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ABOUT CORRELATION BETWEEN THE PERCOLATION RATE OF MOISTURE THROUGH THE SEMI-PERMEABLE MEMBRANES AND THE STANDARD MEASUREMENTS OF THEIR PERMEABILITY OR EVAPORATIVE RESISTANCE

A variety of test methods to estimate the water vapour transmission (WVT)-rate of thin membranes do not provide, unfortunately, the reliable basis to compare the permeability of different fabrics. Their results are crucially dependent on the details and construction of experimental methodologies as well as on the accepted by the different authors conditions of measurement. In this work, we propose the universal approach and demonstrate its adequate realization to compare the transport properties of any semi-permeable membranes measured by the conventional test-methods. The purpose is to avoid any confusion in such procedure of comparison. We have analysed below the WVT-rates measured by six alternative test-methods, which have been applied step-by-step to six different fabrics. In opposite to the widespread search for a pair correlation between the above results obtained by any two methods we treat them, in total, for each fabric in terms of the reduced variables. This approach is based on the novel concept of the moisture percolation (MP)-rate which combines the diffusion and convective contributions in a transport process. It leads to the well-established general estimates of the normalized WVT-rates measured by the standard test-methods. Another advantage of the developed approach is its thermodynamic consistency, which offers the appropriate fluctuation model to take into account the porosity of any semi-permeable membranes.

Keywords: *Water vapour permeability – Standard test-methods – Moisture percolation rate*

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ПРО КОРЕЛЯЦІЮ ШВИДКОСТІ ПЕРКОЛЯЦІЇ ВОЛОГИ КРІЗЬ НАПІВПРОНИКНІ МЕМБРАНИ І СТАНДАРТНИХ ВИМІРЮВАНЬ ПРОНИКНОСТІ АБО ОПОРУ ВИПАРЮВАННЮ

Різноманітні тест-методи, запропоновані для оцінки швидкості переносу вологої водяної пари (WVT-швидкості) крізь тонкі мембрани не забезпечують, на жаль, надійної основи для порівняння паропроникності різних тканин. Їх результати вирішальним чином залежать від конструктивних деталей експериментальних методологій, а також від прийнятих різними авторами умов вимірювань. В цій роботі ми пропонуємо універсальний підхід і демонструємо його адекватну реалізацію при порівнянні транспортних властивостей будь-яких напівпроникних мембран, вимірюваних прийнятими тест-методами. Метою є бажання уникнути будь-яких неузгоджень в такій процедурі. Ми проаналізували WVT-швидкості, виміряні шістьма методами, які були застосовані крок за кроком до вивчення шести різних тканин. В протилежність широко-поширеному пошуку парних кореляцій між подібними результатами, одержаними з допомогою будь-яких двох методів, ми обробляємо їх, в цілому, для кожної тканини в термінах приведених змінних. Цей підхід заснований на новій концепції швидкості перколяції вологи (MP), яка комбінує дифузійний і конвективний внески в процес транспорту. Вона приводить до добре-визначених узагальнюючих оцінок, нормованих WVT-швидкостей, спочатку виміряних стандартними тест-методами. Другою перевагою розвинутого підходу є його термодинамічна узгодженість, яка веде до придатної флуктуаційної моделі, враховуючої пористість будь-яких напівпроникних мембран.

Ключові слова: *паропроникність – стандартні тест-методи – швидкість перколяції вологи*

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I. INTRODUCTION

A textile fabric provides the effective weather protection and thermal comfort of clothing systems if it realizes the concept of semi-permeable membrane. Such fabric is waterproof and windproof yet permeable to water vapour and to other types of internal moisture. There are a variety of standard test methods to measure the respective permeability arising due to the pressure, temperature and the relative humidity drops across the sample of a breathable fabric. Unfortunately, the distinctions with respect to their constructions, test conditions and the technique of measurements lead, often, to the quite different estimates of the water vapour transmission (WVT)-rate. Moreover, this property itself is not, strictly speaking, the characteristic of fabric but it reflects the dynamical reply of a clothing system to the existence of a directed thermodynamical force (i.e. above-named drops).

We have considered six waterproof breathable materials 1-6 (Table 1) including the samples of high (1,2), medium (3,4) and lower (5,6) water vapour permeability membranes laminated to textile fabrics. The following set of the standard test-methods have been used to measure the WVT-rates and the evaporative resistances as well.

I – *Sweating guarded hot plate test* specified in ISO 11092 [1] (it is applicable to estimate only R_{ef}, m^2 Pa/W);

II – *Upright cup method* specified in ASTM E96, Procedure B [2] (abbreviated as E96-B below which gives the smallest WVT-estimates [6];

III – *Inverted cup method* specified in ASTM E96, Procedure BW [2] (abbreviated as E96-BW below);

IV – *Dynamic moisture permeation cell (DMPC) test method* specified in ASTM F 2298 [3] (abbreviated as F 2298);

V – *Desiccant Inverted cup test method* specified in ISO 15496 [4] (it gives the biggest WVT-estimates [6];

VI – method developed by Huang and Qian (abbreviated as HQ below which has been accepted in [6] and in this work as the reference WVT- and R_{ef} -measurements).

The distinction of above test methods in construction mechanisms, test conditions, measurement parameters and units lead to the quite different WVT-estimates for the same fabrics and/or other porous materials. Our purpose below is to propose and use the novel methodology of a universal treatment, which should be applicable to the results of any test methods. Such approach provides the basis to compare the actual properties of fabrics instead of the ill-defined ones. Another aim of the proposed universal approach is the development of strategy for the further detailed thermo-physical investigation of a semi-permeable membranes based on their realistic porous structures following from the unified experimental WVT-estimates.

This work develops the novel consistent methodology to offer the realistic WVT-estimate of a fabric, based, simultaneously, on the results of different standard test methods. The theoretical concept of a moisture percolation rate is used below to obtain the adequate WVT-model.

II. CONCEPT OF NOVEL METHODOLOGY AND ITS EXPERIMENTAL FOUNDATION

The comparison of different standard test-methods in use [1-5] proposed to study the WVT-rate of textile fabrics and/or other porous materials is about the common place for the relevant investigations [6,7]. As a rule, their authors formulate the following goal if such works. One should reveal the presumable correlation existing between any two sets of experimental WVT-rates obtained independently for the same several materials by the pair of alternative measurements.

A good illustrative example of this approach is the work of Huang and Qian [6] in which the results of five test-methods have been compared in a step-by-step manner I-V for six different fabrics 1-6 with the results of new WVT-method VI developed by these authors themselves [5] and applied to the same 1-6 fabrics. The identification of chosen fabrics i=1,…,6 and their specific parameters (thickness δ^i mm, surface density σ^i g/m^2 and volume density $\rho^i = \sigma^i / \delta^i$ kg/m^3, fabric description) are represented in Table I taken from [6].

Table 1 – Specification of the Fabrics

	Sample code and description	Surface density kg/m^2	ρ_M, kg/m^3	δ, mm
1	PTFE laminated to a nylon tricot	$94.5 \cdot 10^{-3}$	410.9	0.23
2	Cotton/polyester knitted fabric	$237.8 \cdot 10^{-3}$	264.2	0.90
3	Polyester fabric laminated with PU film	$148.3 \cdot 10^{-3}$	449.4	0.33
4	Densely woven polyester fabric	$96.9 \cdot 10^{-3}$	969.0	0.10
5	Polyester polar fleece laminated with TPU film	$275.8 \cdot 10^{-3}$	195.6	1.41
6	Nylon rip stop weave laminated with TPU film	$125.8 \cdot 10^{-3}$	405.8	0.31

The *sequence* of fabrics in the set 1-6 was selected from the most permeable ones (1,2) up to the hardly permeable ones (5,6) through the intermediate permeable (3,4) ones. For each fabric, the WVT-rate obtained by method VI have been consequently compared with its estimate based on one of the other methods II-V (E96-B [2], E96-BW [2], F2298 [3], ISO 15496 [4], respectively). The method I (ISO 11092) [1] which provides *only the evaporative resistance of fabric* R_e^i, s/m = m^2 Pa/W *but not the WVT-rate itself* should be omitted at the first stage of analysis. The identification of used test-methods, k=I,…VI, their specific fea tures and the controllable parameters (temperature T,K, relative humidity *etc*. are represented in Table 2 taken also from [6].-

Table 2 – Comparison of Experimental Setup for Six Test Methods

Descriptors	ASTM E96 B	ASTM E96 BW	ISO 15496	ASTM F2298	ISO 11092	HQ
relative humidity	50%	50%	23%	5%	40%	0
air velocity	2.8 m/s	2.8 m/s	not controlled	not controlled	1 m/s	0.4 m/s
test temperature	23ºC	23ºC	23ºC	20ºC	35ºC	20ºC
air layers (al)	al on either side of PS	external al	no al	small al on either side of PS	boundary al subtracted out	small al subtracted out
pressure gradient across PS	not controlled	not controlled	not controlled	0	not controlled	not controlled

The results of described approach shown graphically as well as by the calculated coefficient of correlation in [6] are typical for many similar works, which lead to the common (rather trivial one, from our viewpoint) conclusion. The correlation exists actually between any two standard test- methods [2-5] of WVT-measurements and also with the method VI developed by Huang and Qian [6]. As a consequence, the approximately linear dependences based on the WVT-data represented by four method-dependent points for an each fabric are shown in the set of coordinate planes VI-II,…,V for all six fabrics 1-6.

Unfortunately, the drawbacks of such analysis are evident. Firstly, the above lines with coefficients calculated by lsq-method have not the physically-motivated zero-point in the origin of coordinates. This artificial *shift* between the measured WVT-values can be explained only by the *uncontrollable distinctions in the used test-methods* but not by the specific properties of tested fabrics. Secondly, the observable *different slopes* of lines cannot be exclusively attributed to the permeability of fabrics just due to the method-dependent technique of their calculation. Thirdly, (and this shortcoming is the most serious one) the adopted by the different methodologies [1-6] mass-transport WVT-equation is not, at all, specified.

To elucidate the last statement let us assume as a first approximation that the linear quasi-diffusion connection *do exists* between the measurable WVT-rate, j_m^{ik} , kg/m^{2}s and the generalized thermodynamic force-gradient $\Delta P^k / \delta^i$, kg/m^{2}s^2:

$$j_m^{ik} = -D_P^i \Delta P^k / \delta^i = -\alpha R^i \Delta P^k , \qquad (1)$$

where ΔP^k , $\mathrm{Pa} = \mathrm{N/m^2}$ is the usually uncontrollable method-dependent drop of the partial moist-air's pressure, α<<1 is the universal adjustable coefficient and D_P^i, s is the respective generalized coefficient of a quasi-diffusion mass-transfer though the *i*-th fabric. We determine also the generalized moisture's resistance R^i of *i*-th fabric by the second equality in Eq.(1), the effective velocity of transport u^i and the respective diffusion coefficient D^i , m^2/s which is inversally proportional to D_P^i:

$$u^i = \alpha \cdot \delta^i / D_P^i \ (a) \quad D^i = \alpha \delta^{i2} / D_P^i = \delta^i \cdot u^i \ (b) \quad (2)$$

Our main argument directed against the conventional methodology of comparison used, for example, in [6] is following. *One could not determine the actual specific characteristics of i-th fabric without the consistent measurement just of the ratio* $j_m^{ik} / \Delta P^k$ *to eliminate the influence of a method-dependent k-th factor*. In opposite case, the implicit usage of different scales along the coordinate axes in the plane $j_m^{iVI} - j^{iII}$, for instance, leads to the quite arbitrary meaning of above-discussed *shifts and slopes*. Their presumable physical interpretation (see next Section 3) becomes, as a result, rather elusive.

To avoid such situation we propose below the well-established sequence of statements and steps:

(a) - the analysis in terms of the undimensional mass-density flows j_m^{ik} reduced to the common scale-factor j_m^{iVI} , for example, is preferable to be performed separately for an each *i*-th fabric;

(b) - it follows from Eq.(1) that only one chosen scale-factor's drop of pressure ΔP^{VI} should be measured or given to estimate the other ones ΔP^k if the reduced WVT-rates are known and the external conditions of measurements are same ones:

$$\Delta P^k = \Delta P^{VI} \, j_m^{ik} \big/ j_m^{iVI} \ ; \qquad (3)$$

(c) - the information following from (a) and (b) at these assumptions is necessary and enough to estimate approximately the actual characteristics of the *i*-th fabric's permeability D_P^i, R^i by Eq.(1) as well as to calculate their physically-connected counterparts u^i, D^i by Eq.(2):

(d) - the comparison between the resultant convection-diffusion density ρ, kg/m^3 of WVT-flow: $j^i = \rho u^i$, its experimental value $j_e^i = \rho / R_e^i$ determined directly by the method I for example [1,6] and the measured WVT-rate j_m^{ik} may provide, in principle, the fundamental insight on the role of *porosity* in the problem of permeability and its adequate physical modelling.

III. REALIZATION OF NOVEL METHODOLOGY FOR SIX DIFFERENT FABRICS

There are some alternative strategies to realize the proposed concept of novel methodology (Section2). We consider below the simplest possible one based on

Table 3 – Ratio of the WVT-value from HQ-method VI to those following from II;III;IV;V methods

Sample code	WVT-ratio HQ/E96-B	WVT-ratio HQ/E96-BW	WVT-ratio HQ/F2298	WVT-ratio HQ/ISO 15496
1	7.88	1.49	1.45	0.38
2	4.85	1.47	1.16	0.50
3	4.21	1.64	1.30	0.74
4	3.41	2.11	1.03	0.75
6	2.43	0.67	0.91	0.45
5	1.55	0.65	0.58	0.44
k-1	1	2	3	4

the WVT-rates measured in [6]. We *have represented here the following modified sequence of fabrics*: i=1,2,3,4,6,5 and test-methods k=I,II,III,V,IV,VI (in comparison with those *accepted in* [6] to obtain the monotonic trends. The reduced coordinates: $y^i = j_m^{iVI} / j_m^{ik}$ and $x^k = \Delta P^{VI} / \Delta P^k$ were calculated in accordance with (a)- and (b)-steps. The input WVT-data have been evaluated at the estimation of y^i-values for all methods k=II,…,V represented in Table 3. Of course, one should not use at the start of procedure the primitive equality: y=x following from Eq.(3) because *any information about* x^k *-value is a priori unknown and the conditions of experiment are not the same ones* (Table 2).

To illustrate the developed strategy and to obtain the numerical estimates we have adopted *on the ad hoc basis* that: $\Delta P^{VI} = 5\cdot 10^2$ Pa and the trial x^k-values coincide with their specification by the (k-1)-index from Table 3, i.e. $x^{II} = \Delta P^{VI} / \Delta P^{II} = 1$, $x^{III} = \Delta P^{VI} / \Delta P^{III} = 2$ etc.

It should be emphasized that the decrease of y-values with the growth of x-values observable at this treatment is, exclusively, the result of chosen here sequence in the set of k-th methods taken, mainly, from [6]. Hence, the negative sign of a coefficient-slope b^{ik} from Table 4 does not contain any physical content. It serves only for aim of approximation (performed by the standard lsq-method).

Taking into account the evident decreasing trend of the experimental WVT-data, we have used the simplest linear function *y(x)* for approximation (Table 4) but the more complicated variants of description are also admissible.

Table 4 – Coefficients used to estimate the pressure drop of different test methods by Eq.(4) (as an alternative to Eq.(3)).

Coefficient	i					
	1	2	3	4	6	5
a^{ik}	8.435	5.335	4.66	4.09	2.54	1.655
$-b^{ik}$	2.254	1.336	1.075	0.906	0.57	0.34
$-a^{ik}/b^{ik}$	3.74	3.99	4.33	4.51	4.46	4.87

One can easily derive now the set of equalities to estimate the respective kinematic characteristics of any i-th fabric determined by Eq.(2):

$$\Delta P^k = \Delta P^{VI} b^{ik} / \left(a^{ik} - y^i\right) \quad (4)$$

$$u^i = \alpha \cdot \left(\Delta P^k \cdot 864 \cdot 10^5\right) / j\,(a) \quad D^i = \delta^i u^i\ (b) \quad (5)$$

where the numerical coefficient $864\cdot 10^5$ is necessary to transform the standard unit of WVT-rate j_m, g/m^{2}day [6] into SI-unit, kg/m^{2}s. To determine the universal scale-coefficient in Eqs.(1,2) $\alpha \cong 1\cdot 10^{-10}$ we have used the average effective resistance: $R^{VI} \approx 0.2$ s/m measured simultaneously with the WVT-rate in the method VI developed by Huang and Qian [5,6]. This universal coefficient takes into account also the standard pressure drop $\Delta P^{VI} = 5\cdot 10^2$ Pa accepted above for the same method.

The results of such calculations are represented in Table 5 and shown in Figure 1. They are quite promising and realistic from the physical viewpoint. One obtains the good correspondence between the so-called air-permeability (AP) expressed usually in units of kinematic velocity:

$$AP^{ik} = \Delta V^k / \left(A_\perp^i \Delta t^k\right), \text{ m/s} \quad (6)$$

and its WVT-based counterpart u^i introduced by Eqs.(2a) and (5a). The latter follows from the independently measured WVT-rates j_m^{ik} which are much more discussable and measurable [6]. Nevertheless, just AP^{ik}-quantity and the effective kinematic velocity u^i are mostly connected with the properties of i-th fabric. To make this connection to be more explicit we propose in Section 4 the interpretation of Eq.(6) based on the determination of a convective mass-flow:

$$j^{ik} = \rho \cdot AP^{ik} = \rho\, \Delta V^k / \left(A_\perp^i \Delta t^k\right) \quad (7)$$

where ρ, kg/m^3 is the volume density of a dry air.

IV. FLUCTUATIONAL-THERMODYNAMIC MODEL OF MOISTURE TRANSPORT THROUGH THIN POROUS MATERIALS

The thermodynamic force $\Delta P/\delta$ and its dimensionality determined by Eq.(1) is not unique in accordance with the generalized Gibbs-Duhem equality (First Law) for a pure substance:

$$\frac{\Delta\rho}{\delta} = \rho \cdot \left(\frac{\Delta\mu}{\delta} + s\,\frac{\Delta T}{\delta}\right) \quad (8)$$

where μ, J/kg=m^2/s^2 – chemical potential and s, J/kg K – specific entropy. One can add to the right-hand side the other gradients (of the electrostatic potential, $\Delta\varphi/\delta$, for example) to define the alternative sources for the transport of mass, heat, electric charge etc. through the thickness of material δ. Unfortunately, the above heat-parameters μ, s are unmeasurable and, as a result, uncontrollable in the standard WVT-experiments.

To avoid this difficulty one supposes usually the *isothermal restriction* $(\Delta T = 0)$ of measurements (Table 2) and determines on the ad hoc basis the generalized Fick's law of self-diffusion:

$$j_m = \Delta m/(A_\perp \Delta t) = -D\,\Delta\rho/\delta \qquad (9)$$

where D, m^2/s – the diffusion coefficient. It has also meaning of a *kinematic viscosity* and/or *temperature-conductivity* in theory of gases:

$$D = \eta/\rho \quad (a) \qquad D = \lambda/(\rho C_v) \quad (b) \qquad (10)$$

where the dynamical viscosity η, kg/m·s =Pa·s and the heat conductivity λ, W/m·K are the standard transport coefficients while C_v, J/kg·is the equilibrium isochoric heat capacity. All above quantities η, λ, C_v in Eqs.(9,10) are measurable in the framework of Newton's and Fourier's laws but just a pair of quantities D, ρ forms the "bridge" between the linear non-equilibrium thermodynamics [8,9] and its molecular-kinetic interpretation in theory of the dilute gases [10]:

$$D = \langle u \times l \rangle / 3. \qquad (11)$$

The statistical-average velocity $\langle u \rangle$ and free-path parameter $\langle l \rangle$ can be expressed via the molecular characteristics of mass m_0, kg and effective diameter d_0, m:

$$\langle u \rangle = \sqrt{8k_B T/(\pi m_0)}\,(a) \quad \langle l \rangle = k_B T/\left(\sqrt{2}\pi d_0^2 P\right)(b) \quad (12)$$

The volume density $\rho = n m_0 = N m_0 / V$ is connected here with the pressure and temperature by the primitive ideal-gas equation of state (EOS) for any gaseous substance:

$$\rho = P m_0/(k_B T) = PM/(RT) \qquad (13)$$

where $M = m_0 N_A$, kg/mol, R = 8.314, J/(mol·K), N_A – the Avogadro number.

The restrictions and constraints of this famous deterministic model developed for the linear transport process are obvious but its attractive features should be noted too. These are, first of all, simplicity, physical plausibility and thermodynamic consistency of approach in which such cross-types of transport as the thermo-diffusion, for example, can be studied simultaneously with the respective "pure" process of self-diffusion and heat conductivity. Taking into account these advantages we propose below to modify the physical meaning of some input ingredients $D, \langle u \rangle, \langle l \rangle, \rho$ from Eqs.(11-13) in application to the thin porous structures where the quantities $D^i, u^i, \delta^i, \rho^i$ are essential but to conserve the general physical ideas of the described approach.

Its main concept leads to the use of a following modification for the generalized thermodynamic force $\Delta P/\delta$ in Eq.(8) without any restrictions imposed on its right-hand side:

$$\frac{\Delta\rho}{\delta}\cdot\frac{1}{\rho\,\chi_T} = \frac{\Delta\rho}{\delta}\cdot\left(\frac{\rho\,\Delta\mu}{\Delta\rho} - \frac{s}{\alpha_P} + \ldots\right) \qquad (14)$$

where the thermodynamic derivatives (isothermal compressibility χ_T and thermal expansion α_P determine the real *fluctuation nature* of the propose here approach:

$$\chi_T = (1/\rho)(\Delta\rho/\Delta P)_T\,(a) \quad \alpha_P = -(1/\rho)(\Delta\rho/\Delta T)_P\,(b) \quad (15)$$

while the absolute values of unmeasurable variables μ, s become formally inessential for the transport of mass. In other words, one may include a set of appropriate gradients of the scalar thermodynamic fields without their detailed specification for WVT-process In accordance with Second Law $\chi_T > 0$ is always positive but the cross-process' characteristic of thermo-diffusion $\alpha_P \gtreqless 0$ can change its at the special conditions.

We determine now on the base of definitions used in Eq.(2a) and Eq.(2b) the *convective velocity of air u* and its *density of flow j* through *i*-th fabric:

$$u = \alpha\,\delta/D_P \quad (a) \qquad j = \rho u = \rho\,\alpha\,\delta/D_P \quad (b) \qquad (16)$$

This modification provides the quite interesting interpretation of the adopted transport WVT-rate's Eq.(1):

$$j_m = -\frac{\alpha}{\rho u}\frac{\Delta\rho}{\chi_T} \quad (a) \qquad j_m \cdot j = -\frac{\alpha\,\Delta\rho}{\chi_T} \quad (b) \qquad (17)$$

where the fluctuation χ_T -parameter defined by Eq.(15a) has been taken into account. Its determination for *i*-th fabric is, of course, non-trivial but very important problem, which needs the modelling of a *respective porous structure*. However, if such problem is solved, for instance, by the search for an appropriate EOS of *i*-th fabric, one obtains the powerful methodology based on Eq.(17b) to study the *interaction between the diffusion and convective flows* of moist air through any thin porous material. Moreover, the respective density drop $\Delta\rho$ from Eq.(14) and Eq.(17) can be now reliably estimated on the base of experimental WVT-rates to use it for the calculation of an *effective diffusion coefficient D* in Eq.(9). Its value can be useful at the description of viscosity η and heat conductivity λ from Eq.(10a) and Eq.(10b), respectively. For this aim, the moist air density ρ should be reliably estimated too (Sectio nV).

V. MOISTURE PERCOLATION RATE

We consider now that the complex transferability of a semi-permeable membrane can be adequately described in terms of the novel MP-concept. Its meaning is evident from Fig.1 and Table 5, which demonstrate, as a matter of fact, the *reciprocal MP-rate* i.e. MP-resistance R_{MP} corresponding to the well-established slope of each *i*-line for the respective fabric. Physical sense of our estimates represented on terms of such slopes in the ($u_i, \Delta P^k$)-plane is essentially different from that discussed for the effective evaporative resistance R_{ef} in [6]. This distinction is expressed, first of all, in the used units of measurement. The former is R_{MP}, m² s/kg while the latter is R_{ef}, m² Pa/W=s/m. Besides, the evaporative resistance R_{ef} defined by the different test-methods is rather elusive quantity.

For example, the standard *sweating guarded hot plate test* (ISO 11092 [1]) is based on the following methodology. After steady-state of a moisture transport was reached one calculates, firstly, the so-called total evaporative resistance R_{et} of a fabric:

$$R_{et} = \frac{A_{\perp}(P_s - P_a)}{H - \Delta H_e} \qquad (18)$$

where R_{et}, m² Pa/W is provided by the membrane, fabric itself and boundary air layer which is, in fact, an arbitrary quantity of any calculations. To eliminate its influence one determines, then, R_{ef} as the difference:

$$R_{ef} = R_{et} - R_{eb} \qquad (19)$$

where the *combined* evaporative resistance R_{eb} of the membrane and boundary air layer was preliminarily estimated by conducting a test on the bare plate without a fabric over the membrane. The serious shortcoming is here the presumed isothermal assumption of measurements by ISO 11092-methodology in which the water vapour pressure P_s, P_a at the surface of the measured unit is assumed to be equal just to the saturation vapour pressure of pure water at 308 K while the water vapour pressure of the moist air P_a, P_a corresponds to the measurable relative humidity. The correction term ΔH_e, W subtracted in Eq.(18) from the measurable heating power *H*, W is also ill-defined quantity, to our mind.

In spite of above criticism, it is interesting to compare our R^i_{MP}-estimates following from the linear trends (Fig.1, Table 5):

$$u^i = u_0^{ik} + R_{MP}^{ik} \Delta P^k \qquad (20)$$

with those reported as R_{ef}, m² Pa/W and R_f, s/m in [6].

We have represented the main results of the proposed universal methodology in Fig.2 as well as in Table 6. It is obviously that the most simple E96 B-test is the most appropriate at the treatment of experiment in accordance to the obtained here estimate.

We consider Eq.(20) as the physically-motivated equivalent of Eq.(1) in which the universal scaling (adjustable) coefficient α is the same i.e. $\alpha=1\cdot10^{-10}$. The negative value - ($-u_0$) is the virtual velocity of an air diffusion transport realized through the given fabric without the pressure drop ΔP^k. The calculated from Eq.(20) universal method-independent MP-rate j^i_{MP} for each *i*-th fabric is the most important result of the novel methodology.

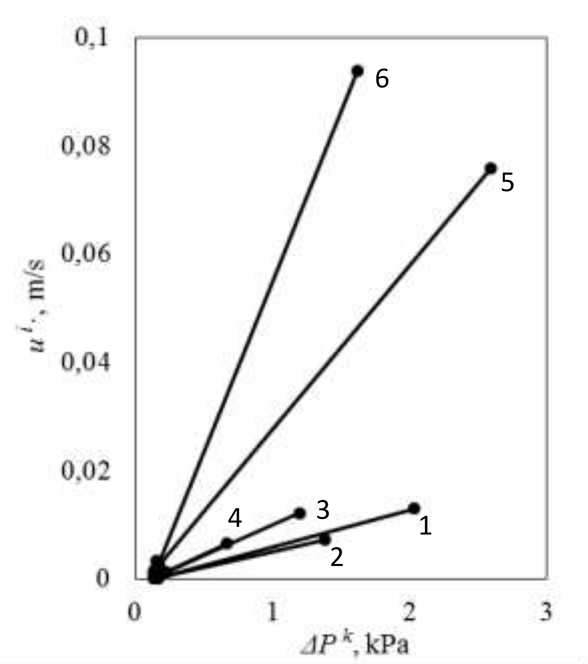

Figure 1 – Resultant dependence of combined convective-diffusion velocity in a fabric as a linear function of the method-dependent pressure drop.

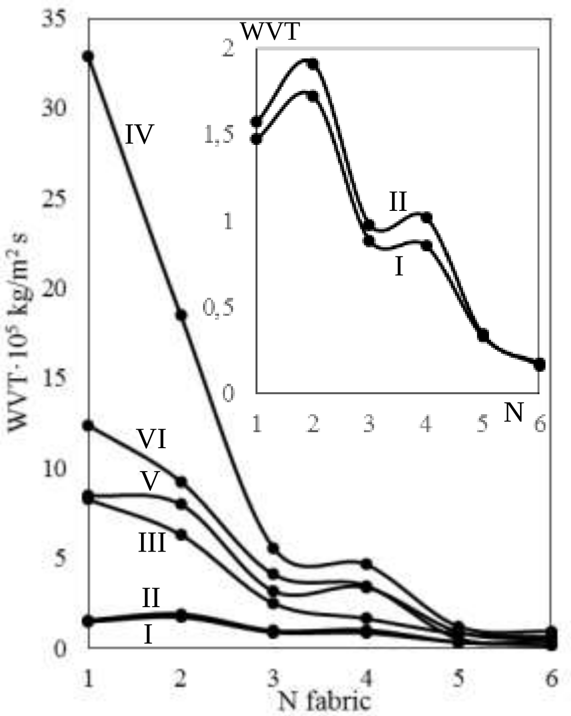

Figure 2 – Comparison of WVT-values predicted in this work (I) with those obtained experimentally by the different methodologies II-VI for the different fabrics 1-6 (smooth curves drawned via the experimental points [6] exclusively for the convenience of reader).

Table 5 – Comparison of MP-rates Obtained in This Work with the Results of Input Test Methods

Fabric	R_f [6] (s/m)	R_{ef} [6] (m^2 Pa/W)	$R_{MP}\cdot 10^3$ (m^2 s/kg)	$j_{MP}\cdot 10^7$ (kg/m^2 s)	$-u_0$ (m/s)
1	31.9	2.6	0.68	147.06	0.0009
2	76.1	3.9	0.58	172.41	0.0007
3	313.4	13.4	1.13	88.50	0.0013
4	380.3	15.1	1.17	85.47	0.0013
5	3126	275.5	3.05	32.79	0.0031
6	3941	363.9	6.24	16.03	0.0072

Table 6 – Comparison of WVT$\cdot 10^5$-values predicted in this work with those obtained experimentally by the different methodologies II-VI for the different fabrics 1-6.

Fabric	This work (I)	E96 B (II)	E96 BW (III)	ISO 15496 (IV)	F 2298 (V)	HQ (VI)
1	1.4706	1.57	8.28	32.9	8.5	12.4
2	1.7241	1.91	6.31	18.5	7.99	9.26
3	0.885	0.978	2.5	5.58	3.18	4.11
4	0.8547	1.02	1.65	4.66	3.38	3.48
5	0.3279	0.341	0.81	1.21	0.906	0.528
6	0.1603	0.172	0.623	0.925	0.458	0.419

One should estimate additionally only the MP-density ρ to predict the actual velocity provided by a fabric through the matrix of its semi-permeable membrane.

CONCLUSIONS

There are a variety attempts [7] to interpret the discussed problem on the molecular level. We have proposed in this work the useful novel methodology to connect, firstly, the experimental macro-observations of WVT-rate with its thermodynamic nature as well as with the possible molecular-kinetic explanation of the MP-transport processes. The results look to be quite promising for the further investigation and development.

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О КОРРЕЛЯЦИИ СКОРОСТИ ПЕРКОЛЯЦИИ ВЛАГИ ЧЕРЕЗ ПОЛУПРОНИЦАЕМЫЕ МЕМБРАНЫ И СТАНДАРТНЫХ ИЗМЕРЕНИЙ ПРОНИЦАЕМОСТИ ИЛИ СОПРОТИВЛЕНИЯ ИСПАРЕНИЮ

Исследование полупроницаемых пористых структур и, в частности, их способности пропускать потоки влажного воздуха и тепла, преимущественно, только в одном направлении является фундаментальной задачей для многих отраслей современных высоких технологий. Геометрия подобных структур, в которой длина и ширина образца превалирует над выделенным направлением толщины, позволяет отнести их к типу тонких плёнок, называемых также полупроницаемыми мембранами. В работе представлен критический анализ шести основных тест-методов, большинство которых стандартизовано, как в Европе, так и в США. К сожалению, разброс предсказываемых с их помощью характеристик проницаемости одной и той же мембраны столь широк, что не даёт, по сути, основания предпочесть, например, одну ткань с априори требуемыми свойствами при сравнении с другой. С этой точки зрения универсальная, т.е. пригодная при обработке любых разнородных данных по проницаемости новая методология, предложенная в работе, имеет большое прикладное значение. Кроме того, она, фактически, фиксирует и описывает основные физические и геометрические параметры пористых структур, подлежащие экспериментальному измерению, что даёт возможность, в дальнейшем, обоснованно моделировать протекающие в них динамические транспортные процессы.

***Ключевые слова**: паропроницаемость – стандартные тест-методы – скорость перколяции влаги*

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