Ramp-Up Centrifugation of Capillary Pressure Experiments

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Centrifuge experiments have been widely practiced in the oil and gas industry to determine capillary pressure data. The theoretical foundation of such experiments was laid by Hassler and Brunner (1945). A systematic summary was given by Ruth and Chen (1995) to cover both theoretical and experimental aspects of centrifuge technique. In addition, a new three-dimensional theory for a clearer description of the centrifugation physics was presented (Chen and Ruth, 1995), which demonstrates the gravity degradation effect at low centrifuge rotational speeds during the ramp-up process. The ramp-up displacement of this centrifugation process is further elaborated.

Conventional Beckman centrifuges for capillary pressure curves have fixed, horizontal rotors, stretching out from the central axis of rotation. Such a configuration is depicted in Figure 1. In this discussion, the concept of *equipotential surface* is borrowed from a previous work (Ayappa, et al., 1989) to assist the investigation. The initial state of the potential field distribution is considered to be the hydrostatic distribution. As the spinning speed is gradually increased, the progressive movement of the equipotential surfaces entails a 90 degree change from vertical to horizontal. The equipotential surfaces will also undergo this change during the ramp-up process, that is, when the centrifuge is started and brought to its first speed regardless of how high that speed is. A concern has been raised (Forbes, 1994) that there is the potential for imbibition to occur in the course of this transition. The suspected imbibition, as shown in Figure 2, is considered to possibly occur during the transition process of the potential fields from the purely hydrostatic distribution, which is projected as horizontal layers inside the core plug (represented by ω_1 in Figure 2), to the centrifugal distribution which is projected as vertical disks inside the core plug (represented by ω_3 in the figure). This gradual transformation between the two limiting cases is suspected to cause the redistribution of the fluid pair inside the core plug due to the inclination of the equapotential surfaces (the shadowed portions in the figure), and lead the fluids to imbibe, as the equipotential surfaces slowly "stand up" and become "vertical" (as $\omega_1 \Rightarrow \omega_2 \Rightarrow \omega_3$).

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To get some idea of how the displacement starts and proceeds, we will examine the contours of an equipotential surface inside the core plug at the central plane ($y=0$) during ramp-up. The true capillary pressure distribution, as previously derived as

$$P_c(r,z) = \frac{1}{2}\Delta\rho\omega^2\left[r_{0\,\max}^2 - r^2 - C_g(R-z)\right] \tag{1}$$

can be used to calculate how the profile contour of an equipotential surface at $y=0$ (the surface is thus reduced to a line) varies with the rotation speed during the ramp-up for a particular capillary pressure. In order that no imbibition occurs during this process, the condition that must be satisfied is that the equipotential surfaces moves continuously forward as the speed increases, that is

$$\frac{\partial r_0}{\partial \omega} \geq 0 \tag{2}$$

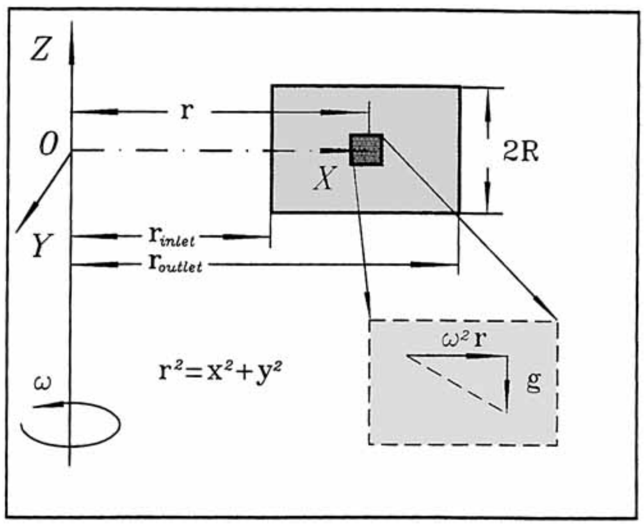

Figure 1. Gravity degradation effect.

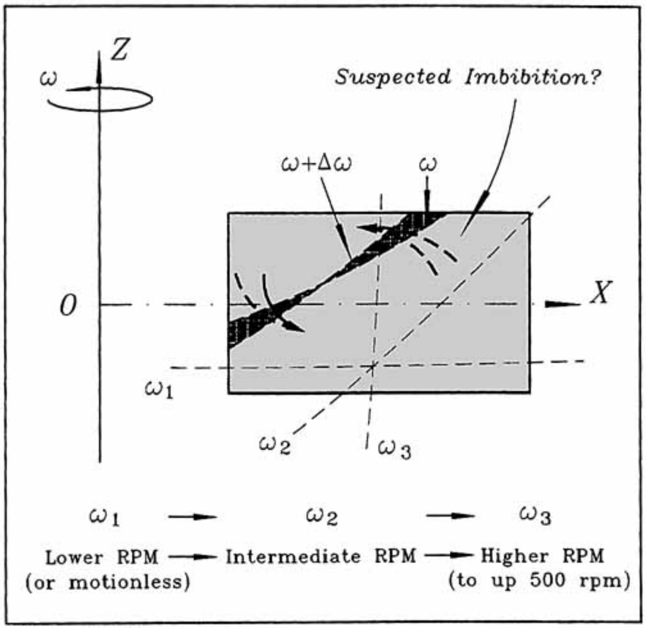

Figure 2. Suspected imbibition during ramp-up.

for all $P_c > P_{ct}$, where P_{ct} is the threshold capillary pressure (the pressure required to initiate drainage of the wetting phase). Here, we can use Eq. 2 to determine the criterion of the minimum rotation speed below which inbibition occurs.

According to the previous work by Chen and Ruth (1995), two regions of rotational ramp-up speeds are found with the separating condition $C_g = 2R$, which results in an equivalent cut-off speed ω in rpm, and also two boundary conditions for the maximum reference rotation radius $r_{0\,\max}$. Consider low speeds, when $C_g \geq 2R$ and $r_{0\,\max}^2 = r_{\text{outlet}}^2 + 2RC_g$, the capillary pressure, P_{c0} at the point $r = r_0$ and $R = z$ is

$$P_{c0} = \frac{1}{2}\Delta\rho\omega^2\left(r_{\text{outlet}}^2 + 2RC_g - r_0^2\right) \tag{3}$$

Using the definition of $C_g = 2g/\omega^2$, this results in

$$\frac{2P_{c0}}{\Delta\rho} = (r_{\text{outlet}}^2 - r_0^2)\,\omega^2 + 4Rg \tag{4}$$

or

$$r_0^2 = r_{\text{outlet}}^2 - \frac{1}{\omega^2}\left(\frac{2P_{c0}}{\Delta\rho} - 4Rg\right) \tag{5}$$

Taking the derivative of r_0 with respect to ω and applying Eq. 5 will lead to

$$r_0\frac{dr_0}{d\omega} = \frac{2}{\omega^3}\left(\frac{2P_{c0}}{\Delta\rho} - 4Rg\right) \geq 0 \tag{6}$$

This yields the criterion for no imbibition

$$P_{c0} \geq 2R\Delta\rho g \tag{7}$$

Note that for the fixed, horizontal rotor system, the minimum potential field equals the hydrostatic gravity field inside the core plug. Therefore, provided that the threshold pressure is sufficiently high that the sample remains fully saturated at zero rotational speed, inbibition will not occur. The capillary pressure at this hydrostatic equilibrium is actually expressed as

$$P_{c0} = \Delta\rho g H \tag{8}$$

where $H = 2R$ under this situation (refer to Figure 1). Therefore, $P_{c0} = 2R\Delta\rho g$ represents the minimum threshold capillary pressure field for a core plug centrifuge experiment, and as long as any capillary pressures during the ramp-up process are greater than this value, the drainage displacement will proceed and no inbibition displacement will occur. For a typical centrifuge rotor (such as Beckman L/M 55), when the core plug length $L = 2.54$ cm, and core plug radius $R = 1.27$ cm, this capillary pressure is 0.00542 psi for a typical fluid pair system of oil-water. See Figure 2 for suspected imbibition during ramp-up.

For the higher speed consideration, when $C_g \leq 2R$ at the same point of $r = r_0$ and $z = R$, we follow a similar derivation and will utilize the other equation $r_{0\,\max}^2 = r_{\text{outlet}}^2 + R^2 + RC_g + (C_g^2/4)$. The equivalent result is

$$\frac{2P_{c0}}{\Delta\rho\omega^2} = r_{\text{outlet}}^2 + R^2 - r_0^2 + \frac{2Rg}{\omega^2} + \frac{g^2}{\omega_4} \tag{9}$$

or

$$r_0^2 = r_{\text{outlet}}^2 + R^2 + \frac{2Rg}{\omega^2} + \frac{g^2}{\omega^4} - \frac{2P_{c0}}{\Delta\rho\omega^2} \tag{10}$$

Taking the derivative with respect to ω produces

$$2r_0\frac{dr_0}{d\omega} = -\frac{2}{\omega^3}\left(Rg - \frac{P_{c0}}{\Delta\rho} + \frac{g^2}{\omega^2}\right) \geq 0 \tag{11}$$

which yields

$$\frac{P_{c0}}{\Delta\rho} - Rg \geq \frac{g}{\omega^2} \tag{12}$$

For this case, the minimum critical rotational speed ω, if any, should occur at $C_g = 2R$. If we substitute this condition into the above equation, we end up again with

$$P_{c0} \geq 2R\Delta\rho g \tag{13}$$

which is identical to Eq. 7.

These derivations (Eqs. 7 and 13) show for both cases here that there is no minimum spinning speed below which inbibition would occur. As an illustration, we can utilize Eq. 1 to investigate the contour changes of any equipotential surfaces under various capillary pressures. Figure 3 shows a set of

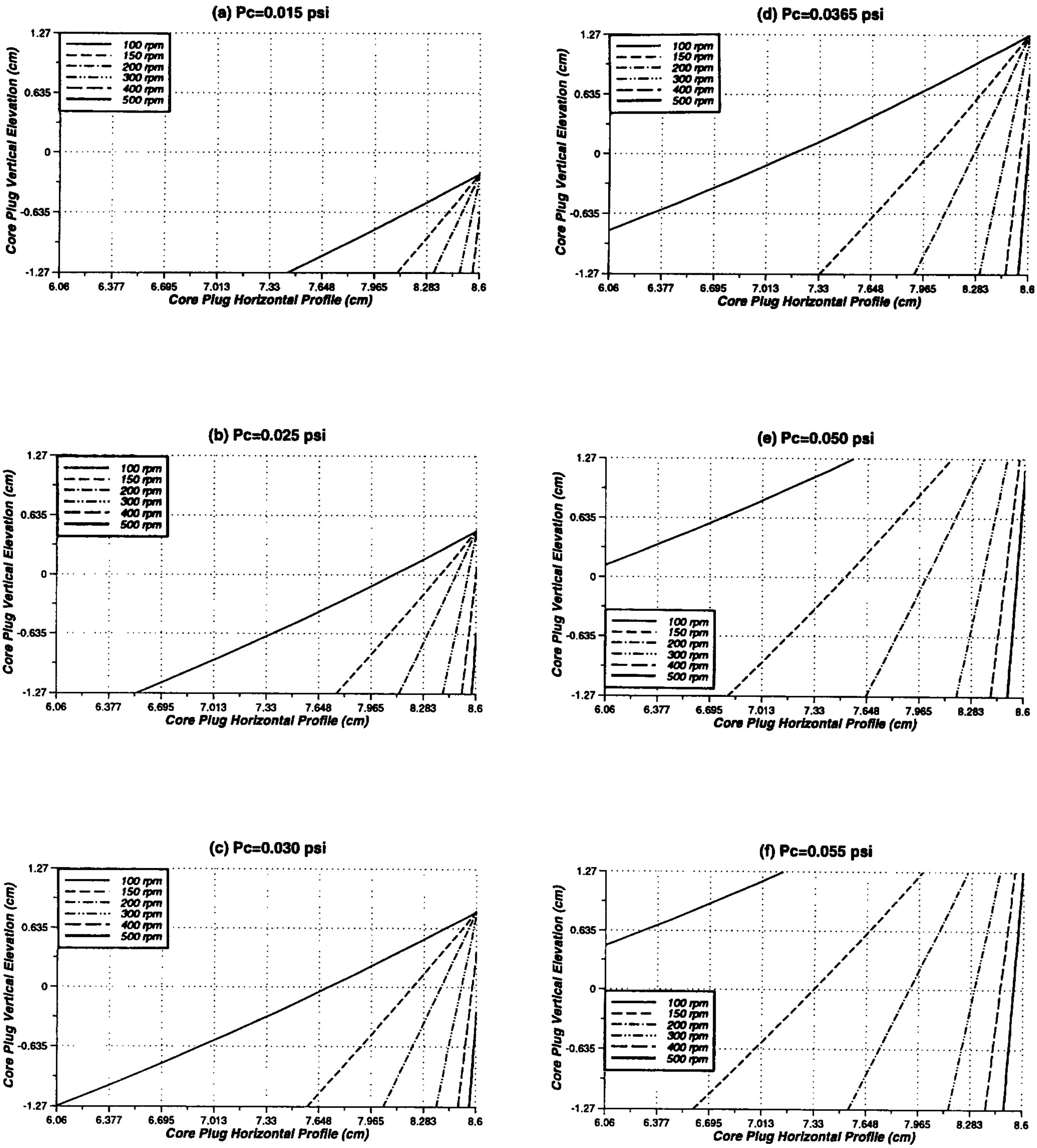

Figure 3. Profile changes of iso-Pc contours during ramp-up: oil-water case.

changes with the iso-P_c contours at the central line ($y = 0$, which demonstrates the worst situation), along with elevated rotational speeds for the oil-water fluid pair system (the density difference of the fluid pair is taken as 0.15 g/cm^3) using the synthesized data from Chen and Ruth (1995). The capillary pressure values projected in this figure all exceed the minimum threshold value calculated according to Eq. 8. This figure provides a complete picture of what happens during the ramp-up process. Drainage will proceed from the top right edge point of the inlet endface, regardless of the capillary pressure values. Figure 4 shows an oil-gas case with the density difference of the fluid pair of 0.85 g/cm^3.

In conclusion, the analysis of ramp-up physics shows that no imbibition will happen at low rotational speeds for horizontal fixed rotational system, provided that the sample remains fully saturated for $\omega = 0$.

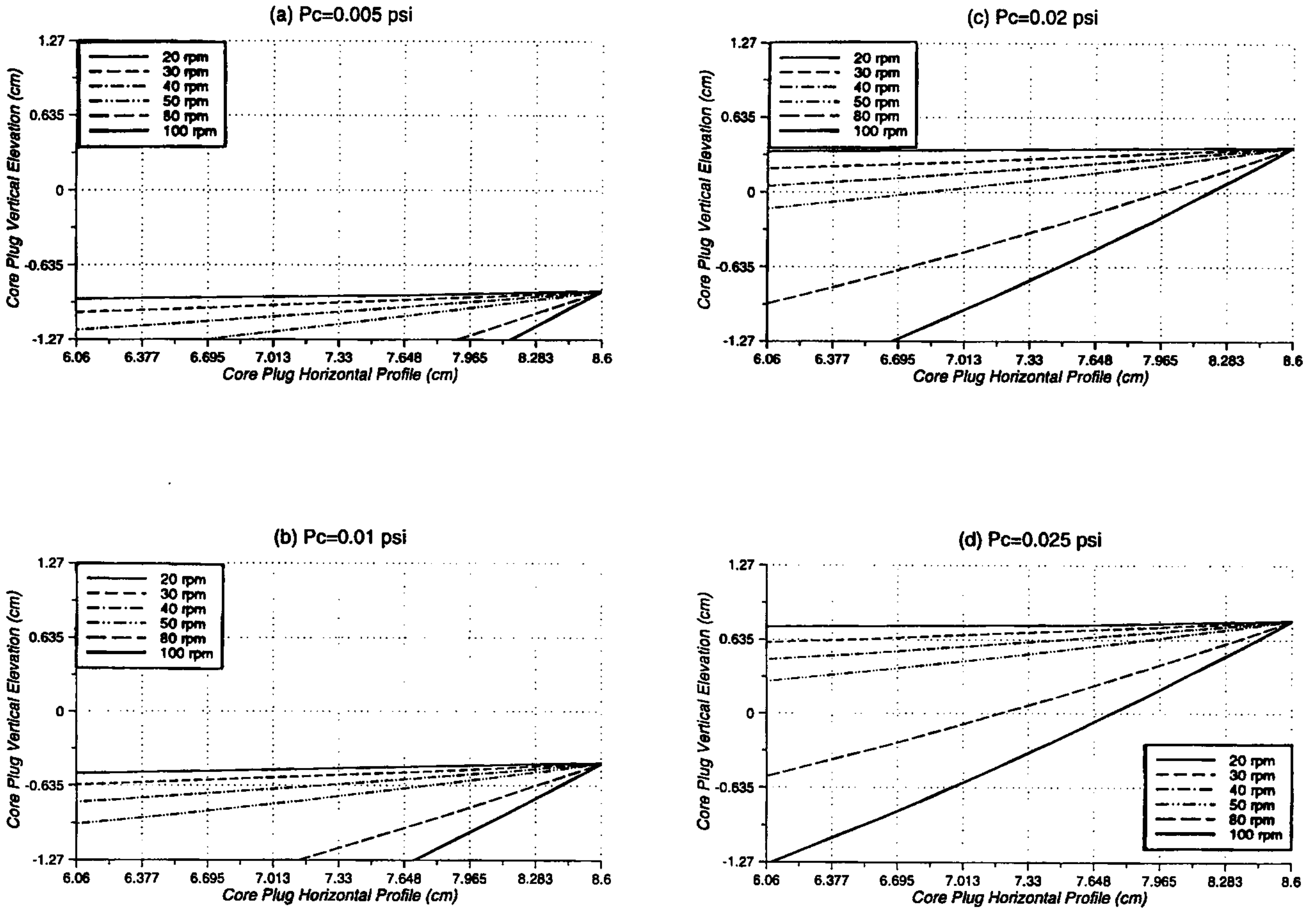

Figure 4. Profile changes of iso-Pc contours during ramp-up: oil-gas case.

Acknowledgments

We thank Imperial Oil and NSERC of Canada for their financial supports to this project.

Notation

C_g = characteristic factor
g = gravitational acceleration
P = potential
$P_{c\,max}$ = maximum reference capillary pressure
r = rotation radius
r_{outlet} = horizontal distance of core plug outlet
z = coordinate
$\Delta\rho$ = density difference of fluid pairs

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Manuscript received Sept. 9, 1996.