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# THE UNIFORM MAGNETIC FIELD INFLUENCE ON THE MAGNETIC FLUID MENISCUS MOTION IN THE CYLINDRICAL CAPILLARY

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An improvement of liophobic capillary-porous systems using magnetic fluids is proposed. The cycle of non-wetting liquid penetration and displacement is realized experimentally in the presence of the uniform magnetic field. Experimental investigations of the effect of the external uniform magnetic field on dynamics of capillary penetration of the Newtonian magnetic fluid into cylindrical capillaries at zero gravity and under gravity are presented. It is found that the pressure difference in the magnetic fluid between a meniscus and a free surface in a vessel increases in the field longitudinal to the capillary and decreases in the transverse one. In the longitudinal field, the velocity of penetration increases at zero gravity and does not vary under gravity. The transverse field slows down the process.

## 1 Introduction

Processes of capillary penetration and displacement of magnetic fluids have good prospects of their application in heat-mass transfer technique, apparatuses of chemical technology and mining engineering. The most interesting application of these processes can be found in devices operating on the base of liophobic capillary-porous systems.

These systems represent a capillary-porous body and a non-wetting liquid [1]. The latter penetrates into micro-pores of the body under high external pressure and is displaced under its capillary pressure. This penetration-displacement cycle was proposed to be used in some power devices, such as heat-engines, accumulators, dampers [2]. Non-wetting conditions are created by covering micro-pores with a thin molecular layer of organophobic material. That is rather complicated from the technology standpoint.

In order to except these difficulties, we propose to use two immiscible liquids, which wet pores in contact with the ambient air. In contact with each other, one of the liquids will be wetting and the other will be non-wetting if their surface tensions on the liquid-solid interface are different [3]. By analogy with systems of one liquid, while penetrating of the non-wetting liquid, the work is done under the system, and while displacing, the system does work returning the energy accumulated. Liophobic capillary-porous systems are purely dynamic ones and energy dissipation takes place. As for dissipation mechanisms, they can be the viscous one in volumes and on the interface of the liquids as well as viscous friction of the wetting perimeter. The latter determines the dynamic wetting angle of the system.

Using a magnetic fluid as one of the liquids makes possible to control capillary and dynamic processes in these systems by magnetic controlling capillary and viscous properties of magnetic fluids. Detailed investigations of magnetic fluid penetration and displacement are necessary for development of devices operating on the base of the principle described above.

Theoretical and experimental development of this problem is not completed yet. Investigations of statics and dynamics of capillary rise of the magnetic fluid under the non-uniform magnetic field have shown that a fluid column is drawn in the domain of a stronger field, and the main factor of the magnetic field effect is the volume magnetic force caused by the external magnetic field gradient [4,5]. As has been shown in [6], the effect of the external uniform magnetic field on statics of ascension into a cylindrical capillary is defined by effects of internal uniform and of induced non-uniform fields. The second effect is dominant in case of ascension from a thin layer of the magnetic fluid, the capillary rise height increases in the magnetic field longitudinal to the capillary and decreases in the transverse one as the square of the induction of the field.

Experimental studies of dynamics of penetration of wetting Newtonian magnetic fluid into a cylindrical capillary as well as results on experimental realization of penetration-displacement cycle are presented here. The velocity and the time of penetration are determined.

One of the mechanisms of the external uniform field effect on dynamics of magnetic fluid penetration is the same as the effect on statics of a fluid column in a capillary i.e. influence of the magnetic field on the pressure difference in the magnetic fluid. This pressure difference is regarded as that between free surfaces inside the capillary (meniscus) and outside it. Other mechanisms, such as the magneto-viscous effect, the field effect on wetting hysteresis, are not considered here.

## 2 Experiment

The experimental cell used for cycle realization and for investigation of magnetic fluid penetration at zero gravity is shown in Fig. 1a. A glass cylindrical vessel of diameter 25 mm with a vertically adjusted capillary both filled with the magnetic fluid are placed in a rectangular plexiglass box filled with aqueous solution of calcium chloride. Equal densities of liquids and their equal levels in the vessels (the layer depth of the magnetic fluid is 20 mm) provide conditions of hydroimponderability.

The experimental cell used for investigation of magnetic fluid penetration into a vertical capillary under gravity is shown in Fig. 1b. A glass cylindrical dish 120 mm in diameter is filled with the magnetic fluid, the layer depth is 8 mm. The capillary is stationary adjusted to the vertical position. The lower capillary end is immersed into the magnetic fluid.

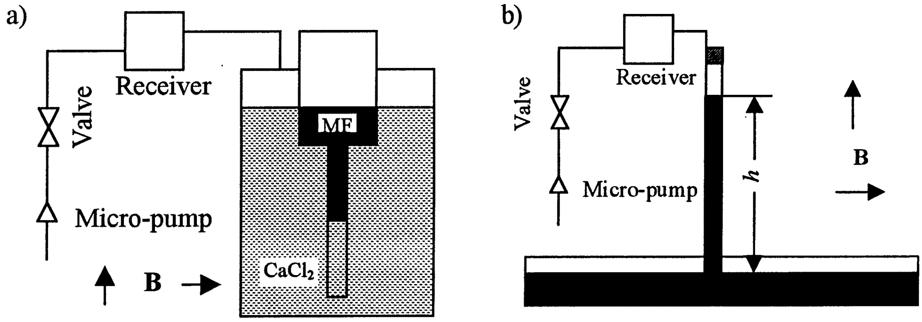


Fig. 1. Experimental cells for investigation of magnetic fluid penetration at zero gravity (a) and under gravity (b)

In contact with the ambient air as well as with solution of calcium chloride, the magnetic fluid wets capillary walls. The borosilicate glass cylindrical capillaries of diameter $d$ = 0.27 mm or 0.80 mm and length $l$ = 40 mm are used. The box of the first cell (Fig. 1a) and the capillary of the second one (Fig. 1b) are connected with the piston micro-pump. It produces pressure required to hold the meniscus at a given position in the capillary. This pressure determines the pressure difference $\Delta p$ in the magnetic fluid and it is measured by the micro-manometer.

A method of cycle realization follows. A meniscus is initially situated on the capillary end immersed into the non-magnetic liquid. The pressure in this liquid is adjustable continuously from zero to the value such that the meniscus "breaks away" from the capillary end. This pressure exceeds slightly the pressure difference in wetting magnetic fluid. Under this pressure, the meniscus moves slowly along the capillary and quasi-stationary penetration of the non-wetting non-magnetic liquid takes place. The pressure is released drastically by the valve when the meniscus reaches the opposite capillary end. At this instant the meniscus changes direction of its way and returns to its initial position displacing the non-wetting liquid. The receiver smoothes pressure oscillations after valve opening.

While studying penetration dynamics of the wetting magnetic fluid under gravity (Fig. 1b), the meniscus is held at its initial position on the capillary end immersed into the magnetic fluid. Pressure is released drastically and the meniscus begins to move over the wetted surface of the capillary. The meniscus stops having reached the maximal capillary rise height $h$. Dynamics of the process is recorded by the video camera at 50 frames/sec and at exposure of 0.002 sec.

The uniform magnetic field longitudinal or transverse to a capillary (the induction $B$ = 0 - 25 mT) is produced by Helmholtz coils. The magnetic fluid on the magnetite and kerosene base has density $\rho$ = 1320 kg/m$^3$, surface tension $\sigma$ = 0.029 N/m on the border with air and $\sigma$ = 0.012 N/m on the border with solution of calcium chloride, wetting angle $\gamma$ = 25 - 30$^0$ in contact with glass and air and $\gamma$ = 45 - 50$^0$ in contact with glass and solution of calcium chloride, dynamic viscosity $\eta_1$ = 0.0054 Pa × sec, magnetization of saturation $M_s$ = 38.2 kA/m. The magnetic fluid magnetization law is linear over the experimental range of the magnetic field, relative magnetic permeability is $\mu$ = 2.7. Evaluation of the magneto-viscous effect shows that the latter does not exceed 2% within the field range considered. Aqueous solution of calcium chloride has density $\rho$ = 1320 kg/m$^3$, dynamic viscosity $\eta_2$ = 0.0022 Pa × sec.

## 3 Results

### *3.1. Penetration-displacement cycle*

This cycle realized in the absence and in the presence of the magnetic field is presented in $z$-$\Delta p$ coordinates in Fig. 2. Here $z$ is the meniscus coordinate. The area inside closed curves of the cycle multiplied by the cross-section of the capillary presents the work expended on non-wetting liquid penetration and the work done in the process of displacement: $A = \Delta p \cdot (\pi d^2/4) \cdot l$. In the absence of the magnetic field, this work is given by $A = (\sigma \cdot \cos \gamma) \cdot (\pi d l)$. As is seen from Fig. 3, the pressure $\Delta p$ exerted on the non-wetting liquid and required for meniscus break from the capillary end increases in the longitudinal field (by two times at $B = 25$ mT) and remains almost constant in the transverse field. That points to a possibility of magnetic control of processes in such liophobic systems.

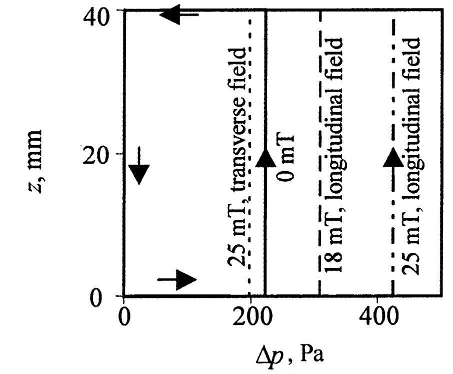


Fig. 2. The cycle of penetration and displacement of the non-wetting liquid contacting with wetting magnetic fluid

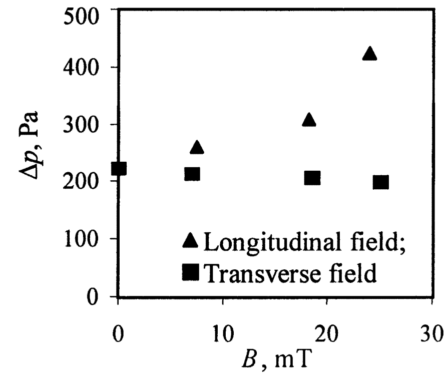


Fig. 3. Dependency of the pressure required for penetration of the non-wetting liquid into the capillary on the induction of the magnetic field

### 3.2 *Effect of field on dynamics of magnetic fluid penetration*

Penetration curves of the magnetic fluid (dependence of the meniscus position $z$ on the time $t$) are presented in Fig. 4 for the case of zero gravity. Data point to the influence of the magnetic field on the penetration characteristics: the whole time of penetration $T$ decreases in the longitudinal field (two times) and increases in the transverse one (by 50%) (Fig. 5). Accordingly, the velocity of penetration defined as $V = l / T$ increases in the longitudinal field and decreases in the transverse one.

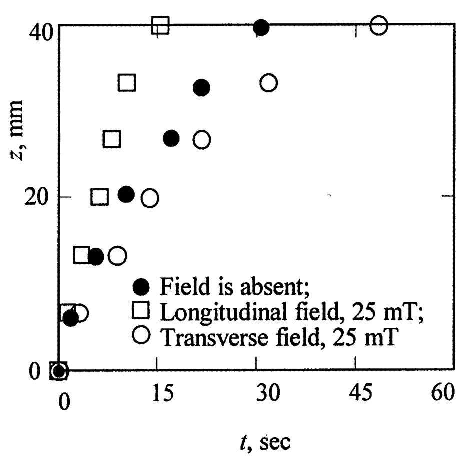


Fig. 4. Penetration curves of the magnetic fluid at zero gravity

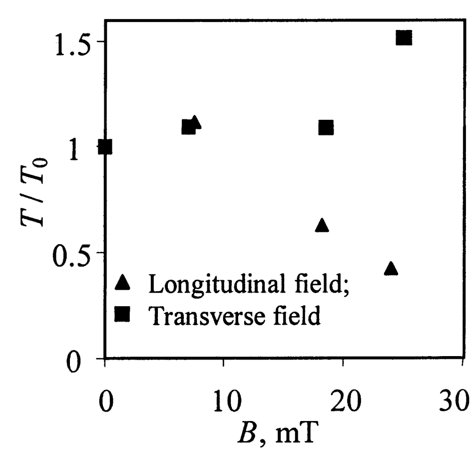


Fig. 5. Dependency of the dimensionless whole time of penetration on the induction of the magnetic field (zero gravity)

In case of capillary rise from a thin layer of the magnetic fluid under gravity, penetration curves have a saturation section with an asymptote $h$ that is function of the magnetic field (Fig. 6). The maximal rise height $h$ is given by the following semi-empirical expressions [6] for longitudinal and transverse fields respectively:

$$\rho g h = 4\sigma \cos \gamma / d + (\mu - 1)^2 / (2\mu) \cdot (B^2 / \mu_0), \quad (1)$$

$$\rho g h = 4\sigma \cos \gamma / d - (\mu - 1) / 2 \cdot [1 - 4 / (\mu + 1)^2] \cdot (B^2 / \mu_0), \quad (2)$$

where $g$ is gravity acceleration, $\mu_0$ is magnetic permeability of vacuum.

At $h > 0.5d$ these dependencies fit the experimental data well (Fig. 7) The experimental range of the vertical field is limited by the threshold value of the induction $B \approx 8.5$ mT such that the fluid surface in the vessel becomes unstable.

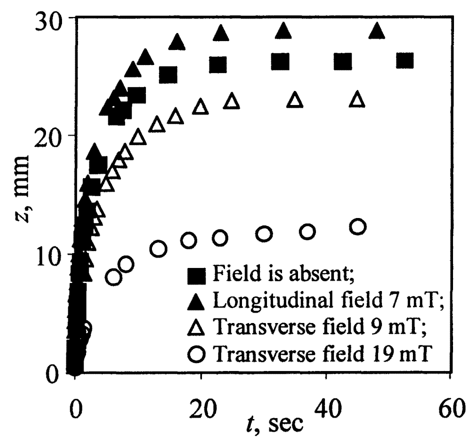


Fig. 6. Penetration curves of the magnetic fluid under gravity

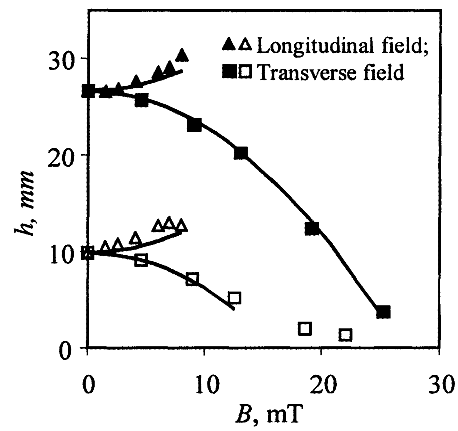


Fig. 7. Dependencies of the capillary rise height on the induction of the field

Since the whole time of the process is infinite, define the characteristic time $T$ of penetration in terms of the period of meniscus passage of 90% of its maximal height. The characteristic velocity $V$ of the meniscus will be $V = 0.9h / T$. It is found that the time $T$ increases both in the longitudinal field (by 35% for 0.80 mm capillary at $B = 8$ mT) and in the transverse one (by 80% for 0.27 mm capillary at $B = 19$ mT) (Fig. 8). The velocity $V$ decreases in the transverse field (by 75% for 0.27 mm capillary at $B = 19$ mT) (Fig. 9). Influence of the longitudinal field on the velocity $V$ is not found.

In Fig. 5, 8, 9 $T_0$, $V_0$ are values of $T$ and $V$ respectively in the absence of field. In liquid-liquid system (Fig. 1a) $T_0$=32 sec, $V_0$=1.2 mm/sec (0.27 mm capillary); in liquid-gas system (Fig. 1b) $T_0$=10 sec, $V_0$=2.4 mm/sec (0.27 mm capillary) and $T_0$=0.66 sec, $V_0$=13 mm/sec (0.80 mm capillary). In Fig. 5, 7, 8, 9 solid dots correspond to 0.27 mm capillary, open dots correspond to 0.80 mm capillary. In Fig. 7 lines correspond to the theory (1), (2).

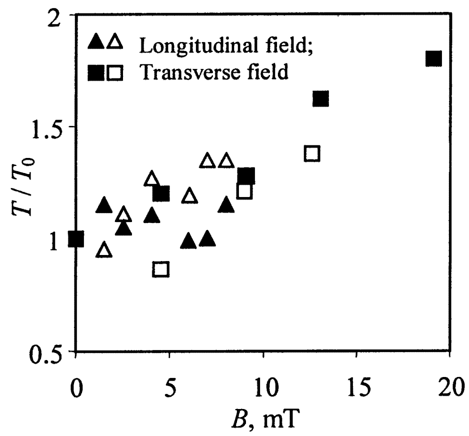


Fig. 8. Dependencies of the dimensionless characteristic time of penetration on the induction of the magnetic field (under gravity)

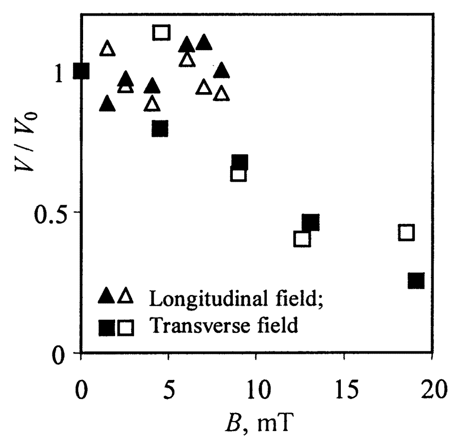


Fig. 9. Dependencies of the dimensionless characteristic velocity of penetration on the induction of the magnetic field (under gravity)

In the presence of the external uniform magnetic field, penetration of the Newtonian magnetic fluid is given by classical Washburn equation [7]. Assuming the pressure difference $\Delta p$ in the magnetic fluid to be constant during penetration, this equation gives the following $t$ vs. $z$ dependencies:

$$t = 32 / (\Delta p d^2) \cdot [(\eta_1 - \eta_2) \cdot (z^2/2) + \eta_2 l z] \quad (3)$$

for the case of liquid-liquid system at zero gravity and

$$t = (32\eta_1 h) / (\rho g d^2) \cdot [-z/h - \mathrm{Ln}(1 - z/h)] \quad (4)$$

for the case of liquid-gas system under gravity.

So, the expressions for the time of penetration will be:

$$T = 16 l^2 \cdot (\eta_1 + \eta_2) / (\Delta p d^2) \quad (5)$$

for the case of liquid-liquid system at zero gravity and

$$T = (44.8\eta_1 h) / (\rho g d^2) \quad (6)$$

for the case of liquid-gas system under gravity.

As is seen from analyses of (5), at zero gravity, the time of penetration should decrease in the longitudinal field and remain constant in the transverse one according to the dependence of the pressure difference $\Delta p$ on the magnetic field. That is supported by the experiment in case of the longitudinal field ($\Delta p$ gives double increase, $T$ gives double decrease at $B = 25$ mT) but it is not absolutely true for the transverse field (Fig. 3, 5).

As for penetration under gravity, equation (6) gives linear dependence of the time $T$ on the capillary rise height $h$ and suggests that the velocity $V = 0.9h / T$ is independent of $h$. Hence, the characteristic time of penetration should increase in the longitudinal field and decrease in the transverse one. The characteristic velocity of penetration should remain constant at any field values and directions. That is qualitatively supported by the experiment in case of the longitudinal field. The experimental data show an opposite tendency in the transverse field (Fig. 8, 9).

Unexpected deceleration of penetration in the transverse field in both cases is probably connected with dynamic hysteresis of the wetting angle. Assuming the dynamic wetting angle to be field independent, taking into account relations between the latter and the velocity in Washburn equation does not explain this result. Possibly, the transverse magnetic field influences on the mechanism of wetting perimeter viscous friction, decreasing the dynamic wetting angle so that the pressure difference $\Delta p$ at a given meniscus position decreases together with the velocity of the meniscus.

## 4 Conclusions

1. The proposed improvement of liophobic capillary-porous systems is 1) use of two immiscible wetting liquids with different interfacial tensions, 2) use of magnetic fluids for magnetic control of capillary and dynamic processes in these systems.
2. "Motive power" of magnetic fluid penetration is the pressure difference in the fluid between the meniscus and the free surface in the vessel. The pressure difference increases in the field longitudinal to the capillary and decreases in the transverse one. In the longitudinal field, the velocity of penetration increases at zero gravity and does not vary under gravity. In the transverse field, it decreases in both situations.

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