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ONE-PHASE AND TWO-PHASE FLOW IN HIGHLY PERMEABLE POROUS MEDIA

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ABSTRACT

Many industrial and natural processes involve flow in highly permeable media, such as heat and mass exchangers, canopy, networks of urban canyons, etc. For these systems, the traditional assumptions made prior to upscaling pore-flow equations do not hold anymore. Reynolds numbers may be high enough so Darcy's law is no longer valid, Capillary and Bond numbers may be also sufficiently large to invalidate the quasi-static assumptions used when upscaling multiphase flows. Several time-scales of very different order of magnitudes may be at play. Based on new experimental data and upscaling results, this paper reviews several approaches that have been developed to handle such cases. The case of one-phase flow has been largely studied from various point of views. This led to various forms of the macro-scale momentum equation: generalized Forchheimer equation, macro-scale turbulent models. The case of two-phase flow is more complicated and largely remains an open problem. The possibility of deriving macro-scale models from the pore-scale equations is discussed and potential macro-scale models are introduced: generalized Darcy's laws, model with various form of inertia terms, cross terms accounting for the viscous interaction between the two flowing phases, dynamic models. Classes of models suitable for describing flow in structured media like, for instance, chemical exchangers made with structured packings, are also introduced. Finally, hybrid models are presented involving the coupling between two-different scale modeling, for instance a network approach coupled with dynamic rules coming from pore-scale numerical simulations or experiments. This is useful, for example, in describing the apparent diffusion of impinging jets in packed beds which often cannot be described properly by capillary diffusion.

INTRODUCTION

Current trends in porous media physics involve research on very small pores, i.e., material with very low permeability, like oil-shales, nanoporous materials, etc... The opposite case, i.e., flow in highly permeable media, is also of current interest. This is the case in chemical engineering, with, for instance trickle beds with particles of several millimeters diameter or in the case of structured packings, for which the pore-scale characteristic length is about 1 cm. Flow in some fractured media, in very coarse sand, in canopies, nuclear reactors as well as debris beds for damaged cores, etc..., are other examples of particular interest in many different fields. In classical applications, macro-scale models are developed based on a series of assumptions about the value of the relevant dimensionless numbers. For instance, one-phase flow are considered in the limit Reynolds number (Re) going to zero, and this leads to the classical Darcy's law [1]. In the case of two-phase flow in porous media, Reynolds (Re), Bond (Bo) and capillary (Ca) numbers are assumed to be small and this represents an important assumption justifying the use of the so-called generalized Darcy's laws [2]. What happens to these macro-scale modeling questions when one or all of these numbers becomes very high? This has been the subject of intensive research in the past decades, the underlying multiple-scale analysis problems are reviewed below in the case of the flow of one phase and in the two-phase flow case. The emphasis is on the discussion about the structure of the macro-scale models which may be developed. Other questions like numerical modeling, or specific experimental techniques that must be used in such cases, are beyond the scope of this review.

ONE-PHASE FLOW

The pore-scale problem describing the flow of one phase, β , within a porous medium may be written for a Newtonian fluid with constant density, ρ_β , and viscosity, μ_β , as

$$\nabla \cdot \mathbf{v}_\beta = 0 \text{ in } V_\beta \quad (1)$$

$$\rho_\beta \frac{\partial \mathbf{v}_\beta}{\partial t} + \rho_\beta \mathbf{v}_\beta \cdot \nabla \mathbf{v}_\beta = -\nabla p_\beta + \rho_\beta \mathbf{g} + \mu_\beta \nabla^2 \mathbf{v}_\beta \text{ in } V_\beta \quad (2)$$

$$\text{B.C.1} \quad \mathbf{v}_\beta = 0 \text{ at } A_{\beta\sigma} \quad (3)$$

where \mathbf{v}_β and p_β are the fluid velocity and pressure respectively, \mathbf{g} the gravity acceleration, and $A_{\beta\sigma}$ stands for the interface between the fluid and solid phase.

Depending on the pore-scale Reynolds number that may be defined as

$$\text{Re} = \frac{\rho_\beta U_r l_\beta}{\mu_\beta} \quad (4)$$

where U_r is a reference velocity taken usually as the intrinsic average velocity and l_β a pore-scale characteristic length, one may distinguish various types of flow patterns [3].

In the limit $\text{Re} \rightarrow 0$ (creeping flow) there is a robust consensus that, providing that the separation of scale assumption holds, the macro-scale model describing the momentum balance may be written under the form of a Darcy's law [1] such as

$$\mathbf{V}_\beta = -\frac{1}{\mu_\beta} \mathbf{K} \cdot (\nabla P_\beta - \rho_\beta \mathbf{g}) \quad (5)$$

where \mathbf{V}_β is the filtration velocity, P_β the intrinsic average pressure and \mathbf{K} the intrinsic permeability tensor. Indeed, starting with the pore-scale problem described by Eqns 1 through 3, upscaling theories give a sound physical basis for the use of Darcy's law. This is the case by using homogenization theory [4] or by using a volume averaging technique [5, 6]. This is a well known theoretical problem and it will not be discussed further.

Increasing the Reynolds number, inertia terms start to play a dominant role. In this case, the relation pressure drop/velocity is no-longer linear. While this is the subject of various discussions and controversies [7–11], the pressure-velocity dependence may roughly be described as in Fig. 1. The pressure drop - velocity relationship departs from the linear case with a cubic behavior $\approx \text{Re}^3$ called weak inertia regime. The flow is still laminar but inertia effects start to affect the friction term. Increasing again the Re number leads to a strong inertia regime for which the pressure drop can be approximated as $\approx \text{Re}^2$. Often, the correction to Darcy's law in the weak inertia regime is small (while it can be

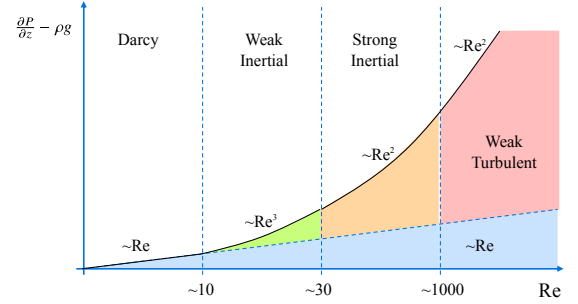


FIGURE 1. VARIOUS FLOW REGIMES

measured with a proper accurate experimental system [12]) and only the quadratic correction has a significant impact. This led to the proposal of heuristic laws having the form of a Forchheimer equation, which can be written in a very general manner as

$$0 = -\nabla P_\beta + \rho_\beta \mathbf{g} - \mu_\beta \mathbf{K}^{-1} \cdot \mathbf{V}_\beta - \mathbf{F}(\mathbf{V}_\beta) \cdot \mathbf{V}_\beta \quad (6)$$

where the term $\mathbf{F}(\mathbf{V}_\beta) \cdot \mathbf{V}_\beta$ is called a generalized Forchheimer term in reference to the work of [13].

If one solves the upscaling problem in terms of an asymptotic expansion with the Reynolds number, the first correction to Darcy's law, i.e., in the weak inertia regime, is cubic in terms of the velocity [7–9, 11, 14], i.e.,

$$\mathbf{F}(\mathbf{V}_\beta) \sim \|\langle \mathbf{v}_\beta \rangle\|^2 \quad (7)$$

Increasing again the Reynolds number while keeping a laminar flow, inertia effects may be approximated macroscopically by a quadratic term, i.e.,

$$\mathbf{F}(\mathbf{V}_\beta) \sim \|\langle \mathbf{v}_\beta \rangle\| \quad (8)$$

This is supported by experimental data [13, 15–18] as well as numerical predictions [11, 19].

While the above expression suggest the potential existence of anisotropy effects for the Forchheimer terms, simpler expressions are used in the engineering practice, in particular Ergun's equation [15] which is written as

$$0 = -\nabla P_\beta + \rho_\beta \mathbf{g} - \mu_\beta K^{-1} \mathbf{V}_\beta - \rho_\beta \eta^{-1} \|\mathbf{V}_\beta\| \mathbf{V}_\beta \quad (9)$$

where η is called the *passability*. Based on collected experimental data, Ergun proposed correlations for K and η in the case of packed beds which are used frequently in the engineering practice:

$$K = \frac{\varepsilon^3 d^2}{h_K (1 - \varepsilon)^2} \quad ; \quad \eta = \frac{\varepsilon^3 d}{h_\eta (1 - \varepsilon)} \quad (10)$$

where d is the equivalent particle diameter and $h_K = 150$ and $h_\eta = 1.75$ (other values can be found in the literature [12]).

If a generalized Forchheimer equation can be reasonably used, up to an accuracy about 10%, to describe strong inertia effects in laminar regimes, this model is also used in the case of unit-cell localized or periodic turbulence, as shown theoretically in [10, 20], while the resulting pressure drop is not necessarily quadratic. If one increases again the Re number, turbulence is not always of the periodic type as illustrated by the direct numerical simulations in [21]. One would call such a situation as macro-scale turbulence and several attempts have been made to develop *macro-scale* turbulence models. The velocity and pressure fields are no longer steady-state and the development of macro-scale models requires a double averaging with respect to space and time. While the operators for spatial and time averaging may in principle be exchanged [22], the application in a sequential manner, as illustrated below

$$\text{I. } \mathbf{v}_\beta \rightarrow \langle \mathbf{v}_\beta \rangle \rightarrow \overline{\langle \mathbf{v}_\beta \rangle} \quad (11)$$

$$\text{II. } \mathbf{v}_\beta \rightarrow \overline{\mathbf{v}_\beta} (\text{RANS}, \dots) \rightarrow \langle \overline{\mathbf{v}_\beta} \rangle \quad (12)$$

where $\langle \varphi \rangle$ stands for the spatial averaging of a variable φ while $\overline{\varphi}$ stands for the time average, may lead to different macro-scale models. The fundamental reason is due to the fact that each up-scaling or averaging step introduces approximations which do not in general commute. Scheme I, favored by [23, 24] among others, involves a first spatial averaging. Assuming that the closed macro-scale equations have the form of a generalized Forchheimer equation, it is subsequently time averaged. Since it was found that the assumption in step 1 is difficult to justify theoretically, most researchers follow scheme II. In this case, it is assumed that the Navier-Stokes equations may be time averaged and the resulting equations are subsequently spatially averaged [22, 25–27]). The result is in general some sort of effective RANS macro-scale model. It must be emphasized that, in the two cases, it is difficult to justify the possibility of a decoupled closure for both averages. A complete validation through experiments or numerical modeling is still an open problem. The need for such models has not also been fully assessed. Interestingly, it has been observed using direct numerical simulations that turbulence generated in a fluid layer or at the interface between fluid and porous layers may penetrate a distance of several unit cells into the porous domain and that in this area a macro-scale turbulence model is needed [28].

TWO-PHASE FLOW

The pore-scale problem for two-phase flow in porous media involves mass and momentum balance equations for both phases, denoted β and γ , and boundary conditions. To understand what is at stake in the upscaling problem, it is interesting to have a

look at the condition at the interface between both fluids. The boundary condition for the momentum equation reads

$$\begin{aligned} & -\mathbf{n}_{\beta\gamma} p_\beta + \mu_\beta \mathbf{n}_{\beta\gamma} \cdot (\nabla \mathbf{v}_\beta + (\nabla \mathbf{v}_\beta)^T) = \\ & -\mathbf{n}_{\beta\gamma} p_\gamma + \mu_\gamma \mathbf{n}_{\beta\gamma} \cdot (\nabla \mathbf{v}_\gamma + (\nabla \mathbf{v}_\gamma)^T) + 2\sigma H_{\beta\gamma} \mathbf{n}_{\beta\gamma} \text{ at } A_{\beta\gamma} \end{aligned} \quad (13)$$

where σ is the interfacial tension, $H_{\beta\gamma}$ the interface curvature and $\mathbf{n}_{\beta\gamma}$ the normal to the interface. Introducing macro-scale quantities and deviations, such as

$$p_\beta = P_\beta + \tilde{p}_\beta \quad (14)$$

for the β -phase, this BC can be transformed into

$$\begin{aligned} & \mathbf{n}_{\beta\gamma} (P_\gamma|_{\mathbf{x}} - P_\beta|_{\mathbf{x}}) + \mathbf{n}_{\beta\gamma} \mathbf{y}_\beta \cdot ((\nabla P_\gamma|_{\mathbf{x}} - \rho_\gamma \mathbf{g}) - (\nabla P_\beta|_{\mathbf{x}} - \rho_\beta \mathbf{g})) \\ & + \mathbf{n}_{\beta\gamma} \mathbf{y}_\beta \cdot (\rho_\gamma - \rho_\beta) \mathbf{g} + \dots = -\mathbf{n}_{\beta\gamma} (\tilde{p}_\gamma - \tilde{p}_\beta) \\ & + \mu_\gamma \mathbf{n}_{\beta\gamma} \cdot (\nabla \mathbf{v}_\gamma + (\nabla \mathbf{v}_\gamma)^T) - \mu_\beta \mathbf{n}_{\beta\gamma} \cdot (\nabla \mathbf{v}_\beta + (\nabla \mathbf{v}_\beta)^T) \\ & + 2\sigma H_{\beta\gamma} \mathbf{n}_{\beta\gamma} \text{ at } A_{\beta\gamma} \end{aligned} \quad (15)$$

where \mathbf{y}_β describes the position of a point in the β -phase relative to the centroid of some averaging volume at position \mathbf{x} . The curvature within the averaging volume will depend on (i) the capillary pressure ($P_\gamma|_{\mathbf{x}} - P_\beta|_{\mathbf{x}}$), (ii) gravity effect, (iii) viscous effects, (iv) dynamic effects (important values of the pressure deviations related to the flow or of terms like $(\nabla P_\gamma|_{\mathbf{x}} - \rho_\gamma \mathbf{g}) - (\nabla P_\beta|_{\mathbf{x}} - \rho_\beta \mathbf{g})$).

Depending on the assumptions made, several models can be developed. Their physical meaning and mathematical structure are discussed in the next sections.

Quasi-Static Models

The boundary condition Eqn 15 can be replaced, for small capillary and Bond numbers defined as

$$\text{Ca} = \frac{\mu_r U_r}{\sigma} \quad ; \quad \text{Bo} = \frac{|(\rho_\beta - \rho_\gamma) g| r_0^2}{\sigma} \quad (16)$$

by

$$P_\gamma|_{\mathbf{x}} - P_\beta|_{\mathbf{x}} = 2\sigma H_{\beta\gamma} \quad (17)$$

As a result, the interface curvature is locally constant and *quasi-static* and this allows to introduce a macro-scale capillary pressure condition as

$$P_\gamma - P_\beta = p_c(S_\beta, \dots) \quad (18)$$

This is the base for the heuristic generalized Darcy's laws model classically used in engineering practice [2]. The whole model reads

$$\frac{\partial \varepsilon S_\beta}{\partial t} + \nabla \cdot \mathbf{V}_\beta = 0 \quad (19)$$

$$\mathbf{V}_\beta = -\frac{1}{\mu_\beta} \mathbf{K}_\beta \cdot (\nabla P_\beta - \rho_\beta \mathbf{g}) \quad (20)$$

$$\frac{\partial \varepsilon S_\gamma}{\partial t} + \nabla \cdot \mathbf{V}_\gamma = 0 \quad (21)$$

$$\mathbf{V}_\gamma = -\frac{1}{\mu_\gamma} \mathbf{K}_\gamma \cdot (\nabla P_\gamma - \rho_\gamma \mathbf{g}) \quad (22)$$

with phase permeabilities generally written with relative permeabilities as

$$\mathbf{K}_\beta = \mathbf{K} k_{r\beta}(S_\beta) \quad ; \quad \mathbf{K}_\gamma = \mathbf{K} k_{r\gamma}(S_\gamma) \quad (23)$$

Triple line and wettability effects are taken into account in the classical model in the non-linear expressions for the capillary and relative permeability relationships.

If one keeps the viscosity terms in Eqn 15 while making the assumption of quasi-staticity, small Bond and Reynolds numbers, one finds [5, 29–32, ...] slightly different macro-scale momentum balance equations with cross terms which read

$$\mathbf{V}_\alpha = -\frac{1}{\mu_\alpha} \mathbf{K}_\alpha \cdot (\nabla P_\alpha - \rho_\alpha \mathbf{g}) + \mathbf{K}_{\alpha\kappa} \cdot \mathbf{V}_\kappa \quad (24)$$

$$\alpha, \kappa = \beta, \gamma \quad \alpha \neq \kappa$$

Their importance is the subject of controversies [30, 33, 34, ...] and they are so far discarded in petroleum engineering and many other fields. They account however for a drag force necessary to explain the retention of water observed in a vertical column subject to an upward gas flow in the case of a high permeability medium [14, 35–37]. This effect is in particular important in chemical engineering or in nuclear safety (debris bed reflooding) applications.

Dynamic Models

One may want to remove the drastic assumptions made previously (quasi-staticity, etc...) and this has led to various proposals for dynamic models which are only mentioned in this paper:

1. Dynamic effects are taken into account in petroleum engineering by introducing additional non-linear dependencies in the capillary pressure, relative permeabilities, which are called pseudo-functions [38–42],

2. several models propose different forms of equations taking into account dynamic effects induced by Darcy-scale heterogeneities and multi-zones [43], multi-zones [44], meniscus propagation [45],
3. using the theory of irreversible thermodynamics leads to models introducing the specific area of the fluid-fluid interface as a primary variable [46–48, ...]

This is beyond the scope of this review to provide a comprehensive literature survey of dynamic models. To illustrate the complexity, equations coming from [43] are given below as

$$\begin{aligned} \mathbf{V}_\beta = & -\frac{1}{\mu_\beta} \mathbf{K}_\beta^* \cdot (\nabla P_\beta - \rho_\beta \mathbf{g}) - \mathbf{u}_\beta \frac{\partial \varepsilon S_\beta}{\partial t} \\ & - \mathbf{U}_\beta \cdot \nabla \frac{\partial \varepsilon S_\beta}{\partial t} - \frac{1}{\mu_\beta} \mathbf{M}_\beta : \nabla \nabla P_\beta \\ & - \frac{1}{\mu_\beta} \Phi_\beta - \frac{1}{\mu_\beta} \mathbf{R}_\beta : \nabla \Phi_\beta \end{aligned} \quad (25)$$

or

$$p_c - 2\sigma H_{\beta\gamma} \mathbf{n}_{\beta\gamma} = L_1 \frac{\partial (\varepsilon S_l)}{\partial t} \quad (26)$$

taken from [46], where L_1 is a phenomenological parameter.

Models with Inertia Effects

When the Reynolds number becomes large, inertia effects start to play a significant role. The simplest proposals to take these effects into account are based on variants [49, 50] of a generalized Ergun's law such as

$$0 = -\nabla P_\beta + \rho_\beta \mathbf{g} - \mu_\beta \frac{1}{K k_{r\beta}} \mathbf{V}_\beta - \frac{\rho_\beta}{\eta \eta_\beta} \|\mathbf{V}_\beta\| \mathbf{V}_\beta \quad (27)$$

where $k_{r\beta}$ is the relative permeability of the β -phase and where the Forchheimer term involves a relative passability η_β . These parameters depends on saturation and are often assigned the following forms

$$k_{r\beta} = (1 - S_\gamma)^n \quad ; \quad \eta_\beta = (1 - S_\gamma)^m \quad (28)$$

$$k_{r\gamma} = S_\gamma^p \quad ; \quad \eta_\gamma = S_\gamma^q \quad (29)$$

with the exponents taking different values [51–53, ...]. While this form may account for the pressure drop increase due to inertia effects, it does not fully take into account the drag between both phases and the resulting retention effect. Several

models have been proposed to reproduce these facts like, for instance [37]

$$0 = -\nabla P_\beta + \rho_\beta \mathbf{g} - \mu_\beta \frac{1}{K k_{r\beta}} \mathbf{V}_\beta - \frac{\rho_\beta}{\eta \eta_\beta} \|\mathbf{V}_\beta\| \mathbf{V}_\beta + \frac{\mathbf{F}_{\beta\gamma}^S}{S_\beta} \quad (30)$$

$$0 = -\nabla P_\gamma + \rho_\gamma \mathbf{g} - \mu_\beta \frac{1}{K k_{r\beta}} \mathbf{V}_\beta - \frac{\rho_\beta}{\eta \eta_\beta} \|\mathbf{V}_\beta\| \mathbf{V}_\beta - \frac{\mathbf{F}_{\beta\gamma}^S}{1 - S_\beta} \quad (31)$$

A generalized form of two-phase flow equations accounting for cross terms and inertia effects has been obtained theoretically through upscaling [54], it reads

$$\begin{aligned} \mathbf{V}_\alpha = & -\frac{1}{\mu_\alpha} \mathbf{K}_\alpha \cdot (\nabla P_\alpha - \rho_\alpha \mathbf{g}) - \mathbf{F}_{\alpha\alpha} \cdot \mathbf{V}_\alpha \\ & + \mathbf{K}_{\alpha\kappa} \cdot \mathbf{V}_\kappa - \mathbf{F}_{\alpha\kappa} \cdot \mathbf{V}_\kappa \quad \alpha, \kappa = \beta, \gamma \quad \alpha \neq \kappa \end{aligned} \quad (32)$$

These models require to determine several effective properties which depend non-linearly upon saturation and velocities, which today is a challenging task not well understood.

To illustrate the capabilities of the various models, let us consider flow in a vertical column of high permeability (and hence low capillary effects) initially saturated by a liquid phase, β , and subjected to the upward flow of a gas phase, γ . Using the more general form Eq. 32, the case $V_L = 0$ requires that

$$0 = -\frac{1}{\mu_\beta} K_\beta \left(\frac{\partial P_\beta}{\partial z} - \rho_\beta \mathbf{g} \cdot \mathbf{e}_z \right) + (K_{\beta\gamma} - F_{\beta\gamma}) V_\gamma \quad (33)$$

With the classical generalized Darcy's laws, i.e., $(K_{\beta\gamma} - F_{\beta\gamma}) = 0$, one gets $\frac{\partial P_\beta}{\partial z} = \rho_\beta \mathbf{g} \cdot \mathbf{e}_z$. This result is not supported by experimental data [55, 56]! On the contrary, keeping the extra terms in Eq. 33 allows to account for liquid retention due to the drag force imposed on the liquid by the upward flow. Various expressions have been proposed for the non-linear effective parameters, but the lack of data and the number of parameters to determine lead to strong difficulties in the identification procedure which explain the discrepancy often observed between data and predictions [56–58] as it is shown in Figs 2 and 3 adapted from [56].

TWO-PHASE: SPECIAL MODELS

In this section, we review two-phase flow models that have been proposed to reproduce certain mechanisms observed at high capillary and Bond numbers. In such cases, the time and length-scale constraints which are necessary to develop two-phase flow

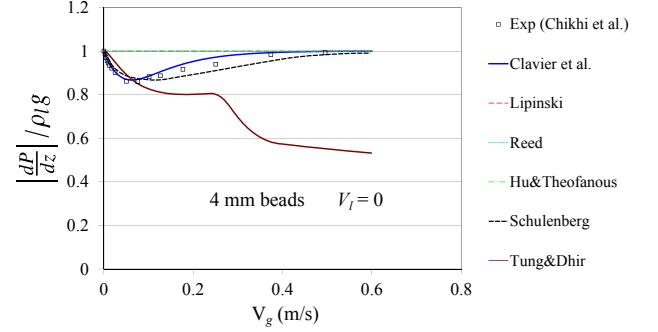


FIGURE 2. EXPERIMENTAL AND MODELING RESULTS FOR THE NORMALIZED PRESSURE DROP VERSUS THE GAS VELOCITY AT $V_L = 0$ (Clavier et al.= [59]).

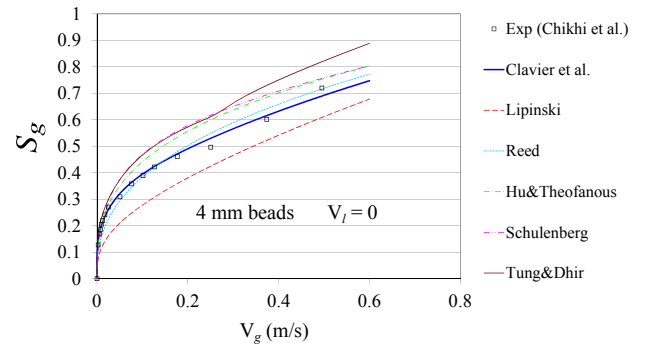


FIGURE 3. EXPERIMENTAL AND MODELING RESULTS FOR THE GAS SATURATION VERSUS THE GAS VELOCITY AT $V_L = 0$ (Clavier et al.= [59]).

models are not fulfilled. This call for specific treatments. Two types of model have been proposed and are the subject of current research. They are briefly presented below.

Models with Splitting of Phase

Structured packings have been extensively used in the past decades in absorption and distillation columns or chemical reactors. They are made for instance from assembling corrugated metal sheets, alternating the orientation from one sheet to another, thus creating a porous medium having the honeycomb structure illustrated Fig. 4. The resulting material has a relatively high surface area with very low gas flow resistance.

However, the alternating directions for the liquid spreading may create preferential paths which are followed by only a portion of the fluid. In this case, a single macro-scale equation for describing the liquid phase flow is very difficult to develop. Models with a splitted liquid phase, i.e., one macro-scale equation for the gas phase but two macro-scale equations for the liquid, have been proposed to handle such cases [60–62]. In this framework, one has a balance equation for the gas phase (a single effective



FIGURE 4. PHOTOGRAPH OF STRUCTURED PACKINGS (WIKIMEDIA COMMONS, AUTHOR: LUIGI CHIESA).

phase is enough in the context of structured packings so far), γ , and two balance equations for liquid phase part 1, β_1 , and liquid phase part 2, β_2 . For instance, this leads to the three mass balance equations below:

$$\varepsilon \frac{\partial S_\gamma}{\partial t} + \nabla \cdot \mathbf{U}_\gamma = 0, \quad (34)$$

$$\varepsilon \frac{\partial S_{\beta_1}}{\partial t} + \nabla \cdot \mathbf{U}_{\beta_1} = \dot{m}, \quad (35)$$

$$\varepsilon \frac{\partial S_{\beta_2}}{\partial t} + \nabla \cdot \mathbf{U}_{\beta_2} = -\dot{m}. \quad (36)$$

where \dot{m} is the mass exchange term which must be modeled in terms of the three "phases" saturation, pressure and velocities.

While there were attempts to develop these models through some averaging methodology, part of the resulting models are still heuristic. In particular, the description of the exchange of mass (and momentum) between the two macro-scale liquid phases remains an open question. The spreading of a jet impinging such a porous medium as described by these models is illustrated Fig. 5 taken from [62]. One sees, depending on the intensity of the exchange term, that the two liquid phases show a distinct shape with two separate jets when there is barely no exchange, while the jet spreads more like the classical solution for a capillary porous material when the exchange is strong. These two shapes have been observed experimentally [61]. Therefore, it seems that these models have the correct structure, but it must be emphasized that correlations for the effective properties require further investigations.

Hybrid Models

In porous media with low capillarity effects, the liquid moves by a series of mechanisms involving films over the grain

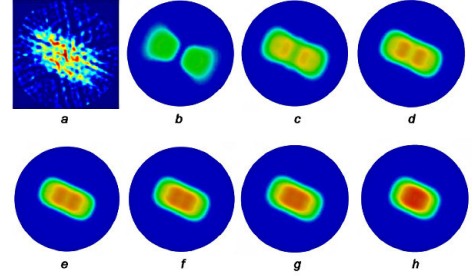


FIGURE 5. SATURATION SHOWING THE SPREADING AT A GIVEN COLUMN CROSS-SECTION OF A TOP OF COLUMN IMPINGING JET (FROM [62]): a) EXPERIMENTAL RESULTS FROM [63], b-h) NUMERICAL RESULTS WITH INCREASING MASS EXCHANGE FROM [62].

surfaces, bridges between these films when close to contact points, bulging films due to either instabilities or high Bond numbers, etc... As a consequence of the diversity of mechanisms at play, several flow regimes are observed as illustrated, for instance, in [64–67, ...]. This is the case when looking, for example, at the quasi-2D flow of a liquid in a bundle of cylinders as illustrated in Fig. 6 taken from [68]. In principle, the flow complexity can be captured by direct numerical modeling [69] as illustrated in Fig. 6 where the flow between the cylinders is obtained numerically using a Volume of Fluids method. However, this is very difficult to get accurate solutions, even on a limited number of pores, and certainly to date beyond the capabilities of modern computers for a large amount of pores. However, even for a porous medium with a pore correlation length on the order of the grain size, the phase repartition pattern may encompass dozens of pores. Therefore, in such cases, we are faced with the following difficulties:

1. pore-scale mechanisms complexity, time and spatial characteristic scales, make the development of a macro-scale model very difficult to achieve,
2. Direct Numerical Solution (DNS) is equally very difficult to carry on because of the number of pores involved.

When such complex percolation mechanisms are encountered, it is often convenient to use a meso-scale description of the porous medium under the form of a pore network model. Rules describing the flow between nodes must be introduced. This is relatively straightforward for classical percolation problems (Poiseuille like pressure drop for instance, quasi-static capillary effects, ... [70, 71]). These rules must be adapted for the cases under consideration in this section which feature more dynamic types of flow. Hybrid models were proposed to handle such situations. The idea behind hybrid models is to couple the pore-network description with local pore-scale simulations carried out with, for instance, a Volume of Fluid numerical model. The lo-

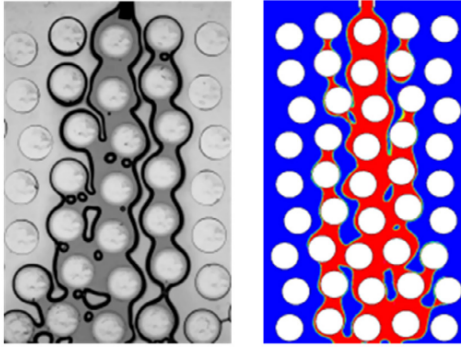


FIGURE 6. EXPERIMENTAL DATA AND NUMERICAL SOLUTION FOR TWO-PHASE FLOW IN A BUNDLE OF CYLINDERS, FROM [68].

cal VOF simulations will provide the dynamic rules necessary to advance the fluid flow in the pore network model. Published results show the ability of such tools to handle more dynamic percolation problems [19, 67, 72, ...]. Clearly, however, further work is needed to make these models operational for the engineering daily practice. It must also be reminded that meso-scale models need more computational resources than full macro-scale models. Therefore, efforts to obtain more dynamic macro-scale models must obviously continue.

CONCLUSIONS

In this paper, we have reviewed the implications in terms of macro-scale modeling of high values of transport dimensionless numbers in the case of flow through highly permeable media. The introduction of inertia effects into the one-phase flow models is handled by modification of Darcy's law up to full macro-scale turbulent models. In the case of two-phase flow with high Reynolds number, several models were proposed:

1. Extensions of Ergun's one-phase model to the two-phase flow case with relative permeabilities and passabilities,
2. Models with interaction terms obtained heuristically or through some upscaling procedure.

These latter models proved to have the good ingredients to reproduce the scarce experimental data available. However, it is clear from the comparison between predictions and experimental data that additional work should be done to provide good estimates for the various non-linear correlations found in these models.

Problems remain also largely open for two-phase flow at large Bond and Capillary numbers, for which several hybrid models have been proposed. This is also the case for specific porous media having a structure favoring the almost independent behavior of portions of the liquid phase. In this case, models with a splitting of the liquid (or gas) flow into two macro-scale

fluids have shown the ability to reproduce actual phenomena but, once again, much work should be devoted to the validation of the mathematical structure of such models and the estimation of the relevant effective transport properties.

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