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A DESIGN CONCEPT OF A DEVICE FOR MEASURING AIR FLOW RESISTANCE IN VEHICLE FILTERS

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Abstract

Internal combustion engines have to be supplied with adequate amounts of fuel and air. The required amount of fuel and air is determined by the engine controller to guarantee that the fuel reaching the cylinder is burned effectively and that the composition of exhaust gas meets standard requirements. The air supplied to an internal combustion engine has to be adequately filtered because impurities reaching the engine can accelerate the wear of engine components. The air intake system features a filtering partition which captures impurities and prevents them from reaching the engine. However, the filtering process decreases the rate at which cylinders are filled with fresh air, which can compromise engine performance. Therefore, effective solutions are needed to ensure that the flow of filtered air does not significantly decrease the volumetric efficiency of cylinders.

This study presents a design concept of a device for measuring pressure in the air intake system in front of and behind the filtering partition. The proposed device can be useful for measuring filter wear. A prototype of the proposed device was built and tested on several air filters. To eliminate throttle valve impacts, the device was tested in a compression ignition engine. The results of the conducted tests demonstrated that the device correctly measured air flow. The conducted measurements also revealed that the presence of impurities in the air filter induced differences in pressure in the air intake system in front of and behind the filtering partition. The maximum air flow resistance in a clogged filter could be even 100% higher than in a brand new filter.

Keywords: internal combustion engine, filter, impurities, air flow resistance

1. Introduction

Internal combustion engines are immensely popular around the world, and they are used main to power motor vehicles and machines. Long engine life and reliability are very important parameters because they minimize repair and servicing costs. The operating fluids in a vehicle should be characterized by adequate purity to meet the requirements of both engine designers and users. Vehicle fluids are purified by filtration. Internal combustion engines are equipped with three basic types of filters: the air filter, the oil filter, and the fuel filter. Depending on their structural characteristics, engines can also be equipped with other types of filters.

The purity of the air drawn in by the engine significantly affects the engine's life, performance and operating parameters such as the maximum power and torque. The quality and purity of operating fluids, including fuel and engine oil, are not regulated by universal standards, which is why impurities should be effectively filtered out during vehicle operation. Air is contaminated with impurities of both anthropogenic (industry, fuel combustion in power plants) and natural origin (such as volcanic eruptions) (CHŁOPEK, JAKUBOWSKI, 2009). The presence of hard particulate matter in air can lead to the gradual degradation and loss of engine components due to mechanical friction. Particles with a diameter equivalent to the thickness of lubricant oil film which is formed at the point of contact between engine components pose the greatest threat (DZIUBAK, 2016). Atmospheric particulate matter is composed mainly of hard particles that are deposited between interacting surfaces inside the engine (CHŁOPEK, JAKUBOWSKI, 2010, CHŁOPEK 2012, DZIUBAK 2003, 2006, DZIUBAK, BORCHET, 2017). Other pollutants, including organic particulate matter, can also compromise engine performance.

Air-borne impurities have to be filtered out before they reach the engine. However, every filter adds resistance to the flow of air and decreases the rate at which cylinders are filled with air. Various air filtering solutions for internal combustion engines have been proposed over the years. The optimal solution should be characterized by high filtering efficiency, low air flow resistance and a long service life. Every filtering partition adds resistance to the air drawn in by the engine. The higher the generated resistance, the smaller the quantity of air reaching the engine's combustion chamber. Flow resistance is determined by the difference in air pressure in front of and behind the filter. The difference in air pressure on both sides of the filter can be measured to calculate flow resistance.

2. Types of air filters in internal combustion engines

The optimal air filter in an internal combustion engine should be characterized by high filtering efficiency (above 99%), the lowest possible air resistance, and a long service life. The filter should be reliable, small and light-weight (DZIUBAK, SZWEDKOWICZ, 2013). The flow resistance of an air filter directly influences the volumetric efficiency of cylinders.

According to Polish Standard PN-B-76004:1996, the dust for filter efficiency tests should have the following composition:

- 72% of Arizona desert sand (mostly silica) with an estimated density of 2.7 g/cm^3, where the majority of particles have a diameter of around 7.7 μm,
- 23% of soot,
- 5% of cotton linter.

Various air filters that differ in parameters and structure have been designed over the years. Mesh filters are composed of fine metal strips, metal rings or labyrinth strips enclosed by wire mesh. These filters have small dimensions, and they can be applied in motorcycles and low-power industrial engines (KORDZIŃSKI, ŚRODULSKI, 1968). Another type of air filters are foam filters where air passes through a thin layer of liquid oil or thick oil foam. Foam filters are more efficient than mesh filters, but they are also characterized by higher flow resistance. Particulate matter is trapped in oil which has to be regularly replaced. Foam filters are large, and they are used mainly in heavy-duty machines. Dry filters containing absorbent paper are most popular. Machines that operate in a dusty environment are equipped with cyclone filters which are also known as centrifugal separation filters. Cyclone filters are characterized by low flow resistance. They can be coupled with dry paper filters and used as coarse filters in the first stage of the filtration process, which considerably prolongs the service life of the entire filtering system.

2.1. Dry air filters

In dry air filters, air flows through a porous filtering layer which constitutes a structural partition. Air-borne impurities are trapped by fine fibers of the filtering material. The cartridges in dry air filters consist of absorbent paper or heavy polyester felt. Woven fabric made of natural material or polyester is rarely used. Filter cartridges (Fig. 2.1) remove impurities from air without the involvement of liquids to facilitate the process. The temperature under the hood of a car can reach 120°C; therefore, air filters have to be flame retardant. Phenolic resins are sprayed on the surface of dry filter cartridges to offer additional protection against heat. Most dry air filters contain cellulose fibers impregnated with resin (HUTTEN, 2016). The average density of a cellulose fiber filter ranges from 110 g/m^2 in light panel filters to 210 g/m^2 in two-layered composite filters. The engines of heavy-duty machines do not require highly efficient air filters, and filtering materials for this type of equipment are characterized by lower density in the range of 90-160 g/m^2.

Figure 2.1. Examples of dry paper filters

Modern filtering fibers have a gradient structure, where the packing density of fibers increases in the direction of air flow (Fig. 2.2) (DZIUBAK, SZWEDKOWICZ, 2014).

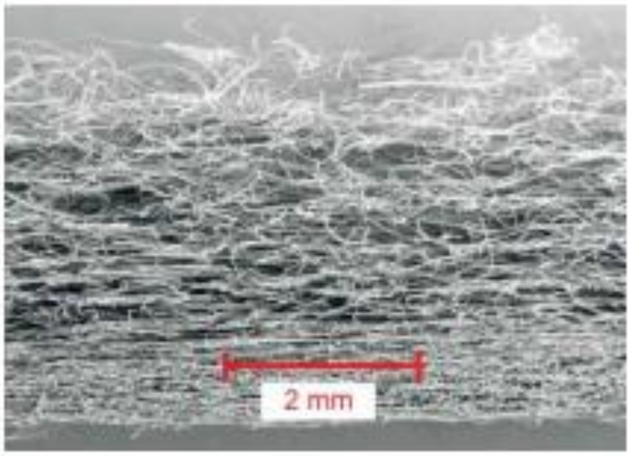

Figure 2.2. Filtering material with a gradient structure and increasing fiber packing density (DZIUBAK, SZWEDKOWICZ, 2014)

Polymer nanofibers manufactured by the electrospinning technology are a novel filtrating medium. Electrospun fibers have a diameter of 1 – 2000 nm. Nanofibers are formed in an nanomesh with a thickness of 1-5 µm. A nanomesh is composed of very densely packed fibers, and it can capture particles with a diameter of less than 5 µm; therefore, the generated flow resistance is minimal (DZIUBAK, SZWEDKOWICZ, 2014). However, nanomeshes have very low mechanical resistance, and they cannot be applied independently as filtering materials. A thin nanomesh layer is applied to conventional filtering materials such as absorbent filter paper or filter fabric.

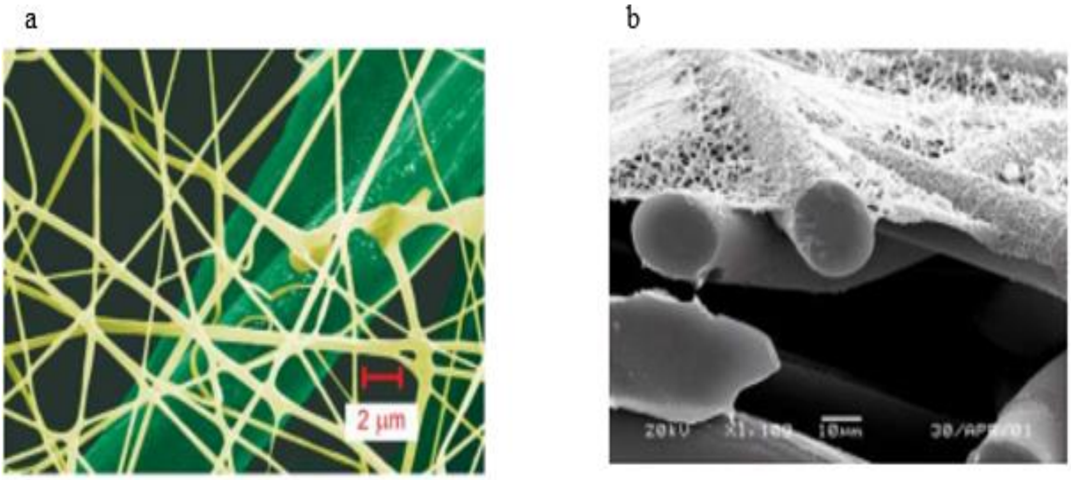

Figure 2.3. Nanomesh layer applied to cellulose fibers: (a) top view, (b) cross-section. Nanofibers have a diameter of around 250 nm, and cellulose fibers have a diameter of around 10 µm (DZIUBAK, SZWEDKOWICZ 2014)

2.2. Cyclone filters

A cyclone filter relies on the principle of inertia to remove particulate matter from air. A cyclone filter does not contain a filtering partition or liquid to capture impurities. Air is fed into the centrifuge chamber where a spiral vortex is created. The force of inertia acts on dust particles which are thrown against the walls of the separating chamber. A cyclone filter which removes impurities through centrifugal separation is presented in Figure 2.4.

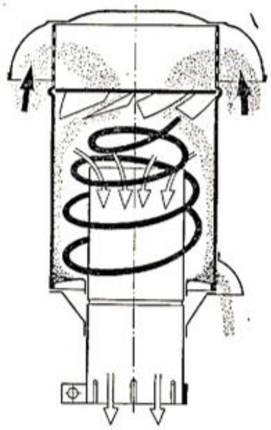

Figure 2.4. A cyclone filter where impurities are removed through centrifugal separation. The direction of air flow is marked with arrows (KORDZIŃSKI, ŚRODULSKI, 1968)

3. Research objective

Air filters in internal combustion engines have to be regularly replaced. In some cases, the replaced filter is still fit for use, which generates additional and unnecessary costs. For environmental reasons, filters should be replaced only when they are clogged. Spent filters cannot be reused and they generate additional waste, which has an adverse impact on the environment. An air filter should be replaced when air flow resistance exceeds the threshold value specified by the manufacturer. Air flow inside the filter and the degree of filter wear could be measured with a dedicated device to determine whether the cartridge should be replaced. Such a device could be used in automotive garages and repair shops to generate environmental benefits.

The aim of this study was to design and build a device for measuring air flow resistance in an engine air filter. The device measures air pressure in front of and behind the filter. The designed device was tested by measuring air flow resistance generated by various types of engine air filters.

4. Design assumptions for a device measuring air flow resistance in engine air filters

A dedicated device for measuring air flow resistance in an engine air filter was designed. Air flow resistance is determined by measuring the drop in air pressure on both sides of the filtering partition. Based on the adopted requirements, the proposed device should:

- consist of low-cost and widely available components,
- measure air pressure in front of and behind the air filter,
- be easy to use,
- be light-weight and portable,
- be compatible with various devices that generate air flow,
- operate without a power supply cable (powered by battery or PC via a USB port)

The designed device consists of a unit that measures the resistance of air flowing through the filtering partition and a unit that generates air flow. Air flow resistance was determined by measuring air pressure in front of and behind the filter. Air flow was generated by an internal combustion engine. The pressure in front of and behind the air filter was measured by sensors. A block diagram of the designed device is presented in Figure 4.1.

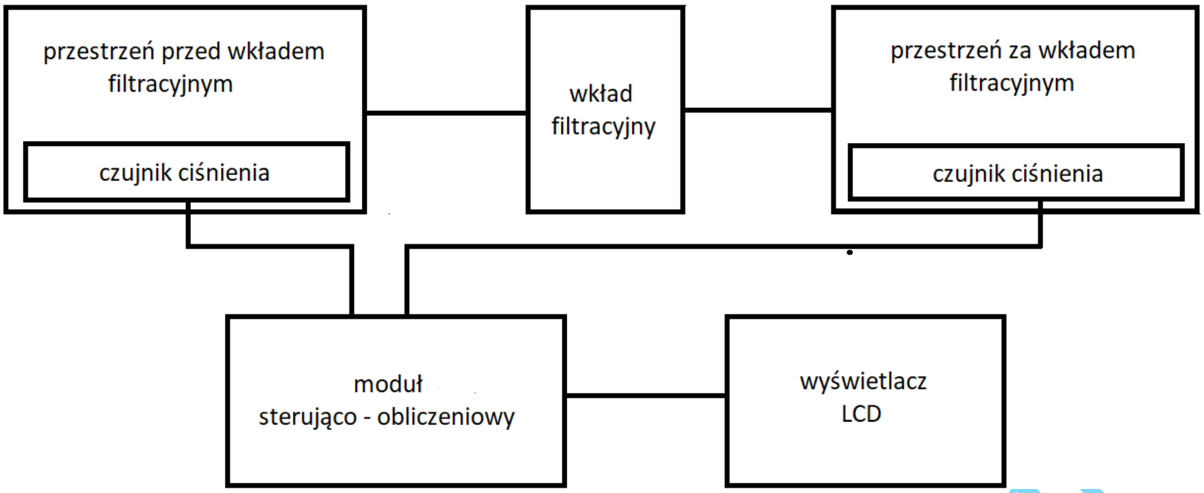

Figure 4.1. Block diagram of the designed device for measuring air flow resistance generated by an engine air filter.

The device was equipped with plastic housing where the tested air filter was mounted. Static pressure sensors were installed inside the rigid housing. The device was connected to an internal combustion engine via a PVC pipe with an internal diameter of 60 mm. The structure of the proposed device supported testing and rapid replacement of various air filters, both brand new and used. The shape of the tested filter had to be compatible with the assembly site to guarantee tight connections between the spaces in front of and behind the filtering partition. For the device to operate with various devices that induce air flow, the connecting pipes should have compatible diameters and the device has to be supplied with power, for example from a laptop. Air flow resistance generated by the tested filter was measured in the following steps:

1. The device for measuring air flow resistance was connected to the device that generates air flow.
2. The tested air filter was mounted in the housing.
3. The measuring device was supplied with power.
4. Both devices were activated.
5. Air pressure was read from the LCD display.

Pressure values were recorded and used to calculate air flow resistance with the use of the following formula:

$$P - Z = R \qquad (4.1)$$

where:
P – pressure in front of the filtering partition,
Z – pressure behind the filtering partition,
R – pressure drop.

The device was equipped with the Arduino MEGA electronic control unit which is highly popular and widely available in retail. This controller has the required number of ports for connecting the device, and it is compatible with the applied pressure sensors. The Arduino MEGA controller communicated with pressure sensors and the LCD display via the I^{2}C interface with 4 pins: serial data line (SDL), serial clock line (SCL), positive power supply (VCC) and power ground (GND). Each device communicating with the I^{2}C bus should have a different address. The designed device was equipped with two pressure sensors with different addresses: BMP 180 with address 0x67, and BMP 280 with address 0x66. Two pressure sensors were used instead of a single differential pressure due to lower cost. When operated at a temperature of 0-65°C, sensor BMP 180 has a pressure measuring range of 950-1050 hPa with an accuracy of ±1 hPa, and sensor BMP 280 has a pressure measuring range of 300-1100 hPa with an accuracy of ±1 hPa (Bosch datasheet). Sensor BMP 180 has a sampling rate of up to 120 Hz, and sensor BMP 280 – up to 157 Hz. Sensor data were displayed on an LCD display with 4x20 characters. The circuit diagram of the designed device is presented in Figure 4.2.

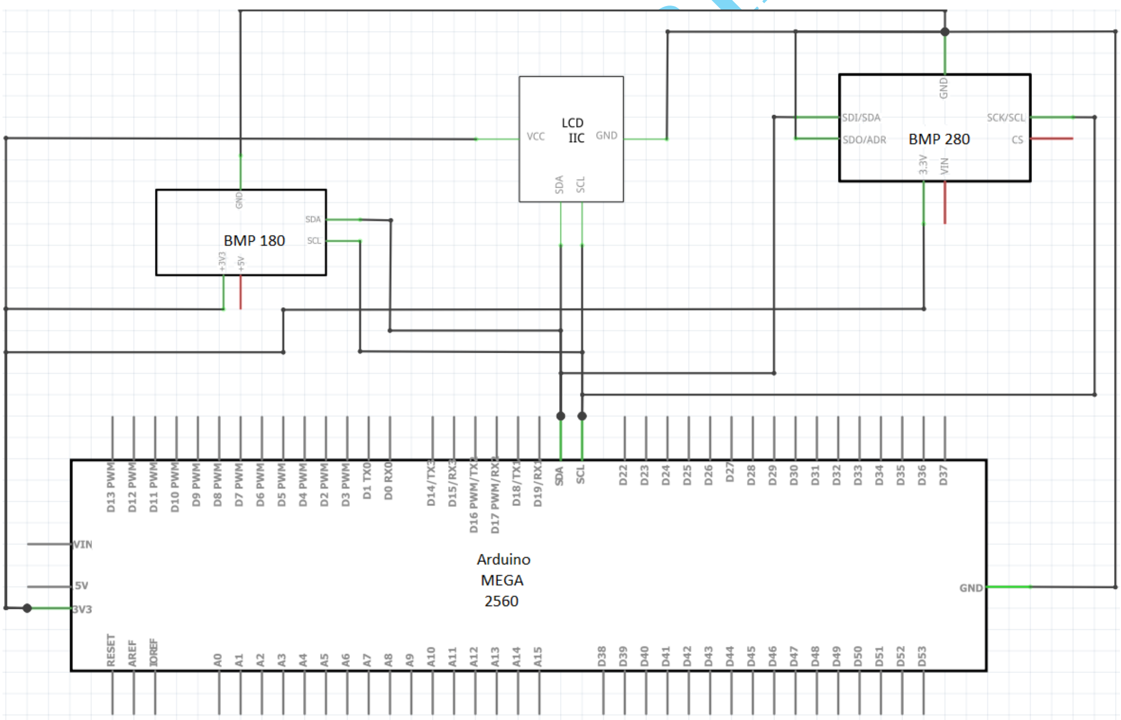

Figure 4.2. Circuit diagram of the designed device.

5. Measurements of air flow resistance in various types of air filters and discussion of the results

The operation of the proposed device was tested by measuring air flow resistance added by various types of air filters. Air flow was generated by a Volvo compression turbocharged compression ignition engine. The engine was mounted in a vehicle with a mileage of around 460,000 km. The technical specification of the engine is presented in Table 5.1.

Table 5.1. Technical specification of a turbocharged compression ignition engine

Displacement	2401 cm^3
Fuel	Diesel oil
Maximum power	163 KM (120 kW) at 4000 rpm
Maximum torque	340 Nm at 1750 rpm
Compression	turbocharged
Engine layout	DOHC
Number of cylinders	5
Cylinder configuration	inline
Number of valves	20
Compression ratio	18.0 : 1
Injection	common rail direct injection
Ignition	compression ignition

The proposed measuring device before connection to the engine is presented in Figure 5.1.

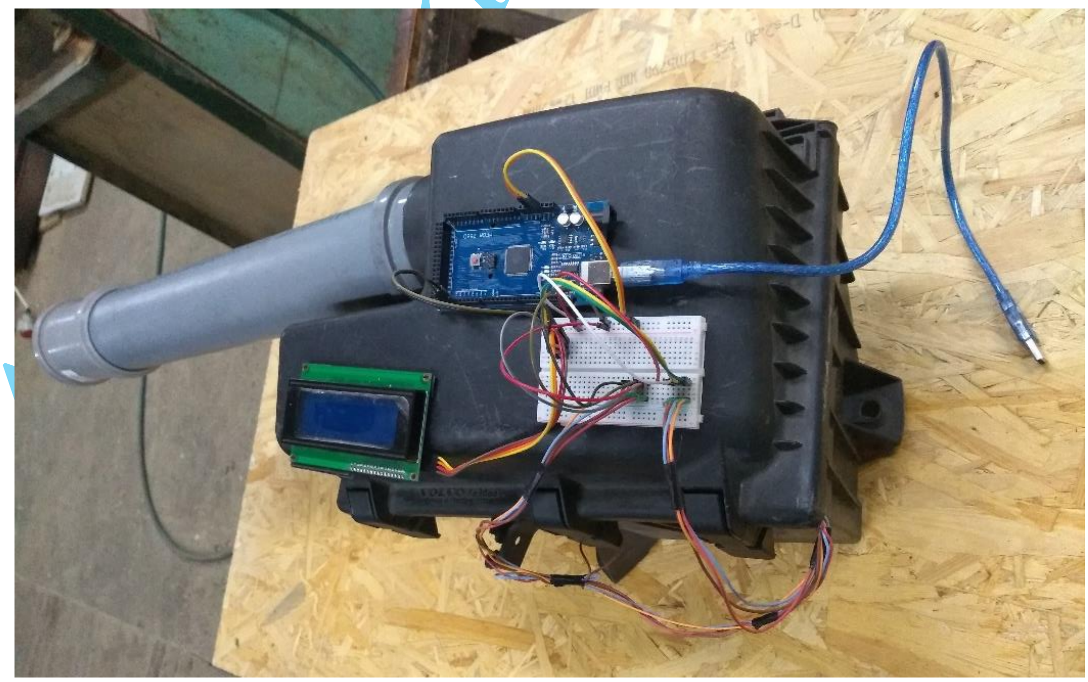

Figure 5.1. The proposed device before connection to the engine

Four air filters with suitable dimensions for mounting inside the housing of the developed device were used in air flow resistance tests:

- brand-new high-performance Pipercross air filter for motor sports (Fig. 5.2.),
- brand-new standard Mann-Filter air filter (Fig. 5.3.),
- used standard air filter with a mileage of 10,000 km (Fig. 5.4.),
- used standard air filter with a mileage of 20,000 km (Fig. 5.5.).

The tested air filters are presented in Figures 5.2-5.5.

Figure 5.2. Brand-new high-performance Pipercross air filter

Figure 5.3. Brand-new standard Mann-Filter air filter

Figure 5.4. Used standard air filter with a mileage of 10,000 km

Figure 5.5. Used standard air filter with a mileage of 20,000 km

5.1. Experiment and measurement results

The developed device for measuring air flow resistance was tightly connected to the engine’s air intake system before the air flow meter with the use of tubes with an internal diameter of 60 mm. The measuring device was powered from a laptop via a USB port. The measuring device connected to a compression ignition engine is presented in Figure 5.6.

Figure 5.6. Measuring device connected to a compression ignition engine

The measurements were conducted indoors at a temperature of around 25-30°C. During measurements, the rotational speed of the engine was maintained at the desired level with the accelerator pedal in the vehicle, and air pressure at the inlet and outlet of the air filter was read and recorded. The rotational speed of the engine was read to the nearest 100 rpm. The operation of the measuring device was validated based on the results of a single series of measurements because the test stand did not support further measurements under repeatability conditions.

The differences in air pressure in front of and behind the air filter and error bars representing errors at the measurement points are presented in Figure 5.7. Pressure values were converted to kilopascals [kPa]. Since only a single series of measurements was conducted, the maximum error had to be calculated and taken into account based on the technical specification of the pressure sensors. The maximum measurement error was estimated at ± 0.2 kPa. Measurement results were registered with the use of formula 5.1 (BIELSKI, CIURYŁO 2001).

$$i = (\{x\} \pm \{\Delta x\}) \quad (5.1.)$$

where:

i – measurement result

x – measured value

Δx – maximum error

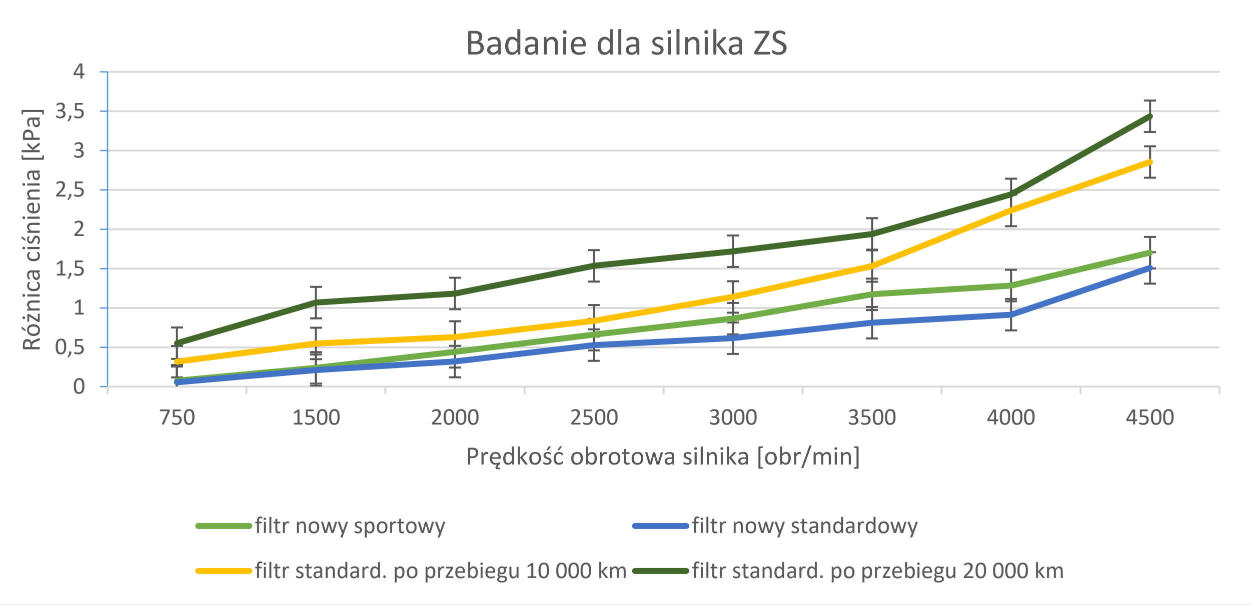

Figure 5.7. Difference in the pressure of air flowing through the air filter

5.2. Discussion

The filtering partition adds resistance to the flow of incoming air, which leads to changes in air pressure in the air duct, measured directly in front of and behind the filtering partition. The proposed device was used to determine the relationship between the degree of filter wear and the resulting drop in air pressure. Air pressure in the inlet duct decreased relative to atmospheric pressure with an increase in the rotational speed of the engine. As demonstrated by the diagram in Figure 5.7, the pressure drop generated by all of the tested filters was exacerbated by a rise in engine speed. This is because the rate at which air is sucked into the engine increases, whereas the surface area of the filtering partition remains unchanged.

When pressure measurements are conducted at low engine speed, the average air pressure may be difficult to determine because pressure values fluctuate rapidly, but within a limited range of values, in front of and behind the filtering partition. The above could be attributed to the fact that drawn air does not flow with uniform velocity in the direction of the cylinders. Cylinders, opening and closing valves, and the specific shape of the inlet duct create a pressure wave and cause air to bounce back and forth across the intake manifold. These phenomena are particularly visible at low rotational speeds of the engine.

The results shown in Figure 5.7 present the resistance generated by the tested filters. The standard filter, both brand-new and with a mileage of 10,000 km, created the smallest resistance.

In the standard filter, air pressure decreased due to the accumulation of particulate matter over time, which led to a minor decrease in dust-holding capacity, but increased filtering efficiency. The high-performance filter for motor sports produced interesting results. Theoretically, this filter should add least resistance to air flow. However, the results of the study indicate that the high-performance filter induced a greater drop in air pressure than a brand-new standard filter. Air flow resistance was highest in the standard filter with a mileage of 20,000 km. In this filter, the greatest difference in air pressure on both sides of the air filter was around 3.5 ± 0.2 kPa at engine speed of 4500 rpm. The most worn-out filter was considerably clogged with dust, and it put up the greatest resistance to the flow of incoming air. The smallest difference in air pressure was observed in the brand-new standard filter where the maximum resistance reached 1.5 ± 0.2 kPa at engine speed of 4500 rpm.

The results of the conducted tests demonstrated that the proposed device meets expectations and correctly measures changes in air pressure. Tests involving the designed device should be conducted indoors to minimize the impact of weather phenomena (rain, wind) and sudden changes in temperature.

6. Conclusions

This study addresses the problem of air impurities in internal combustion engines. Various types of air filters were described. A device for measuring air flow resistance in filters was designed and built based on the adopted requirements. The device was tested on various air filters in a compression ignition engine. The results revealed that the proposed device meets expectations and correctly measures air pressure in front of and behind an air filter in a compression ignition engine. An analysis of test results confirmed the presence of a correlation between various types of filters and filter wear. A standard air filter with a mileage of 20,000 km added the greatest resistance to air flow. At engine speed of 800 rpm, air flow resistance was very high at 0.5 ± 0.2 kPa. The operation of an idling engine was disrupted and rough when the most worn filter was installed. The remaining filters did not generate such problems. The results of this study indicate that high-performance air filters for motor sports are not always characterized by lower air flow resistance than standard filters. The proposed device and the described research methodology can be used to measure air flow resistance generated by air filters in motor vehicles.

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