

INVESTIGATION OF THE DYNAMICS OF HEAT AND MASS TRANSFER DURING ADIABATIC EVAPORATION

E. N. Bukharkin

UDC 536.423.1

This article presents the results of an experimental investigation of heat and mass transfer during evaporation of water by high-temperature gases and shows that the moisture-content distribution during the process follows a logarithmic rule, while the temperature distribution deviates from a logarithmic rule.

Calculations for heat exchangers are made from the heat-transfer equation $Q = KF\Delta T_{av}$, in which the average quantities K and ΔT should be used [1]:

$$(K\Delta t)_{av} = \frac{\int_1^2 c_p dt}{\int_1^2 \frac{c_p dt}{K\Delta t}}$$

Assuming $K \approx \text{const}$ and $c_p \approx \text{const}$, we derived the well-known formula for the mean logarithmic temperature difference

$$\Delta t_{av} = \frac{\Delta t_1 - \Delta t_m}{\ln \frac{\Delta t_1}{\Delta t_m}}$$

The validity of these assumptions for heat exchangers with a partition follows from the fact that the value of K is determined with average process conditions, while the heat capacity c_p changes relatively little. For example, when air is cooled from 1000 to 100°C, its heat capacity changes from 0.272 to 0.244 kcal/kg · deg C, i. e., by 10%.

The change in heat capacity in heat exchangers with direct contact between a gas and water is due both to the decrease in gas temperature and to the change in gas mass resulting from attachment (or loss) of water vapor. The influence of the latter factor depends on the mass transfer rate and can be quite substantial. Thus, air cooled from 1000 to 100°C undergoes evaporation amounting to

$$\Delta d = \frac{10^3 (c_{p1}t_1 - c_{p2}t_2)}{r} = 10^3 \frac{(0.272 \cdot 1000 - 0.244 \cdot 100)}{539} = 460 \text{ g vapor/kg air}$$

and the heat capacity of the mixture increases from $c_{cm1} = 0.272$ to $c_{cm2} = c_{p2} + 10^3 dc_{wv} = 0.244 + 0.46 \cdot 0.48 = 0.464$ kcal/kg · deg C. Hence it is clear that the assumption $c_p = \text{const}$ is inapplicable in this case and that use of the mean logarithmic temperature difference leads to errors in the calculations.

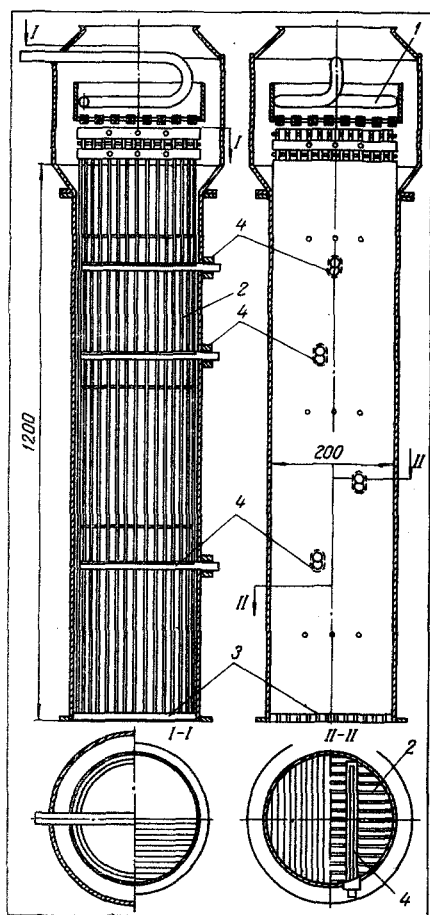


Fig. 1. Experimental column: 1) sprinkler; 2) sheets; 3) supporting framework; 4) thermometer sleeves.

K. D. Pamfilov Academy of Communal Economy, Moscow. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 17, No. 6, pp. 999-1004, December, 1969. Original article submitted January 6, 1969.

© 1972 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

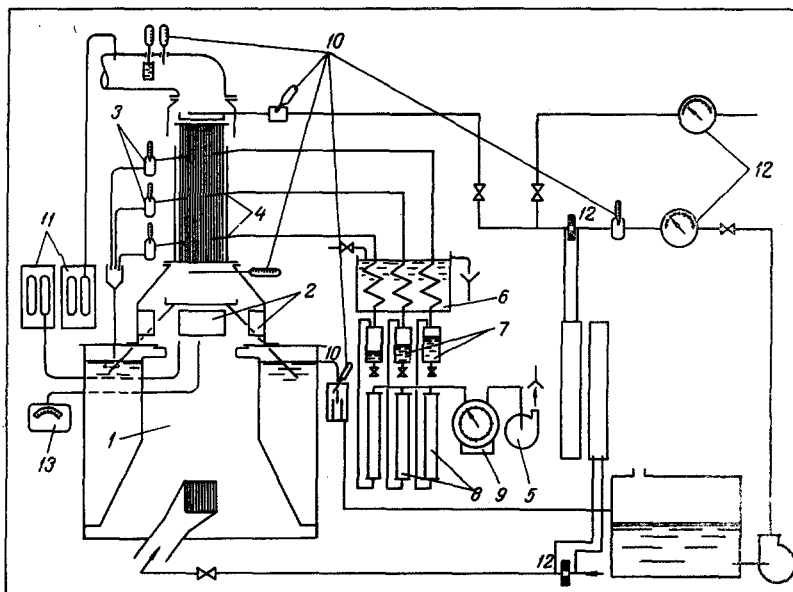


Fig. 2. Experimental apparatus: 1) gas heaters; 2) air ports; 3) thermometer sleeves; 4) gas-sampling probes; 5) vacuum pump; 6) condensers; 7) burettes; 8) flow meters; 9) gas meters; 10) thermometers; 11) gas analyzers; 12) water meters; 13) pyrometer.

TABLE 1. Design Data for Apparatus and Experimental Regimes

Column diameter and height, mm	Heat-exchange surface, m	Temperature		Gas flow speed, m/sec	Reg	Sprinkling rate, kg/m ² ·h	Initial difference in	
		gas	water				moisture content, g/kg	temperature °C
d=200 H=1200	4,2	155-1300	55-83	0,80-4,3	900-3500	350-370	90-610	105-1220

Assuming that relatively cold vapor attached to the gas causes additional cooling, we would expect the temperature curve for a gas cooled in contact with water to lie below that for heat exchange through a partition. There should accordingly be a redistribution of the gas temperature along the length of the heat exchanger.

In view of the difficulty of obtaining an analytic function for the true temperature distribution along a heat exchanger, we made an experimental study of the temperature and gas moisture content distributions under adiabatic vaporizations conditions.

The experimental apparatus consisted of a column (Fig. 1) containing vertical aluminum sheets 1.0 mm thick, which formed slits 9 mm wide. Hot water was poured over the sheets from above, its temperature being given by a wet thermometer. At the upper end of the sheets was a special sprinkler, which ensured uniform wetting of the sheets and complete coverage of their surface with a water film. Hot gases from the heater 1 were admitted at the bottom of the column (Fig. 2). The gas temperature was regulated by mixing in atmospheric air through special ports 2. In order to monitor the water temperature along the height of the column, there were five thermometer sleeves 3 with a longitudinal slit along the upper part; in order to avoid overheating by the gases, the lower portion of each sleeve was protected by a screen with apertures for water flow. In order to determine the moisture content, there were five gas probes 4, through which gases could be drawn off by vacuum pump 5 through condenser 6 for condensation of the vapor. The resulting condensate ran into measuring burettes 7 and the purified gas was supplied to a vacuum pump through flow meters 8.

In order to obtain samples, the apertures in the gas-sampling probe were uniformly distributed over the column cross section, each in the center of a slit. The experimental pumping rate was less than the maximum for removal of water drops with the gas; in order to obtain complete reliability, the probes were tilted toward the sampling points. The basic design data for the apparatus and the experimental regimes

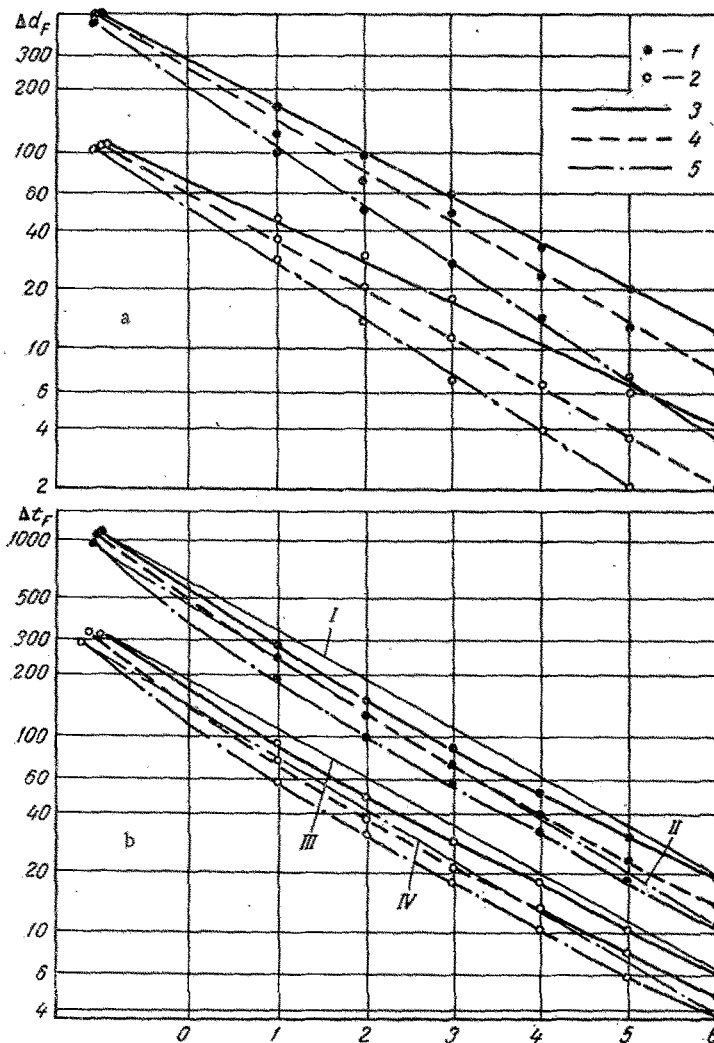


Fig. 3. Progressive differences in moisture content along height of column. a: 1) $\Delta d_0 = 450-500$; 2) $100-120 \text{ g/kg}$; 3) $Re_g = 3500-3700$; 4) $2000-2200$; 5) $1200-1300$; b: 1) $\Delta t_0 = 950-1000$; 2) $300-330$; I, II, III, IV) logarithmic functions. The other symbols are analogous to those used in Fig. 3a. The figures along the abscissa represent measurement points.

TABLE 2. Comparison of Calculated Mean Logarithmic and Experimental Differences in Moisture Content (1) and Temperature (2) of Heat-Transfer Agents during Adiabatic Evaporation

$\Delta d_0, \Delta t_0$	Re_g							
	1000		2000		3000		4000	
	I	II	I	II	I	II	I	II
1. (Δd_{av})								
500	104	102	120	121	128	126	140	139
350	73	70	83,5	82	90	92	100	104
200	42	43	46	45	51,5	50	57	55
100	24	23,5	26	26,5	28,5	27	31,5	31
2. (Δt_{av})								
1200	255	187	271	199	283	210	294	222
800	171	132	183	144	190	150	197	152
500	107	88	113	91	119	101	123	106
200	47,5	40	51	43,1	55	47	58	51

Note. I) Calculated data, II) experimental data.

are shown in Table 1. The experimental results are given in Fig. 3a and b. Figure 3a shows the progressive heat differences in heat-transfer-agent moisture content $\Delta d_F = d^n - d_g^F$ for different measurement points. The experimental points coincided well with a straight line of semilogarithmic coordinates, satisfying the equation

$$\Delta d_F = \Delta d_0 \exp\left(-\frac{\beta F}{G_g}\right).$$

As can be seen, the initial difference $\Delta d_0 = d^n - d_g^0$ lay to the left of the initial column cross section, since the working process began at the bottom (see Fig. 2), where the water from the column ran.

Figure 3b shows the corresponding progressive temperature differences. As can be seen, these points did not form a straight line corresponding to an exponential function on semilogarithmic coordinates; the greatest deviation was characteristic of the initial stage of the process. The reduction in temperature due to heating of the captured vapor to the mixture temperature had the greatest effect in this zone.

As the gas cooled and its mass increased, the relative proportion of the heat required to warm the vapor to the mixture temperature decreased and the temperature curve approximated to the logarithmic curve.

Table 2 compares the mean logarithmic and experimental values for the differences in heat-transfer-agent moisture content and temperature.

As can be seen, the experimental values of Δd_{av} were close to the mean logarithmic values, while the experimental Δt_{av} were somewhat less than the calculated values.

NOTATION

c_p, c_{wv}	are the heat capacities of dry gas and water vapor, kcal/kg · °C;
d^n, d_g^0, d_g^F	are the saturation moisture content at water temperature and initial and current gas moisture contents, g/kg;
$\Delta d_0 = d^n - d_g^0, \Delta d_F = d^n - d_g^F$	are the initial and current difference of moisture contents of heat transfer agents, g/kg;
d_e	is the equivalent diameter, n;
F	is the heat and mass transfer surface, m ² ;
G_g, G_v	are the flow rate of dry gas and vapor, kg/h;
K	is the heat transfer coefficient, kcal/m ² · °C · h;
Q	is the amount of heat transferred, kcal/h;
Δp_{av}	is the mean difference of vapor partial pressures, atm;
r	is the latent heat of condensation, kcal/kg;
w	is the mean velocity of mixture, m/sec;
$t_1, t_2, \Delta t_0, \Delta t_{av}, \Delta t_1, \Delta t_m$	are the initial and final gas temperatures; initial, mean, large, and small temperature differences, °C;
β	is the mass transfer coefficient, kg/m ² · atm · h;
ν	is the viscosity, m ² /h;
Re_g	is the Reynolds number for gas.

LITERATURE CITED

1. T. Khobler, Heat Transfer and Heat Exchangers [in Russian], Goskhimizdat (1961).