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

PRO KOREЛЯЦIЮ ШВIДКОСI ПЕРКОЛЯЦIЇ ВОЛОГI КРИЗЬ НАПiВПРОНiКНi МЕМБРANI І СTАНДАРТNIХ ВИМiРЮВANЬ ПРОНiКНOSTi ABO OPORУ ВИ-PAЮВАНню

Рiзноманiтнi тест-методи, запропонованi для оцiнки швидкостi переносу вологої водяної пари (WVT-швидкiсть) крiзь тонкi мембрани не забезпечують, на жаль, надiйної основи для порiвняння паропроникностi рiзних тканин. Їх результати визначаються не тільки конструктивними деталями експериментальних методологiй, а також залежать вiд прийнятих змiнних або умов вимiрювання. В цiй роботi ми, на основi власного пiдходу, i демонструємо його адекватну реалізацiю при порiвняннi транспортних властивостей будь-яких напiвпроникних мембран, оцiненнi двома методами. Метою є саме вони, не залежно вiд будь-яких умов i вимiрювань, цi методи. Ми проаналiзували WVT-швидкiсть i, згодом, кiлька мембран, оцiненi двома методами, якi вiдповiдають i вiдповiдають, на жаль, незалежно вiд будь-яких умов i вимiрювань, цi методи.

Ключовi слова: паропроникнiсть – стандартнi тест-методи – швидкiсть перколюцiї вологи

DOI: 10.15673/0453-8307.1/2015.36784

This work is licensed under the Creative Commons Attribution International License (CC BY).

http://creativecommons.org/licenses/by/4.0/
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 \( R_{ef} \), m² 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);


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 \( i=1,\ldots,6 \) and their specific parameters (thickness \( \delta^i \) mm, surface density \( \sigma^i \) g/m² and volume density \( \rho^i = \sigma^i / \delta^i \) kg/m³, fabric description) are represented in Table I taken from [6].

<table>
<thead>
<tr>
<th>Sample code and description</th>
<th>Surface density ( \rho_M ) kg/m²</th>
<th>( \rho_M ) kg/m³</th>
<th>( \delta ) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PTFE laminated to a nylon tricot</td>
<td>94.5·10⁻³</td>
<td>0.099</td>
<td>0.23</td>
</tr>
<tr>
<td>2 Cotton/polyester knitted fabric</td>
<td>237.8·10⁻³</td>
<td>264.2</td>
<td>0.90</td>
</tr>
<tr>
<td>3 Polyester fabric laminated with PU film</td>
<td>148.3·10⁻³</td>
<td>449.4</td>
<td>0.33</td>
</tr>
<tr>
<td>4 Densely woven polyester fabric</td>
<td>96.9·10⁻³</td>
<td>969.0</td>
<td>0.10</td>
</tr>
<tr>
<td>5 Polyester polar-fleece laminated with TPU film</td>
<td>275.8·10⁻³</td>
<td>195.6</td>
<td>1.41</td>
</tr>
<tr>
<td>6 Nylon rip stop weave laminated with TPU film</td>
<td>125.8·10⁻³</td>
<td>405.8</td>
<td>0.31</td>
</tr>
</tbody>
</table>

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 = m² Pa/W but not the WVT-rate itself should be omitted at the first stage of analysis. The identification of used test-methods, \( k=I,\ldots,VI \), their specific features and the controllable parameters (temperature \( T \), relative humidity \( \iota \), etc. are represented in Table 2 taken also from [6].
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 each fabric are shown in the set of coordinate planes VI-...V for all six fabrics 1-6.

Unfortunately, the drawbacks of such analysis are evident. Firstly, the above lines with coefficients calculated by isq-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 does exist between the measurable WVT-rate, \( j_m \), kg/m²s and the generalized thermodynamic force-gradient \( \Delta P^k / \delta^i \), kg/m²s²:

\[
j_m = -D_p \Delta P^k / \delta^i = -\alpha R^i \Delta P^k ,
\]

(1)

where \( \Delta P^k \), Pa = N/m² is the usually uncontrollable method-dependent drop of the partial moist-air’s pressure, \( \alpha \ll 1 \) is the universal adjustable coefficient and \( D_p \), 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 \( D^i \), m²/s which is inversally proportional to \( D_p \):

\[
u^i = \alpha \cdot \delta^i / D_p, \quad (a) \quad D^i = \alpha \delta^i / D_p = \delta^i \cdot u^i, \quad (b)
\]

(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 \( j_m^i / \Delta P^k \) 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 \( j_m^i / \Delta P^k \), 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 \( j_m^i \) reduced to the common scale-factor \( j_m^i \), 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 \( \Delta P^i \) should be measured or given to estimate the other ones \( \Delta P^k \) if the reduced WVT-rates are known and the external conditions of measurements are same ones:

\[
\Delta P^k = \Delta P^i \cdot j_m^i / j_m^i ; \quad (3)
\]

(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 \( D_p, R^i \) 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 \( \rho \), kg/m³ of WVT-flow: \( j^i = \rho u^i \), its experimental value \( j^i = \rho / R^i \) determined directly by the method I for example [1,6] and the measured WVT-rate \( j_m^i \) 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 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  | 23°C            | 23°C            | 23°C             | 20°C              | 35°C             | 20°C              |
| air layers (al)   | al on either    | al on either    | no al            | small al on either| boundary al       | small al          |
|                   | side of PS      | side of PS      |                  | side of PS        | subtracted out   | subtracted out    |
| pressure gradient | not controlled  | not controlled  | not controlled   | 0                 | not controlled   | not controlled   |

---

© V.B. Rogankov, N.P. Suprun, M.V. Shvets, A.V. Shchutska, 2015
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: \( y^i = \frac{j_m^{VI}}{j_m^{ik}} \) and \( x^k = \frac{\Delta P^{VI}}{\Delta P^{ik}} \) 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 3 – Ratio of the WVT-value from HQ-method VI to those following from II,III,IV,V methods

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

\[ \Delta P^k = \Delta P^{VI} b^{ik} \left( q^{ik} - y^i \right) \] (4)

\[ u^i = \alpha \left( \Delta P^{k} \cdot 864 \cdot 10^{-5} \right) / j \ (a) \] \[ D^i = \delta^i \ u^i \ (b) \] (5)

where the numerical coefficient \( 864 \cdot 10^{-5} \) is necessary to transform the standard unit of WVT-rate \( j_m \), g/m²/day [6] into SI-unit, kg/m²s. To determine the universal scale-coefficient in Eqs.(1,2) \( \alpha \approx 1 \cdot 10^{-10} \) we have used the average effective resistance: \( R^V \approx 0.2 \) 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:

\[ AP^k = \Delta V^k \left( A_{ik} \Delta t^{k} \right) , \text{m/s} \] (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 \( AP^k \)-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:

\[ j^k = \rho \cdot AP^k = \rho \Delta V^k \left( A_{ik} \Delta t^{k} \right) \] (7)

where \( \rho \), kg/m³ 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:

\[ \frac{\Delta P}{\delta} = \rho \left( \frac{\Delta \mu}{\delta} + s \frac{\Delta T}{\delta} \right) \] (8)

where \( \mu \), J/kg=m²/s² – chemical potential and \( s \), J/kg K – specific entropy. One can add to the right-hand side the other gradients (of the electrostatic potential, \( \Delta \psi/\delta \), etc.)
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:

\[
j_m = \Delta n / (A_1 \Delta t) = -D \Delta \rho / \delta
\]

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

\[
D = \eta / \rho \quad (a) \quad D = \lambda / (\rho C_v) \quad (b)
\]

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

\[
D = \langle u \times l \rangle / 3.
\]

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 \(d_{eq}\), m:

\[
\langle u \rangle = \sqrt{8k_B T / (\pi m_0)} \quad (a) \quad \langle l \rangle = k_B T / \sqrt{2 \pi m_0 \rho} \quad (b)
\]

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

\[
\rho = P m_0 / (k_B T) = PM / (RT)
\]

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

The restrictions and constraints of these 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 \(D', u', \delta', \rho'\) 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:

\[
\frac{\Delta P}{\delta} \cdot \frac{1}{\rho \chi_T} = \frac{\Delta \rho}{\delta} \left( \frac{\rho \Delta u}{\Delta \rho} - \frac{s}{\alpha_p} + \ldots \right)
\]

where the thermodynamic derivatives (isothermal compressibility \(\chi_T\) and thermal expansion \(\alpha_p\) determine the real fluctuation nature of the propose here approach:

\[
\chi_T = \langle l / \rho \rangle (\Delta \rho / \Delta P)_T \quad (a) \quad \alpha_p = -\langle l / \rho \rangle (\Delta \rho / \Delta T)_T \quad (b)
\]

while the absolute values of unmeasurable variables \(\mu, s\) become formally essential 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 \(\alpha_p \geq 0\) 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:

\[
\alpha \Delta P / D_p \quad (a) \quad j = \rho u = \rho \alpha \Delta P / D_p \quad (b)
\]

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

\[
j_m = -\frac{\alpha}{\rho u} \Delta P / \chi_T \quad (a) \quad j_m \cdot j = -\frac{\alpha}{\chi_T} \Delta P
\]

where the fluctuation \(\chi_T\) -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 \(\eta\) and heat conductivity \(\lambda\) from Eq.(10a) and Eq.(10b), respectively. For this aim, the moist air density \(\rho\) 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 \(R_{dp}\), \(m^2\) \(s/kg\) while the latter is \(R_{ef}\), \(m^2\) \(Pa/W=\)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 \(R_\alpha\) of a fabric:

\[
R_\alpha = \frac{A_i (P_s - P_a)}{H - \Delta H_c} \tag{18}
\]

where \(R_\alpha\), \(m^2\) \(Pa/W\) 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, \(R_{df}\) as the difference:

\[
R_{df} = R_\alpha - R_{dp}\tag{19}
\]

where the combined evaporative resistance \(R_{dp}\) 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 \(P_a, P_s\) corresponds to the measurable relative humidity. The correction term \(\Delta H_c\), \(W\) 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 \(R_{dp}\)-estimates following from the linear trends (Fig.1, Table 5):

\[
u^i = u_0^{ik} + R_{MP}^{ik} \Delta P^k \tag{20}
\]

with those reported as \(R_{df}\), \(m^2\) \(Pa/W\) and \(R_{df}\), \(s/m\) 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 \(\alpha\) is the same i.e. \(\alpha = 1 \times 10^{-10}\). The negative value \(- (\alpha u_0^{ik})\) is the virtual velocity of an air diffusion transport realized through the given fabric without the pressure drop \(\Delta P^k\). The calculated from Eq.(20) universal method-independent MP-rate \(f_{MP}\) 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.](image1)

![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 drown via the experimental points [6] exclusively for the convenience of reader.](image2)
One should estimate additionally only the MP-density $\rho$ 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.

**REFERENCES**

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 превалируют 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 ими 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

ЛИТЕРАТУРА