Journal of Engineering Physics and Thermophysics, Vol. 74, No. 4, 2001

CONJUGATE PROBLEMS OF HEAT AND MASS EXCHANGE AND THE PHYSICOMATHEMATICAL THEORY OF FOREST FIRES

A. M. Grishin

UDC 533.6.011.6+634.0.431

A short review of the works on the problem of mathematical and physical simulation of forest fires is given. Basic results of the investigation of this problem at the Tomsk State University are presented.

The Current State of the Theory of Forest Fires. Forest fires represent a catastrophic natural disaster, especially for densely populated regions and territories with a limited (insufficient) area of forest cover. At the same time, they inflict tremendous economical and ecological damage on all countries and regions. It is for this reason that a decision on the concept of stable development of humanity was adopted at the UN Conference in Rio de Janeiro. The essence of the term is "to satisfy the needs of the present without undermining the capability of future generations to satisfy their needs" [1]. In view of this, the preservation and protection of forest from fires was declared at the UN Conference as one of the most urgent problems [1].

To carry out successful and efficient control of forest fires, of great importance is the understanding of the essence of the physicochemical processes of the occurring phenomena.

At the present time, two trends in investigations with mathematical simulation of forest fires have been developed in the world:

(1) forest pyrology, in which descriptive methods of investigation of forest fires are adopted with the use of simplified models based on the well-known data concerning the behavior of actual forest fires [2–8];

(2) the theory of heat and mass exchange in multiphase reacting media within the framework of which special models are used for physical and mathematical modeling of forest fires that take into account the laws of mass, momentum, and energy conservation and the entire range of physicochemical phenomena; the results of the modeling are compared with the data of laboratory and field experiments [9–20].

The *first trend* in Russia was developed at the Institute of Forest and Wood of the Siberian Branch of the Russian Academy of Sciences of Prof. N. P. Kurbatskii with co-workers and continues to be developed at the Institute of Forests, Siberian Branch of the Russian Academy of Science, at the Siberian Technological University, and also at the St. Petersburg Research Institute of Forestry (St. Petersburg) and at the International Institute of Forests (Moscow). Within the framework of this trend, a classification of forest fires is given and empirical formulas for the velocity of propagation and also a numerical procedure for determining the contours of low-land forest fires are suggested [2, 3].

A considerable contribution to the development of the theory of forest fires was made by foreign scientists ([4–8] etc.).

The second trend in Russia was developed mainly at the Tomsk State University, where, as a result of comprehensive theoretical and experimental investigations, a general physicomathematical model of forest fires was developed. In [8], it was called the model of the future.

In recent times, the physicomathematical theory of forest fires has attracted attention in the U.S. at the Los Alamos National Laboratory [21] and in France at Marseille University [22].

Tomsk State University, Tomsk, Russia; email: fire@fire.tsu.tomsk.su. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 4, pp. 48–52, July–August, 2001. Original article submitted July 17, 2000.

The Theory of Conjugated Problems of Convective Heat Exchange and the General Mathematical Model of Forest Fires. The theory of conjugated problems of convective heat- and mass-exchange, whose foundations were laid at the Heat and Mass Transfer Institute of the Academy of Sciences of BSSR under the leadership of the late A. V. Luikov, has played an enormous role in the creation of the general mathematical model of forest fires [23].

The distinctive feature of forest fires is their strong influence on the near-ground atmospheric layer, which in turn influences the state of the fire front. At the same time, for forest fires we still do not know the heat- and mass-exchange coefficients α and β, owing to which it would have been possible to determine the densities of heat and diffusion fluxes, as is done for many problems of thermal engineering. Therefore, from the very beginning of investigations into problems of the theory of forest fires [9], the methodology of conjugate problems of heat exchange [23, 24] was used, within the framework of which the heat- and mass-transfer equations were solved simultaneously for both the near-ground atmospheric layer and the layer of forest combustible materials (FCM).

Within the framework of the general mathematical model developed at the Tomsk State University, the forest in fire is considered to be a multilevel porous-disperse reactive solid medium which is inhomogeneous in structure and composition. On the interfaces between the levels, conditions are used which, according to A. V. Luikov, are generalized boundary conditions of the fourth kind. Estimates show that the characteristic distance between trees is many times smaller than the characteristic horizontal size of a typical tract of forest, which makes it possible to use the methods of continuum mechanics for mathematical description of forest fires. In the course of the work on the mathematical model, it became clear that information is required on the mechanism of energy transfer between the levels of the forest and from the fire front to the surrounding medium, on the coefficients of transfer, and on kinetic characteristics of chemical reactions that include pyrolysis of forest combustible materials and reaction of oxidation of gaseous and condensed combustible products of pyrolysis. In analyzing heat and mass exchange between the levels of the forest at the interfaces between the levels of the forest and the near-ground atmospheric layer, boundary conditions were set that express the laws of mass, momentum, and energy conservation. Moreover, it was necessary to create a relatively simple semiempirical model of drying forest combustible materials and also to know the volumetric fractions of the phases, aerodynamic characteristics of forest tracts, and other parameters that determine the structure of such an unusual continuum as a forest [11]. In this connection, numerous semifield and laboratory experimental investigations were carried out and procedures developed for solving inverse problems of the mechanics of reacting media that in the first approximation made it possible to determine the above-indicated parameters and to create a bank of initial data required for mathematical simulation of forest fires.

As a rule, there is a turbulent regime of flow of gaseous and dispersed combustion products in forest fires. Therefore, much attention was paid to the selection of the model of turbulence. Use was made of the modified Prandtl model and also the K–ε and K–l models of turbulence [11, 14].

Basic Results of the Physicomathematical Theory of Forest Fires. For the investigation of forest fires a comprehensive theoretical-experimental approach was used. As a result of semifield and laboratory experiments, the physicochemical mechanism of the inception and propagation of forest fires was studied and a physical model was created, which is a set of cause and effect relationships (see Fig. 1).

The basic results of experimental investigations are as follows:

(1) The fronts of low and crown forest fires include zones of warming, drying, and pyrolysis of forest combustible material and also of diffusion combustion of gaseous, and afterburning of condensed, products of pyrolysis [9–15] (Fig. 2).

(2) The temperature profiles of gaseous and condensed phases in the front of the crown forest fire have the form of a Gaussian curve. The temperature of the condensed phase is lower than the temperature of the gaseous one, with the maximum difference being equal to 200–300 K [10–13] (see Fig. 2).

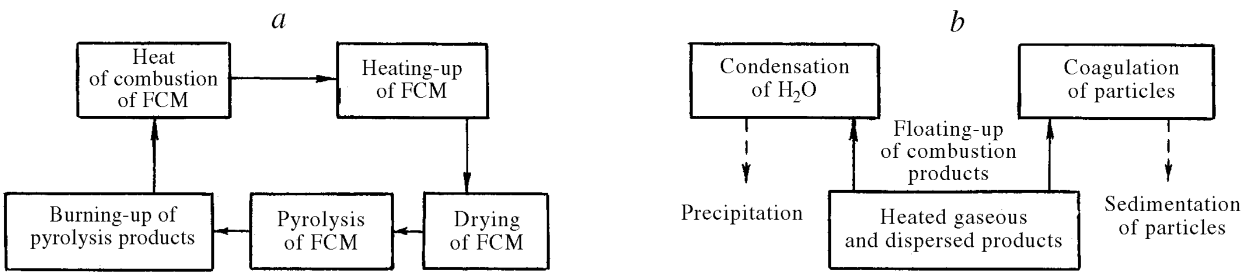

Fig. 1. Schemes of physicochemical processes in the zone of a forest fire (a) and in the near-ground atmospheric layer (b).

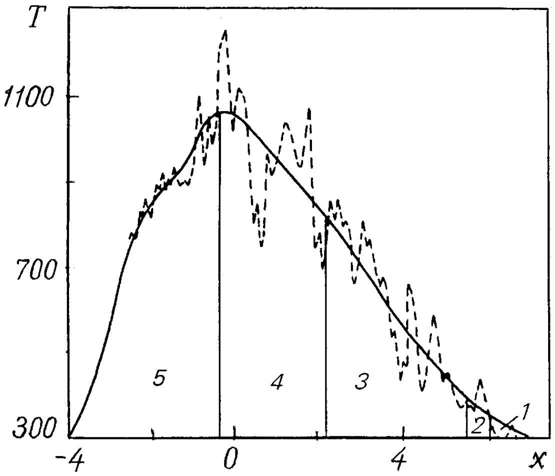

Fig. 2. Structure of the front of the crown forest fire: 1) zone of the heating up of FCM; 2) zone of drying of FCM; 3) zone of pyrolysis of FCM; 4) zone of combustion of gaseous products of pyrolysis; 5) zone of burning-up of condensed products of pyrolysis; solid curve, profiles of averaged temperature; dashed curve, profiles of instantaneous temperature in the fire front. *T*, K; *x*, m.

(3) The crown forest fire arises as a result of ignition of the tops of trees from a plume of the flame of the low-land forest fire. A relatively stable propagation of the crown forest fire over the tops of trees is observed if the wind velocity in the forest canopy exceeds 2.5 m/sec [11–15].

(4) On the basis of the heat- and mass-exchange theory, the front of the crown forest fire represents a kind of heat curtain whose characteristics depend on the intensity of heat emission, the wind velocity, the height of the forest canopy, the type of vegetation, the relief of the locality, and the intensity of turbulence [10].

(5) The elements of the forest combustible materials (thin branches and pine needles) in the forest-fire front vibrate and produce characteristic rustle and noise, and the temperature of the elements of forest combustible materials depends nonmonotonically on time [11–15].

(6) Gas flow in the forest-fire front is turbulent, resulting in the fluctuation of temperature and other characteristics of a gas phase [9–15].

(7) Flow in convective columns, i.e., in jets of air mixed with the combustion products of forest combustible materials, is turbulent, and the temperature rapidly decreases with increase in the height [10].

(8) The diffusion regime of combustion is realized in the forest-fire front [9–17].

(9) As a result of numerical solution of plane two-dimensional problems of the aerodynamics of forest fires, it has been established that in interaction of wind with the combustion products injected from the

forest-fire front there are two limiting types of flow: unidirectional (a jet boundary layer) and a convective column (an inclined jet of heated gas-dispersed combustion products). For the latter type of flow, a large toroidal vortex is realized ahead of the forest-fire front, as a result of which the flow velocities near the underlying surface and in the near-ground atmospheric layer have different directions, with the wind velocity near the forest-fire front in the near-ground atmospheric layer being increased [11–17].

(10) It has been shown numerically that the friction stress ahead of the fire front falls sharply and the heat flux changes its sign; this testifies to the fact that the unidirectional flow and heat transfer in the near-ground atmospheric layer in the vicinity of the fire front at a considerable wind velocity have the character of a heat curtain. It has been found that in this case free convection of heated combustion products relatively weakly influences the magnitude of a convective heat flux ahead of the fire front [11, 15].

(11) The laws governing the propagation of burning particles ahead of the fire front were investigated. It has been shown that as the wind velocity, angle of escape, and temperature of particles increase, the distance of their flight increases, whereas it decreases as their size and density decrease [11, 15].

(12) As a result of numerical solution of the problem of aerodynamics of an axisymmetric forest fire, it has been shown that in its vicinity there is a large toroidal vortex that ensures heat- and mass-exchange of the combustion zone with the outer medium [11, 15]. It was determined numerically with the use of the exact K–ε model of turbulence [11, 15] that to describe steady-state turbulent flows an equilibrium K–ε model of turbulence (modified Prandtl model) can be used, whereas for unsteady flows the use of a simplified model leads to considerable errors in determination of velocity and temperature fields.

(13) Within the framework of the theory of thermals, it has been shown numerically that the trajectory of the center of mass of the thermal appearing in a forest fire is greatly influenced by the Coriolis force [11, 15].

(14) A self-consistent mathematical model of crown forest fires has been suggested, which, within the framework of the laws of mass, momentum, and energy conservation, takes into account heat and mass exchange between the near-ground atmospheric layer and the canopy of the forest during forest fire. As a result of numerical solution of the problem of occurrence and propagation of a crown fire, the same, as in experiments, structure of the front was obtained, and it was found that combustion in the front of the fire was of a diffusion character, i.e., it is limited by the inflow of an oxidant and gaseous combustible products of pyrolysis into the zone of combustion. It has been shown that the main amount of energy in this zone is emitted in combustion of the gaseous products of pyrolysis [11, 15].

(15) Theoretically, by the method of small perturbations [11, 15], and numerically, the stability of the forest-fire contour has been investigated with account for the complex structure of its front. It has been proved that the forest-fire contour is completely unstable against small perturbations. For large forest fires, when the transverse dimension of the fire site exceeds a certain value, the contour loses its initial shape and becomes convex-concave.

(16) With the use of the method of small perturbations and numerical methods, it has been found that there exist limiting conditions for the propagation of forest fires as regards the storage and moisture content of forest combustible materials, the wind velocity, and the rate of heat and mass exchange [11, 15].

(17) As a result of mathematical and physical modeling of heat and mass transfer in forest phytocoenosis during forest fires, it has been shown that for crown top forest fires propagating in blown forest phytocoenoses the basic amount of energy from the front of fire to the phytocoenosis ahead of it is transferred by forced convection (wind), as a result of which the flame jet deviates greatly from the vertical [12], whereas for low and continuous top forest fires transfer of energy by radiation is of great value [11, 15].

(18) As a result of simplifying assumptions, approximate analytical formulas have been obtained for the velocity of propagation of low and top forest fires, the density of the overall heat flux, and the width of the forest-fire front that satisfactorily agree with the results of numerical calculations and experimental data [11, 15].

(19) It has been found numerically and analytically that antifire barriers in forests are more efficient for antifire control than forest-fire explosions [11, 15].

(20) As a result of mathematical simulation of low-to-top fire transition, it was established [15] that for the stand of pine trees this phenomenon occurs at the height of the lower boundary of the tops of trees above the height of the soil cover of about 0.7 m on condition that the specific heat pulse to the canopy of the forest is not less than 2600 kJ/m^2; this agrees with the experimental data of [11]. It has been found that the coefficient of radiation ε is a function of time which depends parametrically on forest-pyrological properties of low fire and forest phytocoenoses. It has been shown that ignition of the forest canopy has a gas-phase character, whereas the neglect of the two-temperature nature of the medium in the forest canopy leads to a decrease in the critical height of the forest canopy by 40–50% [15].

(21) A thermocouple-thermovision procedure has been developed for laboratory investigations of the incipience and propagation of low forest fires [19, 20]. The front of the low forest fire was shown to have the same structure as the front of the crown forest fire.

(22) Theoretically and experimentally, the ignition of a layer of forest combustible materials by a standard source of ignition was investigated. The limiting values of the energy of ignition depending on the moisture content of forest combustible materials have been found [20].

(23) The trends in ignition of forest combustible materials in a flow of a heated gas have been investigated [12]. It has been established that an aggregate of pine needles with other conditions being equal, is ignited at a lower temperature of the gas flow than a separate needle, which is explained by the gas-phase mechanism of ignition of these forest combustible materials.

(24) Methods of carrying out semifield experiments have been developed and described in detail [10–15]. Moreover, numerous laboratory experiments on recording the decrease in the mass of forest combustible materials as a result of drying and pyrolysis have been carried out, which allowed one to determine the thermokinetic constants of these processes [11, 15].

(25) It has been established by means of mathematical simulation [16, 17] that, depending on the distances between forest tracts and the light radiation source, three regimes of ignition are realized: degenerated, normal, and nonignition [25, 26]. As a result of calculation, times of ignition were obtained that were less than the corresponding times of arrival of an explosion wave at the underlying surface, which agreed with the results of examination of the territory of Hiroshima and Nagasaki after atomic bombing in 1945 and the region of the fall of Tunguska meteorite in 1908.

(26) It has been shown that for technogenic catastrophes (air nuclear explosion) the contour of ignition for a homogeneous forest tract has the shape of a circle with the center at the epicenter of the explosion [26], whereas for natural (collisional) catastrophes the shape of the ignition contour differs from a circle [25]. In particular, according to the data of observations, the shape of the ignition contour on explosion of the Tunguska meteorite represents a set of the arc of a circle with an arc of an ellipse whose large semiaxis is elongated to the side of motion of the meteorite [25]. The parametric analysis of the solution of these problems showed that the area S_* of the ignition region increases with increase in the total energy E evolved in the catastrophe, in the kinetic energy τ of a dangerous space object that was converted into radiation, and in the ratio ε of the energy of explosion E_0 to E_1. It has been established that the general mathematical model makes it possible to obtain S_* which satisfactorily agrees with the results of investigation of the area where the Tunguska meteorite fell. As a result of mathematical simulation, it has been shown that ignition of forest combustible materials is of a gas-phase character, i.e., the gaseous products of the pyrolysis of forest combustible materials are ignited. Moreover, on being ignited, these pyrolysis products do not burn out entirely. A portion of them rises up, under the action of the mass force, toward the incident shock wave and explodes in interaction with it. Estimations made from the well-known data for the Tunguska celestial body showed [25] that up to 20% of the recorded energy of the explosion can be provided by the explosion of gaseous combustible products of the pyrolysis of forest combustible materials.

(27) By using a conjugate formulation of the problem, the problem of transition of the low forest fire to the crown one was investigated theoretically in [26]. The limiting height of the lower boundary of the branches of trees was found and also the limiting energy of ignition of the tops of pine trees.

(28) It was established [27] that vibrations of the elements of forest combustible materials (thin branches, pine needles or leaves) caused by gusts of wind and turbulent oscillations of the flux in the front of a forest fire exert a considerable effect on heat and mass exchange at the front of the forest fire.

To obtain a numerical solution of problems of the theory of forest fires, the earlier developed iterative-interpolation method [28] and special procedures of numerical solution based on the Patankar–Spalding method [29] were used. Moreover, the stability of the propagation of forest fires was analyzed analytically by the method of small perturbations [11, 15].

The principal result of the mathematical simulation of forest fires was the determination of the limiting conditions for the propagation of forest fires under which the process of combustion stops:

$$\rho_b < \rho_{b*}\,, \quad W > W_*\,, \quad \alpha_v < \alpha_{v*}\,, \quad c_1 < c_{1*}\,, \quad c_2 < c_{2*}\,, \quad u_\infty > u_{\infty *}\,.$$

Knowledge of the limiting conditions made it possible to find a sequence of actions with the aid of which the limiting conditions of propagation in the zone of fire are found and, on this basis, to suggest 18 new methods and devices for controlling forest fires [15–18] and also a new concept of this control [11, 12, 14, 17].

Refinement of the General Mathematical Model and Prognosis of Ecological Consequences of Forest Fires. On the basis of generalization of the well-known experimental and theoretical data, a mathematical model of forest fires of first generation was suggested in [9, 10], within the framework of which a forest was modeled by a porous-disperse medium and its skeleton was considered to be a nondeformed solid body. This model was many times refined and improved. In particular, in the first version of the mathematical model of forest fires the radiation was considered to be grey [9, 10]. Thereafter, to describe energy transfer by radiation in the forest-fire zone the so-called group diffusion approximation [11, 15] was used, within the framework of which it is possible to determine the density of radiation in different spectral ranges. This opens up new possibilities for early discovery and identification of the type of forest fire using the data of aerospace monitoring of forests, general mathematical model of forest fires and, A. N. Tikhonov’s method [30] for solving inverse problems of mathematical physics. As it turned out, the model of the first generation is adequate on the whole to the studied phenomenon and can serve as a basis for creating a mathematical theory of forest fires. At the same time, there arose the necessity of refining this model and creating a general mathematical model of crown and low forest fires of the second generation. In particular, it is known [31] that vibrations of the elements of heat exchangers (tubes and rods of various diameters and shapes) exert a strong effect on the characteristics of heat and mass exchange with a high-enthalpy flow. In [31] it is shown that nonsymmetric detachment of a stream flowing past a rod excites natural vibrations of the heat-exchanger tube that can be enhanced if the frequency of the most representative turbulent fluctuations of the stream is close to the natural frequency of fluctuations. This effect leads to a change in the coefficient of heat and mass exchange of the elements of forest combustible materials (thin branches and pine needles) with the gas stream and finally to a change in the speed of propagation of forest fires, since a diffusion regime of combustion is realized in the front of a forest fire. Therefore, recently equations were introduced into the model that take into account vibrations of the elements of forest combustible materials, and a closed model of second generation was created [32].

This work was carried out with financial support from the Russian Federation Basic Research Foundation (grant Nos. 98-01-03005 and 99-01-00363) and "Universities of Russia — Fundamental Investigations" ("Mathematical Simulation" division).

NOTATION

ρ_b, density of a bed of forest combustible materials; W, moisture content of forest combustible materials; u_∞, equilibrium wind velocity in the forest canopy; α_v, coefficient of volumetric heat exchange; c_1, concentration of oxygen in the front of the fire; c_2, concentration of a combustible gas in the fire front. The subscript $_*$ characterizes the critical values of the above-listed quantities.

REFERENCES

1. V. A. Koptyug, *UN Conf. on the Environment and Development. Information Review* [in Russian], Novosibirsk (1992).
2. É. N. Valendik, P. M. Matveev, and M. A. Sofronov, *Huge Forest Fires* [in Russian], Moscow (1979).
3. É. N. Valendik, *Fighting Huge Forest Fires* [in Russian], Novosibirsk (1990).
4. F. A. Albini, in: *Proc. 11th Int. Symp. on Combustion*, Ca, Pittsburgh (1967), pp. 553–560.
5. A. I. Finklin, *Meteorological Factors in the Sundance Fire RUN.* Intermountain Forest and Range Experimental Station, Ogden, Utah (1973).
6. R. C. Rothermal, *A Mathematical Model for Predicting Fire Spread in Wildland Fuels.* U.S. Forest Service. Intermountain Forest and Range Experimental Station, Missoula, Montana (1972).
7. C. E. Wan-Wagner, *Can. J. Forestry Res.*, **7**, 23–28 (1977).
8. R. O. Weber, *Progr. Energy Combust. Sci.*, **17**, 65–82 (1990).
9. A. M. Grishin, *Chisl. Metody Mekh. Sploshn. Sred* (Novosibirsk), **9**, No. 6, 25–37 (1978).
10. A. M. Grishin, *Mathematical Models of Forest Fires* [in Russian], Tomsk (1981).
11. A. M. Grishin, *Mathematical Models of Forest Fires and New Methods of Fighting Them* [in Russian], Novosibirsk (1992).
12. A. M. Grishin, *Physics of Forest Fires* [in Russian], Tomsk (1994).
13. A. M. Grishin, in: R. Brun and L. Z. Dimitresku (eds.), *Shock Waves Marseille III. Shock Waves in Condensed Matter and Heterogeneous Media*, Berlin–Heidenberg–New York (1995), pp. 411–416.
14. A. M. Grishin, *Mathematical Modeling of Forest Fires and New Methods of Fighting Them* [in Russian], Tomsk (1994).
15. A. M. Grishin, in: J. G. Goldammer and V. V. Furyaev (eds.), *Fire in the Ecosystem of Boreal Eurasia*, Netherlands (1996), pp. 285–302.
16. A. M. Grishin, in: G. Eftichidis, P. Balabanis, and A. Ghazi (eds.), in: *Proc. Adv. Study Course on Wildfire Management (under the Environment Climate Program of the European Commission)*, October 6–14, 1997, Marathon, Greece, (1999), pp. 369–384.
17. A. M. Grishin, in: G. Eftichidis, P. Balabanis, and A. Ghazi (eds.), in: *Proc. Adv. Study Course on Wildfire Management (under the Environment Climate Program of the European Commission),* October 6–14, 1997, Marathon, Greece, (1999), pp. 385–398.
18. A. M. Grishin, in: V. E. Zharko et al. (eds.), *Prevention of Hazards and Explosions,* Netherlands (1994), pp. 305–318.
19. A. M. Grishin, A. A. Dolgov, V. P. Zima, A. V. Isakov, and V. V. Reino, *Fiz. Goreniya Vzryva*, **32**, No. 6, 87–95 (1996).
20. A. M. Grishin, A. A. Dolgov, V. P. Zima, D. A. Kryuchkov, V. V. Reino, A. N. Subbotin, and R. Sh. Tsvyk, *Fiz. Goreniya Vzryva*, **34**, No. 6, 14–22 (1998).
21. R. Linn, *Transport Model for Prediction of Wildfire Behavior*, Los Alamos Natl. Lab., LA-13334-T. Thesis US-905, Issued: July 1997.
22. B. Porterie, D. Morvan, M. Larini, and J. C. Lorand, *Fiz. Goreniya Vzryva*, **34**, No. 2, 26–28 (1998).
23. A. V. Luikov, in: *Heat and Mass Transfer* [in Russian], Moscow (1978), pp. 250–290.

24. A. M. Grishin and V. M. Fomin, *Nonstationary and Conjugate Problems of the Mechanics of Reacting Media* [in Russian], Novosibirsk (1984).
25. A. M. Grishin, K. N. Efimov, and V. A. Perminov, *Fiz. Gorenya Vzryva*, **32**, No. 2, 18–31 (1996).
26. A. M. Grishin and V. A. Perminov, *Fiz. Goreniya Vzryva*, **32**, No. 5, 116–124 (1996).
27. A. M. Grishin and V. A. Perminov, *Fiz. Goreniya Vzryva*, **34**, No. 4, 13–22 (1998).
28. A. M. Grishin, V. N. Bertsun, and V. I. Zinchenko, *Iteration-Interpolation Method and Its Application* [in Russian], Tomsk (1981).
29. V. A. Perminov, *Mathematical Modeling of the Incipience of Bulk and Crown Forest Fires with Account for Radiative-Convective Heat and Mass Transfer*, Dissertation for the title of Candidate of Physical and Mathematical Sciences, Tomsk (1995).
30. A. N. Tikhonov and V. Ya. Arsenin, *Methods for Solving Ill-Posed Problems* [in Russian], Moscow (1974).
31. A. A. Zhukauskas, *Convective Transfer in Heat and Mass Exchangers* [in Russian], Moscow (1982).
32. A. M. Grishin, in: *Proc. Int. Conf. "Conjugate Problems of Mechanics and Ecology"* [in Russian], Tomsk (2000), pp. 88–137.