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EXPERIMENTAL INVESTIGATION OF MECHANICAL VIBRATIONS OF THE ELEMENTS OF COMBUSTIBLE FOREST MATERIALS

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Vibrations of elements of combustible forest materials (CFMs) in a laminar air flow are studied experimentally using optical-fiber facilities. The elastic properties of combustible forest materials – the Young modulus and the rigidity, whose values in the limiting cases are in satisfactory agreement with the known data – are determined. It is stated that vibrations of combustible forest materials can affect their heat and mass exchange with the environment. The results obtained made it possible to evaluate the limiting value of the equilibrium velocity of wind in the forest cover at which a crown forest fire can originate or die down.

Formulation of the Problem and Technique of Experimental Investigation. From the viewpoint of mechanics, any tree is a complex structure of elastic elements, which includes a trunk, large branches, thin twigs, and needles on them. Each element of this structure has eigenfrequencies of vibrations. Since needles and thin twigs make up 70% of the elements of combustible forest materials [1–3], they became the object of investigations. The present work continues the investigations the results of which are published in [4].

The present work is aimed at investigating experimentally the mechanism of origination of vibrations of typical elements of combustible forest materials in a gas flow, determining the eigenfrequencies of vibrations and the elastic properties of combustible forest materials, and also refining the critical velocity of wind at which a crown forest fire can originate. The necessity of this investigation is obvious, since the available reference literature [5] lacks data on the Young modulus E for the elements of combustible forest materials.

Figure 1 presents the schemes of the experiments. Figure 1a corresponds to a flow past an individual needle, Fig. 1b – to a flow past a typical thin twig, Fig. 1c and d – to longitudinal and transverse flows past twig–needle cantilevers, and Fig. 1e – to a flow past a twig with needles. It should be noted that cross sections of twigs have the shape of a circle, i.e., they have a simple geometric shape, whereas the cross section of a needle is complex and crescent-shaped [2].

These elements of combustible forest materials were placed in the working section of a subsonic wind tunnel of the MT-324 type manufactured at the Department of Physical and Computational Mechanics of the Tomsk State University. The arrows in Fig. 1 show the directions of the velocity of a laminar air flow. The value of the flow velocity was measured by a thermoanemometer and a Pitot–Prandt tube (mouthpiece) and varied within the range u_∞ = (1.0–3.6) m/sec. The air flow induced periodic vibrations in needles 1 and twigs 2 (see Fig. 1) in the planes xz and yz; arrows 3 show the shifts x relative to the position of equilibrium. The value of the shift and the frequency of vibrations of the needles f were recorded using two optical-fiber sensors 4 made on the basis of quartz-polymer light-guides, one of which recorded vibrations in the plane xz and the other in the plane yz.

Results of Investigations of the Natural Vibrations of the Elements of Combustible Forest Materials. At the first stage of investigation, we compared the eigenfrequencies of vibrations of individual nee-

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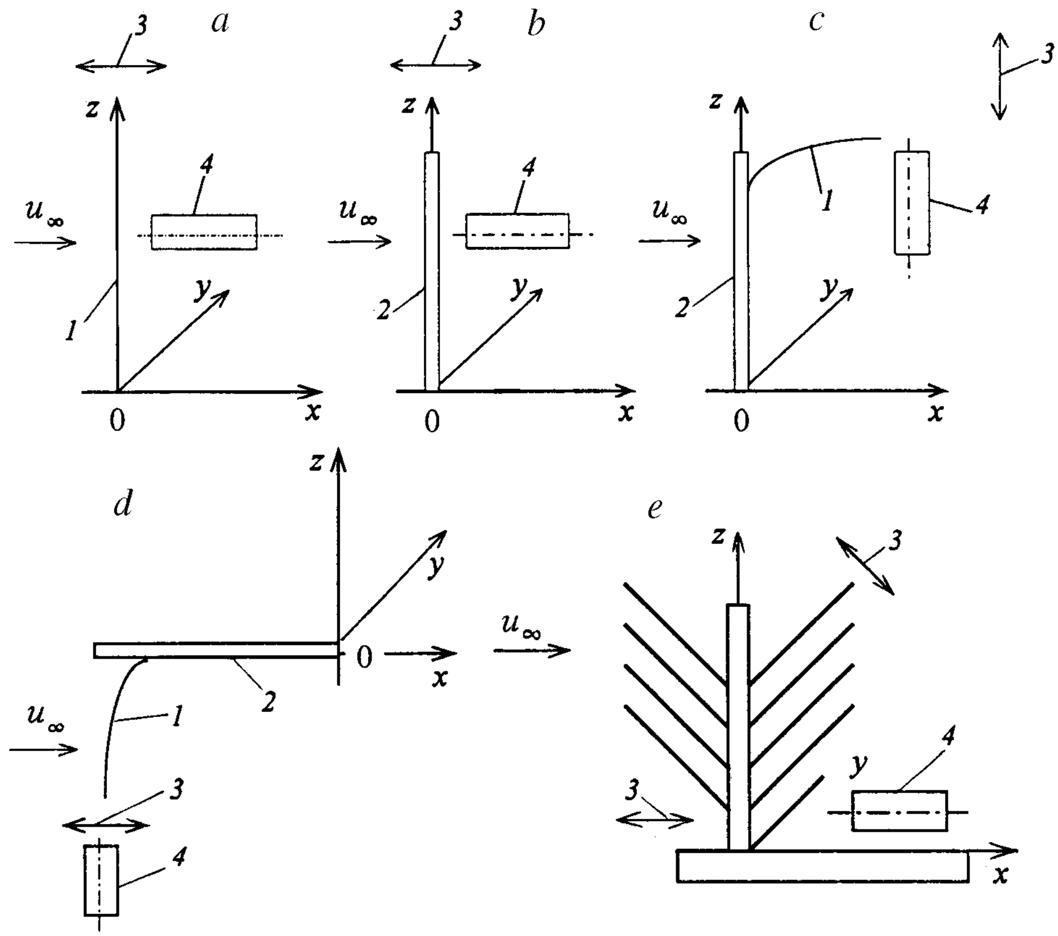

Fig. 1. Layout schematic of the elements of combustible forest materials.

TABLE 1. Frequencies and Amplitudes of Vibrations of Combustible Forest Materials as a Result of the Effect of a Single Initial Disturbance ($\Delta_0 = 2.0 \cdot 10^{-3}$ m)

Type of needles	$l_s \cdot 10^{-3}$, m	$d \cdot 10^{-3}$, m	W, %	f, Hz
Pine	26	0.7	11.2	20.0
Pine	41	0.9	19.1	21.4
Pine	43	1.0	54.2	16.7
Cedar	80	1.0	12.1	38.5
Spruce	16	0.7	12.7	4.4
Pine	60	4.0	–	2.1

dles and twigs (schemes of flow a and b in Fig. 1) as a result of the effect of a single disturbance (Table 1) and a continuous disturbance caused by the action of the laminar air flow in the wind tunnel (Table 2).

Figure 2a and b presents oscillograms of measurement of the amplitude of vibrations as a function of time for the effect of a single disturbance (damped vibrations) and in the air flow (nearly harmonic undamped vibrations).

The change in the initial amplitude of vibrations A_0 owing to the effect of the initial disturbing force within the range $(0.5–4.5) \cdot 10^{-3}$ m did not lead to a change in the frequency of natural vibrations of the elements of combustible forest materials. The fact of a rather strong dependence of the frequency of natural vibrations on the moisture content is noteworthy.

TABLE 2. Frequencies and Amplitudes of Vibrations of Combustible Forest Materials in a Laminar Air Flow

u_∞, m/sec	1.1	1.6	1.9	2.5	3.1	3.6
Pine needle, W = 19.1%, $l_s = 41 \cdot 10^{-3}$ m, $d_s = 0.9 \cdot 10^{-3}$ m						
f, Hz	20–26	18–22	18–22	20–25	20–26	20–25
$A \cdot 10^{-3}$, m	1.15	1.56	1.74	1.91	2.07	2.20
Re	68.3	99.3	117.9	155.2	192.4	223.4
Sh	$18 \cdot 10^{-3}$	$12.4 \cdot 10^{-3}$	$10.4 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$6.4 \cdot 10^{-3}$	$5.5 \cdot 10^{-3}$
Pine twig, $l_s = 60 \cdot 10^{-3}$ m, $d_s = 4.0 \cdot 10^{-3}$ m						
f, Hz	2.1	2.0	2.1	2.0	2.1	2.1
$A \cdot 10^{-3}$, m	0.10	0.12	0.13	0.14	0.16	0.17
Re	100.5	436.9	518.8	682.9	846.6	983.0
Sh	$7.6 \cdot 10^{-3}$	$5.0 \cdot 10^{-3}$	$4.4 \cdot 10^{-3}$	$3.2 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$

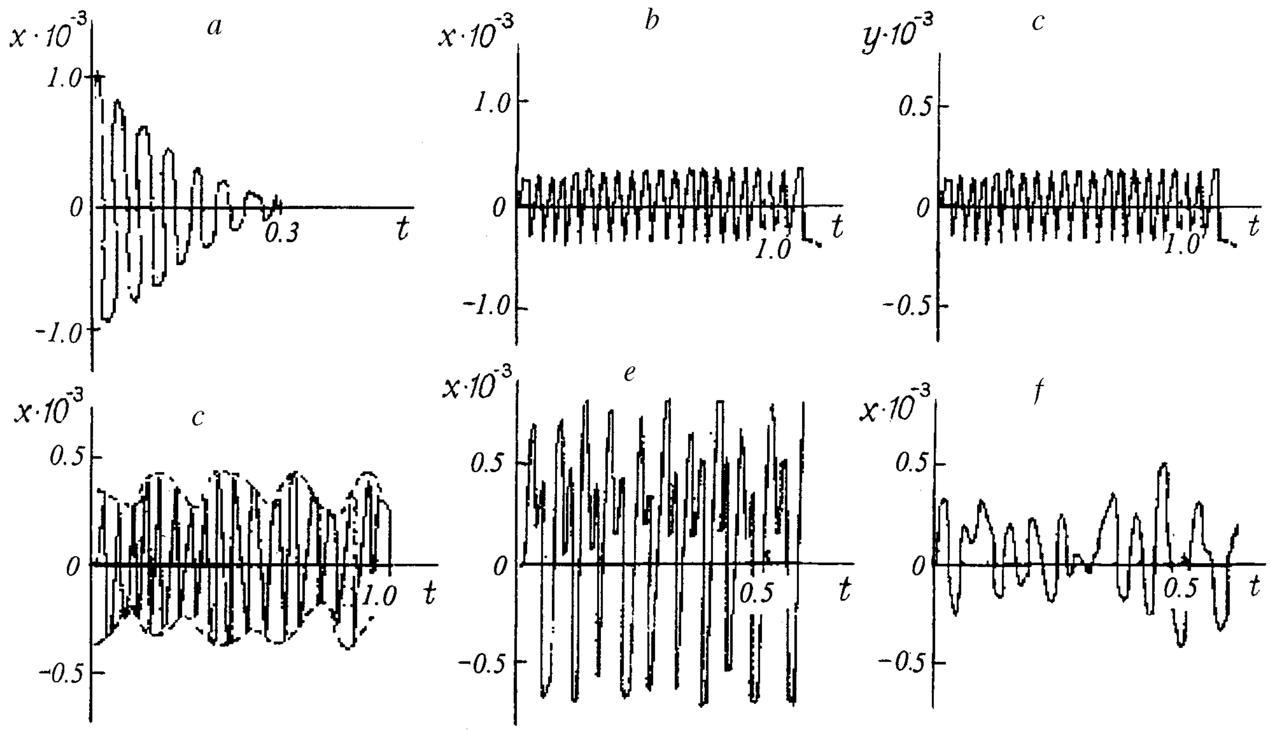

Fig. 2. Oscillograms of vibrations of the elements of combustible forest materials.

The coincidence of the frequencies of vibrations of pine needles in the air flow with the frequencies of their natural vibrations in motionless air and the absence of the dependence on the initial disturbance and the wind velocity indicates that the elements of combustible forest materials in the air flow vibrate with frequencies equal to the frequencies of natural vibrations.

It is known that in the case of flow past tubes in heat exchangers, the effect of aerodynamic vibrations of tubes and building structures that is caused by the nonsymmetric separation of the flow [1, 3, 6, 7] can originate; in this case, a portion of the flow energy is spent on sustaining vibrations of the tube with a frequency close to its eigenfrequency of elastic vibrations. Visualization of the hydrodynamic pattern of flow of a smoke plume past combustible forest materials showed the presence of the nonsymmetric separation of

TABLE 3. Characteristics of the Elastic Properties of Combustible Forest Materials

Type of combustible forest material	f, Hz	$m \cdot 10^3$, kg	$l_s \cdot 10^3$, m	$d_s \cdot 10^3$, m	W, %	E_{ef}, N/m^2	EI, N·m^2	ΔE, N/m^2
Spruce needles	4.4	2.1	16	0.7	11.3	$0.94 \cdot 10^7$	$2.24 \cdot 10^{-7}$	$\pm 0.03 \cdot 10^7$
Cedar needles	38.5	4.8	80	1.0	10.8	$0.78 \cdot 10^9$	$7.65 \cdot 10^{-5}$	$\pm 0.05 \cdot 10^9$
Pine needles	21.4	2.9	41	0.9	16.2	$3.24 \cdot 10^{10}$	$4.11 \cdot 10^{-4}$	$\pm 0.07 \cdot 10^1$
							$(3.89 \cdot 10^{-4})$	0
Pine needles	16.7	4.6	43	1.0	34.9	$1.79 \cdot 10^{10}$	$7.2 \cdot 10^{-4}$	$\pm 0.06 \cdot 10^1$
								0
Pine needles	20.0	5.4	43	0.9	67.8	$0.85 \cdot 10^{10}$	$5.47 \cdot 10^{-4}$	$\pm 0.05 \cdot 10^1$
								0
Pine twigs	2.1	3.6	60	4.0	–	$0.89 \cdot 10^{10}$	0.22	$\pm 0.02 \cdot 10^1$
						$(0.9 \cdot 10^{10})$	(0.19)	0

TABLE 4. Frequencies and Amplitudes of Vibrations of Combustible Forest Materials According to the Schemes of Fig. 1c and d

Experimental conditions	Scheme in Fig. 1c						Scheme in Fig. 1d		
u_∞, m/sec	1.1	1.6	1.9	2.5	3.1	3.6	1.1	3.1	3.6
f_1, Hz	20–26	18–22	18–22	20–25	20–26	20–25	20–25	19–25	20–26
$A \cdot 10^{-3}$, m	1.15	1.56	1.74	1.91	2.07	2.20	1.30	1.41	1.50
f_2, Hz	–	40–46	40–42	39–41	40–41	40–45	–	–	–
f_3, Hz	–	–	–	–	–	–	5–6	5–6	5–6

the flow behind individual needles. Moreover, it was found that needles and twigs vibrate not only in the plane xz (see Fig. 1c) but also in the plane zy. This result indicates that the vibrations of needles and thin twigs are caused by the nonsymmetric separation of a laminar flow [1, 3, 4, 6, 7].

Information on the frequencies of natural vibrations of the elements of combustible forest materials can be used for determining the elastic properties, such as the effective Young modulus E_{ef} and the rigidity EI. For calculation of E_{ef} and EI we used the formulas [1, 8, 9]

$$f_s = \frac{3.52}{l_s^2} \sqrt{\frac{EI}{m_l}} , \quad m_l = m / l_s , \quad I = \frac{\pi d^4}{32} , \tag{1}$$

obtained for a cylindrical cantilever.

In the calculations, the moment of inertia of a real needle was replaced by the moment of inertia of an effective cylinder with a radius $r_{ef} = \sqrt{s/\pi}$ (here s is the area of the midsection of the real needle). Moreover, the moment of inertia was calculated numerically from the formula [9]

$$I = \iiint (x^2 + y^2) \, \rho_s dv . \tag{2}$$

To evaluate the accuracy of the results obtained, we made test measurements and calculations of f for cylinders made of pine and steel. For a pine cylinder with $l_s = 72 \cdot 10^{-3}$ m, $d_s = 0.5 \cdot 10^{-2}$ m, the density $\rho_s = 0.5 \cdot 10^3$ kg/m^3, and the Young modulus $E = 1 \cdot 10^{10}$ N/m^2, the calculations of the frequency of natural vibra-

TABLE 5. Frequencies and Amplitudes of Vibrations of Combustible Forest Materials According to the Schemes of Fig. 1e

Type of combustible forest material	u_∞, m/sec	1.1	1.6	1.9	2.5	3.1	3.6
Twig	$A \cdot 10^{-3}$, m	0.40	0.45	0.46	0.52	0.58	0.62
	f_3, Hz	2.0	2.0	2.1	2.1	2.1	1.9
Needle	$A \cdot 10^{-3}$, m	0.75	0.89	0.99	1.39	1.52	1.70
	f_2, Hz	60–70	62–70	58–67	60–70	65–70	60–70
	f_3, Hz	2.0	1.9	2.0	2.1	2.0	2.1

tions from formula (2) gave f_{calc} = 861 Hz; the measured frequency was f = 667 Hz. For a steel cylinder with $l_s = 53 \cdot 10^{-3}$ m, $d = 1 \cdot 10^{-3}$ m, $E = 20 \cdot 10^{10}$ N/m^2, and ρ_s = 7800 kg/m^3, we have the calculated value f_{calc} = 365 Hz and the measured value f = 312 Hz. The values of E are taken from [5].

The relative errors were $\varepsilon = \Delta/f$ = 22.5 and 14.5%, and they indicate satisfactory agreement between calculations and measurements.

Table 3 gives the values of the elastic characteristics of typical elements of combustible forest materials. The value of E from [5] for wood cylinders is given in parentheses. Comparison of the results obtained with the known data confirms and substantiates the suggested technique of determination of elastic properties of combustible forest materials.

Confidence intervals of ΔE were calculated from the results of 4–5 experiments with a confidence level of 0.95.

The values of the rigidity of combustible forest materials are given in parentheses; formula (2) was used to calculate I.

Figure 2c and d gives typical oscillograms of the transverse displacement of a needle x with time t: for Fig. 2c (see Fig. 1c) u_∞ = 1.1 m/sec, and for Fig. 2d (see Fig. 1d) u_∞ = 1.1 m/sec. Table 4 presents typical values of the vibrational frequencies f and amplitudes A for different experimental conditions.

Table 5 gives the values of the frequencies and amplitudes of vibrations for the conditions of the experiment by the scheme of Fig. 1e (oscillogram in Fig. 2d).

According to the analysis of the results presented in Fig. 2 and Tables 4 and 5, no more than three dominating frequencies [f_1 = (18–25) Hz, f_2 = (40–46) Hz, and f_3 = (5–6) Hz] are present in the spectra of vibrations of the twig–needle system. As the velocity of the air flow increases, the amplitude of vibrations increases monotonically, while the frequency virtually does not change. This conservative dependence of the frequency of vibrations of the elements of combustible forest materials on the velocity of the air flow (driving force) is associated with the fact that the frequency of vibrations is a function of the geometric dimensions, mass, and elastic properties of twigs and needles [1–3].

For the velocity of the air flow $u_\infty \approx$ 1.5 m/sec, the vibrations of a twig with the frequency $f_2 \approx 2f_1$ are superimposed on the vibrations of a needle (see Fig. 1d); the fact that the displacement of the needle end caused by the vibrations of a twig is always $x > 0$ is noteworthy. Figure 1d explains this fact: vibrations of a twig are limited by pressure from the side of the air flow. Measurements of the frequency of vibrations of the needle base (twig end) gave values of f = (36–42) Hz close to the values of f_2; this confirms the mechanism of origination of f_2.

Results of the Analysis of Vibrations of the Twig–Needle System. In the case of air flow past the twig–needle system, according to the scheme of Fig. 1c modulation of the transverse vibrations of the needle occurs (see Fig. 2c), which originates for a velocity of the air flow $u_\infty \geq 1.1$ m/sec. The frequency of modulating vibrations f_3 = (5–6) Hz, as well as the frequency of vibrations of needles, virtually does not depend on the velocity of the air flow. The modulation is caused by the composition of the transverse vibrations of the needle and the longitudinal vibrations of the twig (see Fig. 1b). This is confirmed by measurement of the frequency of vibrations of the needle base (twig end) $f = (5–8)$ Hz.

It is shown in [1, 3] that the burning of combustible forest materials is diffusional. Therefore, the mechanical vibrations of needles and thin twigs can increase the inflow of the oxidizer to the needle burning in the forest cover, which will result in an increase in the rate of burning of combustible forest materials. On the other hand, if the wind velocity is very high, the process of combustion can cease owing to extremely high heat losses caused by the interaction of an elementary plume surrounding the burning element of combustible forest materials and a relatively cold air flow. This conclusion can easily be drawn on the basis of a simple experiment with one burning needle or a match if vibrational motions are executed by a hand holding this needle. This is also confirmed by the theoretical results of [1, 3], where, using the method of small perturbations, it is shown that the lower and upper limits of propagation of a crown forest fire by wind velocity $\underline{u}_\infty$ and $\overline{u}_\infty$ exist.

Discussion of the Results. On the basis of the results of [5, 6] and experimental data given above, we can assume that the mechanism of origination of the vibrations of elements of combustible forest materials (needles and thin twigs) is as follows:

1) for relatively small values of the Reynolds number, separationless flow past an element of combustible forest materials occurs, the pressure profile on its surface is symmetric, and there are no vibrations of this element;

2) as the Reynolds number increases, an early nonsymmetric separation of the flow for an angle of $\varphi_s = 82^o$ reckoned from the front critical point of the cylinder occurs, which causes the asymmetry of the pressure profile and the displacement of the element of combustible forest materials toward a lower pressure;

3) in separation of the vortex on the opposite side, the element of combustible forest materials shifts to the side opposite to the vortex and thus the vibrations of a needle or a thin twig originate, which manifest themselves experimentally in acoustic noise excited by vortex trails;

4) the element of combustible forest materials vibrates under the effect of pressure forces from the side of the gas flow, inertia forces, and elasticity forces; in this case, the motion of the element owing to vibrations along and across the direction of the flow velocity becomes orbital.

The value of the equilibrium wind velocity $u_\infty = 2.2$ m/sec for a needle obtained in [1–3] can be interpreted as the lower limit (limit of origination of $\underline{u}_\infty$) of a crown forest fire. This value is in agreement with results of semi-full-scale experimental studies [1–3], in which it was found that the ground forest fire in pine undergrowth changes over to a crown fire for a wind velocity of 3 m/sec.

CONCLUSIONS

1. The technique of experimental investigation of vibrations of elements of combustible forest materials using optoelectronic facilities in a laminar air flow was developed for the first time. Comparison of experimental data with the frequencies of cantilevers of steel and pine wood found theoretically showed that the error of determination of the amplitudes and frequencies of natural and forced vibrations changes from 15 to 22%.

2. On the basis of experimental data on the minimum frequency of vibrations and formula (2), we suggested a technique for determining the Young modulus E and the rigidity EI of elements of combustible forest materials, which were found for needles and thin twigs. The values of E and EI were obtained for needles of pine, spruce, and cedar for the first time. In the last case, it was found that E and EI decrease with increase in the moisture content.

3. It was found experimentally that the interaction of the elements of combustible forest materials and the air flow leads to a nonsymmetric separation of the flow, thus causing the vibrations of needles and twigs of certain frequencies $f \sim (18–25)$ Hz, which are conservative to a change in the flow velocity and equal to

the frequencies of the natural vibrations of combustible forest materials. The increase in the velocity of the flow leads to an increase in the amplitude of vibrations and can turbulize the air flow near the elements of combustible forest materials. The effects of amplitude modulation of the resultant vibrations, which are induced by the vibrations of the twig–needle system, can originate in the spectra of vibration frequencies.

4. The experimental investigations conducted open up the possibility of mathematical modeling of vibrations of combustible forest materials to the processes of origination and propagation of crown forest fires.

The results obtained served as an experimental basis for the development of a refined general mathematical model of forest fires [10] within the framework of which the influence of vibrations of combustible forest materials on the heat and mass exchange of these elements with the environment in propagation of forest fires is taken into account.

NOTATION

u_∞, velocity of the oncoming flow; A, amplitude of vibrations; f and f_{calc}, measured and calculated frequency of vibrations; t, time; Δ, absolute error of frequency measurement; ε, relative error of measurement; W, moisture content; d, effective diameter; l_s, length of the element of combustible forest materials; $\mathrm{Re} = u_\infty d/\nu$, Reynolds number; ν, kinematic viscosity; $\mathrm{Sh} = fd/u_\infty$, Strouhal number; E, Young modulus; I, moment of inertia; ρ, density; x, y, z, Cartesian coordinates; m, mass of a needle or a thin twig; ρ_s, density of combustible forest materials; $\underline{u}_\infty$ and $\overline{u}_\infty$, lower and upper limits of the velocity of propagation of a crown forest fire by wind velocity. Subscripts: s, for a solid body; ∞, for gas velocity; 0, initial values; l, along the length of combustible forest materials.

REFERENCES

1. A. M. Grishin, *Mathematical Modeling of Forest Fires and New Methods of Fighting Them* [in Russian], Novosibirsk (1992).
2. A. M. Grishin, *Physics of Forest Fires* [in Russian], Tomsk (1994).
3. A. M. Grishin, *Mathematical Modeling of Forest Fires and New Methods of Fighting Them*, Tomsk (1997).
4. A. M. Grishin and A. N. Golovanov, *Sib. Fiz.-Tekh. Zh.*, Issue 6, 102–106 (1997).
5. G. W. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants* [Russian translation], Moscow (1962).
6. A. A. Zhukauskas, *Convective Transfer in Heat and Mass Exchangers* [in Russian], Moscow (1982).
7. E. Simiu and R. Scanlan, *Effect of Wind on Buildings and Constructions* [Russian translation], Moscow (1984).
8. J. P. den Hartog, *Mechanical Vibrations* [Russian translation], Moscow (1960).
9. L. D. Landau and E. M. Lifshits, *Continuum Mechanics* [in Russian], Moscow (1953).
10. A. M. Grishin, in: *Proc. Int. Conf. "Conjugate Problems of Mechanics and Ecology"* [in Russian], Tomsk (2000), pp. 88–137.