REVIEW ARTICLE

APPLICATION OF ELECTRIC ANALOG SIMULATION TO THE SOLUTION OF PROBLEMS OF HEAT AND MASS TRANSFER

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Inzhenerno-Fizicheskii Zhurnal, Vol. 11, No. 6, pp. 809–831, 1966

UDC 536.24.01

This article gives a brief review of research undertaken in the Soviet Union and abroad during the period that has elapsed since publication of reviews [92, 108].* The bibliography also includes certain references which for various reasons were omitted from [92, 108].

The following types of models have been used to solve problems of heat and mass transfer.

For solving stationary problems: models made from conductive paper (cp), electrolytes (el), resistance networks (R), combined models—combinations of resistance networks and conductive media (cp, el). In recent years little use has been made of various kinds of metal foil for solving problems by the method of electrothermal analogies (ETA).

Nonstationary thermal fields are determined by means of resistance networks for solving finite-difference equations of nonstationary heat conduction by the Liebmann method (L), R-C networks, and combined models—combination of a conductive medium (cp, el) and discrete R and C elements.

Problems of stationary and nonstationary heat conduction have also been solved with the help of structural models, combined models—combination of analog and structural model, combination of analog and electronic digital computer (EDC), combinations of structural models and EDC. The last two types of combined models are sometimes called hybrid models.

Analog systems solve problems by the method of analogy, i.e., resolve the solution not into individual operations (as in structural models) but into physical elements. In the elements of the analog system the physical process is directly described by the equation to be solved.

References [92, 108] give a fairly thorough account of the advantages and shortcomings of various types of models used for solving the equations of Laplace, Poisson, and Fourier and the equations of nonstationary and stationary heat conduction with nonlinearities, variable values of the thermophysical characteristics of the materials, variable boundary conditions, and heat sources (sinks). They also consider various methods of electric analog simulation that make it possible to extend the capabilities of ordinary models, for example, by taking into account $\lambda = \lambda(T)$, specifying α-varia, etc.

It is characteristic that in recent years not only have the models mentioned in [92, 108] been used on an ever-increasing scale for solving problems of heat and mass transfer, but new types of models have been introduced and, in particular, new improved methods of solving problems on models of different kinds have been employed.

In this review we will dwell on those types of models and methods of solution that have been developed or begun to be used in the last few years and appear most promising. Network schemes for solving finite-difference equations of nonstationary heat conduction on models of various types are shown in the figure.

In solving problems of nonstationary heat conduction ever-increasing reliance is being placed on the Liebmann method using R networks or combined models (conductive medium-R network). The Liebmann method makes it possible to solve difficult problems (nonlinear, three-dimensional) in formulations—variable boundaries, thermophysical characteristics, boundary conditions, with allowance for phase transitions, etc.—that cannot be solved by any other method.

This conclusion is confirmed by numerous studies [14, 76, 87, 93, 94, 96–101, 103–107, 109–111, 211, 227, 281–283, 301, 325, 346], etc., and opposing view being expressed only in [331].

No less valuable in this respect than the Liebmann method is the method proposed by Vulis and Luk'yanov [2, 42–45, 59–62, 143, 144] for solving finite-difference equations by means of a single node of an R network, where the voltages are fed to a single computing element in order to obtain an explicit solution of the finite-difference equation of heat conduction.

The advantage of a static integrator is the presence of a small number of resistors. When one considers that in obtaining solutions on a static integrator it is possible to use not only the ordinary explicit method but also other methods of solving finite-difference equations,* then the advantages of the static integrator become particularly clear. It is true that to analyze different variants of the solution it is necessary to repeat the solution in its entirety, but this can be

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*Paper [108] was presented to the First All-Union Conference on Analog Computer Technology (April 1963, Moscow), in which Soviet research was reviewed. In [38] the editors of the collection gave a shortened version of the bibliography of [108].

*For example, the Dufort-Frankel scheme (explicit method using more than two time series).

avoided by using an analog of the entire system, and not a single node "moving is space and time."

There have been no practical applications of the method of solving nonstationary problems on C networks, also proposed by Vulis and Luk'yanov.

The introduction of static integrators—R node (st)—has been encouraged by the fact that an integrator designed by Luk'yanov and coworkers is being serially produced on a commerical basis. In Czechoslovakia an original method proposed by I. Kunes [337, 379, 380], which the author calls the "method of figures," is being used for solving problems of nonstationary heat conduction.

However, neither the method proposed by I. M. Tetel'baum and El Meshad [266] nor the Kunes method, which as far as electrolytic simulation is concerned coincides with the method of [266], has yet been widely adopted. Obviously, uses will be found for the method of determining temperature gradients on electric models—conductive media (cp, el)—proposed by Kunes [132a] and employed by him to solve important practical problems of stationary heat conduction.

This method of determining temperature gradients can evidently be developed for investigating nonstationary temperature fields as well.

Karplus [133, 360] (see the figure) has proposed a new and still unexploited method of solving problems of heat conduction which, as noted by the author in [133], is a development of the Liebmann method.

All the advantages of this new method become apparent when it is used to solve problems for processes described by partial differential equations, not for processes of nonstationary heat conduction but for others (diffusion with displacement of physical masses, wave and biharmonic equations, etc.).

The special DSDT (discrete space, discrete time) network model is a combined model consisting of a resistance network containing precision resistors and dc amplifiers. Each node unit also contains amplifiers, the active elements of the circuit. They are used to avoid the successive adjustment of the voltage sources during the solution process and also to obtain negative resistances.

The implicit difference equation approximating the Fourier equation is written in the form

$$(T_{m+1,n} - T_{m,n-1}) + (T_{m-1,n} - T_{m,n-1}) - 2\,(T_{m,n} - T_{m,n-1}) = \frac{h^2}{a\,\delta t}\,(T_{m,n} - T_{m,n-1}) \qquad (1)$$

instead of in the form

$$\frac{T_{m+n,n} - 2T_{m,n} + T_{m-1,n}}{h^2} = \frac{T_{m,n} - T_{m,n-1}}{a\,\delta t}\,, \qquad (2)$$

which is used for deriving the parameters of the network solving the Fourier equation by the Liebmann method.

The figure shows elements of the networks solving the Fourier equation by the methods of Liebmann (a) and Karplus (b) and in accordance with the explicit scheme used in the static integrators of Vulis and Luk'yanov (c).

We will dwell in somewhat greater detail on the Karplus method since the Liebmann method and the static integrator method have already been quite closely examined in the literature.

We will consider parts of the networks solving the Fourier equation (diffusion) by the methods of Liebmann (see the figure, d) and Karplus (e). To each node of the line n (see the figure, e) there are connected variable sources of constant voltage, which are selected so that the potential of each node of the line n − 1 takes a value determined by the initial conditions of the problem.

The voltages at the nodes of line n, corresponding to the field potentials at time n, are registered and used as the initial conditions for the next stage of the solution.

The voltage sources are now regulated so that values of the voltages measured in the preceding stage at the nodes of line n are established at the nodes of line n − 1.

The values obtained for the voltage sources in this stage of the solution represent the field potentials at the moment n + 1 and must be taken as the initial conditions in the next stage of the solution. The process is repeated until a solution is obtained over the entire interval of time of interest. A change in the voltage of any source affects the potential of all the nodes of the network. If it were necessary to carry out the regulation sequentially and manually, an iterative method would be used and the entire process would require a considerable amount of time.

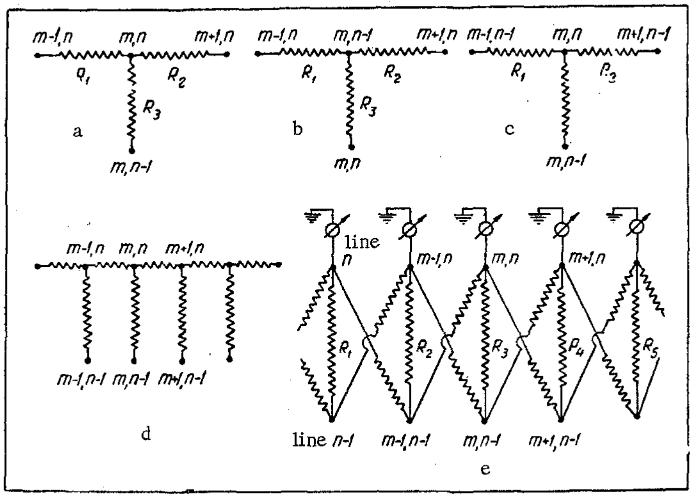
In [133, 360] it was shown how an electronic circuit can perform the adjustment process automatically and instantaneously, i. e., the source voltages take the necessary values directly. When the active circuits proposed in [133, 360] are used, there is no need for a process of sequential adjustment.

Since the DSDT model makes it possible to solve a broader range of problems than the Liebmann model, when such models are available they should also be used for solving problems of nonstationary heat conduction. However, it is not expedient to build such models specially for solving the Fourier equation, since R-C networks enable the problem to be solved in the same formulation but with simpler means.

The method proposed by V. T. Chernoval [249, 250], intended for solving nonstationary problems (method of "interchange of stationary states"), has likewise not been used very widely.

Hybrid models (combinations of analogs and EDC) are still used only on a limited basis for solving thermophysical problems, evidently because of the high cost of the equipment and the relatively narrow range of thermophysical problems within which these models are most effective.

Greater use is being made of hybrid combinations of analogs and structural models for solving problems of heat transfer in heat exchangers of various types (regenerators, recuperators).



Node diagrams (a b, c) and part of network models (d, e) for solving problems of nonstationary heat conduction by the methods of Liebmann (a, d), Vulis and Luk'yanov (c), and Karplus (b, e).

Methods of solving equations of the heat conduction type on analog structural models are still not very popular.

There has been some work in this direction abroad [131, 271, 409] and in the Soviet Union [30, 31], but the numerous assumptions involved make these methods applicable only to a narrow range of problems.

This is the conclusion reached, for example, by the authors of the review [325], although this direction is not without promise, as indicated, for example, by the work being done under the supervision of I. M. Vitenberg.

In the last few years the first books wholly or almost wholly devoted to the problems of electric analog simulation of heat transfer phenomena have been published in the Soviet Union. These include a monograph by M. P. Kuz'min [132], a collection edited by K. P. Seleznev, A. I. Taranin, and V. G. Tyryshkin [222], and the monograph [103].

In [132] there is a description of an R-C model that makes possible the determination of nonstationary temperature fields in multilayer plates with given boundary conditions of the third kind (one-dimensional problem, asymmetric heating of wall).

The problem is solved in the usual formulation for R-C models, when the thermophysical characteristics of the material are assumed constant and independent of the temperature, while the boundary (temperatures of media and heat transfer coefficients) and initial conditions are constant.

These assumptions are typical of the use of R-C analogs, but the employment of special units for setting the boundary conditions makes it possible to take into account variable boundary conditions and thus expand the capabilities of R-C systems.

Reference [132] gives an incomplete survey of methods of solving problems of heat conduction on computers; for example, the Liebmann method is not considered. The book contains certain inacurracies—the explicit method of solving finite-difference equations is incorrectly explained, the recommendations concerning the method of using analog quantities in applying the method of analogies are unsatisfactory.

In spite of these errors, the book [132] is undoubtedly useful, since it intensifies the interest of thermophysicists in ETA methods, describes a new and relatively simple type of R-C model, and solves some interesting heat-engineering problems.

In the collection [222] most of the articles are devoted to investigations performed at the Central Boiler-Turbine Institute (TsKTI) on the SEI-01 integrator designed and built at the TsKTI, which has been used to make a whole series of studies of the stationary and nonstationary temperature fields in various steam and gas turbine parts. However, the shortcomings of the R-C model somewhat reduce the effectiveness of these studies, since on the SEI-01 it is impossible in determining nonstationary fields to take into account the temperature-dependent quantities λ and $c\gamma$ and the variable α, and it is difficult to adjust the variable temperatures of the media.

The monograph [103] includes a detailed description of the solution of various problems on R networks and combined models by the Liebmann method. The good and bad points of the book are noted in reviews [82, 206]. It should be emphasized that the weakest point of the Liebmann method considered in [103] is the difficulty of automating the solution. This difficulty can be overcome [346]; however, an automated model working on the Liebmann principle loses it chief advantage—the solution of nonlinear problems in the most general formulation. Therefore it is more effective to use completely automated R-C models, since the automated R network working on the Liebmann principle does not have any advantages compared with the R-C model.

Progress in the design of power plants has made necessary a more or less accurate picture of the stationary and nonstationary thermal fields in the various components. Therefore there have been many studies of the temperature fields in the nozzle and moving blades, rotors and stators of steam and gas turbines [19, 47, 65, 73, 74, 175, 198–203, 222] (R–C, cp, c-R-cp).

In [173] (cp) the temperature fields in turbine rotors were obtained in the presence of friction in the seals.

In [49, 177a, 222] electric analog simulation is used for solving inverse problems—determining the boundary conditions (α, q) for given temperatures of the turbomachine components and the ambient media (the temperatures of the media are required to determine α).

Integrators of types NSM-1, EHDA, EI-12 have been used successfully to investigate the temperature fields in the rotors and stators of turbomachinery under stationary conditions [55–58, 84, 254–261] (R, cp, el, c-R-cp).

The method of solving problems of heat conduction on electric analog computers is somewhat different when the temperature fields in the rotors of radial turbines are determined, for example, [95] (R–L), [103] (R, R-L), [115] (cp), [192, 226] (cp), [443] (R).

In this case special interest attaches to investigations where the temperature field of the rotor is obtained together with the field of the blade, since the blades of radial turbines operate under less favorable conditions than in axial-flow turbines, where more intense cooling is possible.

R, R-L, c-R-cp, and cp models [93, 95, 96, 101, 103, 106, 109] make it possible to obtain quite accurate results in the investigation of the thermal fields in the rotors, stators, and solid and hollow nozzle and moving blades of gas turbines under steady-state and start-up conditions, since in the Liebmann method used in these studies it is easily possible to take into account the variability of the boundary conditions and the temperature dependence of λ, $c\gamma$.

The correctness and accuracy of the analytic method of calculating turbine rotor fields proposed in [178–180] are checked by the author on an electric analog system (cp), but, in spite of this, [179] gives a nonobjective evaluation of the ETA method, since the problem solved in [178–180] is solved more accurately, more simply, and more rapidly precisely by the ETA.

In [255, 256, 258–260] combined models (cp-R) are used to investigate three-dimensional stationary temperature fields; however, certain errors in [255], noted in [247], in connection with the construction of the combined models reduce the accuracy of the results obtained.

Numerous foreign studies [136, 278, 287–289, 294, 301, 313, 314, 346, 354, 371, 392, 413–415, 418–420, 446] (R-C, R, R-L, c-cp-C, el), [344] (EDC) present the results of investigations of the temperature fields in turbomachine rotors. Of particular interest is [354], where a combined model—conductive paper and discrete C—was used to determine nonstationary temperature fields.

In [301, 346] an automated integrator (R) was used to solve a problem of nonstationary heat conduction by the Liebmann method.

References [75] (R), [76] (R–L), [84, 175] (R–C), [203, 222] (R–C), [261, 313] (R–C), [391] (R–C), [287–289] (R–C) are devoted to the determination of the temperature fields in turbomachine stators.

In [76] there is a description of an improved form of the MSM-1 integrator, which makes it possible to solve problems of nonstationary heat conduction by the Liebmann method.

A series of papers has been devoted to the determination of the stationary and nonstationary thermal fields in solid and hollow fixed and moving gas turbine blades (with external and internal cooling).

In [71] the correctness and accuracy of a solution of the problem of finding the stationary field of a blade obtained with the help of an EDC is checked by electric analog simulation (cp).

In [149] (cp) the nonstationary temperature field of a hollow blade with internal cooling is investigated, the number and shape of the internal channels being selected by electric analog simulation so as to ensure minimum temperature gradients along the profile.

In [176] an analytic method is proposed for calculating the temperature of the trailing edge of a cooled blade. The results of the calculation are compared with the data obtained by electric analog simulation (cp). Although the authors used the electric model as a standard for checking the correctness of their analytic method, it is pointed out in [176] that the analytic method gives better results than analog simulation.

In [182, 183] the fields of gas turbine blades are investigated by analog simulation, [182] being devoted to a study of the three-dimensional thermal field of a blade with twin-circuit cooling on a set of unconnected plane models. Some of the ideas about electric analog simulation in [182] are borrowed without suitable acknowledgement from the work of O. A. Gerashchenko and L. A. Kozdoba published in the fifties.

References [106, 109] (c-R-cp) give a solution of the three-dimensional problem of determining the thermal field in a moving blade-wheel rim unit with a very detailed breakdown of the unit into longitudinal and transverse sections.

Combined models (cp-R) were used in [55, 254–260] for investigating the fields not only in the rotors but also in the moving blades of gas turbines.

In many foreign studies [237, 306] (R–C), [316, 317] (R), [372–377, 380] (el, cp, R), [384] (cp), [405] (el) electric analog simulation of various types has also been successfully used to investigate nonstationary and stationary fields in turbomachine blades.

In [132a] the author proposes a method of determining temperature gradients which is used to investigate the thermal regime of a gas turbine blade.

Electric analog simulation continues to be successfully used in determining the temperature fields in components of the cylinder-piston assembly of internal combustion engines (ICE) [20–22] (R), [69] (cp), [91, 103, 204, 205] (R, c-cp-R), [150] (R–C), [160] (cp).

References [20–22, 69, 150] (especially [150]) are interesting in that they describe the use of electric analog simulation to solve inverse problems—determination and refinement of the boundary conditions in ICE cylinders.

In [22] the boundary conditions are not formulated quite correctly in solving the direct problem; therefore some of the author's conclusions are debatable.

The data of [160] can be used only for a qualitative evaluation of design variants, since the method of investigating the fields in axisymmetric bodies used in [160] may lead to serious quantitative errors in determining the fields in cooled ICE piston heads.

Abroad, electric analog simulation of various types has been used to study the thermal fields in spark plugs [378] (cp, el), in the escape valves of ICE [390] (R), and for solving inverse problems of heat transfer in the cylinder-piston assembly [456].

In building thermophysics electric analog simulation continues to be widely employed, and is beginning to be used for solving problems of heat and mass transfer in structures [223–225].

In [42] (R-st), [138] (cp), [322, 255] (c-cp-R), [397, 462–464] (cp) problems connected with the fields in structures are solved, the form factor of structural elements is determined, etc. Electric analog simulation is beginning to be used to investigate the thermal regimes and storage capacity of interior spaces [335, 353, 364].

In [103] a description is given of a method of electric analog simulation of the storage capacity of a room, when the one-dimensional problem is solved. Reference [110] gives a detailed account of a method of determining the thermal regime of a complex of ship's compartments by electric analog simulation (R-L) with allowance for the various materials used in the walls and their insulation and lining.

Reference [210] (R-L) shows how to determine the thermal conditions in the hold of a ship for boundary conditions that vary during the voyage with a view to developing optimal ventilation conditions for ships' holds. Electric analog simulation is also being used to investigate the form factors characteristic of the structure of modern ships [208, 209] (cp, R), [347, 355].

The data of numerous foreign and Soviet studies of this problem are presented in books and manuals recently published in the Soviet Union [53, 63, 64, 245], where an extensive bibliography on the corresponding use of ETA may be found.

Electric analog simulation is also being evermore widely employed to study the thermal regimes of electrical and radio-engineering devices: in electric machines [312] (el), [365, 408, 422] (R), [435, 458, 468, 469] (R-C), in radio components and flip-flops [39], in semiconductor rectifiers [80] (R-C), micromodules [244] (R), transistors [369], and in thermoelectric generators [454] (R).

In [312] use is made of the method of solving Poisson's equation in electrolytic baths proposed by V. S. Lukoshkov [141] and widely employed in the Soviet Union.

It should be noted that for investigating the thermal regimes of electric machines structural models and EDC are in widespread use [10, 15–17, 48, 88, 146, 251–253].

This is because the description of the thermal regime of an electric machine usually reduced to a system of ordinary differential equations. The thermal properties of the individual units of the machine are reduced to the properties of points, which make it possible to go over from partial to ordinary differential equations.

Certain studies [328, 367] have been devoted to the investigation by electric analog simulation (r-C, etc.) of the thermal processes that occur during induction heating.

The ETA method is being increasingly and very successfully used to investigate the termal regimes of parts and tools in material forming processes such as cutting, stamping, etc. [187–191] (cp, R, R-C), [194] (cp), in metallurgy, and in welding technology [18],* [211] (R-L), [240, 246] (R-C), [227] (R), [407, 293] (R-C), [295] (str), [332, 399, 400], [386] (R-C), [9]** (str), [389, 424].

EDC are beginning to be used to solve problems of heat transfer in welding [185], but in this case the problem is considerably simplified; the heat sources and thermophysical characteristics are assumed constant, the problem is treated as one-dimensional.

In [94, 99, 103, 104] electric analog simulation (ep, c-cp-R, R) was successfully used not only to determine the temperature fields in parts during welding or surfacing, but also to determine the shape and size of the weld pool and the moving temperature field [9] (c-cp-R).

In [114] (R) there is an account of an interesting method of solving Stefan and Verigin problems by a method which is a development of the Liebmann method and also of the methods considered in [85] in relation to problems of heat conduction with moving boundaries.

Many Soviet and foreign authors report the solving of a variety of heat-engineering problems by the ETA method. For example, in [5] the heat transfer in a massive body with internal heat sources was investigated; in [59–62] (R-st) nonlinear nonstationary problems were solved with allowance for variable heat sources; in [227] (R-L) the characteristics of built-in alpha-calorimeters are investigated; in [262] (R) the stationary thermal field in a finned wall is determined, and in [305] (R) the temperature field in a bath of molten glass.

Various problems are solved on a wide range of models in [14] (R-L), [66, 67] (R-C), [116, 137] (cp), [193] (el), [267] (R-C with nonlinear converter), [269] (foil), [273, 274] (R-C), [280–283] (R-L), [287–289] (str and EDC), [291, 292, 297, 302] (analogy between

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*Hybrid model—str and EDC elements.

**V. Paschkis has made an interesting contribution to the discussion of [9].

eddy currents and conduction equations), [303] (c-el-C),* [307,308] (c-R-str), [315] (R-C), [321] (R-C), [323] (cp), [329,331] (R-L), [342] (R-C), [349] (str), [351,352,359] (str), [364,382,383,393], (R), [406,416, 418,421] (cp), [429] (str), [436,437] (R), [439,441,446, 447] (R-C), [449,450] (str-EBC), [461,467].

A new method of solving nonstationary problems on R-C models with amplifiers was proposed in [197]. A criticism of this method by Paschkis was published in an interesting discussion of [197].

An original application of electric analog simulation is described in [472], where the heat transfer between a clothed human being and his environment is investigated by the ETA method.

A number of interesting studies have been devoted to the simulation of radiative heat transfer ("pure" radiative heat transfer and the problem of heat conduction in a solid exposed to radiative heating) [87] (R, cp with nonlinear converter), [70] (R-C-str), [285, 385,426,427,440]. In [51,52] an EDC was used to solve problems of radiative heat transfer.

The thermal regimes of heat exchangers are mainly investigated by means of structural models; however, combined models have recently begun to be used for this purpose (network-str) [6] (and also [74] where the method of [6] is simplified and developed) [12,13, 23,89,90,119–122,124,134,135,212,217,218,265,276, 279,299,310,320,326,337,338,341,348,387,388,401, 403,404,428,433,444,470].

EDC are also coming into use in heat exchanger design [83,139,153,275,433,470], but in constructing the programs it is customary to use the same approach as in constructing a structural model (reduction of the properties of the body to the properties of point, etc.).

As already mentioned [223–225], electric analog simulation is being developed and beginning to be used for solving systems of heat and mass transfer equations.

An interesting method is proposed in [243] (R-C), where R-C networks simulating the temperature field and the moving mass field are combined. In [243] there is no allowance for the specific features of the process of assigning actual nonlinear boundary conditions (especially with respect to the moving mass field), though this is characteristic of heat and mass transfer problems; therefore the method proposed in [243] requires refinement.

References [100,103,111] (R-L), [336,268] (cp), [298] (R-C), [428] (str) are devoted to the solution of problems of heat and mass transfer. In [111] the nonlinear problem is solved in a very general formulation, but as distinct from [243] the method of [100,103,111] still does not permit the complete automation of the solution process.

Electric analog simulation makes it possible not only to determine the temperature fields in machine parts, but also to discover new effects associated with the transfer of heat by conduction in bodies of various configurations.

In [102] (R, c-cp, R) an investigation of the thermal regime of the electrodes of a low-temperature plasma generator revealed the so-called "critical thickness" effect in thin, intensely cooled shells locally heated by a concentrated point or strip heat source. The "critical thickness" effect was studied in greater detail in [107] (R, c-cp-R) for plane and cylindrical shells in the presence of various external heat sources.

Analog and structural models are used for investigating the thermal regimes of individual reactor elements (fuel elements, vessel) and complete nuclear reactors [159] (str), [248,290,343,381] (c-cp-R-C), [471].

More and more use is being made of electric analog simulation for solving inverse problems—determining the boundary conditions (α, q) for stationary and nonstationary heat conduction. One of the first studies in this direction was made by M. M. Litvinov and published in the proceedings of the Inter-University Conference on the Application of Physical Simulation to Electrical Engineering Problems and Mathematical Modeling (Moscow, 1957). Inverse problems were solved in [20–22,103,150,199,219,222,469].

Particularly promising are investigations in which electric analog simulation is used not only to solve internal problems of heat conduction but also to find the fields in a part and in the medium flowing over it [182,184]* (combined problem).

In recent years increasing attention has been paid to solving nonlinear problems of heat conduction. The corresponding methods of solution are briefly reviewed in [92], but more recent studies [59–62] (st), [87] (R-L), [117–129] (c-R-str), [148,149] (R, cp, el), [161] (EDC), [387,388] (R-C), [395,455] (EDC), [457,148,149, 97, 100,103] (R-L), [40] (R-C) employ new methods of solving nonlinear problems using Kirchhoff integral transforms, substitutions of the Schneider type, auxiliary nonlinear units, and transitions to linearized heat conduction equations.

Structural models and EDC are being increasingly employed for solving problems of stationary and nonstationary heat conduction, although analog systems are still the most effective means of solving partial differential equations, because of a number of specific characteristics of str and EDC.

If the required accuracy of the solution is less than 0.01%, the advantages of the EDC are indisputable and analog systems and structural models cannot compete. However, when the permissible accuracy is greater than 0.01%, in most cases it is more efficient to solve heat conduction problems on analog systems, in spite of the essentially unlimited possibilities of EDC. This is because, on the one hand, the analog system operates almost instantaneously and the required accuracy of solution of thermophysical engineering problems is

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*This study was noted in [85].

*In [184] cp, sheet steel and foil of other metals are used for modeling processes.

relatively low,* while, on the other hand, writing computer programs can be very time-consuming in solving problems for parts of complex configuration, with nonlinear boundary conditions varying in space and time, materials with variable thermophysical charactertistics, and in view of the limited storage capacity of even modern computers.

Structural models and EDC were used for solving heat conduction problems in [7,10,15–17,28,30–32,** 48,54,79,88,131,147,151,152,155–158,177,238,251–253,271,286,289,319,344,398,402,409,425,427,430, 438,455].

It should be noted that in [155–158] an attempt was made to solve on EDC problems whose solution has traditionally been entrusted to analog systems—the investigation of the temperature fields in turbomachine rotors. Unfortunately, studies [155–158] show that overestimating the capabilities of EDC may lead to unfavorable results. The assumptions made in formulating the problem and assigning the boundary conditions in [155–158] can only compromise the work of adapting EDC to the solution of such problems. Investigations [155–158] may be only first (if not zeroth) approximations, whereas analog systems give results differing from the data of thermal experiments by not more than 1.5–2%. The boundary conditions and configuration of the structure are specified on analog systems much more accurately than is the case, for example, in [155–158], where EDC solutions are obtained.

In recent years there have been numerous attempts to develop methods of electric analog simulation of partial differential equations on models of various types and to develop essentially new models. These attempts include efforts to improve the operation of conductive-medium and R network [11,24,25,33,34,36,40,41,68, 76,104,133,165–172,186,207,213–216,228–232,281–283,296,311,333,334,360,451,466]; R-C network models [40,66,112,130,140,154,162–164,220,222,308, 309, 318, 411, ***416–418, 442]; combined conductive medium-network models [93,94,97,99,102,103–106, 109,213–216,241,242,284,303,410,423,448]; and electrolyte models [50,141,142,228,272,330,370–372, 375,432]. Particular interest attaches to the investigation of asymmetric networks (R, R-C) and combined models designed on the basis of the method of analyzing asymmetric networks [105,327,394].

The static integrators of Vulis and Luk'yanov are being increasingly used to solve nonlinear problems of heat conduction [2,42–45,59–62,143,144,181].

A whole series of studies has been devoted to the investigation of the accuracy of various types of models [78,165,324,340,383,431,453,460,467]. It should be emphasized that investigation of accuracy forms part of most studies, in which various types of models are proposed and employed for solving specific problems.

Many papers published both in the Soviet Union and abroad [3,33,36,86,113,130,165–172,195,228–232, 249,250,308,309,434,467] have been devoted to the technology of electric analog simulation, methods of solving problems described by partial differential equations of the Laplace, Poisson, and Fourier types, and nonstationary heat conduction with account for nonlinear λ, $c\gamma$, α, q.

In [92,108] attention is drawn to the trend toward checking the correctness and accuracy of newly proposed analytic methods of solving problems of heat conduction on electric models [72,178–180], solutions obtained on EDC also being checked by the ETA method [71].

In [26] the authors, having proposed and utilized an analytic method of solving the two-dimensional problem of heat conduction with mixed boundary conditions, stress that such problems are solved more simply on electric models.

Thus, the perfectly correct notion that the analytic solution is the natural solution only when the method is suitable for practical engineering calculations is beginning to find support not only among people occupied with solving practical problems of thermophysics but also among mathematicians and thermophysicists occupied with the development of analytic methods, who sometimes forget the clumsiness and impracticality of lengthy final formulas obtained after sophisticated analytic calculations.

Combined models (cp-R) are being increasingly used for solving two- and three-dimensional problems of stationary and nonstationary heat conduction. The idea of using such models was proposed in 1955 by P. F. Fil'chakov and V. I. Panchishin, and now ever wider practical use is being made of a number of combined models: conductive medium-R network, conductive medium-R-C network, network-structural model [29, 94,99,100,103,117–129,219,220,270,304,308,309, 345,358,360–363,368]. Very recently there has been an obvious increase in the use of hybrid models—combinations of analog machines and EDC.

A number of recently published books [35,46,90, 165,229,233,241] deal with the mathematical modeling of physical fields. In varying degrees, the material contained in these books, especially [165,229,241], can be applied to the electric analog simulation of heat and mass transfer phenomena.

The technical literature, textbooks, and manuals [1,46a,53,63,64,77,81,145,187,239,245] dealing with a variety of thermophysical topics are beginning to devote more and more space to ETA methods, since electric analog simulation has become an irreplaceable tool for solving the most complicated heat-engineering

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*This is usually attributable to the inaccurate representation of the boundary conditions and the thermophysical characteristics of the materials.

**In [32] the inverse problem is solved—values of λ are determined from the solution of the equation.

***In [411] it is reported that in the United States an R-C model has been built and successfully used for solving nonlinear problems.

problems, whose solution by other methods (even full-scale experiment) is either extremely awkward or totally impossible.

Sometimes, for example, in [46a], the ETA method is the subject of nonobjective and superficial criticism. For some reason the authors of [46a] group the ETA method with methods of determining heat fluxes, when in the overwhelming majority of cases electric analog simulation is used for determining temperature fields; in addition, the authors of [46a] exaggerate the errors obtained when the ETA is used to investigate steady-state and nonstationary fields.

One of the ETA methods of solving stationary problems mentioned in [46a] in connection with cp models was only developed by O. A. Gerashchenko in relation to such models, being first proposed in 1938 by S. N. Syrkin for models made of foil. The ETA method of solving stationary problems on foil model with specified boundary conditions of the third kind, proposed by Syrkin, was developed and applied by Gerashchenko in solving stationary problems with boundary conditions of the third kind on conductive paper.

Such nonobjective criticisms can only lead astray investigators who might obtain more reliable results by the ETA method than by other methods, even including full-scale experiment ([46a] was devoted to methods of making thermal measurements).

At international, All-Union, and Republican conferences and meetings both on heat and mass transfer and on electric analog simulation evermore importance is being accorded to work on the application of ETA methods [4, 27, 37, 38, 221, 234, 235, 357, 473].

Numerous review articles have been published in the Soviet Union and abroad on the application of ETA to various branches of thermophysics [103, 132, 222, 268, 291, 296, 300, 325, 331, 350, 351, 356, 366, 396, 411, 412, 452, 458, 460, 464, 465], indicating both intensified interest in the method itself and the expansion of the area of application of ETA methods.

Particularly noteworthy is the bibliographic review of the literature [264] on the electric analog simulation of physical fields, published under the supervision of L. V. Nitsetskii, in which more than 2350 Soviet and foreign publications are cited.

A comparison of the list published in [92], which was concerned with the period starting from 1845 (Kirchhoff) and the above-mentioned review indicates that in the last 4–5 years more than twice as many studies of ETA applications have appeared than in the previous 115 years.

Of course, neither [92] or the above-mentioned bibliography included all the work that has been done in this direction, since ETA methods are employed in the most diverse branches of technology and the results are published in journals devoted to the most varied and unrelated areas of science and technology, which nevertheless have in common certain requirements for the solution of thermophysical problems.

The broad introduction of the ETA method is attributable to the fact that in designing structures minimum safety factors are beginning to be established, working parameters are increasing, and the choice of the optimal variant of a structure or optimal operating conditions is becoming unthinkable without an accurate determination of the thermal state of the part under steady-state and transient conditions.

Electric analog simulation makes it possible to obtain a sufficiently accurate estimate of the thermal regimes of a structure rapidly and without much expense, and to provide during the actual design process itself all the necessary information about the effect of the boundary conditions, the geometry of the part and other factors on the thermal state of the structure in stationary and nonstationary regimes.

It is possible to observe the following trends in the application of computer technology to the solution of problems of heat and mass transfer.

1. Development and application of methods of solving nonlinear problems of heat and mass transfer.
2. Use of analog systems to check analytic methods of solution and EDC programs.
3. Solution of inverse problems of heat conduction on computers.
4. Expansion of the area of application of combined and hybrid models.
5. Wider use of analog systems rather than EDC for solving problems of stationary and nonstationary heat conduction, since more complicated problems can be solved with fewer assumptions.
6. Models based on the Liebmann method and the static integrators of L. A. Vulis and A. T. Luk'yanov appear to be most promising for solving nonlinear problems in the most general formulation.

NOTATION

cp—conductive paper; el—electrolyte; R—resistance network R network; R-C—resistance-capacitance network (R-C network); c—combined model; st—static integrator (node of R network); str—structural model; δt and h—intervals of time and space, respectively; λ—thermal conductivity; c—specific heat; a—thermal diffusivity; α—heat transfer coefficient; q—specific heat flux at surface; T—temperature; ETA—method of electrothermal analogies; EDC—electronic digital computer; L—Liebmann method. Indices: n—number of time step ($t = n\delta t$), m—number of space step ($x = mh$).

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