EQUILIBRIUM MOISTURE CONTENT OF MATERIALS IN VAPOR AND VAPOR-AIR ENVIRONMENTS

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Results are presented of experimental measurements of the equilibrium moisture content of fabrics in vapor and vapor-air environments. It is shown that it is possible to determine the equilibrium moisture content of a material in a steam environment at any temperature and pressure from test data relating to moist air.

In such textile processes as drying, moistening, steaming, and fixation of dyes, heat exchange takes place between the material and a vapor or vapor-air medium, the rate depending on how far the given hygrothermal state of the material is from the state of equilibrium with the surrounding medium that the material is from the state of equilibrium with the surrounding medium that the material will reach on completion of the process. In the equilibrium state the material has a certain, so-called equilibrium, moisture content, depending on the parameters of the medium and the properties of the material. While there is sufficient test material on equilibrium moisture content values in moist air up to 373° K [1], there are no data relating to processes occurring in a steam environment.

The present article reports results of an experimental determination of equilibrium moisture content of certain fabrics in vapor and vapor-air environments at different temperatures.

The investigations show that when the dry material is located in superheated steam, moistening of the material occurs, just as in moist air, and a definite moisture content equilibrum is established after a certain time. The rate of moistening in a steam environment is one or two orders higher than it is in moist air. Moistening is not completed in saturated steam even at a high moisture content of the material, when there is already capillary moisture in the material. During moistening in saturated steam, considerable fluctuations are observed in the rate of moistening of the cloth, which may be due to the fact that because of instability of the state of the dry saturated steam, the latter is practically always supercooled or superheated.

In superheated steam a quite definite value of equilibrium moisture content of the material is attained, depending on the steam temperature and the initial moisture content of the material. When very moist cloth is placed in steam, there is partial loss of moisture by the cloth, resulting in the establishment of a greater equilibrium humidity of the cloth than when dry cloth is placed in steam. The desorption process is not only observed when very moist cloth is placed in steam. Cold cloth condenses moisture when placed in steam, and may become moistened because of this to a humidity exceeding the equilibrium humidity for steam of the given temperature. Following the initial overmoistening due to condensation, a desorption process ensues.

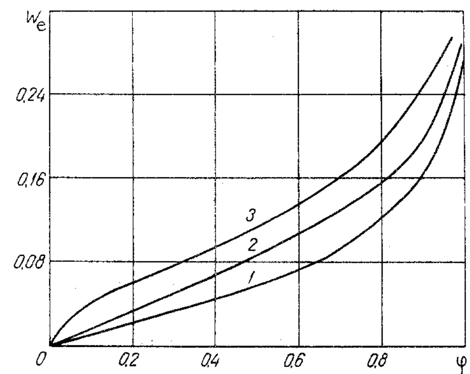

Fig. 1. Dependence of equilibrium moisture content W_e (kg/kg) of rayon staple cloth on relative humidity φ: 1) sorption in vapor; 2) desorption in vapor; 3) sorption in air at 293° K.

The equilibrium moisture content of cloth located in steam is higher, the closer the steam temperature is to the saturation temperature at the given pressure.

It is known that the equilibrium humidity of a material in air depends on the air humidity and temperature. Usually the content of water vapor in the air is described by the relative humidity of the air or by the degree of saturation φ, defined as the ratio of the partial pressure of vapor in the air to the saturated vapor pressure at the same temperature, the saturation pressure usually being regarded as constant, equal to atmospheric pressure, for temperatures above 373° K. For this reason the lines φ = const on Ramzin's I-d diagram for moist air undergo a discontinuity at 373°. There are however no discontinuous changes in the properties of a vapor-air mixture in going from the temperature region below 373° to that above 373°. The question of the correct definition of φ should be given special attention. Together with the temperature, the relative humidity φ determines the energy of the moisture bond, which is important for elucidating the form of the bond of the moisture with the material. The mass transfer potential of a substance is also expressed in terms of the relative humidity and the temperature.

Our experimental data show that the basic laws of the processes of sorption and desorption, established for the temperature region up to 373° also hold for the region above 373°, as well as for a pure vapor environment, if relative humidity is assumed to be defined as the ratio of the pressure of the vapor to that of the saturated vapor at the given temperature, without limiting the latter to the value of the total pressure of the environment.

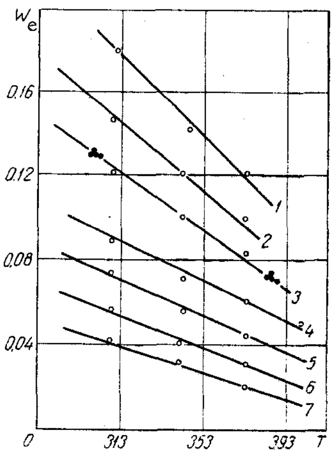

Fig. 2. Dependence of equilibrium moisture content of rayon fiber on temperature T (°K) and relative humidity φ of the environment: 1) φ = 0.8; 2) 0.7; 3) 0.6; 4) 0.4; 5) 0.3; 6) 0.2; 7) 0.1.

Figure 1 shows the relation $W_p = f(\varphi)$, where φ is determined for a vapor environment as the ratio of the vapor pressure (for our tests this is atmospheric pressure) to that of saturated steam at the same temperature. With increase of temperature the equilibrium moisture content at the same value of relative humidity diminishes. For this reason the equilibrium moisture content during sorption from air at 293° K is greater than during sorption from a vapor environment. Curve 3 is a sorption isotherm. Curves 1 and 2 are not isotherms, since the process of attainment of an equilibrium state in this case proceeds in a vapor environment of different temperature (375° K and above).

Figure 1 shows that the equilibrium mosture content of cloth in a vapor environment varies with variation of φ in a similar way to the variation of moisture content of cloth in air. The discrepancies between the curves of equilibrium moisture content in the vapor and vapor-air environments are due to the influence of the different temperatures at which equilibrium is established.

Figure 2 presents the test data on variation of equilibrium moisture content of rayon at constant relative humidity φ as a function of temperature on the test materials cited in [1]. The points labelled by solid circles refer to rayon fabric in our tests, the environment being pure steam at 388° K. These points fall on the same line of variation of equilibrium moisture content that joins the test points for moist air. Therefore, to determine the equilibrium moisture content in a vapor environment, we may use the existing data on equilibrium moisture content of materials in a vapor-air environment introducing only the corrections for temperature.

For example, it is required to determine the equilibrium moisture content of acetate silk in superheated steam at atmospheric pressure and a temperature of 388° K. In this case

$$\varphi = \frac{1 \cdot 10^5}{1.68 \cdot 10^5} = 0.6$$

($1 \cdot 10^5$ N/m^2 is the vapor pressure; $1.68 \cdot 10^5$ N/m^2 is the pressure of saturated steam at 388° K).

From the tables of equilibrium moisture content [1] for acetate fiber in a sorption process with φ = = 0.6, the equilibrium moisture content at 373° K is 0.0435 kg/kg of dry material, and at 323° it is 0.0526 kg/kg, i.e., 4.35 and 5.26%, respectively.

Assuming a linear dependence of moisture content on temperature, we determine the equilibrium moisture content in superheated steam at 388° K:

$$W_{e_2} = W_{e_1} - k(T_2 - T_1) =$$
$$= 4.35 - \frac{5.26 - 4.35}{373 - 323}(388 - 373) = 4.08\,\%.$$

For a number of materials there is practically no dependence of equilibrium moisture content on temperature. In this case, with an accuracy sufficient for practical purposes we may determine the equilibrium moisture content in a vapor environment from the value of φ alone, without bringing in a correction for temperature.

Thus, the properties of a vapor environment in sorption and desorption processes are described in the same way as those of moist air; the relative humidity is φ, if in defining $\varphi = p_V/p_S$ we take the pressure of the saturated steam p_S as dependent only on the temperature of the environment, independently of the total pressure.

At present drying of yarn on bobbins is often accomplished in drying machines in which the drying environment is superheated steam at a pressure of $5 \cdot 10^2$–$12 \cdot 10^5$ N/m^2 (5–12 atm). Using the above-mentioned postulate, we may determine the equilibrium moisture content even for these conditions, taking account of the data available in the literature on equilibrium moisture content of this material in air.

On the I-d diagram for moist air which we used, in the temperature region above 373° K the lines φ = = const are vertical, since the saturation pressure in this case is equal to the barometric. The equilibrium moisture content of the material in any temperature range retains the same nature of dependence on relative humidity of the vapor-gas mixture under another definition of humidity. In determining $\varphi = p_V/p_S$ it will evidently be more correct not to put in the condition of limiting the saturation pressure to the value of the total environmental pressure. This kind of definition of φ has been assumed by a number of investigators [2, 3].

When examining conditions of equilibrium of vapor and a liquid bonded to the solid skeleton of a material at some moisture content or other, we may note the following analogy.

Variation of the difference of temperature of equilibrium of moist material and of free water (i.e., saturation temperature in the latter case) with vapor of a given pressure (which may be also a partial pressure in the case of a vapor-air mixture) a similar variation occurs of difference of boiling temperature of solutions and of the pure solvent (the so-called temperature depression). The treatment of test data given above shows that there is an analogy of the Babo law (i.e., for a given concentration of solution $\varphi = A = \text{const}$) and the corrections of Stabnikov's law (i.e., A depends somewhat on temperature differently for different solutions, to a greater or lesser degree).

NOTATION

p_s) pressure of saturated steam; T) ambient temperature, °K; p_v) vapor pressure (partial pressure of vapor for a vapor-air environment); φ) relative humidity of the vapor-air mixture; w) moisture content of material; W_e) equilibrium moisture content.

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