

Alternate Basic l/b-model of Effective Porosity Created for Hydrophilic (l) and/or Hydrophobic (b) Moist Textile Materials

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Abstract

There are several standard test methods (based on different construction mechanisms) and the respective experimental conditions (relative humidity, air velocity, test temperature) which lead to essentially different estimates of water vapour permeability as well as the effective transport coefficients for the same textile materials. To develop objective comparative methodology within a set of similar materials, one needs either to eliminate completely the effect of both factors above or to take into consideration their combined influence on the textile transport characteristics in a self-consistent manner. The latter, a more promising strategy of comparison, requires, first of all, a correct definition of properties related just to the textile materials, but not to the specific test-methods or to their experimental conditions and peculiarities. This work is an attempt to create a physically-plausible alternate model of hydrophilic (l) and/or hydrophobic (b) textile materials by the special concept of effective porosity dependent on the moisture content and, as a result, on the bulk density of fabric. We consider the permeability in the generalized Darcy's-Fick's law as the function of effective porosity, which controls all main transport coefficients of textile material. Any adjustable coefficients are absent in the alternate basic l/b-model proposed.

Key words: permeability, moist bulk density, hydrophilic fabrics, hydrophobic fabrics, asymptotic properties, thin permeable media.

Survey of symbols and abbreviations used below

k – permeability in Darcy's law in m^2 ,
 ν – kinematic viscosity in $m^2 \cdot s^{-1}$,
 τ – characteristic time-lag of mass transport in s ,
 j_m – density of water vapour transmission (WVT) or mass-flux in $kg \cdot m^{-2} \cdot s^{-1}$,
 g – standard undimensional porosity,
 ρ_V, ρ_M – densities of dry permeable material and its matrix in $kg \cdot m^{-3}$,
 $a, b \gg \delta$ – geometric sizes of thin material in m ,
 γ – mass per unit of area of textile material in $kg \cdot m^{-2}$,
 $A_{\perp} = ab$ – normal section of flux across TM in m^2 ,
 $V = A_{\perp} \delta$ – total volume of material in m^3 ,
 $V_M < V$ – volume of matrix in m^3 ,
 $\rho(T, P_0)$ – density of water at atmospheric pressure P_0 in $kg \cdot m^{-3}$,
 l, b – marks of hydrophilic and hydrophobic TMs,
 $\varepsilon, \varepsilon^0$ – effective and actual (maximum) porosities,
 ρ_V^0, ρ_M^0 – densities of alternate basic (AB) model in $kg \cdot m^{-3}$, in relation to ρ_V, ρ_M ,
 g^0, w^0 – AB-model's porosity and hygroscopicity,
 $\gamma_{hphl}^0, \gamma_{hphb}^0$ – asymptotic ($\delta \rightarrow 0$) mass per unit of area in $kg \cdot m^{-2}$,
relative vapour permeability (RWVP) in %, [2],
 j_q – density of heat-flux in $W \cdot m^{-2}$, [2].

Introduction

There are two main obstacles to make an objective comparison and choice of a preferable variant within a set of appropriate textile materials (TMs) when considering the wide type of thin permeable media (PMs):

1. the different experimental methodologies and tools used by different authors for an estimate of the water vapor transmission (WVT)-rate;
2. the laboratory conditions of such measurements and the 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 within the generalised frameworks of PMs Darcy's and Fick's laws:

$$k(g) = \nu \tau, \quad (1)$$

where, undimensional g – porosity, ν – kinematic viscosity of TM and τ – characteristic time-lag of WVT-process. Let us emphasise here that all phenomenological coefficients in **Equation 1** should be considered below as the *steady* properties of TM without any reference to the actual non-stationarity of real transport processes. Besides this, we consider both kinetic coefficients ν & τ in the r.h.s. of **Equation 1** as *measurable* properties of TM in spite of the non-stationarity above, while the permeability in its l.h.s

as an apriori unknown model function of porosity $k(g)$. One needs its explicit form to optimise the choice of appropriate TM for any aim proposed.

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

$$\rho_V = \rho_M(1 - g), \quad (2)$$

where, $\rho_M(g \rightarrow 0)$ – asymptotic density of *dry matrix* for a given TM. Any TM is usually considered as a specific *thin PM (TPM)* in which two sizes of width b and length a are much more than in third one – its thickness δ . As a result, the convenient information reported for each TM in the relevant papers is a pair of measured quantities: *thickness* δ and the so-called *mass per unit of area* [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:

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

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

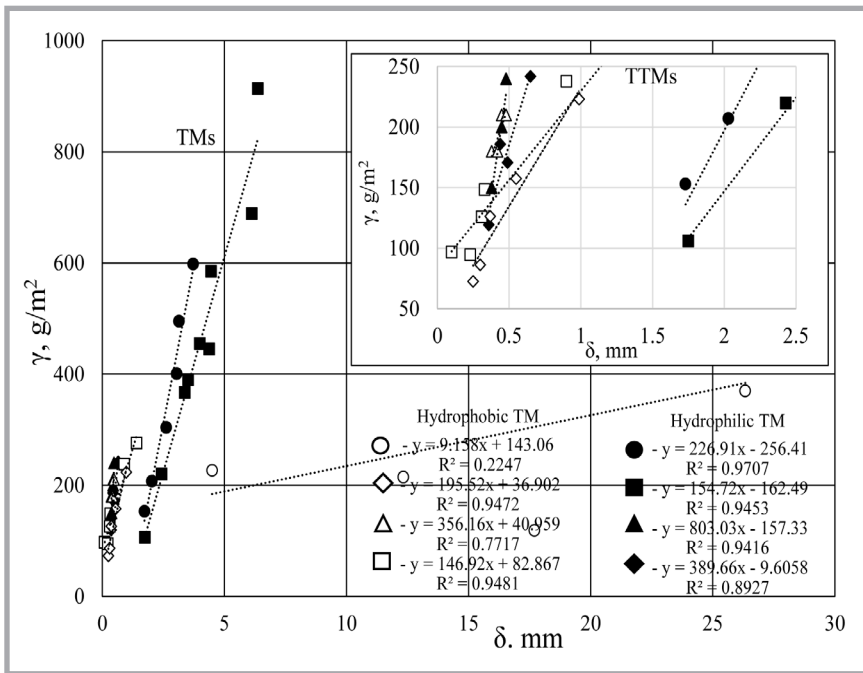


Figure 1. Linear trends for two groups (see text) of 41 (in total) experimental (γ, δ) -points for TMs [2 - 6] represented by black (hydrophilic ones) and white symbols (hydrophobic ones) in the γ - δ plane (distinctions between $\Delta\gamma/\Delta\delta$ -slopes are here only quantitative).

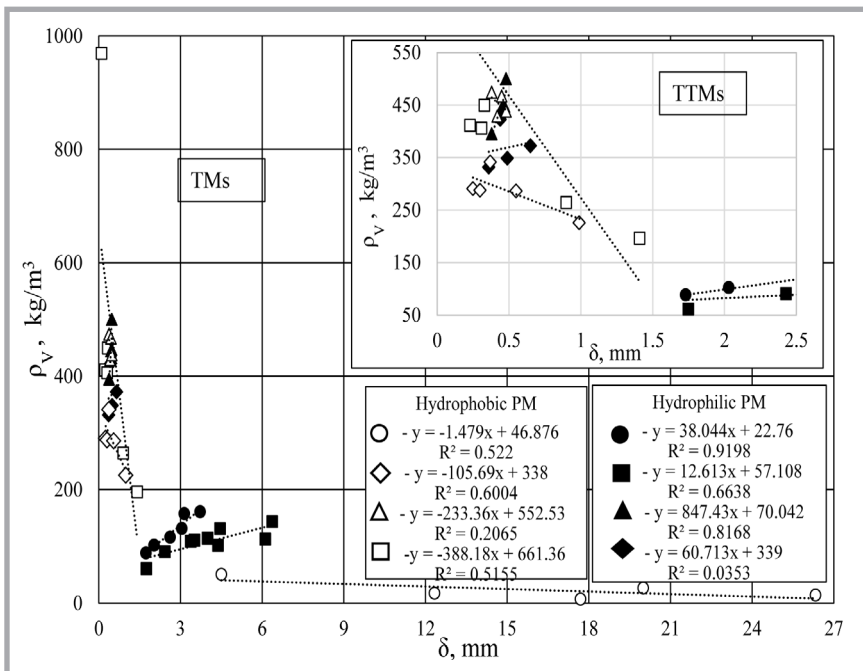


Figure 2. Linear trends for two groups (see text) of 41 (in total) experimental (ρ_V, δ) -points for TMs [2 - 6] represented by black (hydrophilic ones) and white symbols (hydrophobic ones) in the (ρ_V, δ) plane (distinctions between $\Delta\rho_V/\Delta\delta$ -slopes become qualitative).

This work is an attempt to overcome the obvious restriction of such methodology in which the porosity plays a subsidiary role in WVT-measurements. We have considered below several typical ones [2 - 6], in which only two groups of authors [3, 4] reported g -values (without any comments) for the set of TMs investigated. Nevertheless, one has to take into account the *reversionary influ-*

ence 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 in **Equation 3** or uses the *structure-destroying* [1] estimation of ρ_M from **Equation 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 from ρ_V **Equation 3**. Any of its content in the ambient moist air becomes essential.

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

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

$$\rho_M = \rho_V \rho_M^0 / \rho_V^0 \quad (a) \quad (4)$$

$$g = g^0 \quad (b)$$

$$\varepsilon = \frac{g^0 \cdot \rho_M}{\rho_M - \rho_V^0} = \frac{\rho_V (\rho_M^0 - \rho_V^0)}{\rho_V \rho_M^0 - \rho_V^0} \quad (5)$$

$$\varepsilon^0 = \varepsilon(2 - \varepsilon) \quad (a) \quad (6)$$

$$w^0 = \varepsilon^0 / \varepsilon - 1 = 1 - \varepsilon(b)$$

here, ε^0 , w^0 - model's maxima of *actual porosity* and *hygroscopicity*, respectively. Thus the effective porosity ε can be expressed exclusively in terms of the moist measurable density of TM ρ_V by **Equation 5** if the asymptotic basic parameters are known. Of course, one should not mix the different types of moisture transport through TMs. In this work, we have only attempted to study their cumulative effect. Once again, such a model is not "conclusion" of the problem but only, from our viewpoint, the first step necessary to investigate the other essential and actual details of transport.

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 **Equation 5**, the TM-permeability k in the AB- l/g -model becomes a non-linear function of effective porosity, which depends on the measurable bulk density ρ_V :

$$k[\varepsilon(\rho_V)] = v \cdot \tau, \quad (7)$$

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

Alternate basic l/g -model of hydrophilic and/or hydrophobic TM

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

To avoid the controversial interpretation of permeability k above one needs a universal and independent estimates of all TM-characteristics $\varepsilon, \rho_V, v, \tau$ from **Equation 7**. The former two (ε, ρ_V) should be interconnected, and their interrelation is the subject of this work. The first step is to argue that the bulk density is a much more informative quantity than the respective mass per unit of the area characteristic of the TM-structure, with both considered as a function of the thickness δ . This conclusion follows immediately from a comparison of **Figure 1** with **Figure 2**. The change in 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 with such a concept, moisture penetrates the entire thickness of hydrophilic TMs, but not of the hydrophobic ones. In the second case, a certain film-resistance of the liquid barrier to further penetration of moisture has to be formed in the external thin layer of hydrophobic TMs. It conserves their internal layers in a relatively dry state. As a result, the volume density ρ_V decreases in spite of the growth in thickness δ in comparison the thinner PMs, in which the effect of a heavier surface layer is more pronounced.

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

The striking feature of the approach proposed is a possibility to form an AB- l/b -model (alternate basic model of hydrophilic and hydrophobic sets of TMs) expressed in the same asymptotic reference

terms from **Equations 4 & 5**, namely, $\rho_V^0 < \rho_V, \rho_M^0 < \rho_M$. It was formulated for the hydrophilic TMs as:

$$\gamma_{hphl}(\delta) = \rho_M^0 \delta - \gamma_{hphl}^0 \quad (a) \quad (8)$$

$$\rho_V(\delta) = -(\gamma_{hphl}^0 / \delta_0^2) \delta + \rho_V^0 \quad (b)$$

and for the hydrophobic TMs as (see also, **Figure 3**):

$$\gamma_{hphb}(\delta) = \rho_V^0 \delta + \gamma_{hphb}^0 \quad (a)$$

$$\rho_V(\delta) = -(\gamma_{hphb}^0 / \delta_0^2) \delta + \rho_M^0 \quad (b) \quad (9)$$

where, $\gamma_{hphl}^0(\delta \rightarrow 0)$ and $\gamma_{hphb}^0(\delta \rightarrow 0)$ were termed the surface densities of the 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 $d\rho_V/d\delta$ -slopes determined at finite densities γ^0 :

$$\rho_V(\delta \rightarrow 0) = \gamma^0 / \delta \quad (a) \quad (10)$$

$$d\rho_V(\delta \rightarrow \delta_0) / d\delta = -\gamma^0 / \delta_0^2 \quad (b)$$

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

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

Indeed, it follows from **Figure 4.a** that in the calculation of porosities recommend-

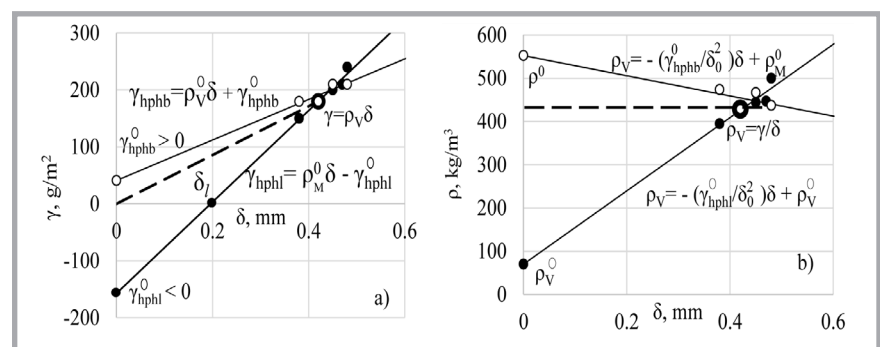


Figure 3. Typical strategy of AB-model in (γ - δ)- and (ρ_V - δ) planes used to separate the hydrophilic samples (represented by 5 black circles for the [2] variants of pure (100%) wool measured) from the hydrophobic samples (represented by 4 white circles) for the blended variants of wool measured (45% either with viscose (55%) or polyester (55%)). The asymptotic mass per unit area is 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].

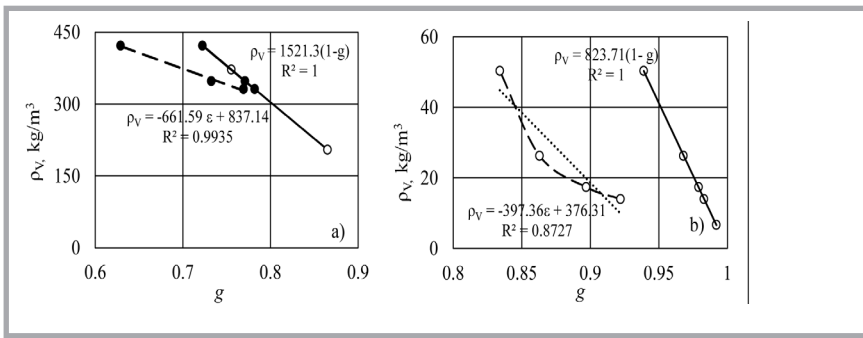


Figure 4. Revision of ρ_M -estimate from 1521.3 kg/m³ to 837.1 kg/m³ for cotton-based fibre [3], obtainable due to the correct selection for analysis of only hydrophilic purely-cotton samples (a); revision of ρ_M -estimate from 824.75 kg/m³ to 376.31 kg/m³ for non-woven fibres of “Hollow fibre” [4] due to the correct account of the environmental humidity of the experiment (b).

ed for cotton-based TMs, the authors [3] used the “mixture” of hydrophilic (3 points), purely (100%) cotton fibres and hydrophobic viscose (20%) and polyester (18%), which was still cotton-based (80%) fibres. This incorrect, to our mind, use of **Equation 2** for all fabrics in the common set of TMs leads to the strong overestimation in [3] of the common density of cotton-based dry matrix $\rho_M = 1521.3$ kg/m³. For comparison, the AB-*l/g*-model’s estimate for purely-cotton fibres is $\rho_M = 831.1$ kg/m³. Another reason for uncertainties follows from **Figure 4.b**, in which $\rho_M = 824.75$ kg/m³, recommended in [4] for a set (4 points) of hydrophobic non-woven “Hollowfibre”-materials and calculated by the same linear extrapolation based on **Equation 2**. In this case, a rather confused calculation procedure was used in [4] to estimate preliminarily the average (also overestimated) value $\rho_M = 824.75$ kg/m³. For comparison, the AB-*l/g*-model’s estimate for “Hollowfibre” PMs ($\delta > 4.5$ mm) is $\rho_M = 376.31$ kg/m³. For the convenience of the reader, four basic parameters of dry hydrophilic and hydrophobic PMs and TPMs are collected in **Table 1**. In order to avoid misunderstanding, it should be emphasised that the values of γ^0 , ρ_V^0 , ρ_M^0 are not actual

values, but those of the model calculated according to **Equations 8, 9 and 10**. The number of points mentioned at particular positions are related to measuring points taken from charts included in the references [2 - 6].

Concepts of effective porosity and maximal hygroscopicity of TMs

To go beyond the *standard but restrictive definition of porosity g* by **Equation 2**, we have conceded that the AB-*l/g*-interpolation between the pair of “moist” measurable densities ρ_V , ρ_M and their “dry” counterparts ρ_V^0 , ρ_M^0 (common to the entire set) is related to the standard porosity g in accordance with **Equation 4.b**. This admission allowed us to estimate preliminarily by **Equation 4.a** 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 here is to introduce a simplified estimate of its deviation from the *measurable effective porosity* by means of **Equation 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 **Figure 4.a, 4.b** by straight solid lines. One may, of course, speculate as to the influence either the density of threads (warp/weft-type of TM) or the type of fibrefill (regular for woven TMs and chaotic for non-woven, rather thick PMs) on the effective ρ_M -value. However, in any case, to state that there is a common constant value ρ_M for a “mixed” set of different hydrophilic and hydrophobic structures (as is seen from **Figure 4.a, 4.b**) is certainly an oversimplification. Besides this, such an assumption can lead to obviously erroneous theoretical estimates of ρ_M -value.

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

In this problem we have used simplified maximal estimates of ε^0 and w^0 following from **Equation 6**, where the *internal mesoporosity* of threads and their permeability for moisture were approximately taken into account. The results of calculations based on **Equation 6** sometimes look unwonted because the *hydrophobic*

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

PMs	N	Nomenclature of samples	δ_0 , mm	γ^0 , g/m ²	γ_V^0 , kg/m ³	γ_M^0 , kg/m ³
Hydrophilic	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
Hydrophobic	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/polyester, TPU/polyester, TPU/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

blended fibres [2] of wool (45%) with the addition either viscose (55%) or polyester (55%) demonstrate much more hygroscopicity (23 - 31%) in comparison with that for the *hydrophilic* pure (100%) wool (7.3 - 7.6%). Our classification here of the wool-viscose sample as hydrophobic (at the condition of experiment) is exclusively based on its observable properties, and not on the general consideration of its underlying microstructure. The latter can be taken into account in the discussion of dominant components in the WVT-process.

Nevertheless a possible explanation of this observation follows directly from **Figure 5**. One may compare three $\alpha(\rho_V)$ -curves located in a relatively narrow range of bulk densities (400 - 480 kg/m³) for *hydrophilic* pure wool [2], for hydrophobic samples of laminated nylon and polyester [6], and for hydrophobic blended wool/viscose and wool/polyester samples [2]. Their negative slopes $\Delta\alpha/\Delta\rho_V$ are quite different and just this factor could determine the level of maximum hygroscopicity w^0 .

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

$$\frac{dw^0}{d\rho_V} = -\frac{dg}{d\rho_V} = \frac{1}{\rho_M} \quad (11)$$

$$\frac{dw^0}{d\rho_V} = -\frac{d\varepsilon}{d\rho_V} = \frac{\rho_V^0(\rho_M^0 - \rho_V^0)}{(\rho_M^0\rho_V - \rho_V^0)^2} \quad (b)$$

The restrictive meaning of the standard estimate by **Equation 11.a** becomes obvious here, but is still physically plausible: the *more density of the matrix* ρ_M for any (*hydrophilic or hydrophobic*) TMs the less the “rate” of hygroscopicity $dw^0/d\rho_M$. On the other hand, the influence of ρ_V on the same “rate” is more sophisticated according to **Equation 11.b**. It can be expressed, similar to **Equation 11.a**, in terms of the ρ_M -value, taking into account **Equation 4.a**:

$$\frac{dw^0}{d\rho_V} = -\frac{d\varepsilon}{d\rho_V} = \frac{\rho_M^0 - \rho_V^0}{(\rho_M - \rho_V^0)^2} \quad (12)$$

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

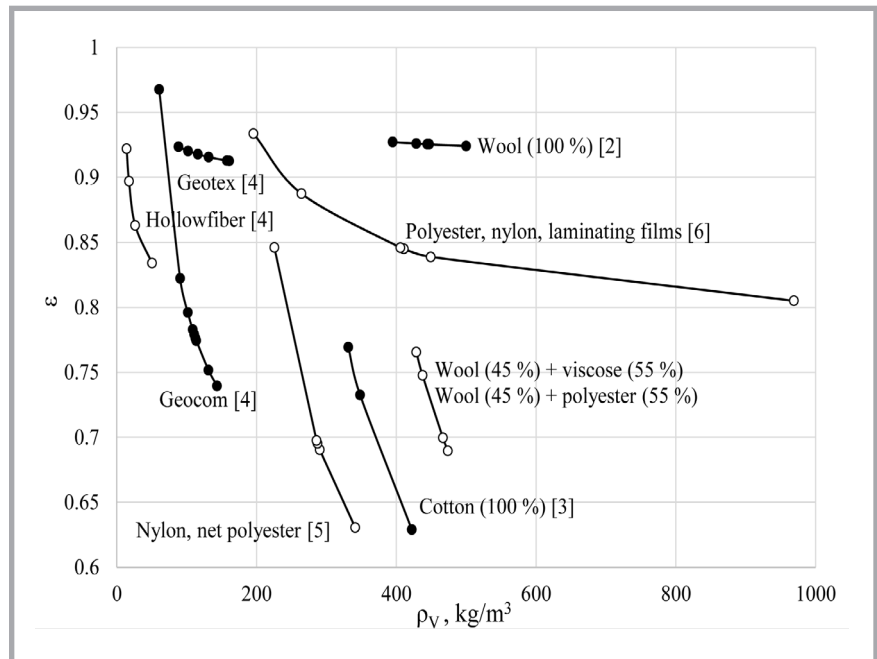


Figure 5. Effective porosity of hydrophilic (black points) and hydrophobic (white points) TMs as function of the bulk density predicted by the AB-l/b-model.

Concerning an appropriate choice of independent variables

In this work only the static (time-independent) characteristics of TM and its porosity have been determined by the AB-l/g-model. However, some results obtained may have an influence on the correct interpretation of the standard test-method’s results obtained for any PM-objects. The dynamic nature of WVT-measurements of the mass-flux density $j_m = \Delta m/(A_\perp \Delta t)$ is obvious, while the respective choice of a thermodynamic force (either the gradient of pressure $\Delta P/\delta$ or 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 of partial water-vapour (WV-) pressures (and, also, WV-concentrations) can be appropriate.

One may note that the transport coefficients for TM, ν and τ , from **Equations 1 & 7** can be *independently* determined by a WVT-experiment (in which the mass-flux density j_m is usually reported [6]) only if the respective thermodynamic force (gradient type) is also given. Recently we have considered [8] this problem in terms of a set of measurable *i*-test-method-dependent fluxes: $j_m^i/j_m^0 = \Delta P^i/\Delta P^0$ reduced to the reference flux chosen: j_m^0 with a known experimental pressure-

drop ΔP^0 . The ΔP^i -value calculated (this important characteristic of any transport process is, as a rule [6, 7], uncontrollable by the WVT-experimentalist) was 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] with the generalised resistance of the *k*-th fabric.

Thus the concrete choice of a pair: *density of flux-thermodynamic force* often leads to *dynamic*, by nature, transport coefficients expressed, however, in terms of (reciprocal) the kinetic effective velocity u^{-1} in s/m. Typical examples of such a “substitution” are [2] the *mass transfer coefficient* β_p [kg·m⁻² Pa⁻¹ s⁻¹] = s/m = $[j_m]/[\Delta P]$ and *evaporative resistances* of the air gap (between skin and fabric) R_{etg} , the fabric itself R_{et} , and the external boundary layer R_{et0} [Pa·m²/W] = s/m = $[\Delta P]/[j_q]$. All are dependent on the (chosen by chance) time-interval Δt of the WVT- or WVP-measurements as well as on the arbitrarily chosen geometric characteristics A , δ of the 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 R_{etg} of thickness h : $R_{etg} = h/D_p$, while R_{et0} is represented simply as: $R_{et0} = 1/\beta_p$.

Recently we have developed an alternative approach to the mass-heat-charge transport problems in TPMs [8] which is based on the model of Fluctuational 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:

$$\Delta P/\delta = \rho (\Delta\mu + s_m\Delta T + e_m\Delta\phi)/\delta \quad (13)$$

where, μ in J/kg – chemical potential, ϕ in J/C1 – electric potential, s_m in J/kg K – specific entropy e_m , and C1/kg – the specific electric charge. The special role of the 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 **Equation 13** that the fluctuational equation (FEOS) developed to describe the WV-properties [9] could be very useful for the problems of TPMs discussed. In particular, for the isothermal neutral fluid the gradient of chemical potential (corresponding to the thermodynamic force in the generalised Fick's law for self-diffusion) becomes the known function of the gradient of pressure: $\Delta\mu/\delta = \Delta P[\rho; T = \text{const}, \phi = 0]/\rho \delta$. This observation leads to the special role of the bulk density ρ_V as the independent variable for PMs. One may note that the effective porosity $\varepsilon(\rho_V)$ introduced in this work also demonstrates the similar role of ρ_V for TPMs. It should also be emphasised that **Equations 1 & 7** were derived [8, 9] to eliminate any influence of the arbitrary parameters in WVT-measurements ($\delta, A; \Delta t$) on the kinetic effective transport coefficients defined just for TM, i.e. ν and τ .

From what has been said 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 the *relative WVP* (RWVP)-quantity in % with PERMETEST apparatus. According to the standard ISO 11092 developed for TMs, it determines the following: the thermal resistance in a dry state R_{ct} in $\text{K}\cdot\text{m}^2\cdot\text{W}^{-1} = [\Delta T]/[j_q]$, the RWVP-quantity and the evaporative resistance R_{et} of the fabric by equalities:

$$RWVP = (j_q^s/j_q^0) 100 \quad (14)$$

$$R_{et} = (P_w^s - P_w^0) (1/j_q^s - 1/j_q^0) = C (100 - \phi) (1/j_q^s - 1/j_q^0) \quad (15)$$

where, j_q^s and j_q^0 indicate the *heat-flux density lost* and the approximation by the *adjustable apparatus-dependent constant* C , Pa has been used to calculate the drop in partial pressures. The independent variable for analysis of the RWVP (R_{et})-function was firstly the mass per unit of area γ , and then the undimensional relative moisture U of the fabric:

$$R_{ctw} = R_{ct}(1 - kU) \quad (16)$$

where, the *thermal resistance in a wet state* R_{ctw} in $\text{K}\cdot\text{m}^2\cdot\text{W}^{-1}$, is approximated by the other *adjustable apparatus-dependent constant* k .

The variety of parameters, adjustable constants, and types of fluxes make the ISO 11092-methodology and its useful modified PERMETEST-version, in general, rather formidable but 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 the ISO 11092-test are uncorrelated with other test-methods, and for this aim proposed to consider the reciprocal $1/R_{et}$ -quantity with the dimensionality of kinetic velocity u [m/s]. This seems reasonable if one takes into account the consideration above and that the units of standard convection-diffusion WVT-measurements [6, 7] j_m in $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ can be composed of a product of two units: $[\rho][u] = \text{kg}\cdot\text{m}^{-3}\cdot\text{m}\cdot\text{s}^{-1}$.

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

If one omits the usage of percent definitions for the relative humidity of air and RWVP, **Equations 14 & 15** can be easily transformed to represent the PERMETEST-measurements [2] with two consistent equalities:

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

where, the supposed relationship:

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

has been used. One needs only the isobaric heat capacity of moisture in $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ to approximately determine the specific internal energy: in **Equations 17 & 18**.

The result obtained here seems important and interesting. Its comparison to the standard definition of porosity g by **Equation 2** confirms, first of all, the existence of functional connections between any permeabilities and porosities in which the porosities are the functions of the common independent variable. The similarity between physical conclusions with respect to permeability based on the WVT-measurements of mass-fluxes [3 - 6] and on the PERMEREST-measurements of heat-fluxes [2] corroborates their consistency.

The choice of the mass per unit of area γ as an independent variable has been plotted in **Figures 4 & 5** from [2] despite its conclusion in the comparison of linear trends: the *higher the RWVP-quantity, the lower the -value seems rather trivial, at least for dry 100% wool fabrics* taking into account **Equation 18** at a 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) made in **Figures 8 - 10** [2] in terms of the relative moisture U from **Equation 16** is more promising from our viewpoint. One may note that this variable corresponds approximately to one used in the AB- l/g -model:

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

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

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

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

Another interesting correspondence between our observations and the PERMETEST-measurements [2] follows from a comparison between the two above-named cooling heat fluxes for wet 100% wool fabric (**Figure 8** [2]) and wet 45% wool/55%viscose fabric (**Figure 9** [2]) and wet 45% wool/55% polyester fabric (**Figure 10** [2]). The first sample is supposedly hydrophilic, while the second and third samples – hydrophobic. The respective quantitative change in the slopes is shown in **Figure 3.b**. Authors [2] observed a *similar change in the slopes in plane RWVP-U*. Taking into account our interpretation of variable U by way of **Equations 19 & 20** may be the decisive factor in the choice of clothes to provide better thermal comfort in spite of their moisture content.

Conclusions

The novel AB- l/g -model of effective hydrophilic and hydrophobic porosity ε proposed on the basis of experimental (γ , δ)-data for 41 different TMs taken from [2 - 6] enables the elimination of the influence of the measuring laboratory's conditions e on the results of measurements. The simple model's estimates of the matrix density, observable porosity ε and maximum hygroscopicity can be obtained from **Equations 4 - 12** with the use of the bulk density only and without any ad-

justable coefficients. The interesting correspondence between the AB- l/g -model's predictions and PERMETEST-measurements of the RWVP-quantity is revealed. One may consider the AB- l/g -model proposed as the necessary preliminary steps for a further, more detailed study of the permeability considered as a function of the effective porosity within the framework of **Equation 7**. The variety of theoretical models proposed at present for permeability in which the porosity is only an adjustable parameter can now be considered from a general physical viewpoint. The practical usage of the AB- l/g -model for the comparison of different TMs may be quite promising for the further investigations of PMs in general.



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