, express their connections with clear logic.

Tab. 1 Calculated and measured parameters

Measurement							
p_{V2}	5.69	5.05	4.63	3.52	2.99	2.83	[bar]
p_{V3}	4.77	2.78	2.58	1.64	1.16	0.95	[bar]
Blow-by	13.90	34.90	42.70	56.61	60.26	60.65	[l.min^{-1}]
Calculation							
$p_{V}S3$	5.23	3.91	3.61	2.58	2.07	1.89	[bar]
$c_{V}S3$	119.55	207.86	205.60	229.60	249.18	261.26	[m.s^{-1}]
ρ_{V2}	6.71	5.95	5.45	4.15	3.53	3.33	[kg.m^{-3}]
$\rho_{V}S3$	6.17	4.62	4.26	3.05	2.45	2.24	[kg.m^{-3}]
$\rho_{v(Blow\text{-}by)}$	1.14	1.14	1.14	1.14	1.14	1.14	[kg.m^{-3}]
$m_{v(Blow\text{-}by)}$	0.26	0.66	0.81	1.07	1.14	1.15	[g.s^{-1}]
$\mu_{S3} \cdot S_{S3}$	1.94	2.80	3.46	4.11	4.03	3.87	[mm^2]
The maximum flow cross-section S3: Ø3.1 mm with a plate lift of 0.5 mm is 4.9 mm^2.							

It was found through trial calculations that dividing the pressure drop into halves is satisfactory. The first half of the pressure drop is for the flow through cross-section S3 in the self-acting valve, and the second half of the pressure drop is used to bypass the valve plate. Refinement of the computational processing would require the determination of the pressure drop used for the flow through the self-acting valve (i.e. outlet cross-section S3). However, it would be more reliable to experimentally verify this assumption, e.g. by directly measuring the pressure in the bypass part of the plate. In such a case, it would be sufficient to make a separate part to assemble only the self-acting valve, in which another pressure sensor would be installed.

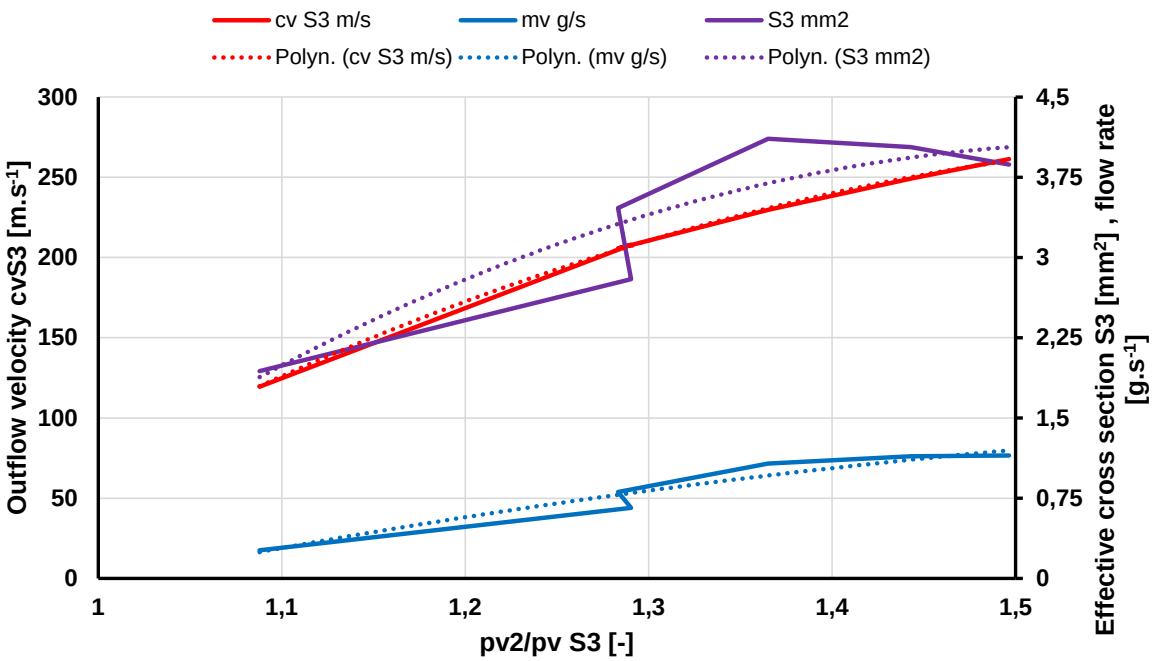


Fig. 7 Courses of quantities characterizing air flow through measuring cross-section S3 depending on the pressure ratio.

5 Blowing of compressed air by the automatic valve into the engine cylinder during the working cycle of the motoring engine

The area where a dose of compressed air is blown into the engine cylinder by a self-acting valve is illustrated in Fig. 3. The mass of air blown into the cylinder depending on the position of the crankshaft was calculated according to the relationships given in chapter 3 “Experimental investigation of compressed air flow through an automatic valve” above. Findings from the investigation of the flow properties of the self-acting valve were also included in the calculations. The pressure drop between the air pressure in the supply pipe in front of the self-acting valve and the pressure in the cylinder has a decisive influence on the mass flow of compressed air into the cylinder. If the pressure in the cylinder is higher than the air pressure in the compressed air reservoir (p_{PAR}), the self-acting valve is closed, and the volume of the supply pipe V2 (see Fig. 5) is in front of the valve will have a pressure of p_{PAR}. In the position of the crankshaft, when the pressure in the cylinder drops below p_{PAR}, compressed air begins to flow through the valve into the volume of the cylinder, and the pressure in the volume of the supply pipe in front of the valve decreases. At the same time,

compressed air begins to flow from the pressure reservoir through cross-sections S1 and S2 into the volume of the supply pipe.

Theoretically, the instantaneous mass flow rates of the air blown into the cylinder and the air flowing into the intake pipe should be the same. In volume V2, depending on the amount of airflow into the cylinder, there will be a pressure lower than the pressure in the PAR pressure reservoir. Dimensioning of the cross-sections S1 and S2 in the supply of compressed air from the reservoir to the volume V2 of the supply pipe is sufficient for rapidly replenishing compressed air into the supply pipe. At the end of blowing air into the cylinder of the cranked engine, the pressure in the supply pipe volume is set to the value of the pressure in the PAR reservoir. Fig. 8 shows this graphically.

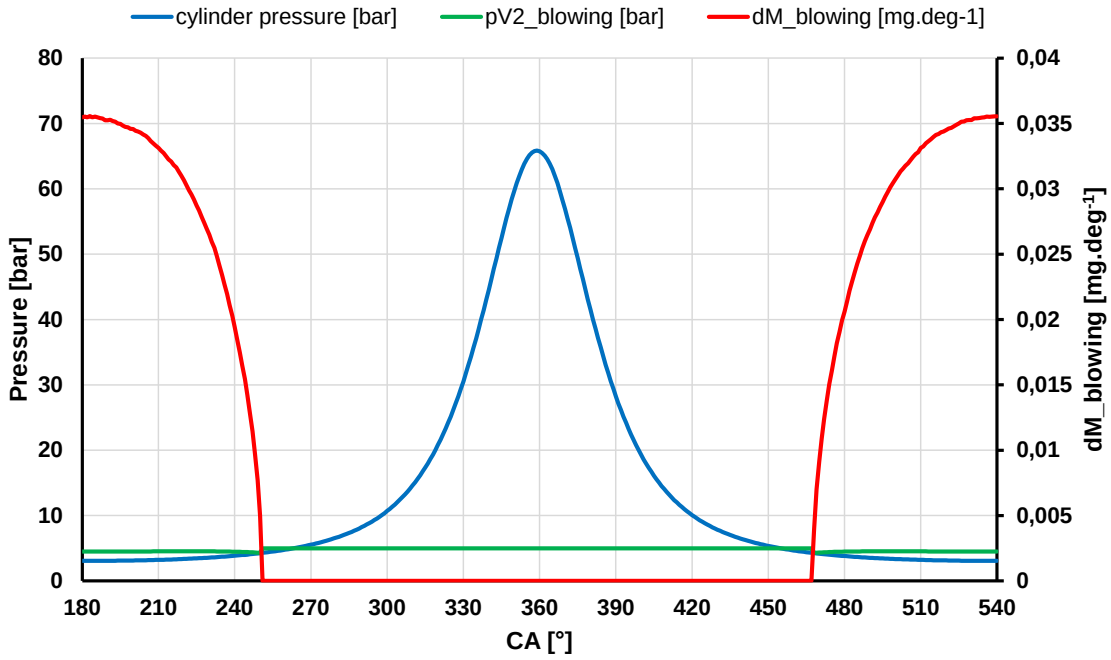


Fig. 8 Computational solution of the mass course of air injection into the cylinder volume and the pressure in the volume V2 of the supply pipe, together with the measured course of pressure in the cylinder of the motoring engine.

During the measurement, the four-cylinder inline engine with a volume of 1.5l motored in a stable operating mode of 4500 rpm with an air pressure of 5 bar(abs) in the pressure tank (indicator diagram is identical to Fig. 3). The total flow of compressed air through the self-acting valve per working cycle of the cranked engine is 0.004 g/cycle. The same result of calculating the injected dose by a different procedure was achieved when analyzing the measurement results on the second overturned four-cylinder inline engine 1.6l with permanently closed valves at 3000 rpm and air pressure of 6 bar(abs) in the pressure air reservoir. The correctness of this calculation is also confirmed by the agreement with the measurement of Blow-by for a cranked engine in steady operating mode.

CONCLUSION

The new method of measuring the mechanical losses of the ICE by motoring with increased pressure in the cylinder (the same as the pressure during real operation of the engine with the combustion of a fuel-air mixture) is suitable for the development and production of

ICE both in the scientific and research area and especially in the automotive industry. Described is a variant of motoring a 4-stroke engine with permanently closed valves (with a deactivated valve train), where special multifunctional screws are mounted in the cylinder head instead of spark plugs. The area for replacing the cylinder filling is removed from the working circuit (the low-pressure part is not in the p-V diagram). This new method of determining mechanical losses is ideal for accelerated life tests of engine friction pairs (piston group - cylinder). The advantage is that the piston group is loaded twice the frequency (double compression and expansion phase) compared to a standard four-stroke ICE. The conducted experiments and their evaluation show the connections between the quantities that determine the flow properties of compressed air through a one-way self-acting valve for setting the working pressure in the cylinder of the motorized engine. The calculation results are a theoretical addition to the described new method.

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