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POSSIBILITY OF CLEANING A CHANNEL IN A SNOWY ATMOSPHERE BY A SUPERSONIC OFF-DESIGN JET

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It has been found that the threshold value of the product of the excess gas pressure in the forechamber by the area of the nozzle throat is responsible for the appearance of the cleanup effect for a fixed nozzle–photodetector distance. The thermodynamic and dynamic criteria for the occurrence of the cleanup of the laser-beam trajectory have been formulated.

Introduction. An automated system of laser monitoring of the state of railway wheels has been developed and currently adopted [1]. The laser method of monitoring of the state of car wheel pairs is based on processing the signals of the incident laser beam and of that reflected from the wheel; the monitoring is carried out in real time, when the train passes by a working station located on the general frame near the track. The incident beam from the laser-radiation source and the beam reflected from the car wheel as far as the sensor traverse distances of 310 to 540 mm at an angle of 25^{o} to the earth's level. The air wave accompanying the passing train and propagating approximately with its speed raises roadside dust and snow in winter, forming a two-phase mixture of gas and solid particles. The scattering of the laser beam in the atmosphere is enhanced by the snow dust, produces noise, and makes it impossible to process a signal, particularly under instrument meteorological conditions. Figure 1 gives the time signal of a Kompleks system without noise and with noise produced by the snow dust (the data have been proposed by the Design and Technology Institute of Scientific Instrument Engineering of the Siberian Branch of the Russian Academy of Sciences).

The use of jet flows seems promising for solution of the problem on cleaning a channel in a snowy atmosphere to permit unobstructed passage of laser radiation. In the present work, we have elucidated the fundamental possibility of "cleaning up" the dusty space along the laser-beam path using supersonic gas jets. The experiments were conducted on a test bed with a laser-radiation source, a forechamber with a transparent end wall for introduction of the laser beam, and a photodetector arranged on a mobile rack. The maximum distance from the nozzle exit section was 480 mm, whereas the minimum distance was 300 mm. The forechamber with a nozzle and a laser-radiation source was rigidly mounted to an optical bench where the photodetector was also rigidly mounted. The optical bench was placed in a closed working part of a wind tunnel into whose upper port we added snow if the need arose. The laser beam traversing the forechamber and the nozzle axis arrived at the photodetector. The signal from the photodetector was fed to a measuring system.

The intensity of "snowing" was determined from the form of the signal from the photodetector in the regime where noise was produced by the two-phase mixture of snow and air on the path of propagation of the laser beam in a stationary atmosphere. Furthermore, filming by a digital video camera was carried out. The efficiency of cleanup was determined by comparing signals from the photodetector. One signal corresponded to the initial, snow-free space, whereas the other resulted from the action of a supersonic jet on a snowy space. By changing the pressure in the nozzle forechamber we found the minimum pressure at which the signal from the photodetector had no noise due to the presence of snow. This minimum pressure in the nozzle forechamber was determined as $P_{\rm m}$, i.e., the effective threshold pressure for cleaning the channel of laser radiation.

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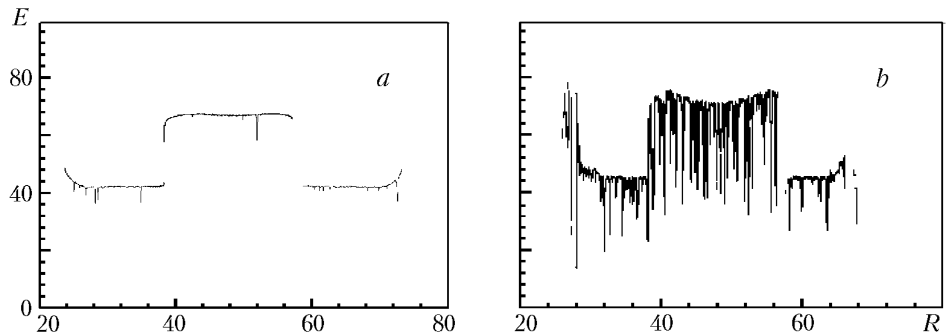


Fig. 1. Signal from the sensors of the profile of a railway wheel without the noise from snow (a) and with noise (b). E and R, arbitrary units.

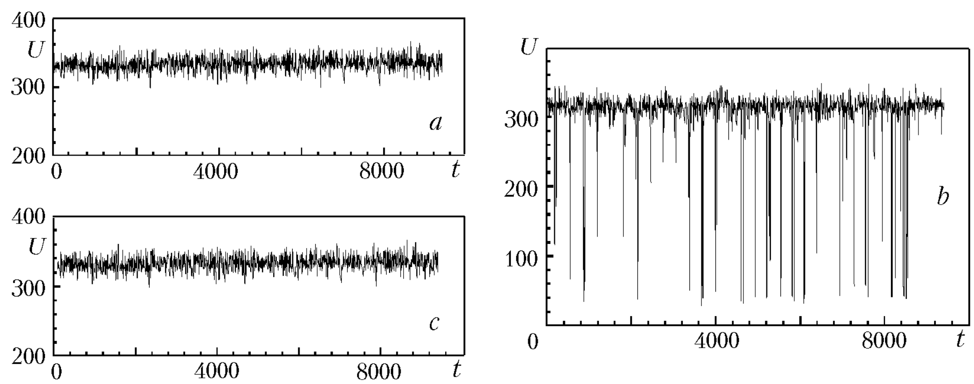


Fig. 2. Signal from the photodiode without the covering with snow and a jet (a), in covering with snow without a jet (b), and with the jet-cleaned laser-beam path (c). U, mV; t, msec.

Experiments on Gasdynamic Jet Cleaning of the Laser-Radiation Channel in a Snowy Atmosphere. A pointer laser coaxially mounted on the forechamber casing was used as the laser-radiation source. The laser beam passed through the window [1] and next, along the axis of the air jet, through the nozzle throat and arrived at the photodiode at the required distance. Detachable nozzles were installed on the forechamber by threaded connection. A bed where the forechamber and an arm with a built-in FD-K-155 photodiode under safety acrylic plastic were rack-mounted was assembled in the Eiffel chamber of the wind tunnel. In the experiments, we rack-mounted the photodiode at distances L = 300, 390, and 480 mm from the nozzle exit section. Snow was delivered to the chamber's working region via the upper port so that the entire length of the basic distance L was "snowed in." Covering was carried out by shaking snow masses out of a plastic vessel of volume 5 liters via a neck of diameter 40 mm for 20 sec.

The problem was to determine the threshold pressure in the forechamber nozzle beginning with which we had a sufficient cleanup of the laser-beam path for this nozzle at a fixed distance L. The order of the experiments was as follows. First we recorded the time signal from the photodiode in its exposure to the laser without snow in the working volume and with no acting air jet; the level of the signal was ≈330 mV (Fig. 2a). This signal was basic for comparison with those obtained in other operating regimes in the presence of snow and the jet. Next, when an individual covering with snow was carried out (Fig. 2b), we took the signal from the photodiode. Noise in the time signal is similar in character to the full-scale noise (see Fig. 1), which points to the identical physical pattern of radiation scattering. Thereafter we conducted experiments with blowing of the snowy space with an air jet. We found the air pressure in the nozzle forechamber P_{m}, at which the supersonic jet began to clean the channel where laser radiation propagated of snow. This threshold pressure was determined from the form of the signal from the photodiode, which was no different from the basic signal (Fig. 2c). It is noteworthy that the supersonic jet of a wave structure in the form of successive "barrel cells" does not introduce marked distortions into the signal of the laser beam from the photodetector.

TABLE 1. Basic Parameters of Jet Flows

d_{th}, mm	L, mm	P_m, 10^5 Pa	G, kg/sec	M	Q, 10^5 Pa	Re $\cdot 10^5$	L_b, mm	L_p, mm	L_s, mm	K, Pa·mm^2
4.10	300	21.0	0.07	3.27	3.00	6.02	46.6	346.3	1222.7	277.1
9.30		3.0	0.07	2.16	1.35	4.32	17.6	82.1	132.7	203.7
13.22		2.0	0.10	1.97	1.09	4.99	21.2	97.9	138.0	274.4
15.34		1.0	0.09	1.71	0.82	4.25	19.5	87.0	96.8	184.7
4.10	390	24.0	0.08	3.36	3.16	6.55	52.0	385.2	1400.0	316.7
9.30		4.0	0.08	2.23	1.50	5.09	20.0	94.0	167.4	271.6
13.22		2.25	0.11	2.02	1.15	5.31	22.2	103.1	151.6	308.7
15.34		1.5	0.11	1.85	0.97	5.06	22.1	101.7	130.7	277.1
4.10	480	26.5	0.09	3.43	3.29	6.99	56.5	418.0	1552.5	350.6
9.30		5.0	0.10	2.42	1.62	5.71	22.2	103.7	197.2	339.5
13.22		2.5	0.12	2.07	1.22	5.62	23.3	107.3	162.8	343.0
15.34		2.0	0.13	1.97	1.09	5.79	24.6	113.6	160.1	369.4

Kinds of Snow Used in the Experiments. Snow is known [2] to be subdivided into the following groups: (1) freshly fallen, (2) compacted (stale), and (3) old (firnified) snow. Each group is additionally subdivided according to the kind of snow. The density of snow can vary with its kind up to 70 times [2].

The results obtained on the threshold pressure P_m are dependent on the group of snow used and its density, the aerodynamic characteristics of particles, and the dynamics of flight of snow flakes or grains. Under the actual conditions of use of a Kompleks laser system, the velocity head of the air cowave carries aloft mainly snow of group 1; this snow is of the lowest density and its flakes have variously shaped polygonal crystals and possess a high scattering power.

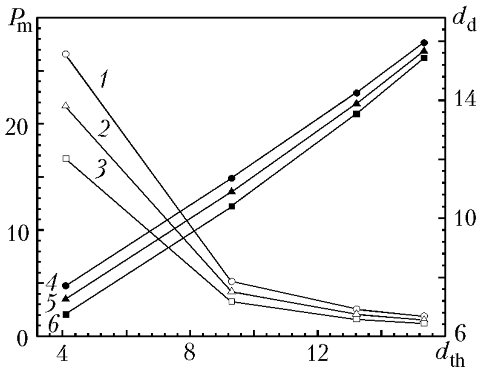
In the experiments, we used snow of group 2 — compacted stale snow with particles in the form of crystal grains. A jet with a larger velocity head or a higher value of the pressure P_m was necessary for cleaning the laser-beam path. We assume that the experiment with this kind of snow was conducted under more severe conditions of operation of the Kompleks system where a jet with a lower threshold pressure P_m can be used. We note that the first experiments under natural conditions confirm this assumption.

We conducted qualitative special measurements of the average density of the snow used. For this purpose we shook the snow out of a plastic vessel by batches and measured the weight of the snow batch and the height of the column in the process of free fall of this batch. We fed both the freshly fallen snow (group 1) and compacted snow (group 2) into the vessel in these experiments. The average density of snow in the batch in the atmosphere of the experimental setup was found from the known weight and volume of the snow batch. It was 5 and 400 kg/m^3 respectively for groups 1 and 2. This means that the volume concentration of snow particles ranges approximately within $(5\text{–}400)\cdot 10^{-3}$, i.e., is quite significant.

Discussion of Results. In the experiments described, we used nozzles with a conic supersonic profile (half-opening angle $\theta = 24^o$) and throat diameters of 4.1, 9.34, 13.22, and 15.34 mm. The threshold pressures P_m determined for fixed nozzle-photodiode distances L = 300, 390, and 480 mm are comparatively low; at such pressures in the nozzle forechamber, the supersonic regimes of outflow correspond to off-design overexpanded ones. The off-design condition of outflow on the nozzle exit section is $n < 0.1$.

Table 1 gives results of calculating the flow parameters for all variants of nozzles and distances to the photodiode: Mach number M (from the condition of separation of the flow on nozzle walls for the off-design condition $n = 0.4$ [3], velocity head Q, Reynolds number of the throat diameter Re, mass flow rate of air G, and product $K = P_m S_{th}$.

The effect of jet "cleaning" for a fixed nozzle–photodetector distance can be evaluated from the threshold value of K. This value holds for nozzles with different values of the throat diameter. Increase in the spread in K for L = 300 mm is due to the larger variation of the kind of snow used in this case. If we multiply K by a fixed L, we obtain that the threshold work done by pressure forces on expanding gas is nearly constant for different nozzles. This is precisely the basis of the proposed procedure of determination of the threshold pressure in the forechamber and the diameter of the nozzle exit section for the design regime of outflow of the jet as a function of the assigned diameter of the nozzle throat (Fig. 3). The pressure in the forechamber P_m on the nomogram is calculated from the formula



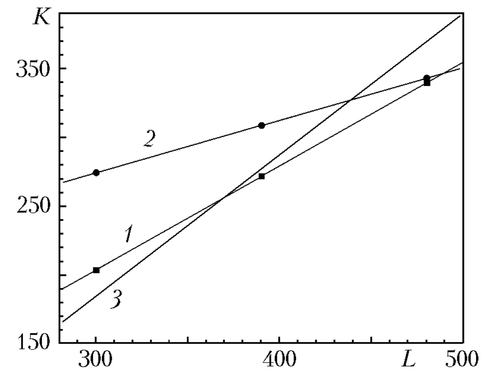


Fig. 3. Nomogram for determination of the threshold pressure P_m (1–3) and the diameter of the nozzle exit section d_d (4–6): 1 and 4) L = 480, 2 and 5) 390, and 3 and 6) 300 m. P_m, 10^5 Pa; d_d and d_{th}, mm.

Fig. 4. Force K vs. distance L: 1) d_{th} = 9.3, 2) 13.22, and 3) 15.34 mm. K, 10^5 Pa·mm^2; L, mm.

$$P_m = \frac{4\overline{K}}{\pi d_{th}^2}.$$

Here $\overline{K}$ is the average value of the product of the threshold pressure in the forechamber by the area of the nozzle throat for different nozzles but at one distance to the photodiode. The diameter of the nozzle exit section is determined for the design regime of outflow of the jet at $n = P_a/P_g \approx 0.1$. The required diameter of the nozzle throat is assigned by the dimension of the incident or reflected laser beam. From this diameter, we determine the threshold pressure of the air in the forechamber and the diameter of the nozzle exit section.

The Reynolds numbers Re calculated from the flow parameters at n = 0.4 and from the diameters of the nozzle throat are also close to constant values. We note that the minimum velocity head of the jet Q is reduced with increase in the dimension of the nozzle throat, with the effect of laser-beam "cleanup" with the jet being preserved. The required threshold pressure P_m grows with distance from the nozzle to the photodiode. It is of practical interest to determine K as a function of the nozzle–photodetector distance. Figure 4 gives results for different diameters of the nozzle throats. It is seen that they are well approximated by linear functions in the region of the investigated distances L. Using this plot, we can evaluate the excess threshold pressure for nozzles with a throat diameter d_{th} for an assigned L.

It seems useful to compare the lengths of the characteristic portions of supersonic jet flows and the basic nozzle–photodetector distance L. The empirical formulas for calculation of the geometric dimensions of jets flowing out into a submerged space, from which we can calculate the length of the first "barrel" for overexpanded jets L_b, the potential core L_p, and the supersonic portion of a jet L_s

$$L_b = d_s\,(1.36\mathrm{M}\sqrt{n} + 1.05\sqrt{\tan\theta} - 2)\,, \tag{1}$$

$$L_p = (5.22\mathrm{M}_d^{0.9} + 0.22)\,d_d\,, \tag{2}$$

$$L_s = (5\mathrm{M}_d^2 + 0.8)\,d_d \tag{3}$$

have been given in [4, 5].

The values of the characteristics of the jet (1)–(3) for the threshold pressures in the nozzle forechamber P_m are given in Table 1. The calculations show that the dimensions of the potential and supersonic jet portions are noticeably smaller than L for all the nozzles with $d_{th} > 4.1$ mm. This means that the transverse dimensions and velocity

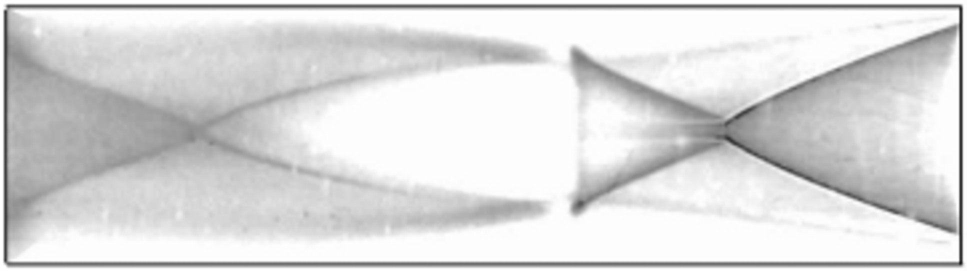


Fig. 5. Schlieren photograph of a supersonic overexpanded jet. d_{th} = 15.32 mm and M = 1.6.

heads of the jets turn out to be sufficient for the solid phase to have no time to reach the axial regions of the jet, where the laser beam is located. For the nozzle with a throat diameter d_{th} = 4.1 mm, the transverse dimension of the jet is small; in this case the condition $L_p \approx L$ must be observed.

From a qualitative analysis of the dynamics of an individual particle in jet flow, we obtain the dynamic criterion of cleanup of the laser-beam path. Let the particle arrive at the jet on the nozzle exit section. Then, disregarding the gravity force, we can show, from the equations of motion of this particle, that its longitudinal and transverse coordinates are found as

$$x(t) = \frac{Ft^2}{2m}, \tag{4}$$

$$y(t) = ut. \tag{5}$$

The basic dynamic condition of cleanup is that, over the period of traversal of the basic distance by the particle, it does not reach the axis of the jet where the laser beam is located. From Eq. (4) when $x = L$ we obtain the time of traversal of the distance L by the particle:

$$t_L = \sqrt{\frac{2Lm}{F}}.$$

Substitution of this expression into Eq. (5) yields

$$y_L = u\sqrt{\frac{2Lm}{F}}. \tag{6}$$

The transverse dimension of the jet is close to $d_d\sqrt{n}$. When $y_L = d_d\sqrt{n}$ we obtain the value of the transverse velocity of the particle for which it reaches the jet axis:

$$u_0 \simeq d_d\sqrt{\frac{nF}{2Lm}}. \tag{7}$$

For evaluation we take $F \approx P_m s$, L = 380 mm, d_d = 10 mm, n = 0.4, $P_m = 4\cdot10^5$ Pa, s = 4 mm^2, and m = 5 mg. Then, from formula (7), we obtain $u_0 \simeq$ 4 m/sec, and the free-fall velocity of snow particles was ~3 m/sec under these experimental conditions. However, this simple dynamic model does not allow for the turbulent character of the mixing layer in jet flow in which the particles follows intricate random paths; therefore, expression (7) yields the lower bound for the limiting transverse particle velocity.

The schlieren photography of the supersonic overexpanded jet for d_{th} = 15.34 mm and M = 1.6 obtained in our experiments is given in Fig. 5. The initial portion of the first "barrel" is inside the nozzle; the number of barrel-shaped structures is equal to 2. It follows from what has been said above that the presence of inhomogeneities in the jet itself has no pronounced effect on the value of the signal from the laser beam.

CONCLUSIONS

1. From the results of the experiments conducted, it has been established that the use of supersonic jets for cleaning of the channel of traversal of laser radiation in a snowy atmosphere is quite efficient.

2. For a fixed distance between the nozzle and the photodetector (L = const), we have determined the minimum pressure in the nozzle forechamber at which the cleanup effect begins for nozzles with different throat diameters. The range of the excess threshold pressures is 1–5 atm.

3. We have shown that the product of the threshold value of the excess gas pressure in the forechamber by the area of the nozzle throat is preserved nearly constant in all the nozzles investigated, whereas supersonic jet flows do not introduce marked distortions into the signal from the laser beam.

NOTATION

d_{th}, diameter of the nozzle throat, mm; d_d, diameter of the nozzle exit section at $n = 1$ mm; E, signal from the equipment of the Kompleks system, arbitrary units; F, aerodynamic force acting on a particle in the longitudinal direction x, N; G, rate of flow of the gas through the supersonic nozzle, kg/sec; $K = P_m S_{th}$, pressure force, Pa·mm^2; L, distance from the nozzle exit section to the photodetector, mm; L_b, length of the first "barrel" in the jet, mm; L_p, length of the potential portion in the jet, mm; L_s, length of the supersonic portion in the jet, mm; m, particle mass, mg; M_d and M, Mach numbers of the jet at n = 1 and 0.4 respectively; $n = P_a/P_g$, degree of off-design condition of the nozzle; P_a, static pressure in the nozzle outlet section, Pa; P_g, pressure of the ambient gas, Pa; P_m, threshold excess pressure in the forechamber, at which the cleanup of the laser-beam path begins, Pa; Q, velocity head of the jet, Pa; R, coordinate of the profile of a railway wheel in the Kompleks system, arbitrary units; Re, Reynolds number; s, cross-sectional area of particles, mm^2; S_{th}, area of the nozzle throat, mm^2; t, time, sec; U, signal from the photodiode, V; u, transverse velocity of particles in the jet, m/sec; x and y, longitudinal and transverse coordinates in the jet, mm; θ, angle of half-opening of the jet, deg. Subscripts: a, in the nozzle outlet section; th, throat; m, minimum; g, in the ambient gas; 0, on the jet axis; d, design (calculated); s, supersonic; b, "barrel"; p, potential.

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