# THE EXPERIMENTAL ASSESSMENT OF AIR SUPPLY SYSTEM MODIFICATION ON INLET AIR FILTRATION EFFICIENCY AND MILITARY VEHICLE ENGINE EFFECTIVENESS IMPROVEMENT

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*Abstract*

*Specific features of air inlet system of BWP-1 vehicle UTD-20 engine are shown. The tests results of filtration efficiency and air flow drag for BWP-1 vehicle air filter standard version are presented. The necessity of UTD-20 engine air supplying system constructional changes are proved. The inlet air filtration system for BWP-1 engine with the porous filter was proposed and performed. The characteristics of the air purification efficiency $\varphi=f(m_p)$ and flow drag $\Delta p= f(m_p)$ $\Delta p= f(Q_G)$ for designed air filter were determined. Absorbency of filter for air nominal stream of engine BWP-1 was specified. The designed and executed partition air filter was subjected to comparative tests on an engine test bench. The influence of modernized air filter and fuel dose increase on engine effective parameters were determined. The tests covered comparison of effective parameters (determined for maximum load) of a UTD-20 engine equipped with a standard air filter (variant 1), a modernized air filter (variant 2) and additionally, for the modernized air filter, with injection pump with fuel dose increased (variant 3). There were determined the influence the proposed changes on indicated and effective torque during engine free acceleration and its mechanical efficiency as well.*

*Keywords: combustion engines, air filters, filtration efficiency, flow drag, filter absorbency, effective parameters of the engine, mechanical efficiency*

## 1. Introduction

Off-road vehicles, and in particular military motor vehicles are operated in wilderness and in sandy terrain, where dustiness is particularly great and often exceeds the value of $1g/m^3$. These vehicles are usually equipped with powerful compression ignition engines of large (e.g. the T-72 tank - 3300 $m^3$/h) air requirement. For this reason they are equipped with filters performing two-stage air filtration, where the first cleaning stage consists of an inertial dust extractor: multi-cyclone or mono-cyclone, characterized by ability of separation of significant dust mass from large volumes of passing air at low flow resistance, maintenance freedom and dust extraction effectiveness reaching (96-98%) [1, 3, 4].

Multi-cyclones as the first stage of air cleaning are found among other things in PT-91, T-72, Leopard 2 and Abrams tanks, Autosan buses, Star 266 and 1466, Volvo and Scania trucks. Single cyclones stop grains of dust sized over 15-30 μm [1, 3, 4]. As the second stage of intake air cleaning in internal combustion engines, filter beds are applied in the form of irregular mesh bed or porous partition of filtration paper. Greatest wear of engine elements (e.g.: the association piston - piston rings - cylinder) is caused by dust grains sized 2-35 μm [1, 2, 8] and therefore they should be stopped with greatest effectiveness.

## 2. Air intake system characteristics of the UTD-20 engine

The air intake system of the UTD-20 BWP-1 engine (Fig. 1) is characterized by complicated design, significant length and complexity of shapes of its individual components, which is very rarely
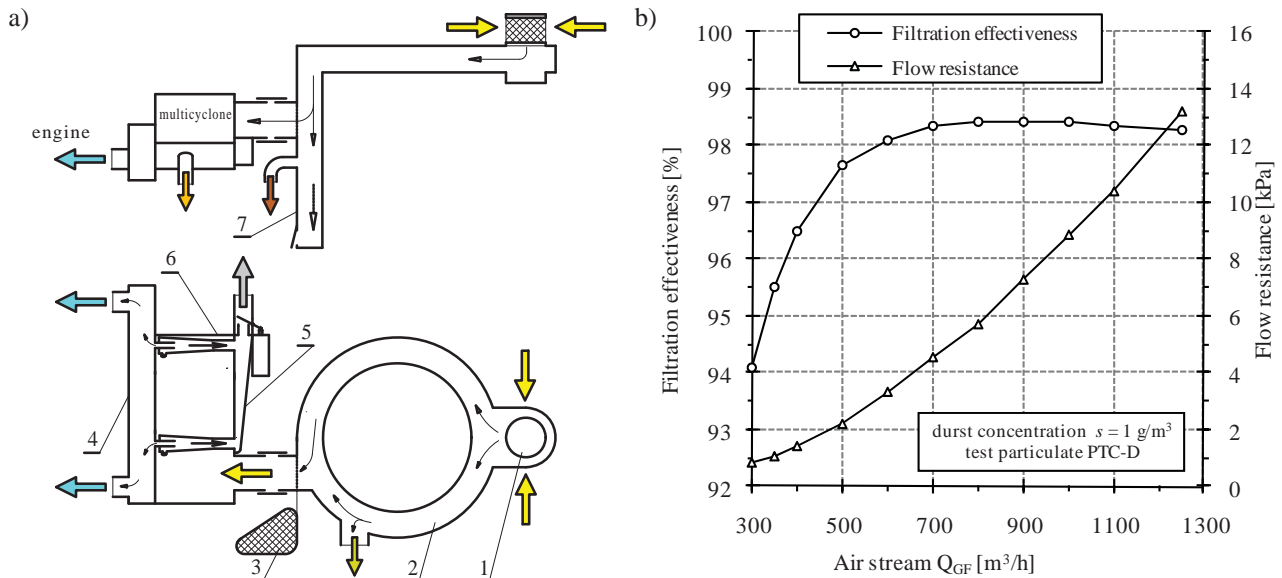
*Fig. 1. Air supply system of the BWP-1 armoured personnel carrier (a) and characteristics of dust extraction effectiveness $\varphi_f = f(Q_{GF})$ and flow resistance $\Delta p_f = f(Q_{GF})$ of the BWP-1 air filter (b): 1 – air intake, 2 – under turret main, 3 – filtration mesh, 4 – clean air outlet collector, 5 – dust settler, 6 – air filter - multi-cyclone, 7 – impurity settler*

found in other vehicles. The air filter is an inertial dust extractor (multi-cyclone) built of returnable cyclones with tangential intake, situated horizontally in three rows (of 13 cyclones each), closed in a tight, rectangular case, to which air is fed through an intake stub pipe from the under-turret main and partially through an inlet from about the radiator.

Atmospheric air is sucked into the system via intake *1* (Fig. 1a) located above the main armour plate behind the turret, and subsequently transported via toroidal under turret main *2*, located around the turret bearing, to the filter multi-cyclone. The frequently changing volumes and cross-sections of the UTD-20 engine air intake system, separation and merging of its main stream cause variations in velocity of the flowing air and are a source of increased flow resistance. Air cleaned in the cyclones flows into the cumulative collector *4*, from where via two cylindrical stub pipes it flows to engine intake manifolds. dust stopped by the cyclones is stored in the dust settler *5*, from where (on a current basis) as a result of exhaust ejective action it is removed outside the vehicle.

From the characteristics of dust extraction effectiveness $\varphi_f = f(Q_{GF})$ and flow resistance $\Delta p_f = f(Q_{GF})$ of the BWP-1 air filter (Fig. 1b) it follows that increase of the air stream flowing through the filter (flowing out of the filter) $Q_{GF}$ is followed by increased dust extraction effectiveness $\varphi_f$ and simultaneous increase of flow resistance $\Delta p_f$.

In the first period of operation of the filter in the scope of small values of air stream ($Q_{GF} = 300\text{-}600$ m³/h), increase of dust extraction effectiveness $\varphi_f$ is significant. Above 600 m³/h effectiveness $\varphi_f$ levels out, slightly exceeding 98%. Increase of air stream $Q_{GF}$ is followed by continuous (parabolic) increase of flow resistance $\Delta p_f$ of the filter from the value $\Delta p_f = 0.85$ kPa (for $Q_{GFmin} = 300$ m³/h) to the value $\Delta p_f = 13.21$ kPa for the maximum air requirement of the engine $Q_{GFmax} = 1250$ m³/h. Such course of dust extraction effectiveness and flow resistance in the multi-cyclone is a reflection of operation of individual cyclones and is compliant with literature information [1, 3, 4] provided for this type of dust extractors.

The air filter of the BWP-1 armoured personnel carrier is characterized by very large (5-13 kPa) flow resistance in working scope of operation, by far exceeding admissible flow resistance of air filters for other vehicles (e.g. for the MAN D0826 engine of the STAR 1466 truck it has the value of $\Delta p_{fdop} = 5$kPa). Increase of air filter flow resistance $\Delta p_f$ by 1 kPa causes an average drop of power by 0.4-0.6% and increase of unit fuel consumption of a compression ignition engine by

about 0.3-0.5% [5].

Analysis of the air filter applied in the BWP-1 has shown that it fails to meet the requirements posed before modern air filters of traction internal combustion engines of vehicles operated in conditions of high dustiness, particularly concerning possibly low flow resistance and ensuring properly high effectiveness of small particles filtration.

## 3. Modernization concept of the UTD-20 engine air intake system

For the UTD-20 engine, an intake air filtration system is proposed in the form of a partition filter with paper filtration inserts in place of the multi-cyclone dust extractor. Airflow into the filter will take place from the environment via a conduit and intake situated above the armour. The proposed scope of changes follows, among other things, from a need for location of the modernized filtration assembly in the limited space of the drive compartment.

The proposed partition air filter for the engine of the armoured personnel carrier is built of three basic elements – Fig. 2a: filtration insert *1*, filtration insert housing *6* along with air inlet, cumulative clean air collector *9*.

The filtration insert is a complex of four parallel cylindrical filtration elements of symbol AM 406/1 (Fig. 2c) made of pleated filtration paper. Intake of air into the filter housing takes place via a stub pipe of diameter $D_0 = 150$ mm. Air cleaned in the filter flows to a cumulative collector ending with two outlet air stub pipes *10* enabling connection of the filter to the engine intake manifolds.
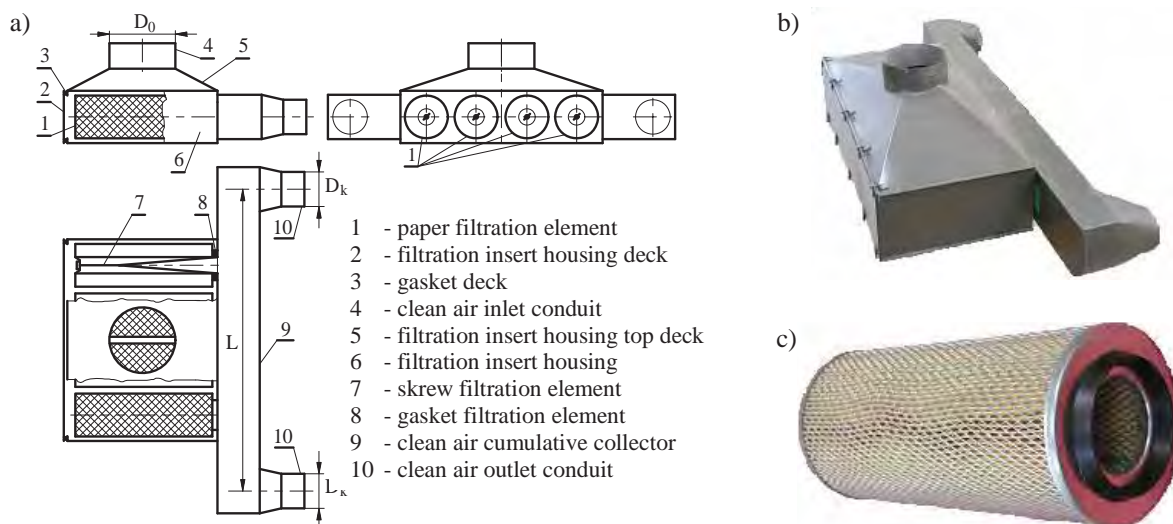


1 - paper filtration element
2 - filtration insert housing deck
3 - gasket deck
4 - clean air inlet conduit
5 - filtration insert housing top deck
6 - filtration insert housing
7 - skrew filtration element
8 - gasket filtration element
9 - clean air cumulative collector
10 - clean air outlet conduit

*Fig. 2. Diagram of executed partition air filter for the armoured personnel carrier (a), its general view (b) and the filtration element (c)*

## 4. Methodology of testing of the partition filter

Experimental tests of the executed air filter were carried out on a stand (Fig. 3) enabling measurement of basic characteristics: dust extraction effectiveness and air filter flow resistance in the air stream range of $Q_{GF} = 300\text{-}2000$ m³/h for dust concentration of up to 2 g/m³.

The scope of tests covered determination of the following filter characteristics:
- aerodynamic $\Delta p_f = f(Q_{GF})$ (for the filter with clean filtration insert and following effectiveness tests),
- filtration effectiveness $\varphi_f = f(m_p)$, $m_p$ – dust mass stopped in the filtration insert,
- flow resistance $\Delta p_f = f(m_p)$.

Aerodynamic characteristics tests $\Delta p_f = f(Q_{GF})$ were carried out in the scope of air stream $Q_{GF} = (350\text{-}1250)$ m³/h corresponding to volume air requirement of the engine (flowing out of the

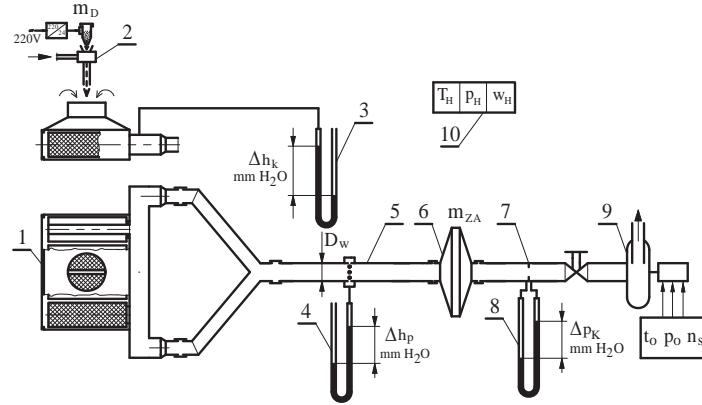filter) in the scope of engine rpm $n_{min}$-$n_{max}$.



*Fig. 3. Diagram of the stand for air filter testing for the UTD-20 BWP-1 engine: 1 – air filter, 2 – dust batcher, 3, 4, 8 – U-tube liquid manometers, 5 – air filter flow resistance measurement conduit, 6 – dust measurement filter (absolute), 7 – measuring orifice plate, 9 – air stream generating fan Q, 10 – environment conditions measurement set*

Flow resistance of the air filter was determined as the drop of static pressure in the measurement conduit behind the filter $\Delta p_{fp}$ and in the cumulative air filter collector $\Delta p_{fk}$ for subsequent selected air stream values $Q_{GF}$ (repeating the measurement $n$ – times) according to the relation:

$$\Delta p_{fp(k)} = \frac{\overline{\Delta h}_{f(k)}}{1000} (\rho_m - \rho_H) \cdot g \ [\text{Pa}],\tag{1}$$

where:

$\overline{\Delta h}_f$ - mean value of static pressure drop for each adopted air stream value $Q_{GF}$ (measurement point) from $n = 5$ measurement cycles [mm $H_2O$],

$g$    - local acceleration, $g = 9.812$ m/s$^2$,

$\rho_m$   - density of manometric liquid (water) at measurement temperature $t_H$ [kg/m$^3$],

$\rho_H$   - density of atmospheric air in measurement conditions [kg/m$^3$].

Characteristics of filtration effectiveness $\varphi_f = f(m_p)$ and flow resistance $\Delta p_f = f(m_p)$ of the air filter were determined for air stream $Q_{max} = 1250$ m$^3$/h and for dust in air concentration s = 0.5 g/m$^3$.

Filtration effectiveness was determined with the gravimetric method in compliance with PN-S-34040 in test cycles of duration of $\tau_C$ based on the relation:

$$\varphi = \frac{m_P}{m_D} = \frac{m_D - m_A}{m_D} \cdot 100 [\%],\tag{2}$$

where:

$m_P$   - dust mass stopped in time $\tau_C$ by the filter,

$m_D$   - dust mass introduced uniformly (in time $\tau_C$) into the filter along with the inlet air stream $Q_{0F\,max}$,

$m_A$   - dust mass stopped in time $\tau_C$ by the measurement (absolute) filter.

For determination of air filtration effectiveness in the filter, PTC-D test particulate was applied, being a domestic replacement for the AC Fine test particulate of maximum grain size $d_z = 80$ μm and $SiO_2$ content - 69% and $Al_2O_3$ content - 17%.

## 5. Test results analysis

Results of tests of aerodynamic characteristics of the designed BWP-1 air filter with clean inserts are presented in Fig. 4a, whereas results of tests and calculations of filtration effectiveness $\varphi_f$ and

flow resistance $\Delta p_f$ in the function of stopped dust mass $m_p$ in Fig. 4b.
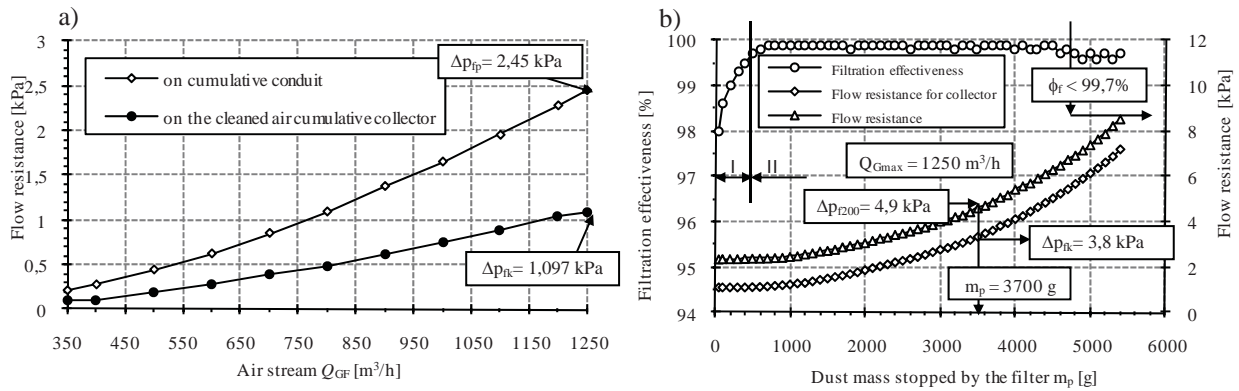


*Fig. 4. Aerodynamic characteristics of the tested BWP-1 air filter with clean inserts (a) and characteristics of filtration effectiveness $\varphi_f = f(m_p)$ and flow resistance $\Delta p_f = f(m_p)$ (b)*

Increase of air stream $Q_{GF}$ is followed by continuous increase of flow resistance, which at $Q_{GF} = 1250$ m$^3$/h achieves the following values: on the cleaned air cumulative collector $\Delta p_{fpk} = 1.097$ kPa and on the cumulative conduit $\Delta p_{fp} = 2.45$ kPa, therefore more than twice the filter resistance $\Delta p_{fpk}$, which follows from significant length of conduits on the section from the collector to the place of measurement of filter resistance.

With regard to the achieved values of filtration effectiveness, operation time of the tested filter may be divided conventionally into two periods. First (*I*), characterized by low values of filtration effectiveness, which systematically and abruptly increase along with the dust mass stopped by the filtration paper. This period (transient filtration) lasts from the moment of commencement of the filtration process until achievement by the paper of maximum stable filtration effectiveness. The following second period (*II*) of filtration (stable filtration period) is characterized by much higher and stable level values of filtration effectiveness. In case of the tested filter, the division zone of the two periods was assumed upon achievement by the paper of filtration effectiveness of $\varphi_f = 99.5\%$. Along with the growth of dust mass $m_p$ stopped by the filtration paper of the insert, flow resistance $\Delta p_f$ of the tested filter systematically grows all the time, respectively from the value $\Delta p_{fp} = 2.365$ kPa to the value of over 8.5 kPa, recorded after the last measurement cycle. Flow resistance of the filter on the cumulative collector assumes the values $\Delta p_{fk} = 1.085$ kPa and 7.166 kPa, respectively.

Simultaneous increase of filtration effectiveness and flow resistance of the paper filtration insert as a result of dust mass stoppage is a know phenomenon and compliant with literature information provided for partition filters, and follows from changes of the filtration partition structure as a result of stopping and settling of dust particles on the fibres as a result of operation of various filtration mechanisms. In the period of transient filtration this phenomenon occurs chiefly on the first layers of fibres and with time proceeds deeper into the material. The result of this phenomenon is obstructed free flow across the bed, which manifests itself through increased flow resistance. After the filter has stopped dust mass $m_p = 4591.2$ g a slight drop of filtration effectiveness is noted to $\varphi = 99.6\%$, which may be a signal of „punch-through” of the filtration paper, and therefore beginning of loss of filtration properties of the filter and its absorbing capacity. According to the PN-S-34040 standard, filter absorbing capacity $\Delta m$ is defined as dust mass stopped by the filter until:

a) achievement by the filter at nominal air stream of resistance equal to 200% of value of resistance measured for clean air filter;

b) drop of filtration effectiveness below the value determined for the given type of filter.

The absorbing capacity of the filter measured in these conditions should not be lower than the theoretical value calculated according to the relation:

$$\Delta m_t = k \cdot Q_{GF\,max} \ \text{[g]}, \tag{3}$$

where: $k$ - factor depending on the filter type.

For the factor $k = 140$ g min/m$^3$ and air stream $Q = 1250$ m$^3$/h = 20.83 m$^3$/min the filter absorbing capacity required under the PN-S 34040 standard in compliance with the above relationship is 2917 g.

Flow resistance of the air filter with clean filtration inserts measured on the cumulative conduit achieves the value $\Delta p_{fp} = 2.45$ kPa at $Q_{GFmax} = 1250$ m$^3$/h, then 200% of the value of resistance measured for clean air filter is $\Delta p_{fp200} = 4.9$ kPa. The dust mass stopped by the filtration insert until achievement by the filter at nominal air stream of resistance equal to $\Delta p_{fp200} = 4.9$ kPa (Fig. 5b) is $m_{p200} = 3700$ g. Since until the filter stopped at nominal air stream the dust mass $m_{p200} = 3700$ g no drop of filtration effectiveness was recorded, then flow resistance value $\Delta p_{fp200} = 4.9$ kPa of the tested filter should be considered admissible $\Delta p_{dop}$. It therefore follows that the designed air filter meets the condition of required dust absorbing capacity.

## 6. Tests on engine test bench and in transient conditions

The designed and executed partition air filter was subjected to comparative tests on an engine test bench. The tests covered comparison of effective parameters (determined for maximum load) of a UTD-20 engine equipped with a standard air filter (variant 1), a modernized air filter (variant 2) and additionally, for the modernized air filter, with injection pump with fuel dose increased by ca. 7% (variant 3). The methodology and manner of execution of the performed tests were aligned with the recommendations provided in appropriate Polish standards. Selected tests results are shown in Fig. 5.

For the engine in the second equipment version a slight increase of effective parameters was achieved in almost the entire rev range in comparison to the standard engine (variant 1). The greatest increase is observed for the rev range of 1600…1800 rpm (over 1%), the smallest for the rev range of 2300…2600 rpm (0.4% - within the limits of measurement error). The observed slight increase of power and torque for this engine equipment variant was obtained at lower hourly fuel consumption (on average by 1.5%). This justifies the proposition that given the same fuel dosage ($G_{pal}$) it would be possible to obtain increase of effective parameters of the same order.
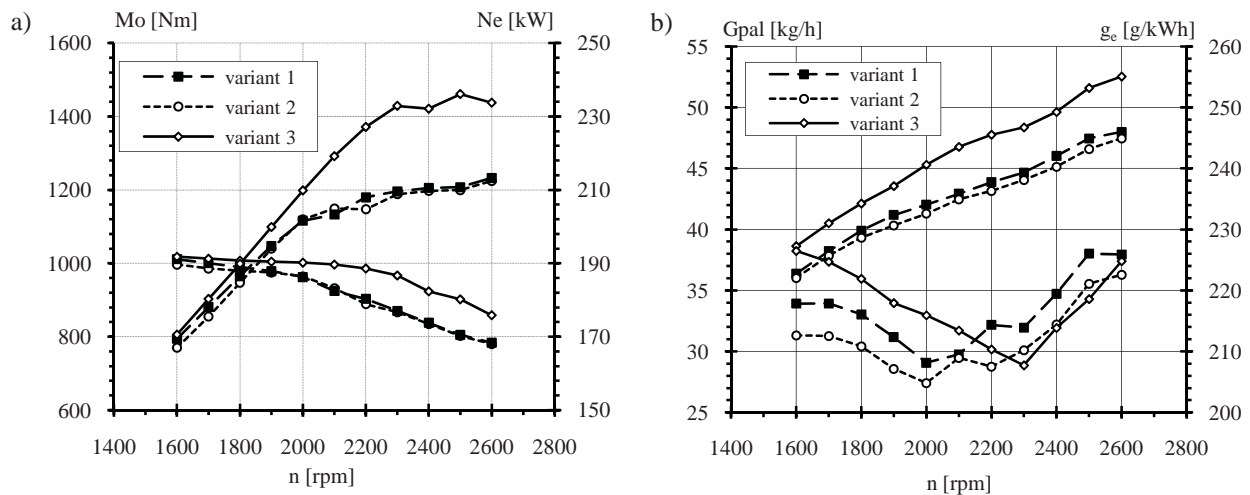


*Fig. 5. Course of external characteristics: a) effective power Ne and torque Mo, b) hourly $G_{pal}$ and unit $g_e$ fuel consumption of the UTD-20 engine*

For the engine with increased fuel dose and modernized air filter (variant 3), a significant increase of power and torque was obtained. The higher the rev speed, the higher (in general) the increase of effective parameters. It is somewhat over 2% (for rev speed of 1600 rpm) and over 10% for rev speeds of 2200…2600 rpm, at slight (less than 2%) increase of unit fuel consumption in comparison to the values obtained for variant 1. This increase is much smaller than the increase of effective parameters (Ne, Mo) of the engine, which for the considered rev range (1600…2600 rpm) is on

average 7%. This shows more effective utilization of the increased fuel dose (pump adjustment) and air volume (lower flow resistance – better filling). This is confirmed by increase of exhaust temperature (on average by 20ºC), observed during tests.

Tests were also performed in transient conditions, determining so-called dynamic engine characteristics, based on which comparisons were made of effective torque, indicated torque (sum of effective torque and engine resistance) and mechanical efficiency of the UTD-20 engine for three tested variants of its equipment. Measurements were taken using a computerized measurement set for engine rev speed and crankshaft acceleration, with rev speed measurements accuracy of ±0.05% [6, 7].

For the analysis, average values of torque (effective, engine resistance) were adopted as determined from thirty acceleration processes (3 series of 11 accelerations – the result of the first acceleration was rejected) in rev speed brackets of 100 rpm. In the first place, by means of Cochran's C and Student's t statistical tests of comparison of mean values at significance level $\alpha = 0.05$, it was found that mean values of engine resistance torque for all tested engine equipment variants were almost equal for all considered rev speed brackets. This indicates comparable engine heat condition (value of engine resistance) during the tests.

The obtained in transient conditions relative (percentage) change of torque and effective power of the UTD-20 engine for individual equipment variants is slightly lower (by about 1%) than in case of measurements made on the engine test bench. The indicated engine torque with modernized air filter and increased fuel dose across the entire considered rev range is higher on average ca. 59.7 Nm (6%) in comparison to indicated torque generated by the engine in the standard equipment variant (Fig. 6a). Increase of indicated torque is close to the amount of increase of effective engine torque determined for measurements in transient conditions.

Based on the determined dynamic characteristics, mechanical efficiency curves $\eta_m$ were determined for the UTD-20 engine (Fig. 6b), which was calculated from the relationship given in the figure, where $M_{ind}$, $M_e$, $M_{ow}$ stand for indicated torque, effective torque and engine resistance, respectively, determined in conditions of transient engine operation (free acceleration and breaking).

For the first two engine equipment variants, the same curves of UTD-20 engine mechanical efficiency were obtained. For variant 3, the increase of mechanical efficiency is on average over 1% and varies depending on engine rpm. The highest increase was observed for engine speeds of over 2000 rpm, for which it exceeds 2% .
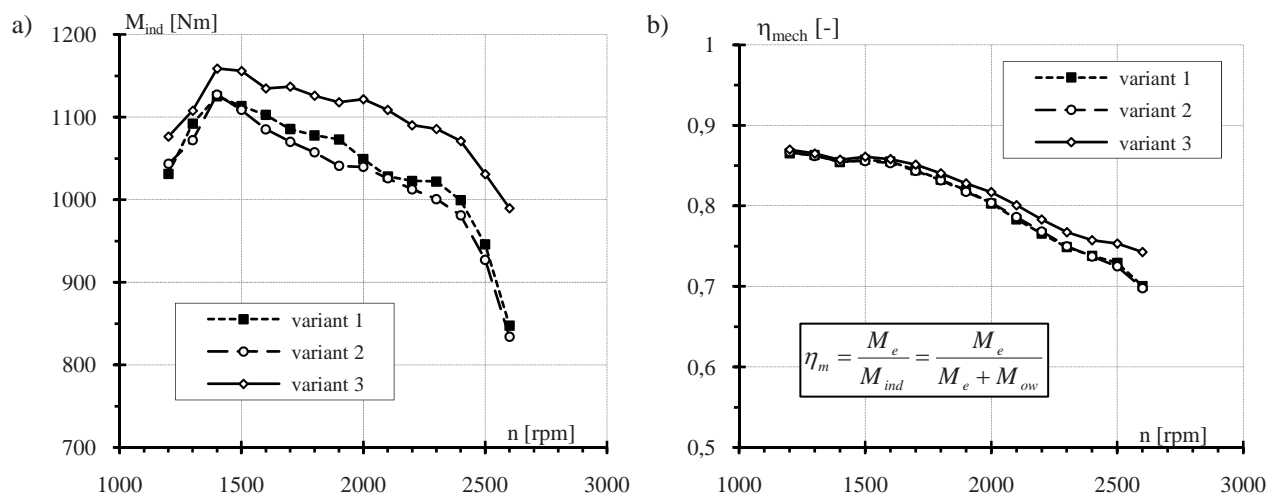


*Fig. 6. Curves: indicated torque (a) and mechanical efficiency (b) determined in conditions of transient operation of the UTD-20 engine for the three tested equipment variants*

## 7. Conclusions

The modernized air filter of reduced flow resistance enabled improvement of cylinder fill, which

given increased fuel dose by over 7% enabled increase of effective parameters of the UTD-20 engine on a similar level in comparison to the engine in standard version. The obtained improvement of effective parameters is visible particularly over engine speeds of 2200 rpm, exceeding 10% in this range (over 20 kW).

Improvement of effective parameters of the UTD-20 engine with modernized air filter and pump with increased fuel dose is visible not only in quasi-stable operation conditions, but also in transient conditions. During free acceleration, growth of power and torque is slightly lower (on average 6%) that for stable conditions. Confirmation obtained improvement of overall effectiveness of the fuel combustion process in the UTD-20 engine is increase of its mechanical efficiency of ca. 1.5%.

## Acknowledgements

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