STATIC AND DYNAMIC ANALYSIS OF DRIERS BY THE MASS AND ENERGY FLOW NETWORK METHOD

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1. Drier system problems

1.1. *The systems approach of the drier operation*

A short description is given of a calculation method for determining the static and dynamic operational characteristics of driers with engineering accuracy likely to suit other complex technological processes as well [1].

Drying, — accuring in all fields of national economy, — is an important operation, affecting the quality, and of high energy consumption, so its economy is of a paramount importance.

The drying of a material is the outcome of a number of interrelated processes, therefore it may be conceived as a *system* of these partial (component) processes. Co-ordination of the component processes (material preparation, charging, material transfer within the drier, heat transfer, material dehydration, vapour exhaustion) in a predetermined manner is precondition of a satisfactory quality and due economy.

The component processes are carried out in units of the drier, such as the medium conveyors, flow pipes, calorifers mixing spaces, separators, ets. The drier is an active (so-called behaviourial) system of these units, *responding* to some *action* as imposed by the resultant of interactions between the system units, of sets of their interdependent actions [1, 2, 15, 16].

1.2. *Drier operation engineering*

The drier engineering system problems are both of *analysis* and *synthesis* type [3, 4]. For instance to find the response of a given drier to a given action (i.e. the operational characteristics of the dier under given service conditions) is an *analysis type* system problem. Such an analysis type system problem has a *single solution*, needed both by the operator and the controller of the drier. The *engineering analysis is restricted to specific answers*, because the engineer always directs his examinations to some *concrete aim*. For instance, response of the drier on various expected disturbances, on the changes of the operational conditions or its sensitivity to the variation of certain characteristics (input moisture content, state determinants of the energy carriers, material flow etc.) may be wanted.

The design of a drier for a given task is essentially a *synthesis-type* system problem. In this case the influence and the expected response are given and a system susceptible of the required response is wanted. The synthesis-type problems have theoretically an *infinity of solutions*. The engineer restricts generally the set of the possible solutions by *further objectives*, by specifying further requirements for the construction, the size, the price, etc. of the equipment. The *engineering synthesis* usually approximates the solution likely to offer the expected effect by sequential analyses. Harmful disturbances may be prevented by *controlling* the drier via interference in the component processes on the basis of information feedback [6]. *The condition of an efficient and economical control is to taken the aspects of process control already in the planning stage of the drier into consideration.*

As mentioned above, the behaviour of the drier as a system is determined by the outcome of the interaction of its component units. The stationary operational characteristics of the drier developing under determined *conditions, constant in time* are called *static* operational characteristics, while the functions of the operational characteristics during the transition into a new operational state are called *dynamic operational characteristics*.

2. Principles of drier system modelling

2.1. *The model conception*

For determining the static and the dynamic operational characteristics a *model conception*, suitable to describe the behaviour of the system, is required. Simulation is greatly facilitated by recognition of principle and law affinities. *The isomorphism in transport processes* is reflected by the well-known *Onsager linearity law* stating that in *near-equilibrium states* the generalized current can be written as the product of a conductivity-type quantity, and a general thermodynamical force [4, 8, 9, 10]:

$$\mathbf{\Phi} = \frac{1}{R} X$$

The Onsager law is valid for the compensation currents of a wide range of extensives. In the case of a direct *current of electric charge*, **X** is proportional to the potential difference, R to the ohmic resistance of the conductor (Ohm's law); in case of *heat flux*, **X** is proportional to the temperature difference and R to the heat transfer resistance (Fourier's law); in the case of a macroscopic *mass flow*, **X** is proportional to the pressure difference and R to the flow resistance (Poiseuille's law) and in the case of a *diffusion mass flow* **X** is proportional to the concentration difference and R to the diffusion resistance (Fick's I^{st} law).

In the sense of the above any system accommodating transport processes, may be regarded as a network (where R is the resistance of the corresponding section of the network [4, 5, 7, 11]).

In the operation of most driers, *thermal* and *flow* processes prevail, with *energy* and *mass* as flowing extensives. Therefore the driers as systems are likely to be simulated as *mass and energy flow networks* and the static and dynamic operational characteristics determined (with an engineering accuracy) by applying the basic laws of networks [1, 2].

2.2. *The construction principles of the network model*

The network model of the material and energy flow in the drier is constructed of *elementary units* interconnected by material and energy flows.

The elements of the real system are represented by those of the network only *functionally*; e.g. from the aspect of the material flow the heat exchanger is represented only as an element of flow resistance and from the aspect of the energy current as an absorber of the passing heat transfer medium, while from the aspect of the heat absorbent medium as a heat source (applying a concentrated parameter description).

Any elementary unit may be a complex system in itself. So e.g. *in design, the heat exchanger* is treated as a composite system, but in the drier as a simple functional unit.

For the functional treatment of the elementary units the laws of the accommodated processes must be known and involved in the formulation of the *state function* of the elementary unit (e.g. pump function $\Delta p(\Phi)$, heat exchanger functions $t(\Phi)$ for both media, etc. [2, 5]).

3. Construction of the mass and energy flow network model of driers

The construction of the driers is exceedingly variegated, therefore the network model must be developed *individually for each case*. But some *general essential aspects* are to be taken into consideration in constructing a network in any case.

3.1. *Flow paths and transfer points*

The network is based on the material flow paths in the system [1, 3]. *As many flow paths are interpreted, as there are material varieties flowing in the system.* The flow paths consist of elementary units joining at nodes. In this way the network is *sectionalized* by the nodes and each section is a functional unit described by concentrated characteristics (e.g. pipe section resistances, heat transfer resistances, thermal capacities, storage capacities, etc.).

Rather than to be independent, the flow paths of each material interact at some *transfer point*, resulting in material, or energy transfer. The transfer point is a sink for the transferred material and a source for the transferring medium; e.g. the material to be dried is a moisture source for the drying air: acting in turn as a moisture absorbent from the material to be dried. In intermittent driers *the intensity of the moisture source is time-dependent* and can be closely approximated by empirical relationships suggested by FILONENKO, LIKOV KRISCHER and others for the drying rate curve [20...23].

The functions of source and sink, as well as the state functions of the elementary units may be derived by applying the operation sciences.

3.2. *Main functional units. Examples of network models*

The main functional units of the driers are [1, 2]:

1. medium transporters, pressure boosters (pumps, fans, mechanical conveyers).
2. flow pipes (resistance elements).
3. sets (transfer points: drying space, heat exchanger; mixers: mixing chamber, burning chamber, injector).
4. reservoirs (flow-through vessels, capacity flows, capacities, tanks).

The layout scheme and the network scheme of an oil-fired direct convection type drum-drier are shown in Fig. 1 as an example. The system model is based on the flow paths of three materials: the air, the fuel oil and the material to be dried. The fan V delivers the air mass flow Φ_{ml} through the flow pipe of resistance R_{E2} into the set K_1. (The burning chamber K_1 mostly receives air preheated by flue gases, therefore a heat exchanger is installed between R_{E2} and K_1. For simplicity's sake this is omitted here.) The burning chamber K_1 is a mixer-type apparatus, where the combustion heat is the heat source Φ_{h1} depending on the oil mass flow Φ_{m0} of the oil pump S_0. The flow resistance of the pump delivery line including the atomizer system is R_{E1}. The hot flue gases of mass flow Φ_{mf} flow into the drying drum K_2 to directly contact the material to be dried. The drum is generally of multiway construction with flue gas flow resistances R_{E3} and R_{E4}, which can usually be combined. The set K_2 is a transfer point, where moisture mass-flow Φ_{mn} passes from the drying material into the flue gas through the moisture transfer resistance R_N. The average partial vapour pressures on the evaporating surface of the drying material and in the fuel gas are p_{ga} and p_{gf}, resp. Simultaneously the heat transfer resistance R_{h2} transmits heat flux Φ_{h2} from the flue gas into the material.

The flow path of the material to be dried consists of the feeder-storage system $M_1 - T_1$, the drying drum $M_2 - T_2$ as material transporter and tank, and the material handling — storage system $M_3 - T_3$ collecting and removing of the dried mass Φ_{ms}.

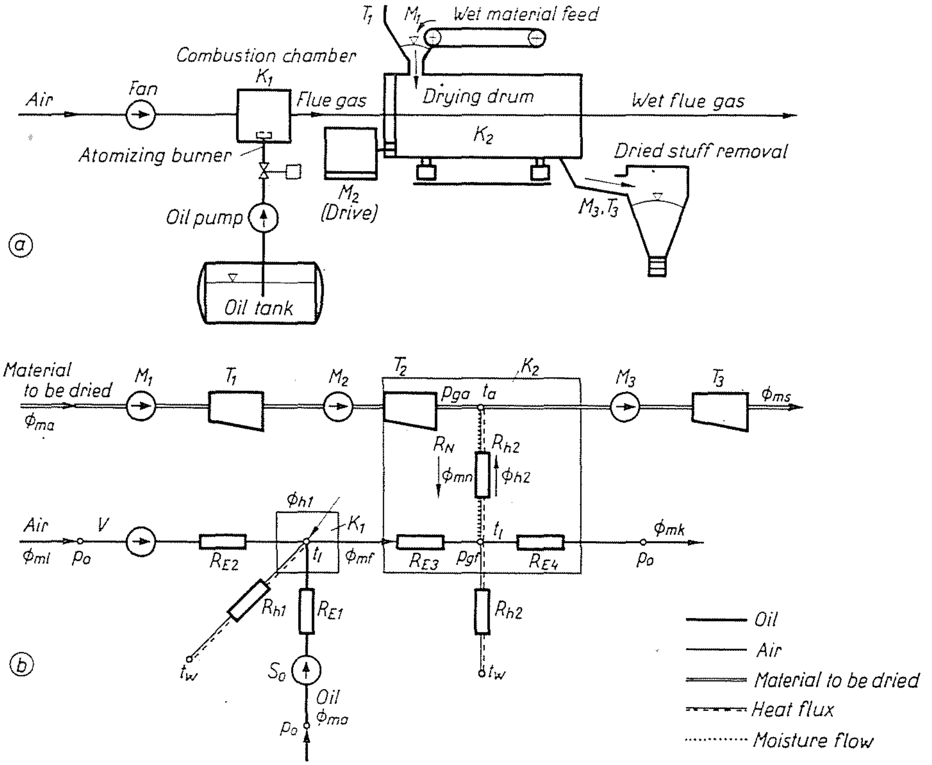

Fig. 1

If the dried product of the rotary drum-type drier is ground, briquetted, packaged, then the system is purposefully completed by the corrsponding elements.

Fig. 2 shows the layout and the network model of a *contact cylinder type drier*.

The network consists of the flow paths of three materials: the material to be dried, the heating steam and the air to remove the vapour.

The material to be dried is fed in a mass flow Φ_{ma} by the pump S_a through the pipe of flow resistance R_{E3} into the drying cylinders, i.e. into a space of atmospheric pressure p_0 (0 point in the figure). Since then, the material is conveyed by the transport drives M of the rotating cylinders, with surfaces coated by a thin layer of the material. The layer thickness, hence the mass of

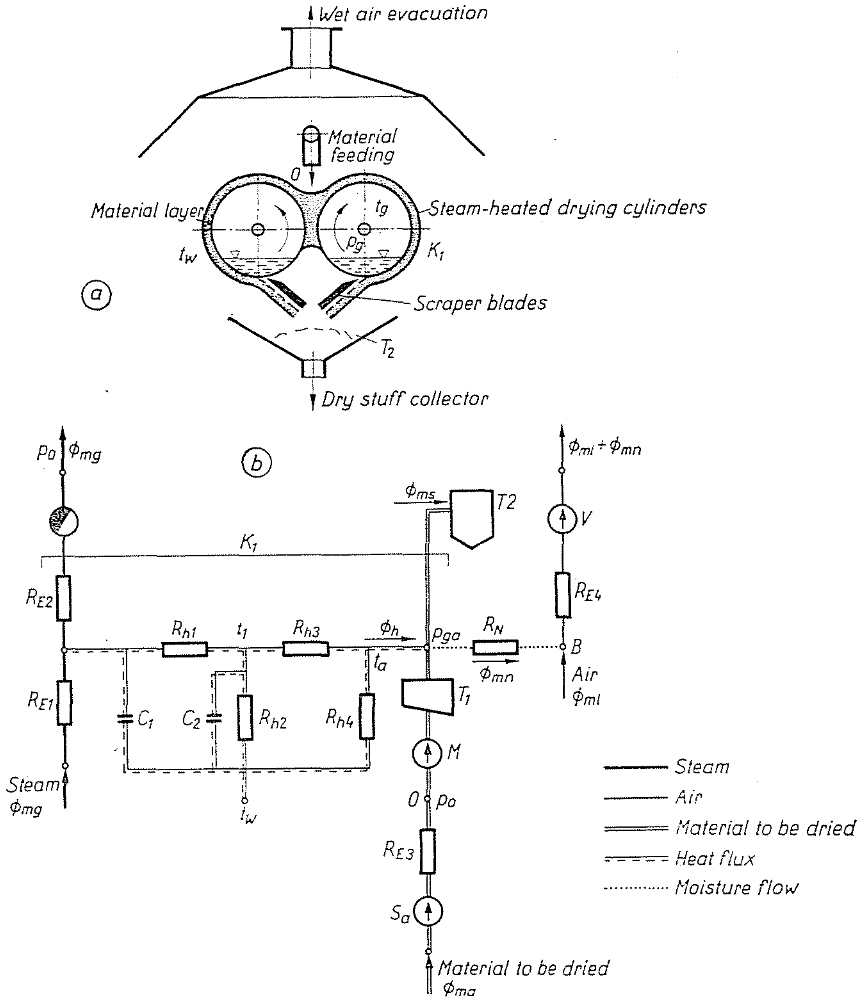

Fig. 2

the material deposited at once on the cylinders may be controlled by the rotational speed of the cylinders, so the cylinders act as a flow-through mass tanks as well (T_1).

From the steam condensed inside the walls of the drying cylinders a heat flux Φ_h passes into the material through the network RC representing the set K_1. The heat capacity of the condensate on the cylinder wall is C_1, that of the cylinder wall is C_2, the heat transfer resistance between the steam and the cylinder wall — affecting the heat loss to the ambience at t_w from the wall of average temperature t_1 — is R_{h2}, and R_{h3} is the contact resistance between the cylinder and the drying material. The thermal resistance of the cylinder wall is neglected. R_{h4} is the resistance to the heat transfer from the material surface of average temperature t_a to the environment. The dried material of mass flow Φ_{ms} is collected in tank T_2.

From the material of average partial vapour pressure p_{ga} the moisture flow Φ_{mn} passes via the moisture transfer resistance R_N into the air of partial vapour pressure p_g, removed in turn by the air flow Φ_{ml} of fan V at mixing point B.

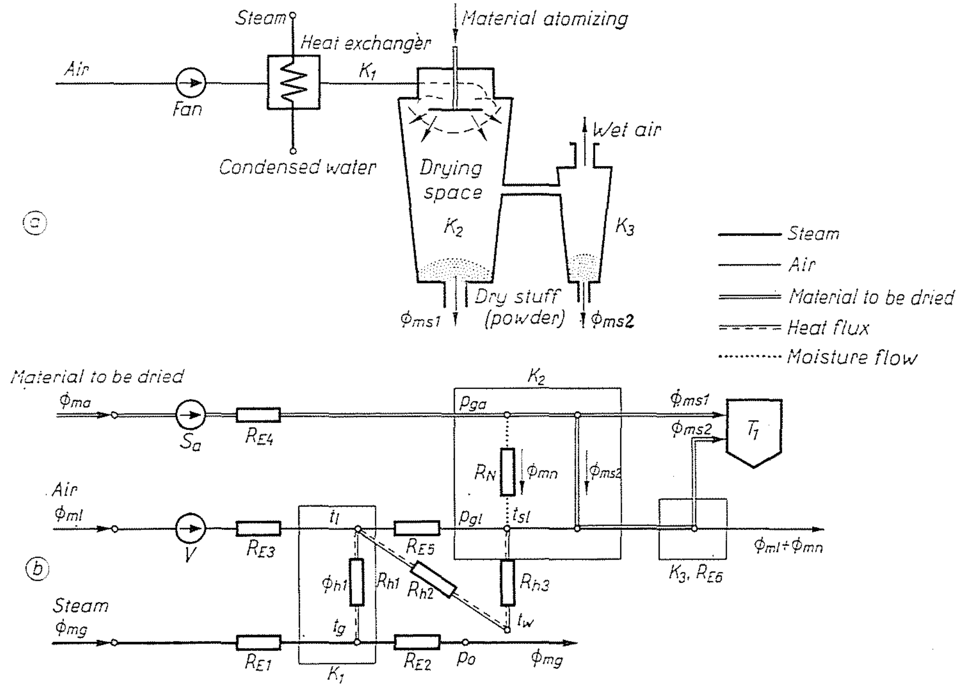

Fig. 3

Fig. 3 shows the simplified layout scheme and the network model of an *atomizing drier*.

The network consists of the flow paths of the material to be dried, the drying air and the steam.

The air mass flow Φ_{ml} of fan V passes through the pipeline of flow resistance R_{E3} into the heat exchanger K_1. R_{E3} includes also the air-side flow resistance of the heat exchanger. In the heat exchanger from the steam a heat flux Φ_{h1} gets into the air imposed by the mean temperature difference $t_g - t_l$ opposed by the heat transfer resistance R_{h1}. The heat loss of the heat exchanger is represented by the heat flux to the environment opposed by the heat transfer resistance R_{h2}.

The mass flow Φ_{ma} of the material to be dried is delivered by the pump S_a through the pipeline and atomizer of flow resistance R_{E4} into the drying space K_2, where it is mixed with air to transmit it a moisture mass flow Φ_{mn}, proportional to the moisture transfer resistance R_N. In the separator section of the drying space K_2, mass flow Φ_{ms1} of the dry material (powder) is separated from the air to get into tank T_1. The mass flow Φ_{ms2} of the fines is separated from the air by the separator cyclone K_3.

If the wall of the drying space K_2 is heated, then an additional heat transfer resistance at R_N has also be taken into account.

4. Characteristics of the mass and energy flow networks in stationary state (static examination)

4.1. *The basic laws of networks*

In stationary state, the capacitive components of the system are in charged, so the network may be treated as a resistance network.

One of the basic laws of networks is the *nodal law* (*Kirchhoff I*) of the general substance balance stating that the sum of the characteristic input and output flows of the extensives in all nodal points of the network is zero:

$$\sum_i \Phi_i = 0 \tag{2}$$

where i is the number of branches joining at the actual node (also the transfer-source-point is understood as a branch). For c nodal points in the flow paths of the actual estensive, c balance equations can be established.

The second basic law of networks is the *law of loops* (*Kirchhoff II*) stating that in every loop a flow is stabilized, of the magnitude to exactly consume the effect $P(\Phi)$ exciting and maintaining the flow. If the reduction of the effect drop $U(\Phi)$, then

$$\begin{aligned} P_1(\Phi_1 \ldots \Phi_n) - U_1(\Phi_1 \ldots \Phi_n) &= 0 \\ &\vdots \\ P_h(\Phi_1 \ldots \Phi_n) - U_h(\Phi_1 \ldots \Phi_n) &= 0 \end{aligned} \tag{3}$$

where h is the number of loops and n that of the branches in each loop. (For instance, for a mass flow the effect is the pressure difference and the effect drop is the pressure drop.)

The nodal point and loop relationships (2) and (3), resp. of the network, always permit to determine the branch flows Φ_i and, — in knowledge of the resistance functions $R(\Phi)$, — also that of the effect drops:

$$U = \Phi R(\Phi). \tag{4}$$

In the case of mass flow networks this means the determination of the flows in each branch, and of the pressure distribution.

The characteristics of the input material flow are modified by the transfer points (sets) in the network, as expressed by the *state functions* relating — the input and output characteristics [2, 5]:

$$\begin{aligned} p_{\text{out}} &= z_p(\Phi_{\text{in}}, p_{\text{in}}, t_{\text{in}} \ldots), \\ t_{\text{out}} &= z_t(\Phi_{\text{in}}, p_{\text{in}}, t_{\text{in}} \ldots). \end{aligned} \tag{5}$$

The characteristics in the state functions of the connected units are not independent, but follow self-evident *connection rules*:

$$p_{(i)\text{out}} = p_{(i+1)\text{in}}. \tag{6}$$

4.2. *The solution of the equation system*

The equation system consisting of four types of equations contains just as many relationships as needed to determine the stabilized parameter distribution of the mass flow network [5].

The resistance functions and the state functions are generally multivariable and non-linear, therefore computerized numerical solution methods are advantageous. For instance, use of a variety of the Newton—Raphson method, based on the linearization of the non-linear equation system in a restricted environment of the steady state of the network, and refining the parameter distribution by iteration [14] may be advisable.

The risk of divergence in multiple iterations increases with the quadratic number of variables. Therefore, in the case of big systems it is advised to reduce the number of variables, for instance by decomposing the equation system to virtually independent partial equation systems, e.g. the systems of nodal and loop equations, or the equation system of the state functions as the pressure drop due to the material flow is but a secondarily influenced by the temperature and the composition. Their pre-estimation offers usually an acceptable approximation in determining the branch currents and the pressure drop values. Naturally in this case the solution is also decomposed in two iteration cycles: the solution of each partial equation system, the substitution of the solutions into the original equation system and refining by iteration.

For the accuracy of the branch flow estimations there are no conditions whatever. In the knowledge of the sources the convergence is fast, even if each branch flow is assumed to be zero in the first approximation.

4.3. *Relative transfer factors*

The static analysis results in determining an output signal composition assigned to some input signal composition (Fig. 4.) This is ultimately the *marking out of a determined working point* of the drier.

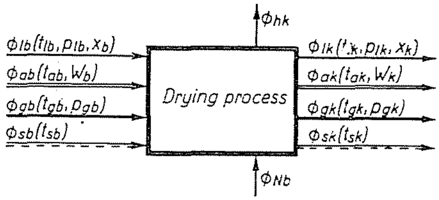

Fig. 4

If *one of the input characteristics* is modified by a definite percentage, the corresponding output characteristics will also change. The ratio of the relative changes of the output to the input characteristics yields the so-called *relative transfer factor*:

$$A_{ij} = \frac{\dfrac{\Delta X_{\mathrm{out}\,j}}{X_{\mathrm{out}\,j}}}{\dfrac{\Delta X_{\mathrm{in}\,i}}{X_{\mathrm{in}\,i}}} \, . \tag{7}$$

Although the non-linearity of the system restricts the validity of the relative transfer factors to analyze the consequences of the changes occurring *in a restricted environment of the initial state*, yet they are of use in designing the drier control system [12, 13].

The relative transfer factors represent the intensity of the interrelations between the various input and output characteristics and point out those of them, for whose changes *the system is most sensitive to react*. Their knowledge permits to designate characteristics to be varied for the greatest ease of control (intervention).

5. Dynamic properties of mass and energy flow networks

5.1. *The principle of dynamic analysis*

The *drying* of the material *is an instationary process, even under constant ambient conditions*, because the moisture content of the material varies with time. So the operation of the *intermittent* (e.g. cabinet) driers can only be described by dynamic characteristics. Under steady-state initial and ambient conditions in driers of continuous material flow (e.g. conveyor tunnels) the *local* value of the source intensity and so a stabilized (global) source intensity may prevail between the material mass flow in the drying space and the air mass flow, therefore the input and output characteristics may be constant in time.

In reality, however, the mass and energy flows entering the drier from outside, the material composition, the ambient temperature, i.e. *the initial and limit conditions of drying* fluctuate, almost permanently, and so does the parameter distribution in the network and the quality of the dried material [18, 19]. The planned control of the drier operation aims at attenuating the disturbance effects, in order to safeguard the quality of the final product. For an efficient control, the response functions of the drier to disturbances of a definite character must be known (dynamic analysis [14]).

After completing the network and the static analysis the dynamic analysis of the drier can be started in knowledge of the steady state (initial) parameter distribution.

The dynamic behaviour of the drier is composed of the *overall dynamic effect* of the units.

In this case *the state functions of the units* are differential equations (dynamic state functions), including the variables of the input and output flow functions (Φ, p, t), and in the general case their derivates of various orders.

The *coupling equations* expressing the topology of the network are algebraic equations, as also this time the phenomena are regarded to occur a concentrated within the units.

After determining the location and the nature of the disturbing functions, the equation system may be solved by any conventional integration method [2, 5, 14].

5.2. *Dynamic state functions and equations*

For a simple discussion of dynamic analyses it is useful to introduce the concept of the *flow function.* The material flow entering the unit is characterized by a function whose variables are the flow (mass, or volume), pressure, temperature, concentration, etc. The input material flow function is modified by the nature and operation of the unit, hence the output variables of the flow function generally differ from the input ones.

The dynamic analysis of a technological process is understood as the solution of the following problem: by what time functions will the flow functions $S(\Phi, p, t, c)$ of the network simulating the technological process vary, when external disturbances cause the system to deviate from its stationary state. The solution will permit to indicate the time function of the variation of the mass, or volume flow, the pressure, the temperature, etc. in different points of the network upon a definite disturbance. These functions are the response functions of the technological process to disturbances of a definite character.

The disturbances may be changes of the external, operational parameters of the network, or of the position of the intervention unit built into the process for the sake of control. The dynamic analysis are utmost difficult because of three circumstances:

1. The dynamic functions describing the units of the network are non-linear.

2. Rather than on the actual disturbance alone the response functions of the system to definite disturbances depend also on the former, initial steady state of the system.

3. Conventional analysis of rather complex networks is extraordinarily labour consuming.

The difficulty No. 2. ensues from statement 1. Because of the above difficulties, dynamic analyses advisably made according to the systematic method presented in connection with the steady state to describe the mass flow networks. The relationships should be written up in a unified manner to fit computerization.

The dynamic analysis of the technological process is also facilitated by constructing the complete mass flow network from units. The dynamic properties of a unit can be described by a differential equation to determine the change in time of the flow function at the output of the unit, in knowledge of the input flow function.

Let us denote the input and output flow functions of the unit by $u(\Phi, p, t, c, \ldots)$ and $v(\Phi, p, t, c, \ldots)$, or in short, by u and v respectively. The differential equations describing the dynamic behaviour of the unit relate the variables of u and v, i.e. connect the time functions of the input and output mass flow, pressure, temperature, etc. These equations may be formally combined in a single differential equation:

$$F(u,\ v,\ \dot{u},\ \dot{v}\ \ldots) = 0. \tag{8}$$

This differential equation includes the variables of the input and output flow functions, and in the general case their derivatives of various order.

In the canonical form we have:

$$\dot{v}_i = f_i(v_1,\ v_2\ \ldots\ v_n,\ u), \tag{9}$$

where $i = 1 \ldots n$.

The left side is the time derivative of the i-th component of the output flow function. On the right side there are no derivatives, but only p components of the output material flow function and the complete material input flow function.

In general the equations contain implicitely as independent variables, the initial values of the function u valid in the steady state (u_0). This follows from the non-linearity of the dynamic state functions of the units. With the emphasis on this circumstance the relationship runs as follows:

$$\dot{v}_i = f_i(v_1, v_2 \ldots v_n, u, u_0), \tag{10}$$

where $i = 1 \ldots n$.

In treating the dynamic conditions of mass flow networks the dynamic state function of every unit will be written in the canonical form (10).

In addition to the differential equations of type (10) also the equations expressing the topology of the network, i.e. the coupling of the flow function variables are required for determining the dynamic conditions of the network. These can be proved to be simple algebraic equations. Namely all phenomena occuring in the network are considered as concentrated in the units, so the variables of respective output and input flow functions of consecutive units are identical.

So the general form of the coupling equation is:

$$G(u_1 \ldots u_i \ldots v_1 \ldots v_j) = 0. \tag{11}$$

Accordingly the equation system describing the dynamic behaviour of the network consist of the dynamic state functions written in canonical form, and the coupling equations. On the basis of relationships (10) and (11) we have:

$$\begin{aligned} \dot{v}_{1i} &= f_{1i}(v_{11} \ldots v_{1n}, u_1, u_{10}) \\ &\vdots \\ \dot{v}_{mi} &= f_{mi}(v_{m1} \ldots v_{mn}, u_m, u_{m0}) \end{aligned} \tag{12a}$$

$i = 1 \ldots n$.

$$\begin{aligned} G_1(u_1 \ldots u_i, v_1 \ldots v_j) &= 0 \\ &\vdots \\ G_r(u_1 \ldots u_i, v_1 \ldots v_j) &= 0 \end{aligned} \tag{12b}$$

where n — number of the components of the mass flow vector
m — number of units in the network
r — number of nodal points of the network.

Thus, the dynamic equation system contains as many dynamic state functions for each unit, as there are flow function variables, and as many coupling equations as there are nodal points in the network.

By means of r algebraic (coupling) equations, the independent variable u and/or u_0 may be eliminated from the state functions. In this case the equation system (12) is transformed to miss the coupling equations and the functions u and u_0 appear only in the first m to r state functions:

$$\begin{aligned} \dot{v}_{1i} &= f_{1i}(v_{11} \ldots v_{1n}, u_1, u_{10}) \\ \dot{v}_{2i} &= f_{2i}(v_{21} \ldots v_{2n}, u_2, u_{20}) \\ &\vdots \\ \dot{v}_{mi} &= f_{mi}(v_{m1} \ldots v_{mn}) \\ & \qquad i = 1 \ldots n. \end{aligned} \tag{13}$$

This equation system is called the reduced dynamic equation system of the mass flow network.

5.3. *The dynamic analysis method*

The aim of the dynamic examination according to the above is to determine, — in the knowledge of the external disturbing functions $u(\tau)$ acting upon the technological process treated as a material flow network, and of the stabilized parameter distribution prevailing at the time of the incidence of the disturbance, — the response functions of the parameters at the various points of the network.

In the examination, of course, the dynamic state functions of the network's units are assumed to be known or producible and the static equation system to describe the network to be available. This latter is required for determining the initial values of the response functions and those assumed in the new, stabilized state.

The method is applied in the following steps:

a) The material flow network corresponding to the technological process is constructed.

b) The flow functions assigned to the initial state for each branch are calculated by the method described in the preceding.

c) The static functions of the mass flow network (resistance — pressure boosting — static state functions) are replaced by the proper dynamic state functions, i.e. the differential equations type (10) are produced.

d) Coupling equations type (11) expressing the interconnections of the units are written according to the circuit scheme.

e) Superfluous variables are eliminated by coupling equations to obtain reduced dynamic equation system type (13).

f) Position and nature of disturbing functions $u(\tau)$ are determined.

g) The equation system is solved by any conventional integration process.

The solutions supply the complete series of the required response functions.

6. Example for determining the static operational characteristics and relative transfer factors of the drier by the network method

6.1. *The circuit scheme and the network model of the tested drier*

As an example, examination of a *steam-heated convection-type textile drier* (Fig. 5) by the network method will be presented. The fabric to be dried, — very thin as compared to its width, — is passed through the tunnel-shaped drying space strained on an endless frameband. The drying air preheated in

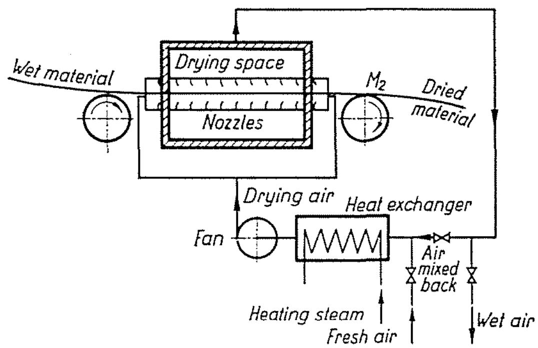

Fig. 5

the steam-heated heat exchanger is forced by a fan into the distribution pipe, to nozzles arranged on both sides of the material. Part of the wet air is released outside and fresh air is added to make it up.

According to the scheme in Fig. 4, the aim of the static examination is formulated to assign the stabilized output characteristics to the input characteristics of the material flows, i.e. the *air*, the *material to be dried*, the *steam* and the *conveyor belt*, — in the knowledge of the technological and technical characteristics of the drier.

The network scheme of the drier is shown in Fig. 6, with four material flow paths.

6.2. *The equation system describing the drier*

The static equation system of the drier modelled by the network is seen arranged in Table I. The applied notation are given in Table II. The *first group* (Eq. 1 through 4) contains the simple nodal laws of the mass flow network, the *second group* (Eqs 5 and 6) the air flow loop laws refering to the closed air circuit and the one containing the mixing space and closing in the atmosphere. In the *third group* the static state functions for the drier (Eqs 7 through 11), the mixer (Eqs 12 and 13) and the heat exchanger (Eq. 14) are written. Eq. 7 is the complete energy balance of the drier. Eqs 8 and 9 are the material balances, while Eq. 10 represents the mass flow of the moisture released into the air, as derived from the approximate relationship by FILONENKO [20] (source term). Eq. 11 is the enthalpy balance of the air, Eq. 12 the moisture-related mass balance of the mixing space, Eq. 13 the energy balance of the mixing, Eq. 14

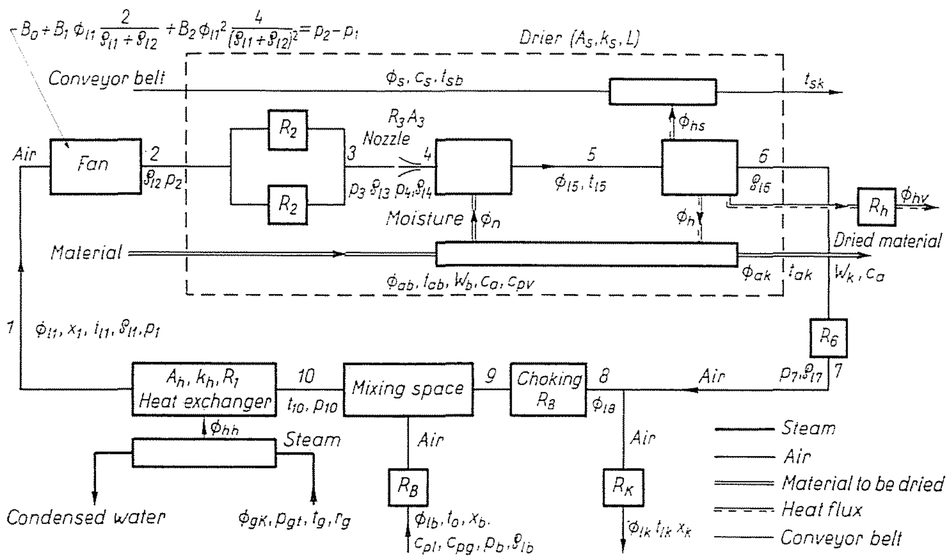

Fig. 6

the energy balance of the heat exchanger on the air side and Eq. 15 contains approximative assumptions. Substituting the drier data system into the static equation system, the output after 5–6 iteration steps was of an engineering accuracy.

The flow chart and the report in Algol language of the computer process will not be presented here (for details see [2]).

The outputs are given in Table III and the relative transfer factors in Table IV. The running time for each analysis amounts to 1.5 minutes on an ODRA computer.

6.3. *Outputs*

In the table of relative transfer factors, the sensitive relationships are marked by high numerals. The horizontal row of the headings contains the inputs, the ambient characteristics and the adjustment values of the intervention organs, while in the vertical columns the output characteristics are given.

Table I

The static equation system of the drier modelled by the network in Fig. 4

Nodal laws of the material flow network		1. $\Phi_{l1} + \Phi_{n} - \Phi_{l5} = 0$ 2. $\Phi_{l5} - \Phi_{lk} - \Phi_{l8} = 0$ 3. $\Phi_{l8} + \Phi_{lb} - \Phi_{l1} = 0$ 4. $\Phi_{ab} - \Phi_{n} - \Phi_{ak} = 0$
Loop laws of the material flow network		5. $B_0 + B_1 \frac{2}{\varrho_{l1} + \varrho_{l2}} \Phi_{l1} + \left[B_2 \frac{4}{(\varrho_{l1} + \varrho_{l2})^2} - \frac{R_2}{2\varrho_{l2}} - \frac{R_3}{2_l\varrho_3} - \frac{R_1}{\varrho_{l1} + \varrho_{l10}}\right] \Phi_{l1}^2 - \frac{R_6}{2\varrho_{l6}} \Phi_{l5}^2 - \frac{R_8}{2\varrho_{l7}} \Phi_{l8}^2 = 0$ 6. $- \frac{R_b}{2\varrho_{lb}} \Phi_{lb}^2 + \frac{R_8}{2\varrho_{l7}} \Phi_{l3}^2 - \frac{R_k}{2\varrho_{i7}} \Phi_{lk}^2 = 0$
State functions	Drier	7. $\frac{\Phi_{ab}}{1 + W_b} c_a t_{ab} + \frac{W_b}{1 + W_b} \Phi_{ab} c_{pv} t_{ab} + \frac{\Phi_{l1}}{1 + x_1} \Phi_{l1}(r_0 + c_{pg} t_{l1}) = \frac{\Phi_{ak}}{1 + W_k} c_a t_{ak} + \frac{W_k}{1 + W_k} \Phi_{ak} c_{pv} t_{ak} + \frac{\Phi_{l5}}{1 + x_k} c_{pi} t_{lk} + \frac{x_k}{1 + x_k} \Phi_{l5}(r_0 + c_{pg} t_{lk}) + c_s \Phi_s (t_{ak} - t_W) + k_s A_s (t_{l5} - t_W)$ 8. $\frac{\Phi_{ab}}{1 + W_b} = \frac{\Phi_{ak}}{1 + W_k}$ 9. $\frac{\Phi_{l1}}{1 + x_1} = \frac{\Phi_{l5}}{1 + x_k}$ 10. $\Phi_n = \frac{L/(t_{l1} - t_{l1n}) \sqrt{\frac{\Phi_{l1}}{A_3}} (W_b - W_k)}{320\left[25 \ln \frac{W_b - W_{bb}}{W_k - W_{bb}} + 75(W_b - W_k)\right]}$

Table I (cont.)

State functions	Drier	11. $c_{pl}t_{l1} + x_1(r_0 + c_{pg}t_{l1}) = c_{pl}t_{l\,\ln} + \frac{t_{l\,\ln} - D_1}{D_0}(r_0 + c_{pg}t_{l\,\ln})$
	Mixer	12. $\frac{x_1}{1+x_1}\Phi_{l1} = \frac{x_k}{1+x_k}\Phi_{ls} + \frac{x_b}{1+x_b}\Phi_{lb}$ 13. $\frac{\Phi_{ls}}{1+x_k}c_{pl}t_{lk} + \frac{x_k}{1+x_k}\Phi_{ls}(r_0 + c_{pg}t_{lk}) +$ $+ \frac{\Phi_{lb}}{1+x_b}c_{pl}t_0 + \frac{x_b}{1+x_b}\Phi_{lb}(r_0 + c_{pg}t_0) = \frac{\Phi_{l1}}{1+x_1}c_{pl}t_{10} +$ $+ \frac{x_1}{1+x_1}\Phi_{l1}(r_0 + c_{pg}t_{10})$
	Heat exchanger	14. $\frac{\Phi_{l1}}{1+x_1}c_{pl}(t_{l1} - t_{10}) + \frac{x_1}{1+x_1}\Phi_{l1}c_{pg}(t_{l1} - t_{10}) =$ $= k_h A_{h0}\left(t_g - \frac{t_{l1} + t_{10}}{2}\right)$
	Approximative assumptions	15. $t_{l5} = \frac{t_{l1} + t_{lk}}{2}$ 16. $t_{ak} = t_{l\,\ln}$ 17. $t_{l\,\ln} = D_0 x_n + D_1$ ($i - x$ diagram, linearization of the curve $\varphi = 1$ in the environment of point 1.)

One of the most important output characteristics is, the *integer moisture content of the final product* W_k. The numbers in this row show the effect of the input characteristics on W_k in the determined operational state. The *highest relative transfer* factor ($\Phi_{ab} = 4.33$) *is found in the column of the input material mass flow*. This means that a 10% variation of the input material mass flow (with other input characteristics unchanged) alters W_k by 43.3%. Also the input material moisture (W_b) and the steam temperature (t_b) effects are of importance. The other characteristics have no important effects.

Table II

Notations to Fig. 4 and Table I

Symbol	
A	surface, cross-section
B	constant
k	heat transfer rate factor
L	calculated material length
t	temperature
Φ	flow
x	air (flue gas)
r	absolute moisture content of the evaporation heat
R	resistance
W	material moisture referred to the dry mass
ϱ	mass density
c_p	specific heat at constant pressure
Subscript	
a	material
b	input
e	equilibrium
g	steam
h	heat
ho	heat exchanger
k	output
l	air
m	mass
n	moisture
hk	convective heat flux
hs	irradiation heat flux
hv	conduction heat flux
s	belt
v	water

The relative transfer factor is very low or even zero for parameters, for which the process is not very sensitive and insensitive respecting.

If several input characteristics are varied simultaneously near to the initial (calculated) operational state, then the variation of the studied output characteristic may be approximated by *superposition*. Thereby *in a limited range of the operating point*, the output characteristics for a different operational state may quickly be approximated, without recomputing the whole system.

Rather than to driers alone the presented mass and energy flow network method may be applied to other complex technological equipment.

Table III

Outputs

Symbol	Index	Measuring unit	
Φ_{lk}	1.159	kg s^{-1}	
t_{lk}	119.5	C°	drying air output;
x_k	0.1198	kg/kg	
Φ_{ak}	0.1264	kg s^{-1}	
t_{ak}	60.13	C°	material output
W_k	0.0533	kg/kg	
Φ_{gk}	0.02278	kg s^{-1}	mass flow of the condensed heating steam
Φ_{hh}	$4.62 \cdot 10^5$	W	heat flux released into the air from the drier
Φ_{hk}	44404	W	heat flow losses
Φ_{hv}	42550	W	
Φ_{hs}	1854	W	
Φ_{l1}	7.183	kg s^{-1}	
x_1	0.1023	kg/kg	
t_{1l}	164.4	C°	drying air in state 1.
$t_{l\,\ln}$	60.13	C°	
p_1	99780	N m^{-2}	
p_2	100600	N m^{-2}	pressures at positions 2 and 4
p_4	100300	N m^{-2}	
Φ_n	0.1136	kg s^{-1}	mass flow of the moisture
Φ_{l5}	7.296	kg s^{-1}	drying air in state 5
t_{l5}	141.9	C°	
Φ_{lb}	1.045	kg s^{-1}	— air intake
p_7	10020	N m^{-2}	pressure at position 7
t_{10}	106.1	C°	drying air in state 10
p_{10}	99950	N m^{-2}	

Table IV

Relative trans-

	Φ_{ab}	t_{ab}	W_b	x_b	t_0
Φ_{lb}	−0.04	0	−0.03	−0.01	−0.02
Φ_{lk}	+0.03	0	0.02	−0.01	−0.01
x_k	0.7	0	0.48	0.1	0.01
t_{lk}	−0.06	0.02	−0.16	0.01	0.02
t_{ak}	0.17	0	0.11	0.03	0
W_k	4.33	−0.01	0.74	0.06	−0.01
Φ_{hv}	−0.15	0.01	−0.09	0	−0.15
Φ_{hs}	0.25	0	0.17	0.04	−0.49
Φ_{gk}	0.39	−0.02	0.24	−0.01	−0.07

Summary

The systems approach of drier operation. Component processes, units. Engineering tasks related to the drier operation, analysis and synthesis-type system problems. The basic principles of network modelling. Construction of network models, material flow paths, functional elements, source and sink components.

The basic laws of networks. The equation system of static analysis.. The relative transfer factors. The principle of dynamic analysis.

Example for the determination of the static operational characteristics and the relative transfer factors of a textile drier by the network method.

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fer factors

t_g	R_s	R_k	R_b	Φ_{lb}	Φ_{lk}
−0.03	0.43	−0.29	−0.17	—	1.10
−0.01	0.39	−0.26	−0.16	0.91	—
0.19	−0.37	0.26	0.16	−0.86	−0.95
1.26	−0.01	0.01	0.01	−0.02	−0.03
0.22	−0.1	0.07	0.04	−0.23	−0.29
−3.14	−0.18	0.15	0.09	−0.42	−0.46
1.30	0	0	0.01	0	0
0.33	−0.16	0.11	0.07	−0.37	−0.41
0.98	0.08	−0.06	−0.05	−0.19	0.21

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