THERMOPHYSICAL RESEARCHES AT LENINGRAD INSTITUTE OF FINE MECHANICS AND OPTICS

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In 1938, this institute set up a department concerned with thermal power monitoring and automatic control, which was headed by Professor G. M. Kondrat'ev. In 1947, the department was incorporated into the Engineering Physics Faculty and converted to a specialized thermophysics department, which trained engineering thermophysicists. After 10 years, a task laboratory was set up in the department. From 1958, the department and laboratory were directed by Kondrat'ev's student Professor G. N. Dul'nev. The scientific line for the department in the early years and up to the mid-1950s was concerned with the theory of regular thermal conditions together with methods and instruments based on it for thermal and temperature measurements [1, 2]. Professor Kondrat'ev, the originator of the theory, was awarded a state prize for this work.

Latterly, the topics have extended considerably, including research on heat transfer in instrumentation, where the following lines have been examined: heat and mass transfer in instruments, thermostable system design, transfer coefficients in inhomogeneous materials, methods and instruments for thermal and temperature measurements, and heat and mass transfer in optical engineering.

Heat and Mass Transfer in Instruments and Thermostable System Design. In electronics, optics, and other branches of instrumentation, there is increasing interest in heat transfer for several reasons. Firstly, normal thermal conditions are required for instrument operation, i.e., the temperatures in all the components should not exceed certain permissible ranges. The latter are related to reliability in electronic devices, while in optoelectronic and optical instruments, they are related to permissible aberrations, noise level, and so on. In certain instruments such as lasers, the thermal processes are associated with other physical phenomena governing the operation.

It is very laborious or often impossible to attain a permissible thermal state in a device by trial and error on prototypes; it is more economical to define the optimum design by calculation.

For more than a quarter of a century, the task laboratory in the thermophysics department has researched heat transfer in thermostats for lasers and for optical and electronic devices, as well as semiconductor converters and combinations of such instruments. Models have been devised for the processes and computer methods have been set up for the thermal design of such devices and for their cooling and thermostatic-control systems [3, 4].

These models involve new difficult problems in thermophysics and applied mathematics; in particular, heat transfer occurs under specific conditions: natural and force convection in channels with any variation in wall temperature [5]; force convection in channels having large ridges [6, 7]; convection in bounded volumes containing discrete sources [4, 6]; convective transfer over a wide gas pressure range [8]; emission from semitransparent media having complicated shapes [9]; heat transfer through contacts in various types of unit [6], etc. Mathematical methods have been proposed for analyzing the temperature patterns in systems containing bodies having local variable heat sources [5, 6, 10]. Approximate methods have been devised for analyzing parabolic and elliptic equations, and limits to their use have been defined [10-15].

Many different disciplines are increasingly involved in designing modern instruments; there is interaction between electronics, optics, thermophysics, gas dynamics, mechanics, and so on. Current design methods should correspond to the complexities involved, and during the last decade, resort has been made to computer-aided design CAD, in which the thermal design represents a subsystem. A thermal model in general is based on numerous regions complicated in shape containing sources and sinks. The fullest description for the patterns is provided by nonlinear conduction equations for solids together with the equations governing the energy,

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the motion, the continuity, and the state, together with the corresponding boundary conditions for the coolant fluxes, to which one sometimes has to add equations for radiation transport through various media. Such models are often difficult or impossible to apply even with computers. Also, it is often undesirable to solve such a treatment because we do not have appropriate accurate input data.

The problem becomes even more difficult if it is necessary to consider various physical processes occurring together; experience with calculating thermal conditions in instruments at the department has led to a general approach called stage simulation [6]. A complicated instrument can be referred to a restricted number of models, whose implementation may be analytic or numerical, so the thermal conditions are calculated in several stages by means of differing models. At the start, with minimal detail, one considers the system as a whole, where one incorporates the external factors and the positions of the devices in the object structure, so one can derive the mean surface temperatures and the heat-carrier fluxes. One then identifies the subsystems to give a more detailed description. The boundary conditions in the models for the various stages are written approximately, i.e., the true temperature and heat-flux distributions at the subsystem boundaries are replaced by average ones derived from earlier stages. The regions are identified and the boundary conditions are specified approximately in an iterative fashion until the required detail is obtained. The general scheme is qualitatively quite clear and follows logically from the general principles of systems analysis, which is used in conjunction with systems theory based on aggregation and decomposition [16]. However, it is insufficient to have a general scheme for this simulation, and one has to perform exact estimates on the errors arising from the assumptions, while the equation system has to be closed properly. This problem arises because there is some information loss on averaging the temperatures, fluxes, and so on. Such evaluations have been published by the department [6, 17, 18]. The method provides for analysis and synthesis at various levels and has been used for various complicated engineering or natural systems.

For many years, members of the Department have researched methods of calculating thermal conditions and designing cooling and thermostatic systems for various electronic equipments, electronic instruments, and computers. Recently, a series of studies has been performed on the thermal design and optimum construction for instruments of this type. The results are reflected in monographs [3, 4, 19] and textbooks [5, 6]. In the early 1980s, there was a substantial increase in the number of applications involving thermal conditions considered in conjunction with other physical phenomena, which has extended the research base and led to the synthesis of thermally stable devices. Collaboration with the Electronic Machine Design Institute has been concerned with research on the thermal conditions in a cryoturbo generator [20]; recommendations have been made on the optimum cooling systems for high-power semiconductor converters [21]; thermooptic phenomena in quantrons have been researched [22-24]; a method has been devised for simulating thermal conditions in optoelectronic devices [25]; and methods have been set up for analyzing and synthesizing thermal conditions in thermostatic devices [26-29].

The department has recently conducted many studies for space research; stage simulation has proved adequate and has been used in designing a thermostable TV camera for the Vega space project; a laser device and a video spectrometer have been designed. Design principles have been utilized for optimum instruments involving thermal, optical, and quantum-mechanical processes, which interact [30, 31].

The performance has been demonstrated in simulating heat transfer in the human body in order to identify the diagnostic limits to infrared vision [32].

The extensive research program on this line has led to a new discipline involved with heat and mass transfer in instruments; the laboratory data have been used in sectional standards, technical recommendations, and computer-aided design programs. The new application has opened up considerable scope for research in this field. There are teaching plans for specialities related to designing electronic and computing instruments, which have been incorporated into the course on heat and mass transfer in electronic devices.

This simulation method for synthesizing thermostable instruments has been widely used and is one of the bases for CAD.

Inhomogeneous-System Transport Coefficients. For more than a quarter of a century, the department has researched these coefficients for heterogeneous materials; when any device is to be designed, or any engineering process is to be planned, one inevitably has to select materials with appropriate physical properties. This applies particularly to the transport coefficients: thermal and electrical conductivities, dielectric constant, magnetic susceptibility, diffusion coefficient, viscosity, speed of sound, refractive index, and mechanical and other parameters.

The literature carries a vast amount of information on heterogeneous systems, which needs to be surveyed from a unified viewpoint to give compact forms for representing the information. Analytic methods applied to the parameters of mixtures provide substantial assistance in designing materials with preset properties and in classifying measurements and carrying them out.

Let the transport coefficients for the components K_1, K_2,... and the concentrations m_1, m_2,... be known for some heterogeneous material; one needs an analytic relationship between effective K and parameters $K = K(K_i, m_i)$ where one has to incorporate physicochemical interactions between the components, which requires an analysis at the molecular level. If those interactions are negligible, one can use phenomenological methods. In general, one needs a combined model.

Research has been conducted on transport coefficients for inhomogeneous materials since the end of the last century; in those 100 years, numerous methods, theories, and formulas have accumulated, and there are major difficulties in comparing these critically, while the first impression is that of extreme confusion. Members of the department have performed a careful analysis of the various methods and have identified the reasons for the numerous approaches; the transport in an inhomogeneous material leads to the number of unknowns being larger than the number of equations, i.e., the system needs to be closed. The lacking information can be derived from the structure, measurements, additional physical conditions, and so on. There are many methods of closing the system, and also many structures, and there may be differences in state of aggregation or physical properties between the materials, so there are numerous ways of combining methods of calculating the coefficients.

The performance has been evaluated for various methods in our laboratory, and recommendations have been made on those that are sound and give satisfactory accuracy, while suggestions have also been made on new methods in application to various heterogeneous systems. A model has been devised for an infinite cluster in a randomly inhomogeneous material, and penetration theory has been applied to transport. A method has been devised for considering a heterogeneous system in an external field, which provides a basis for research on thermoelectric, galvanomagnetic, and thermomagnetic parameters. A heterogeneous system in two or more fields acquires essentially new features absent from homogeneous substances. Members of the department have surveyed much evidence on thermal conductivity in granular, fibrous, and bonded materials, as well as in gaseous and liquid mixtures, molten metals, other melts, semiconductors, and composites; a method has been proposed for determining the conductivity in a phase transition in a solid [33]. Some research results here are reflected in books [34, 35].

These methods have had an interesting application in astrophysics in determining planetary structure; radio telescopes have given the thermal conductivities of planetary surfaces, and simulation has then been used to select a structure having a similar conductivity [36]. This research line was very active and involved collaboration with radio physicists at Gor'kii University in 1965-1975, and in particular in 1963 a correct prediction was made about the structure of the upper layer in the moon before the first soft landing by the Luna-9 probe [37].

In the 1980s, members of the physical chemistry department at the Institute made a new material: a matrix microcomposite, the basis being a microporous matrix (silica, glass, silcon, or certain metals), where the open pores were filled with various substances. Such a composite can have a desirable set of characteristics and provide new components. Members of the departments of thermophysics and physical chemistry at the Institute have collaborated with the Institute of General Physics, USSR Academy of Sciences, in introducing some new devices. For example, dies can be introduced into porous silica matrices to make solid laser media; compounds forming surface complexes can also be introduced into porous matrices for optoelectronic gas analyzers; the pores can be packed with a carbon filler to give a material providing a sensitive element for low-temperature resistance thermometers (4-400 K) [38]; and such materials have been used in an optoelectronic cell based on thermally controlled light scattering in a porous glass—liquid crystal system, which can be used for a data display [39]. The above methods of considering transport have been used in these researches.

Thermal and Temperature Measurement Methods and Instruments. This is a traditional topic in the laboratory. The Institute has proposed familiar regular-mode methods for measuring thermophysical parameters [1] and the monotone heating methods [40], which have been used in a group of commercially proposed instruments.

A second line in thermal measurements is concerned with integral and local heat fluxes varying in time.

The department has devised measurement methods for use in instruments; physiologists have used some of these instruments for measuring heat production by organisms (small animals and man) in normal and pathological states [41]. Nonstationary heat fluxes can be measured with meters as used in various branches of engineering [42, 44]. The department has developed some promising instruments and methods for examining local variable heat fluxes, porosity, and velocity in fluidized beds, whose application to common engineering processes has opened up scope for designing and choosing optimum processes and for quality control in chemical engineering and power production in the combustion of powdered fuel in fluidized or fountain beds [45].

In the 1950s, space engineering made it necessary to measure rapidly varying temperatures; the thermal inertia means that the temperature in a sensing element can differ quantitatively or even qualitatively from the actual temperature, so one needs principles for designing such sensors and means of interpreting the measurements. Research in the department are reflected in monographs [46, 47].

Since the early 1970s, the department has vigorously developed automation applied to thermophysical researches.

Data-acquisition suites DAS have been devised for these thermal tests on various instruments; these DAS have been used in thermal vacuum tests on the Vega equipment (the Venus—Halley international project) [48]. A similar suite also developed at the department has been used in testing the first cryoturbo generator type KTG-20 [49]. Such suites have also been used in testing and controlling the first commercial cryogenic turbo generator, the KTG-300. These DAS developed at the department enable one to measure temperature patterns with high precision and give very reliable data.

Temperature monitoring in engineering (particularly in making fiber optics and optical materials) is based on optical pyrometers, which have been developed for these purposes and for research ones in the department; a partial-radiation pyrometer operating at 5 μm has been designed to operate at 800-2500°C with a measurement error of 1-2 K and an area resolution of 2 mm^2. The instrument is comparable with the best foreign competitors such as the Irkon pyrometer made in the USA, and it is now in production [50]. A radiation pyrometer containing a CCD matrix as sensing element has been built. Novel instruments competitive with the best foreign ones have been built for monitoring diameter and shape on blanks and for monitoring refractive index in tubes for drawing optical fibers.

Heat and Mass Transfer in Optical Technology. Fiber guides and single-strand rigid guides of high quality require a new approach to process design. Three basic principles are involved: 1) details of the physicochemical processes, 2) models for the individual processes, which are used in numerical experiments to give correlations and regression lines providing a basis for the optimum technology and appropriate equipment, and 3) production computerization, including sensors and instruments for control and quality monitoring, which may be linked to a computing network and to effector mechanisms.

Experts consider that 70-90% of the processes in making fiber optics involve heat and mass transfer; for example, an optical fiber having a diameter of about 10 microns may be pulled from a billet 10-20 mm in diameter, which is made by vapor deposition. In the MCVD method, a silica tube rotating around its axis receives silicon, germanium, and phosphorus chlorides and so on in excess oxygen. An oxyhydrogen burner reciprocates on the outside of the tube, which produces a local heated zone, where the chlorides react to give oxides, which condense and produce critical nuclei, from which clusters grow, and thus particles of some hundreds of angstroms in diameter are deposited. When a given layer has been deposited, the burner temperature is raised and the tube collapses into a rod under surface tension. When the surface has been treated, the rod is heated in a suitable device (burner, resistance furnace, HF furnace, or with a laser) and the fiber is drawn. The fiber is protected by a liquid polymer deposited on the surface, which is polymerized in a thermal or UV oven. Then the fiber is wound on a drum and passes to the manipulation unit. We have simulated virtually all these processes by computer.

During the last decade, thermophysicists mainly in the USA and USSR have devoted detailed attention to these processes and have suggested a mathematical description; however, researches in this area have not yet satisfied industrial requirements, particularly as regards a fuller and more rigorous description of the complicated heat and mass transfer, which requires various plant trials and computer experiments, as well as the definition of clear-cut recommendations on the processes. Such research has been conducted by the department recently, and the necessary instruments have been built, while some of the results have been implemented [51, 52].

During the period 1957 to 1987, nine members of the laboratory or its students have presented DSc theses: (G. N. Dul'nev, A. I. Lazarev, B. N. Olinik, N. A. Yaryshev, E. S. Platunov, A. O. Sergeev, A. M. Azizov, V. V. Kurepin, and E. Ya. Litovskii), and there have been over 50 PhDs; about 800 engineering thermophysicists have been trained. Members of the department have published 15 monographs and textbooks as well as over 700 papers and have developed and introduced more than 40 novel instruments.

The department has set up a new scientific line: heat and mass transfer in instrumentation, which has been widely recognized in the USSR and elsewhere. At present, the departmental team is continuing to extend the traditional scientific lines and is extending the research to new areas in science and engineering.

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