ТЕПЛОФІЗИКА ДИСПЕРСНИХ СИСТЕМ

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Novel alternative model of effective porosity for hydrophilic and/or hydrophobic thin permeable media

The proposed methodology is based on the novel analysis of the water vapor transmission rate through the thin natural and polymer materials including the semi-permeable membranes. The concept of such approach and its realization reveals the spectacular difference between the behavior of hydrophilic and hydrophobic systems. Due to this distinction, the realistic model of effective porosity has been proposed to eliminate the standard uncertainties at the determination of it by the conventional methodologies.

Introduction

There are two main obstacles to perform the objective comparison and choice of preferable variant within the set of appropriate textile materials (TMs), related to the wide type of thin permeable media (PMs):

1. the different experimental methodologies and tools usable by different authors for an estimate of water vapor transmission (WVT)-rate;
2. the laboratory conditions of such measurements and a variety of experimental means proposed at present [1] for an estimate of TM-porosity.

Both items can be interconnected by the fundamental characteristic of permeability k in the frameworks of generalized for PMs Darcy's and Fick's laws:

$$k(g) = \nu\tau, \tag{1}$$

where undimensional g – porosity; ν – kinematic viscosity of TM and τ – characteristic time-lag of WVT-process. Let us emphasize here that all phenomenological coefficients (1) should be considered below as the steady properties of TM without any appeals to the actual non-stationarity of real transport processes. Besides, we consider the both kinetic coefficients ν, τ in r.h.s. of (1) as the measurable properties of TM in spite of the above non-stationarity while the permeability in its l.h.s as an apriori unknown model function of porosity $k(g)$. One needs its explicit form to optimize the choice of appropriate TM for any posed aim.

In this context porosity becomes the independent variable of problem and the measurable bulk density ρ_V of TM is its linear function defined by the standard equality:

$$\rho_V = \rho_M(1 - g), \tag{2}$$

here $\rho_M (g \to 0)$ – the asymptotic density of ultra-dry matrix for a given TM. Any TM is usually considered as the specific thin PM (TPM) in which two dimensions – width b and length a are much more than third one – its thickness δ. As a result, the convenient information reported on each TM in the relevant papers is a pair of measured quantities: thickness δ and the so-called square mass [2] $\gamma = m / A_\perp$ where $A_\perp = ab$. Since the total volume is $V = \delta A_\perp$, one obtains the bulk density of a dry TM as:

$$\rho_V = \gamma / \delta \qquad (3)$$

and only the experimental or theoretical estimate of ρ_M is necessary to evaluate the conventional porosity g (2).Once more, a variety of rather complicated and, often, expensive methods have been developed until now [1] to determine the density of ultra-dry matrix ρ_M and the resultant porosity g.

This work is an attempt to overcome the obvious restriction of such methodology in which the porosity plays a subsidiary role at the WVT-measurements. We have considered below several typical ones [2-6] and only two groups of authors [3, 4] reported g-values (without any comments) for the set of investigated TMs. Nevertheless, one has to take into account the reversionary influence of the WVT-experimental conditions (see above-point 2) on this characteristic of TM. As a rule, the investigator seldom measures its actual dry density ρ_V (3) or uses the structure-destroying [1] estimation of ρ_M from (2). The effect of ambient humidity on the TM-properties including permeability $k(g)$ cannot be negligible [2] because the density of liquid water $\rho_l (T, P_0)$ at atmospheric pressure $P_0 \approx 101$ kPa is always more than the relevant dry ρ_V from (3). Any its content in the ambient moist air becomes essential.

To take into account the factor of moist or even wet bulk density ρ_V and the respective possible change in the density of TM-matrix ρ_M one should distinguish between absorbtive and desorbtive trends of their interaction with the ambient moisture. The respective TM-structures can be, briefly, termed either hydrophilic (l) or hydrophobic (b) ones. The internal structure of basic natural or synthetic fibres, permeability of their walls for moisture, a possible presence of two alternative types (permeable and/or impermeable) in the blended TM are also important factors for the estimation of limitative actual porosity ε^0.

In this work we have tried to obtain the preliminary but crucial for any correct WVT-measurements information on the effective TM-porosity ε $\left(\varepsilon < \varepsilon^0 \right)$. It is based exclusively on the input (δ, γ) – data for a set of TMs studied at the same laboratory conditions. Three asymptotic basic parameters: $\rho_V^0 (\delta \to 0)$, $\rho_M^0 (\delta \to 0)$, $\gamma^0 (\delta \to 0)$ have been introduced and well-established for an each similar set. The express-analysis of effective porosity in these terms leads to the following main definitions of a proposed alternate basic l/b (AB-*l/b*) model:

$$\rho_M = \rho_V \rho_M^0 / \rho_V^0 \qquad (a) \qquad\qquad g = g^0 \qquad (b) \qquad (4)$$

$$\varepsilon = \frac{g^0 \cdot \rho_M}{\rho_M - \rho_V^0} = \frac{\rho_V \left(\rho_M^0 - \rho_V^0 \right)}{\rho_V \rho_M^0 - \rho_V^{0^2}}, \qquad (5)$$

$$\varepsilon^0 = \varepsilon(2 - \varepsilon) \qquad (a) \qquad\qquad w^0 = \varepsilon^0 / \varepsilon - 1 = 1 - \varepsilon \qquad (b) \qquad (6)$$

here ε^0, w^0 – model's maxima of actual porosity and hygroscopicity, respectively. Thus, effective porosity ε can be expressed exclusively in terms of the moist measurable density of TM ρ_V (5) if the asymptotic basic parameters are known.

Since this work has been, in particular, stimulated by the recent paper presented by Boguslawska-Baczek and Hes [2], it was interesting to compare in Section 4 our predictions with those from [2] based on the PERMETEST-measurements. In accordance with (5) TM-permeability k becomes in AB-l/g-model the non-linear functional of effective porosity which depends on the measurable bulk density ρ_V:

$$k\left[\varepsilon(\rho_V) \right] = v \cdot \tau, \qquad (7)$$

while authors [2] consider the relative water-vapor-permeability (RWVP – see below) as the linear decreasing function of square mass γ from (3).

Alternative basic *l/g*-model of hydrophilic and/or hydrophobic TM.

The well-known differences [7] between the such standard WVT-methodologies as ISO 11092, ASTM E96 (procedures B and BW), ASTM F2298, ISO 15496, their conventional modified versions (PERMETEST [2], Huang's test-method [6]) leads to the significant discrepancies in the WVP-estimates obtained for the same TMs. One may compare the fabrics within the single set of measurements but not for the several conjugated experiments in which the obtained WVT-data become test-method-dependent. Moreover, the WVP-term itself is some elusive in the discussed below works [2-6]. The certain authors mean it simply as the WVT-quantity i.e. the steady density of mass-flu*x* j_m. This medley of terms and results related to the permeability k (determined formally by Darci's law) is inacceptable if one desires to compare the actual properties of TMs measured by different test-methods.

To avoid the above controversial interpretation of permeability k one needs the universal and independent estimates of all TM-characteristics ε, ρ_V, v, τ from (7). The formers two (ε, ρ_V) should be interconnected and their interrelation is the main object of this work. Its first step is to argue that the bulk density ρ_V is the much more informative quantity than the respective square mass characteristic of TM-structure both considered as a function of thickness δ. This conclusion follows immediately from comparison of Fig. 1 with Fig. 2. The change of slope's $\Delta \rho_V / \Delta \delta$ sign in the latter can be attributed, from our viewpoint to the distinction between the effective hydrophilic (positive sign) and the effective hydrophobic (negative sign) types of TMs. In accordance to such concept, the moisture penetrates the entire thickness of the only hydrophilic TMs but not of the hydrophobic ones. In the second case, the certain liquid barrier's film-resistance for the further penetration of moisture has to be formed in the external thin layer of hydrophobic TMs. It conserves their internal layers to be in the relatively dry states. As a result, the volume density ρ_V decreases in spite of
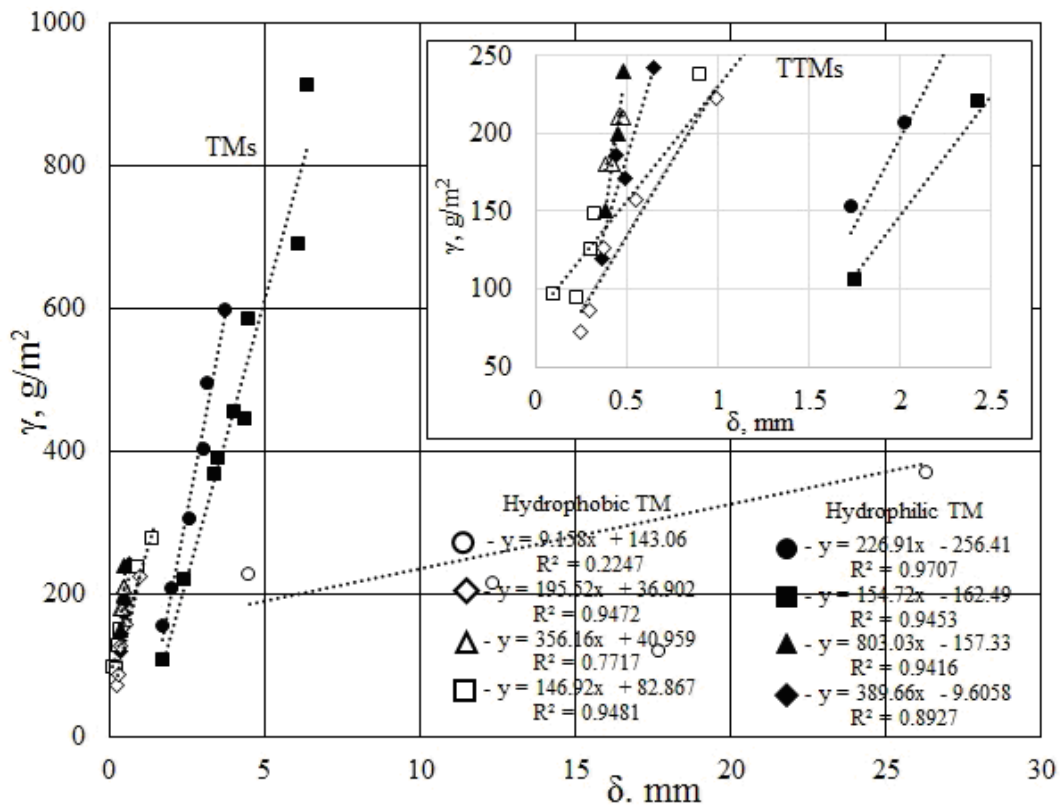
Fig. 1. Linear trends for two groups (see text) of 41 (in total) experimental (γ,)-points for TMs [2-6] represented by black symbols (hydrophilic ones) and by white symbols (hydrophobic ones) in γ-δ plane (distinctions between $\Delta\gamma/\Delta\delta$-slopes are here only quantitative).
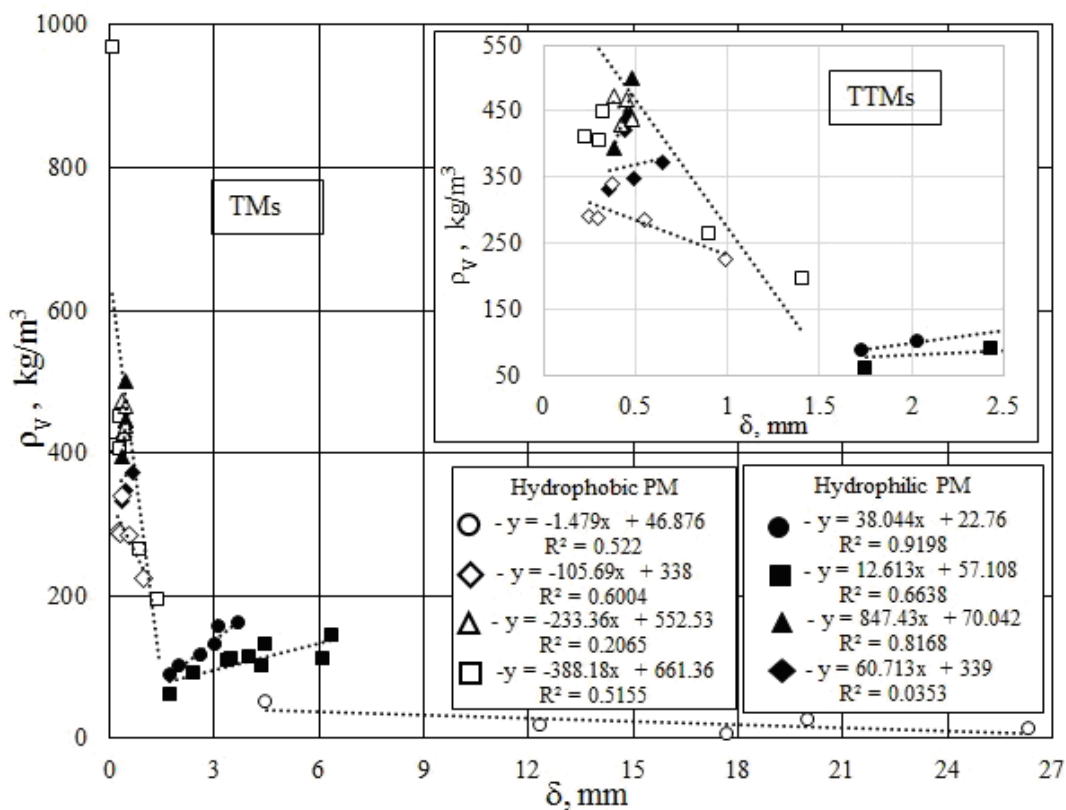

Fig. 2. Linear trends for two groups (see text) of 41 (in total) experimental (ρ_V, δ)-points for TMs [2-6] represented by black symbols (hydrophilic ones) and by white symbols (hydrophobic ones) in (ρ_V-δ) plane (distinctions between $\Delta\rho_V/\Delta\delta$-slopes become here qualitative).
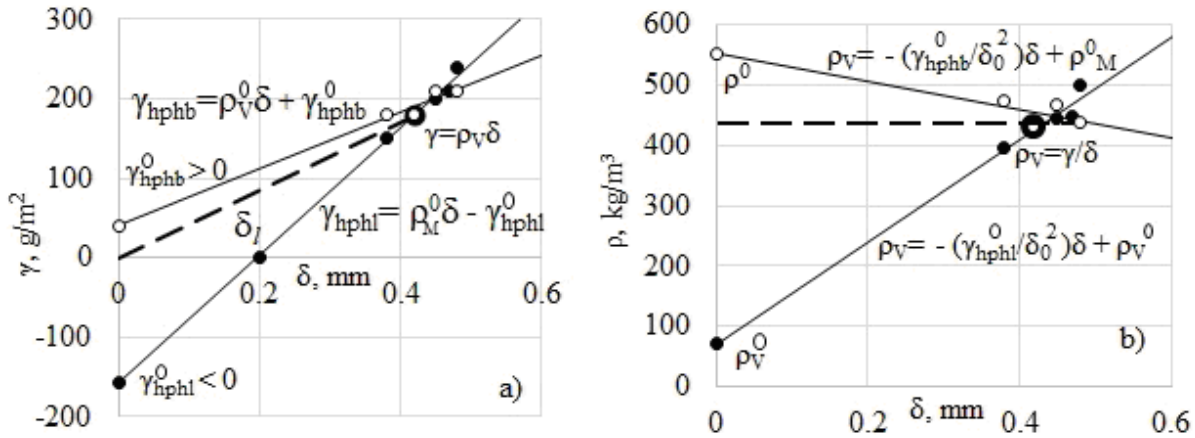
Fig. 3. Typical strategy of AB-model in (γ-δ)- and ($ρ_V$-δ) planes used to separate the hydrophilic samples (represented by 5 black circles for the measured [2] variants of pure (100 %) wool) from the hydrophobic samples (represented by 4 white circles) for the measured [2] blended variants of wool (45 %) either with viscose (55 %) or with polyester (55 %). Asymptotic surface densities are shown by the respective symbols. One black point is selected, by chance, to compare the AB-treatment with the standard one (dashed lines) used by authors [2].

growth of the thickness $δ$ in comparison to the more thin PMs in which the effect of surfacial heavier layer is more pronounced.

One may note that the verification of above promising concept may be fulfilled exclusively for the set of different TMs investigated at the same ambient experimental conditions (temperature, pressure, humidity). Beside, one should analyze the arbitrary sets of TMs chosen by each authors from the list [2-6] to separate the hydrophilic samples from hydrophobic samples. The typical scheme of the proposed analysis applied below to the data [2] is shown in Fig. 3(a,b) for the planes γ-δ and $ρ_V - δ$ used also in Figs. 1,2. The entire set of TMs from [2] is composed, to our mind, by five purely (100 %)-wool hydrophilic samples and by four blended samples of 45 % wool with either two additions of 55 %-viscose or two additions of 55 %-polyester. The both added synthetic components transform the range of hydrophilic behavior for the purely wool samples into that related to hydrophobic ones.

The striking feature of the proposed approach is a possibility to formulate the *AB-l/b-model (*alternate basic model of hydrophilic and hydrophilic sets of TMs) expressed in the same asymptotic reference terms from (4,5) namely, $ρ_V^0 < ρ_V$, $ρ_M^0 < ρ_M$. It is formulated for the hydrophilic TMs as:

$$γ_{hphl}(δ) = ρ_M^0 δ - γ_{hphl}^0 \quad (a) \qquad ρ_V(δ) = -\left(γ_{hphl}^0 / δ_0^2\right)δ + ρ_V^0 \quad (b) \qquad (8)$$

and for hydrophilic TMs as:

$$γ_{hphb}(δ) = ρ_V^0 δ - γ_{hphb}^0 \quad (a) \qquad ρ_V(δ) = -\left(γ_{hphb}^0 / δ_0^2\right)δ + ρ_M^0 \quad (b) \qquad (9)$$

where $γ_{hphl}^0(δ \to 0)$ and $γ_{hphb}^0(δ \to 0)$ were termed the surfacial densities of hydrophilic (*hphl*) and hydrophobic (hphb) TMs. The change of signs before these steady characteristics of different TMs correlates to the above-discussed respective trends in the asymptotic $dρ_V / dδ$ – slopes determined at the finite densities $γ^0$:
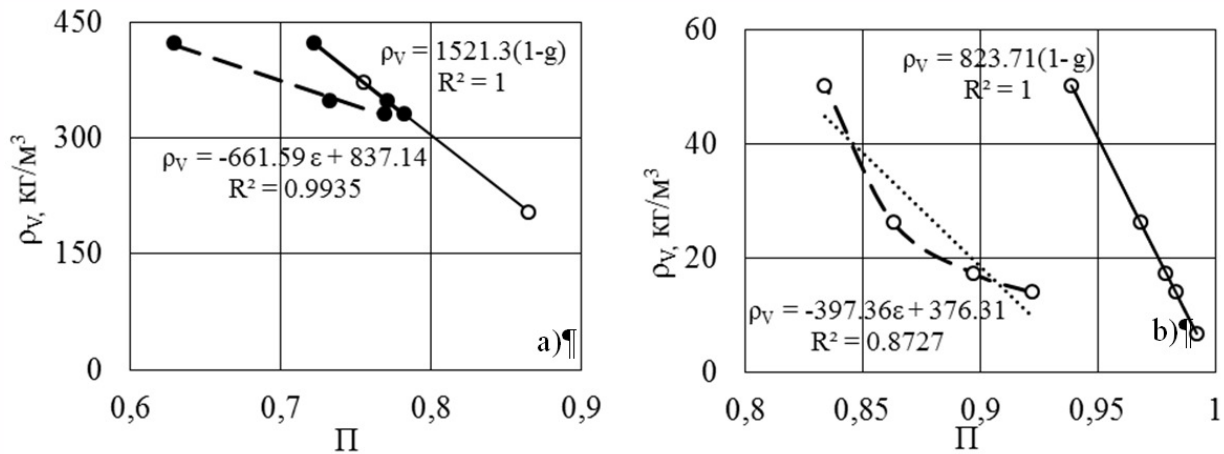
Fig. 4. Revision of ρ_M-estimate from 1521.3 kg/m³ to 837.1 kg/m³ for cotton-based fibre [3] achievable due to the correct selection for analysis of only hydrophilic purely-cotton samples (a); revision of ρ_M-estimate from from 824.75 kg/m³ to 376.31 kg/m³ for non-woven fibres of "Hollowfiber" [4] due to the correct account for the environmental humidity of experiment (b).

$$\rho_V(\delta \to 0) = \gamma^0 / \delta \quad (a) \qquad d\rho_V(\delta \to \delta_0)/d\delta = -\gamma^0 / \delta_0^2 \quad (b), \qquad (10)$$

where δ_0 is the characteristic reference thickness of a set of TMs.

Thus, AB-*l/g*-model introduced by (8,9) offers one-to one self-consistent mapping of the linear (γ, δ)- and (ρ_V, δ)-trends represented in Fig. 1,2 into the physically meaningful reference parameters: $\rho_V^0, \rho_M^0, \gamma^0, \delta_0$ illustrated by Fig. 3. Any specially adjustable parameters are absent in the proposed transformation which revises crucially the widespread uncertainties in the estimation of actual ρ_M – values [1] by (2).

Indeed, it follows from Fig. 4(a) that the authors [3] have used at the calculation of recommended porosities for cotton-based TMs the "mixture" of hydrophilic (3 points) of purely (100 %)-cotton fibres with 2 points of hydrophobic blended with viscose (20 %) and polyester (18 %) but still cotton-based (80 %) fibres. This incorrect, to our mind, use of (2) for all fabrics in the common set of TMs leads to the strongly overestimated in [3] common density of cotton-based dry matrix ρ_M = 1521.3 kg/m³. For comparison, the AB-*l/g*-model's estimate for the purely-cotton fibres is $\rho_M = 837.1$ kg/m³. Another reason of uncertainties follows from Fig.4b in which ρ_M = 824.75 kg/m³ recommended in [4] for the set (4 points) of hydrophobic non-woven "Hollowfiber"-materials was calculated by the same linear extrapolation based on (2). In this case, the rather confused calculation procedure was used [4] to estimate preliminarily the average, (also overestimated) value ρ_M = 824.75 kg/m³. For comparison, the AB-*l/g*-model's estimate for the "Hollowfiber" PMs (δ > 4.5 mm) is ρ_M = 376.31 kg/m³ . For a convenience of reader four basic parameters of dry hydrophilic and hydrophilic PMs and TPMs are collected in Table 1.

Concepts of effective porosity and limitative hygroscopicity of TMs.

To go beyond the standard but restrictive definition of porosity *g* (2) we have admitted that the AB-*l/g*-interpolation between the pair of "moist" measurable densi-

Table 1. AB-l/g – model's parameters extracted from experimental (γ, ρ)-data [2-6].

N	Nomenclature of samples	δ_0, mm	γ^o, g/m^2	ρ_V^0, kg/m^3	ρ_M^0, kg/m^3
Hydrophilic PMs					
1-6	"Geotex" [4] (GT-150, 200, 300, 400, 500, 600) – 6 points	2.60	256.41	22.76	226.91
7-15	"Geocom" [4] (GC-B360, B450, D100, D200, D350, D400, D600, D700, D900) – 9 points	3.59	162.49	57.11	154.72
16-20	100 % wool [2] – 5 points	0.43	157.33	70.04	803.03
21-23	100 % cotton [3] – 3 points	0.36	28.743	271.08	435.56
Hydrophilic PMs					
24-27	"Hollowfiber" [4] (mP15, cP5191, mP453, mP608) – 4 points	9.84	143.06	9.158	46.876
28-31	woven nylon – 3 points, net poly-ester [5] – 1 point	0.59	36.902	195.52	338.0
32-37	PTFE/nylon, cotton/polyester, PU/polyester, dense woven/poly-ester, TPU/polyesterTPU/nylon [6] – 6 points	0.46	82.867	145.92	661.36
38-41	Wool (45 %)/viscose (55 %) – 2 points, wool (45 %)/polyester (55 %) – 2 points [2]	0.42	40.959	356.16	552.53

ties ρ_V, ρ_M and their "dry" counterparts ρ_V^o. ρ_M^o (common to the entire set) is related to the standard porosity g in accordance with (4b). This admission let us estimate preliminarily by (4a) the effective specific density of each TM-matrix ρ_M determined at the same conditions of a given experiment for each (γ, δ)-point. Of course, the other theoretical suppositions as well as the independent experimental determination [1] of porosity g are also possible but our goal is here to introduce the simplified estimate of its deviation from the measurable effective porosity by (5).

This deviation follows immediately from the main requirement adopted in this work. In accordance with it, one should take into account the steady presence of some moisture simultaneously in both measurable quantities ρ_V and ρ_M. It seems that the above-discussed assumption for ρ_M-estimation is, at least, more realistic in comparison with those demonstrated in Fig. 4(a,b) by straight solid lines. One may, of course, speculate as to influence either of density of threads (warp/weft-type of TM) or the type of fiberfill (regular for woven TMs and chaotic for non-woven, rather thick PMs) on the effective ρ_M-value. However, in any case, an admission of its common constant value ρ_M for the "mixed" set of different hydrophilic and hydrophobic structures (as is seen from Fig. 4a,b) is certainly oversimplified one. Besides, such assumption can lead to the obviously erroneous theoretical estimates of ρ_V-value.

Hygroscopicity of TMs is closely relevant characteristic at any consideration of porosity. As it follows from Fig. 5 in which the resultant AB-*l/g*-model's predictions of $\varepsilon(\rho_V)$-function are shown for 41 PMs, the location of hydrophobic and hydrophilic curves can be close one to another. At the same time, the distinctions in hygroscopicity between both are, as a rule, striking and important from the practical viewpoint. Authors [3] noticed that the recommended level of hygroscopicity for the child's cotton-based underclothes is often too restrictive for the real hydrophilic TMs.

We have used in this problem the simplified limitative estimates of ε^o and w^o following from (6) where the internal mesoporosity of threads and their permeability for moisture were approximately taken into account. The results of calculations based on (6) look sometimes unwonted because the hydrophobic blended fibres [2] of wool (45 %) with the addition either viscose (55 %) or polyester (55 %) demonstrate the much more hygroscopicity (23-31 %) in comparison with that for the hydrophilic pure (100 %) wool (7.3-7.6 %).

Nevertheless, the possible explanation of this observation follows directly from Fig. 5. One may compare three $\varepsilon(\rho_V)$-curves located in the relatively narrow range of bulk densities [$400 \div 480$ kg/m^3] for hydrophilic pure wool [2], for hydrophobic samples of laminated nylon and polyester [6], for hydrophobic blended wool/viscose and wool/polyester samples [2]. Their negative slopes $\Delta\varepsilon / \Delta\rho_V$ are quite different and just this factor could be determinative for the level of maximum hygroscopicity w^o.

To corroborate such statement let us compare two variants of its definition by (6) expressed in terms of two functions: standard porosity $g(\rho_V)$ from (2) and effective porosity from(5). The respective slopes are:

$$\frac{dw^0}{d\rho_V} = -\frac{dg}{d\rho_V} = \frac{1}{\rho_M} \ \text{(a)} \qquad \frac{dw^0}{d\rho_V} = -\frac{d\varepsilon}{d\rho_V} = \frac{\rho_V^{0\,2}\left(\rho_M^0 - \rho_V^0\right)}{\left(\rho_M^0\rho_V - \rho_V^{0\,2}\right)^2} \ \text{(b)} \quad (11)$$

The restrictive meaning of standard estimate by (11a) becomes here obvious but still physically plausible: the more density of matrix ρ_M for any (hydrophilic or hydrophobic) TMs the less "rate" of hygroscopicity $dw^0/d\rho_V$. On the other hand, the influence of ρ_V on the same "rate" is more sophisticated in accordance with (11b). It can be expressed, similarly to (11a), in terms of ρ_M-value, taking into account (11b):

$$\frac{dw^0}{d\rho_V} = -\frac{d\varepsilon}{d\rho_V} = \frac{\rho_M^0 - \rho_V^0}{\left(\rho_M - \rho_V^0\right)^2} \ . \tag{12}$$

Again, the role of ρ_M is physically plausible but more subtle in (12) than that in (11a).

About appropriate choice of independent variables

In this work the only static (time-independent) characteristics of TM and its porosity have been determined by AB-*l/g*-model. However, some obtained results may have an influence on the correct interpretation of standard test-method's results obtained for any PM-objects. The dynamical nature of WVT-measurements of the
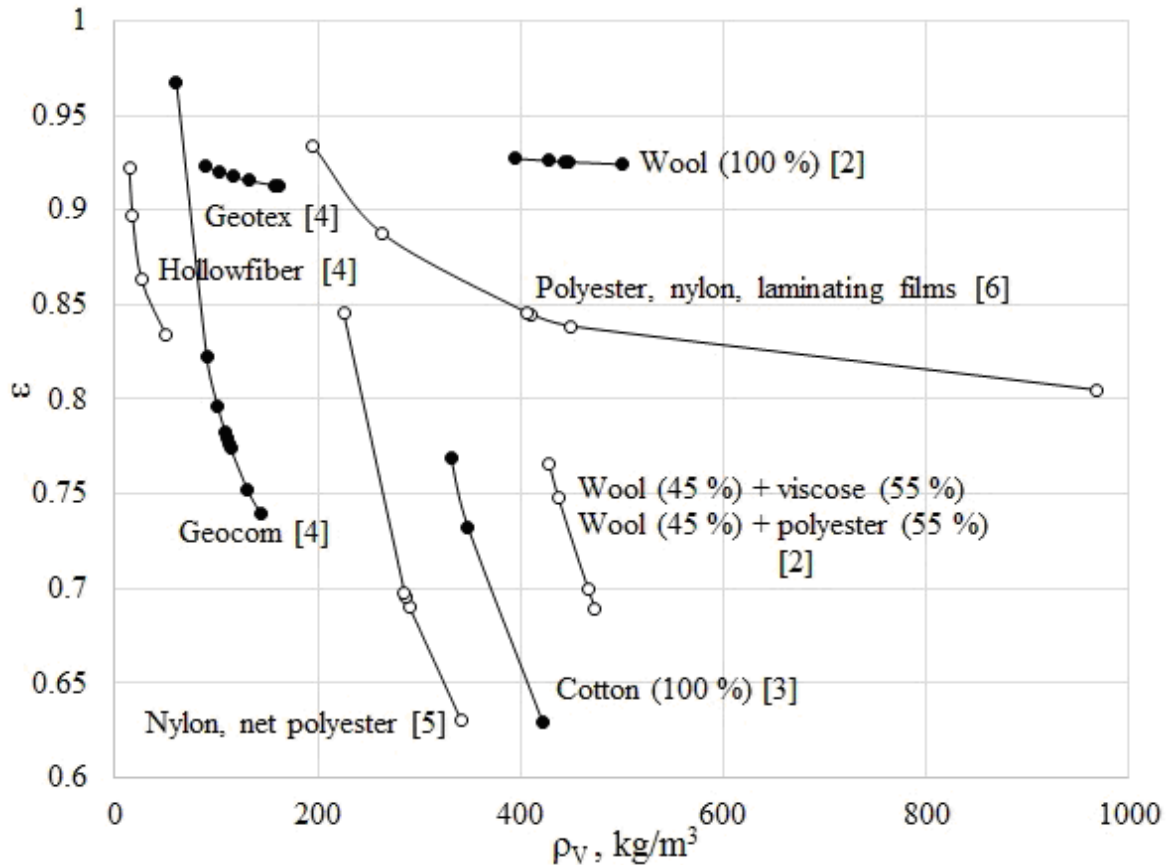
Fig. 5. Predicted by AB-l/b-model effective porosity of hydrophilic (black points) and hydrophobic (white points) TMs as function of bulk density.

mass-flux density $j_m = \Delta m/(A_\perp \Delta t)$ is obvious while the respective choice of a thermodynamic force (either gradient of pressure $\Delta P/\delta$ or gradient of density $\Delta \rho/\delta$ existing between the internal and external surfaces of TM) is not so straightforward. The same is true for the heat-flux density: $j_q = \Delta q/(A_\perp \Delta t)$ for which either the gradient of temperature $\Delta T/\delta$ or the gradient of partial water-vapor (WV-) pressures (and, also, WV-concentrations) can be appropriate.

One may note that the transport coefficients for TM v and τ from (7) can be independently determined by WVT-experiment (in which mass-flux density j_m is usually [6] reported) only if the respective thermodynamic force (gradient's type) is also given. Recently we have considered [8] this problem in terms of the set of measurable i-test-method-dependent fluxes: $j'_m / j^o_m = \Delta P' / \Delta P^o$ reduced to the chosen reference flux: j^0_m with the known experimental pressure-drop ΔP^0. The calculated ΔP^i-value (this important characteristic of any transport process is, as a rule [6,7], uncontrollable by the WVT-experimentalist) has been, then, used to predict the effective kinetic velocity u^{ik} of the convection-diffusion transport of moisture through the k-sample of TM. Its reliable estimate should be consistent [8] to the generalized resistance of k-th fabric.

Thus the certain choice of a pair: density of flux-thermodynamic force leads often to the dynamical, by nature, transport coefficients expressed, however, in terms of (reciprocal) kinetic effective velocity u^{-1}, s/m. The typical examples of such "substitution" are [2] mass transfer coefficient β_P [kg·m⁻² Pa⁻¹ s⁻¹] = s/m = $[j_m]/[\Delta P]$ and evaporative resistances: of the air space (between skin and fabric) u^{-1}, of the fabric itself R_{etg}, of the external boundary layer R_{et} [Pa·m²/W] = s/m = $[j_m]/[\Delta P]$. Both ones are dependent on the chosen by chance, time-interval Δt of WVT- or WVP-measurements as well as on the arbitrarily chosen geometric characteristics $A_\perp, \delta$ of a TM-sample. The relevant diffusion coefficient related to WV-partial pressure and heat flow is defined as [2]: D_P[W/Pa·m] = m²/s to represent the evaporative resistance of the air gap D_P with the thickness h: $R_{etg} = h/D_P$, while R_{etg} is represented simply as: $R_{et0} = 1/\beta_P$.

We have developed, recently, the alternative approach to the mass-heat-charge transport problems in TPMs [8] which is based on the model of Fluctutional Thermodynamics (FT-model) proposed by one of us [9]. In accordance with the generalized Gibbs-Duhem form all gradients of thermodynamic fields are inter-connected:

$$\Delta P/\delta = \rho\left(\Delta\mu + s_m\Delta T + e_m\Delta\varphi\right)/\delta, \tag{13}$$

here μ, J/kg – chemical potential, φ, J/Cl – electric potential, s_m, J/kg K– specific entropy and e_m, Cl/kg– specific electric charge.

The special role of local density ρ in any variant of the continuum non-equilibrium theory is well-known. Its other role is the equilibrium independent parameter of the Equation of State (EOS) for any fluids: $P = P(\rho, T)$. It follows from (13) that the fluctuational equation (FEOS) developed to describe the WV-properties [9] could be very useful for the discussed problems of TPMs. In particular, for the isothermal neutral fluid the gradient of chemical potential (it corresponds to the thermodynamic force in the generalized Fick's law for self-diffusion) becomes the known functional of the gradient of pressure: $\Delta\mu/\delta = \Delta P[\rho; T = const, \varphi = 0]/\rho\delta$. This observation leads to the special role of bulk density ρ_V as the independent variable for PMs. One may note that the effective porosity $\varepsilon(\rho_V)$ introduced in this work demonstrates the similar role of ρ_V for TPMs too. It should be emphasized also that (7) have been derived and aimed [8, 9] to eliminate any influence of the arbitrary parameters in WVT-measurements $(\delta, A_\perp; \Delta t)$ on the kinetic effective transport coefficients defined just for TM, i.e. ν and τ.

As outlined above it is interesting to compare the AB-*l/g*-model's results with those following from the RWVP-measurements in [2]. Boguslawska-Baczek and Hes [2] performed the measurement of relative *WVP* (RWVP)-quantity in % with PERMETEST apparatus. Accordingly to the standard ISO 11092 developed for TMs it determines: the thermal resistance in an ultra-dry state R_{ct}, K·m²·W⁻¹ = $[\Delta T]/[j_q]$; the RWVP-quantity and the evaporative resistance R_{ct} of the fabric by equalities:

$$RWVP = \left(j_q^s / j_q^0\right)100\%, \tag{14}$$

$$R_{et} = \left(P_w^s - P_w^0\right)\left(1/j_q^s - 1/j_q^0\right) = C\left(100 - \varphi\right)\left(1/j_q^s - 1/j_q^0\right), \qquad (15)$$

where R_{ct} and j_q^s mean the heat-flux density lost and the approximation by the adjustable apparatus-dependent constant C, Pa has been used to calculate the drop of partial pressures. The independent variable for analysis of RWVP (R_{et})-function was, firstly, square mass γ and, then, the undimensional relative moisture U of the fabric:

$$R_{ctw} = R_{ct}\left(1 - kU\right), \qquad (16)$$

where the thermal resistance in a wet state $R_{ctw} = R_{ct}\left(1 - kU\right)$, K·m²·W⁻¹ is approximated by the other adjustable apparatus-dependent constant k.

A variety of parameters, adjustable apparatus-dependent constant k, types of fluxes makes the ISO 11092-methodology, in total, and its useful modified PERMETEST-version rather formidable and laborious. Unfortunately, its results are unquestionably test-method-dependent. Huang and Qian [6] noticed in the comparative analysis of different standard WVT-methodologies that the R_{et}-estimates obtained by ISO 11092-test are uncorrelated with the other test-methods and proposed to consider for this aim the reciprocal R_{et}-quantity with the dimensionality of kinetic velocity u [m/s]. This proposition seems reasonable if one takes into account the above consideration and that the units of standard convection-diffusion WVT-measurements [6,7] $1/R_{et}$, kg m⁻² s⁻¹ can be composed by product of two units: $[\rho][u] = $ kg m⁻² s⁻¹.

We suppose now that the effective convection mass-heat transfer flow $j_q = \rho i_m u_e$ (i_m, J/kg – specific internal energy) can be generalized for the isothermal diffusion-rate of moisture through TM if the respective effective velocity $u_e = R_{et}^{-1}$ is appropriately determined by the reciprocal evaporative resistance. However, the meaning of local bulk density of heat ($\rho \cdot i_m$) in such reasonable generalization should be, additionally, specified.

If one gives up an usage of percent definitions for relative humidity of air $\varphi = \rho\left(T, P\right)/\rho'\left(T\right)$ and RWVP, equations (14, 15) can be easily transform to represent the PERMETEST-measurements [2] by two consistent equalities:

$$RWVP \equiv \frac{j_q^s}{j_q^0} = 1 - \frac{\rho_V i_m}{\Delta P_w} = 1 - \frac{\rho_V i_m}{100 C\left(1 - \rho/\rho^s\right)}, \qquad (17)$$

where the supposed here relationship:

$$j_q^s R_{et} = i_m \rho_V \qquad (18)$$

is used. One needs only the isobaric heat capacity of moisture $C_P(T)$, J/kg to determine approximately the specific internal energy: $C_P(T)$ in (17,18).

The result obtained appears to be important and interesting. Its comparison to the standard definition of porosity g by (2) confirms, first of all, the existence of functional connections between any permeabilities and porosities $\left(k\left[\varepsilon\left(\rho_V\right)\right]\right)$, $RWVP\left[g\left(\rho_V\right)\right]$ in which the porosities are the functions of common independent variable ρ_V. The similarity of physical conclusions on permeability based on the WVT-

measurements of mass-fluxes j_m [3-6] and on the PERMEREST-measurements of heat-fluxes i_q [2] corroborates their consistency.

The choice of square mass γ as independent variable has been plotted in Figs. 4,5 from [2] though its conclusion at the comparison of linear trends: the higher the RWVP-quantity, the lower the R_{ct}-value seems rather trivial at least for dry 100 % wool fabrics taking into account Eq.(18) at constant $i_m\rho_V$-value. The comparative analysis of two cooling heat fluxes (from the fabric surface and the total one from the body's skin) fulfilled in Figs. 8-10 [2] in terms of relative moisture U from (16) is more promising, from our viewpoint. One may note that this variable corresponds approximately to one used in the AB-*l/g*-model:

$$U = m / m_0 = \gamma / \gamma^0 = \rho_V / \rho_V^0. \qquad (19)$$

However, the former was applied to the same sample of TM in [2] while the latter - to the different samples of an arbitrary measured set of TMs. Nevertheless, the combination of Equations 16 and 19:

$$u_{ew} = u_e / \left(1 - k\rho_V / \rho_V^0\right) \qquad (20)$$

leads to the well-founded conclusion: the higher the moisture of a sample, the more effective velocity of heat flux u_{ew} in a wet fabric (due to the higher thermal conductivity of water).

Another interesting correspondence between our observations and the PER-METEST-measurements [2] follows from the comparison between two above-named cooling heat fluxes for wet 100 % wool fabric (Fig. 8 [2]) and wet 45 % wool/55 %viscose fabric (Fig. 9 [2]) and wet 45 % wool/ 55 % polyester fabric (Fig. 10 [2]). The first sample is supposedly hydrophilic while the second and third samples – hydrophobic. The respective quantitative change of slopes u_{ew} is shown in Fig. 3b. Authors [2] have observed the similar change of slopers in the plane RWVP-U. This result taking into account our interpretation of variable U by (19,20) may be elucidating factor at the choice of clothes providing the better thermal comfort in spite of their moisture content.

Conclusions

The novel AB-*l/g*-model of effective hydrophilic and hydropholic porosity ε proposed on the base of experimental (γ, δ)-data for 41 different TMs taken from [2-6] provides an elimination of the measuring laboratory conditions' influence on the results of measurements. The simple model's estimates of the matrix density ρ_M, observable porosity ε and maximum hygroscopicity $w^0(\varepsilon)$ can be obtained from (4-12) with use only bulk density ρ_V and without any adjustable coefficients. The interesting correspondence between the AB-*l/g*-model's predictions and the PERMETEST-measurements of RWVP-quantity is revealed. One may consider the proposed AB-*l/g*-model as the necessary preliminary steps for the further more detailed study of the permeability $k\left[\varepsilon(\rho_V)\right]$ considered as the functional of effective porosity in the framework of (7). A variety of theoretical models proposed, at present, for permeabil-

ity in which the porosity is only an adjustable parameter can be considered now from the general physical viewpoint. The practical usage of AB-*l/g*-model for the comparison of different TMs may be quite promising at the further investigations of PMs, in total.

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Роганков О.В. мл., Швец М.В., Калинчак В.В., Роганков В.Б.

Новая альтернативная модель эффективной пористости для гидрофильных и/или гидрофобных тонких проницаемых сред

АННОТАЦИЯ

Предлагаемая методология основана на новом анализе скорости переноса паров воды через тонкие натуральные и полимерные материалы, включая полупроницаемые мембраны. Концепция такого подхода и его реализация раскрывает резкое различие между поведением гидрофильных и гидрофобных систем. С его учётом предложена реалистичная модель эффективной пористости для исключения неопределенностей при её определении с помощью стандартных методологий.

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Нова альтернативна модель ефективної поруватості для гідрофільних та/або гідрофобних тонких проникних середовищ

АНОТАЦІЯ

Методологія, що пропонується, заснована на новому аналізі швидкості переносу водяної пари крізь тонкі природні та полімерні матеріали, включаючи напівпроникні мембрани. Концепція такого підходу і його реалізація розкриває різку відмінність між поведінкою гідрофільних і гідрофобних систем. З її врахуванням запропонована реалістична модель ефективної пористості для виключення похибок при її визначенні з допомогою стандартних методологій.