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STUDY OF THE AIR FLOW THROUGH A FIBROUS POROUS MEDIUM BASED ON LUFFA CYLINDRICA'S FIBERS

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Abstract

This paper reports an experimental study of the air flow through a fibrous porous medium based on Luffa cylindrica's fibers. For this purpose, an experimental set-up has been performed to determine the evolution of the pressure drop as a function of flow mean velocity. The results show that for the values of speed below 0.175 m /s, the pressure drop increases linearly with speed and the flow is correctly described by Darcy's law. Beyond this limit value and up to 0.644 m /s, we found that the pressure drop evolves quadratically with speed as a result of inertial effect that becomes more important. In this region the flow is correctly predicted by the Forchheimer's law. The permeability (K) of the medium was also determined experimentally. The values obtained for K agrees well with that calculated from empirical models of Carman-Kozeny *and d'Ergun.*

Key words: *Luffa cylindrica; air flow; modeling; permeability.*

1. INTRODUCTION

The filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components (Walkeman 2007; Bredina & mullins 2012). The filtering medium have considerably evolved through multiples scientific research focused on developing new materials used as filter medium in diverse forms and also on improving the physical, mechanical and chemical properties of this materials (Sutherland 2013).

Filters based on synthetic fibers dominate the market for their technical and economic advantages (ease of implementation, low cost, etc...). Recently and given that these fibers may present a source of pollution (non-degradable synthetic materials) several filtration specialists have said some renewed natural fibers, particularly vegetable fibers such as wood fiber and cotton linters. Seeing around us, the cellulosic reign very available source, since it is the main constituent of vegetable fibers. Previous research of BAL Et Al. (2000) on the development and extraction of fibers of vascular plants of luffa cylindrica (LC) has raised up to look at this type of material for possible use as a component of a filter medium. In fact, the morphology of this spongy fibers, as shown by the works of bal et al. (2004) can provide a relatively large space for the fluid flow.

In the present study, a laboratory procedure is established for the extraction of fibers from the fibrous cords of LC and making an air filter medium. A specific test bench is designed to generate a pressure drop for a domain of Reynolds number covering the Darcy regime and the inertial regime.

2. MODELS FOR FLOWS IN POROUS MEDIUM

Fluid flows in porous medium have been one of the most important topics due to its wide applications in both science and engineering (Green & Duwez 1951; Lee & Yang 1997) .Several laws and models governing the fluid flow in porous medium have been developed during the past 150 years. The Darcy experiments on the water flow through packed sands at low velocity showed that the pressure drop per unit of length in the direction of *flow* varies proportionally with the flow velocity and the viscosity of the fluid, and inversely with the permeability of the medium. Darcy equation can be written as:

$$\frac{\Delta P}{L} = \frac{\mu}{K} V \qquad (1)$$

Equation (1), known by Darcy law, correctly describes the fluid flow for small values of the velocity or Reynolds number (flow crawling) (Chai et al. 2010). The Darcy law has been supported experimentally, numerically and theoretically. However, when the velocity increases and from a limit value of Reynolds numbers the Darcy's law loses its validity (MacDonald el al. 1979; Andrade et al. 1999 & Comiti et al. 2000). Various

terms, such as non-Darcy flow, turbulent flow, inertial flow, and high velocity flow have been used to describe this behavior.

Many attempts have been made to correct the Darcy equation. Forchheimer (Whitaker 1996) proposed an empirical formula where the inertial effect is represented by the term, $\beta\rho V^2$.

$$\frac{\Delta P}{L} = \frac{\mu}{K}V + \beta\rho V^2 \quad (2)$$

In equation 2, ρ is the density of the fluid, K and β represent the permeability of the medium and the coefficient of inertia respectively. The Darcy–Forchheimer model is probably the most popular modification to Darcian flow utilized in simulating inertial effects. It has been used extensively in chemical engineering analysis and also in materials processing simulations (Attia et al. 2013).

3. EXPERIMENTAL SET-UP AND METHOD

3.1. Elaboration of filter paper samples

Referring to previous works of Bal et al. (2002), we briefly summarize the principal operations for extracting fibers from the fibrous cords of LC:

- washing the fibrous sponge with a solution of distilled water and wetting agent having a concentration of 1 ‰ wt. 70 °C for 2 h. This operation eliminates the impurities and remaining fruit and plant debris that may influence on the quality of the samples;
- the chemical treatment with soda. This operation consists in a cooking in an soda solution and distilled water with a concentration of 5 wt.%, in equal conditions of temperature (90 °C for 4 h). This operation eliminates the lignin which maintains the fibers together and leads to fibers perfectly individualized without altering the cellulose which is the main component of these fibers.

The procedure followed for the elaboration of the paper samples includes the following steps:

- preparation of the suspension: This operation consists in mixing a certain mass of fibers in a volume of water. The mass of fibers considered depend on the desired surface mass of the sample;
- injection of the suspension in a pulper and stirring for a few minutes. The aim of this operation is to ensure the homogeneity of the bulk density over the entire surface of the sample;
- the paw recovered is then passed to the last operation where for 15 minutes is ensures a pressure of 9.18 bar at a temperature of 90 ° C to 94 ° C. This operation allows the drying and the consolidation to the sample.

The manufacturing operations of the filter paper samples were completed on one laboratory equipment existing in the paper mill, CELPAP of Baba Ali (in Algiers). The equipment is of the type "ERNST HAAGE D-4330 Mulheim / Ruhr."

3.2. Physical characterization of the filter papers samples

We tested two types of filter papers samples, the commercial filter paper sample containing synthetic fibers, and one developed from LC fibers. The thickness, L, of the samples was measured using an electronic thickness meters and the mean diameter, d_f, of the fibers is determined from a optical microscopic examination. Finally the porosity, ε, of the samples has been calculated from the equation (3) wherein, ρ_f, is the density of the fiber material and, m_s, the *surface mass of the filter paper sample*. The physical and structural characteristics of the filter papers are reported in Table 1.

$$\varepsilon = 1 - \left(\frac{m_s}{\rho_f . L} \right) \quad (3)$$

Table 1. Physical and structural characteristics of the filter papers samples.

Filter paper	L (µm)	m_s (g/m^2)	d_f (µm)	ε
Commercial	470	110	22	0.75
From LC fibers	450	171	45	0.60

3.3. Experimental set-up

To study the evolution of the pressure drop as a function of air flow rate through the filter paper samples we have designed for this purpose a suitable experimental set-up. This experimental set-up is illustrated in Figure 1and Figure 2.

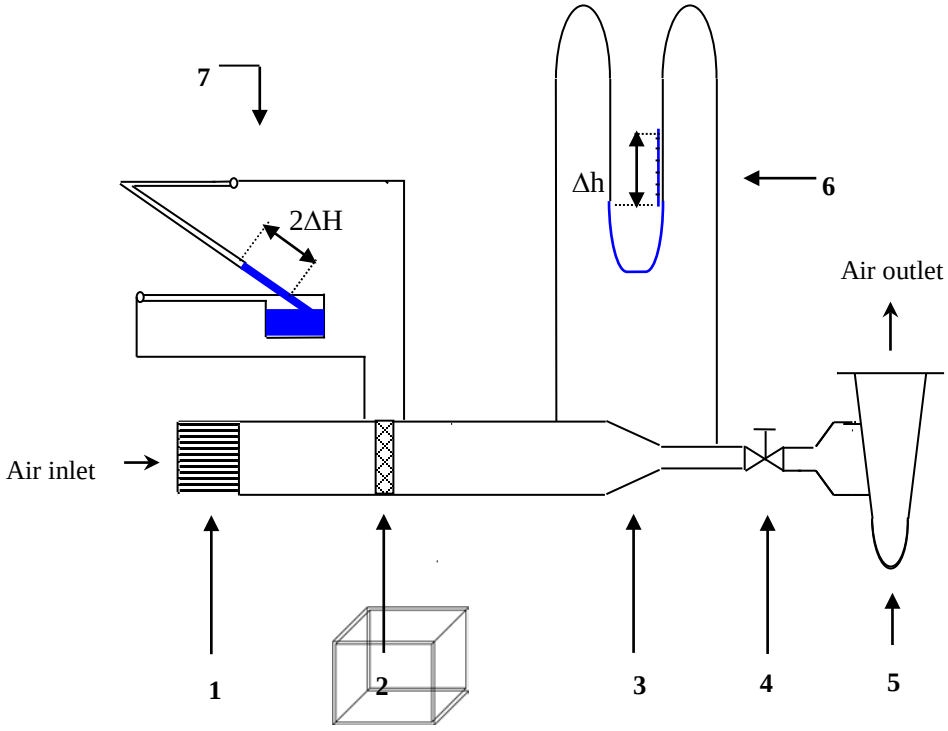

Fig. 1. Experimental set-up: 1- Honeycomb, 2- Support of the filter paper sample, 3- Convergent, 4- Valve, 5- Aspirator, 6- U-tube manometer, 7- Differential manometer.

In the experimental setup, the honeycomb (1) acts as a calming zone of the flow at the inlet of the pipe, thus, the turbulences are avoided at the entrance to the pipe. The valve (4) allows us to vary the air flow rate through the filter paper sample. In order to make accurate measurements of small pressure drop across the filter paper sample, the U-tube manometer is inclined by 30° angle.

It is well known that fluid flow through a convergent undergoes the venturi phenomenon (Silva et al. 2009). The consequence of this effect is an increase of the velocity of the fluid and temporarily a decrease of its pressure. The pressure drop between inlet and throat is developed. This pressure drop is correlated to flow rate. The expression for theoretical flow rate is obtained by applying the continuity equation and energy equation at inlet and throat section, and assuming the fluid to be ideal is given by (Hauke 2008):

$$Q_v = \frac{A_2 \sqrt{2g.\Delta h}}{\sqrt{\left[1-\left(\frac{A_2}{A_1}\right)^2\right]}} \quad (4)$$

Where, A1, and, A2, are areas at inlet and throat and, Δh, pressure drop between inlet and throat section in term of meter of manometer fluid. Equations derived above relating flow rate to the differential drop cannot be applied directly. The flow meter needs calibration. The converging of the pipe has been calibrated and the read values of, Δh, are converted to air flow rate using equation 5 derived from the calibration.

$$Q_v = 22.92\ 10^{-3}\sqrt{\Delta h} \quad (m^3/s) \quad (5)$$

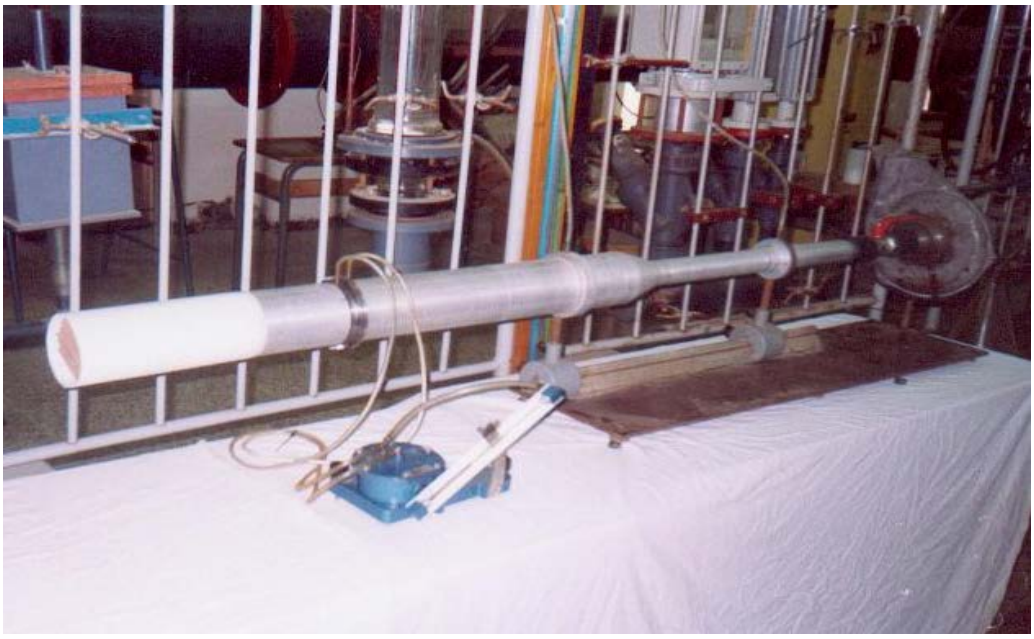

Fig. 2. Photograph of the experimental set-up.

3.4. Principle and test conditions

We prepared samples with a diameter, D, equal than the inner diameter of the sample holder (D= 10 cm). For each test, we measured the values (in mm) of ΔH and Δh. The flow rate is calculated by the equation 5, thus, the flow velocity is deduced from the continuity equation (Hassanizadeh 1980):

$$V = \frac{Q_v}{A} \quad (m/s) \quad (6)$$

Where, A, is the area of the sample. The pressure drop (in m) is converted in Pascal (Pa) using the hydrostatic equation:

$$\Delta P = \rho_{eth}.g.\Delta H \quad (Pa) \quad (7)$$

Where, ρ_{eth}, represents the ethanol density, used as manometer fluid, whose value corresponding to the atmospheric conditions in the laboratory is equal to 804 $Kg.m^{-3}$. The values of the density, ρ, and the viscosity, μ, of air remain practically constant during all experiments (ρ=1.172 $Kg.m^{-3}$ and μ=1.856 10^{-5} Pa.s).

4. RESULTS AND DISCUSSION

4.1. Experimental values of permeability

For the experimental determination of the permeability, we have shown in Fig. 3 and Fig. 4 the evolution of the pressure drop per unit of thickness of the sample, $\left(\frac{\Delta P}{L}\right)$, as a function of the mean velocity, V. By analyzing these curves, we observed the existence of the two types of flow regimes.

- *Laminar flow regime*: For the velocity values less than 0.133 m /s for the commercial filter paper and 0.175 m/s for the filter paper of LC fibers, the evolution of the pressure drop is linear with velocity. We approached this part of the curve by a straight line where the flow is correctly described by Darcy law. The identification of the equation of this line with that of Darcy (Eq. 1) allowed us to deduce the value of the permeability corresponding to the laminar flow regime. These values are recorded in Table 2.

- *Inertial flow regime*: Beyond these limit values of the velocity, it is found that the pressure drop evolves quadratically with the speed and then the gap between the parable approaching the experimental values and the line gradually increases with velocity. This is explained by the inertia effect that appears in this area of the flow and which becomes more important with velocity. The flow is therefore no longer governed by Darcy's law. Forchheimer law (Eq. 2) which takes into account the effects of viscosity and inertia will represent the flow behavior in this area. The identification of the polynomial regression equation with that of Forchheimer (Eq. 2) has allowed us to deduce the permeability corresponding to the inertial flow regime, the results are reported in Table 2.

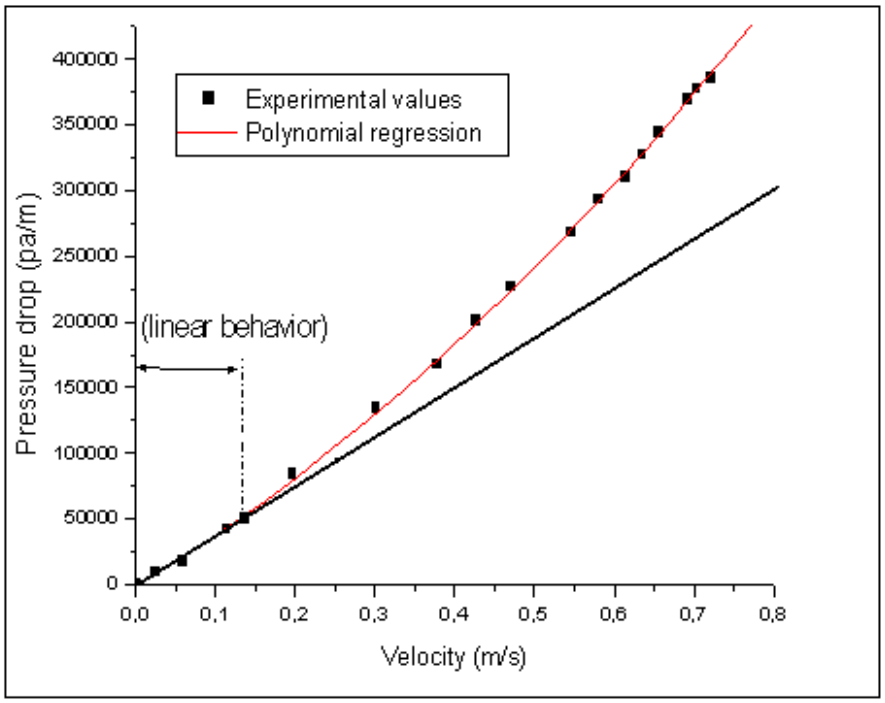

Fig. 3. Evolution of the pressure drop as a function of the velocity through the commercial filter paper sample.

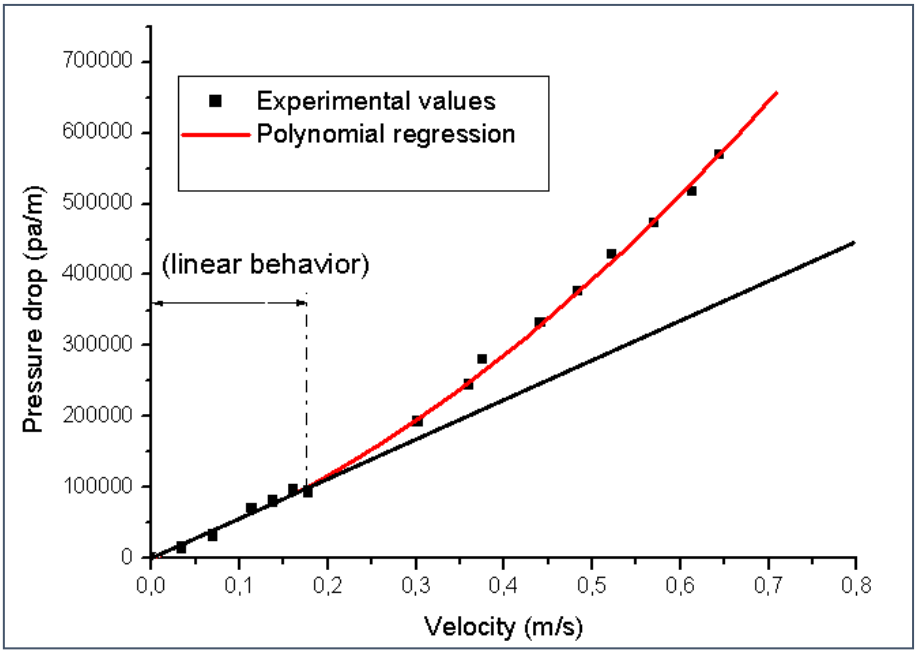

Fig. 4. Evolution of the pressure drop as a function of the velocity through the filter paper sample from LC fibers.

4.2. Comparison of experimental values of permeability with empirical models

In order to compare the permeability values obtained experimentally to those offered by empirical models, we considered two typically capillary models. The first model is that of Carman-Kozeny developed for porous medium of low porosity ($\varepsilon < 0.8$) and for flows with low values of Reynolds number. The Carman-Kozeny equation is the most well-known model on permeability, which relates the permeability K to porosity ε as (Heijs & Lowe 1995) :

$$K = \frac{d_f^2}{16\,K_0}\frac{\varepsilon^3}{(1-\epsilon)^2} \quad (m^2) \qquad (8)$$

Where, K_o, is the Kozeny constant. We adopted for our calculations the value proposed in the literature for the configuration where the flow is perpendicular to the fiber axis (K_o =5) (Carman 1956). The second model that we have considered is that of Ergun. This model is proposed for fibrous medium, it is applicable for a wide range of Reynolds numbers where the inertial regime is predominate. The expression of the permeability from this model is:

$$K = \frac{d_f^2}{67}\frac{\varepsilon^3}{(1-\varepsilon)^2} \quad (m^2) \qquad (9)$$

Calculation results of permeability are reported in Table 2.

Table 2. Experimental and calculated values of the permeability

Permeability (10^{-11} m^2)				
Filter paper	Darcy	Forchheimer	Carman-Kozeny	Ergun
Comercial	4.7	5.0	4.1	4.9
From LC fibers	3.3	4.1	3.4	4.0

The experimental and calculated values (Table 2) show that the permeability of the two experimented filter papers is in the range of 10^{-11} m^2. These results are in good agreement with the permeability of the air filter shown in the literature (Igwe 1987). The differences between the experimental values and the calculated values from empirical models are considered fairly low given the uncertainties that may be related to the measuring devices.

The permeability obtained for the inertial flow regime is higher than that obtained for the laminar flow, this is due to the fact that the coefficient of the viscous term is weaker in the inertial flow regime. The permeability of the filter paper from LC fiber is slightly smaller than the permeability of the commercial filter paper, this is due to the porosity (Table 1). Indeed, when the porosity of the medium decreases, the permeability decreases as.

4.3. Critical Reynolds number

The Reynolds number is the criterion that has been widely used to locate the transition zone between the laminar flow regime (Darcy flow) and the inertial flow regime (Darcy-Forchheimer) (Zeng & Grigg 2006). The Reynolds number is defined as the ratio of inertial force to viscous force.

By considering the characteristics of the filter papers samples, the physical properties of air and the limits values of the velocity, we calculated the critical Reynolds number based on fiber diameter (d_f):

$$Re_f = \frac{\rho V d_f}{\mu(1-\varepsilon)} \quad (10)$$

The results obtained are 0.74 for the commercial filter paper and 1.24 for the filter paper from LC fibers. It is not easy to compare the results with those of the literature, in fact, several definitions of the Reynolds number are proposed. However the limits values proposed by some authors are between 1 and 10 (Zimmerma et al 2004).

5. CONCLUSION

The work presented was aimed to study the behavior to air flow of a new filter medium designed from fibers of luffa cylindrica. It allows us to characterize in terms of permeability, the evolution of the pressure drop for velocities up to 0.644 m / s. The results discussed have shown that within this range of velocity, the flow covered the two types of flow regime. We considered the models of Darcy and Forchheimer to experimentally determine the values of permeability. These values were compared to those calculated from empirical models of Carman-Kozeny and Ergun.

The filter paper from fiber of luffa cylindrica has a permeability that can her offer a quality industrial as air filter paper. This claim can be validated by a complementary study which will interest the air flow loaded by calibrated particles to examine the behavior of the filter paper and its particle retention capacity.

NOMENCLATURE

Latin letters

A	area of the filter paper sample, m^2
d_f	fiber diameter, m
D	Sample diameter, m
g	gravitational acceleration, $m.s^{-2}$
K	Permeability of the filter paper sample, m^2
K_0	Kozeny constant (Eq. 8), adimensional
L	thickness of the sample, m
m_s	*surface mass of the filter paper sample, $kg.m^{-2}$*
Q_v	flow rate (Eq. 4 & Eq.5), $m^3.s^{-1}$
Re_f	Reynolds number based on fiber diameter (Eq. 10), adimensional

V mean velocity, $m.s^{-1}$

Greek letter

ε porosity of the medium, adimensional

ρ air density, $Kg.m^{-3}$

ρ_{eth} ethanol density, $Kg.m^{-3}$

ρ_f density of fiber, $Kg.m^{-3}$

μ viscosity of air, Pa.s

β inertial coefficient (Eq. 2), m^{-1}

Δh pressure drop through the convergent, m of ethanol

ΔH pressure drop through the sample, m of ethanol

ΔP pressure drop, Pa

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