# Hydraulic Description of Biological Beds – a Generalized Approach

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The experimental results concerning the hydraulics of selected natural commercial, wetted and mechanically loaded beds were presented. The data were elaborated with the use of the dependence $Eu = f(Re)$ in connection with Windsperger's equation for estimation of the equivalent diameter. It was concluded that for practical purposes it is possible to employ the equation $Eu = CRe^A$ for calculation of pressure drop with a good accuracy.

*Key words:*
Biological beds, hydraulic, pressure drop

## Introduction

Biological beds are commonly used in deodorization. It is a result of their accessibility, relatively low costs and a good efficiency, in the removal of various substances from air.[1,2] *Kozłowska*[3] revealed that the application of biofilters is less expensive than other deodorization methods (eg. absorption, chemisorption, after-combustion, ozonization). Biofilter beds, similarly as packed beds of catalytic reactors or packed columns, belong to porosity beds, so their application for practical purposes requires at least primary knowledge as far as the hydraulics behavior is concerned. It means that a set of dependencies describing flow resistance as a linear function of gas velocity (usually calculated for the empty cross section area) should be known. Because of significant differences in bed properties (e.g. porosity, particle shape and size, contact area), it is expected that each of them has their own, individual values of parameters in equation for $\Delta p$. For this reason it seems to be worthwhile to perform investigations on hydraulic properties of selected biological active beds. The research into selected beds was performed in a cylindrical column with the cross section area of 0.024 m$^2$ and the height of 0.45 m, placed on the specially prepared grid. Air at stabilized temperature (20 °C) and humidity ($\varphi$ = 80 %) was used as a working medium.

## Aim and scope

The experimental results dealing with the flow resistance in selected natural commercial and wetted beds, are presented. The following beds were examined:

– pine barks
– preselected barks from deciduous tree
– preselected pine barks
– straw
– mushroom bed
– vegetable soil
– wooden chunks
– heather
– peat
– wooden chips

Some beds including heather, wooden chips, and straw, have very large porosity ($\varepsilon_{\text{heather}} = 0.982$, $\varepsilon_{\text{chips}} = 0.995$, $\varepsilon_{\text{straw}} = 0.977$), and thus, comparatively not a very large contact area. The increase of the contact area requires decreasing of $\varepsilon$. If humidifying does not cause a significant growth of $d_e$, it can be obtained by breaking the bed into fragments, fracturing the bed before its humidifying or by the mechanical loading of a loosely poured bed in the column. Therefore, the research on hydraulic properties of three selected beds was also carried out. These beds were selected taking into account differences in their porosity (high, average and low) at a different mechanical loading.

The research was performed in the range of superficial gas velocity equal to $\boldsymbol{v} \approx 0.022 \div 0.18$ m s$^{-1}$.

The aim of this work was to calculate values of parameters in a generalized dependence[5]

$$Eu = C \cdot Re^A \qquad (1)$$

for individual beds in the tested range of the Reynolds number.

## Preparation of the beds

Hydraulic measurements for each bed were conducted twice: for the commercial bed (dry) and then for the wetted one. Humidifying the bed consisted of its flooding, leaving the bed for 48 hours (however, in case of vegetable soil humidifying was performed by pouring water until flowing out, drops appeared under the bed) and draining off until the last drop did not flow out. In order to describe the influence of a mechanical loading on pressure drop the beds were appropriately loaded. The investigations were performed for following surface load, $q$/N m$^{-2}$: 409.0 N m$^{-2}$, 1223.0 N m$^{-2}$ and 2039.5 N m$^{-2}$. They were carried out as follows: after filling the column up to 0.15 m by bed material[4], a performed disc with the weight was placed on the leveled surface of the bed and left for about 15 minutes. After this time, the disc and the weight were removed, the column was filled up to 0.30 cm and again the weight was placed on the surface and left for the next 15 minutes. As a last stage – humidified bed material was added up to 0.45 m, then the bed was loaded once more and its surface was leveled up to 0.45 m without the surface load. A similar method was applied for porosity measurements[6]. Two tanks were employed: the first one was filled by the bed examined, the second one was empty. The valve system enabled one to cut off the empty tank after its connection to the vacuum pump and then its further connection with the tank packed with a bed. Vacuum measurements in the empty tank and after connection of two tanks, i.e. the empty one and packed with a bed, enables one to calculate a value of bed porosity.

## Results of investigations

The pressure drop across a porous motionless bed can be described by a generalized dependence in the form (1).

For biological active beds, consisting of elements with different granulation and shape, the determination of $d_e$ requires arduous statistical research. For this reason the relationship proposed by Kawalec-Pietrenko and associates[3] is quite attractive. They recommended for peat bed the use of comparatively new relationship, employing the product of the resistance coefficient and pores tortuosity given by Windsperger[6]. Windsperger proposes the following equation for pressure drop calculations

$$\Delta p = \lambda \cdot \zeta \cdot \frac{3h \cdot (1-\varepsilon) \cdot \rho \cdot \boldsymbol{v}^2}{4d_\mathrm{e} \cdot \varepsilon^3} \tag{2}$$

where $\lambda = f(Re_\mathrm{w})$

$$\mathrm{Re}_\mathrm{w} = \frac{2\boldsymbol{v} \cdot d_\mathrm{e} \cdot \rho}{3(1-\varepsilon) \cdot \eta} \tag{3}$$

According to [2] and [7]

$$\lambda \cdot \zeta = 2.2 \left(\frac{0.4}{\varepsilon}\right)^{0.78} \left(\frac{64}{\mathrm{Re}_\mathrm{w}} + \frac{1.8}{\mathrm{Re}_\mathrm{w}^{0.1}}\right) \tag{4}$$

Substituting (3) first to (4), then to (2) and solving the result, one can obtain the equation (comprises both laminar and turbulent terms) which makes possible to calculate $d_e$ by the use of the iterative method

$$Bd_\mathrm{e}^2 - Ed_\mathrm{e}^{0.9} - G = 0 \tag{5}$$

where:

$$B = \Delta p \cdot \varepsilon^{3.78} \tag{6}$$

$$E = 0.69621 \cdot (1-\varepsilon)^{1.1} \cdot \rho^{0.9} \cdot \boldsymbol{v}^{1.9} \cdot \eta^{0.1} \tag{7}$$

$$G = 35.655 \cdot \eta \cdot \boldsymbol{v} \cdot (1-\varepsilon)^2 \tag{8}$$

In the turbulent flow regime $d_e$ can be calculated using a simplified formula

$$(d_\mathrm{e})_\mathrm{turb} = \left[\frac{1.5135 \cdot h \cdot (1-\varepsilon)^{1.1} \cdot \boldsymbol{v}^{1.9} \cdot \eta^{0.1}}{\Delta p \cdot \varepsilon^{3.78}}\right]^{\frac{1}{1.1}} \tag{9}$$

and for laminar flow a following equation can be employed:

$$(d_\mathrm{e})_\mathrm{lam} = 8.804 \cdot (1-\varepsilon) \cdot \left[\frac{h \cdot \eta \cdot \boldsymbol{v}}{\varepsilon^{3.78} \cdot \Delta p}\right]^{\frac{1}{2}} \tag{10}$$

Using of the experimental values of pressure drop for various flow velocities, a set of the equivalent diameters was calculated for each individual bed according to Eq.(7). Then the average values of equivalent diameters were calculated. The obtained results were used for calculation of the individual values of $\boldsymbol{v}$ and $\Delta p$, Reynolds and Eulers numbers. Then values were correlated according to Eq.(1), which enabled one to obtain $A$, and $C$ parameters for tested beds. A course of the function according to Eq.(1) the selected bed of preselected pine tree barks from desiduous tree is presented in Fig.1 The appropriate values of $A$ and $C$ are shown in Tab.1. The average values of $\varepsilon$ evaluated by measurements and $d_e$ calculated according to Eq.(5), were also presented in Tab.1. The authors own research method described in[5] was used in the investigations. The method was based on the measurements of vacuum in two identical containers, one of them filled in by

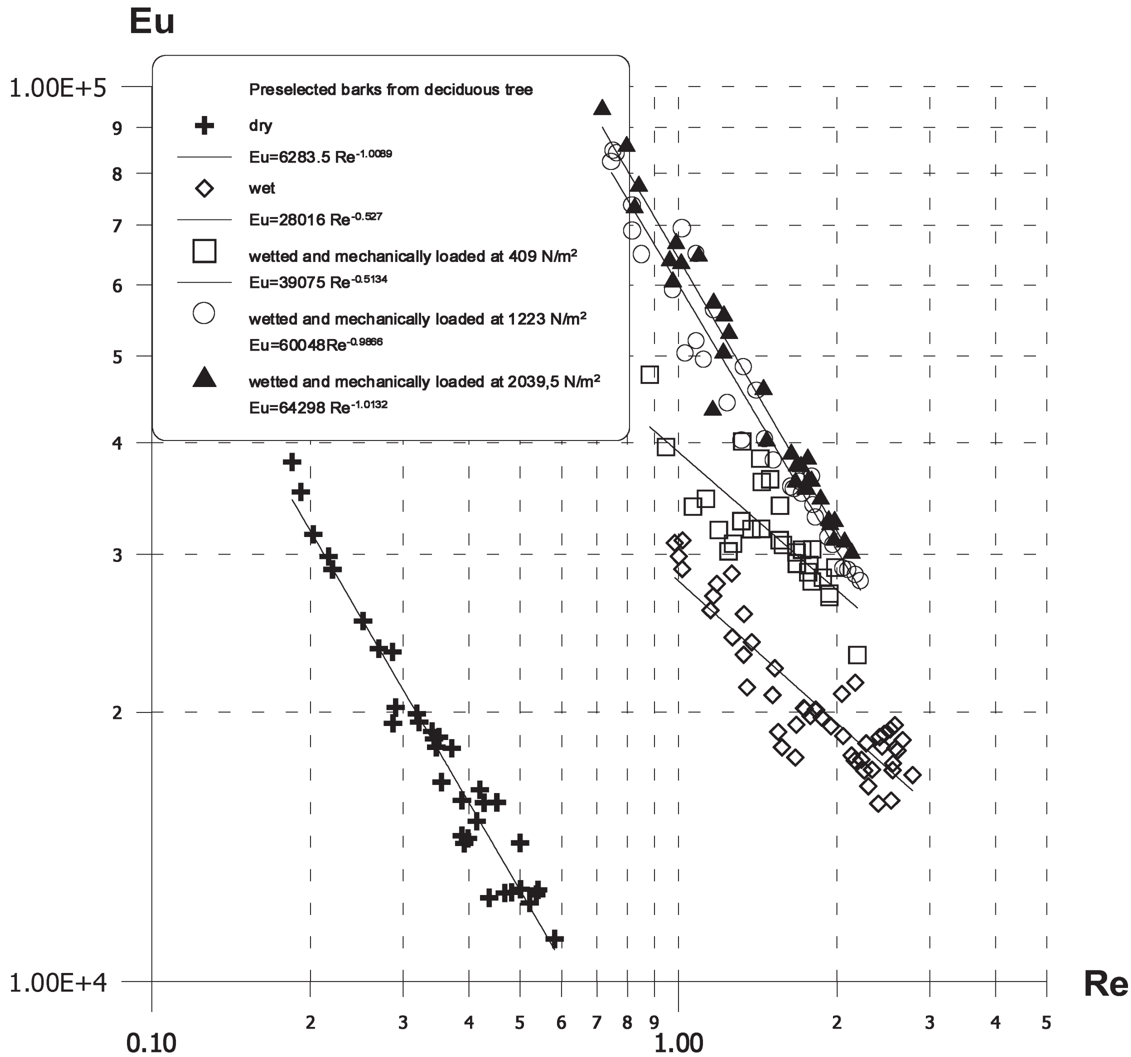


Fig. 1 – *Relationship Eu = f (Re) for dry (commercial), wetted and wetted after mechanically loaded preselected barks.*

the tested bed. The system of valves enabled one to cut off of the containers appropriately. The measurements relied on the vacuum determination in the empty container, while the filled one was connected to atmosphere. Then the vacuum was measured when the both tanks are connected. This procedure was used separately for commercial and wetted beds.

Generally, it can be stated that for beds under research and in the linear flow velocity range of $\boldsymbol{v}$ = 0.022 ÷ 0.18 m $s^{-1}$, the application of generalized Eq.(1) makes possible to complete gas flow resistance calculations for the applied beds with a good accuracy. The Windsperger equation enables one to calculate the bed equivalent diameter in a relatively easy method. This method, in practical issues connected with the determination of pressure drop values for the individual bed, applies parameters *A* and *C* taken from Eq.(1). Analyzing the values of parameters *A* and *C*, it is possible to draw a conclusion that a bed preparation method (humidifying, arrangement, granulation) is a very important factor, essentially influencing pressure drop across the bed. The influence of the loaded weight on pressure drop and individual hydraulic properties, was analyzed in details in.[8] For example – analyzing the results for wetted, preselected barks from deciduous tree, mechanically loaded in the range from 409 to 2039.5 N $m^{-2}$, the parameter *C* grew up from 39075 to 64298, and the value of parameter *A* decreased in the range from –0.5134 to –1.0132. Together with the increase of mechanical load, what means the decrease of the bed porosity, the growth of parameter *C* took place. For wetted tree chips in the pressure drop measurements, the constant *C* is equal to 2778, and after application of the mechanical load of 2039.5 N $m^{-2}$, the *C* value increased over three times obtaining 6479. Similarly, for wetted peat was *C* = 78940, and for wetted and the mechanical load 2039.5 N $m^{-2}$ – *C* = 378620, respectively. Moreover, it can be seen from Fig.1 that for the specified Re, the Euler number takes the higher values the

Table 1 – *Coefficients A and C in Eq.(1) and ε and $d_e$ values for selected natural beds*

| Type of the bed | $Eu = C \cdot Re^A$ | | $R^2$ | Range of $Re$ | $\varepsilon$ | $d_e\ 10^4$ m | Number of measurement points in equalization |
|---|---|---|---|---|---|---|---|
| | $C \cdot 10^{-3}$ | $A$ | | | | | |
| Dry preselected barks from deciduous tree | 6.2835 | –1.0089 | 0.983 | 0.1847…0.5818 | 0.876 | 1.48 | 35 |
| Wetted preselected barks from deciduous tree | 28.016 | –0.5272 | 0.909 | 0.9839…2.7821 | 0.650 | 6.57 | 50 |
| Wetted preselected barks from deciduous tree mechanically loaded at 409.0 N m$^{-2}$ | 39.075 | –0.5134 | 0.796 | 0.8819…2.1856 | 0.637 | 5.81 | 30 |
| Wetted preselected barks from deciduous tree mechanically loaded at 1223.0 N m$^{-2}$ | 60.048 | –0.9866 | 0.973 | 0.7465…2.2179 | 0.614 | 5.90 | 33 |
| Wetted preselected barks from deciduous tree mechanically loaded at 2039.5 N m$^{-2}$ | 64.298 | –1.0132 | 0.982 | 0.7170…2.1332 | 0.608 | 5.97 | 31 |
| Dry (commercial) preselected pine barks | 8.4508 | –0.5107 | 0.931 | 0.4644…1.2934 | 0.822 | 3.17 | 18 |
| Wetted preselected pine barks | 13.627 | –0.8300 | 0.949 | 0.7596…2.5036 | 0.728 | 6.57 | 34 |
| Dry (commercial) preselected pine barks | 41.591 | –0.9379 | 0.965 | 0.4004…1.7812 | 0.864 | 1.11 | 59 |
| Wetted preselected pine barks | 15.728 | –0.7451 | 0.939 | 0.1199…0.2969 | 0.656 | 5.19 | 31 |
| Dry tree chips | 0.0746 | –1.0467 | 0.910 | 0.0169…0.0456 | 0.995 | 0.123 | 30 |
| Wetted tree chips | 2.7778 | –1.1034 | 0.955 | 0.4144…1.0001 | 0.885 | 2.87 | 21 |
| Wetted tree chips mechanically loaded at 2039.5 N m$^{-2}$ | 6.4789 | –0.4701 | 0.941 | 0.4848…1.2772 | 0.837 | 3.46 | 22 |
| Dry wooden chunks | 12.112 | –0.4671 | 0.843 | 0.6410…1.3208 | 0.764 | 4.82 | 34 |
| Wetted wooden chunks | 29.744 | –1.1131 | 0.973 | 0.9314…2.5349 | 0.666 | 7.55 | 29 |
| Dry peat | 48.955 | –0.3526 | 0.801 | 0.6016…1.7302 | 0.6361 | 5.11 | 31 |
| Wetted peat | 78.940 | –0.4618 | 0.889 | 1.6687…3.8437 | 0.472 | 13.2 | 28 |
| Wetted peat mechanically loaded at 2039.5 N m$^{-2}$ | 378.62 | –0.4889 | 0.916 | 2.1960…5.6733 | 0.327 | 17.1 | 25 |
| Dry vegetable soil | 47.841 | –0.8479 | 0.987 | 0.2251…0.5204 | 0.747 | 1.71 | 34 |
| Wetted vegetable soil | 110.92 | –0.8745 | 0.957 | 0.4327…1.0796 | 0.610 | 3.43 | 30 |
| Dry straw | 3.4762 | –0.6399 | 0.947 | 0.025…0.0693 | 0.977 | 0.196 | 38 |
| Wetted straw | 3.6316 | –1.2582 | 0.994 | 0.0416…0.1085 | 0.929 | 0.356 | 34 |
| Dry heather | 1.4730 | –0.6063 | 0.879 | 0.0357…0.0939 | 0.982 | 0.288 | 25 |
| Wetted heather | 3.0514 | –0.7832 | 0.938 | 0.1509…0.3745 | 0.931 | 1.08 | 28 |
| Dry mushroom bed | 2.3442 | –0.9557 | 0.965 | 0.0164…0.0449 | 0.975 | 0.136 | 37 |
| Wetted mushroom bed | 42.037 | –0.6481 | 0.934 | 0.3302…0.6673 | 0.744 | 2.24 | 27 |

higher mechanical load was used. The experimental points, obtained for the mechanical load equal to 2039.5 N $m^{-2}$, are situated higher than points for the loads of 409 N $m^{-2}$ and 1223.0 N $m^{-2}$. Such result is easily understandable because the mechanical load results in decreasing of the porosity bed. It should be also emphasized, that the regression correlation coefficient in log $Eu = f(\log Re)$ coordinate system, was at all cases close to 1. It is also worth while to point out that above shown results are close to presented in.[4]

The hydraulics of biologically active beds can be described by a set of equations presented in.[4] One of them is the original Ergun equation, which after incorporating the Carman permeability concept, enables one to avoid a necessity of using the equivalent diameter and, moreover, it is valid in the whole range of $\boldsymbol{v}$. An alternative method of the description of bed hydraulics is the Leva formula, based on the experimentally determined parameters for individual beds collected in.[4] The nearly linear course of the relationship $\Delta p = f(\boldsymbol{v}^2)$ allows one to state, that for linear gas velocities close to 0.18 m $s^{-1}$, i.e. for the highest values of $\boldsymbol{v}$ used in experiments, the turbulent term is prevailing in pressure drop calculations. One can conclude that the Leva dependence is also valid for higher values of $\boldsymbol{v}_0$.

## Conclusions

On the basis of the research results the following conclusions can be drawn:

1. For humidified and dry beds, such as: pine barks, peat, mushroom bed, heather, wooden chunks, straw, vegetable soil, preselected barks from deciduous tree, pine preselected bark and sand chips, the hydraulic characteristics differ from each other significantly.

2. In the description of hydraulics the general relationship in the form of Eq.(1) can be used. It is based on the experimentally determined parameters $A$ and $C$, collected for the tested beds in Tab.1. Eq.(1) is valid in the range of $\boldsymbol{v}$ equal to 0.022 ÷ 0.18 m $s^{-1}$. The investigated range of $\boldsymbol{v}$ includes the values used in practical applications.

3. The method of bed preparation, humidifying, filling or mechanical loading, is a decisive factor for values of pressure drop obtained.

4. The presented generalized relationship, describing the natural bed hydraulics enables one to forecast pressure drop across the tested, commercial and humidified beds in the velocity range equal to $\boldsymbol{v}$ = 0.022 ÷ 0.18 m $s^{-1}$, and therefore it helps in the selection of a proper gas transportation device.

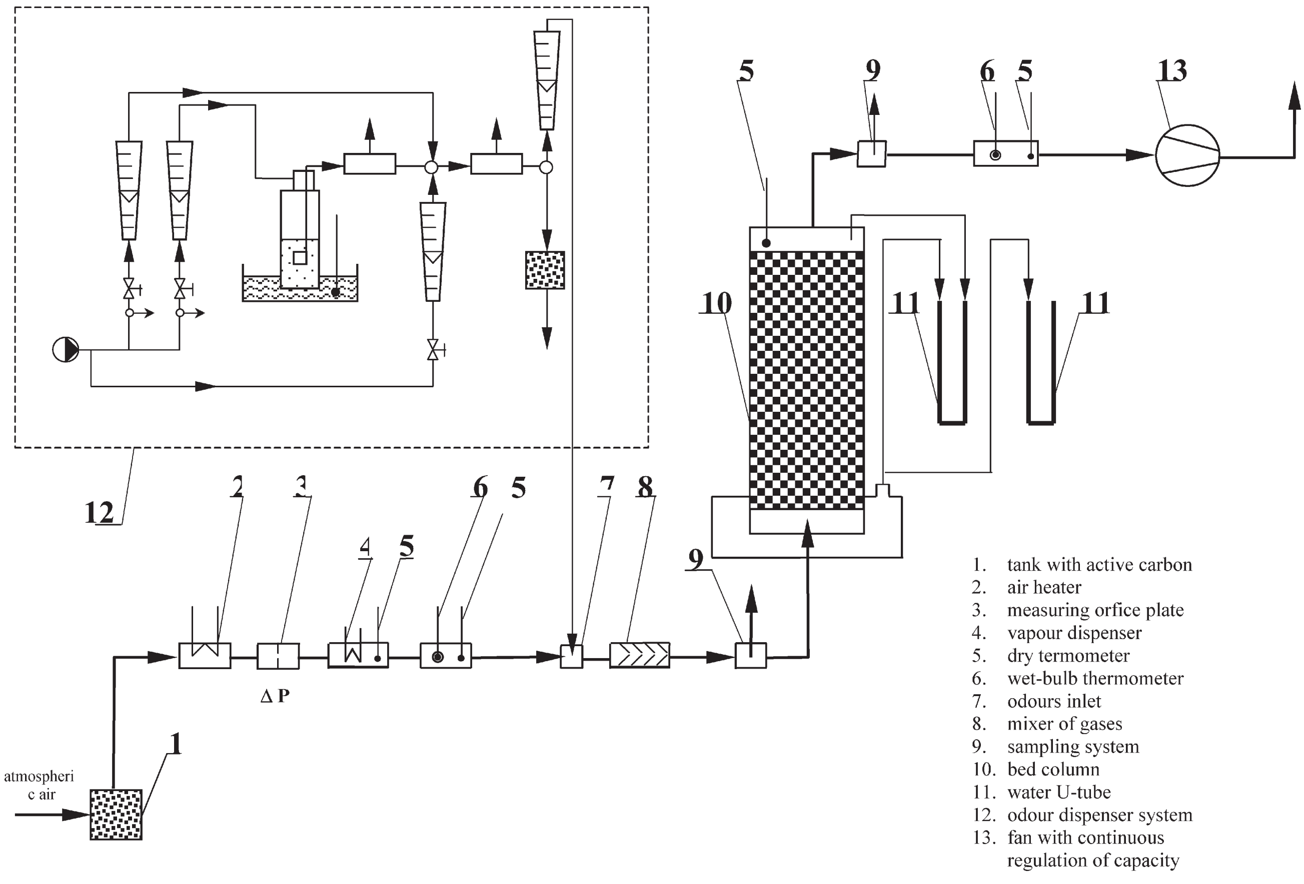


Fig. 2 – *Sheme of the experimental setup*

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## List of symbols

$A$ – exponent in Eq.(1)

$B$ – constant in Eq.(5) calculate according to (6), kg m $s^{-2}$

$C$ – constant in Eq.(1)

$E$ – constant in Eq.(5) calculate according to (7), kg $m^{-0.9}$ $s^{-2}$

$G$ – constant in Eq.(5) calculate according to (8), kg $s^{-2}$

$R$ – correlation coefficient

$d$ – diameter of the bed particle, m

$h$ – height of the bed, m

$\boldsymbol{v}$ – superficial gas velocity, m $s^{-1}$, $m^3$ $s^{-1}$ $m^{-2}$

$\Delta p$ – pressure drop across the bed, Pa

$\varepsilon$ – porosity of the bed, $m^3$ $m^{-3}$

$\eta$ – gas dynamic viscosity, Pa s

$\lambda$ – friction factor

$\zeta$ – pore tortoises coefficient

$\varphi$ – relative concentration of humidity

## Subscripts

$W$ – denotes Windsperger's approach

$e$ – denotes equivalent value

turb – denotes turbulent flow

lam – denotes laminar flow

## Moduls

Eu – Euler number, $Eu = \dfrac{\Delta p}{\rho \cdot \boldsymbol{v}}$

$Re$ – Reynolds number in Eq.(1), $Re = \dfrac{\rho \cdot \boldsymbol{v} \cdot d}{\eta}$

$Re_W$ – Reynolds number according to Windsperger's approach, $\mathrm{Re}_\mathrm{w} = \dfrac{2 \cdot \boldsymbol{v} \cdot d_\mathrm{e} \cdot \rho}{3(1-\varepsilon) \cdot \eta}$