An Experimental Study of Two-Phase Flow in Porous Media with Measurement of Relative Permeability

N. Labed[1], L. Bennamoun[2] and J.P. Fohr[3]

Abstract: Intrinsic and relative permeability are indispensable parameters for performing transfers in porous media. In this paper, the conception and ensuing exploitation of a new testing ground for measuring the relative permeability of water and nitrogen are presented. The experimental work was elaborated in the Laboratory of Thermal Studies in Poitiers, (France) where brick samples were used to verify the performance of the proposed testing strategy. The results prove the existence of several stages during the drainage and the imbibitions. In particular, the three stages observed for the case of gas permeability reduce to only two steps for liquid permeability. Comparison with others scientific works is considered. In addition, the validity and reliability of the testing ground and associated measuring method are discussed.

Keywords: Gas relative permeability, liquid relative permeability, saturation, porous media, two-phase flow.

Nomenclature

A	surface of the sample (m^2)
D	Diameter of the sample (m)
K	Sample permeability (m^2)
L	Thickness of the sample (m)
m	Mass (kg)
P	Pressure (Pa)
Q	Volumetric rate (m^3/s)
S	Saturation (%)

[1] Faculté des Sciences et Technologie, Université Larbi BenM'hidi, Oum El Bouaghi, Algeria, Tel./Fax: +213 32 47 54 51, Email: nabil_lab@yahoo.fr

[2] Department of Applied Chemistry, University of Liege, Bat. 6C, Sart Tilman, 4000, Liege, Belgium, Tel.: +32 4 366 47 23, Email: Lyes.Bennamoun@ulg.ac.be

[3] Laboratoire d'Études Thermiques, URA C.N.R.S., no 1403, Poitier, France.

T	Temperature ($\degree$C)
$\vec{v}$	Velocity
g	Constant of gravitation (m/s^2)

Greek letters

Δ	Difference
ϕ	Porosity (%)
μ	Dynamic viscosity of gas (Kg/m.s)
ρ	Fluid density
∇	Gradient

Subscripts

c	capillary
g	Gas
l	Liquid
p	Particle
r	Relative
0	Normal conditions

1 Introduction

The subject of porous media still represents an intensive research theme due to its practical applications in several fields (such as chemical reactors, heat exchangers, thermal insulations, electronic cooling, bio-mechanics and various food industries and processes). As a proof of such interest, it is worth mentioning the recent studies by Bataller (2010), Al-Ajmi and Mosaad (2012), Hamimid, Guellal, Amroune and Zeraibi (2012), Choukairy and Bennacer (2012), Labed, Bennamoun and Fohr (2012).

For modeling transport in porous media, two main approaches have been developed over recent years, one dealing with microscopic details, the other providing a macroscopic point of view. Erriguible, Bernada, Couture and Roques (2005), Prat (2002), Quintard and Whitaker (2000), Quintard, Kiviany and Whitaker (1997) and Whitaker (1980) contributed to the development of the first approach applied at the microscopic scale. The main idea underlying this approach is that the media may be

regarded as a combination of solid, liquid and gas phases. Heat, mass and momentum balances are applied for each phase. On the other hand, the second approach assumes the media to be formed by packed beds of spheres [Zou, Opara, and McKibbin (2006), Jammalahmadi, Müller-Steinhagen and Izadpanah (2005), Alvarez, Bournet and Flick (2003)] or cylinders [Takhar, Chamkha and Nath (2002), Yang and Lee (1999)]. Several studies, such as Bennamoun and Belhamri (2008a), Bennamoun and Belhamri (2008b), Bennamoun and Belhamri (2006), Arnaud and Fohr (1988) and Daguenet (1985), have applied heat and mass balances for both solid and fluid phases.

Usually, at low Reynolds number, the momentum equation is represented by the empirical Darcy's law:

$$\vec{v} = -\frac{K}{\mu}[\nabla P - \rho g] \tag{1}$$

In the case of more than one fluid phase, Darcy's law is extended by using relative permeabilities, given by the two following equations:

$$\overline{v_g} = -\frac{K.K_g}{\mu_g}[\nabla P_g] \tag{2}$$

$$\overline{v_l} = -\frac{K.K_l}{\mu_l}[\nabla P_g - p_c] \tag{3}$$

Where:

P_c is the capillary pressure.

The Darcy's law iinvolves the velocity, the viscosity of the fluid but also the permeability, written itself as function of the porosity and geometry of the media [Nield and Bejan (2006)]. At high Reynolds number, a second contribution, with the so-called Forchheimer coefficient and permeability, must be added to the first equation [Nield and Bejan (2006), Hsu (2000)]. A more general formula available for a wide range of Reynolds number, still written as function of the permeability was introduced by Hsu (2000). There is evidence that permeability is an essential element deserving special attention. Generally, this parameter is given as function of the particle size, geometry of the media and its porosity as confirmed by Crawford, Jones, You and Wu (2011), Liu, Sano and Nakayama (2009), Dias, Fernandes, Mota and Teixeira (2007), Starov and Zhdanov (2001). The most common mathematical form of the permeability is represented by the following equation:

$$K = \frac{\varphi^3 d_p^2}{a(1-\varphi)^2} \tag{4}$$

Where a is a parameter accounting for the specific geometry of the media.

Shou, Fan, and Ding (2010), Yu, Li, Li, and Zou (2003) have shown that permeability depends on the porosity and the fractal dimension of the studied media. Many scientific works dealing with modeling and simulation permeability can be found. Kantzas and Chatzis,(1988) used preconditioned conjugate gradients methods for the calculus of the permeability. Also, Li, LeBoeuf, Basu, and Mahadevan (2005) used the stochastic method, whereas Hao and Cheng (2010), Singh and Mohanty (2000) apply Lattice Boltzmann method, for modeling permeability in porous media. Network and power law models were developed respectively by Maxiemenko and Kadet (2000) and Reyes, Parades and Gutiérrez (1999). Other scientific works have been concerned with the experimental determination of the permeability. Schembre and Kovscek (2003) presented an innovative experimental method based on X-ray computed tomography scanner. They determined permeability of rock material using saturation profiles and inhibition for water-air and water-oil systems. Based on Darcy's law, Cai and Oliveira (2007) developed another experimental method. They uses filters, manometers and flow meter to determine permeability of different cases of wood with a particular study of the effect of the pre-treatment of the material. Transversal permeability of saturated paper sheets was experimentally determined by Reverdy-Bruas, Serra-Tosio, Chave and Bloch (2001). The fundamental principle of the method was based on the measurement of water flow across a mechanically strained web pad compressed between two permeable surfaces. In addition, to the measurement of the water flow, the hydrostatic and total pressure, the temperature of the water and thickness of the material were also calculated.

In this paper, we present the design and exploitation of a new testing ground for measuring the relative permeability for water and nitrogen. Brick samples were used to verify the performance of the proposed testing ground.

2 Materials and methods

2.1 Sample preparation

Brick samples were specially produced for this study. They have a porosity of about 0.6 and a volumetric mass measured in the laboratory around 1250 kg . m^{-3} [Bennamoun and Belhamri (2009)]. The samples are cylinders of 10 cm diameter and 2 cm thickness. Depending on the required goal, the sample, at the beginning, can be totally dry or completely saturated with water.

For obtaining sample dry mass, we put the sample in the oven for 24 hours under a constant temperature of 105 ˚C. The mass is weighted using electronic balance 0.01 g accuracy. Total saturated sample can be obtained by putting it in a vacuum

cover, as shown in Fig.1. A vacuum pump inspires the air existing in the cover and from the sample. After a while, and once the void is established, the non-mineralized water is send for a complete saturation of the sample (Fig. 1). This allows extraction of all air (sample and cover) and filling pores sample by water making it saturated. The manometer which is positioned inside the vacuum cover permits to control the quality of vacuum. At the end, sample is weighted again to obtain the sample wet mass.

It is important to note that, for partial saturations calculus, sample is dried at ambient environment for 12 hours before its weight. This process is repeated until obtaining the whole points of the permeability curve.
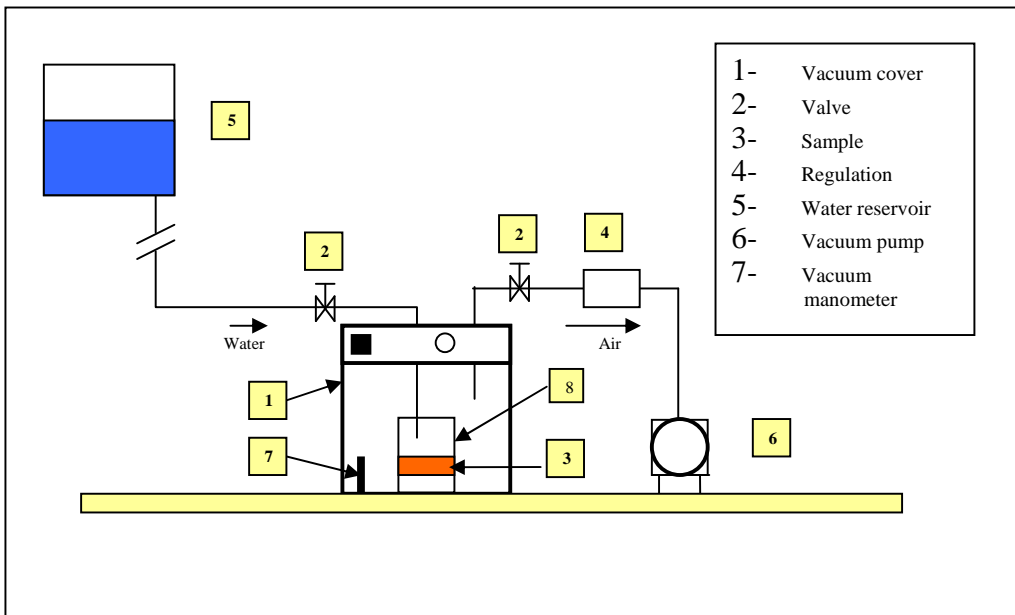

Figure 1: Saturation of the sample

2.2   Presentation of the experimental set-up and the used materials

The main aim of the present work is the study of the diphasic flow in a porous media. First of all, we have to measure the relative permeability of many brick samples; the testing ground is represented in Fig 2.

Regarding the complexity of investigated phenomenon, the measuring devices used for the experimental work are of a high quality precision and reliability. We have
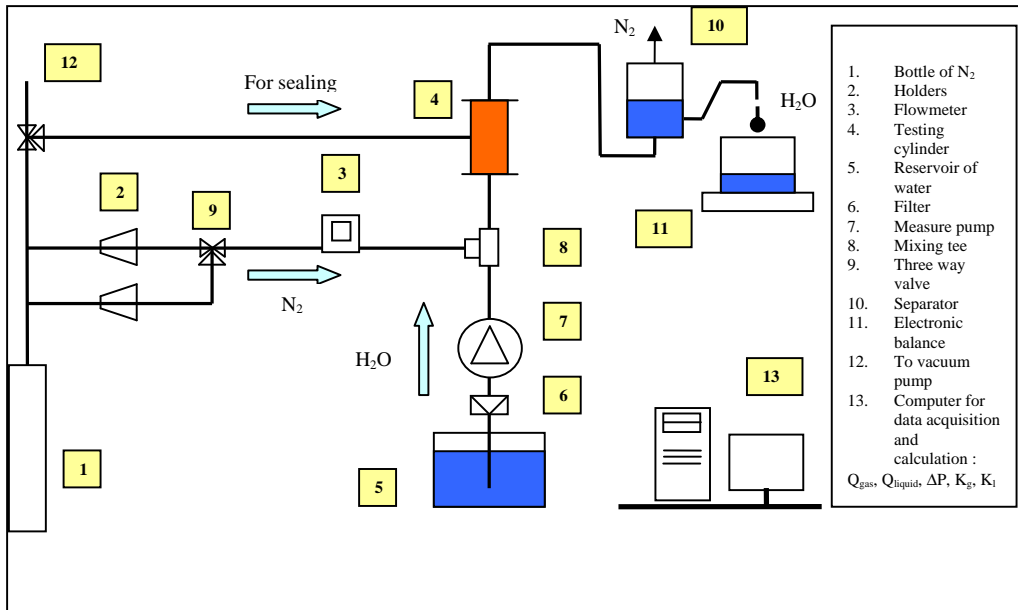
Figure 2: Principle of the experimental system for measuring the relative permeability

got a flow-meter with regulation system (from 0 to 1000 ml/min), a "Furness" very sensitive manometer (0 to 20000 Pa). An electronic balance insures the measure of the water mass out of the specimen and calculation of flow. However, the measure pump can deliver a rate ranging from 0.096 to 120 ml/hour by setting piston stroke and frequency of impulsions. An electronic data card linked to a computer allows resembling the different measured data. A particular attention is given to the used testing cylinder device represented in Fig. 2 and details are given in Fig. 3.

The test cylinder is a well designed stainless cylinder with lot of accessories : a couple of porous plates, called "diffusers", two pieces of cylindrical shape with some grooves, called "distributors", which are placed on both sides of the diffusers. A rubber membrane covers the inner part of the specimen and insures the lateral tightness of the whole thing. The use of some removable wedges allows testing samples with different sizes (Fig. 3).

2.3   *Principle of the used method: The experiment protocol*

First of all, sample is placed in the test cylinder before the setting. Moving through the flow meter and the safety valve, the nitrogen meets the water which is deliv-
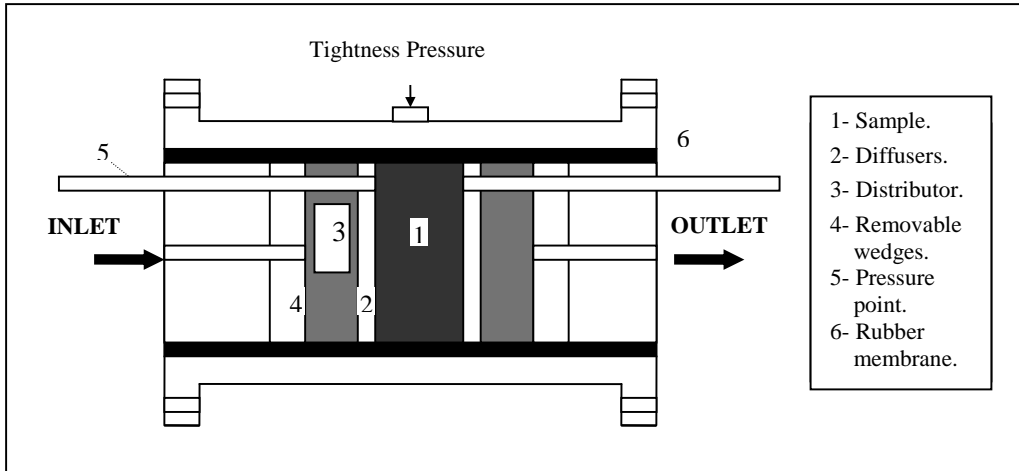
Figure 3: Longitudinal section of test cylinder

ered by the pump in order to form a mixture which finally is introduced inside the sample. On its way out from the test cylinder, the mixture passes through a device which separates water from gas, and hence permits the distinct measure of the rate of two flows.

In this study, several tests have been carried out in order to investigate a variety of possible cases. The preliminary stage which concerns the calibrating and the adjustment of the scaling was necessary. Experiments with a single moving fluid were more successful than simultaneous injection of two fluids.

We start by measuring the intrinsic permeability to water K, by only introducing water for long laps of time. The data are recorded every 10 seconds. A second test is performed by injecting of very small rate of nitrogen. After the establishment of the regime, and the calculation of K_g and K_l, the rate of nitrogen slightly decreased and, once again, the stationary regime is sought. This process is repeated until obtaining the complete curve of K_g and K_l in terms of saturation.

The determination of K_g was made possible by integrating the equation which results from the combination of Darcy's Law, law of perfect gas and the equation of continuity. The influence of the gravity was neglected.

The used equation is presented in the following form [Perré (1987)]:

$$K_g = \frac{L\mu_g}{(\Delta P - \Delta p_c)\,A} Q \frac{2P_0}{P_1 + P_2} \tag{5}$$

Index '0' is relative to the normal conditions of T and P.

P_1 and P_2 are respectively pressures at the above and the lower sides of the treated sample. The term of $\frac{2P_0}{P_1+P_2}$ is used as correcting factor of compressibility of the gas. Nevertheless, concerning the experience, this term has a maximal value of 1.07.

with:

$$\Delta P = P_1 - P_2 \qquad (6)$$

For the calculation of water permeability, the following equation is used:

$$K_l = \frac{Q_l \mu_l}{\Delta P_l} \frac{4L}{\pi D^2} \qquad (7)$$

Relative permeability is written:

$$K_{rg} = \frac{K_g}{K} \qquad (8)$$
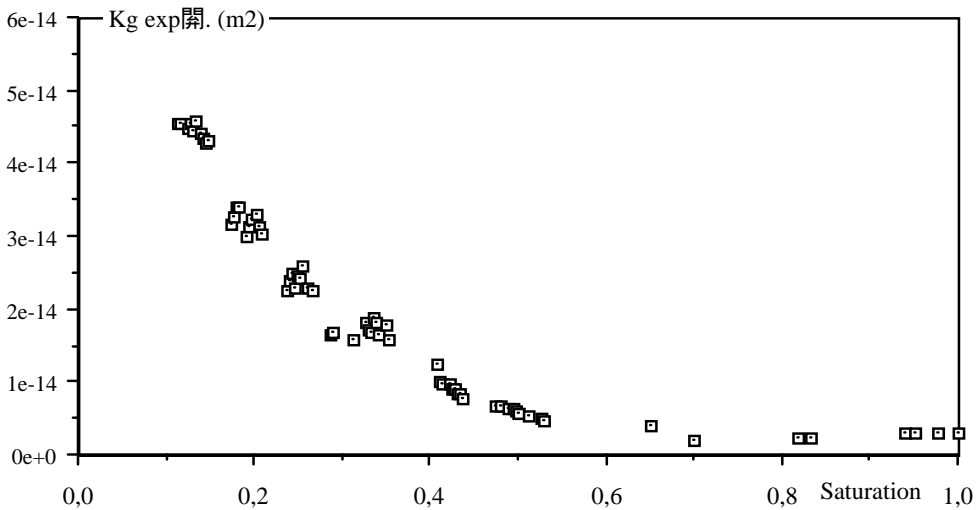
and

$$K_{rl} = \frac{K_l}{K} \qquad (9)$$

Figure 4: Variation of gas permeability

3 Results

3.1 Determination of the gas relative permeability

Fig. 4 plots K_g vs. saturation S and three stages can be clearly seen. The first stage is very short, where we notice an important decrease of S (from 100 to 50%) and approximately K_g is kept constant. This phase starts few seconds after the injection of the nitrogen in the water saturated sample and has duration of a few minutes. During this phase, we observe an important and swift decrease of saturation from 100% to around 50% occurring with quasi-constant gas permeability.

The second stage (S = 50 to 35%) is longer than the first one, and corresponds to almost a linear variation of K_g in terms of S. It is characterized by a decrease of the material saturation from 50% to 35% and linear variation of K_g with saturation.

The third stage is characterised by a strong increase of K_g for a small decrease of S. This stage is very slow and takes several hours. This phase is a very slow as it takes many hours with nitrogen flow attaining 25 ml/mn, which is considered as the maximum flow that can be used. It is observed that we have attained a saturation of 12%, instead of 5% and this probably due to the nitrogen pressure constraints. Also, several other reasons may play a role for reaching this saturation value. Indeed, a deterioration of the sample can occur at high pressure difference, as the measure of the manometer is limited to 20000 Pa.

3.2 Determination of the liquid relative permeability

Curve of relative permeability of water can be obtained after neglecting the effect of the capillary pressure [Souriau (1985)]. On the other hand, intrinsic water permeability was measured by Labed (1988).

Fig. 5, which represents the variations of the liquid permeability as function of the sample saturation, is divided into two main phases. The first phase corresponds to the range of saturation between 100% and 60%. In this interval a consequent variations of the liquid permeability is observed. This may due, essentially, to the existence of an in-stationary pulsed liquid flow, at the exit of the sample. It is important to note that the liquid is a mixture of the injected nitrogen gas and water. This measure is opposing to the measure of K_g, unhurried in stationary regime. The figure shows an important decrease of the liquid permeability with the saturation decrease.

The second phase corresponds to a very weak decrease of the liquid permeability with variation of saturation. Dispersion is less important than precedent phase.
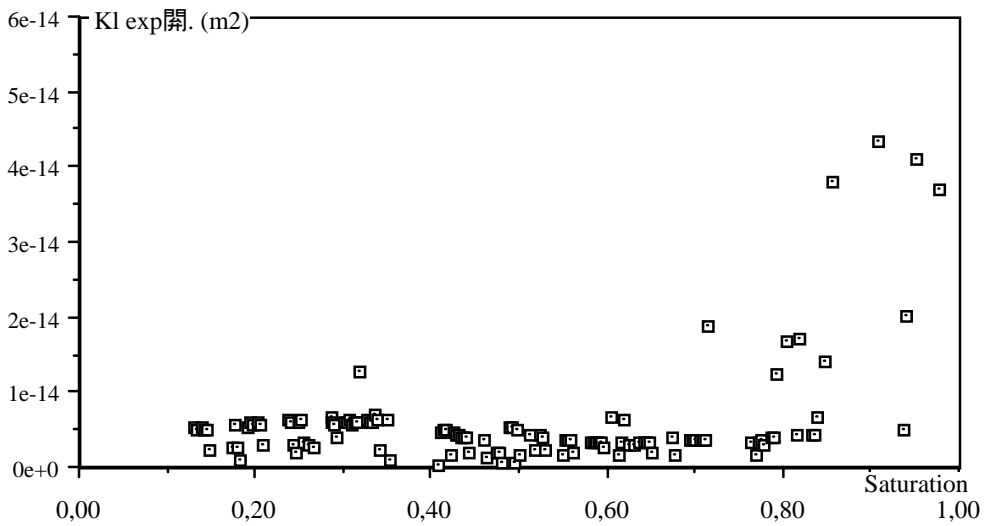
Figure 5: Variation of the liquid permeability

4 Comparison with other studies and conclusions

Fig. 6 shows a comparison of our experimental results with those reported in the theoretical study by Haramathy (1969) for K_g of brick sample, and by Hanarpour, Koedreritz and Harvey (1987) for case of sand. The general shape of the curves is respected. However, we notice an apparent difference for permeability of the gas for S = 60 down to 20%, and for water permeability at S = 80 to 40%. This difference could be due to the simplifications proposed in the theoretical model.

The results presented in this study show that testing ground can be used for measuring the gas relative permeability K_{rg}. The obtained values of K_l are acceptable. Dispersion noticed in Fig. 6 is due to nature of the flow and not to the measure itself. Many measuring tests were conducted to confirm the reproducibility of our results.

References

Al-Ajmi R. and Mosaad M. (2012): Heat Exchange between Film Condensation and Porous Natural Convection across a Vertical Wall, *Fluid Dyn. Mater. Process.*,
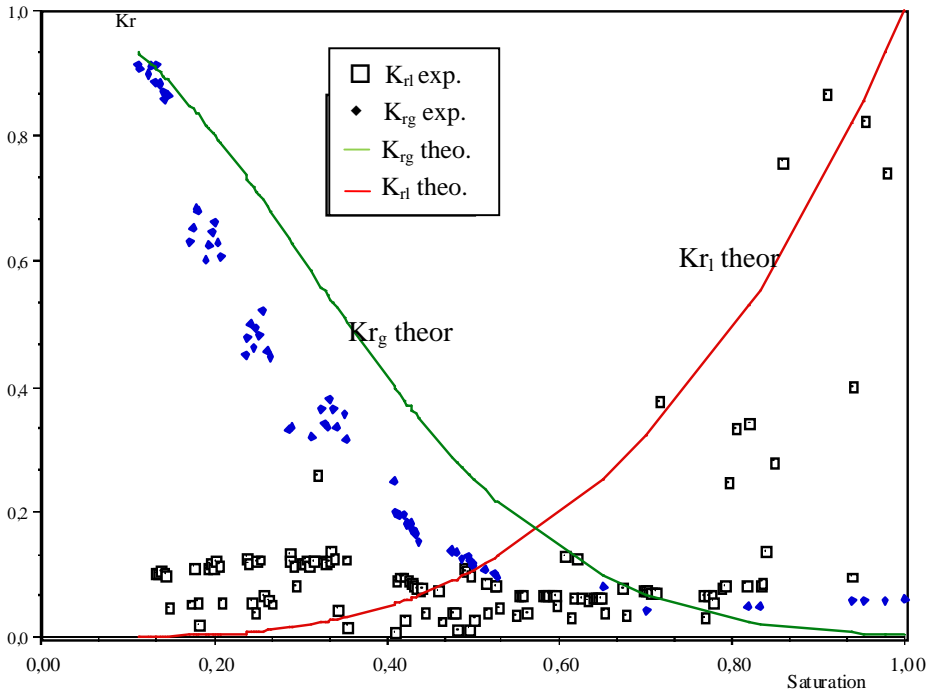
Figure 6: Comparison between experimental and theoretical results

Vol. 8, No. 1, pp. 51-68.

Alvarez, G.; Bournet, P.E.; Flick, D. (2003): Two-dimensional simulation of turbulent flow and transfer through stacked spheres, *Int. J. Heat Mass Tran.*, vol. 46 pp. 2459–2469.

Arnaud, G.; Fohr, J.P. (1988): Slow drying simulation in thick layers of granular products, *Int. J. Heat Mass Trans.*, vol. 31, pp. 2517–2526.

Bataller R.C. (2010): Towards a Numerical Benchmark for MHD Flows of Upper-Convected Maxwell (UCM) Fluids over a Porous Stretching Sheet, *Fluid Dyn. Mater. Process.*, Vol. 6, No. 3, pp. 337-350.

Bennamoun, L.; Belhamri, A. (2009): Application of a diffusion model to predict drying kinetics changes under variable conditions: Experimental and simulation study, *Fluid Dyn. Mat. Processing*, vol. 5, pp. 177-191.

Bennamoun, L.; Belhamri, A. (2008a): Mathematical description of heat and mass transfer during deep bed drying: Effect of product shrinkage on bed porosity, *Appl. Therm. Eng.*, vol. 28, pp. 2236-2244.

Bennamoun, L.; Belhamri, A. (2008b): Study of heat and mass transfer in porous media: Application to packed bed drying, *Fluid Dyn. Mat. Processing*, vol. 4, pp. 221-230.

Bennamoun L.; Belhamri, A. (2006): Study of convective heat and mass transfer in a porous media: Application to packed bed drying, *In: I. Farkas (Ed.), Series Editor: A.S. Mujumdar*, pp. 532-538.

Cai, L.; Oliveira, L.C. (2007): Gas permeability of wet wood and normal wood of subalpine fir in relation to drying, *Dry. Tech.*, vol. 25, pp. 501-505.

Carwford, R.; Jones, G.F.; You, L.; Wu, Q. (2011): Compression-dependent permeability measurement for random soft porous media and its applications to lift generation, *Chem. Eng. Sci.*, vol. 66, pp. 294-302.

Choukairy K. and Bennacer R. (2012): Numerical and Analytical Analysis of the Thermosolutal Convection in an Heterogeneous Porous Cavity, *Fluid Dyn. Mater. Process.*, Vol. 8, No. 2, 155- 173.

Daguenet, M. (1985) : *Les séchoirs solaires: théorie et pratique*, UNESCO.

Dias, R.P.; Fernandes, C.S.; Mota, M.; Teixeira, J.A.; Yelshin, A. (2007): Permeability and effective thermal conductivity of bisized porous media, *Int. J. Heat Mass Trans.*, vol. 50 pp. 1295-1301.

Erriguible, A.; Bernada, P.; Couture, F.; Roques, M.A. (2005): Modeling of heat and mass transfer at the boundary between a porous medium and its surrounding. *Dry. Tech.*, vol. 23, pp. 455–472.

Hamimid S., Guellal M., Amroune A. and Zeraibi N. (2012): Effect of a Porous Layer on the Flow Structure and Heat Transfer in a Square Cavity, *Fluid Dyn. Mater. Process.*, Vol. 8, No. 1, 69- 90.

Hanarpour, M.; Koedreritz, L.; Harvey, A.H. (1987): *Relative Permeability of Petroleum Reservoirs*, CRC Press.

Haramaty, T.Z. (1969): Simultaneous moisture and heat transfer in porous systems with particular reference to drying. Indus. *Eng. Chem. Fund.*, vol. 8, pp. 92-103.

Hao, L.; Cheng, P. (2010): Pore-scale simulations on relative premeabilities of porous media by lattice Boltzmann method, *Int. J. Heat Mass Trans.*, vol. 53, pp. 1908-1913.

Hsu, C.T. (2000): Heat conduction in porous media, In: K. Vafai (Ed.), *Handbook of porous media*, Marcel Dekker, New York.

Jamaalahmadi, M.; Müller-Steinhagen, H.; Izadpanah, M.R. (2005): Pressure drop, gas hold-up and heat transfer during single and two-phase through porous media, *Heat Fluid Flow*, vol. 26, pp. 156–172.

Kantzas, A.; Chatzis, I. (1988): Application of the preconditioned conjugate gradients method in the simulation of relative permeability properties of porous media, *Chem. Eng. Commun*., vol. 68, pp. 169-189.

Labed, N. (1988) : Rapport de stage de DEA. Université de Poitiers.

Labed N., Bennamoun L. and Fohr J.P. (2012): Experimental Study of Two-Phase Flow in Porous Media with Measurement of Relative Permeability, *Fluid Dyn. Mater. Process.*, Vol. 8, No. 4, pp. 423-436.

Li, Y.; LeBoeuf, E.J.; Basu, P.K.; Mahadevan, S. (2005): Stochastic modeling of the permeability of randomly generated porous media, *Adv. Water Resour.*, vol. 28, pp.835-844.

Liu, J.; Sano, Y.; Nakayama, A. (2009): A simple mathematical model for determining the equivalent permeability of fractured porous media, *Int. Commun. Heat Mass Trans.*, vol. 36, pp. 220-224.

Maximenko, A,; Kadet, V.V. (2000): Determination of relative permeabilities using the network models of porous media, *J. Petrol. Sci. Eng.*, vol. 28, pp. 145-152.

Nield, D.A.; Bejan, A. (2006): *Convection in Porous Media*, Springer, USA.

Perré, P. (1987): Measurement of softwoods' permeabilities to air: importance upon the drying model. Int. Comm. Heat Mass Transfer, vol. 14, pp. 519-529.

Prat, M. (2002): Recent advances in pore-scale models for drying of porous media. *Chem. Eng. Journal*, vol.86, pp. 153–164.

Quintard, M.; Whitaker, S. (2000): Theoretical analysis of transport in porous media, *Handbook of Porous Media*, Marcel Dekker, USA.

Quintard, M.; Kiviany, M.; Whitaker, S. (1997): Two-medium treatment of heat transfer in porous media: numerical results for effective properties, *Adv. Water. Resour.*, vol. 20, pp.77–94.

Ram P. and Bhandari A (2012): Flow Characteristics of Revolving Ferrofluid with Variable Viscosity in a Porous Medium in the Presence of Stationary Disk, *Fluid Dyn. Mater. Process.*, Vol. 8, No. 4, pp. 437-452.

Reverdy-Bruas, N.R.; Serra-Tosio, J.M.; Chave, Y.; Bloch, J.F. (2001): Investigation of the transverse permeability of saturated paper sheets, *Dry. Tech.*, vol. 19, pp. 2421-2433.

Reyes, L.I.; Parades, R.; Gutiérrez, V.G. (1999): Power law of the permeability in a two-dimensional disordered porous medium, *Phys. A*, vol. 274, pp. 391-399.

Schembre, J.M.; Kovscek, A.R. (2003): A technique for measuring two-phase relative permeability in porous media via X-ray CT measurements, *J. Petrol. Sci. Eng.*, vol. 39, pp. 159-174**Shou, D.; Fan, J.; Ding, F.** (2010): A difference-fractal model for the permeability of fibrous porous media, *Phys. Lett. A*, vol. 374, pp. 1201-1204.

Singh, M.; Mohanty, K.K. (2000): Permeability of spatially correlated porous media, *Chem. Eng. Sci.*, vol. 55, pp. 5393-5403.

Sourieau, P. (1985) : Réflexions sur les Déplacements en Milieu Poreux. Cas Diphasique. *Ecole d'été [1] "Transferts en Milieu Poreux".* Carcans-Maubuisson (Gironde-France).

Starov, V.M.; Zhdanov, V.G. (2001): Effective viscosity and permeability of porous media, *Colloid Surface A*, vol.192, pp. 363-375.

Takhar, H.S.; Chamkha, A.J., Nath, G. (2002): Natural convection on a vertical cylinder embedded in a thermally stratified high-porosity medium, *Int. J. of Therm. Sci.*, vol. 41, pp. 83–93.

Whitaker, S. (1980): Heat and mass transfer in granular porous media, in: A.S. Mujumdar (Ed.), *Advances in Drying I*, Hemisphere Publication, New York.

Yang, J.H.; Lee, S.L. (1999): Effect of anisotropy on transport phenomena in anisotropic porous media, *Int. J. Heat Mass Trans.*, vol. 42, pp. 2673–2681.

Yu, B.; Li, J.; Li, Z.; Zou, M. (2003): Permeabilities of unsaturated fractal porous media, *Int. J. Multiphase Flow*, vol. 29, pp. 1625-1642.

Zou, Q.; Opara, L.U.; McKibbin, R. (2006): A CFD modeling system for air-flow and heat transfer in ventilated packaging for fresh food: I. Initial analysis and development of mathematical models, *J. Food Eng.*, vol.77, pp. 1037–1047.