DETERMINATION OF HEAT TRANSFER COEFFICIENTS BY MEANS OF DYNAMIC CHARACTERISTICS

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A method is described for determining the heat transfer coefficients from dynamic characteristics of a heat exchanger. The appropriate equations for periodic heat exchangers are given.

In recent years there has been a considerable number of investigations devoted to the study and analysis of the dynamic properties of various industrial plants. The dynamic properties of the items under study are determined in two ways: either analytically, or experimentally, if an analytical derivation is impossible. An analytical determination (sometimes called a "breakdown") of the dynamic properties (characteristics) of the item under study consists of determining its reaction to some control action. The equation derived from experiment determines the dynamic properties of the item as an input-output channel, while the coefficients of the equation are related, naturally, to the properties of the items being examined.

The determination of the dynamic properties (in order to create an automatic control system) is usually the final objective of the investigations. Our method consists of finding the heat transfer coefficients from the known experimental and analytical characteristics. In fact, by equating the coefficients of the analytically derived equations, containing a number of heat transfer coefficients, to the numerical coefficients of the experimental equations, it is easy to obtain the heat transfer coefficients.

The proposed method is of course not in the least opposed to the thermal balance method. The dynamic characteristics of the item are none other than a reflection of the dynamics of the heat transfer process. In other words, the dynamic characteristics show how the temperature varies in a substance receiving heat when the amount of heat supplied varies (according to some law or other). While the well-known method of balance checking examines a steady heat transfer regime, the proposed method examines dynamic heat balance during transition from one steady state to another. It is therefore more convenient to investigate heat transfer in periodic heat exchangers by the method of dynamic characteristics since the heating process for the material in these equipments is itself a transition process.

For periodic heat exchangers the equation describing the dynamic relation between the thermal action (the input) and the temperature of the material being heated (the output) is of the type [1–5]

$$T\dot{t} + t = \Theta.$$

For the most general methods of heating (methods of thermal treatment), expressions have been published [2–8] for determining the time constant T of the heat exchanger (see Table 1).

To determine the heat transfer coefficients we need to calculate the true values of time constant of the heat exchanger under study, from the experimentally obtained values of material temperature and corresponding thermal input.

It is clear that in the proposed method we do not need a number of measurements connected with the direct determination of the amount of heat delivered, as is done in the thermal balance method. Such measurements, in single-phase heat transfer agents, for example, relates the temperature of the agent at the output and its flow rate, and in the induction heater—the amount of induced energy. Therefore the use of the method of dynamic characteristics confers considerable simplification of the experiment.

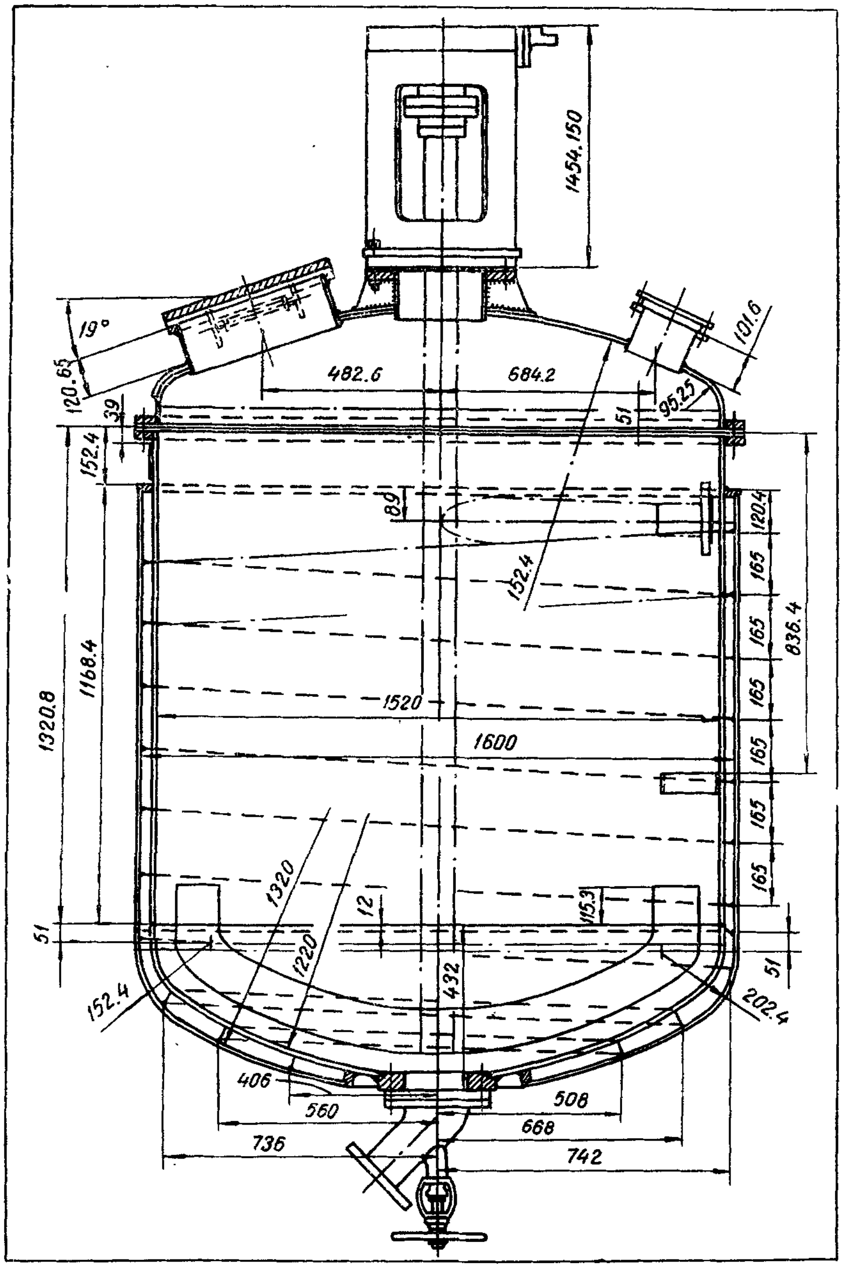
From the experimentally determined heat exchanger time constant T_e it is quite simple to calculate the heat transfer coefficients if all the remaining quantities entering into the expression for T are know (Table 1).

It is clear from the foregoing that calculation of the heat transfer coefficients by the above method is quite simple, especially if we transfer to finite differences in the initial equation. Elimination of the

Table 1

Calculation of Heat Transfer Coefficients

Method of thermal action	Thermal action, °C	Time constant, sec	Heat transfer coefficient, W/m² · °C
Saturated vapors of the heat transfer agents	t_S	$\frac{Mc}{kF}$	$\frac{Mc}{FT_e}$
Single-phase heat transfer agents	t'_T	$\frac{Mc}{W[1 - \exp(-kF/W)]}$	$\frac{W}{F} \ln \frac{WT_e}{WT_e - Mc}$
Electro-induction heating	t_W	$\frac{Mc}{\alpha F}$	$\frac{Mc}{FT_e}$



Schematic of the equipment with spherical bottom and coiled jacket.

Table 2

Time Constant of the Equipment and Values of Heat Transfer Coefficient

τ, min	t, °C	$T_e = \frac{\Delta\tau\,(t'_T - t_i)}{t_{i+1} - t_{i-1}}$, min	k, W/m²·°C	τ, min	t, °C	$T_e = \frac{\Delta\tau\,(t'_T - t_i)}{t_{i+1} - t_{i-1}}$, min	k, W/m²·°C
0	40	—	—	35	175	25.0	398
5	65	37.0	178	40	190	24.0	420
10	88	34.1	242	45	200	27.8	438
15	112	39.5	265	50	208	21.0	442
20	125	36.8	304	55	220	15.0	454
25	146	29.7	345	60	228	—	—
30	160	30.9	370				

mean temperature head from the calculation enhances the accuracy considerably, since, for periodic heat exchangers, because of the unsteadiness of the processes, the temperature head is determined from approximate formulas [9].

Therefore, there is an advantage, even on the computational side of the proposed method.

As an example we shall examine the determination of the heat transmission coefficient for an equipment with a spherical bottom and a coiled jacket (see the figure).

The volume of the equipment is 2.5 m³. The wall thickness of the cylindrical part is 9 mm, that of the bottom (spherical) part is 11 mm, and the material of the inside vessel is stainless steel. The equipment is equipped with an electrical stirrer (60 rpm). The diameter of the stirrer is 0.92 of the inside diameter of the equipment, and the distance from the stirrer to the bottom is 55 mm. The heat exchange area of the equipment is 5.5 m².

The heat transfer agent chosen was tetraarylsilicate, grade TAS-190, whose thermophysical properties are known [3].

The heating is carried out in a qualitative manner, i. e., the volume flow rate of heat transfer agent is kept constant, and therefore also its water equivalent, equal to $1.6 \cdot 10^4$ W/°C.

As the substance to be heated a mixture of sunflower oil and glycerin was used, the mass fraction of the latter being 0.382. The amount of material loaded into the equipment was 1365 kg.

The temperature of the heat transfer agent at the inlet was kept constant at 250° C throughout the whole test. The temperature of the heated material was measured every five minutes with chromel-copel thermocouples on a system with reference potentiometers. The thermocouples were attached to the equipment at various heights with a 150-mm distance between the hot junctions. The temperature of the material was determined as the mean of the thermocouple readings. The experimental data and the values derived therefrom for the time constant of the equipment and the heat transfer coefficient are given in Table 2. In determining k, allowance was made for the temperature dependence of the heat capacity of the heated material.

The error in the method is determined by the assumptions of the analytical approximation and by the experimental errors and does not exceed 10–15% in our investigations, which is fully satisfactory for engineering design.

It should be noted that the method described is also suitable for determination of mass transfer coefficients in mass transfer processes.

NOTATION

t is the temperature of the material being heated, ° C; M is the mass of the material being heated, kg; c is its specific heat, j/kg·° C; Θ is the temperature input at the heat transfer agent, ° C; t'_T is the temperature of a single-phase (liquid) heat transfer agent at the equipment inlet, ° C; t_s is the vapor condensation temperature in the equipment jacket, ° C; t_w is the wall temperature of the equipment during induction heating, ° C; W is the water equivalent of the heat transfer agent, W/° C; F is the heat transfer surface area, m²; k(α) is the coefficient of heat acquisition (or delivery), W/m² · °C; $\dot{t}$ is the derivative with respect to time, ° C/sec; T is the time constant of the heat exchanger, sec; T_e are experimentally determined time constants, sec.

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