OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

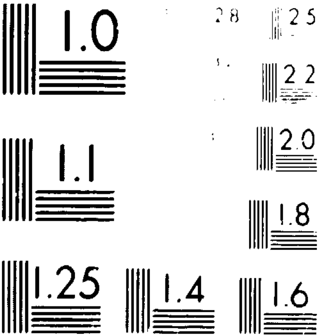
FAIR USE POLICY

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org


1.0
2.8
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

12952 → PEMBLETON SAGE

Distr.
LIMITED

UNIDO-Czechoslovakia Joint Programme
for International Co-operation in the Field of Ceramics,
Building Materials and Non-metallic Minerals Based Industries
Pilsen, Czechoslovakia

JP/46/80
June 1980

ORIGINAL: English

Technical Workshop on Energy Conservation
in Silicate Industries
for the Least Developed Countries

Pilsen, Czechoslovakia
October 1981

SIMULATING OF THERMAL PROCESSES IN SILICATE INDUSTRIES

by: Miloslav Němeček +/

1183

+/ Joint Laboratory for Silicates of the Czechoslovak Academy of Science and the Institute of Chemical Technology, Prague, Czechoslovakia

SIMULATING OF THERMAL PROCESSES IN SILICATE INDUSTRIES

INTRODUCTION

The increase of energy consumption in ceramic industries belongs nowadays to important tasks for both research and production practice. Among many kinds of energy required the thermal energy plays the most distinguished role. To minimize the amount of thermal energy supply, the detailed knowledge of thermal processes in plants and installations of ceramic industries is necessary. Under some circumstances, first of all if

- the plant is only projected, but still not working,
- producing plant is not equipped by measurement system,
- algorithms to evaluate the measured values are still not known,

this knowledge could be, however, difficult to obtain. It is to remove these inconvenient influencing factors that constitute the essencial goal of modelling and simulating techniques.

Generally, only such an object (substantial or abstract) may be considered as a model which has a defined and unambiguous relationship to its prototype. A simple example of an substantial (physical) model is a pattern for manufacturing metal products by casting. The only aspect for designing the pattern is the geometric similarity with respect to the temperature contraction of stiffened metal, and the shape of surfaces to be machined.

Essentially more complicated model then the previous one is the physical model of steady flow of Newtonian fluid through a cylindrical tube. At a point x, sufficiently distant from the tube entry (see Fig. 1), the character of flow (the form of velocity profile) depends only on the product $\bar{v} \cdot D$ of the mean velocity and tube diameter. More detailed experimental investigations lead to recognition of influence of fluid density and viscosity. It was found out that the Reynolds number

$$Re = \frac{\bar{v} D \rho}{\mu}$$

is the main factor of similarity. It determines the character of fluid flow. Experimental results showed the following facts:

- in the range $0 < Re \leq (2200\text{-}2300)$ the flow is laminar and all disturbances within flow are subdued by the governing effect of the viscous force; the velocity profile is parabolic (see Fig. 2a),
- if $Re > (2200\text{-}2300)$, the laminar flow turns into the transient one and at about $Re > 10^4$ the flow is turbulent. The velocity profiles are rather flat then parabolic (see Fig. 2b) and their form depends on Reynolds number.

From this example we can resume: the similarity between model and prototype demands, that

- two objects, both model and prototype have to fulfill the geometric similarity, $\frac{D_m}{D_p} = \frac{x_m}{x_p}$,
- initial and boundary conditions of both objects have to be similar, i.e. similarity of the entrance velocity profiles and that of tangential force on the inner wall of the tube are required
- the value of Reynolds number of both the model and prototype has to be equal; $Re_m = Re_p$.

Then the both dimensionless velocity profiles are equal

$$\frac{v_m}{\bar{v}_m} = \frac{v_p}{\bar{v}_p} \quad , \text{(see Fig. 3)}$$

The possibility to achieve similar flows at an equal Reynolds number by using various modelling fluids is evident. If the fluid with high kinematic viscosity coefficient, $\nu = \frac{\mu}{\rho}$, is used, the product $\bar{v} \cdot D$ must be of great value. This means that one has to work either with hight fluid velocity in the tube of small diameter D or, on the contrary, with small fluid velocity in a wide tube.

It is clear that the physical similarity requires in addition to geometrical similarity also to fulfil the equality of other similarity numbers.

Further experimental results proved that the surface roughness is of a significant influence on the pressure drop in the tube; again the dependence on Reynolds number was found. In the laminar flow region, the roughness affects the fluid surface friction less then in the turbulent one. It has also been experienced that the value of Re about (2200-2300) is the critical one from above only, i.e. below this value the turbulence does not permanently exist. The laminar flow, however, succeeded to exist even at Reynolds number about 10^5, if any tube vibrations and disturbances in the entered flow are eliminated and a perfectly smooth tube is used. Another very important phenomenon was observed if the Reynolds number is above a certain limit (this limit is different by case) the characteristics of flow depend no longer on Re and become approximately constant. Analogous independence has been found at other physical processes (heat, mass transfer, evaporation etc.). The experience was made, that not each model considered useful must be exact. It depends on purpose for which it is designed.

The static (steady-state) models were considered hitherto, their properties did not depend on time an the history of the physical phenomena investigated by modelling. A different type of model is the dynamic one, which describes time dependent processes. The notion of model signifies either the model itself or includes additional equipments as the measuring apparatus or systems, transducers and even analogous or digital computer, etc. Processes of getting information on modelled objects, the modelling or simulating ones, can be related to static or dynamic systems. Most often the latter ones are connected with simulating techniques.

MODELLING AND SIMULATING TECHNIQUES

These techniques represent a width range where many scientific branches are in touch. The interest does not comprise all concerning branches. However, we shall direct our attention to modelling and simulating of thermal processes connected with energy losses and energy consumption. From many possible classification viewpoints, we shall choose the following two:
- analytical type models
- simulating models.

Analytical Models

are based on the assumption of axiomatic validity of fundamental laws of physics. Such laws express in mathematical form the principle of conservation of mass, energy, electric current, etc., and represent an effective starting point to develop analytical models.

Applying the rules of similarity, dimensional analysis, and mathematical analogy and combining them, many kinds of analytical models have been developed (see Table 1). The principle on which the analytical models were derived can be shown at the following example of heat conduction in solids.

The process of nonsteady heat conduction in a body of solid material (see Fig.4) can be described by the

Energy Equation

$$\rho c \frac{\partial T}{\partial t} = \nabla(k \nabla T) + q_v \tag{1}$$

and its boundary conditions

$$h[(T)_s - T_o] = -k_S \left(\frac{\partial T}{\partial n}\right)_s \tag{1a}$$

at the boundary S of the body, and

$$T_1 = T_1(\xi, t) \text{ at the time } t_1 = 0 \tag{1b}$$

(the initial condition).

The following ways of solution to this problem may be shown:

Mathematical Model

Because the solution of Equation (1) in explicit formulae is only rarely reached, the numerical methods performed by computer must be used. The model input and output are the boundary conditions and printed tables of computed values, respectively. These both values represent the field characteristics either in scale of the prototype or more advantageously in dimensionless numbers. The dimension of the printed field data matrix is that as the number of nods in the used space mesh on the investigated body. The number of fields data can be reduced to several most important values at significant points of the body as shown graphically in Fig.4.

Physical Model

The solution of the Equation (1) can be substituted by real heat conduction process performed at a physical model in a determined but not arbitrary scale. Herein the theory of similarity will be applied. Let us write Equations (1) and (1a) with both for the prototype (index p) and model (index m):

$$\rho_p c_p \frac{\partial T_p}{\partial t_p} = k_p \sum_{i=1}^{3} \frac{\partial^2 T_p}{\partial \xi_{ip}^2} \tag{2a}$$

$$\rho_m c_m \frac{\partial T_m}{\partial t_m} = k_m \sum_{i=1}^{3} \frac{\partial^2 T_m}{\partial \xi_{im}^2} \tag{2b}$$

and

$$h_p [(T_p)_{S_p} - T_{op}] = -k_p \left(\frac{\partial T_p}{\partial n}\right)_{S_p} \tag{2c}$$

$$h_m [(T_m)_{S_m} - T_{om}] = -k_m \left(\frac{\partial T_m}{\partial n}\right)_{S_m} \tag{2d}$$

The initial conditions according to (1b) are

$(T_p)_1$ at time $t_{p1} = 0$

$(T_m)_1$ at time $t_{m1} = 0$

One of several efficient procedures of similarity theory, the method of scale coefficients $\varkappa$ was applied.

$$\varkappa_\xi = \frac{\xi_{ip}}{\xi_{im}}, \quad \varkappa_T = \frac{T_p - T_{op}}{T_m - T_{om}}\,^{1)}, \quad \varkappa_t = \frac{t_p}{t_m}, \quad \varkappa_\rho = \frac{\rho_p}{\rho_m}, \quad \varkappa_c = \frac{c_p}{c_m},$$

$$\varkappa_k = \frac{k_p}{k_m}, \quad \varkappa_h = \frac{h_p}{h_m}$$

Introducing these coefficients both into Equation (2b) and (2c) we get

1) Sometimes $\varkappa_T = T_p/T_m$ is defined. It, however, does not respect the temperature region at which to make model experiments would be desired. That is of significant importance if physical properties of both model and prototype substances depend on temperature.

we obtain

$$\frac{\varkappa_t}{\varkappa_\rho \varkappa_c \varkappa_T} \rho_p c_p \frac{\partial T_p}{\partial t_p} = \frac{\varkappa_\xi^2}{\varkappa_k \varkappa_T} k_p \sum_{i=1}^{3} \frac{\partial^2 T_p}{\partial \xi_{ip}^2} \tag{3a}$$

$$\frac{1}{\varkappa_h \varkappa_T} h_p [(T_p)_{S_p} - T_{ap}] = \frac{-\varkappa_\xi}{\varkappa_k \varkappa_T} k \left(\frac{\partial T_p}{\partial n}\right)_{S_p} \tag{3b}$$

Comparison of Equations (3a), (3c) with Equations (2a), (2c) which are valid for prototype gives the conditions

$$\frac{\varkappa_t}{\varkappa_\rho \varkappa_c \varkappa_T} = \frac{\varkappa_\xi^2}{\varkappa_k \varkappa_T} = a_1 \tag{3.1}$$

$$\frac{1}{\varkappa_h \varkappa_T} = \frac{\varkappa_\xi}{\varkappa_k \varkappa_T} = a_2 \tag{3.2}$$

where both a_1 and a_2 are arbitrary constants.

Equation (3.1) leads to the expression

$$\frac{\varkappa_t \varkappa_k}{\varkappa_\rho \varkappa_c \varkappa_\xi^2} = 1$$

from which

$$\frac{k_p}{\rho_p c_p} \frac{t_p}{\xi_p^2} = \frac{k_m}{\rho_m c_m} \frac{t_m}{\xi_m^2} \tag{3.1a}$$

The criterion of similarity, known as Fourier number,

$$Fo = \frac{k}{\rho c} \frac{t}{\xi^2} \tag{4}$$

joints thermal diffusivity $\frac{k}{\rho c}$, time t, and the characteristic length of the body into one independent variable.
The second independent variable (known as Biot number), from Equation (3.2) is

$$Bi = \frac{h\xi}{k} \tag{5}$$

The dimensionless temperature, $\Theta = \varkappa_T$, depends on both numbers, Fo and Bi. Experimental results obtained by modelling can be transferred into the relevant values of the prototype using the rule that the identity of independent variables (criteria) ensures the indentity of the dependent variable for both the model and prototype. From experimental results, diagrams may be constructed (see Fig.4). So the dependence of dimensionless temperature at a significant point of the body on Fourier number and a parameter may easily be read from and transferred from model to the prototype. The parameter refers to boundary conditions (for instance, the Biot number, see Fig.4 , corresponds with the boundary condition of the third kind).

Mathematical Analogy

It is sometimes named also as physical analogy and is based on the equal form of mathematical description (equations) of two or more physically different phenomena or processes. A well known example is the equality of mathematical formulas describing potential fields variables such as temperature, electric potential, hydrostatic pressure, known as electrical network analyzer. These analog models (resistor network = Liebman model, resistor-capacitor network = van Beuken model, see Fig. 5) has been developed to investigate linear heat conduction and diffusion processes. In such models the differential equation of the problem has been transferred into difference equation of the discrete elements of the network. To solve nonlinear problems, these models have to be operated by special procedures. They are often working in connection with digital computers. The whole system is controlled by computer, designed as the hybrid model.

Concept of Physical Modelling of Thermal Energy Transformations

Examples shown above are well known from physics and research practice. That concept, however, can not give the direct answer upon energy balance heat losses, energetic efficiency, etc. It is due to the fact that the fundamental equations did not contain any energy terms written in an explicit form. (Of course, the temperature difference multiplicated by density and specific heat, expresses the thermal energy, but not in the easy-to-balance form). On account of succesful physical modelling of energy in thermal processes, it is necessary to substitute some terms containing intensities by terms expressing energy, power, etc.

After inserting the new variables into Equations (1), (1a) that is

$$P_V = \rho c \frac{\partial T}{\partial t} \qquad \text{(accumulated heat), and} \qquad (6a)$$

$$P_S = -h\left[(T)_S - T_0\right] \qquad \text{(surface power input)} \qquad (6b)$$

and using as above, the scale coefficients method, we get two new similarity numbers

$$En_V = \frac{P_V \xi^2}{k(T-T_0)} = \frac{P_V}{\rho c(T-T_0)} \frac{1}{Fo} \qquad (6c)$$

and

$$En_S = \frac{P_S \xi}{k_S\left[(T)_S - T_0\right]} = \frac{P_S}{h\left[(T)_S - T_0\right]} Bi \qquad (6d)$$

The geometric similarity requires to fulfil the relation

$$\frac{P_V \xi}{P_S} = \text{const} \qquad (6e)$$

That way it is principally possible to start modelling thermal energy processes from the energetic point of view employing these new energy variables. Their direct measurement both on physical models and on prototypes is more advantageous than the integration of the detailed measured temperature or enthalpy fields. It is useful to express energy within the time space $(t-t_1)$ and volume V of the body.

$$\left.\begin{aligned} Q &= \int_{t_1}^{t}\int_{V} \rho c \frac{\partial T}{\partial t}\, dV dt \,, & Q &= \int_{t_1}^{t}\int_{S} \left(k \frac{\partial T}{\partial n}\right)_S dS dt \\ Q &= \int_{t_1}^{t}\int_{V} H_V\, dV dt \,, & Q &= \int_{t_1}^{t}\int_{S} h\left[(T)_S - T_0\right] dS dt \end{aligned}\right\} \quad (6f)$$

This commonly used procedure is less exact (from point of view of energy balance) than the direct measurement of energy values.

The relationship between model and prototype is performed using the scale factors

$$\varkappa_{PV} = \frac{P_{V_p}}{P_{V_m}} = \varkappa_\rho \varkappa_c \frac{\varkappa_T}{\varkappa_t} \tag{7a}$$

and

$$\varkappa_{PS} = \varkappa_h \varkappa_T \tag{7b}$$

from Equations (6a) and (6b), respectively is performed. Equations (7a), (7b) lead to scale factor

$$\varkappa_Q = \frac{Q_p}{Q_m} = \varkappa_{PV} \varkappa_V \varkappa_t \tag{7c}$$

Complex Processes

Problems to be solved in practice are, however, more complex than those shown above. Besides the scalar energy equation for fluid flow -

Energy Equation

$$\rho c\left(\frac{\partial T}{\partial t} + \vec{v}\,\nabla T\right) = \nabla(k\,\nabla T) + q_{V\Sigma} \tag{8a}$$

other equations of conservation take part in their description. If dealing with mass transport (drying, absorption, evaporation etc.) the set of scalar diffusion equations for a flow of multi-component mixture assumes the following form:

Diffusion Equations

$$\frac{\partial C_i}{\partial t} + \vec{v}\,\nabla C_i = \nabla(D_{im}\,\nabla C_i) + g_{Vi} \tag{8b}$$

$$i \in (1, I)$$

where the index i denotes the i-th component of the fluid mixture (index m);

If we investigate the velocity and pressure fields, the use of momentum equation is of importance. This nonlinear vector equation, has three components (in directions ξ_1, ξ_2, ξ_3 of Cartesian ordinates. In Navier-Stokes representation the

Momentum Equations

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\,\nabla)\vec{v} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}(\nabla^2 \vec{v}) \tag{8c}$$

has evidently simple form.

The nonlinearity of this equation has a consequence that its solutions are not always unambiguous. This refers both to the mathematical and physical models. The ambiguity of physical model at its working point and at surroundings must be experimentally investigated. If this investigation gives a positive answer, the physical model for other working point must be built to prove if unambiquity can be reached.

To Momentum equation belongs the

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \vec{v} = 0 \tag{8d}$$

This scalar equation summarises the system of diffusion equations (8b).

The radiative energy transfer in semitransparent media (flame, firing gases, glass etc.) is subjected to

Equation of Radiative Intensity

$$\frac{dI_\lambda}{dx} + \frac{k_\lambda}{\cos\vartheta} I_\lambda = \frac{\gamma_\lambda}{\cos\vartheta}\frac{E_{B\lambda n}}{\pi} + \frac{\delta_\lambda}{\cos\vartheta}\frac{D_\lambda}{4\pi} \tag{8e}$$

$(I_\lambda = I_{\lambda+} + I_{\lambda-}\ ;\ 0 \le \vartheta \le 2\pi\ )$.

The deficit between absorbed and radiated energy represents the radiative part q_{Vr} of the specific heat source q_{VZ} in energy equation (8a).

In an electrically conductive substances, the electric current causes the source of Joule heat output

$$q_{Ve} = \gamma(\nabla U)^2 \tag{8f}$$

which is another possible component of the term q_{VZ} in Equation (8a). The presence of the electric current field is usually expressed by Equation of Electric Potential

$$\nabla(\gamma \nabla U) = 0 \tag{8g}$$

All the equations written above represent, with their boundary conditions, the starting point for solving analytical problems at mathematical, physical and analoque models. They yield essential advantage for investigating many physical problems. Therefore they

- enable us to get information about even projected processes and objects (equipments, plants and their models)
- make easier to develop algorithms for evaluating of measured data
- give information even for improvements of simulating models, especially, enable the statement of relations and connections between inner variables of physical processes and their outer effects at such models.

Approximate Modelling

It exist some complex physical processes, impossible to be exactly modelled. At this cases it is necessary to be satisfied with only approximate models developed by using the approximate similarity principles. The approximity can be caused by the

- form of fundamental equations, where some terms are neglected either to enable the solution of the equation or to simplify the problem formulation,
- simplification or approximate prescription of boundary conditions, enforced by either unsufficient knowledge or boundary data at prototype or decision to avoid complications in computing, or

or other reasons,

- physical properties of model fluid, that do not comply all similarity numbers at convenient temperature, pressure etc. ranges,
- other causes, as to stochastic character of measured values, and from outside comming disturbances, decision to work with similarity numbers characterizing only the most significant processes
- endeavour to take for constant variables, those are only little varying within the given region of independent criteria.

Simulating Techniques

They belong to approximate techniques, but they are not coherent with approximate similarity. Simulating models as abstract objects can also be named as structural models. The significant advantage of a simulating model is the fact that model relations comprise both physical and nonphysical (e.g. logical, technological, qualitative, ets.) values and data.

The task of a general simulating problem (see Fig.6a) is to determine coefficients of a conveniently elected system of differential equations which express relations between independent X variables and the dependent Y ones. This means to transform the system of equations

$$F(Y,X) = 0 \qquad (9a)$$

into the system

$$y' = f(y,x) \qquad (9b)$$

of differential equations, with the boundary condition $y_0 = y(x_0)$ (this is necessary above all for purposes of automatic control of technological processes). These systems and the relevant computing programs represent the simulating model of the problem to be solved. Beneath variables mentioned above, as well, the other ones for example quantity and quality of product, material, energy and other costs can be considered. Then energy losses, energy consumption and any other parametors do not represent any difficulties.

The advanced simulating techniques are developed into routine use, described by detailed instructions including computer programming languages and programs. Experimental techniques and experimental data (see Fig.6b) play an important irreplaceable role in simulating techniques.

Optimization

Within this last stage of research and design the results of modelling and simulating investigations would be utilized. There is the most substantial task there , to formulate the goal of optimization and criteria of optimality and to choose way and means for achieving it. Usually the simplest procedure is used to reach optimum in one or two most important indices, for example to reach highest financial profit, highes manufacture output at lowest energy and material costs etc.

From this point of view it is quite obvious that thermal processes participate only with various relevance among other factors which could influence the total economic effect. Therefore modelling and simulating thermal processes must be considered as an implement which contributes to more complex look at the problem of optimization.

APPLICATION

Mathematical Modelling of Heat Losses through a Furnace Wall

Steady State (Static) Model

a) thermal conductivity coefficients k of refractory and insulation layers in the wall construction are temperature independent. The prescribed temperature difference (see Fig.7) is

$$T_i - T_s = \frac{q_{lmax}}{K} \qquad (10a)$$

with

$$K = \left(\frac{1}{h_i} + \sum_{n=1}^{N} \frac{\delta_n}{k_n} + \frac{1}{h_s} \right)^{-1} \qquad (10b)$$

where q_{lmax} - is allowed heat loss $[Wm^{-2}]$.

The number N and thickness' δ_n of wall components are to be found.

Because h_i and h_s are known functions of variables T_1 and T_N respectively, the model consisting of Equations (10a), (10b) and given functions $h_i(T_i,T_1)$ and $h_s(T_s,T_N)$ can be solved by numerical methods only.

b) thermal conductivity coefficients k_n depend on temperature ${}_{(n)}T$ within thickness of the n-th component of the wall construction. Because it is $k_n = k_n({}_{(n)}T)$, the temperature ${}_{(n)}T$ must be implicitely expressed by integral equation

$$ {}_{(n)}T - T_{n-1} = \int_{x_{n-1}}^{x_{n-1}+\delta_n} \frac{q_{lmax}}{k_n({}_{(n)}T)} dx \tag{10c} $$

or

$$ q_{lmax} \cdot \delta = \int_{T_{n-1}}^{{}_{(n)}T} k_n({}_{(n)}T)\, d_{(n)}T \tag{10d} $$

and the solution is to be obtained by numerical way, for example by succesive approximations by specialized computer programs. As an example let us show the result of solution Equation (10d) for one layer of refractories of the type 1711 and 1681 at $q_{lmax}\delta \in \langle 50;5000 \rangle\ [Wm^{-1}]$, (see Fig.8). The computed diagram in Fig.8 was applied to design the refractory wall thickness δ of a glass melting tank..

Dynamical Models

Static models are inconvenient to solve nonsteady problems connected with incontinual thermal processes in industrial furnaces. The essential task of modelling is to optimize manufacturing process. As to energy consumption , the dynamic model would have to find optimal relations between energy costs losses etc. and other factors, for instant quality and quantity products, material costs etc. Unlike in the previous examples the energetic efficiency represents the steady-state heat loss flux, $[W]$, $[Wm^{-2}]$, in dynamic model, the energetic efficiency must be connected with the total amount $Q_p [Wh]$ of heat losses within the time space t_2-t_1

$$Q_p = \int_{t_1}^{t_2} P_{Lp}\, dt$$

where P_{Lp} - heat loss flux $[W]$, t_2-t_1 $[h]$ - time period of thermal process.

Because heat losses P_{Lp} are dependent on furnace inner temperature T_i, then the total heat loss Q_p within the time space t_2-t_1 depends on the period t_2-t_1. This shows in two examples Fig.9. In case a) (see Fig.9a), the furnace works at high inner temperature T_i and in case b) (see Fig. 9b), at the lower one. In the case a) both the inner furnace temperature and the temperature of goods surface increase rapidly.

The amount of heat accumulated by furnace walls is increasing as well. The case b) is designed by smaller increase of temperature and accumulated heat , the time period t_2-t_1 at the same furnace type and the same goods is shorter then that in case a). Hea s amount $Q_{p(b)}$ however, cannot be the same as the $Q_{p(a)}$. task for dynamical modelling is to choose an adequate dyn al model and to carry out model experiments (physical measurement, computations) , to find out the heat loss amount Q_p as a function belonging to various conditions. The next task, optimization of energy losses can be solved either by improvements of furnace design (for example by substituting dense ceramic insulating material by ceramic fibres felt in the wall contruction, to reduce accumulated heat) or by optimization of technological process in furnace (for example, among all possibilities such a process must be selected, to minimize the heat loss amount Q_p)

Heat Recovery

Modelling or simulating of heat recovery devices by mathematical way is most convenient both for periodic and continuous processes. The problem can be formulated as a static or as a dynamical one. The former is usually solved by using thermal efficiency balance, the latter by the energy one. Some diagrams of heat recovery devices are shown at Figs. 10,11,and 12.

Mathematical Analytical Models of Simultaneous Fields

Very complicated mathematical models are developed for computing complex (simultaneous) fields, as to temperature, velocity, pressure, radiation and electric current ones in glass melting furnaces. Figs 13 and 14 demonstrate some results obtained by two and three-dimensional models. Here the finite difference method was used.

Physical Models

The most complex models were constructed and equipped to investigate the fluid flow, temperature and electric current fields in oil fired, electrically boosted or all-electric glass melting furnaces. Principle of working circuits of the model of an all-electric glass melting furnace is given in Fig.15. Photos in Figs. 16,17 and 18,19 show views and results respectively of two different models of glass melting furnaces. At the present state, models are static i.e. working in a steady-state régime. The similarity of energy values is only investigated. Model fluid properties do not regard the heat to be spent for melting of the batch and chemical reactions taking part in melting process. An example of use of physical analogy the modelling of Laplace equation by means of rheoelectric analogy device is shown in Figs. 20,21 and 22.

CONCLUSIONS

The recent simulating and modelling techniques are a very efficient implement in research and manufacturing practice. They demand, however, to master the measurement and computer techniques, both theoretical (mathematics,physics, chemistry etc.)

and practical knowledge and well to plan and organize working teams of specialists taking part on solution theoretical and practical problems.

Acknowledgement

This paper summarizes ideas and results contained in discussions between the coworkers of the Laboratory of Silicates of the Czechoslovak Academy of Sciences and the Institute of Chemical Technology and the author.

Nomenclature

a	constant, coefficient
C /kg m^{-3}/	concentration
c /J kg^{-1} K^{-1}/	specific heat
$D = 2\,R$ /m/	tube diameter
$D_{i,m}$ /m^2 s^{-1}/	diffusion coefficient
$D_\lambda \cdot \frac{\delta_\lambda}{4\pi}$ /Wm^{-3} sr^{-1}/	monochromatic dispersed radiative intensity
$E_{B\lambda n}$ /Wm^{-3}/	monochromatic emissive power of the black body surface within semitransparent surroundings
F, f	function
g /kg m^{-3} s^{-1}/	volumetric mass source due to chemical reactions
H /Jm^{-3}, kJm^{-3}/	enthalpy
h / $Wm^{-2}K^{-1}$/	heat transfer coefficient
I /$Wm^{-3}sr^{-1}$/	radiative intensity
k /Wm^{-1} K^{-1}/	thermal conductivity
p /P /	pressure
Q /W,KW/	heat input
q_v /Wm^{-3}, kWm^3/	volumetric heat source due to radiation, chemical reactions, electrical and mechanical energy dissipation

q_1 /Wm^{-2}/	surface heat input
S /m^2/	surface
T /kJ/	temperature
t /s,h/	time
v /ms^{-1}/	velocity
x /m/	length, distance
y	function
β_λ /m^{-1}/	monochromatic absorption coefficient of semitransparent medium
Δ	difference , ∇^2
σ_λ /m^{-1}/	monochromatic dispersion coefficient
δ /m/	thickness
ϑ /$^\circ$/	angle
$\varkappa$	scale factor
λ /m/	wave length
μ /$kg\ m^{-1} s^{-1}$/	dynamic viscosity
$(\xi) = \xi_1, \xi_2, \xi_3$ /m/	Cartesian coordinates
ρ / $kg\ m^{-3}$/	density
∇	Hamilton vector operator

Indices

0,1	boundary
i	component of fluid mixture
m	model
p	prototype
S	surface
V	volumetric
λ	monochromatic
Σ	total

Books recommended for individual study:

1. Staněk, J.: Electric Melting of Glass, Elsevier Scientific Publishing Company, New York, NY, 1977

2. Bird, R.B.-Stewart,W.E.- Lightfoot,E.N.: Transport Phenomena. New York, J. Wiley, 1960

3. Siegel,R.-Howell,J.R.: Thermal Radiation Heat Transfer. Mc-Graw-Hill 1972

4. Mc Lead, J.: Simulation. The Dynamic Modeling of Ideas and Systems with Computers. New York,Mc Graw-Hill 1968

5. Karplus, W.J.: Analog Simulation. Solution of Field Problems, New York, McGraw-Hill,1958

Paschkis,V.- Ryder, F.L.: Direct Analog Computers, New York J.Wiley 1968

6. Bellman, R.E.- Dreyfus, S.E.: Applied Dynamic Programming. Princeton University Press 1962

7. Wilde, D.J.: Optimum Seeking Methods. Prentice Hall, Englewood Cliffs 1964

8. Feller, W.: An Introduction to Probability Theory and Its Applications, New York, J. Wiley 1957

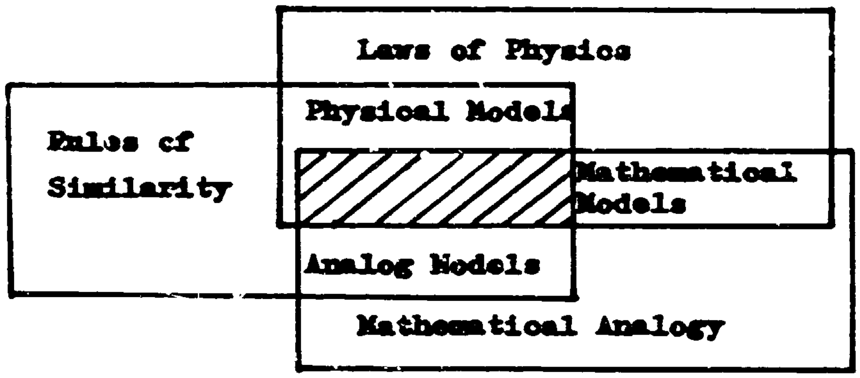
9. Hogg, R.V. - Craig, A.T.: Introduction to Mathematical Statistics. New York, The Mac Millan Company 1965

10. Ralston, A. - Wilf, H.S.: Mathematical Methods for Digital Computers, New York, J.Wiley 1965

Table 1.

a.

Analytical models



b.

Analytical models	Purpose				
	Research	Plants design	Process planning	Process control	Optimisation
Mathematical m.					
Physical m.					
Analog m.					

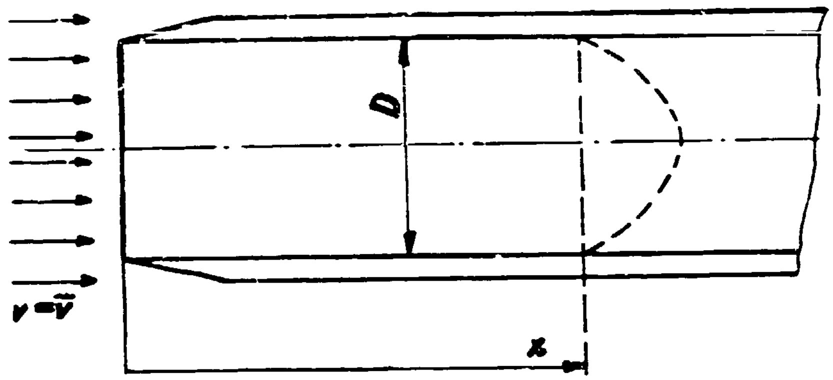


Fig. 1. Cyllindrical tube; coordinates

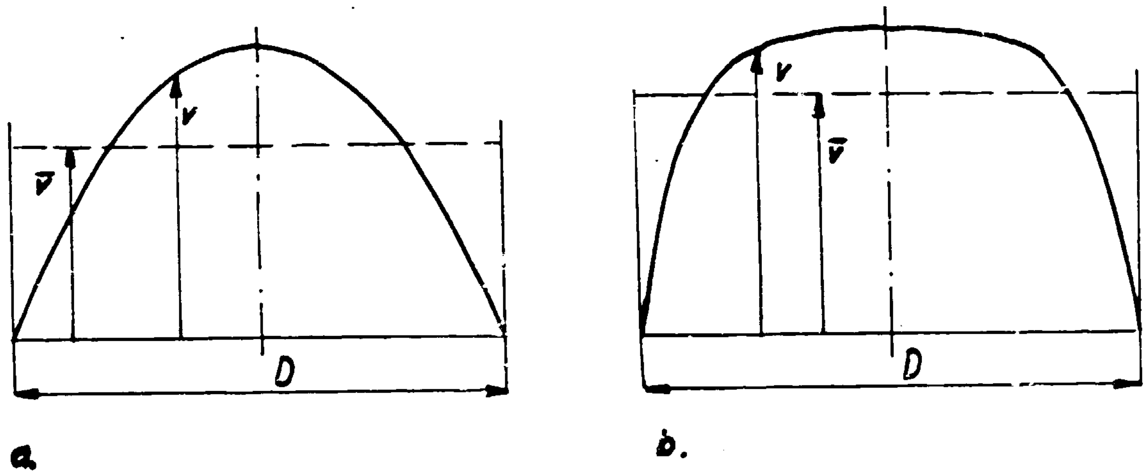


Fig. 2. a) laminar flow, parabolic velocity profile
b) nonlaminar (turbulent or transient) flow; velocity profile nonparabolic

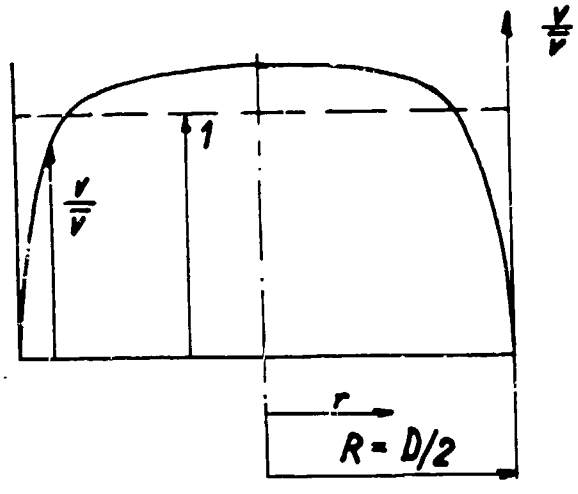
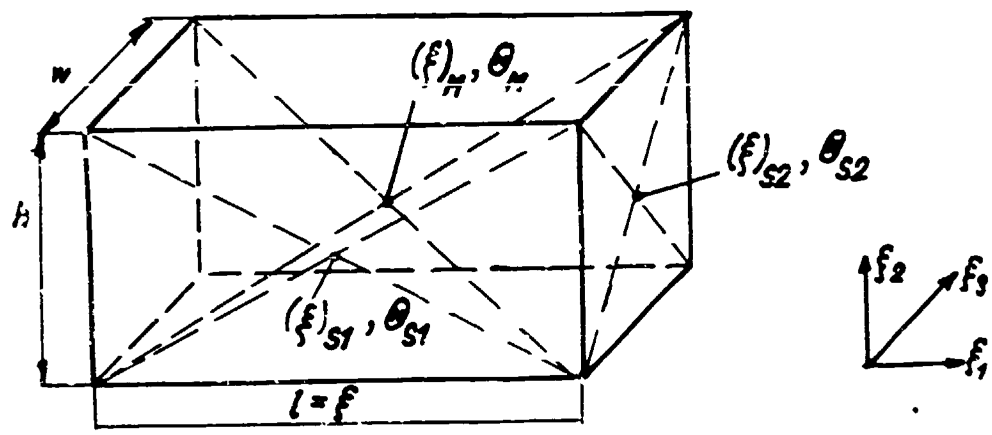
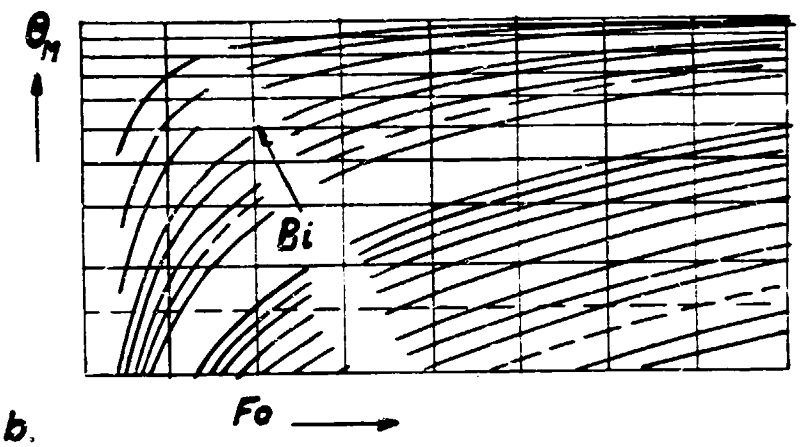


Fig. 3. Dimensionless velocity profile in the tube flow



a.



b.

Fig. 4. Nonsteady heat conduction;
a) shape of the body and Cartesian coordinate system
b) temperature field data, referred to point $(\xi)_M$.

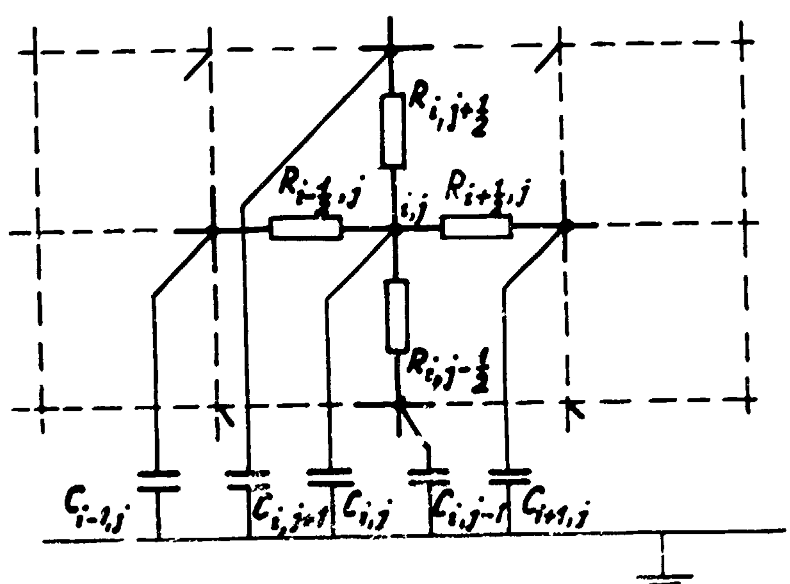
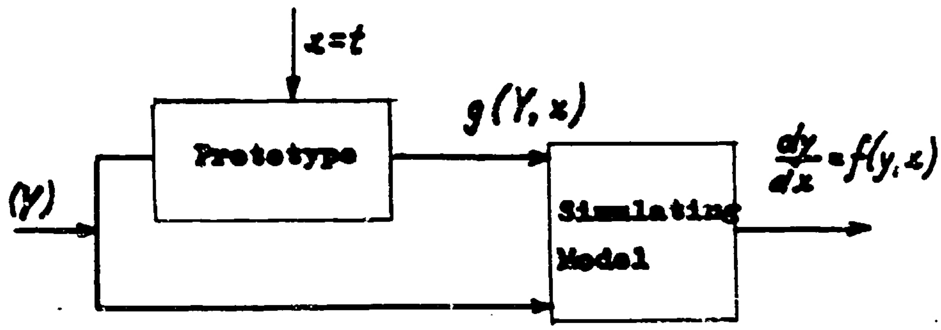
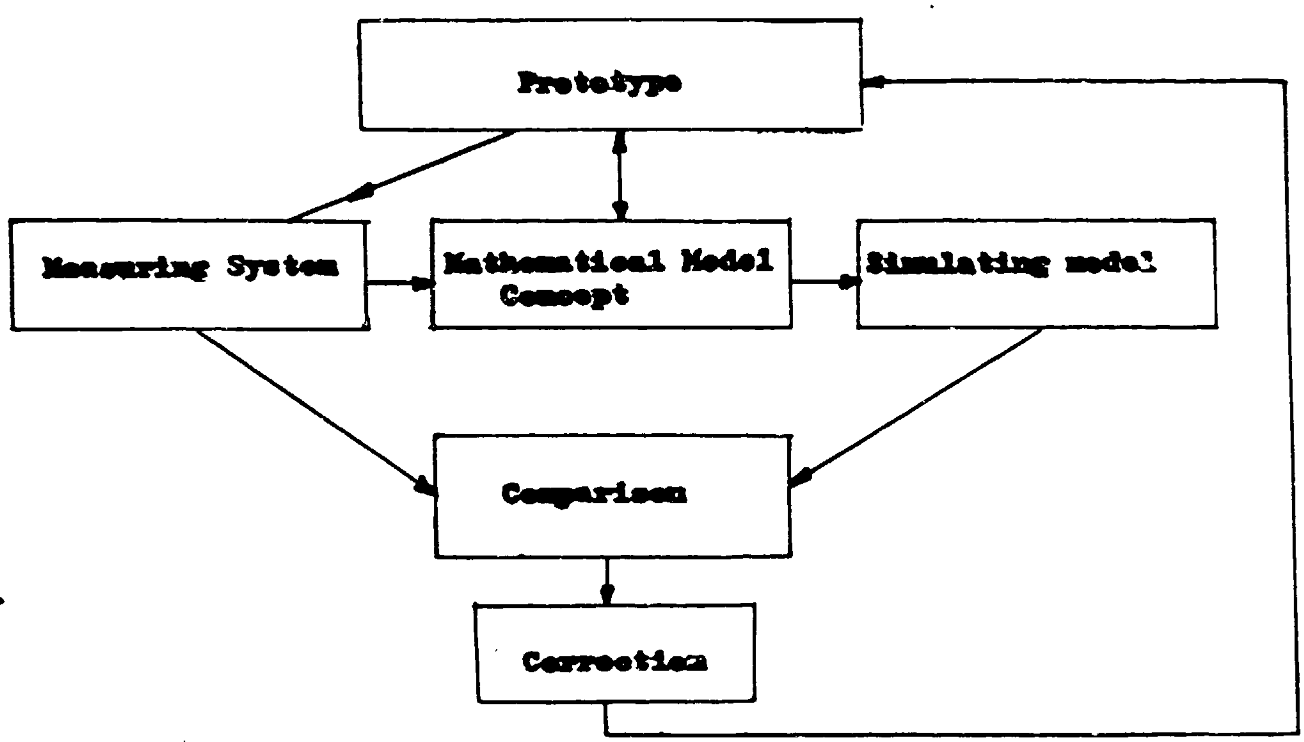


Fig. 5. Principal scheme of an R-C network (van Beuken-model) for two dimensional discrete modelling of nonsteady potential fields.



a.



b.

Fig.6. Simulating problem diagram

a) the task of simulation

b) relation between simulating model and the prototype

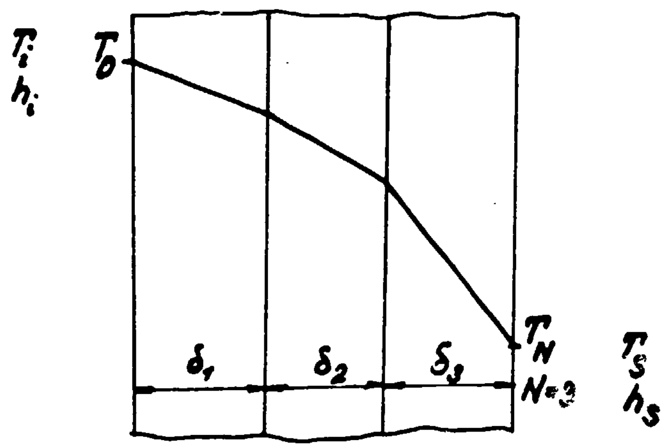


Fig. 7. Scheme of temperature profiles in the heat conducting furnace wall

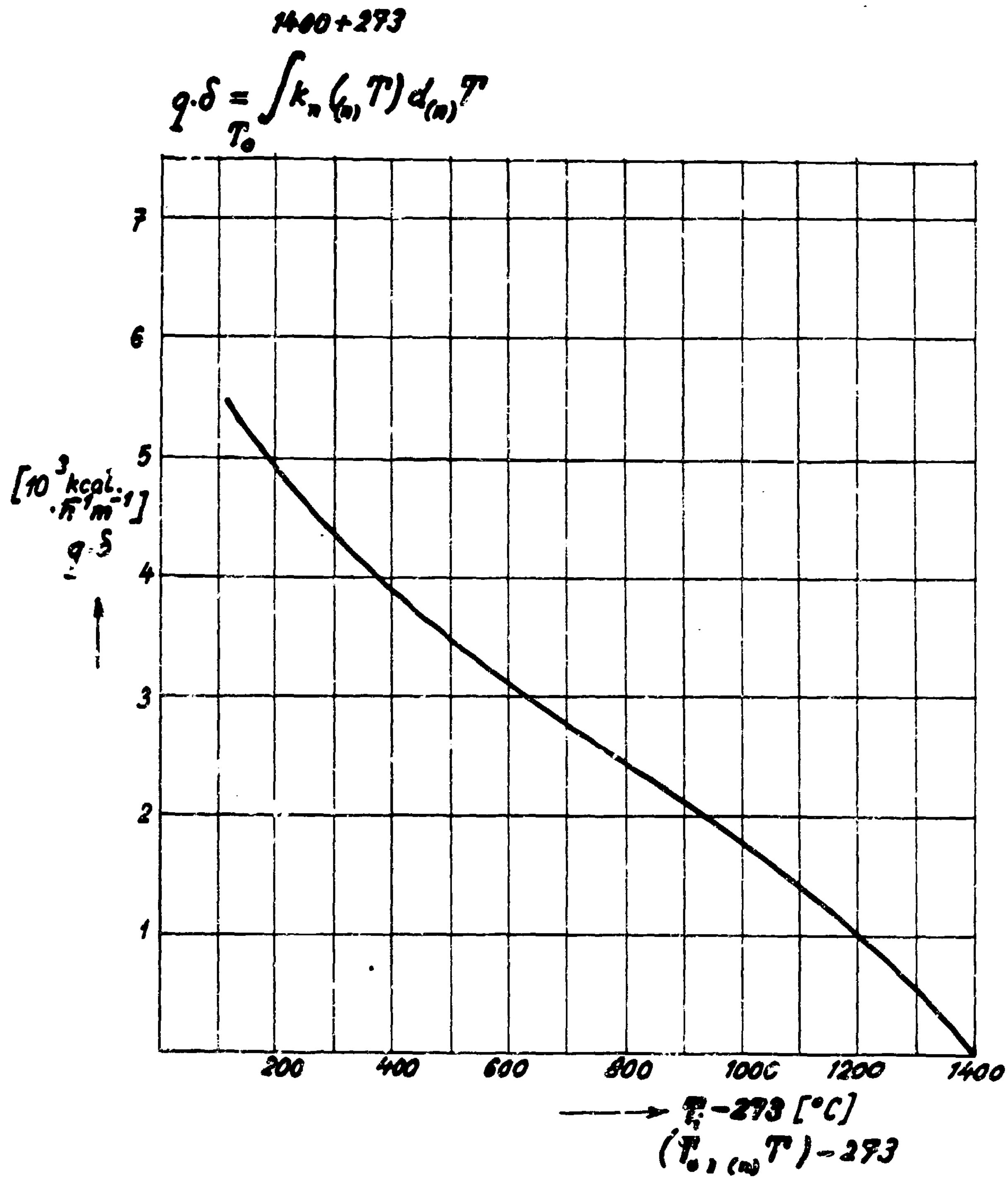


Fig. 8. Solution of the Equation (10d) for temperature $T_i = 1673$ /K/

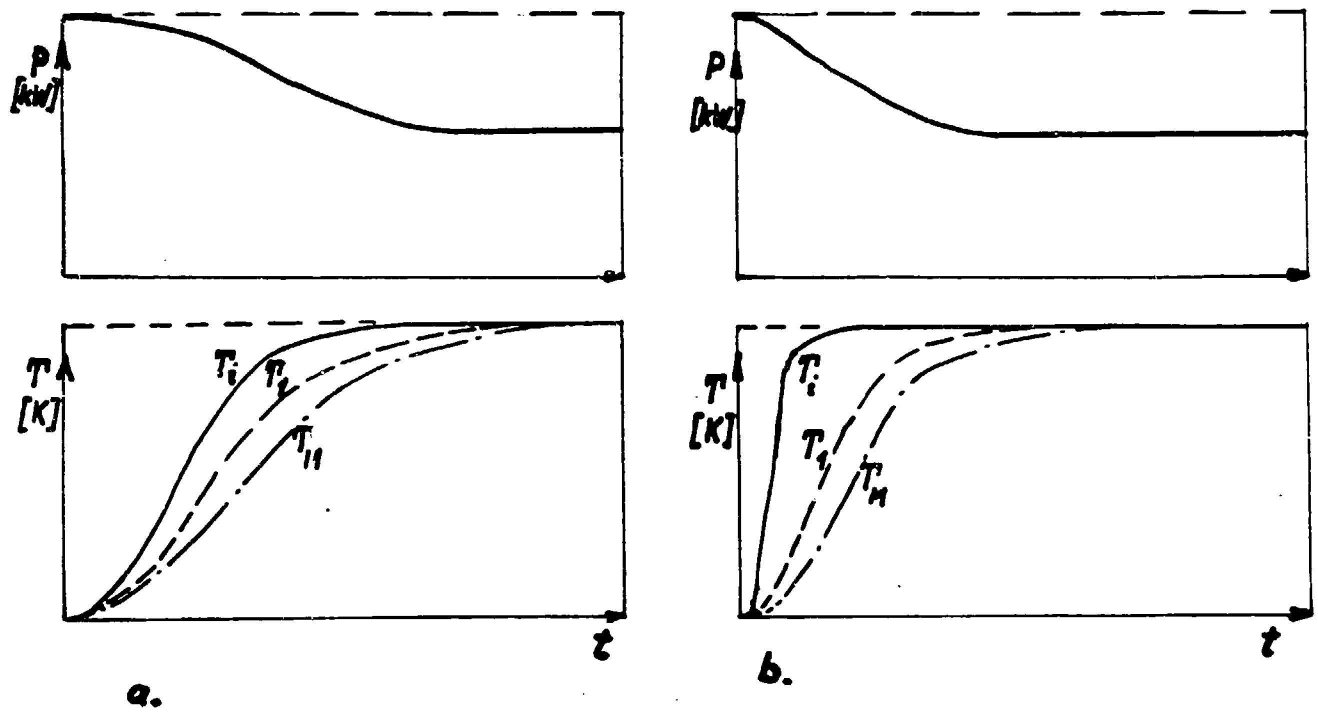


Fig. 9. Characteristics of energy consumption and losses at a furnace-goods system; wall construction with reduced heat accumulation (b).

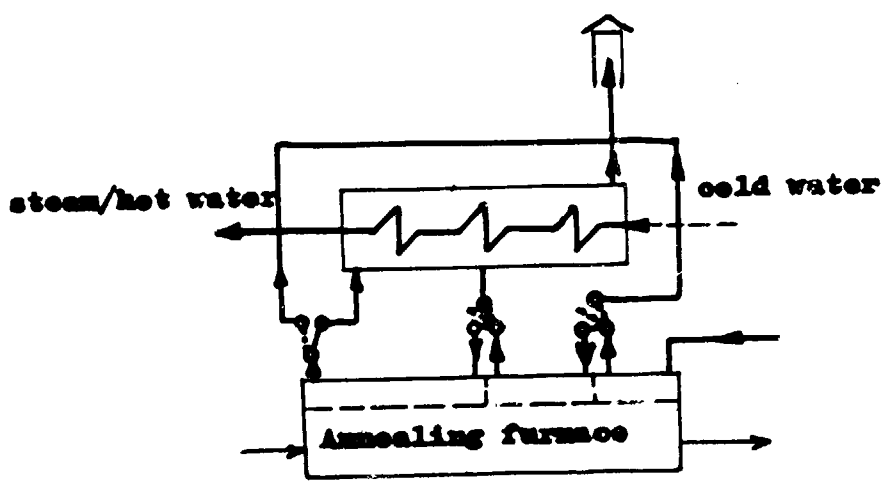


Fig. 10. Scheme of a simple counterflow reheat equipment coupled with glass or ceramic annealing kiln

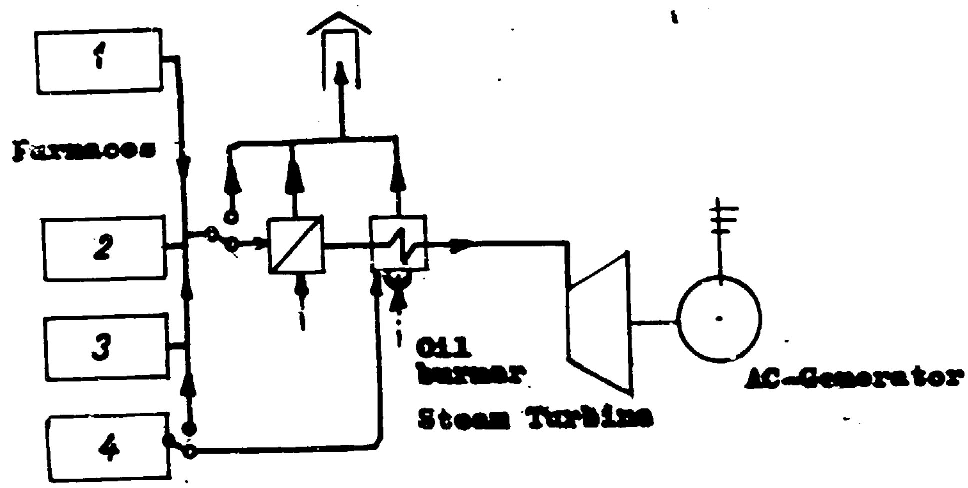


Fig. 11. Scheme of energy recovering plant of four flame fired furnaces

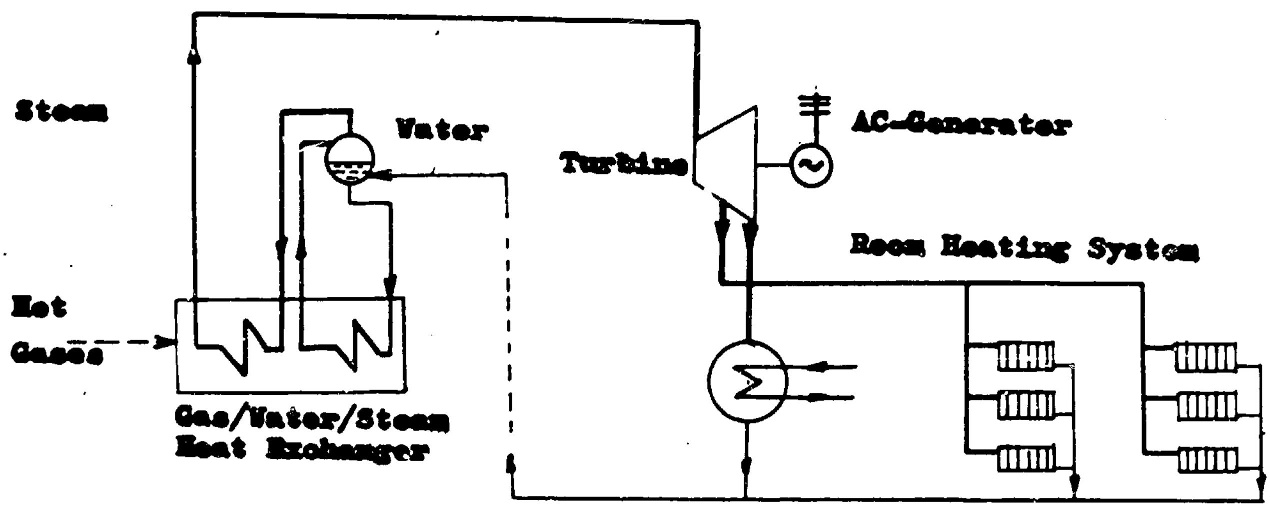


Fig. 12. Scheme of energy recovering equipment for a flame fired glass melting furnace

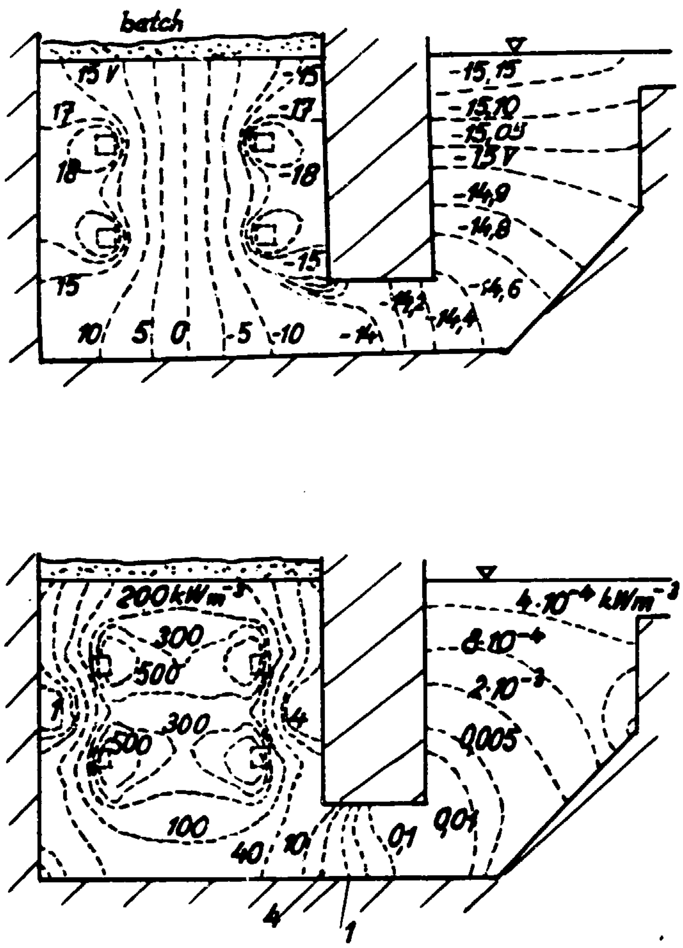


Fig. 13. Results of solution of two dimensional mathematical analytical model of electric glass melting furnace;

a) Electric potential field

b) Field of the Joule heat output

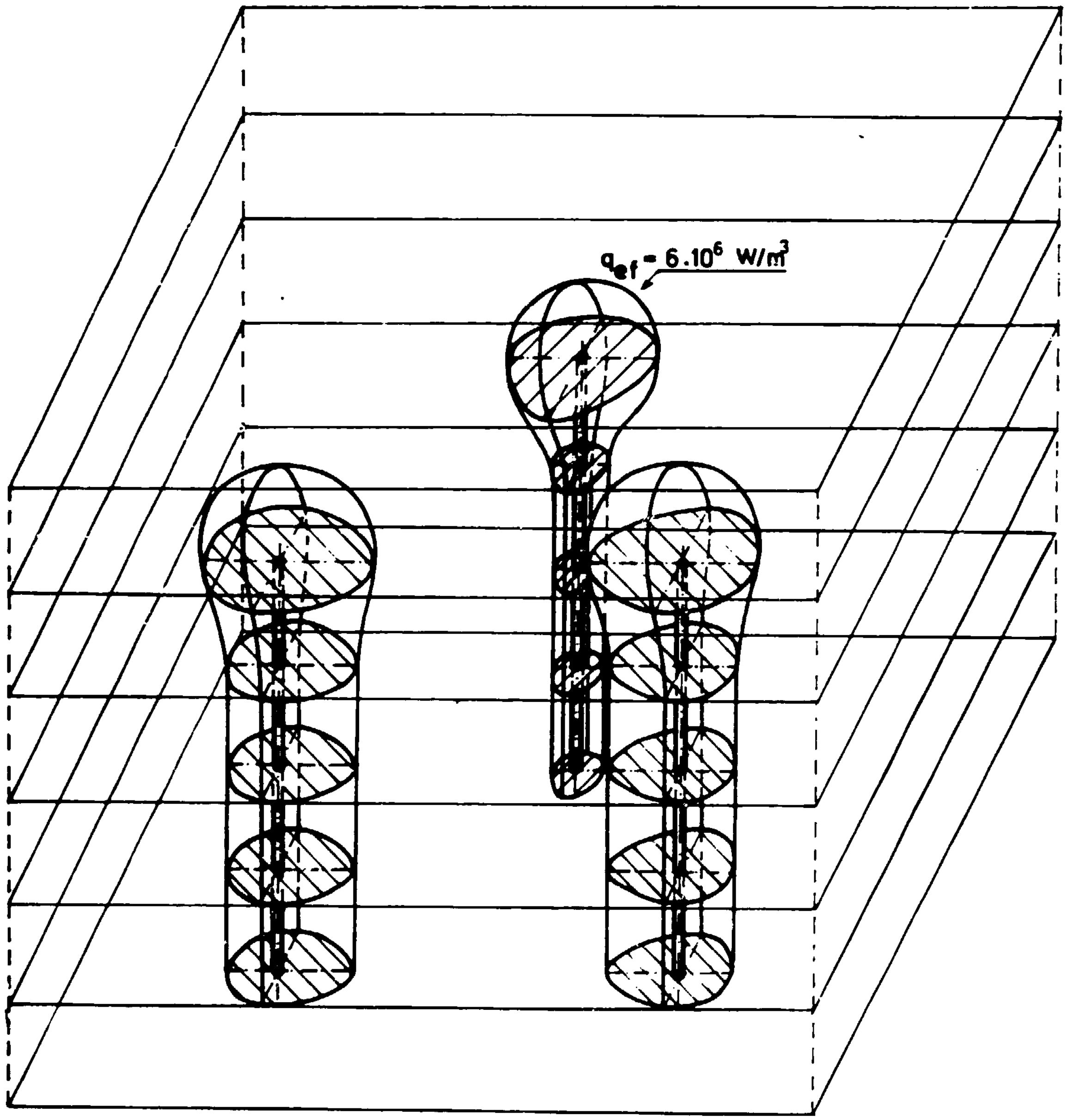


Fig. 14 a. Three dimensional mathematical analytical model of a simple three electrodes electric glass melting furnace; field of the Joule heat output q_{ef}.

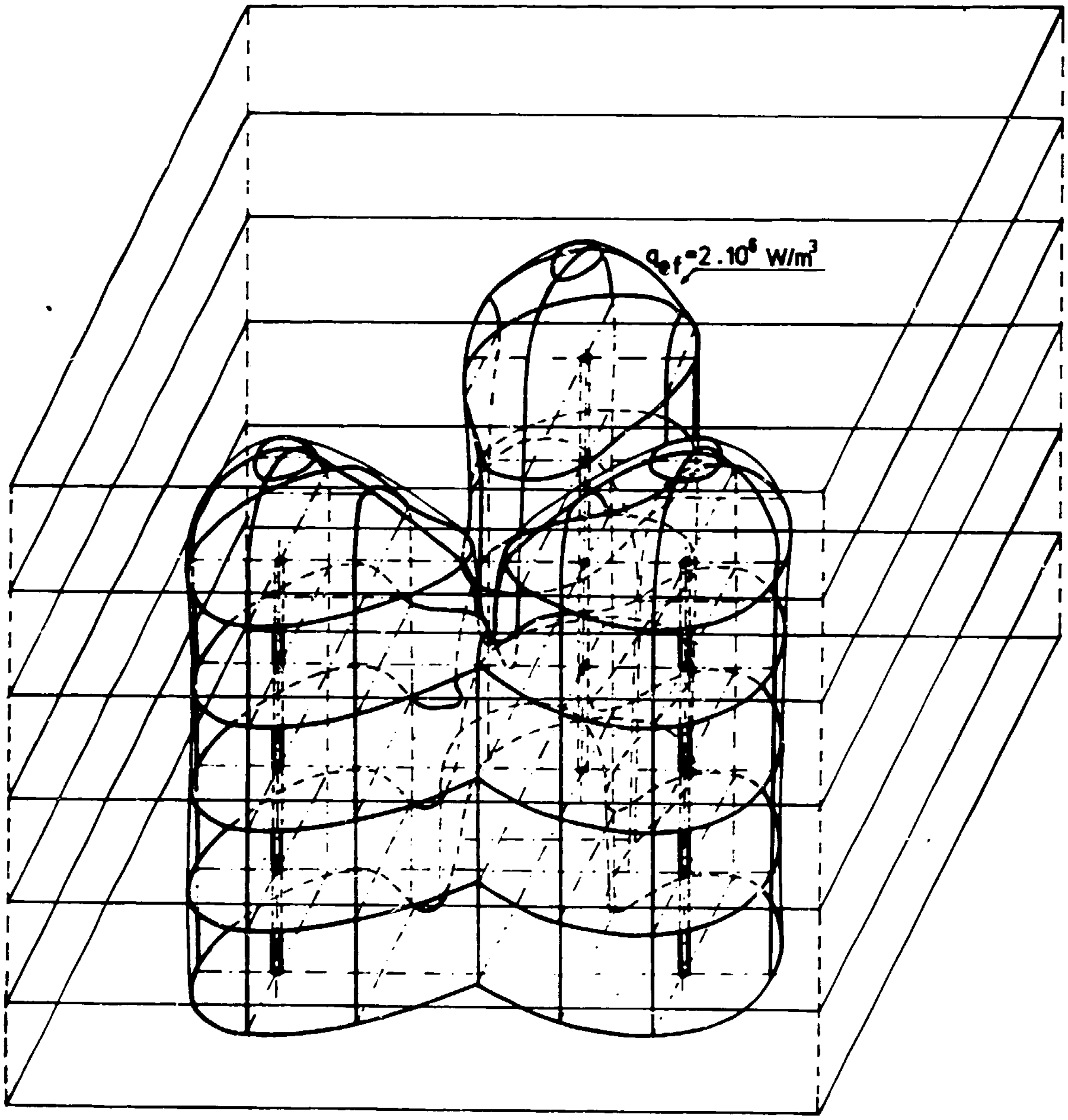


Fig. 14 b. Three dimensional mathematical analytical model of a simple three electrodes electric glass melting furnace; field of the Joule heat output q_{ef}.

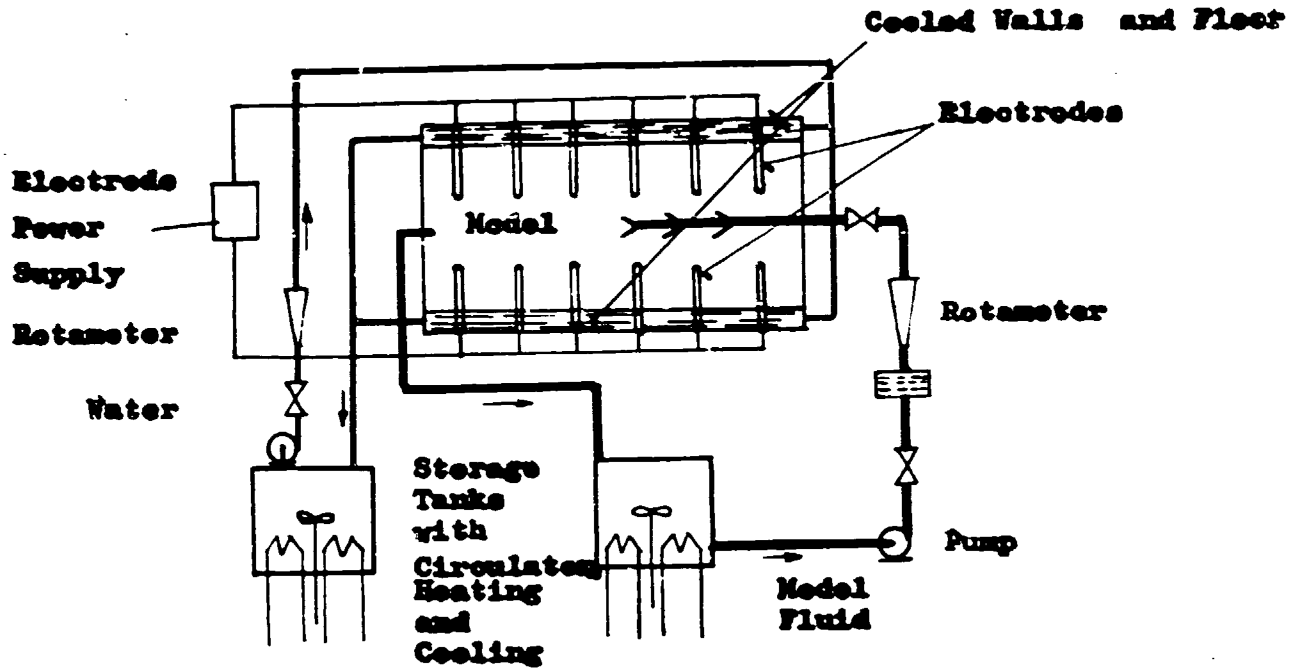


Fig. 15. Diagram of working circuits of a physical model of glass melting tanks

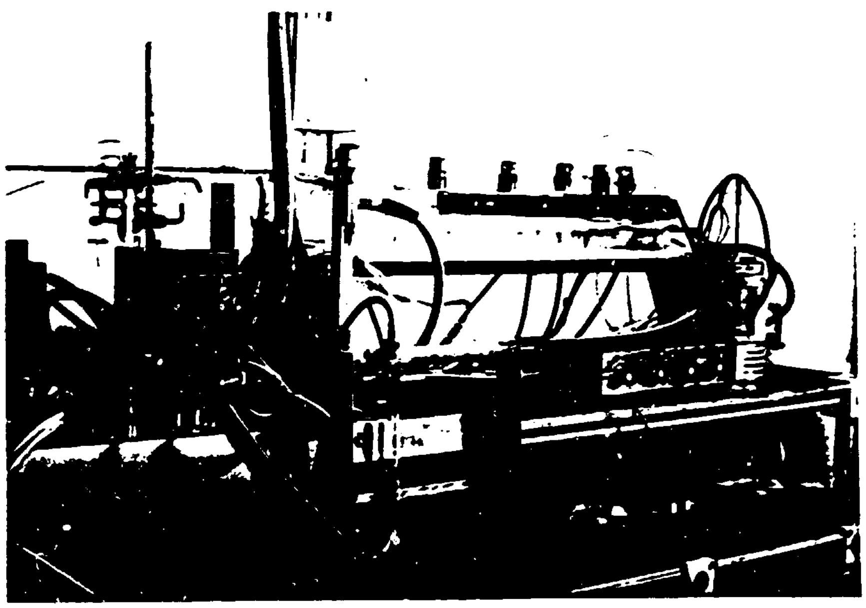


Fig. 16. Physical model of an electrically boosted glass melting furnace "Unit Melter"

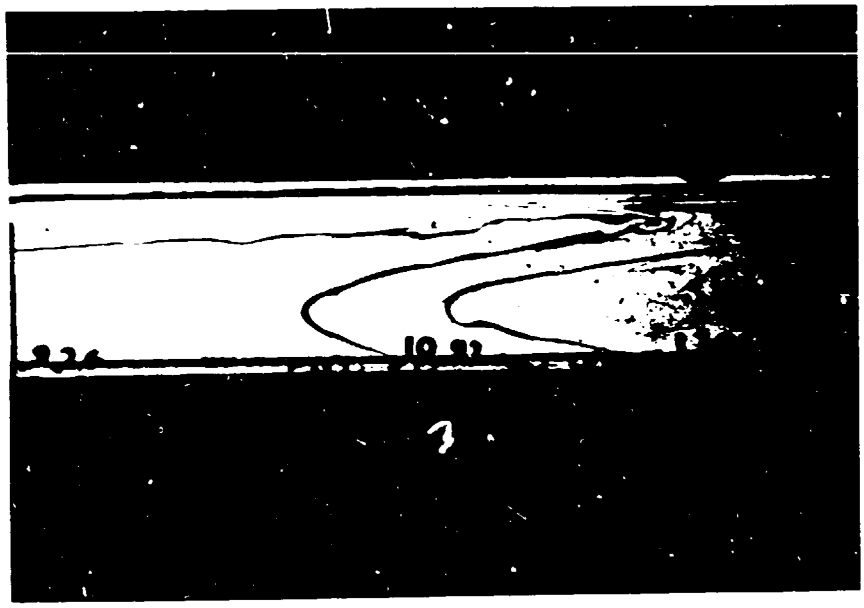


Fig. 17. Convection pattern of model liquid in the lengthwise vertical section of the "Unit Melter" visualised by injection of colour

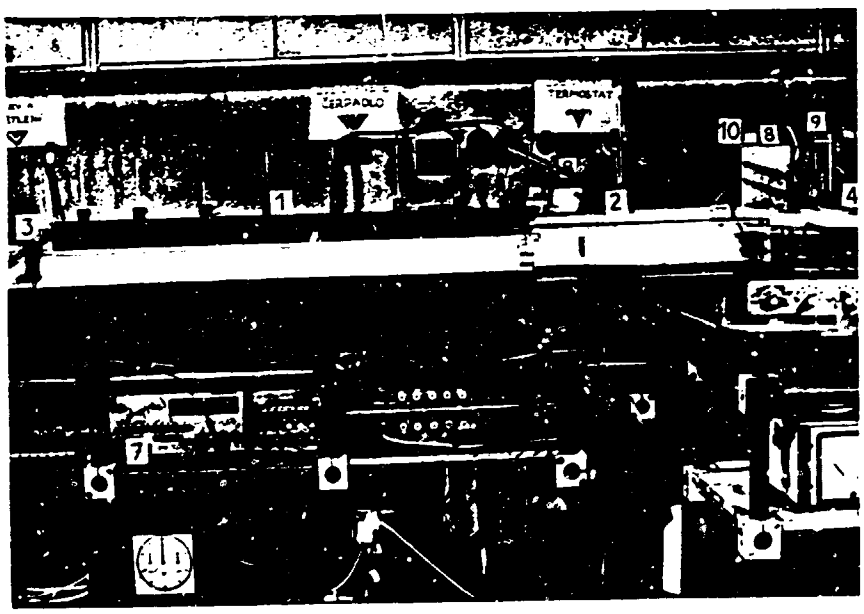


fig. 18. Physical model of electrically boosted glass melting tank furnace 130t per 24 hs.

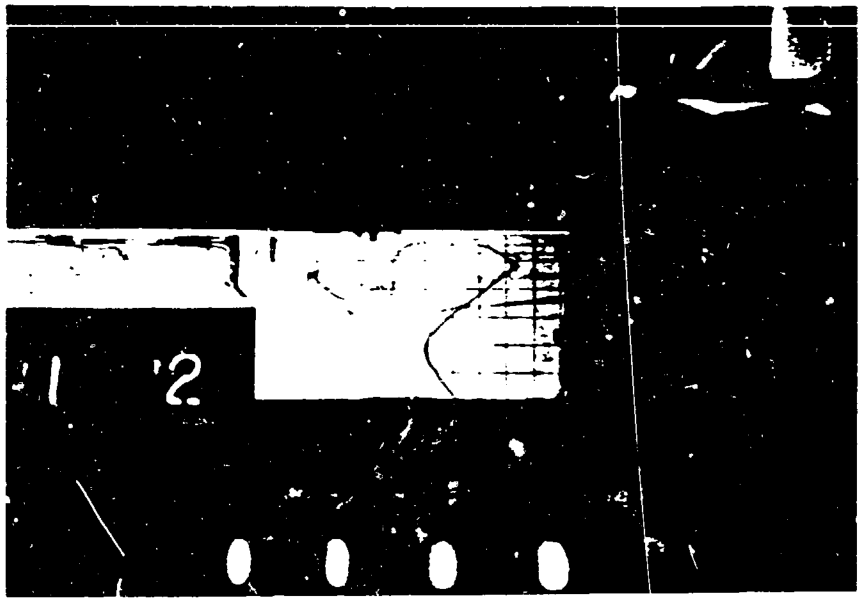


Fig. 19. Visualized flow pattern in the lengthwise vertical section of tank furnace shown in Fig. 18.

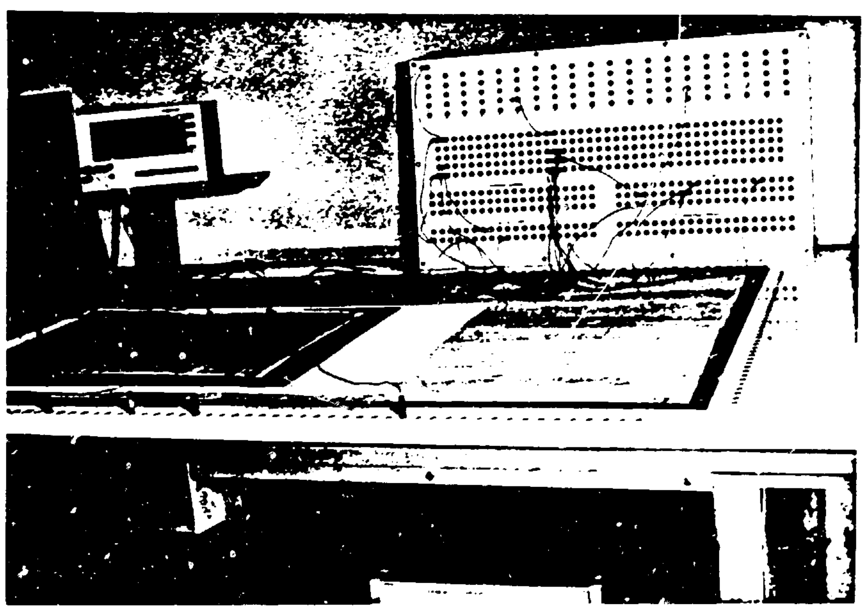


Fig. 20. Common view on rheoelectric analogy device for analog simulation of potential fields

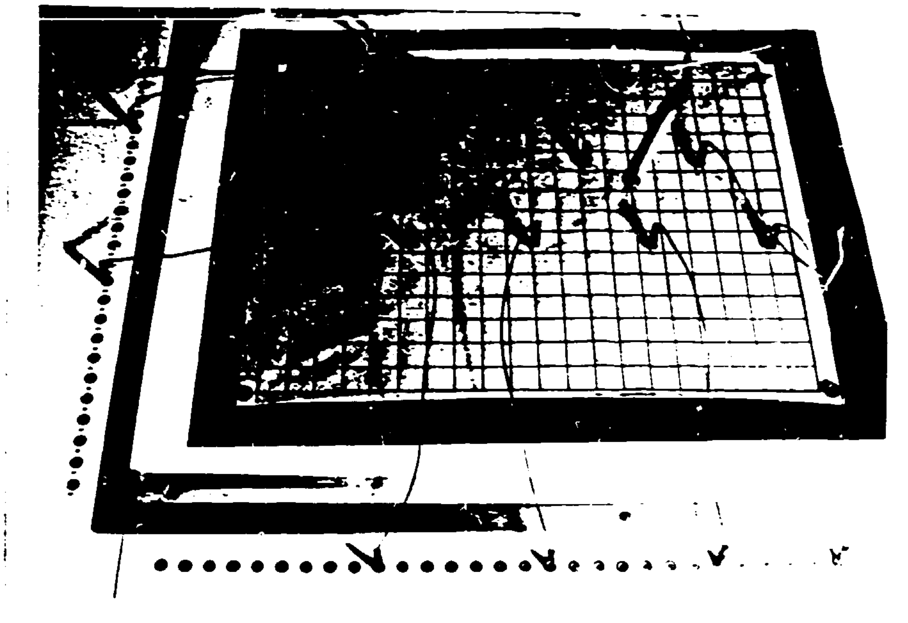


Fig. 21 Electric conductive paper sheet with nods simulating positions of boosting electrodes

Fig. 22. Searching for an equipotential line at the electric conductive surface of the sheet