ANALYSIS OF THE HEAT AND MASS TRANSFER DURING ADIABATIC EVAPORATION OF WATER

E. N. Bukharkin

UDC 536.248.2

The results of an experimental investigation of the heat and mass transfer during evaporation of water are presented and it is shown that within the range of Gu from 0.22 to 0.76 the rate of the transfer processes increases with increasing Gu.

Several earlier studies have been concerned with the heat and mass transfer during adiabatic evaporation [1, 2, 3, 4, 6], mainly in connection with the drying process where gases at moderate temperatures not above 300°C are used. The present study is concerned with adiabatic evaporation within the temperature range 200-1000°C. Higher gas temperatures result in high evaporation rates, which makes it possible to take into account the effect of evaporation on the heat and mass transfer over a wide range of variation in the thermophysical parameters.

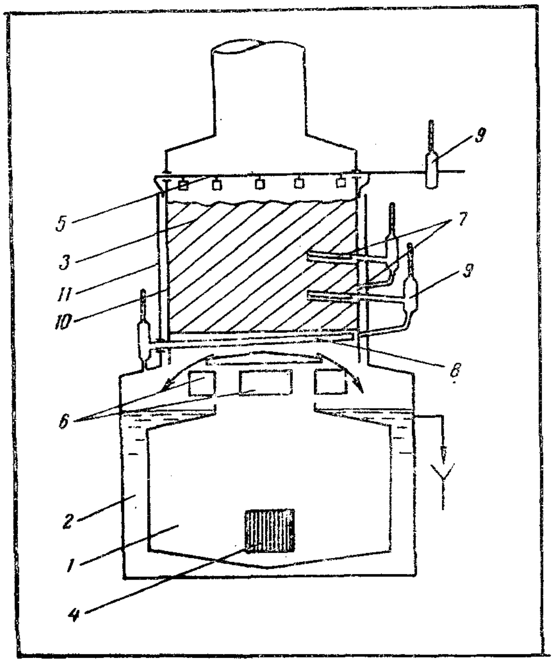

Fig. 1. Schematic diagram of the test apparatus.

The test apparatus (Fig. 1) for this study was made up of a furnace 1 surrounded by a jacket 2 and surmounted by a contact column 3.

Natural gas was used as fuel of the burner (4), and the flue gases were partially cooled while passing through the column 3 filled with a stack of Raschig rings 500 mm high. The rings were 25 × 25 × 3 mm in size. Water coming through holes in collector 5 drenched the ring stack from above and ran off the column into the water jacket 2.

The basic parameters were varied within the limits shown in Table 1.

The tests were performed with gases entering the contact zone at temperatures within the range 150-1000°C. In order to vary the temperature over still wider limits, regulating orifices 6 for passing atmospheric air to the gases were provided.

The test data in [1] concerning the humidification of gases at moderate temperatures were correlated in terms of the Gukhman number Gu = $(T_s - T_m)/T_s$ or the ratio T_s/T_m. Subsequent analysis has justified this approach, since the two parameters are linearly related

TABLE 1

Temperature of gases before column, °C	Initial humidity of the gases, kg/m^3	Reynolds number for the gases	Velocity of gases, m/sec	Temperature of water, °C	Ring stack drenching rate, m^3/m^2·h
165—1010	0,04—0,17	120—590	0,31—1,35	47—83	20

All-Union Correspondence Polytechnical Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 21, No. 6, pp. 1074-1078, December, 1971. Original article submitted June 15, 1970.

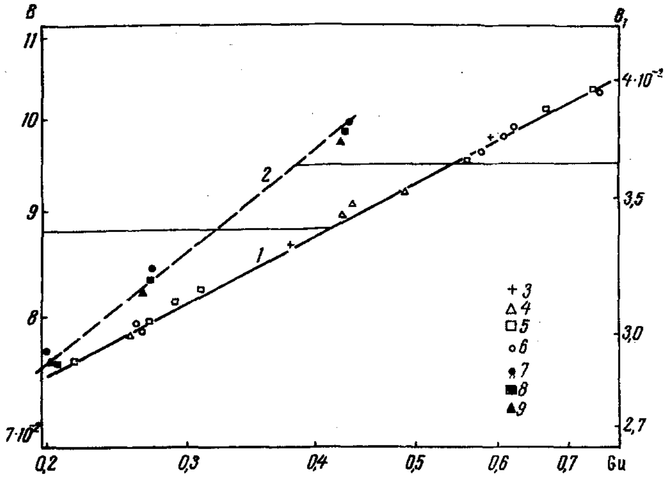

Fig. 2. $B = \mathrm{NuRe}_G^{-0.9}\mathrm{Pr}^{-0.33}$ and $B_1 = \mathrm{Nu_T R}_G^{-0.7}\mathrm{Pr}^{-0.33}$ as a function of the Gu number: 1) our test data; 2) [4]; 3) Gu = 0.22; 4) 0.40; 5) 0.58; 6) 0.76; 7, 8, 9) from [4].

within the range of moderate temperatures (T_s = 30-170°C) and it is correct to use either of them in this case. At elevated temperatures, however, the relation between Gu and T_s/T_m deviates increasingly from linearity and even from a power law (i.e., both in ordinary and in logarithmic coordinates it is not linear). For this reason, within the range of high gas temperatures only one of these parameters may be used. In our case it was preferable to evaluate the test data in terms of Gu. Indeed, if according to [1, 3]

$$\mathrm{Nu} \equiv \left(\frac{T_s}{T_m}\right)^{1.65-2.0},$$

then the heat and mass transfer will be 3.5-4.0 times greater at T_s = 900-1100°C than at moderate temperatures. This is because the increase of T_s/T_m with increasing T_s is almost linear, since T_m increases very little.

The dependence of $\mathrm{NuRe}_G^{-0.9}\mathrm{Pr}^{-0.33}$ on Gu according to our data, and the analogous relation for $\mathrm{NuRe}_G^{-0.7} \cdot \mathrm{Pr}^{-0.33}$ obtained from an analysis of the data in [4] relating to gas humidification at t = 110-370°C are shown in Fig. 2. This relation fits the equation:

$$\mathrm{Nu} = 0.1125\,\mathrm{Re}_G^{0.9}\mathrm{Pr}^{0.33}\mathrm{Gu}^{0.27}. \tag{1}$$

The data in [4] yield the following qualitative relation: $\mathrm{Nu} \equiv C\,\mathrm{Gu}^{0.35}$.

Correspondingly, for mass transfer:

$$\mathrm{Nu}_D = 0.054\,\mathrm{Re}_G\,\mathrm{Pr}_D^{0.33}\mathrm{Gu}^{0.24}. \tag{2}$$

The tests were performed according to the following procedure. Hot water at the required temperature was used to drench the ring stack. The temperature of the gases entering the column was then regulated through the orifices 6 until the temperature of the water entering and leaving the column had become the same. This condition ensured pure evaporation of the water in the column.

Sampling probes 7 were installed for checking the water temperature along the height of the column and the water trapped for this purpose ran into the thermometer wells through a spider spout 8.

In order to reduce the heat dissipation and to ensure adiabaticity of the process, the column jacket was made up of a double layer (10, 11). Part of the water from the supply collector was tapped off for drenching the outside surface of the inner jacket 10, covering it with a thin film and thus providing in addition a water jacket. Furthermore, in order to prevent any contact between hot gases and the wall and to lower its temperature, some of the drench water was in a similar manner spread over the inside surface of the working column 10. All this reduced to a minimum the heat losses into the surrounding atmosphere. According to samples taken, the water temperature did not drop by more than 0.05°C while the water was passing through the column (in still air).

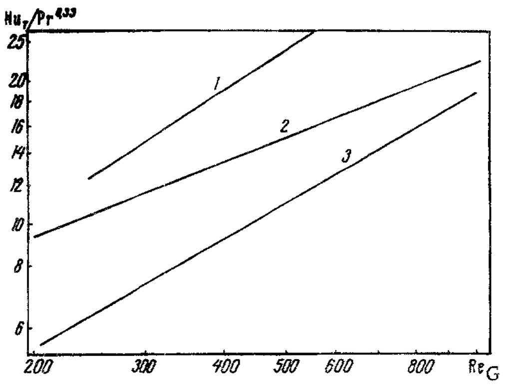

Fig.3

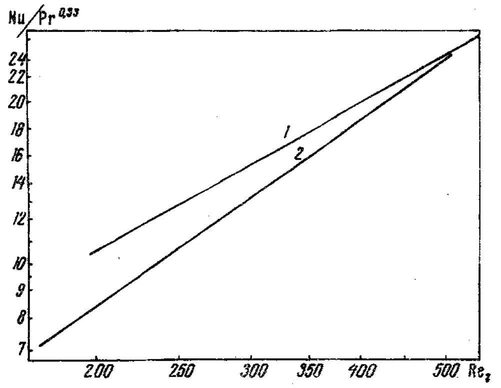

Fig.4

Fig.3. Comparison of test data on heat transfer: 1) our test data; 2) [5]; 3) [6].

Fig.4. Comparison of heat- and mass-transfer numbers, based on the results of this study: 1) Nu; 2) Nu_D.

An analysis of the test data on heat and mass transfer has shown that the rates of both processes depend not only on Re_G but also on the gas temperature.

Notwithstanding the high gas temperatures, the relation established here does not reflect any influence of radiation on the rate of heat and mass transfer. This is explained in that the effective thickness of the radiating layer in the column with Raschig rings was very small and the effect of radiation was insignificant.

The test results are compared in Fig.3 with earlier data shown in [5, 6]. The data in [5] refer to the cooling of dry air without attendant mass transfer, the data in [6] refer to the humidification of gases at a moderate temperature (t = 80°C). As the rate of mass-transfer increases, according to the graph, so does the rate of heat transfer.

In Fig.4 we show the dependences of the averaged values of Nu and Nu_D (for Gu = 0.45) on Re_G obtained in this study. Although there is no analogy between the two numbers, their values are rather close. This can be explained in that, qualitatively, they both are almost equally dependent on the Gu number.

NOTATION

a	is the thermal diffusivity, deg/m · h;
D	is the kinematic diffusivity, m^2/h;
d_e	is the equivalent diameter, m;
w	is the gas velocity, m/sec;
α, β	are the coefficients of heat and mass transfer, respectively, $kcal/m^2 \cdot deg \cdot h$, $kg/m^2 \cdot A \cdot h$;
λ_G	is the thermal conductivity, kcal/m · deg;
ν	is the viscosity, m^2/h;
$Gu = (T_s - T_m)/T_s$	is the Gukhman number;
T_s	is the temperature of the hot gas stream;
T_m	is the temperature of the moist surface;
δ	is the dynamic diffusivity, kg/m;
$Nu = \alpha d_e/\lambda_G$	is the heat-transfer number;
$Nu_D = \beta d_e/\delta$	is the mass-transfer number;
$Re_G = wd_e/\nu$	is the Reynolds number;
$Pr = \nu/a$	is the Prandtl number for heat transfer;
$Pr_D = \nu_G/D$	is the Prandtl number for mass transfer.

LITERATURE CITED

1. G. T. Sergeev, Inzh.-Fiz. Zh., No.2 (1961).
2. A. V. Nesterenko, Zh. Tekh. Fiz., 24, No.4 (1954).
3. B. M. Smol'skii, External Heat and Mass Transfer in Convective Drying Processes [in Russian], Minsk (1957).

4. W. H. McAdams and J. B. Pohlenz, Chem. Engr. Progr., 45, No. 4, 241 (1949).
5. N. M. Zhavoronkov, Hydraulic Principles of the Scrubbing Process [in Russian], Sovetskaya Nauka, Moscow (1944).
6. R. G. Taecker and O. A. Hougen, Chem. Engr. Progr., 45, No. 3, 188 (1949).