SURVEY

PROGRESS IN THE THEORY AND METHODS OF ANALYSIS OF RADIATIVE AND COMBINATION HEAT TRANSFER

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The scientific and technical problems associated with radiative and combination heat transfer span an extensive program of fundamental and applied research aimed at solving specific problems in the formulation of progressive methods for the thermal analysis of boiler systems, metallurgical and heat-treatment furnaces, and air preheaters, in the development of new methods for the utilization of thermal radiation in the chemical, food, and pharmaceutical industries, for assessing the role of thermal radiation in diverse technological processes, etc.

The fundamental investigation of radiative heat transfer includes studies on the development of rigorous and approximative zonal methods for the analysis and calculation of radiative heat transfer in radiating systems of arbitrary configuration filled with transparent, selectively absorbing, radiating, and scattering media, along with studies in devising the most effective techniques for the analysis and calculation of combination (radiative–conductive and radiative–convective) heat-transfer modes.

The present survey covers the most important Soviet theoretical and experimental work in pure radiative and combination heat transfer during the last few years, primarily in application to problems of specific technological processes.

In the development of zonal analytical methods for radiating systems containing transmissive (diathermic) and attenuating media, a great many analytical studies have been carried out on the local and average radiation characteristics in volumes and on surfaces in the case of diffusely and directionally radiating boundaries, in application to the investigation of diverse types of heat-engineering devices.

A distinctive feature of these studies is the use of an iterative zonal method for determining the local and average characteristics of radiative heat transfer; this method permits computations to be carried out with a controllable error.

A great diversity of configurations of radiating systems with a diathermic medium has been investigated (cylinders of finite dimensions, coaxial cylinders, cylinder–cone combinations, truncated cones, prismatic chamber, etc.) [1-4].

Analytical expressions have been derived for the local and average directional factors of radiation in the components of various heat-engineering devices, and the first investigations are being conducted in the selection and preparation of surfaces having directional radiation properties [1-7].

The abundance and diversity of configurations leads to inquiry about the practicality of systematizing the whole body of material in the form of a standard handbook for determination of the optical and geometrical invariants of the radiation of different system configurations.

The development of zonal methods for the calculation of radiative heat transfer in systems with absorbing and scattering media has been aimed at taking account of the selectivity of radiation and the anisotropy of scattering under the conditions of various kinds of heat-engineering devices. Investigations of heat transfer in radiating systems of classical configuration (cylindrical, rectangular, and cubic chambers) filled with selectively absorbing and scattering media make it possible to simulate the heat-transfer conditions in real heat-engineering devices (furnace and heat-treating equipment).

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The cited studies include analytical determinations of the local and average characteristics of radiation in absorbing and scattering media for boundary as well as interior volume zones with regard for the selective nature of the absorption [1-4, 8-12].

We note a marked trend toward work on the analytical determination of the resolving and attenuating (absorbing) capabilities of media with the most general arbitrary optical properties of volumes and boundaries [4, 13]. Approaches of this nature make it possible to obtain compact and physically transparent analytical expressions for computing the integral energy characteristics of heat transfer. These developments prove particularly effective in the formulation of engineering calculations of furnace–boiler aggregates.

Zonal methods for the analysis of radiative heat transfer are finding increasing applications of an extremely diversified character, not only in testing the thermal state of operating equipment, but also for the design of fundamentally new devices (radiant-heat machines for drying, heating, and thermostatic control).

Considerable progress is noted in research on so-called combination (radiative–conductive and radiative–convective) heat transfer in absorbing, radiating, and scattering media.

Algorithms have been developed and numerical and experimental studies carried out in the solution of radiative–conductive heat-transfer problems in plane layers of selectively absorbing gases (carbon dioxide and ammonia), liquids (alcohols, toluene, carbon tetrachloride, etc.), and solids (window glass and clear plastics, alloys of special glasses) [14-18].

It is important to note in this connection the emergence of solutions of nonsteady problems, which are opening up extensive theoretical and practical opportunities [14]. An example of the practical application of this problem is the synthesis of a computer program for the calculation of processes involving the heating of plastics by infrared-radiation sources in accordance with the technological regime under semiindustrial conditions [17].

Research has expanded on radiative–convective heat transfer in radiating systems with absorbing and scattering media as models of various cases of heat-engineering applications (cylindrical, rectangular, and plane ducts). The results are particularly valuable in situations where radiative–convective interaction processes are conspicuous.

Approximative differential methods deriving from the tensorial description of radiative heat transfer have prove effective from the standpoint of simplicity and reliability [19].

This approach makes it possible to solve a broad class of combination heat-transfer problems in cases where the application of rigorous numerical solutions incurs excessive expenditures of machine time. Foremost in this regard are problems in the analysis of anisotropic scattering processes, where it is required to take account of the temperature dependence of the thermophysical and optical properties of media and to solve complex-conjugate problems [20].

A special place in terms of significance is held by work on the development and perfection of a method for the analysis of heat transfer in the furnaces of steam generators [21-33]; this work culminated in 1973 in the issuance of a new standard method for the thermal calculation of boiler systems.

The new standard method [34] mirrors all of the most significant results obtained in recent years. In particular, a zonal analytical method is prescribed for the first time, making it possible to determine the distribution of local heat loads over the height of both single-chamber as well as double-chamber and semienclosed furnaces. The accuracy and reliability of the thermal calculation of boiler systems are raised accordingly.

Later work in this direction has been associated with the acquisition of new experimental data on heat transfer in furnaces and on the radiation properties of flames and heat-sensitive heating surfaces for the purpose of further improving the standard method and enhancing the operational reliability of heat-engineering systems, primarily in application to present-day high-power steam generators. Considerable attention has been given to investigation of the radiation properties of flames and the thermophysical characteristics of heating surfaces contaminated with ash deposits [35-38].

It has been shown that during the burnout of a flame jet a considerable change takes place in the thermal-radiation spectrum of the flame in connection with the variation of the intensity of gaseous emission and the intensity of emission of soot particles. At the same time, the role of gaseous emission in the total thermal radiation of the flame increases. In a coal-dust flame, as in a mazut flame, the continuous radiation spectrum of the dispersed phase is overlaid with the radiation "band" spectrum of triatomic gases. This conclusion is conceptually new, because until recently the majority of researchers treated the coal-dust flame as a gray body. The coal-dust flame is characterized in this case by lower selectivity than the mazut flame.

It has been shown that the modeling of combustion and heat transfer in furnaces in the burning of coal dust must be carried out on a comprehensive scale, combining calculations of radiative heat transfer with calculations of the processes of combustion, convective heat transfer between the burning solid-fuel particles and the gas medium, and turbulent heat and mass transfer in the gas flows, as well as with allowance for the aerodynamics of the system of jets and the firebox. These investigations and developments have provided the basis for recommendations on refining the standard method of thermal analysis of boiler systems. Such refinements take account of the influence of recirculation of gases into the firebox, the position of the flame-temperature maximum, and the mechanism of formation of ash deposits, etc., and result in increased reliability of the thermal analysis of boiler-system furnaces.

Work has commenced on theoretical analyses aimed at ascertaining the possibilities of accounting for the nonisothermicity of the furnace volume in the furnace heat-transfer process. The concept of the nonisothermicity coefficient has been introduced for this purpose, and principles have been set down for its calculation [39, 40].

The investigation and development of methods for the calculation of heat-transfer processes in metallurgical furnaces have recently culminated in the formulation of a number of new and progressive methods for the analysis of such processes in furnaces serving various applications [41-47].

It is important to note the widespread application of zonal methods in this connection for heat-transfer calculations, the frequent recourse to Monte Carlo methods for determining the geometrical invariants of radiation, and in a number of cases concern for the selective nature and anisotropy of radiation [48-52]. Sophisticated methods of thermal analysis are being used in the design of industrial-equipment systems.

It has been verified on the basis of an analysis of the thermal and technological efficiency of furnaces for the radiant heating of metals that the principle of indirect radiant heating by means of specially developed sheet-flame burners for the firing of hot gases of various compositions and caloricities makes it possible to increase the performance of furnaces by a factor of 1.5 or more, to simplify furnace construction, and to improve the quality of heating of metals [53-55]. This effect is elicited by substantial intensification of heat transfer in the situation where the combustion reaction takes place at a phase interface in the wall boundary layer by comparison with the heat transfer from the neutral heated gas.

The results of the investigations have provided the basis for the development of working plans for furnace aggregates serving various purposes, including mechanized fast-heating furnaces. The anticipated cost savings through the use of indirect radiant-heating furnaces (according to just 27 commerical furnaces) in ferrous-metallurgical plants amounts to about 6.0 million rubles.

The need for the design of high-temperature air preheaters calls for a radical solution of the problem of maximum recovery of the heat of exhaust products of combustion in present-day high-performance heating furnaces.

An analysis of the operation of heat-recovery equipment for heating furnaces has led to recommendations for the development of air preheaters with an air heating temperature of 500 to 600°C in combination with a temperature of 1200 to 1300°C for the combustion products at the entry point.

Specially organized experimental studies of heat transfer on the side of the combustion products of a radiative slotted recovery unit have shown that prerecovery radiation plays a significant role in the heat-transfer process on the part of the heating surface adjacent to the flue firewall. These facts are taken into account in the corresponding engineering procedure. Investigations and calculations carried out by such methods have resulted in the development of various groupings of recovery units for furnaces with thermal powers from $0.4 \cdot 10^6$ to $40 \cdot 10^6$ kcal/h [56-58].

The introduction of air preheaters having the indicated parameters lowers the specific fuel consumption in heat-treatment furnaces to 15-30%.

The extensive use of perforated systems as the principal component of gas radiators has been prompted by the need for comprehensive investigations of thermophysical processes associated with the combustion of gases in them. In particular, radiative–convective heat transfer in these systems has been investigated along with its relationship to combustion stability [59-60]. The influence of the structural parameters of systems on the distribution of the self-radiation energy in selected directions has been determined and the law governing the displacement of the radiation maximum has been established for perforated systems with a combustion reaction taking place on the surface. The effective radiation temperature of the firing nozzles of perforated systems has been determined [59-61]. Equations have been derived, taking account of the thermophysical characteristics of these nozzles and permitting analytical methods to be used for the calculation of radiative heat transfer in devices using gas radiators [62, 63].

The program of research on finding the most general laws of combination heat transfer in metallurgical furnaces includes computer numerical studies of radiative–convective heat transfer in cylindrical and slotted channels for various flow regimes of the gaseous medium. Interesting data have been obtained on certain parameters (optical thickness; Péclet, Boltzmann, and Reynolds numbers; channel-wall temperature; heat input) as they affect the characteristics of combination heat transfer [64-69].

It has been shown, in particular, that extremal domains exist in the values of the radiative–convective and radiative heat fluxes toward the wall with variation of the optical thicknesses of the gas (it works best to increase the optical thickness within unit-value limits). It has been shown that axial radiation fluxes should be taken into account in short channels. Correction factors have been proposed for existing convective heat-transfer and gas-emissivity calculations based on the assumption of additive radiation and convection for industrial systems with cylindrical working volumes [70].

The transmissivities through a two-layered gas (steam and carbon dioxide) have been investigated, and the problem has been generalized to the determination of the transmissivity of radiation through an inhomogeneous nonisothermal gas layer. The role of scattering (for nonluminescent flame jets in metallurgical furnaces) has been found to be negligible for values of the Schuster criterion from 0 to 0.6 under conditions of a simple radiating-system geometry and a spherical-scattering diagram. The calculations have been significantly improved by allowing for the radiation selectivity of the flame jet, heat-sensing surfaces, and refractories [71-77]. The spectral and integral radiation characteristics of the main components of the working space of industrial furnaces have been studied [78-84].

Significant progress is noted in engineering methods for calculation of the heating of a metal in heat-treatment furnaces with allowance for the dependence of the thermophysical properties of the charge on the temperature, heat release, and thermal resistances in the metal.

Extensive use is made of present-day methods for numerical solution of the heat-conduction equations (two-dimensional, three-dimensional, anisotropic), as well as appropriate simplified modifications (so-called step methods). In determinations of the local and average directional radiation coefficients, a statistical method is used, making it possible to perform calculations of complex system geometries comprising second-order surfaces. A mesh-point method for the computation of heat transfer has been developed to account for the complex geometry of the profile of a furnace working space and arbitrary stationing of the flame jet [47, 72].

Mathematical models are currently being developed, and algorithms are being formulated for the solution of problems in the heating of a metal in various heat-treatment furnaces, along with corresponding computer programs. This work will make it possible to analyze variants in the design of new furnaces, to decide on control and automation techniques, and to develop an automatic production-control system (APCS) [85-92]. An analysis of the current status and future outlook for of, the development of scientific research on heat transfer in metallurgical heat engineering for the period 1976-1985 may be found in [93].

In the area of experimental work on radiation characteristics there is growing interest in their measurement for high-melting metals (vanadium, titanium, tungsten, molybdenum, tantalum, and niobium), various graphites, and carbides at high temperatures in the visible and near-infrared regions. The first investigations have been carried out on the total emittances and spectral absorptivities of quartz glasses of various grades in the temperature interval from 700 to 1300°K [94-97]. A detailed correlation of published data on the radiation characteristics of metals, alloys, graphite, carbides, borites, nitrides, silicides, oxides, fused quartz, and certain glasses is given in [96].

A complex program of investigations under industrial and test-stand conditions is being carried out in connection with the radiation properties of flames in the burning of liquid, gaseous, and solid fuel. This work includes studies of the absorptivity and emissivity of flames in close correlation with the structural and material composition of the flame. Data have been obtained on the concentration of soot particles in flames and their influence on the thermal radiation of flames [98-103].

Data have been obtained for the first time on the radiation of flames during the recirculation of gases in a firebox. The primary radiation characteristics of coal-dust and coke particles in a coal-dust flame have been determined for the principal types of solid fuels. The emissive properties of gaseous combustion products and solid particles as the main emitters produced in a flame have been determined in connection with the burning of mazut, gas, and coal dust in boiler-system furnaces [104-109] and in metallurgical furnaces. Carburation effects and their influence on flame radiation have been investigated, along with effective means for enhancing the luminosity of flames in metallurgical furnaces. These results have found extensive applications in various branches of engineering.

For example, new reformer designs have been developed for open-hearth furnaces and an original new system for the natural-gas firing of direct-heating glass-melting furnaces has been proposed. Data on the radiation properties of flame have provided the basis for a new standard method of thermal analysis of boiler equipment.

Exhaustive theoretical and experimental studies have been undertaken with a view toward synthesizing a standard method of analysis of tubular furnaces in the petrochemical and petroleum-refining industries. In particular, procedures have been developed for calculation of the total transfer in a furnace, for the zonal calculation of heat transfer in a firebox, for test calculations of a reaction tubular furnace with radiating firebox walls, for aerodynamic analysis of the firebox gas tract, for calculation of the convection section of a furnace on the basis of local characteristics of the process, etc., along with a criterial method for the calculation of heat transfer in tubular furnaces [110-113, 143, 144].

The noticeable recent trend in industry, including the chemical industry, toward the consolidation of a unified power on the part of equipment systems places great urgency on the study of heat-transfer problems both in reactors during chemical reaction and in the space between pipes and tubing. The development of principles for the calculation of combination radiative—convective heat transfer makes it possible to take proper account of the special characteristics of combustion devices and to apply those characteristics toward the creation of more uniform heating over the height of reactors, while maintaining the wall temperature of the reaction tubes at a maximum.

Methods have been developed for analysis of the emissive powers of confined gas volumes (CO, CO_2) under equilibrium as well as nonequilibrium conditions. It has been confirmed that vibratory nonequilibrium processes play a vital role in analysis of the emissive power of molecular gases at low pressures. A diffusion-type approximation has been devised in [114-117], permitting the total radiation flux density to be calculated for arbitrary volumes of a nonequilibrium diatomic gas. An expression has been obtained for the mean free path of quanta in a nonequilibrium medium, representing a departure from the Rosseland and Planck averages.

Practical expressions for the emissive power of two-phase media of plane, cylindrical, and spherical configuration have been proposed [118, 119]. It is shown that allowance for scattering processes and a more realistic configuration of radiating objects is an important consideration in radiative heat-transfer processes.

Theoretical foundations for the optical modeling of radiative heat transfer for systems of arbitrary geometry, filled with selectively emitting, absorbing, and anisotropically scattering media, have been developed on the basis of the integral equations of radiative heat transfer for a generalized effective radiation intensity.

The optical modeling method has been brought to bear on the study of processes in various electrothermal apparatuses [120-121].

Large-scale investigations of radiative heat transfer have been carried out for the development of technological processes in the food industry; in particular, infrared heating proves effective in the baking industry. This approach shortens the baking time of bread and pastry goods, reduces the fuel consumption per unit finished product, cuts down baking losses, and improves the quality of the end product.

Investigations of the optical and regime characteristics of radiators used in ovens, analysis of the parameters characterizing the efficient distribution of products in the baking chambers, and studies of the baking processes for bread and pastry goods have made it possible to determine the singular attributes of the indicated parameters and processes and to develop methods for the calculation of optimal regimes [122-127].

The results obtained to date have culminated in the development of highly perfected variants of infrared-heating ovens. The installation of a series of such ovens (30 type PIK-8 ovens) has yielded an estimated cost savings of about one million rubles.

A series of laboratory experiments on the infrared drying of medicinal plants with various physicobiological properties has been conducted for the purpose of studying the influence of thermal radiation on raw medicinal plant material and predicting the behavior of its dehydration process. A number of empirical relations have been established, taking account of the mutual influence of structural, technological, and energy factors as well as the physicobiological characteristics of the raw material on the drying process, and it has been determined that radiant-heat dehydration under definite conditions and for individual specimens not only elicits a drastic reduction in the process time, but also results in the production of raw material with a higher final content of active agents than when other drying techniques are used.

The thermodynamic, thermophysical, and optical properties of medicinal granulates (methionine, amidopyrine, citramone, dibasol, etc.) have been investigated in detail. The results can be used in the kinetic analysis of heat and mass transfer and for the selection of infrared radiation sources in the drying of medicinal granulates in a vibratory fluidized bed [128-133].

Progressive methods have been devised for determining the optical characteristics of scattering objects in connection with the radiation of antibiotic medicinal preparations [130, 134-139].

A number of new technological heat-treatment regimes for coating–substrate systems have been designed and introduced in industry [140-142]. Experimental samples and series of prototypes of conveyor equipment and mechanized production lines have been designed and put into operation for the drying and hardening of polymer sealer coatings.

An important fundamental fact must be brought to attention, namely, the significant activation of research on radiative heat transfer during the last few years. This observation has implications not only in theoretical studies, but also in experimental and pure applied work, the status of which evinces the effective inroads of scientific developments in various branches of the national economy.

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