

**HEAT PIPE  
TECHNOLOGY**

**Volume I**  
*Fundamentals and  
Experimental Studies*

**Edited by L. L. Vasiliev**

***Proceedings of the 7th International Heat Pipe Conference***



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## P R E F A C E

The 7th International Heat Pipe Conference was held on May 21-25, 1990 in Minsk, at the A.V. Luikov Heat & Mass Transfer Institute Byelorussian Academy of Sciences. Such conferences have been organized and held since 1973 by the International Committee on Heat Pipes chaired by Dr. George Grover, the inventor of heat pipes. Since 1990 the chairman of this International Committee is Prof. Dr. Manfred Groll.

The heat pipe is one of the remarkable achievements of thermal physics and heat transfer engineering in the 20th century. Heat pipes are unique in their capability to transfer heat over large distances without considerable losses, because their thermal resistance is negligibly small and independent of their dimensions and shape.

The heat pipe may be used as a symbol of heat and mass transfer, because this outwardly simple heat-exchanging device embodies most processes of fluid dynamics and heat transfer (conduction, phase transitions, convection, radiation, kinetics, dynamics and heat transfer of the rarefied gas, etc.). The heat pipe operates on the basis of a closed-cycle process of mass and heat transfer that involves phase changes (vaporization, condensation) and can take place over a wide range of temperature and pressure on intricately shaped surfaces of complex structure and in channels of varying geometry and random spatial orientation.

The circulation is caused by a pressure gradient proportional to the temperature gradient. The flow carries energy which is transferred from the hot to the cold end of the heat pipe, or the heat is converted into other forms of energy (electric, luminous, mechanical, etc.). The heat pipe combines the achievements of present-day science and engineering because it may be designed using modern technology in every aspect of its operation.

That is why hundreds of heat pipes and thermosyphons of

varying design, from a few millimeters to several kilometers in length, are employed in industry and agriculture to transfer heat from fractions of watt to hundreds of kilowatts over temperature range from tenths degrees of K ( superfluid helium ) to 2000 K . Thousands of patents have been issued and filed for heat pipes.

The main applications of heat pipes deal with the problems of environmental protection and energy and fuel saving. Heat pipes provide increased heat transfer rates in machines and reactors, cooling of modern electronic equipment, computers, machine tools, chemical and biological integrated systems, and large-scale reduction of harmful emissions from industrial plants. In agriculture, heat pipes can provide optimum climatic conditions for animals and plants, and improved storage conditions for agricultural products.

In the context of commercialization of space, heat pipes are used to improve the methods of producing ultrapure materials, to forecast atmospheric conditions, to develop research equipment, etc.

Heat pipes are used to good advantage in the construction and operation of oil and gas pipes, roads, and dams in the northern areas of the U.S.S.R., the U.S.A. and Canada. Heat pipes are employed to freeze and cool the soil during construction work, to strengthen the earth beds for highways, to regulate subsoil erosion, heaving, and other negative phenomena, occurring in the soil due to disturbed temperature and moisture conditions, to heat up roads, bridges, over- and under passes in order to control icing, snow-drifts, etc.

The Proceedings of the 7th International Heat Pipes Conference will undoubtedly be of interest because of the possible use of heat pipes in new recuperative and regenerative heat exchangers whose operating parameters compare favorably with those of traditional design, make them highly reliable and efficient in operation, and make it possible to keep the heat transfer surface at a constant temperature.

The main purpose of such heat exchangers is to utilize heat recovery systems, particularly those at low potentials.

It is common knowledge that with about 2 billion metric tons of standard fuel consumed annually in the U.S.S.R., the wasted

energy resources account over 350 million kW.

Much of this energy source is at a low potential (below 250 °C), i. e. , in the course of fuel-consumption, the production processes discharge wasted energy resources to the environment at low temperatures .

The 7th International Heat Pipes Conference was attended by more then 200 scientists and experts from 19 countries: 155 papers and 5 lectures were presented to the conference; an International Heat Pipes Exhibition was held during the conference. The International Heat Pipes Conferences have a long history of many years, but it was for the first time that 15 institutions from the U.S.S.R. displayed their products.

Considering the recent increase of interest in the problems of energy consuming , space exploration and nature protection , four sections were set up within the conference to deal with the fundamental problems of heat and mass transfer, technological problems, and also the application of heat pipes in industry and agriculture.

The 7th IHPC Proceedings include the most interesting papers approved by the Chairmen of the sessions and Rapporteurs.

Among the interesting features of these Proceedings are not only the results of new studies on heat pipes, but also lectures on the general problems of heat and mass transfer , the problems of energy and fuel conservation , environmental protection and peaceful space exploration .

I hope that the publication of the 7th IHPC Proceedings will provide a deeper insight into the new problems and contribute to the rational utilization of the latest advances in science and technology for the welfare of mankind.

It is a great pleasure to take this opportunity to express my appreciation to the Sponsoring institutions, members of Committee on International Heat Pipe Conferences, to the authors of papers and lectures, Chairmen and Rapporteurs and members of the Local Organizing Committee of the 7th International Heat Pipe Conference for their cooperation and help.

Leonard L. Vasiliev

Editor, Proceedings of the 7th International Heat Pipe Conference.

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*Basic Processes and Fundamentals*





HEAT AND MASS TRANSFER WITH PHASE CHANGE  
IN CAPILLARY-POROUS BODIES

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**ABSTRACT**

The purpose of this paper is to give a short summary of some results of fundamental research, published during the last decade, on the simultaneous heat and mass transfer with phase change in homogeneous isotropic and non deformable capillary-porous bodies.

The review deals with theoretical and practical aspects of macroscopic modelling of the processes, as they appear in the operating cycle of a porous heat pipe.

Comparisons between numerical and experimental results, achieved in different boundary and thermodynamic conditions, determine the efficiency of the model on whole phenomena observed experimentally.

Despite the limitations of the theory and the underlying assumptions, the results confirm that the macroscopic mathematical model can be used with some confidence to describe and analyse the physical experiments.

**1. INTRODUCTION**

The coupled fluid flow heat and mass transfer in porous media have become a subject of considerable interest in recent years [1], [2], [3]. Though such processes play an important role in thermally enhanced oil recovery, recent expansion in the interest lies in the porous insulation moisture transport [4], the extraction of energy from geothermal reservoirs [5] the drying of materials or vegetables [6], the nuclear waste disposal [7] and the capillary-porous heat exchangers with phase change [8]. In many of these systems the simultaneous transport of heat, liquid, vapor and sometimes of non condensable gas is generally involved. Although this fact has been known for a long time [9], [10], [11], a complete solution of these problems has been severely hampered due to the coupling of transport equations, the strong non linearities of each equation and the difficulties of simultaneously taking into account the interactions with the boundary layer at the surface of the material [12].

To day the availability of computers helps to overcome some of these problems. At the same time it gives the opportunity to evaluate the theory and eventually, to use it as a predictive methodology. It also aids in the identification of the most important transport mechanisms and to rationalize the collection of experimental data.

The purpose of this paper is to examine the recent advances in the

testing of combined heat and mass transfer theoretical models which can be used to describe and analyse the operating cycle of a capillary porous heat pipe. It is not intended to be a comprehensive state of the art review on the subject but rather an attempt to evaluate the present situation with respect to the theory.

After the presentation of macroscopic equations governing the physical phenomena, the discussion will be concentrated on some comparisons between numerical and experimental results that have been published during the last decade on the simultaneous heat and mass transfer in homogeneous, isotropic and non deformable capillary-porous bodies.

## 2. THE DIFFERENTIAL EQUATIONS

The analysis of flow and heat transfer is usually based on the transport equations resulting from the differential balance laws. To predict global effects, such as flow resistance or heat flux, from a given object, requires detailed information on the surrounding velocity and temperature fields. For a continuous media, this information is extracted from the solution of the associated microscopic equations, subject to pertinent boundary conditions.

When a flow through a complex structure, such as a porous medium, is involved, these local or microscopic equations are generally still valid within the pores. However the geometric complexity of the internal solid surface, that bounds the flow domain, inside the porous medium, prevents a general solution of the detailed velocity and temperature field.

To overcome these difficulties, physical phenomena in porous media are generally described by "macroscopic" equations, valid at a level of a block of porous medium : i.e the Representative Elementary Volume (R.E.V.) containing many pores. Either established using "a priori" an equivalence between the heterogeneous porous medium and a fictitious continuum, or rigorously derived from microscopic equations by means of a volume averaging technique [13], [14], these equations are assumed to be representative, on the R.E.V., of average values of microscopic quantities.

The equations used to describe heat and mass transfer in capillary porous bodies were established in 1957 by PHILIP and de VRIES [15] and approximately at the same time by LUIKOV, [16]. Derived from an analysis, in which the porous material was assumed equivalent to a continuum, the resulting equations have been rationally founded [17], [18] using the approach in which the macroscopic balance equations are obtained by averaging balance and transfer microscopic equations over a representative volume.

When the solid, constituting the matrix of the porous structure, the saturating fluid phases and the thermodynamic conditions, obey and satisfy the assumptions and restrictions listed in [17], the macroscopic mass and energy balance equations, governing the phenomena, are respectively :

Mass balance equations :

\* Liquid phase :

$$\frac{\partial}{\partial t}(\rho_0 X_l) + \nabla \cdot (\rho_l \vec{U}_l) = - \dot{m} \quad (1a)$$

\* Gas phase :

$$\frac{\partial}{\partial t}(\rho_0 X_g) + \nabla \cdot (\rho_g \vec{U}_g) = \dot{m} \quad (1b)$$

\* Vapor phase :

$$\frac{\partial}{\partial t}(\rho_0 X_v) + \nabla \cdot (\rho_v \vec{U}_g + \vec{J}_v) = \dot{m} \quad (1c)$$

\* Non condensable gaz :

$$\frac{\partial}{\partial t}(\rho_0 X_a) + \nabla \cdot (\rho_a \vec{U}_g - \vec{J}_v) = 0 \quad (1d)$$

In these equations,  $t$  is the time,  $\rho_i$  are the densities of phases or species,  $\vec{U}_i$  the mass average velocities,  $\vec{J}_i$  the diffusion mass flux

densities and  $m$  is the evaporation rate inside the pore system (its value depends on the vapor liquid condition applied to a representative elementary volume).

Subscripts  $i = l, v, g, a, s$ , refer to quantities defined in the liquid, vapor, gas, non condensable species and solid phases or species.

#### Energy balance equation

$$(\rho C)^* \frac{\partial T}{\partial t} + (\rho_l C_{pl} \vec{U}_l + \rho_g C_{pg} \vec{U}_g) \cdot \nabla T = - \nabla \cdot \vec{\Phi} - \Delta h_v m \quad (2)$$

$$\text{where : } (\rho C)^* = \rho_0 C_{ps} + \rho_l X_l C_{pl} + \rho_g X_g C_{pg}$$

is the apparent heat capacity of the porous media.

$T$  is the temperature,  $C_{pi}$  the specific heat of phases,  $\vec{\Phi}$  the heat flux density and  $\Delta h_v$  the latent heat of evaporation

In the balance equations :

- the first terms represent the time rate of change of mass or of thermal energy,
- the second terms represent the convective mass or energy transport,
- the third terms represent the diffusive mass or energy transfer, and,
- the fourth terms represent the mass or energy sinks created by the vaporization condensation process.

The mass content of phases  $X_l$  and  $X_g$  are related to the volumic content  $\theta_l$  and  $\theta_g$  or to the saturations  $S_l$  and  $S_g$  by :

$$\theta_l = \frac{\rho_0}{\rho_l} X_l = \varepsilon S_l ; \theta_g = \frac{\rho_0}{\rho_g} X_g = \varepsilon S_g$$

where :  $\rho_0 = \rho_s \theta_s$  is the apparent density of the dry porous media.

Closure of the system (1) + (2) requires :

1. - the phenomenological laws giving:
  - . the average mass velocities, :  $U_l$  and  $U_g$  ;
  - . the diffusion mass flux density in the gas phase,  $\vec{J}_v$ , and
  - . the diffusion heat flux density through the porous media,  $\vec{\Phi}$ .
2. - the state laws for the different phases and,
3. - the complementary equations governing the equilibrium conditions between phases.

All these equations are well known and correspond respectively to :

#### Polyphasic Darcy's law :

$$\vec{U}_l = - \frac{K_l}{\mu_l} \cdot (\nabla P_l - \rho_l \vec{g}) \quad (3) \quad \vec{U}_g = - \frac{K_g}{\mu_g} \cdot (\nabla P - \rho_g \vec{g}) \quad (4)$$

These equations are valid when the fluid phases are Newtonian incompressible, immiscible and the inertial and viscosity effects are neglected [19].  $K_l$  and  $K_g$  are respectively the effective liquid phase permeability tensor and the effective gas phase permeability tensor. From

a theoretical standpoint  $K_l$  and  $K_g$  can be expressed as :

$K_l = K k_{rl}$  and  $K_g = K k_{rg}$  where  $K$  is the intrinsic permeability tensor and  $k_{rl}(X_l)$  and  $k_{rg}(X_g)$  are the relative water and gas permeabilities which varie from 0 to 1 for a completely dry material, to 1 or 0 for a fully saturated material.  $K_l$  and  $K_g$  depend on the texture of the porous

media and the amount of fluid in the pore space. They also depend on the past history of drying and wetting, which gives rise to hysteresis effect.

Macroscopic diffusion laws :

$$\text{Fick's law : } \vec{J}_v = - \rho_g \overset{=}{D} \cdot \nabla \left( \frac{\rho_v}{\rho_g} \right) \quad (5)$$

$$\text{Fourier's law : } \vec{\Phi} = - \overset{=}{\Lambda} \cdot \nabla T \quad (6)$$

The use of Fick's law to express the vapor mass flux density in the gas phase is an approximation only valid for the continuum regime, (mean molecular free path small compared to the pore diameter) when the thermal diffusion and pressure diffusion may be neglected [20]. This is generally the case in capillary porous bodies of which the size pore diameter  $r$ , is higher than  $10^{-7}$  m, [18], [20].

The coefficient  $\overset{=}{D}$  which appears in the macroscopic Fick's law is the apparent mass diffusivity tensor for vapor water in air through the porous material. It depends on the texture of the material (tortuosity, porosity distribution, anisotropy) on the moisture content and on experimental conditions.

With regard to the heat flux density,  $\overset{=}{\Lambda}$  is the apparent thermal conductivity tensor which depends on the thermal conductivities of the phases, on the moisture content and on the structural properties of the porous media [20].

Despite the existence of some explicit relations for  $\overset{=}{K}$ ,  $\overset{=}{D}$  and  $\overset{=}{\Lambda}$  it is important to notice that the models used for the predictive computations are generally simple geometrical forms combined with computation assumptions. In order to test, quantitatively, the validity of the mathematical model describing heat and mass transfer in capillary porous bodies, experimental determination of these coefficients is then much more preferable.

State laws :

The gaseous mixture is assumed to be an ideal mixture of perfect gas, so that species' density can be determined by the state laws, with the classical definitions for the total density of the gas,  $\rho_g$ , and the mass average velocity of the gas,  $\vec{U}_g$  :

$$P_i = \rho_i R_i T \quad \rho_g = \sum_i \rho_i \quad \text{with :} \quad (7)$$

$$P = \sum_i P_i \quad \rho_g \vec{U}_g = \sum_i \rho_i \vec{U}_i \quad i = a, v ; R_i = R/M_i$$

Complementary relations :

When two immiscible fluids are in equilibrium in porous medium the interfacial tension causes a pressure discontinuity between these two fluids. This pressure is the capillary pressure :  $P_c$ . It is related to water liquid content and to the temperature so that :

$$P_c(X_l, T) = P(X_l, T) - P_l(X_l, T) \quad (8)$$

Like relative permeabilities, capillary pressure values show hysteresis depending on whether they are determined under drying or wetting

The assumption of local thermodynamic equilibrium connects :

- the partial pressure of the vapor to the capillary pressure via Kelvin's relation :

$$P_v (X_l, T) = P_{vs} (T) \exp - \left( \frac{P_c}{\rho_l R_v T} \right) \quad (9)$$

- the partial heat of wetting to the partial pressure of the vapor via the Clausius-Clapeyron equation :

$$\Delta h_w = - R_v \frac{d(\text{Log } P_v/P_{vs})}{d(1/T)} \quad (10) \text{ and,}$$

- the partial pressure of the vapor to the sorption curve :

$$P_v = P_{vs} (T) \varphi(X_l, T) \quad (11)$$

The closure of the system (1) + ((2) is finally obtained with :

- the volume constraint equation :

$$\varepsilon = \theta_l + \theta_g \quad \text{where } \varepsilon = \text{porosity} \quad (12)$$

and,

- the physical properties evolution equations :

$$\mu_l (T) ; \mu_g (T) ; C_{pi} (T) ; \Delta h_v (T, X_l) \quad (13)$$

→ When we use the equations (3), (4), (5), (6), (8), to express  $\vec{U}_l$ ,  $\vec{U}_g$ ,  $J_v$ ,  $\Phi$ ,  $P_l$ , and the equation (1d) to express P, then, the choice of : temperature, volumic moisture content,  $X_l$ , and total pressure in the gaseous phase, P, as independant variables, enable us to reduce the system (1) to (13) to three coupled non linear partial differential equations [21], i.e. :

\* Moisture mass transport equation :

$$\frac{\partial X_l}{\partial t} + \alpha \frac{\partial X_l}{\partial t} + \beta \frac{\partial T}{\partial t} = \nabla \cdot \left( \overline{D_x} \cdot \nabla X_l + \overline{D_T} \cdot \nabla T + \overline{D_p} \cdot \nabla P + \overline{D_g} \cdot \nabla z \right) \quad (14)$$

(a)

(b)

(c)

(d)

(e)

\* Thermal energy transport equation :

$$(\rho C)^* \frac{\partial T}{\partial t} = \nabla \cdot \left( \overline{\Lambda}^* \cdot \nabla T \right) + \rho_l C_{pl} \left( \overline{D_{xl}} \cdot \nabla X_l + \overline{D_{tl}} \cdot \nabla T + \overline{D_{pl}} \cdot \nabla P + \overline{D_g} \cdot \nabla z \right) \cdot \nabla T$$

(f)

$$+ \rho_g C_{pg} \left( \overline{D_{pg}} \cdot \nabla P \right) \cdot \nabla T + \rho_l \Delta h_v \left( \nabla \cdot \left( \overline{D_{xv}} \cdot \nabla X_l + \overline{D_{tv}} \cdot \nabla T + \overline{D_{pv}} \cdot \nabla P \right) - \alpha \frac{\partial X_l}{\partial t} - \beta \frac{\partial T}{\partial t} \right) \quad (15)$$

(g)

(h)

\* Pressure equation :

Derived from the air mass transfer equation (1d) the time rate of change of total pressure is given by [20] :

$$\gamma \frac{\partial P}{\partial t} - \delta \frac{\partial X_l}{\partial t} - \lambda \frac{\partial T}{\partial t} = - \nabla \cdot \left( \overline{D_{xv}} \cdot \nabla X_l + \overline{D_{tv}} \cdot \nabla T - \overline{D_{pa}} \cdot \nabla P \right) \quad (16)$$

In the moisture mass transport equation, term (a) represents the time rate of change of vapor mass, expressed in equivalent liquid quantity ; terms (b) and (c) the total (liquid + vapor) mass flux density due to the capillary pressure gradients and to the partial water vapor pressure gradient ; (d) and (e) the total mass flux density due to the total pressure gradient in the gas phase and to the gravity force.

In the thermal energy transport equation (f) and (g) are respectively the liquid and gas phase convective energy, while (h) represents the sink energy created by the vaporization process.

As for the time rate of change of the total pressure it depends on the time rate of change of temperature, on the time rate of phase change and on the total mass flux density.

In the equations (13), (14) and (15) :  $D_X = D_{Xl} + D_{Xv}$  ;  $D_T = D_{Tl} + D_{Tv}$  ;  $D_p = D_{pl} + D_{pv}$  ;  $D_{pa}$ ,  $D_{pg}$  and  $D_g$  are respectively : the isothermal mass diffusivity coefficient, the thermomigration coefficient and the mass diffusivity coefficients because of the total pressure gradient and gravity.

These coefficients, as well as  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$ ,  $\lambda$  are explicit functions of :  $K_{rl}$ ,  $K_{rg}$ ,  $P_c$ ,  $D$ ,  $\phi$ , and of thermophysical properties of phases :  $\mu_l$ ,  $\mu_g$ ,  $\rho_l$ ,  $\rho_v$ , [15], [20]. Consequently they depend on  $X_l$ ,  $T$ ,  $P$ , and have to be determined before numerical computation.

The following section mainly deals with the presentation of some recent fundamental studies of coupled heat and mass transfer in homogeneous, isotropic capillary porous bodies and the attempts to test the validity of the theory by comparing experimental and numerical simulations of equations (14), (15), (16).

Due to the complexity of the mathematical model, and the difficulty of finding actual situations in which all the mechanisms are included and play a significant role, only typical examples, corresponding to various thermodynamic conditions will be analysed :

- simultaneous heat and mass transfer at constant and uniform gaseous pressure, where the dominant mechanisms are capillary effects, vapor diffusion and gravity. Such is generally the case when at given total pressure the temperature is lower than the liquid boiling point for instance in the convective drying of a capillary porous body at atmospheric pressure.
- simultaneous heat and mass transfer when the total gaseous pressure is non uniform and the temperature above the liquid boiling point. Such is the case in the operating cycle of a capillary-porous heat-pipe in boiling regime. This situation is more complex and involves capillary effects, vapor diffusion and convective transport.

### 3. COUPLED HEAT AND MASS TRANSFER AT CONSTANT AND UNIFORM GASEOUS PRESSURE

Numerical estimation of transport coefficients and a sensitivity study of the general model to internal parameters, show that many assumptions can be used to simplify the set of heat and mass transfer equations when the total pressure is uniform and constant and the temperature below the liquid boiling point. These assumption are :

- a) the terms  $\alpha \frac{\partial X_l}{\partial t}$  and  $\beta \frac{\partial T}{\partial t}$  corresponding to the time rate of change of the mass of vapor in the mass balance equation (13), assumed negligible in comparison to the time rate of change of the mass of liquid [23], [21],
- b) the liquid and gas convective energy terms assumed negligible in the energy balance equations (14), [21], [22].

Under these circumstances temperature and liquid saturation obey the following equations for an isotropic and homogeneous porous media i.e. :

$$\frac{\partial X_l}{\partial t} = \nabla \cdot (D_x \nabla X_l + D_T \nabla T + D_g \nabla z) \quad (17)$$

$$(\rho C)^* \frac{\partial T}{\partial t} = \nabla \cdot (\Lambda^* \cdot \nabla T) + \rho_l \Delta h_v (\nabla \cdot (D_{xv} \nabla X_l + D_{Tv} \nabla T)) \quad (18)$$

In this theoretical description three mechanisms are responsible of the fluid flows :

- the capillary effects resulting in saturation and temperature variations,
- the molecular diffusion mainly due to the variation of vapor pressure with the temperature,
- the force due to gravity.

In comparison with the numerous works devoted to single numerical simulations, studies focussed on the testing of equations (17), (18) are relatively rare. Among the research dedicated to this fundamental problem during the last decade we shall mainly mention [23] :

- KOOI's study concerning moisture and heat transfer in a cellular concrete roof having large variations in the pore size diameters (from micropores  $r < 10^{-7}$  m to macropores  $r > 10^{-7}$  m) [25].
- JURY's study concerning heat and mass transfer in a sand [26].
- Field experiments (with the inevitable difficulties due to the variability of natural soils and hysteresis effects) [27], [28], [29] and [30] to [34], related to the study on heat and mass exchange between the soil and the atmosphere.
- The recently published comprehensive studies on heat and mass transfer in a sand [35], [36], [37], where various specific conditions were studied and the theory compared with the experimental results in the absence of adjustable parameters.

In these studies, reasonable to good agreement between calculated and measured values of the macroscopic mass diffusivity coefficients was found, except for the isothermal mass diffusivity coefficient of the vapor  $D_{xv}$ . Regarding this coefficient, measured values was nearly an order of magnitude larger than the theoretical values.

Qualitatively explained on the basis of the interactions between the phases (vaporization, condensation phenomena on the meniscus inside the pores), this problem remains an open question and needs further research [38].

Close agreement was also found between the measured temperature dependence of capillary pressure  $P_c$  and of hydraulic conductivity  $\frac{K_l g}{\nu}$ , and that predicted on the basis of the change of the surface tension and kinematic viscosity of water with the temperature.

To test the validity of theoretical modeling, heat and mass transfer experiments were performed on a cylindrical cell of large aspect ratio :  $L/D$  ( $L$  : length,  $D$  : diameter) containing the partially saturated porous medium, whose the heat and mass transfer coefficients were previously determined.

This cylinder was bounded, at  $x$  or  $z = L$ , by an impervious and isothermal metal plate maintained at constant temperature  $T_0$ . The other end at  $x$  or  $z = 0$  was either bounded by an impervious and isothermal metal plate :  $T_1 \neq T_0$  (closed system) or was in contact with an airstream of constant velocity, temperature and relative humidity (open system). The lateral side of the cell was carefully insulated by means of a guard heater and an insulating material. Hence heat and mass transfers were one dimensional. The gas phase pressure inside the porous material

was kept uniform and equal to atmospheric pressure by means of some lateral vent holes.

Given uniform temperature and moisture content,  $(T_0, X_0)$ , as initial conditions, the experimental process was the analysis of the space-time evolution of the liquid saturation and of the temperature, when the thermodynamic equilibrium was disrupted by setting the  $x$  or  $z = 0$  section to  $T_1$ , different from  $T_0$  for the closed system, or in contact with an airstream when the cell is opened at  $z = 0$ .

### 3.1. Closed system

This configuration is specifically adapted for analysing the different mechanisms involved in the moisture movement, their competition and the result of their exact counterbalance in steady-state.

When the axis of the cylinder is horizontal (gravity effect negligible, i.e. moisture movements induced by the temperature gradients from the hot to the cold plate and by the moisture content gradients in opposite direction), some comparisons between the outcome of experiments and prediction of the theory are given on Figures 1 to 2. These results which concern the temperature and moisture evolution profiles obtained for different initial moisture contents, show reasonable, or even good, agreement in qualitative, as well as quantitative aspects of the phenomena and the role of different mechanisms involved.

For example, in steady state, (Figure 1), when the Posnov's number given by the relation :  $P_n = \frac{\delta^* \Delta T}{X_0}$  is lower than 2 (with the thermogradient

$$\delta^* = \frac{(\partial P_c / \partial T)_x}{(\partial P_c / \partial X)_T} \quad \text{and} \quad \Delta T = T_1 - T_0 :$$

- the average slope of the moisture content profile, is proportional to  $\delta^* \approx \frac{D_T}{D_X}$ .

This result confirms the influence of the pore size distribution on the liquid mass transport due to temperature gradients in the funicular zone.

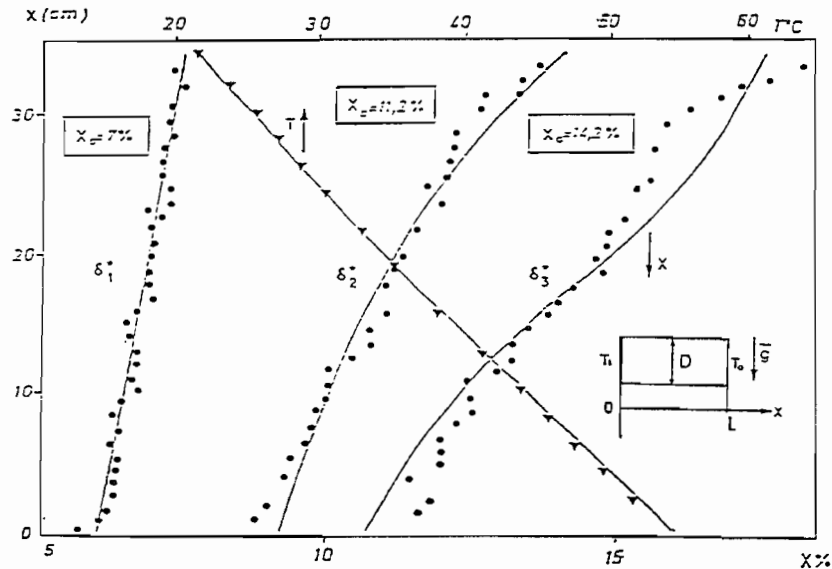


Figure 1 - Moisture profiles - Steady state regime

$$\delta_1^* < \delta_2^* < \delta_3^* \quad ; \quad P_n < 2$$



The more uniform is the pore size function distribution:  $\partial P_c / \partial X \rightarrow 0$ , the larger are the values of the thermogradient coefficient and of the slope of the moisture profile.

It also explains why in a porous medium of non uniform pore size

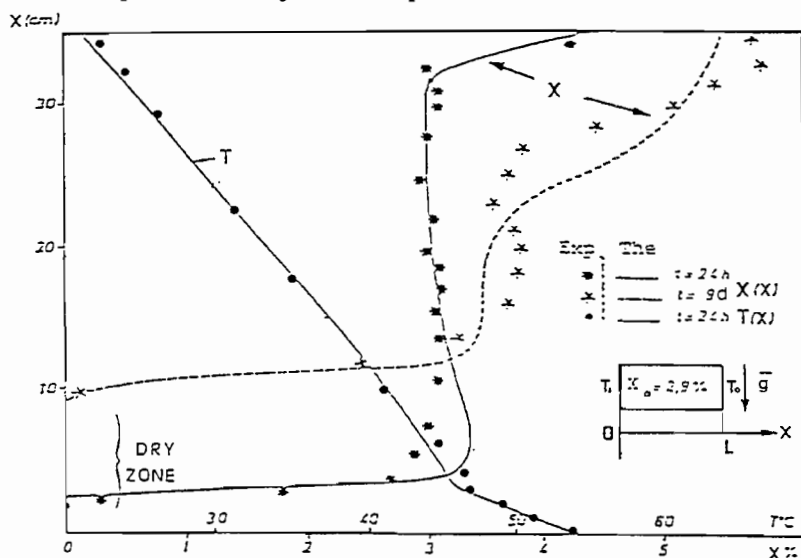


Figure 2 - Transient state regime,  $p_n > 2$

distribution function :  $\left( \frac{\partial P_c}{\partial X} \right)_T$  large, i.e.  $\delta^*$  small, it can be difficult

to observe a liquid mass transport under temperature gradient.

The others points of agreement between experiment and theory concern the existence and the development in time of a dry zone (moisture content  $\theta_l$  or  $X_l = 0$ ) near the heated end of the cell, when the non-dimensional Posnov's number is greater than 2.

As we may see on Figure 2, when this criterion is satisfied, there is also a reasonable agreement between the experimental and the numerical results, corresponding to the transient state evolution of the temperature profile  $T(x, t)$  and the moisture profile  $X(x, t)$ .

Good agreement was also found concerning :

- the front motion law of the interfacial zone at the beginning of the transient state (the movement of the interface is proportional to  $t^{1/2}$ , [40], and
- in the steady state the relation between the size of the dry zone and the Posnov's number (higher is the Posnov, larger is the dry zone).

As a thorough critical examination has recently shown three main causes can explain, the discrepancies, between these quantitative results (excepting inaccuracies in the determining of coefficients). These are :

- the gravity effect, when the capillary pressure tends to the bubble pressure or the critical capillary pressure,
- the wall heat transfer effect due to the shortcoming of the lateral guard heater, and the hysteresis phenomena [37], [46].

### 3.2. Open system

Further results concerning the testing of the capacity of the model to describe heat and mass transfer mechanisms, under more severe constraints, have been also obtained from experimental and numerical studies in open system in the vertical position. For different thermal boundary conditions (lower impervious plate, cooler or warmer than the airstream at the free surface) i.e. temperature gradient collinear or opposite to the gravity, reasonable to good agreement were found on many

points [35], [36].

For instance, Figure 3 show a comparison between the numerical and experimental moisture profiles,  $X$  as a function of  $z$ , corresponding to a transient state regime with temperature gradient opposite to the gravity (lower impervious plate cooler than the airstream). Qualitatively, but also quantitatively, theoretical results give a good description of the whole physical phenomena :

- the development of a dry zone at the upper part of the sample. In this zone, in equilibrium with the relative humidity, the liquid saturation is very low and defined by the sorption curve of the sand,
- the development of a condensation zone, at the bottom of the cell in which the liquid saturation is increasing in time,
- the existence of a receding interfacial zone with a large moisture gradient,
- and finally between the dry zone and the condensation zone, a region in which the moisture content, does not significantly change until the dry and condensation zones join together.

The development of these zones was explained through the analysis of the mass flux densities distribution  $J_i$  in the porous media.

- vapor mass flux density distribution  $J_v$ ,
- liquid mass flux density distribution  $J_l$ ,

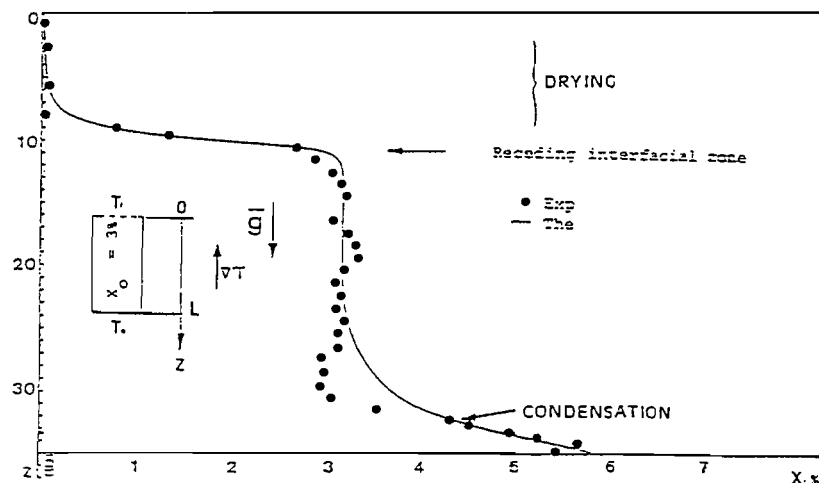


Figure 3 - Moisture profile

- total : liquid + vapor, mass flux density distribution  $\vec{J}_t = \vec{J}_v + \vec{J}_l$ . Mass flux densities are defined negative when the flows are directed towards the surface  $z = 0$  and positive when the flows are directed towards the cold impervious surface  $z = L$ .

As show Figure 4 where the theoretical moisture profile and the corresponding mass flux density profiles are shown at  $t = 9$  days the total mass flux density goes from the interfacial zone to the airstream in the dry zone, and from the interfacial zone to the bottom cold metal plate in the wetted zone.

#### 4. COUPLED HEAT AND MASS TRANSFER WITH VARIABLE GASEOUS PRESSURE

When the simultaneous heat and mass transfer takes place above the boiling point of liquid, the vapor transport under the influence of a total pressure gradient becomes one of the most important mechanisms of the heat and mass transfer. This mode of heat and mass transfer is analogous to the familiar heat pipe phenomenon.

Despite the fact that as for capillary-porous bodies under constant and uniform pressure the assumptions :

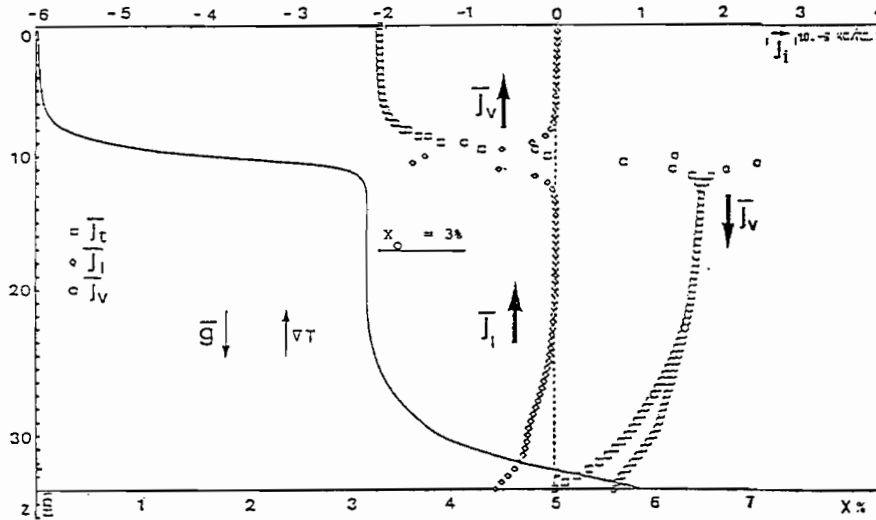


Figure 4 - Mass flux densities

- time rate of change of the mass of vapor in the mass balance negligible,  
 - liquid and gas convective energy negligible,  
 are still valid, [22], the governing equations are more complicated in this case, because including the pressure terms in the mass and energy balances and the pressure equation. They are :

$$\frac{\partial X_l}{\partial t} = (D_x \nabla X_l + D_T \nabla T + D_p \nabla P + D_g \nabla Z) \quad (19)$$

$$(\rho C)^* \frac{\partial T}{\partial t} = \nabla \cdot (\Lambda^* \nabla T) + \rho_l \Delta h_v (\nabla \cdot (D_{xv} \nabla X_l + D_{Tv} \nabla T + D_{pv} \nabla P)) \quad (20)$$

$$\gamma \frac{\partial P}{\partial t} - \delta \frac{\partial X_l}{\partial t} - \lambda \frac{\partial T}{\partial t} = \nabla \cdot (D_{xv} \nabla \theta_l + D_{Tv} \nabla T - D_{pv} \nabla P) \quad (21)$$

In this theoretical model four mechanisms are responsible for the moisture movement : capillary effects, molecular diffusion, total pressure and gravity force.

As in the previous cases this mathematical description was recently evaluated, comparing one dimensional experimental and numerical simulations in closed and open systems.

#### 4.1. Closed system

Experiments performed in order to evaluate the heat and mass transfer mechanism present within a partially saturated capillary driven porous medium were conducted [41] using different sand grain sizes contained in a cylindrical cell of large aspect ratio. The partially saturated sand core was heated from the top and cooled from the bottom.

Prior to each experiment,, air within the core holder was removed then distilled water was allowed to flow into the core until the sand pack was completely saturated. The fluid pressure was controlled during heating by a pressure regulator set slightly above atmospheric pressure. As the water steam was bled-off, condensed and collected in a graduated cylinder in order to obtain the average sand pack water pore volume fraction. Temperature profile along the axis of the sand pack was measured during the experiment.

From these experiments it was found that at steady state conditions, distinct regions appeared as shown in Figure 5. The top region was above the steam saturation temperature with the temperature being linear with respect to distance from the top standard. The bottom region, where

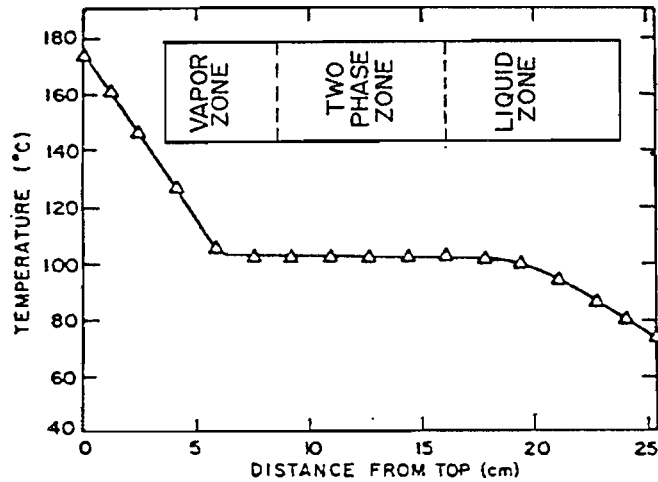


Figure 5 - Temperature profile

measured temperature were less than the saturation temperature also exhibited a linear temperature profile. These results are expected for conduction-dominated heat transfer.

The region separating the top and bottom conduction zones was nearly isothermal with each measured temperature close to the saturation temperature. Since the temperature gradient in this region was small the dominant mode of heat transfer was convection.

From conservation of energy and mass principles it was deduced that there existed an upward mass flux of the liquid phase from the bottom to top of this isothermal zone due to capillary pressure differences and an equal downward mass flux of the vapor from the top to bottom.

The length of the two phase zone was observed to decrease with increasing heat flux (Figure 6).

Using a simplified version of equations (19) and (20) the length of the two-phase convection zone was evaluated. The model was in excellent agreement with the observed results, predicting a decreasing two-phase zone length with increasing heat flux (Figure 6).

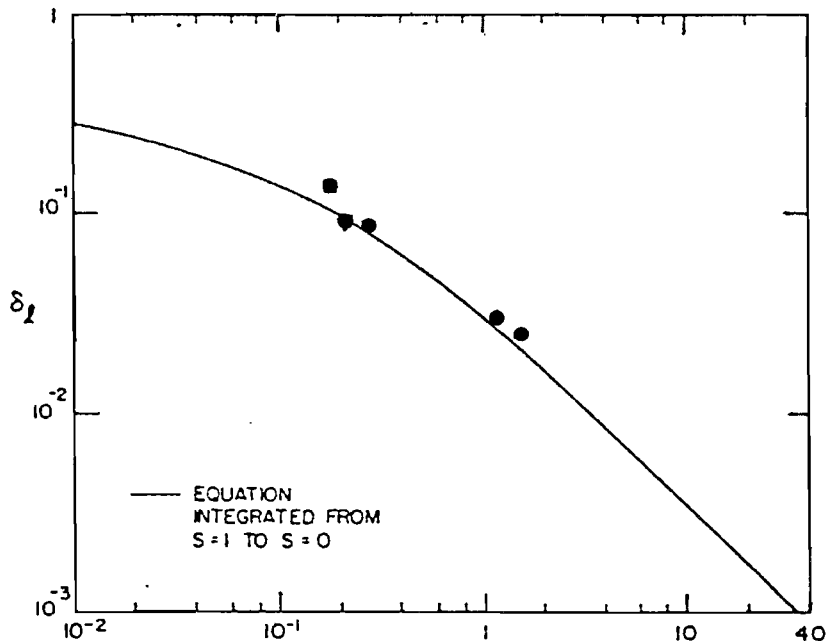


Figure 6 - Height of two-phase zone versus heat flux [41]

#### 4.2. Open system

The simulated case correspond to the experimental condition which can be carried out on an experimental set-up designed to study the monodirectional water flash boiling in homogeneous and isotropic porous media.

During the experiment the following parameters are measured and recorded :  $T(x, t)$  temperature,  $P(x, t)$  pressure,  $S_l(x, t)$  liquid saturation,  $M(t)$  mass of produced fluid,  $h(t)$  enthalpy of produced fluid.

The problem is modelled as an horizontal water saturated cylindrical porous media laterally bounded by an impervious and thermally insulating material. The end  $x = L$  of the cylinder is impervious and adiabatic. The section discharge  $x = 0$  is thermally insulated and closed by a valve.

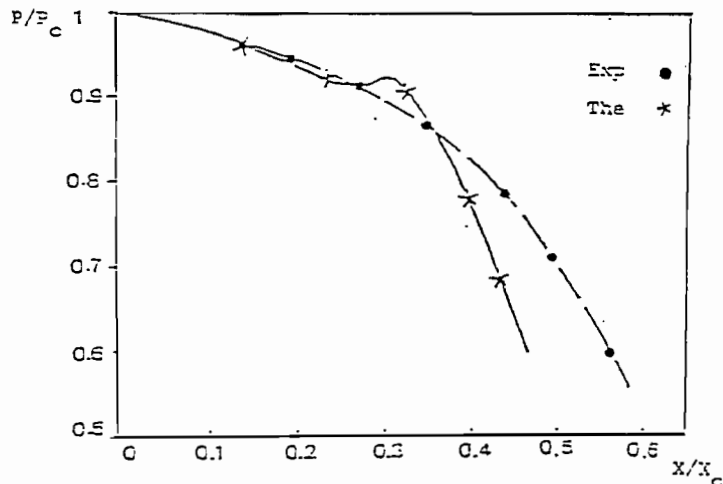


Figure 7 - Pressure evolution

Starting from initial thermodynamic conditions,  $(P_0, T_0)$ , in which the liquid water saturating the porous media is compressed and superheated at  $(P_0, T_0) > (P_{sat}, T_{sat})$  at atmospheric conditions, the flash boiling reaction is obtained by opening instantly the valve setted at  $x = 0$ . The outside atmospheric pressure being lower than the pressure of the water, unidirectional self vaporization occurs inside the porous

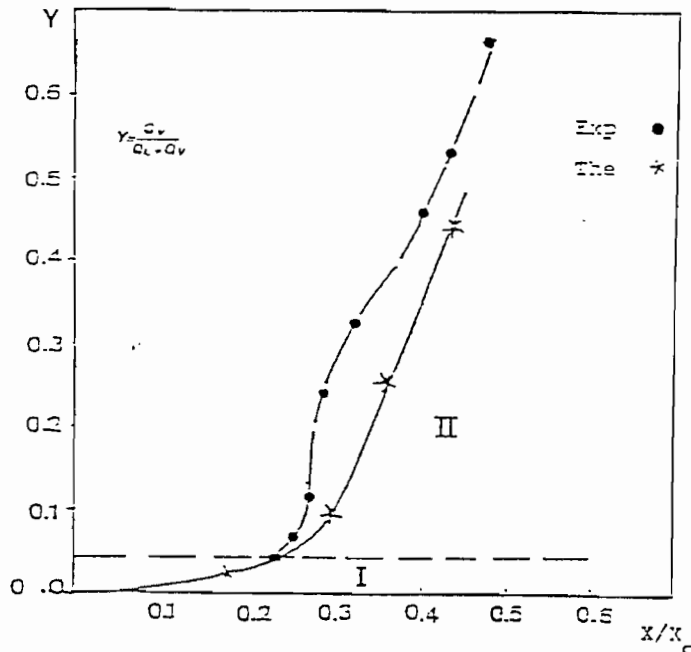


Figure 8

media while the two phase flow is being released through the valve [42], [43], [44].

The results shown in Figures (7) and (8) concern the evolution of the average pressure inside the porous media, and of the ratio of the mass of vapor produced to the total (liquid + vapor) produced mass as a function of the mass of produced fluid, (which is equivalent to time).

On the basis of these figures the comparisons between experimental and numerical values are qualitatively satisfactory, but large discrepancies exist concerning quantitative values.

The results shown in Figure (9) and (10) concern the evolution in space and time of the pressure and of the saturation. The resulting pressure history and the vapor mass fraction :  $Y = Q_v / Q_v + Q_l$  produced at  $X = 0$  are given in Figure (11), ( $Q_v$  and  $Q_l$  vapor and liquid mass flux).

On analyzing these results, three stages can be observed in the evolution of the phenomena during the production time :

- a first stage (I) mainly controlled by the appearance and the expansion of dispersed vapor bubbles inside the part of the porous media where the pressure reaches the saturating vapor pressure. In this first stage which corresponds to the expulsion of the liquid by the steam the mass discharge is high and the enthalpy of the produced fluid low :

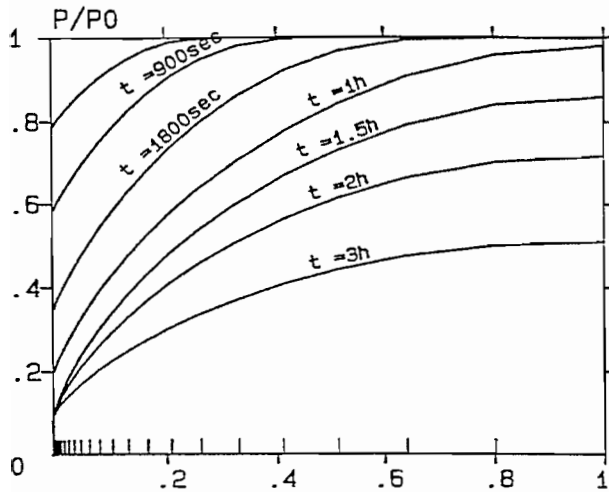


Figure 9 - Pressure profiles

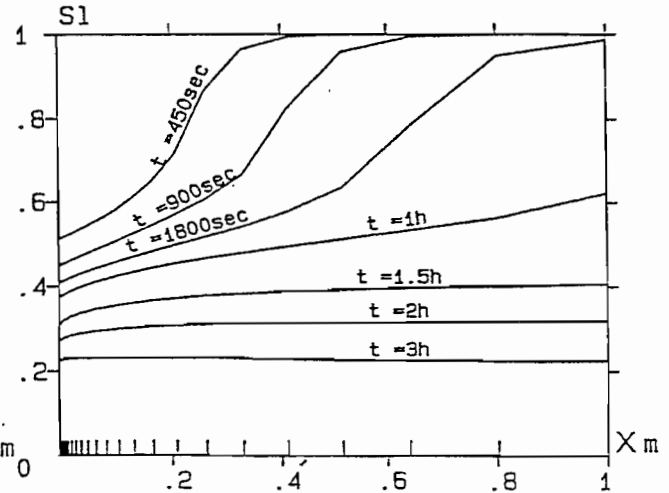


Figure 10 - Saturation profiles

$$\left( \frac{Q_v}{Q_v + Q_l} \text{ small} \right).$$

- a second stage (II) in which the mass discharge decreases and the enthalpy of the produced fluid increases. This stage appears and develops as the gaseous phase connects in the two phase zone. It corresponds to a simultaneous flow of liquid and vapor phases resulting in a reductio of the thermodynamic conditions inside the porous medium. For appropriate boundary conditions, i.e when the opening time of the valve is lower than

the time scale of the pressure diffusion :  $t = \frac{\mu L^2}{k \Delta P}$ , the water content profile exhibits an accentuated S shape with two zones : a single liquid zone, and a liquid-vapor zone (Figures 9 and 10),

- a third (III) stage in which the vapor flow prevails, the mass discharge is very low and the enthalpy of the produced fluids reaches the enthalpy of the steam.

From a quantitative standpoint, a sensitivity study of parameters pointed out the strong influence of relative permeability. This influence appears to be mainly significant at low vapor saturation and at low liquid saturation, i.e. in the transition zones when the single

monophasic liquid flow becomes a two phase flow and the two phases flow becomes a single vapor flow.

Numerical simulation was also used to estimate the influence of initial and boundary conditions (initial values of  $P_0$ ,  $T_0$  and mean discharge rate) on the evolution, as a function of time, of the interface between the boiling zone and the monophasic liquid zone, before the boiling front reaches the end of the porous media  $X = 1$ . The results show, that the propagation of the interface is proportional to  $t^{1/2}$  and strongly depends on the intrinsic permeability  $k$ .

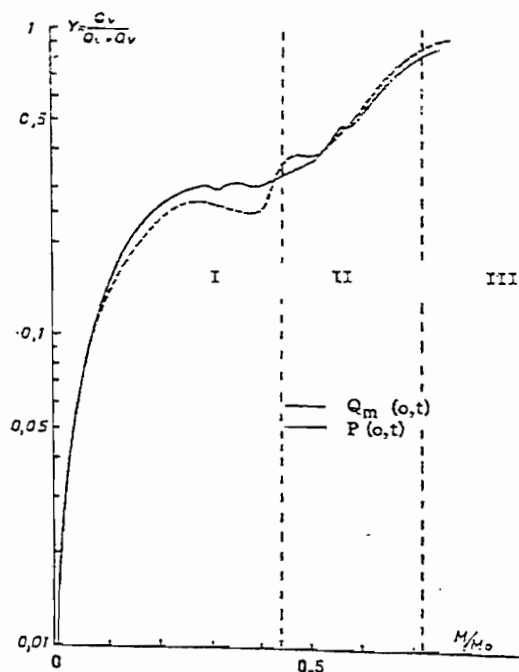


Figure 11 - Produced vapor mass fraction as a function of the total produced mass fraction

## 5. CONCLUDING REMARKS

This paper presents a brief review of some theoretical, numerical and experimental studies, published, during the last decade on simultaneous heat and mass transfer in capillary porous bodies. It focuses on research devoted to the evaluation of the theory and emphasizes on some progress made in the foundation of the mathematical modeling, using the rational volume averaging approach, and on testing of the governing equations.

As far as the evaluation of the theoretical model is concerned, the comparisons made between the outcome of laboratory experiments and numerical predictions have shown a reasonable or even good agreement in most cases studied.

If the theory has proved its usefulness in describing and analysing laboratory experiments nevertheless doubts remain, about the possibility of making accurate predictions on the basis of the mathematical modeling. As mentioned [37], these doubts arise, not only from the inevitable limitations of the theory, but also, from inaccuracies of experimental results, mainly due to the lack of accurate and reliable measurement techniques.

To give an undeniable predictive character to the theory further research are still necessary.

While this research continues, existing general knowledge in the field of simultaneous heat and mass transfer in capillary porous bodies, can be used as a first approach, in the handling of practical problems.

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