WATER VAPOR TRANSFER COEFFICIENTS FOR CALCULATING THE MOISTURE CONDITIONS IN WALLS

V. M. Il'inskii

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Data are given on the computation of surface moisture transfer coefficients and vapor permeability coefficients for the diffusion of water vapor through walls. The theoretical results are compared with the available experimental values.

In the building physics literature it is usually assumed that the surface resistance to transfer of moisture in vapor form is zero or insignificant [4, 2].

Field and laboratory data, however, indicate that this resistance varies quite strongly as a function of the relative humidity of the room air and that these variations are one of the reasons for the discrepancy between the theoretical and actual values of the moisture contents of walls and other elements of buildings.

Thermodynamic equilibrium between the processes of evaporation and adsorption (condensation) *may be expressed by the Clapeyron-Clausius equation:

$$T\left(\frac{dp_s}{dT}\right)(V_V - V_l) = r. \tag{1}$$

The integral of this equation, which expresses the law of the process of evaporation under conditions remote from the condensation point, gives the following relation for the total work of adsorption in the isothermal regime:

$$A = RT\int_{V_1}^{V_2}\frac{dV_0}{V_0} = RT\ln\frac{V_1}{V_2} = RT\ln\frac{p_{s'}}{p_u}. \tag{2}$$

This reasoning has been further developed by Academician P. A. Rebinder [1].

Moisture transfer resistance will depend not only on the conditions of motion of the air near the wall but also on the energy level necessary for equilibrium adsorption of the molecules of water vapor at the surface of the pores and capillaries of the boundary zone of the material.

Until this level is exceeded, as a result of a decrease in the heat transfer coefficient and the related fall in wall surface temperature or an increase in the partial pressure of water vapor in the boundary layer of air, the process of wetting by diffusion of water vapor through the thickness of the material can not continue.

On the basis of the expression for the total work of adsorption, it is possible to determine the moisture transfer resistance at the surface of a wall through which water vapor is diffusing. In order to obtain the moisture transfer resistance, it is necessary to divide (2) by the corresponding value of the heat transfer coefficient at the surface. This heat transfer is the result of air bathing the surface of the wall, and therefore from the viewpoint of dimensionality, the coefficient should correspond not to the ordinary heat transfer coefficient α_W but to the quantity $\alpha_W/c\gamma$.

According to Lewis' data, as corrected by Schmidt [3], this coefficient $\alpha_\beta = 3.72\,\alpha_W$ m/hr.

If on the basis of the experimental data we take $\alpha_W = 5.0 \times 1.163$ watt/m^2 · deg**, then $\alpha_\beta = 18.6$ m/hr.

This can be used as a transitional value in determining the moisture transfer coefficients on the basis of the above mentioned energy level of the total work of adsorption. Then the moisture transfer resistance may be defined as follows:

$$R_{i.v} = RT\ln\frac{p_s}{p_u}\,\frac{1}{\alpha_\beta}. \tag{3}$$

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* Adsorption equilibrium is completely analogous to equilibrium of the condensed phase and its vapor, if the surfaces at which adsorption and evaporation take place are equivalent [9].

** Value obtained in tests conducted in a room about 2.8 m high with a controlled climate. Coefficient varies with the geometry of the test element.

In [3] $R_{i.v}$ is determined from an expression of the form:

$$R_{i.v} = RT\frac{1}{\alpha_\beta}. \tag{4}$$

The dimensionless term p_s/p_u, which takes into account the adsorption energy level, has been omitted and values of the moisture transfer resistance computed from an expression of this type do not depend on the relative humidity of the air and the equilibrium moisture content of the material.

In fact, the lower the relative humidity of the air in the room φ, the greater the resistance to moisture absorption at the wall surface, which at the lower limit of relative humidity increases to a very high value of the energy of adsorption of a monomolecular layer of water vapor.

With increase in relative humidity the resistance falls and when $p_u = p_s$, i. e. in the presence of free water in the material, is equal to zero.

For any values of the relative humidity at the surface the energy level at which the process of wetting of the wall in the vapor phase can proceed may be obtained from expression (2).

We can find the energy level for $\varphi = 0.25$ and $t = 18°C$, starting from the adsorption isotherm, as follows: $A = RT\ln\frac{p_s}{p_u} = 186\cdot 10^3$ j/kg.

If we measure the energy level in units of pressure (newton/m^2), we must introduce into the above result in j/kg a correction factor equal to the ratio of the corresponding numerical values of the universal gas constant multiplied by the molecular weight of water vapor [5].

By dividing the energy level by the coefficient α_β in accordance with (3), we get the required value of the moisture transfer resistance at the inside face of the wall.

Having performed these calculations for typical values of the relative humidity, we can conclude that the moisture transfer resistance at the inside face of exterior walls may in very dry rooms reach values equal to the resistance to vapor penetration of solid dense plaster.

Taking into account the necessary correction for the fall in temperature and increase in relative humidity at the surface of exterior walls as compared with the analogous data for the air of the room means that these values will be reduced, but, nevertheless, the effect on the wetting process in dry rooms remains considerable.

If we assume that under average conditions in the cold season the fall in temperature at the surface of the walls of dry rooms when $R_0^{st} = \min$ will be up to 5°, and in damper rooms when $R_0^{st} = \max$ of the order of 2-3°, then for an approximate computation of the moisture transfer resistance, assuming a linear interpretation of the nonlinear dependence, we may use the following simple formula:

$$R_{i.v} = \left(1 - \frac{\varphi}{100}\right). \tag{5}$$

At the outside face of the wall $R_{o.v}$ will obviously approach zero, since in the cold season the relative humidity of the outside air is about 90%.

The above thermodynamic relations can also be used to determine changes in the values of the vapor permeability coefficients of wall materials in different moisture states.

The vapor permeability coefficients published in the literature and in standards are obtained under isothermal conditions for relative humidities of 100% on the inside face of the specimen, and 60% on the other face. Thus, the mean moisture content of the air medium acting on the specimen is 80% (φ_{80}). This mean moisture content of the air in the pores of the specimen corresponds to a partial pressure of water vapor p_{80}. At a certain lower value of the humidity of the inside air ($\varphi \ll 100\%$), corresponding to the water vapor pressure p_x, the values of the vapor permeability coefficients will be different. These values may be determined from the ordinary laws of thermodynamics. Under isothermal conditions, the work done by the process of diffusion of the water vapor will be [6, 7]:

$$W = RT\ln\frac{p_{100}}{p_x}Q. \tag{6}$$

Suppose we have two similar specimens of material, in one of which the partial pressure of water vapor is p_x while in the other it is p_{80}. Assuming that the differences of the outside partial pressures are the same in both cases and equating the expressions for the work done by diffusion of water vapor in these specimens, we have:

$$\mu_x \ln \frac{p_{100}}{p_x} = \mu_{80} \ln \frac{p_{100}}{p_{80}}$$

or (7)

$$\mu_x \ln \varphi_x = \mu_{80} \ln \varphi_{80},$$

where $\mu_x = RTQ$ and $\mu_{80} = RTQ_{80}$ are the vapor permeability coefficients for humidities $\varphi = x$ and $\varphi = 80\%$, respectively.*

The quantity $\ln \varphi$ is the principal characteristic quantity of the sorption isotherm equation and has the more general form:

$$\frac{1}{\omega_x} = \frac{1}{\omega_{100}} + B \ln \varphi.$$

Thus, the relation between μ_x and μ_{80} depends on the sorption isotherm of the material.

Replacing the value of the integral p_{100}/p_x by its boundary values at the sorption isotherm, we have:

$$\mu_x \frac{\omega_{100}}{\omega_x} = \mu_{80} \frac{\omega_{100}}{\omega_{80}},$$

whence finally

$$\mu_x = \mu_{80} \frac{\omega_x}{\omega_{80}}. \qquad (8)$$

The direct link between the vapor permeability of the materials and their sorption properties enables us to conclude that the variations of μ as a function of the equilibrium moisture content will be different for individual groups of materials characterized by sorption isotherms of different kinds. For wettable materials with a high sorption capacity these variations will be particularly well expressed, whereas for unwettable materials (e. g. mineral wool and felt) they will be relatively imperceptible.

It is of interest to compare the computed values of the vapor permeability coefficients with the available experimental data, particularly the measurements of [8].

These experiments established that at 45% relative humidity the vapor permeability coefficients are reduced as compared with the values at 80% by 1.5 times for organic and 2-3 times for inorganic materials. Only mineral wool gave no changes in vapor permeability due to moisture content. This is in complete agreement with the nature of the sorption isotherm for this material which has a direction almost parallel to the x axis (i. e. relative humidity). The data on the sorption capacity of the corresponding materials, needed for comparison, were ascertained in accordance with [4] and [2] and are presented in the table.

TABLE

Experimental and calculated values of vapor permeability coefficients

Material	Vapor permeability coeff. for humidities of:						acc. to CNS
	30%		50%		70%		
	expt.	calc.	expt.	calc.	expt.	calc.	
Lime mortar	0.003	0.0043	0.0065	0.0058	0.0110	0.0090	—0.018
Cement mortar	0.002	0.0028	0.0035	0.0047	0.0065	0.0068	0.012
Vibrated concrete . . .	—	—	0.0018	—	—	0.0030	0.004
Mineral wool.	0.075	—	0.075	—	0.075	—	0.065

The last column of the table contains values given by CNS (Soviet Construction Norms and Specifications). For wettable materials these values roughly correspond to the moisture state at 80-90%.

The table convincingly shows that the order of the experimental and calculated values of μ for different moisture states of the materials are the same.

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* The inequality of the quantities of water vapor ($Q_x < Q_{80}$) diffusing at different transfer potentials (Δp) through comparable specimens is linked with the different thermal effects of adsorption and the corresponding increase in entropy ($\Delta S_x = \Delta E/T = -R \ln \varphi_x > -R \ln \varphi_{80}$), and hence with the unequal resistance to diffusion. In the first and second cases the work done by diffusion in comparable specimens with the same transfer potentials, but different thermodynamic functions of the system will be the same.

This raises the question of the introduction of the corresponding data into the CNS in order to improve the values of the vapor permeability coefficients used in heating calculations.

The introduction into calculations of the moisture states of walls of the proposed values of the permeability coefficients and moisture transfer resistances will bring the results of computations closer to the real conditions applying to buildings. In particular, more realistic results will be ensured for brick and concrete walls insulated on the inside with cellular concrete and other sufficiently dense insulating materials, when this type of construction is used for dry rooms with normal humidity of the inside air.

NOTATION

p_s — equilibrium water vapor pressure; V_v and V_l — molar volumes of vapor and liquid; r — latent heat of evaporation; $p_{s'}$ and p_u — saturation and investigated water vapor pressure; c — heat capacity of mixture of air and vapor; γ — weight of mixture by volume; R^{st} — heat transfer resistance of walls required by standards; W — work; Q — quantity of moisture in vapor form moving by diffusion; ω_x and ω_{100} equilibrium and maximum sorption moisture content of material; B — a constant.

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Kuibyshev Structural Engineering Institute, Moscow