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# Reduction of emissions in internal combustion engine by air-assist fuel atomization

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**Abstract**

Fuel atomizers in a current use are analyzed and certain outlines are proposed in order to raise the liquid atomization quality. Modified atomizer samples were designed and tested with water. Experimental data have shown that these samples can provide a fine liquid atomization and, as a result, improvement of the mixture quality in internal combustion engines with fuel injection. The proposed atomizer was tested in a Peugeot engine; the obtained results are discussed. It follows from the data that using of the modified atomizer in gasoline engines yields both decrease in air pollution and reduction in fuel consumption.

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## 1 Introduction

As the environmental problems caused by vehicle exhaust emissions become more severe, the emission standards and fuel economy regulations become more stringent. The three main components of gasoline vehicle exhaust emission are HC (hydrocarbon), CO (carbon monoxide), and $NO_x$, with HC being the most tightly restricted component among them [1]. To reduce HC emission, a post-processing method that uses a catalyst is most widely employed [2]. A decrease in amount of emissions can be achieved by using a catalyst with enhanced performance.

In order to improve engine performance, particularly, fuel efficiency and exhaust emission control, different fuel injection systems for fuel supply to the engine are widely used now. In such systems fuel is generally injected into an air induction device or directly into the combustion chamber by a fuel injector. The characteristics of spray produced by the injector are the most important factor in achieving low emission and high performance of the engine. In particular, dynamics of spray at the stage of injection is the key to reducing the solid fraction of a particulate matter in the exhaust. To increase combustion efficiency and decrease pollutants, it is necessary to improve atomization of the supplied fuel. This result can be achieved, for instance, by increasing the supply pressure, the number of outlets for fuel injection, or by fuel injection into a swirled air stream through a number of orifices positioned at different angles [3–5]. Note that in the last case streams with different fuel mixture densities are formed, which, coupled with fuel swirling, provides better atomization and enhances the combustion process.

In this paper we report results of the experimental studies directed to improvement of fuel mixture quality by fine atomization.

## 2 Background

Previous efforts to improve fuel atomization were based mainly on mechanical impact on the fuel jet. For instance, in [6] an atomizer was proposed which uses a nozzle positioned so that a substantial portion of the liquid exiting the nozzle comes into contact with a mobile part of the engine induction tract (one-way valve). This mobile part is in rapid movement responding to engine operation. As a result, the liquid is disintegrated into fine droplets. It should be noted, however, that at present more attention is devoted to solving the same problem by using pressurized air (air-assisted fuel injection) [1, 7]. In this case pressurized air and liquid fuel are supplied to the injector where the gas assists in atomizing the fuel [8]. To provide compressed gas, an air pump is used. Pressurized air enters a common chamber through a system of tangential ducts and generates an intensely swirled stream. The fuel is injected via a valve into the same chamber through a coaxial orifice in the end wall of the chamber opposite to the outlet nozzle. According to [8], interaction of the swirled air stream with the fuel injected coaxially into the chamber provides better quality of the fuel mixture.

The atomization quality is important also for prevention of soot and smoke in exhausted gases. Thus, small droplets in the spray have enough time to evaporate completely ahead of the flame front. Larger drops do not have such time, which results in increased quantity of incompletely burned products. The influence of the fuel drop size on exhaust smoke was investigated in [9] with a kerosene supplied combustor. Specifically, it was shown that reducing the mean drop size from 110 micron to 30 micron almost halves the particulate concentration. The dependence of drop sizes on atomizer design, operating conditions, physical properties of liquid and air is analyzed in [10].

A widely used two-phase atomizer is an atomizer with a liquid delivery tube inside the divergent section of a convergent-divergent gas nozzle, where high relative velocity is provided by a supersonic gas stream. Experimental studies of such a device have shown that it is able to produce drops with SMD (Sauter mean diameter) $\sim$ 60-70 micron [11]. It was also shown that the liquid may be dispersed to fine drops at reasonable temperatures of the phases and atomizer′s geometry if the liquid mass-flow rate is less than half of the gas mass-flow rate [12]. But the need for large gas consumption restricts the use of this device.

In air blast atomizers the fuel is first spread into a thin continuous sheet (a process called "prefilming"), and then exposed to high-velocity swirling air streams on both sides of the sheet [10]. Such design is usually characteristic for gas turbine combustors. It was shown experimentally that this atomizer can provide fine atomization with SMD $\sim$ 50-70 micron [13]. Nevertheless, the device has an essential drawback resulting from high sensitivity of the atomization quality to changes in the liquid flow rate at constant pressure of the gas supply, as well as to changes in the gas pressure. For instance, when the liquid flow rate was raised from 35 to 65 g/s, the SMD value changed from 50 micron to 66 micron. It explains why such atomizers are of limited usefulness because in internal combustion engines the fuel flow rate changes within a wide range. Another reason is the low engine efficiency at large air mass flow rates under high pressure. Note that introducing new elements into existing fuel injection systems in order to improve their atomization quality must not require significant design changes, thus enabling the proposed innovation to be installed in both newly produced engines and those in a current use. These requirements must be taken into account when alternative atomizer designs are developed.

This paper is devoted to experimental study of certain modified atomizers using air-assist fuel atomization. The influence of the air supply pressure on gas emission and fuel consumption has been investigated.

## 3 Experimental studies of atomizers

An atomizer design capable of operating within a feed system with fuel injection in an internal combustion engine is shown in outline in Fig. 1.

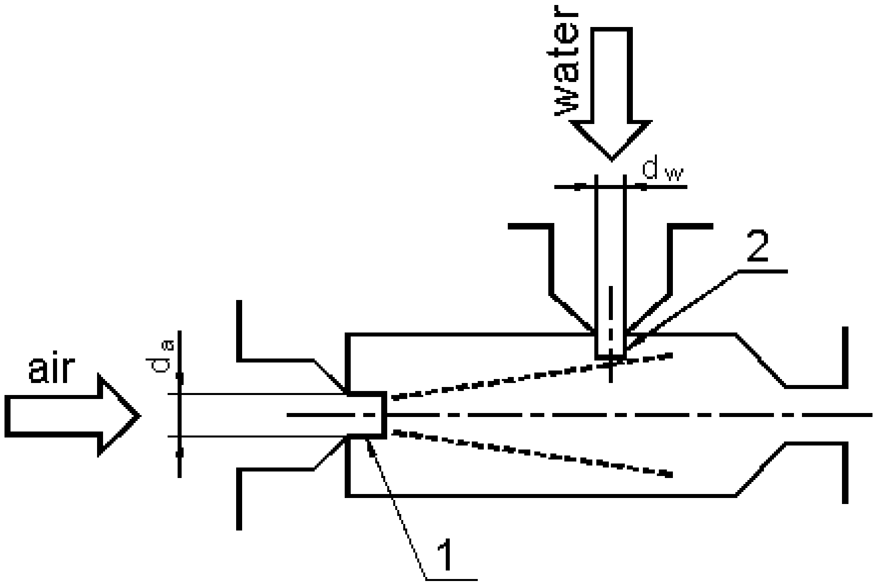


Figure 1: Schematic diagram of atomizer with colliding streams.

The atomizer contains a coaxial nozzle 1 for air injection and a nozzle 2 for liquid injection positioned at $90^{\circ}$ angle to the axis. The diameter $d_a$ of the nozzle 1 was made equal to 2 mm, of the nozzle 2 - $d_w = 1$ mm. This atomizer was tested at constant water supply pressure $P_w = 0.1$ bar and air supply pressures $P_a$ varying from 0.5 to 3 bar. Droplet sizes were measured downstream of the atomizer's exit using an Aerometrics PDPA system. An argon-ion laser, providing 2W power green light, was used by the PDPA. In principle, this system allows to measure droplet sizes in the range $d_p = 0.7$ - 220 micron. However, in practice, when the maximum size detected by the PDPA is equal to, say, 220 micron, the minimum size that can be detected simultaneously is 1/35 of the maximum, i.e., 6.3 micron. The droplet size data were collected and computer-analyzed using Doppler Signal Analyzer (DSA) software from Aerometrics. The SMD is defined as a diameter of droplets having the same volume/surface ratio over the entire spray. Its mathematical expression is given by the formula:

$$SMD = \frac{\sum_{i=1}^{n} n_i d_i^3}{\sum_{i=1}^{n} n_i d_i^2},$$

where $n_i$ and $d_i$ are the numbers of counts in the $i$-th size class and droplet diameter corresponding to $i$-th size class, respectively. The mass flow rates and supply pressures of both the water and the atomizing air were monitored using standard calibrated flow meters and pressure gauges. The water flow rate value was $m_w = 1.6$ g/s at the air supply pressure $P_a = 1$ bar (the test conditions accepted as nominal). The $m_w$ value was changed within the range of 20% depending on the air supply pressure; it was decreased with the rise of the pressure $P_a$. The ratio between flow rates $m_a$, $m_w$ of air and water, respectively, at these conditions was equal to $m_a/m_w = 0.21$. The histogram of the particles diameter distribution in the atomizer is shown in Fig. 2. The SMD value at the test conditions equaled 49 micron.

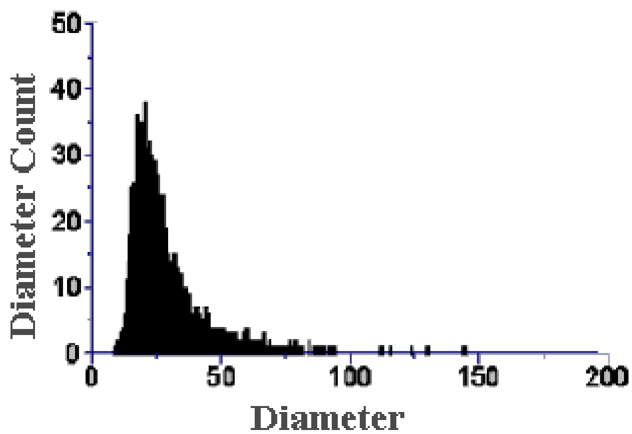


Figure 2: Particle diameter distribution in the atomizer with colliding streams.

As the supply pressure of the atomizing air increases (and, as a result, the flow rate also), the SMD value lowers, and vice versa. Fig. 3 demonstrates the experimental dependence of the particle diameter on the air supply pressure at a constant value of the water supply pressure ($P_w = 0.1$ bar). At the air pressure $P_a = 0.5$ bar the SMD value was found to be equal to 57 micron, whereas the rise of the former to 3 bar reduces the latter to 33 micron. Note weak dependence of the particle diameter on air/water flow rates ratio in this atomizer. The flow rates ratio at the nominal operating mode ($m_a/m_w = 0.21$) is sufficient to provide the required quality of liquid atomization.

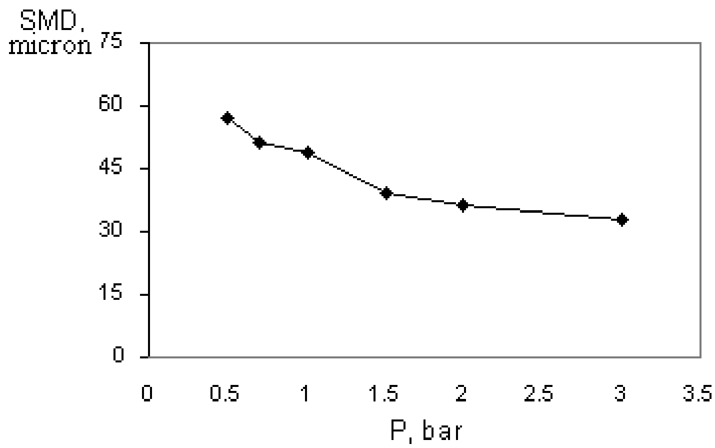


Figure 3: Value of SMD depending on air pressure at the atomizer inlet.

Despite the design simplicity of the above-described atomizer, the search was continued for a design that would provide high quality of liquid atomization with a further decrease in the flow rates ratio between air and liquid. As a result, a vortex gas atomizer has been developed using advantages of flow in a vortex chamber. Studies of vortex chambers hydrodynamics have shown [14, 15] that in such flows the tangential flow velocity rises in inverse proportion to the distance from the chamber axis, while the pressure drops to ambient atmosphere value with approaching the axis. It leads to formation of a stagnant central cavity within the chamber, so that the gas (or liquid) flows out through the gap between the nozzle wall and the cavity boundary. As a result, if the liquid is injected into the gas vortex in the cavity region, the pressure necessary for this is minimal. On the other hand, the interface between vortex flow and cavity region is characterized by high intensity turbulence because tangential velocity of the flow is maximal here. Since the atomization quality rises with the relative velocity between gas and liquid, the injection of a low-velocity liquid jet into the gas stream at the boundary of the gas cavity should provide finest atomization at chosen operating parameters.

A gas atomizer was developed [16] which uses a vortex chamber with gas

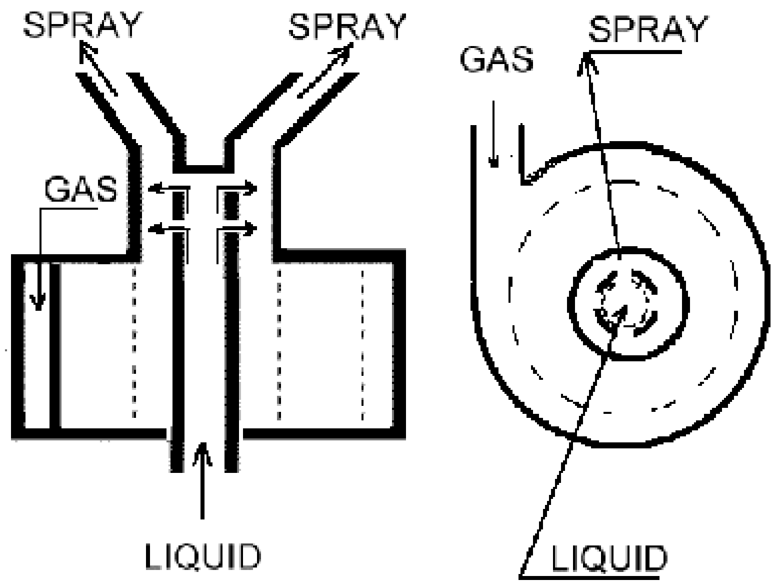


Figure 4: Schematic diagram of the atomizer with vortex chamber.

supplied through tangential ducts (Fig. 4), while the liquid is introduced in the radial direction through the orifices in the liquid delivery duct at the center of the vortex chamber. As the gas enters the device through tangential ducts, it is swirled relative to the chamber axis. The two-phase mixture, formed as a result of liquid jet – gas stream interaction, flows out through the central nozzle in the form of a conical sheet. To achieve the best atomization, the liquid should be injected into the gas stream at a radius close to that of the central cavity region. Therefore, the outer radius of the liquid delivery duct (outer radius of the bush for liquid supply $r_{\mathrm{w}}^{\mathrm{out}}$) can be estimated by the relationship [14]:

$$r_{\mathrm{w}}^{\mathrm{out}} \leq r_n \sqrt{1-\varphi} \quad .$$

Here $r_n$ is the nozzle radius and parameter $\varphi$ relates to the nozzle flow coefficient $\mu$ by:

$$\mu = \frac{\varphi^3}{2-\varphi}.$$

A vortex atomizer for a heat power plant boiler of the above-discussed type was designed and laboratory-tested with water. It has the following dimensions: $d_a = 3.5$ mm; $n_a = 12$ (arranged in three rows with 4 ducts in each); $D_v = 26$ mm; $d_{\mathrm{w}}^{\mathrm{in}} = 9$ mm; $d_{\mathrm{w}}^{\mathrm{out}} = 12$ mm; $d_n = 20$ mm; $d_w$ =1.5 mm; $n_w = 8$ (arranged in two rows with 4 orifices in each). Here $d_{\mathrm{w}}^{\mathrm{in}}$ and $d_{\mathrm{w}}^{\mathrm{out}}$ are inner and outer diameters of the bushing for water supply, $D_v$-diameter of the vortex chamber, $n_a$, $n_w$ - number of air and water inlet ducts, respectively.

The drop size measurements were performed with a laser system. The laser transducer and receiver were located on a probe which was moved into the spray cone in consecutive steps with the aid of a special device. The probe movement interval was specified so that the drop sizes could be measured and then their distribution was evaluated across the stream. The operator can define the measurement parameters: the minimum drop size, the number of drops to be scanned, the number of measurement points and the distance between them. At each step the measurements were conducted till the number of liquid particles reached 300, and then by averaging over these 300 measurements the value of SMD was determined. Further averaging over $n$ steps provided the mean value of SMD characterizing the given test regime. The initial distance between the nozzle and probe was 30 cm, and then the probe was moved into the spray flare by consecutive steps of 7-10 mm to the total penetration depth of about 40 mm. In the considered range of the probe locations along the spray, the values of SMD were only slightly changed. The characteristic values of SMD presented below, correspond to the distance of 30 cm between the nozzle and the probe.

Measurements of atomization quality were made for water supply pressure $P_w = 9$ bar and air supply pressures $P_a$= 5 and 6 bar. It corresponds to the ratio of the air/water mass flow rates about 0.12 - 0.15 (for the water flow rate 1240 kg/hr). Note that the flow rate coefficient $\mu$ for the water outflow through the orifices in the tested atomizer, calculated from the experimental data, was found to be equal to 0.43 and 0.4 at $P_a$= 5 and 6 bar, respectively. The values of SMD for the above air supply pressures were equal to 74 micron and 67 micron. The histogram of drops distribution in the spray for $P_a$= 5 bar is shown in Fig. 5.

Similar measurements were taken for a slightly different atomizer design where the liquid jet was introduced in the tangential direction opposite to air swirling. Drop sizes were measured at the same conditions (air supply pressure 5 bar, water flow rate 1240 kg/hr). The tests showed deterioration in atomization quality - the SMD average drop diameter increased to 97 micron.

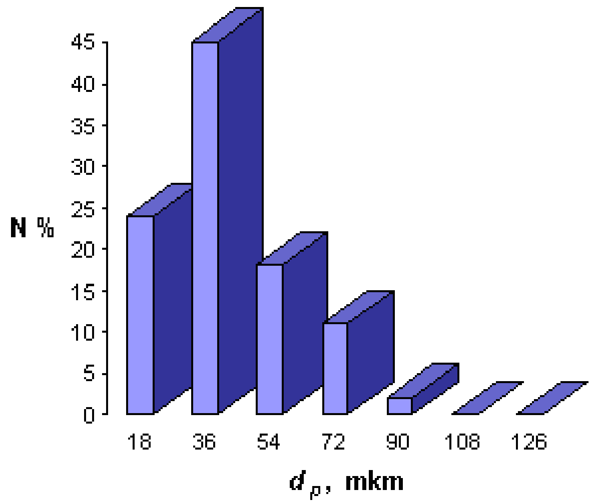


Figure 5: The histogram of drop-size distribution in an atomizer with a vortex chamber.

It should be noted that proper atomizer operation needs certain minimal liquid supply pressure to provide sufficiently intensive interaction of the liquid with the air; otherwise in the absence of a necessary pressure drop the liquid flows almost in the same direction as the gas stream. In the latter case interaction between liquid and air takes place only at the outlet, which essentially worsens the liquid atomization quality. Atomizer operation at these conditions was studied experimentally; the SMD value obtained was about 100-110 micron.

Special tests were performed with the liquid supply duct having the outer diameter 14 mm (instead of 12 mm for the previous tests series), which exceeds the diameter of the central cavity zone. Other geometrical and operation parameters remained unchanged. As a result, it was found that hydraulic resistance to the water flow increased, while atomization quality remained the same (SMD=71 micron). Specifically, the measured water flow rate was equal to 1180 kg/hr instead of 1240 kg/hr for $d_{\mathrm{w}}^{\mathrm{out}} = 12$ mm.

Thus, the experimental studies have demonstrated the possibility of providing sufficiently high atomization quality with small amounts of assisting air at low supply pressures, which can be effectively used in the feeding systems of internal combustion engines.

# 4 Testing of internal combustion engine with air-assist fuel injection

The engine tests were carried out with atomizer using the colliding streams principle. Specially for these tests the outlet part of the atomizer body was made in a form which enabled it to be installed in the engine without adapting the latter. The atomizer inlet was also shaped in a way favored its installation on the outlet of the serial atomizer. The general view of the tested atomizer with air supply tip and the serial atomizer are presented in Fig. 6.

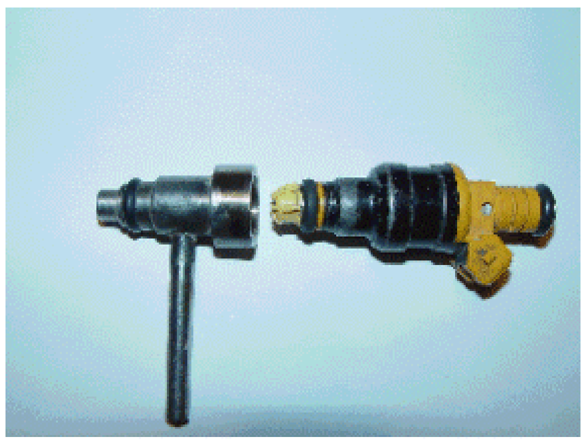

Figure 6: General view of the tested atomizer (on the left) and the serial atomizer (on the right).

The efficiency of air-assist fuel atomization was studied with a 4-cylinder Peugeot engine. The engine operation parameters and parameters of exhaust gases were measured by a Bosch gas analyzer linked to the computer. This device is destined for measuring of the CO and HC content only in the exhaust gases. The fuel flow rate was calculated from the measurements of piezometric height changes with time. First, the engine was tested in the standard assemblage (with serial atomizer). Then in each of the 4 cylinders the atomizers with air supply were installed, and the serial atomizer was attached to each of them. The system was tested at air pressures 1.5, 2, and 2.5 bar (the gas was supplied by compressor); the measurements were made at approximately every 500 RPM (rotation per minute). The air flow rate was not measured in the course of the experiments. The experimental data for different values of engine revolutions are presented in Figs. 7 - 9.

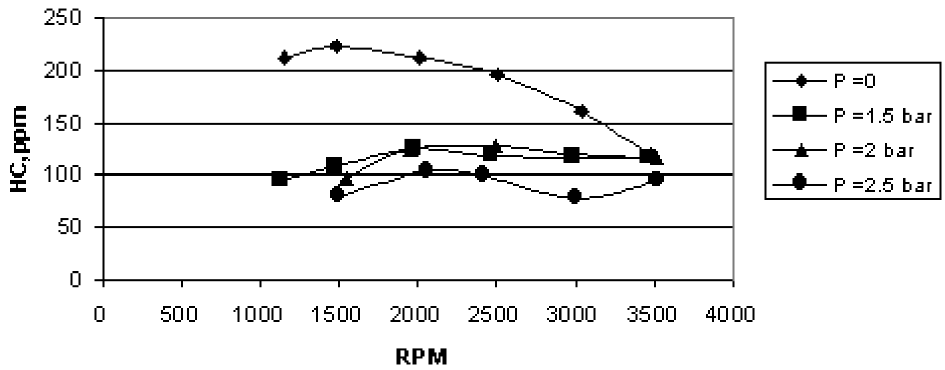


Figure 7: Variation of HC content in exhaust gases with RPM.

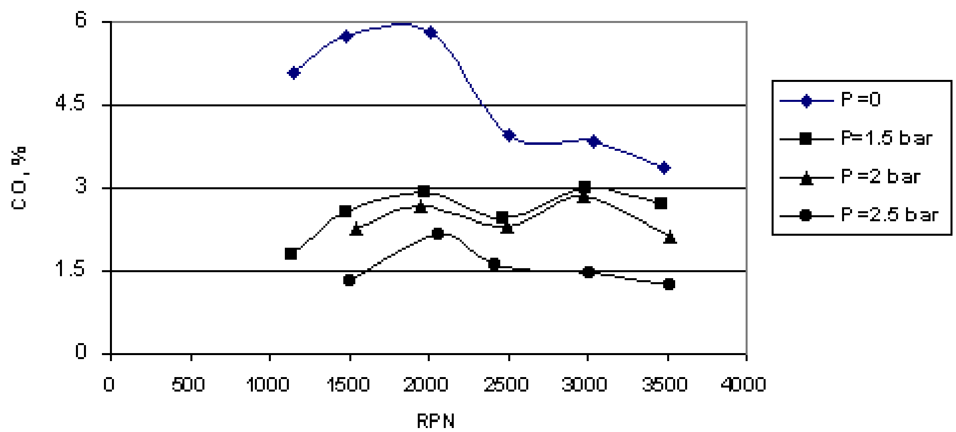


Figure 8: Variation of CO content in exhaust gases with RPM.

The test results demonstrate significant reduction in CO and HC when the modified atomizer is installed. The effect is enhanced with an increase of the assist-air pressure. For instance, the rise in air pressure from 1.5 to 2.5 bar at the number of engine revolutions close to 1500 RPM, reduces CO content from 2.56 to 1.31% as compared with 5.76% in the engine operating without using assist-air (Fig. 7). At the same number of engine revolutions, the HC decreased from 108 to 80 ppm as compared with 223 ppm for the engine using serial atomizer (Fig. 8). Note that essential reduction of the fuel flow rate was also registered. For instance, at the air-assist pressure $P_a = 2.5$ bar and RPM = 2500 the fuel consumption reduced from 0.73 g/s to 0.62 g/s (that is, by 15%) and at RPM = 3000 from 0.94 g/s to 0.83 g/s (by 12%). The changes in fuel consumption resulting from air-assist atomization for different RPM values are illustrated by the data on the Fig. 9.

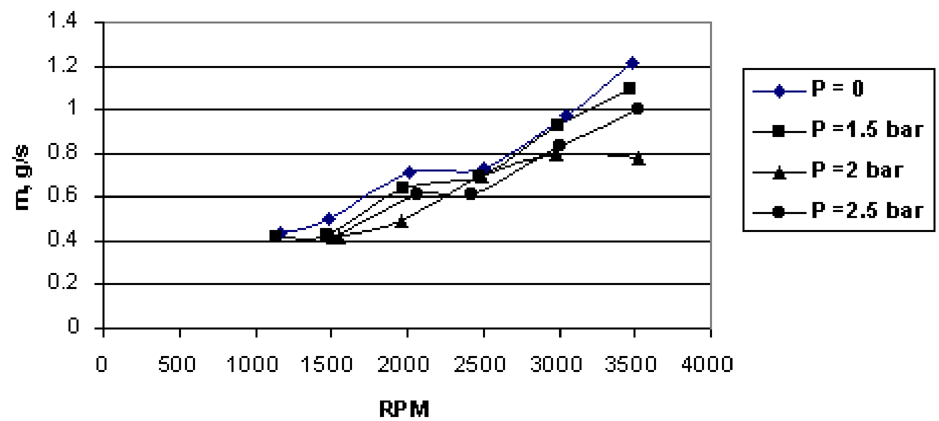


Figure 9: Dependence of the specific flow rate of fuel, $m$, on the engine revolution number.

In Table 1 the values of parameters presented in Figs. 7 - 9 for assist-air pressure 2.5 bar, are given relative to the same parameters corresponding to the engine with serial atomizer (in percent).

| RPM | 1500 | 2000 | 2450 | 3000 | 3500 |
|---|---|---|---|---|---|
| CO | 19.44 | 37.41 | 40.65 | 38.38 | 37.31 |
| HC | 31.38 | 49.06 | 50.51 | 48.44 | 79.83 |
| m | 77.51 | 85.43 | 84.25 | 85.13 | 82.64 |

Table 1. Relative values of parameters.

For example, at 1500 RPM the use of the modified atomizer leads to CO and HC reduction in exhaust gases approximately by 80% and 68%, respectively. This effect is combined with fuel consumption reduction by 15% (the error in fuel economy measurements did not exceed 20%).

With increase in the number of engine revolutions, the efficiency of using air-assist atomization decreases. For instance, at air pressure $P_a = 2.5$ bar the CO content in exhaust gases increased from 1.31% to 1.61% as RPM changed from 1500 to 2500.

## 5 Conclusions

1. Modified two-phase atomizers providing liquid atomization at low values (0.12–0.15) of the air/liquid flow rates ratio are proposed.

2. The characteristics of liquid atomization in modified atomizers were investigated with the emphasis on their dependence on air and water supply pressures. It was found that these atomizers provide atomization quality characterized by the SMD parameter within the range 50–70 micron.

3. The effect of air-assist atomization using colliding streams was studied with a 4-cylinder Peugeot engine. The tests have demonstrated significant reduction of CO and HC.

4. The minimum content of emissions in exhaust gases was found at engine operation close to idle. As the number of engine revolutions increases, the efficiency of fuel atomization with assist-air decreases and at RPM = 3500 does not exceed 200%.

5. The use of assist-air in internal combustion engine leads to fuel consumption reduction by 12–15% (the possible error does not exceed 20%).

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