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DEVISING A MODEL OF THE AIRFLOW WITH DUST PARTICLES IN THE INTAKE SYSTEM OF A VEHICLE'S INTERNAL COMBUSTION ENGINE

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This paper considers the mechanism of malfunction of internal combustion engines that implies the accelerated local wear of parts in individual cylinders as a result of uneven distribution of dust particles that pass through the air filter in the intake system.

In order to acquire quantitative data on the effect of the structure of the intake system on the redistribution of dust in engine cylinders, the two-phase flow of air with dust particles in the standard elements of the intake system was mathematically modeled.

ANSYS software package was used to solve the problem. A simulation technique was devised in which the airflow was first calculated to determine the boundary conditions for dust, after which the flow of air with particles was calculated. The calculations were carried out in a range of air velocities of 5–20 m/s in branching channels with diversion angles of 45°, 90°, and 135° for the most characteristic particle sizes of 5–30 μm. It has been estimated that dust particles deviate from the air streamlines by inertia and can slip through the lateral drain the stronger the larger particle size, diversion angle, and velocity of air.

The comparison of the simulation results with experimental data confirmed that in the intake system of some engines, due to uneven particle distribution, there is local abrasive wear in one or more cylinders, which can significantly reduce the resource. This paper shows the need to take into consideration the centrifugation and redistribution of dust in the intake systems during the design, modernization, expert studies to determine the causes of faults associated with faulty operating conditions, as well as to clarify the regulations for the maintenance of existing engines

Keywords: internal combustion engine, intake manifold, two-phase flow, dust particles, centrifugation

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1. Introduction

For a long time, the practice of designing and operating internal combustion engines (ICEs) assumed that the air entering the engine, after proper cleaning with the air filter, was clean of dust. Then the dust has no effect on the current processes over the life of the engine. Conversely, in the case of dust-cleaning problems, the engine could undergo accelerated abrasive wear.

However, this simplified model of dust effect on the engine does not quite correspond to modern engines, in which accelerated abrasive wear may arise as the consequence of other reasons, including the design features of the intake system.

A standard intake manifold in a multi-cylinder car engine due to a sharp turn of flow can cause the centrifugation of dust and its uneven distribution in cylinders. Under such conditions, the dust particles will be affected by the forces of inertia at sharp turns of the flow, which can lead to uneven distribution of particles through the channels and affect the wear of individual cylinders in the engine. To prevent the engine's resource from decreasing due to the accelerated wear of some of its elements, it is necessary to investigate particle centrifugation processes in individual nodes and the intake manifold in general.

2. Literature review and problem statement

Our review of the scientific literature reveals that the model of simplified, that is excluding dynamic processes in the intake system, effect of dust on the wear of ICE parts, has been widely used. Thus, work [1] shows the most characteristic approach to this issue when the dependence of wear only on the properties of abrasive particles, material and mechanical processing of working surfaces of friction pairs is investigated. Work [2] examines in detail all the tribological aspects of engine wear but does not highlight the impact of the uneven distribution of dust particles across friction vapors.

Traditionally, significant efforts have focused on studying the abrasive wear of parts and how to reduce it as a basic way to improve engine reliability and durability. On the one hand, this pathway involves giving high-strength to friction pairs; work [3] reports a detailed study of materials and their application to reduce the wear of parts. On the other hand, reducing wear requires an increase in the efficiency of air purification, which is tackled, for example, in work [4]. This overlooks the fact that the flow of air with dust particles is 2-phase, and its nature can have an impact on the abrasive wear and durability of the engines.

However, in many ICE studies, this nature of the flow is not taken into consideration. This flow, on the other hand, is explored in detail in applications for industrial centrifugal air purification. For example, work [5] reports a numerical simulation of a two-phase flow, which made it possible to determine the streamlines of air and dust particles in the cyclone separator at different velocities at the inlet. A similar study is described in work [6] but in relation to different shapes and sizes of particles. However, since the conditions, flow parameters, and geometry of the channels do not correspond to the ICE inlet system, it is not possible to apply these procedures and the results to the engines.

Works by modern researchers on the theory [7], the design of engines for passenger transport [8], and heavy machinery [9], operation, malfunctions [10], and diagnostics [11] also do not mention any issues related to 2-phase flows. A conventional approach to this problem also suggests that dust can affect abrasive wear in a standard car engine only if the integrity of the air filter or intake tract is disturbed. Researchers and designers have been building engine and system designs for decades, laying in the calculation models «clean» dust-free air completely cleaned by an air filter. At the same time, those works do not mention any other models while the features of abrasive wear are considered as operational damage, which is typically not taken into consideration in the creation of specific ICE designs. The exceptions are those studies of centrifugal air purification systems and cyclone filters of cars, including both by filter manufacturers [12] and independent researchers [13], where phase flow is taken into consideration in the air filtration quality assessment process. However, the results of filter studies in those works are not applicable and are not used in engine intake manifolds.

At the same time, an analysis of the characteristics of the air filters, reported by independent researchers [14] and manufacturers [15], reveals that the air that passed through the filter is very far from a condition that could be called «clean». Thus, work [16] shows that paper air filters trap only a fraction of the particles the size of that set by the specifications; the smaller the size of the particles, the more such particles pass into the engine. Newer air filters trap more than 99 % of all particles, including the smallest. However, as the filters become clogged during operation, they gradually lose their properties, resulting in dust particles being flowing into the engine.

The situation is complicated by the appearance and distribution of variable length intake systems, which utilize dynamic phenomena to recharge cylinders. For example, paper [7] looks at air flap intake manifold schemes for 2 and 3-step changes in the length of intake pipelines; work [8] shows a large number of other schemes that use this effect. There, the intake manifold is no longer a means of smoothing air pulsations but, on the contrary, the intake manifold can be included in the general vibrational system, and the air velocities in it can be significant. Under such conditions, we should expect uneven redistribution of dust through the intake system channels and cylinders.

3. The aim and objectives of the study

The aim of this study is to build a model of airflow with dust particles in the intake channels and to acquire quantitative data on the effect of the structure of the intake system on the redistribution of dust in the cylinders of an internal combustion engine. This will make it possible to take into consideration the processes of dust centrifugation during design and operation, to avoid reducing the resource of engines and make it easier to find the causes of their malfunctions.

To accomplish the aim, the following tasks have been set:

– to devise a procedure for calculating the movement and distribution of dust along branching intake channels;

– to calculate and assess the impact of the side offtake angle, the velocity of the air, and the size of the particles on the distribution of dust along the channels of the intake system;

– to assess the possible amount of dust that enters the engine cylinders and determine the effect of dust distribution in the intake manifold on the wear and durability of the car's engine.

4. Materials and methods to study the flow of air with dust along the intake channels

It is possible to determine the nature of the movement and to assess the effect of the air velocity and the size of particles on their distribution through the channels of the intake system by numerical modeling of the 2-phase flow (air with dust particles).

One can model working conditions for the selected element in the engine in different ways; we have chosen the distribution of air flow rate at the inlet strictly in half between the direct outlet and side outlet. Thus, the two outlets, direct and side, are taken equally, as is often the case in the ICE intake manifolds. It is in this element that part of the stream rotates, resulting in particles being redistributed unevenly, that is, not proportional to the distribution of air flow rate.

The initial data taken for the simulation included air as a working environment containing dust particles with a density of 2,600 kg/m^3. Particle sizes were consistently set 5, 10, 20, and 30 μm, the velocity of air and particles at the inlet was also set consistently 5, 10, 15, and 20 m/s.

The simulation was carried out with the help of the ANSYS software package, Student version, in several stages: the construction of a finite-volume grid, the creation of the flow model, assigning boundary conditions, the setting of the solver [17, 18]. At the same time, given that the flow of dust particles in the air is a regular 2-phase flow, it was necessary to devise a certain order (technology) of calculations. The main difficulty, which required a special order of calculations, relates to significant differences in the setting of boundary conditions for dust and air.

The mass flow rate of dust particles at the inlet was estimated in the first approximation based on the condition that «over ten years of operation, more than 6 kg of dust attempt to penetrate the engine» [19]. In addition, it was taken into consideration that the modern automotive air filter normally retains up to 99 % of dusty air particles, from which the dust flow rate of 0.016 g/hour or $4.44/10^{-9}$ kg/s was determined.

Next, the trajectories of dust particles are calculated, and, with the help of the built-in function of the calculation module, the number of particles, their velocity, and mass dust flow rate through the channels. Because streamlines provide a more visual representation of the direction and velocity of airflow and particle movement, their diagrams are shown below without individual diagrams of velocity fields.

5. The results of modeling a two-phase flow of air with dust in the intake channels

5. 1. Procedure for calculating the movement and distribution of dust in branching intake channels

It is obvious that the main element of the intake system, in which particle redistribution can occur under the influence of the forces of inertia, is a side outlet tee (Fig. 1). This element is standard of four- and 6-cylinder car engines with a working volume of 1.6 to 3.0 liters or more.

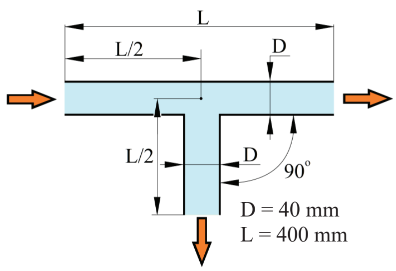


Fig. 1. The geometry of a channel with a side outlet at angle 90° – the length *L* and the diameter *D* are assigned

The following modeling procedure was developed to solve the problem:

1. Build a finite-volume grid with the built-in module of the ANSYS software package. To this end, the size of the flow area element was first set to be 4 mm, after which the entire area was broken into elements with this size. Further, the number of layers of the boundary layer (12) was set, then the size of the border layer elements was obtained from the condition of increasing their thickness from the initial (minimum) factor of 1.2. The grid with 168,267 elements (Fig. 2) was then generated.

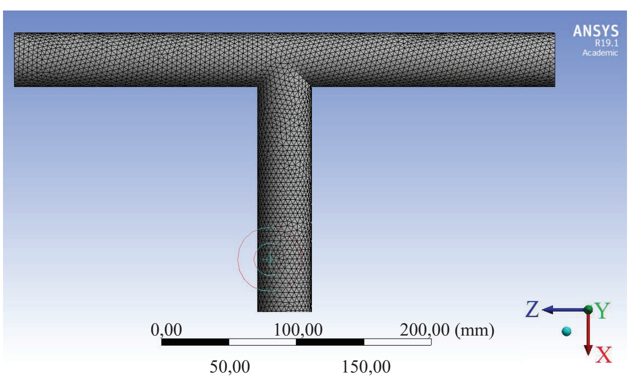


Fig. 2. The finite-volume model of the flow area with a side outlet at 90°

2. Create a calculation model in the standard module (subprogram) Fluent in the ANSYS software package. The calculation model means the choice of material (there are two in the task: air and dust particles), the choice of the flow model, assigning the boundary conditions, the setting of the calculation module (solver).

3. Preliminary calculation of the flow of air. While at the inlet to the pipe the boundary conditions can be set quite simply, then in the outlet cross-sections of the pipes the boundary conditions, namely, pressure, are unknown. Therefore, as the first approximation, only the flow of air was calculated without taking into consideration dust particles.

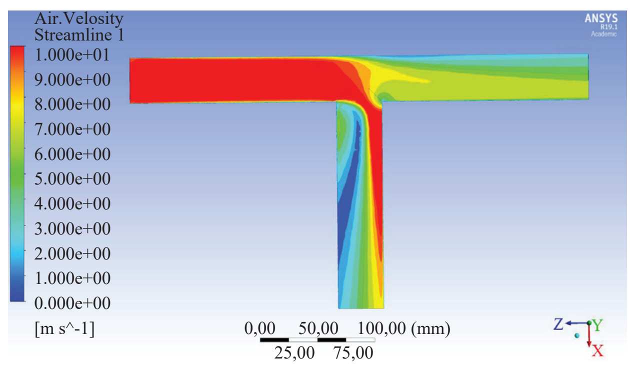
As boundary conditions at the inlet, the velocity of airflow (values in the range of 5–20 m/s) was set, which is accepted equally for the inlet cross-section and directed to it according to normal. A standard k–ε turbulence model was set in the calculation [20]. Mass air flow rate at the inlet was calculated by velocity, area, pressure, and temperature, after which, at each outlet, we established half of this flow rate.

The calculation result yields the fields of pressures, velocities, temperatures, streamlines, etc., derived in the 1st approximation. Also, the average value of the parameters in the cross-sections at the inlet and outlet is determined by the built-in functions of the software module. Then we find the pressure at the outlets as a boundary condition for calculating the movement of dust particles.

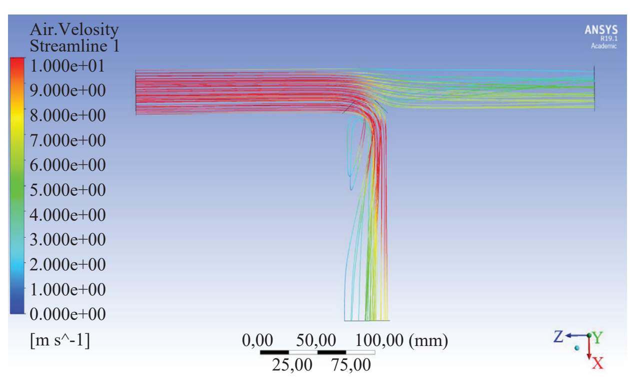
4. Adding a two-phase flow model is done using the Eulerian calculation module. The complete Eulerian model makes it possible to calculate dispersed (multiphase) flows. In our case, there are two phases: air and dust particles, which are considered to be interpenetrating. This model solves its own set of save equations for each phase where phase interaction is described by additional components in the save equations. The types of interaction depend on the class and mode of the flow. At the same time, a special version of the model, Eulerian Granular, to where we assigned a new material – dust particles – was used for a solid dispersed phase.

5. Setting refined boundary conditions. For the air, we set the following boundary conditions: at the inlet – velocity (as in the preliminary calculation), and at the outlet – only pressure, derived in the 1st stage of airflow calculation. For dust particles at the inlet, we set their size and mass flow rate (the velocity of particles at the inlet was taken equal to the air velocity).

6. Start the calculation in the 2nd approximation with new boundary conditions for a 2-phase flow; review and analyze the results. Streamlines and velocity lines are defined, as well as refined air flow rate values in the direct and side outlets (Fig. 3).



a



b

Fig. 3. Results of the refined calculation of the flow of air in a branching channel at angle 90°: *a* – the field of flow velocities, *b* – the flow streamlines

Next, with the program's built-in solver, one can calculate the desired ratio of dust particles in the outlet cross-section to the input flow rate for different particle sizes, air velocities, and side offtake angles.

5. 2. The results of dust distribution calculation at different angles, air velocities, and particle sizes

The resulting 2-phase flow simulations in the air velocity range of 5–20 m/s at the size of particles 5–30 μm show that small particles move almost along the air streamlines. At the same time, the particles do not demonstrate deviations from the air streamlines when turning into a side outlet.

At the same time, the larger the size of particles and the velocity of the air, the more particles do not enter the side outlet, «jumping» by inertia directly through the pipe. As a result, between the flow of small particles (5 μm) at low rate (5 m/s) and large size (30 μm) at high rate (15 m/s), there is an expected and quite noticeable difference (Fig. 4).

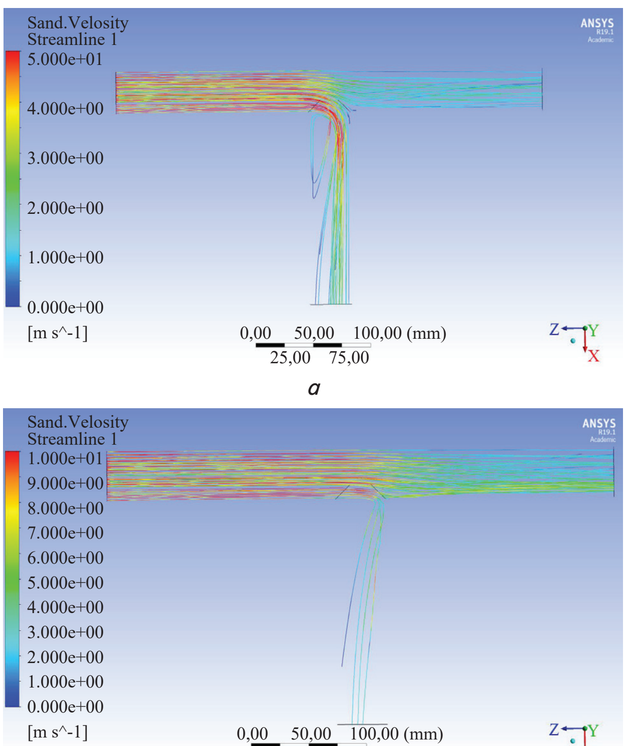


Fig. 4. The trajectories and velocity of dust particles in a branching channel at angle 90°: *a* – particles of 5 μm, which move at the inlet at a rate of 5 m/s; *b* – 30 μm particles that move at the inlet at a rate of 15 m/s

For practical purposes, the mechanism of engine malfunctions is better visually represented not by the air velocity but by the mode of operation of the engine. Indeed, the air velocity is proportional to the engine's mode of operation at the predefined channel cross-sections and cylinder volume; our air velocity range of w=5–20 m/s is roughly equivalent to the engine's 1.6-liter volume in the range of modes n=1,000–6,000 min^{-1} at full capacity.

Assuming that the V_h volume engine cylinder is powered through a side outlet of area F, one can write down the airflow equation in the following form:

$$\rho w F = \mu_V V_h \frac{n}{60}, \qquad (1)$$

where μ_V is the filling factor is (in the 1st approximation, we accepted it constant and equal to 1.0), n is the frequency of rotation.

Formula (1) produces, for the preset initial data, an approximate link between the air velocity and the rotational frequency in the form of n=300, which is convenient to use to illustrate the calculation results.

In addition, there were no calculations when graphically representing the results for a rate of zero. However, for zero velocity, it was conditionally assumed that there was no redistribution of particles in the absence of the action of gravity forces on them (for the horizontal arrangement of a channel) and centrifugal forces.

The results of calculations using the built-in function of the software calculation module relative to the number of particles on the way out of the direct channel are shown in Fig. 5.

The relative flow rate of particles G_{ex} at the outlet of the channel (related to the number of particles G_{in} at the inlet) is noticeable due to the «slipping» of particles past the side outlet with an increase in the air velocity and particle size.

The modeling of the flow for angles 45° and 135° was performed in the same way as it was carried out for an side offtake angle of 90°, that is, with the same initial data. As a result of calculations, streamlines and air velocity streamlines (Fig. 6) were obtained for the assigned offtake angles over the entire range of velocity at the inlet.

The appearance of a double (behind the sharp and blunt angles of the walls) vortex at the turn of the stream at 135° (Fig. 6, *b*) is noteworthy – as opposed to a much smoother turn of 45° (Fig. 6, *a*). It is obvious that the presence of a vortex will affect the trajectory of particles, which was confirmed further in our calculations (Fig. 7, *a*) – dust particles, especially small, repeat the vortex nature of the airflow. At the same time, the movement of dust particles at an side offtake angle of 45° (Fig. 7, *b*) is as smooth as the movement of the air.

The results of our calculation indicate the obvious passage of dust particles under the influence of the forces of inertia past the side outlet, which is stronger, the greater the flow velocity, particle size, and turning angle. A detailed analysis of the location of the flow lines of particles of different sizes, obtained during the simulation, shows that even when turning at 135°, a significant part of the small (5 μm) particles turns into a side outlet along with the air. However, most particles slip past the side outlet already at medium sizes and velocities, and, at a rate of 15 m/s, there is no longer a single particle of 30 μm, which turns into a side outlet. At the same time, when turning at 45°, even at a high rate (15 m/s), there are still a number of large particles (30 μm) that deviate to the side outlet.

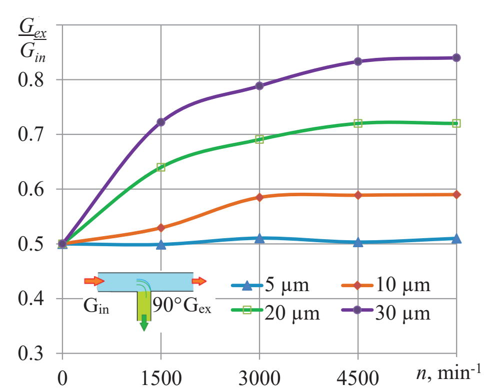
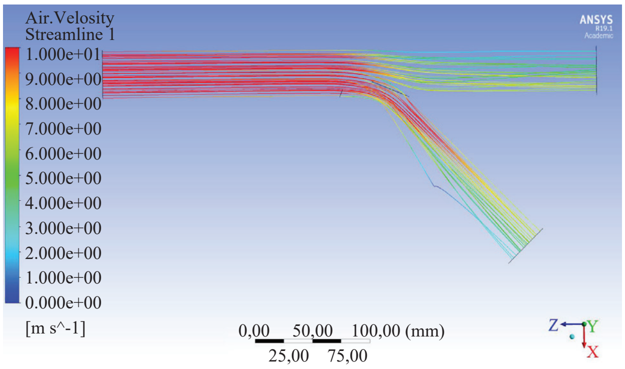


Fig. 5. The results of the simulation of a two-phase flow of air with dust in a channel with a side outlet at an angle of 90°



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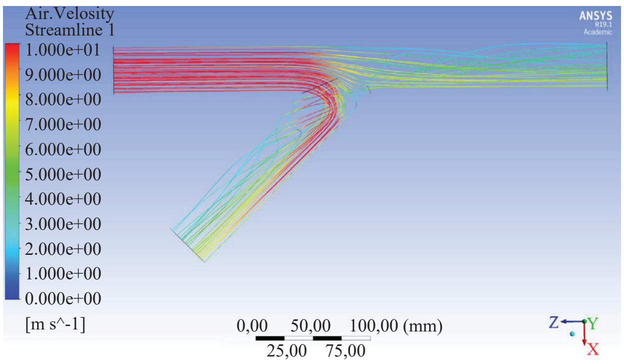
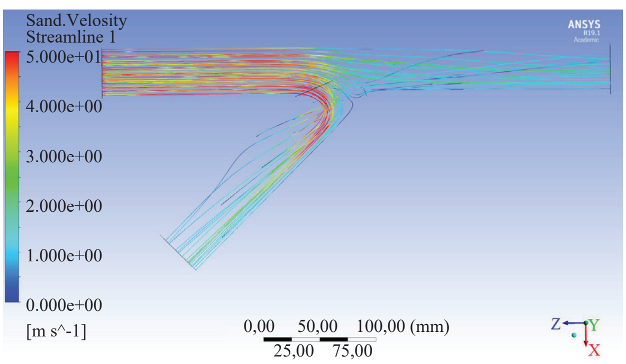


b

Fig. 6. Streamlines and air velocity steamlines (at a 10 m/s rate at the inlet) in a channel with a side outlet at an angle: *a* – 45°, *b* – 135°



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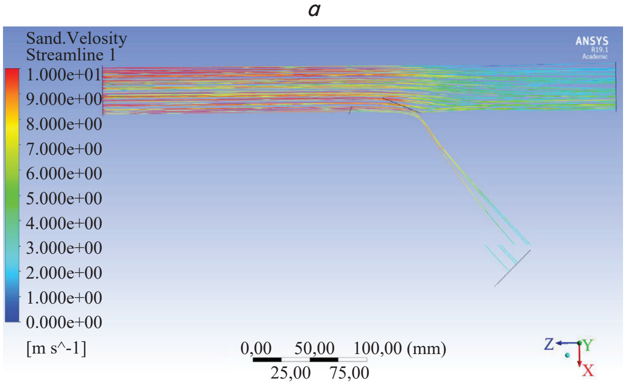
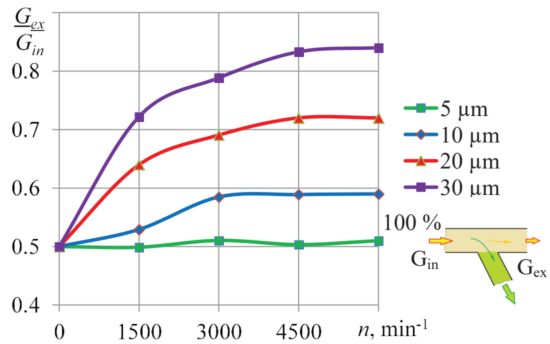


b

Fig. 7. Dust particle flow lines in a channel with outlets at different air velocity and particle sizes: *a* – 135°, *d*=5 μm, *v*=5 m/s; *b* – 45°, *d*=30 μm, *v*=15 m/s

The effect of the engine mode operation (flow velocity) and particle size on their channel distribution along the channels is well illustrated by Fig. 8.



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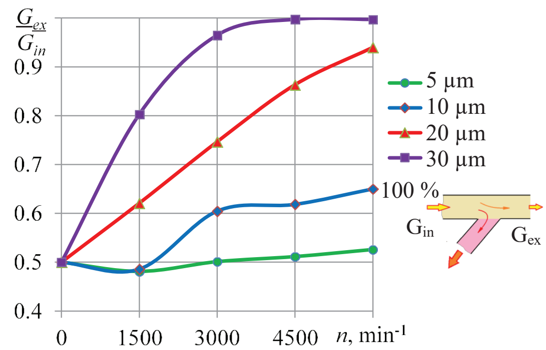


b

Fig. 8. The results of the simulation of a two-phase flow in a channel with a side outlet at an angle: *a* – 45°; *b* – 135°

It is easy to notice that regardless of the side offtake angle, small particles turn into the outlet along with the air under any modes (Fig. 8, *a*). At the same time, large particles on elevated modes and at large angles completely slip through the outlet (Fig. 8, *b*).

5. 3. Assessment of the impact of dust distribution on car engine wear and durability

For practical tasks, the pattern of the redistribution of dust in the entire intake manifold, consisting of several successive outlets, is interesting. One can accurately calculate the distribution of dust for any number of outlets if they are all included in a 3D model of the intake manifold.

However, such a task is complex and requires appropriate software resources. This does not correspond to the tasks of operation of engines, nor expert studies of their technical condition (it is doubtful that in expert practice someone should conduct such complex and expensive research). Therefore, an approximate method was devised, using the results of modeling of individual elements (channels with side outlets).

For example, in the course of expert examination of the technical condition of a 3.5-liter V-shaped petrol engine [21], a significant difference was found between the wear of parts in the cylinder-piston group and the valve mechanism in the cylinders of one row.

The intake manifold of a given engine (Fig. 9) has a variable length and division into the upper and lower parts (for the rows of cylinders), which can connect sequentially or in parallel, depending on the mode of operation of the engine. At the same time, the flow velocity in the middle part of the intake manifold should be enough to implement the wave processes of recharging cylinders, so it is possible to redistribute dust particles through their centrifugation.

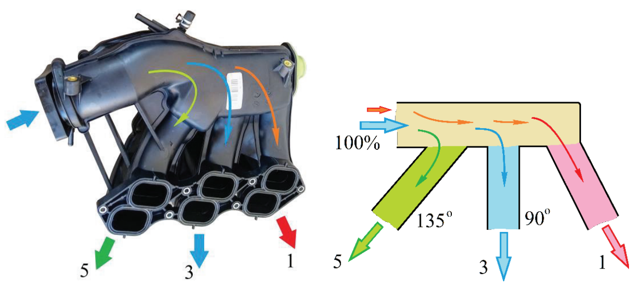


Fig. 9. The ICE intake manifold with different offtake angles (digits 1, 3, and 5 are the numbers of the engine cylinders): *a* – structural execution; *b* – estimation scheme of the channels' offtake angles

Some simplifications have been adopted in modeling the dust redistribution process. Thus, it is accepted that after entering the intake manifold the dust enters cylinder No. 1 after 2 consecutively placed outlets – cylinder No. 5 at an angle of 135°, and cylinder No. 3 at an angle of 90°. In this case, one can apply the results for each of the outlets in the 1st approximation to calculate consistently and obtain the dust distribution across all cylinders.

According to the intake manifold's diagram, the inlet channel of cylinder No. 3 is located at approximately 90°, and cylinder No. 1 is the final cylinder in the bottom part of the manifold. Then, to balance the flow rate of particles entering cylinders 1 and 3 (G_1 and G_3), one can write:

$$\bar{G}_{90}=\frac{G_3}{G_1+G_3},\quad 1-\bar{G}_{90}=\frac{G_1}{G_1+G_3},\tag{2}$$

where $\bar{G}_{90}$ is the relative amount (flow rate) of particles that enter a 90° outlet.

Part of the dust particles, passing from the inlet cross-section, enters the side channel of cylinder 5, located at an angle of 135°, and, only then, the side channel of cylinder No. 3, and, then, directly cylinder No. 1. Then the relative number (flow rate) of particles entering the side channel can be denoted $\bar{G}_{135}$ – it is also calculated above in a 2-phase model.

All cylinders have the same air flow rate, and, from the condition of close air velocities in the intake manifold, one can assume that the flow rate of particles at the inlet to the intake manifold is proportional to the flow rate of air through all three cylinders. This means that the flow rate of particles at the inlet is equal to $G_\Sigma=1{,}5G_{in}$, where G_{in} is the flow rate of particles at the inlet, taken when solving all particular problems with side outlets.

Under this condition, the flow rate of particles G_{1+3}, which pass directly through the intake manifold after being diverted to cylinder No. 5, is then $G_{1+3}=G_\Sigma-G_5$. The relative (with respect to the flow rate in the inlet cross-section of the intake manifold) flow rates of particles entering cylinder No. 5 and, directly to cylinders No. 3 and No. 1, are equal to:

$$\bar{G}_5=\frac{G_5}{G_\Sigma},\quad \bar{G}_{1+3}=\frac{G_\Sigma-G_5}{G_\Sigma}=1-\bar{G}_5.\tag{3}$$

Ratio (3) for $\bar{G}_5$ can be recorded in the following form:

$$\bar{G}_5=\frac{G_5}{G_\Sigma}=\frac{G_{135}}{1.5G_{in}}.\tag{4}$$

Then, we shall use expressions (2) to (4) to find the desired distribution of particle flow rates, that is the relative amount (flow rate) of particles received from the intake manifold (Fig. 10) to cylinders No. 5, No. 3, and No. 1, depending on the relative flow rates through the individual elements of the intake manifold at angles 90° and 135°:

$$\begin{cases}\bar{G}_1=\left(1-\bar{G}_5\right)\left(1-\bar{G}_{90}\right),\\ \bar{G}_3=\left(1-\bar{G}_5\right)\bar{G}_{90},\\ \bar{G}_5=\dfrac{\bar{G}_{135}}{1.5}.\end{cases}\tag{5}$$

The results of the calculation of dust distribution by cylinders (No. 1, No. 3, and No. 5) from formulas (5), based on the data shown in Fig. 5, 8, are illustrated by a diagram in Fig. 10. The curves represented give some good results for expert practice.

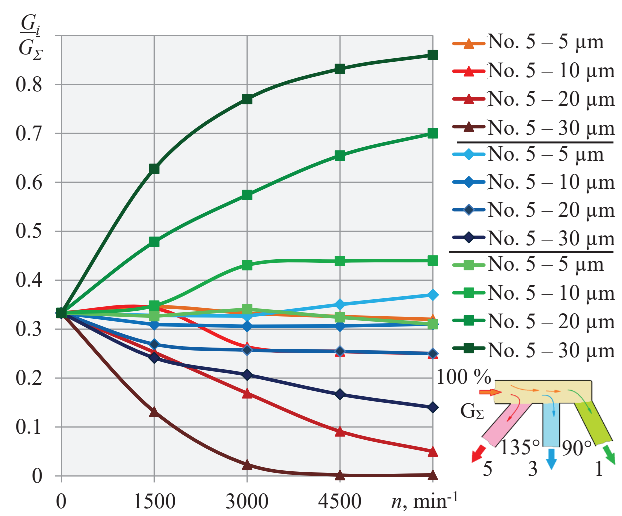


Fig. 10. The ratio of the number of dust particles G_i the size of 5, 10, 20. and 30 μm in the cylinders to the total number of particles G_Σ at the inlet at different rotation frequency n of the crankshaft

Thus, the number of particles entering the middle cylinder (No. 3) weakly varies by regime and conditions. At the same time, the extreme cylinders demonstrate a sharp redistribution of particles towards cylinder No. 1, especially at high rates and large particle sizes. As a result, the greater the velocity and size of particles, the more uneven the distribution of dust in cylinders.

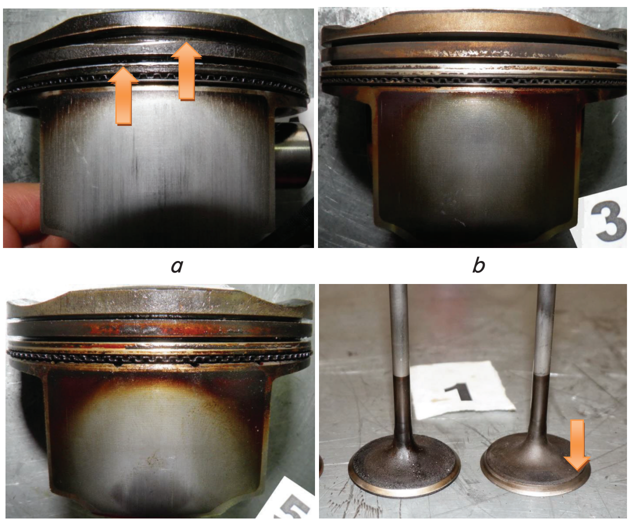
Under medium modes, the extreme (No. 1) cylinder concentrates up to 75–80 % of all incoming dust. At the limit, under the maximum engine mode, 100 % of 30 μm particles are distributed across the cylinders at a ratio of 0 %:15 %:85 %.

Subject to increased modes, this pattern of dust distribution may have a serious impact on the resource of parts in cylinder No. 1. In this case, the durability of parts (and, accordingly, the engine in general) can become many times less than that of other cylinders.

6. Discussion of modeling results and comparison with experimental data

Experience shows that the specific abrasive wear due to the centrifugation of dust in branching channels is observed in the real ICE structures [22, 23]. This wear is particularly severe when operating conditions are violated, from minor violations of engine maintenance regulations and late replacement of the air filter to the improvised modernization of the engine by installing non-regular air filters.

Fig. 11 shows the pistons of cylinders No. 1, No. 3, and No. 5, as well as the valves from cylinder No. 1 of the V6 3.5-liter engine after a car mileage of 24.013 km. The data were acquired under the conditions of violation of operating conditions [21], when using the so-called air filter of «zero resistance» [23]. The engine was equipped with an intake manifold similar to that shown in Fig. 10; it was decommissioned due to excessive oil consumption exceeding the permissible level of 1 liter per 1,000 km of mileage.



a *b* *c* *d*

Fig. 11. V6 engine pistons and valves with an intake manifold shown in Fig. 10 after the operation with a non-regular air filter: *a* — piston No. 1 (arrows show the extremely worn grooves of rings); *b* — piston No. 3; *c* — piston No. 5; *d* — valves of cylinder No. 1 (an arrow shows a heavily worn valve, located further from the inlet to the intake manifold)

The results of micrometric measurements of the parts of a cylinder-piston group are given in Table 1.

The findings suggest that the working surface, piston rings, and piston grooves are most worn in cylinder No. 1. Slightly less wear is demonstrated by cylinder No. 3 (the top rings in these cylinders were broken at the lock due to vibrations caused by an excessive increase in the gap in the pairing with the broken piston groove). At the same time, in other 4 cylinders, the wear is much smaller or even within acceptable limits.

It is difficult to determine the exact quantitative ratios of wear in different types of parts in cylinders by the data obtained for one engine. However, the wear of parts in cylinders No. 1 and No. 3, which is many times larger than in other cylinders, should be paid attention to. This coincides with the distribution of abrasive particles across cylinders (Fig. 10) for the middle engine operational modes. The engine parts of this model are worn out in a very similar way, with a standard air filter, if the rules of its replacement are violated, with the only difference being that the wear lasts for a longer time [21].

Thus, the experimental data obtained from expert examination confirm, in general, the results of our simulation – the dust has not only abrasive properties but also is characterized by particle inertia. Because of this, dust due to particle centrifugation can be unevenly distributed on the elements of the design of the ICE inlet system and concentrated in one of the cylinders, which dramatically increases the wear of its parts. As a result, the durability of the engine is dramatically, by orders of magnitude, reduced and, thus, depends not only on the durability of all parts and the efficiency of the air filter but also on the structures of the intake system.

Analysis of the simulation results and those obtained from experiments shows that the uneven distribution of dust through the channels is due to the significant influence of the forces of inertia and aerodynamic drag on the movement of particles in the airflow. In particular, with the increase in the air velocity, despite the increase in aerodynamic forces, the inertia of particles increases significantly, and the stronger the larger the size and mass of the particle. That causes the trajectories of the particles to deviate from the air streamlines [22]. If small particles follow the air streamlines even at large angles of the flow deviation, at high rates the particles slip past the outlet even at small angles. As a result, with the increase in air velocity (which corresponds to the increase in the rotation speed of the crankshaft and the load of the engine) more particles are collected in the cylinders far from the inlet to the intake manifold.

Table 1

Engine parts measurement results

Parameter		Cylinder No.						Assembly size	Limit size
		Right side			Left side				
		1	3	5	2	4	6		
Clearance in the piston ring lock, mm	Upper	–*	–*	0.55	0.50	0.60	0.45	0.25–0.35	0.5
	Middle	5.50	4.50	1.25	1.45	1.65	1.20	0.5–0.6	0.85
	Oil scraper	0.65	–**	0.60	–**	0.50	0.50	0.1–0.4	0.6
Height of piston rings and piston grooves, mm	Upper groove	1.50–2.50	1.50–2.20	1.23–1.30	1.25–1.30	1.23–1.40	1.26–1.30	1.23–1.26	1.45
	Maximal wear	1.3	1.0	0.07	0.07	0.17	0.07	–	0.20
	Upper ring	1.03	1.04	1.18	1.16	1.14	1.17	1.18–1.19	–
	Maximal wear	0.16	0.15	0.01	0.03	0.05	0.02	–	0.10
Cylinder, mm, upper part	Size***	94.35	94.24	94.14	94.15	94.15	94.15	$94.00^{+0.02}$	94.20
	Maximal wear***	0.35	0.24	0.14	0.15	0.15	0.15	–	0.2

*Note: *– the ring was broken at the lock while the engine was running; ** – the ring lost mobility in the piston groove and was not dismantled; *** – corresponds to the middle ring stop zone in top dead center (TDC).*

The described effect leads to the fact that instead of even distribution of dust and uniform wear of parts in cylinders, the dust is localized in distant cylinders and enhances their wear. At the same time, uneven wear, with the weakening of it in some and simultaneous strengthening in other cylinders, is the reason for the sharp decline in the resource of engines found in this study. It is this feature that can be detected by the proposed model through the simulation of a 2-phase airflow with dust particles instead of «clean» air.

Our results illustrate and explain the mechanism of such specific wear in the operation of engines, including the case of operating conditions violations related to non-compliance with maintenance regulations and replacement of an air filter [21]. It is also necessary to take into consideration the examined mechanism while designing new engines, especially when using devices at the intake that exploit dynamic wave phenomena based on high-speed air movement [7].

Indeed, by applying the data from our study, it can be assumed that some of the principles and models commonly used in engine design do not always produce reliable results. Thus, if calculations and simulations are carried out for «clean» air at the intake, without taking into consideration the actual operating conditions, there is a high risk that the engine resource, in reality, may be significantly, several times, reduced. This conclusion is supported by the expert practice of research into the causes of engine failures.

However, it should be noted that the proposed model is also limited. Thus, this study is based on the modeling of the flow in a simple channel with a side outlet (in our study, the intake manifold was composed of such elements). On the contrary, the actual designs of intake manifolds have a much more complex configuration [8], which affects the results of calculations. In order to acquire more accurate data, it is also necessary to coordinate the flow model with the engine model, which determines the mode of airflow in the intake manifold; in this study, the mode of engine operation was taken into consideration only approximately. In addition, the results reported here are not applicable to all engines but only to those where the high airflow velocity is possible in the intake manifold.

Hence, it follows that the devised model should not be used for all types of designs of modern engines. At the same time, the criteria under which it would be possible to verify and account for the redistribution of dust through the channels of specific structures of intake manifolds have yet to be developed and clarified in future studies.

7. Conclusions

1. We have devised a procedure for modeling a 2-phase flow of air with dust, in which the airflow with particles was calculated first in order to determine the boundary conditions for dust. That has made it possible to determine the air velocity fields and the distribution of dust particles through the intake system channels and explain the mechanism of malfunction in some types of operational damage caused by abrasive wear.

2. The calculations of the 2-phase flow were carried out in the range of air velocities of 5–20 m/s in branching channels with side offtake angles of 45°, 90°, and 135° for the most characteristic sizes of particles of 5–30 μm. The results of the calculations showed that dust particles deviate, due to inertia, from the air streamlines and can slip through the side outlet the stronger the larger the particle size, angle, and air velocity. The uneven distribution of particles under some operational modes is so significant that up to 75–85 % of dust can flow into the extreme cylinder, the most distant from an inlet to the intake manifold. That explains the cause of the observed uneven local abrasive wear of parts in the cylinder-piston group and valve mechanism in individual ICE cylinders and is confirmed by expert examination of the causes of failures.

3. The result of our study has established that the durability of the internal combustion engine can depend not only on the efficiency of air filtration and wear resistance of parts but also on the design of the intake system. Accounting for the distribution of dust particles is important in designing new and modernizing engines already produced, including to clarify their maintenance regulations, in order to prevent a decrease in durability due to local abrasive wear. This feature of the dust effect should also be taken into consideration in expert studies of the technical condition in order to correctly identify the causes of faults associated with operating conditions.

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