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## **Gas/water flow in porous media: effects of an adsorbed polymer layer on core physical properties.**

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### **Abstract**

The presence of hydrosoluble polymer or gel in porous media induces a selective reduction of permeability -called Disproportionate Permeability Reduction, DPR- i. e. a reduction of relative permeability to water much larger than the relative permeability to oil. Several experimental studies have been focused on oil/water systems with different cores, polymers and wettability conditions, confirming the DPR effect. The goal of our study is to investigate polymer effect on gas/water permeability in a wide range of flow rate, reproducing near well-bore conditions in water shutoff applications.

The experimental study presented here proceeds to water and nitrogen injections into sandstone cores before and after polyacrylamide adsorption. Both low-rate Darcy regime and high-rate non-Darcy regime were investigated during gas flow, the later one being modeled using the classical Darcy-Forchheimer formalism. In the Darcy regime, the DPR effect induced by polymer adsorption is more significant when observed on gas/water systems than on oil/water systems investigated under comparable conditions during previous studies. Polymer induces both a strong reduction of the relative permeability to water while affecting very little the relative permeability to gas, and a significant increase of the irreducible water saturation. In the non-Darcy regime, taking into account water saturation and permeability modifications, we observe a reduction of inertial effects when gas is injected after polymer. Experimental data are discussed and confronted with the different hypotheses put forth to explain DPR. Both DPR effect and the reduction of inertial resistance coefficients during gas flow may have important applications in gas well treatments.

### **Introduction**

Gas flow in porous media is a subject of central importance for many applications ranging from Improved Oil Recovery processes based on gas injection to underground temporary gas storage in depleted reservoirs or natural aquifers. A major problem encountered by reservoir engineers during field operations lies in the excessive water production that may cause early well abandonment. This excessive water production is generally due to the effect of natural heterogeneities, fractures or viscous fingering causing channeling of water and leading to high water cut. Among others, a widely used technique to reduce the water cut consists of polymer or gel injection in producing wells in order to reduce water permeability .

Although the physical explanation of the selective effect is still a matter of controversy, the presence of polymer or gel in porous media leads indeed to a selective reduction of permeability, known as “Disproportionate Permeability Reduction” (DPR). Almost all experimental results on oil/water systems reported in the literature show that, after polymer injection, relative permeability to water is more reduced than relative permeability to oil [1-4]. Some experimental results [5-7], also available for gas/water systems, indicate the same behavior and show that water relative permeability is strongly reduced while relative permeability to gas is only slightly affected. A large amount of literature has been dedicated to the DPR mechanism, including, for instance, the role of polymer, core and wettability conditions. Despite or due to all these results, different physical mechanisms have been put forth to explain the origin of DPR [8]. To summarize, they can be classified as follows:

- 1) Fluid partitioning [3, 10]. This scenario considers that oil and water flow in separate pore networks determined by the pore size distribution and that water-based polymer or gel affects the water network only. To our opinion, this interpretation is insufficient to explain DPR since this effect occurs over the whole range of saturation during unsteady state two-phase displacement for which a dynamic configuration of oil and water paths must be considered.
- 2) Swelling/shrinking. This effect, shown by Dawe & Zhang [9] with gel saturated micromodel, is due to hydrodynamic forces that can compress the gel filling the pore space. This mechanism can be easily understood as an additional wall effect described below.
- 3) Wall effects [8]. When a polymer is injected in a porous medium a retention is observed whose major physical origin is an adsorption phenomenon on the solid skeleton. Due to the number of groups constituting polymer macromolecules, adsorption can be considered as irreversible. The presence of this adsorbed polymer layer on pore wall induces steric, lubrication and wettability effects. All those effects are in favor of a more significant permeability reduction for the wetting phase than for the non wetting one. The validity of this hypothesis has been checked by pore scale numerical simulations [11]. Moreover, it has been shown that polymer adsorption occurs on cores with intermediate wettability [12] and leads to DPR effect as well. According to several experimental results published in the literature, for core permeability ranging between 200 mD and 800 mD, wall effects, *i. e.* the presence of an adsorbed polymer layer, seem to be the main cause of DPR.

In addition to these laboratory studies at the core-scale, field applications of polymer or gel water shutoff treatments have been reported in the literature [14]. A recent paper [15] presents an application of polymer treatment on a gas storage reservoir. The success, for years, of this operation illustrates the capabilities of this technique.

The main purpose of the present work is to investigate polymer effect on gas/water permeability at the core-scale in a wide range of flow rates, reproducing near-well-bore conditions in water shutoff applications.

While referring to gas injection or recovery from reservoirs or aquifers one has to consider high values of flow rate in the well-bore vicinity. In conjunction with low gas viscosity this leads to situations where inertial effects become significant and have to be considered explicitly to account for the physics of the flow. In particular, this implies that the classical Darcy's model must be reconsidered to include inertial resistance to flow (*e. g.* Forchheimer model).

### Physical model

When an incompressible fluid flows in a horizontal homogeneous porous medium, the momentum balance is the classical 1D form of Darcy's law

$$v = -\frac{k}{\mu} \frac{dP}{dx} \quad (1)$$

where  $v$  is the Darcy velocity,  $k$  the permeability of the porous medium,  $\mu$  the fluid dynamic viscosity,  $P$  the pressure and  $x$  the 1D space variable.

If the fluid is compressible at the operating pressure, Eq. (1) must be completed with an equation of state. Here, we will assume that the gas phase can be considered as ideal, and under these circumstances, Eq. (1) can be integrated over the core length to give

$$\frac{Q_1}{A} = \frac{k}{2\mu L} \left( \frac{P_1^2 - P_2^2}{P_1} \right) \quad (2)$$

where  $Q_1$  is the gas volumetric flow rate at the core inlet,  $A$  the core section area,  $L$  the core length,  $P_1$  and  $P_2$  are respectively the inlet and outlet pressure.

Darcy's model derives from Stokes flow at the pore scale and for this reason remains valid only for creeping flow corresponding to low values of the pore Reynolds number;

$$Re = \frac{\rho v d_p}{\phi \mu} \ll 1 \quad (3)$$

where  $\rho$ ,  $\phi$  and  $d_p$  are respectively the fluid density, the porosity and an equivalent particle dimension.

When the constraint in Eq. (3) is not satisfied (the Reynolds limiting value can vary from one medium to another depending on the pore structure and the order of magnitude of this limit is between 0.01 and 1), inertial effects cannot be neglected and a deviation from the classical Darcy's model is observed. Several models have been proposed in the literature to take into account inertial effects. A popular one widely employed in petroleum engineering is the empirical model proposed by Forchheimer [16]. This model includes a quadratic velocity correction to Darcy's law. For an incompressible and horizontal fluid flow, it writes

$$-\frac{dP}{dx} = \frac{\mu}{k} v + \rho \beta |v|v \quad (4)$$

where  $\beta$  is the so-called inertial resistance coefficient which depends on the porous medium.

If the fluid is compressible and supposed to obey an ideal gas law, Eq. (4) can be integrated between the inlet and outlet of the core to yield

$$\frac{P_1^2 - P_2^2}{2\mu L P_1 \left( \frac{Q_1}{A} \right)} = \frac{1}{k} + \beta P_1 \frac{M}{\mu R T} \left( \frac{Q_1}{A} \right) \quad (5)$$

where  $M$  is the molar mass of the gas,  $R$  the perfect gas constant and  $T$  the temperature. If we let

$$X = P_1 \frac{M}{\mu R T} \left( \frac{Q_1}{A} \right) \quad (6)$$

and

$$Y = \frac{P_1^2 - P_2^2}{2\mu L P_1 \left( \frac{Q_1}{A} \right)} \quad (7)$$

The Darcy-Forchheimer equation (5) becomes

$$Y = \frac{1}{k} + \beta X \quad (8)$$

This gives the Forchheimer linear plot, used to interpret experimental data. This plot directly provides, from a one-phase flow experiment, the gas permeability and inertial resistance coefficient of a porous medium. At low operating pressure, Klinkenberg effects might appear but this was not observed in the experiments presented below and we do not discuss this phenomenon more thoroughly.

Several authors have shown that the  $\beta$  coefficient depends strongly on other physical properties of the porous medium like porosity, permeability, tortuosity, heterogeneity, coordination number etc., in a complex manner and it is beyond the scope of this work to derive a precise formalism on  $\beta$ . Empirically, Geerstma [17] proposed that the inertial resistance coefficient could be reasonably correlated with porosity and permeability according to

$$\beta = \frac{\lambda}{\phi^{5.5} k^{0.5}} \quad (9)$$

where  $\lambda$  is a core-dependent constant.

This result obtained in the case of single-phase gas flow has been further extended to the case where a liquid -water- phase is trapped in the porous medium. Under these circumstances, Evans et al. [18], proposed the following correlation

$$\beta = \frac{\lambda}{\phi_{\text{eff}}^{5.5} k_{\text{eff}}^{0.5}} \quad (10)$$

where

$$\phi_{\text{eff}} = \phi(1 - S_{wi}) \quad (11)$$

is the effective porosity and;

$$k_{\text{eff}} = k \cdot k_{rg} \quad (12)$$

is the effective permeability where  $k_{rg}$  is the gas relative permeability.

## Experiments

### Core Test Equipment

The experimental coreflood test equipment is represented in Fig. 1. Water and polymer solutions are injected with volumetric pumps into the core confined in a high-pressure cell. Dry gas flows through a gas flow controller located ahead of a water cell used to hydrate the gas. The gas is water-saturated at the inlet pressure and temperature of the core. This step is very important to avoid drying of the core at the irreducible water saturation. Differential pressure transducers are used to measure the pressure drop along the water cell -this is

necessary to evaluate precisely the gas flow rate at the core inlet-, and along the core to determine the pressure drop. The Forchheimer plot of the measured values of pressure and flow rate provides the gas permeability and inertial resistance coefficient of the core. When the porous medium is saturated, water saturation is measured by core weighing. The experimental equipment is located in a temperature-controlled room.

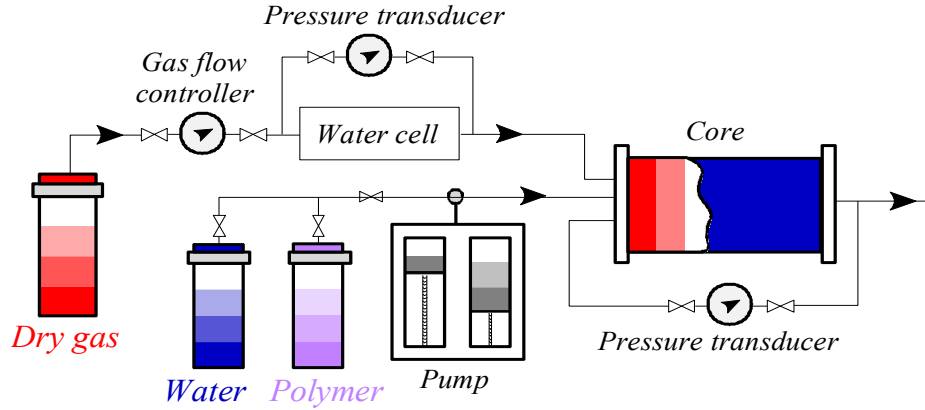


Fig. 1 Coreflood test equipment.

#### *Porous Media*

Two types of water-wet sandstone cores were used in the study. The first one is a Vosges sandstone with low permeability ( $k_w = 63$  and  $47$  mD) and the second one is a Berea sandstone ( $k_w = 318$  and  $392$  mD). Porosity of both types of cores is around 20%.

The three samples were available under the form of cylinders with a diameter of 4 cm and a length of 7 cm.

#### *Fluids*

Synthetic brine ( $10 \text{ g.l}^{-1}$  KI) was used as the water phase. Higher salinity brine ( $50 \text{ g.l}^{-1}$  KI) was used as a tracer to determine polymer adsorption.

Gas was pure nitrogen.

#### *Polymer Solution*

We used a nonionic high-molecular-weight polyacrylamide (FA 920 SH from Floerger®) available under powder form. The solution was prepared at a concentration of  $2500 \text{ ppm}$  in a  $10 \text{ g.l}^{-1}$  KI brine. The solution is filtered with a series of  $8$ ,  $3$  and  $1.2 \text{ }\mu\text{m}$  membranes in order to remove microgels. Viscosity of polymer solution was measured with a Couette viscometer and was  $8 \text{ mPa.s}$  at the Newtonian plateau.

#### *Experimental Procedure*

The objective of our study is to determine the influence of adsorbed polymer on water and gas permeabilities and inertial resistance coefficient. To do so, we want to compare experimental results obtained on original cores -without polymer- with those obtained on the same treated cores -after polymer adsorption. Experimental procedure was as follows

- 1) Measurement of gas permeability,  $k_g$ , and inertial resistance coefficient,  $\beta$ , on the dry original core.
- 2) Brine saturation of the core after  $\text{CO}_2$  flush.
- 3) Measurement of porosity,  $\phi$ , and brine permeability of the original core,  $k_w^{(1)}$ .

- 4) Gas drainage until irreducible water saturation,  $S_{wi}^{(1)}$ , is reached and measurement of effective permeability to gas,  $k_g(S_{wi}^{(1)})$  and inertial resistance coefficient,  $\beta^{(1)}(S_{wi}^{(1)})$  of the original core.
- 5) CO<sub>2</sub> drying of the core followed by brine saturation.
- 6) Salt tracer front followed by an injection of 3 pore volume of polymer. Effluent viscosity is measured in order to determine polymer adsorption.
- 7) Injection of brine to displace the non-adsorbed polymer followed by a measurement of water permeability  $k_w^{(2)}$ . This step leads to a core state called “cleaned core”. If this step is skipped the state is called “full core” meaning that gas is directly injected in the core after the polymer solution.
- 8) Gas is injected until irreducible water saturation,  $S_{wi}^{(2)}$ , is reached. Effective permeability to gas,  $k_g(S_{wi}^{(2)})$ , and inertial resistance coefficient,  $\beta^{(2)}(S_{wi}^{(2)})$ , are determined for the “cleaned core”. Alternatively, irreducible saturation,  $S_{wi}^{(3)}$ , effective permeability to gas,  $k_g(S_{wi}^{(3)})$ , and inertial resistance coefficient,  $\beta^{(3)}(S_{wi}^{(3)})$ , are determined for the “full core” a core saturated with bulk polymer solution (adsorbed + free polymer). This last step is eventually repeated by incrementing the gas flow rate.

## Results and Discussion

### Polymer Adsorption

Polymer adsorption is estimated by the delay of polymer front versus tracer front [12]. This approach remains correct if the excluded pore volume can be neglected [12].

Results obtained with this method yield a polymer adsorption equal to 280  $\mu\text{g.g}^{-1}$  for the Vosges sandstones and 122  $\mu\text{g.g}^{-1}$  for the Berea sandstone.

### Irreducible Water Saturation

Table 1: Physical properties of the cores and permeability reductions.

	Berea sandstone				Vosges sandstone					
	Cleaned core		Full core		Cleaned core			Full core		
	Original	Treated	Original	Treated	Original	Treated		Original	Treated	
$k_w$ (mD)	318	15	392	-	47	0.7		63	-	
$S_{wi}$ (%)	29.7	37.2	24.4	44.2	15.3	39.7	37.1	-	46.8	37.3
$k_g$ (mD)	330	198	351	115	128	97	102	196	106	129
$R_{kw}$	21		-		67			-		
$R_{kg}$	1.5		2.4		0.9	0.9		-		

Experimental results presented in Table 1 show a significant increase of the irreducible water saturation after polymer adsorption. This behavior is identical to the one observed on water/oil system and present results indicate that this effect is stronger for a water/gas system. As already mentioned for a water/oil system, this effect is due to water retention in the hydrosoluble adsorbed polymer and capillary trapping phenomena in the smaller pores [8]. These results are coherent with the wall effect hypothesis considering that irreducible water saturation modification before and after polymer injection is the result of a steric effect.

For the same reason, irreducible water saturation is also increased when the core is saturated with bulk polymer solution. In fact, the gas/polymer mobility ratio is roughly 8 times smaller than the gas/water mobility ratio and this difference leads to a stronger irreducible water saturation on the full treated core.

#### *Permeability Reduction*

Permeability reduction to water and gas are defined as follows

$$R_{kw} = \frac{k_w^{(1)}}{k_w^{(2)}} \quad (13)$$

$$R_{kg} = \frac{k_g^{(1)}(S_{wi}^{(2)})}{k_g^{(2)}(S_{wi}^{(2)})} \quad (14)$$

Results obtained with three different cores are summarized in Table 1. Gas relative permeabilities have been compared at the same water saturation values using a linear cross form.

Reduction of water permeability varies from 21 to 67 while gas permeability reduction is always close to 1. This illustrates and confirms the Disproportionate Permeability Reduction effect of the polymer. As already observed [5], our results indicate that DPR is stronger in the case of gas/water than it is in the case of oil/water systems obtained with similar cores [12].

#### *Inertial effects*

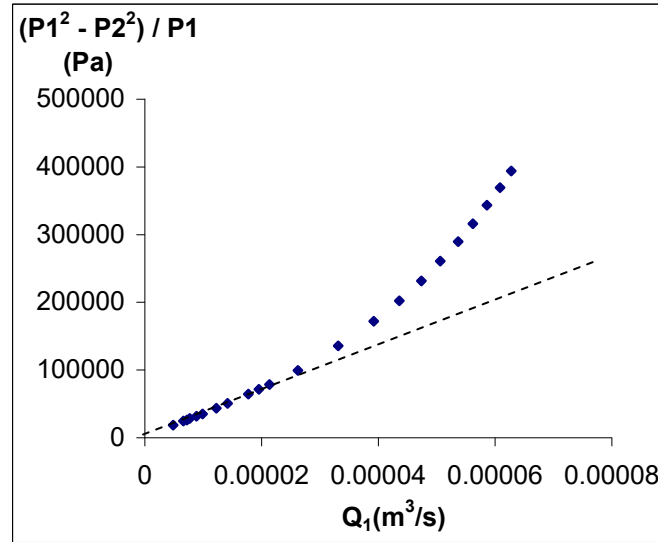


Fig. 2: Darcy plot of experimental data obtained on dry Berea sandstone.

In Fig. 2 we have represented our experimental data obtained from pressure drops and flow rates measurements on a dry Berea sandstone core. Clearly, the deviation from a linear relationship of the pressure drop, corrected from compressible effects, versus flow rate shows that inertial effects are significant. Typically, the pressure drop is higher than expected in a Darcy flow and the increment, as discussed above, can be taken into account by a quadratic term in the Darcy-Forchheimer type of model as displayed in Eq. (5). In Fig. 3, we have



reported the same data using the representation given by Eqs (6) to (8) (Forchheimer plot) from which gas permeability and inertial resistance coefficient can be directly identified.

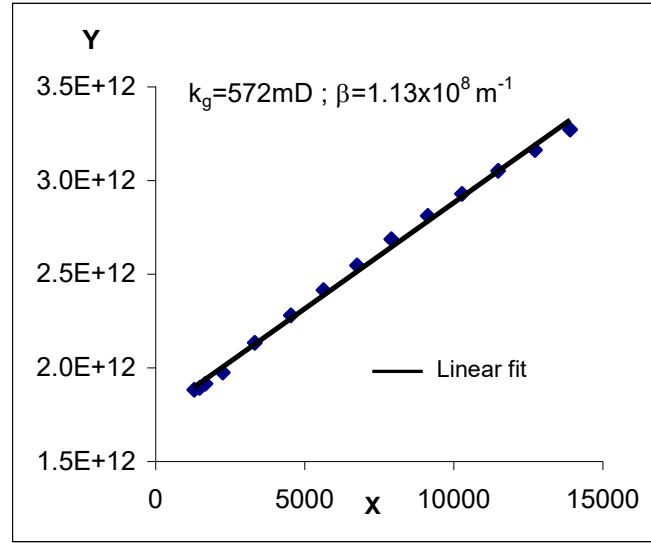


Fig. 3: Forchheimer plot of experimental data on dry Berea sandstone.

Measurements at the irreducible water -or polymer- saturation were performed with the idea that  $S_{wi}$  is a decreasing function of gas flow rate. On this basis, once the irreducible saturation was obtained at a given gas flow rate, permeability and inertial resistance coefficient were determined from a Forchheimer plot issued from data obtained with decreasing gas flow rates. Irreducible saturation was estimated from mass balance. Experiments were performed either on cleaned or full cores.

Table 2: Physical properties of the treated cores.

	Berea sandstone						
	Cleaned core				Full core		
	Original		Treated		Original		Treated
S <sub>wi</sub> (%)	0	29.7	37.2		0	24.4	44.2
k <sub>g</sub> (mD)	570	330	198		572	351	115
β (10 <sup>8</sup> m <sup>-1</sup> )	1.4	3.38	2.9		1.13	2.60	6.98
	Vosges sandstone						
	Cleaned core				Full core		
	Original		Treated		Original		Treated
S <sub>wi</sub> (%)	0	15.3	39.7	37.1	0	46.8	37.3
k <sub>g</sub> (mD)	141	128	97	102	196	106	129
β (10 <sup>8</sup> m <sup>-1</sup> )	1.87	2.69	4.14	3.84	1.47	10.3	3.42

Experimental results on  $S_{wi}$ ,  $k_g$  and  $\beta$  are summarized in Table 2. In Fig. 4 we have represented the  $\beta$  coefficient as a function of  $\phi_{eff}^{-5.5} k_{eff}^{-0.5}$  for original cores, i.e. before polymer injection. This representation clearly indicates that the correlation suggested by Eq. (10) is physically relevant with very close values of  $\lambda$  coefficients for the two sandstones used here.

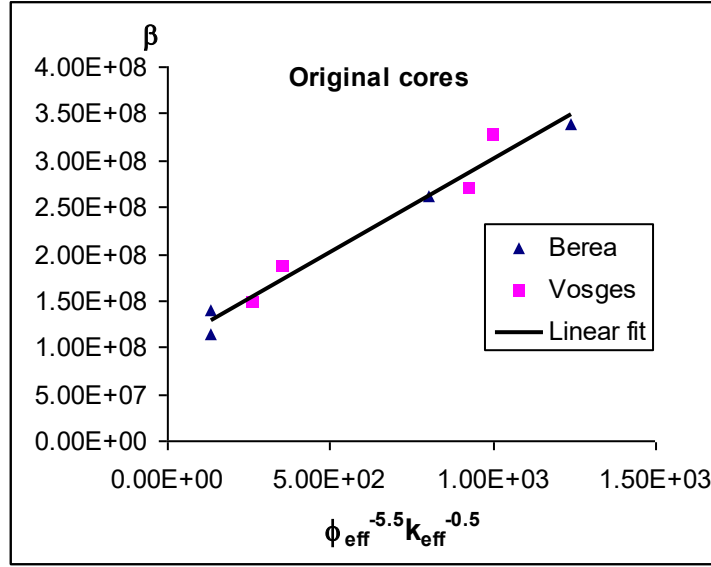


Fig. 4: Inertial resistance coefficient measured on the two types of sandstones. Cores are in their original state.

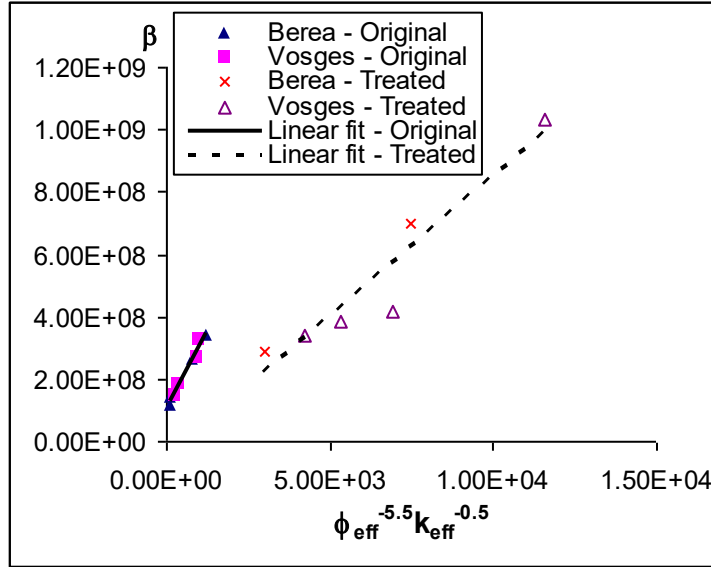


Fig. 5: Inertial resistance coefficients before and after polymer injection.

On the basis of these results, we have represented on Fig. 5, inertial resistance coefficients obtained on original cores and in the presence of adsorbed or bulk polymer. We clearly see that, for treated cores, the correlation given by Eq. (10) is reasonably satisfied. Moreover, this figure indicates that the slope corresponding to original cores is lower than that corresponding to treated cores. This means that the inertial resistance coefficient measured when polymer is adsorbed in the core is lower than what it would have been at the same level of effective properties. In Fig. 5, inertial resistance coefficients are always larger on treated cores, but this is only due to the fact that the product  $\phi_{\text{eff}}^{-5.5} k_{\text{eff}}^{-0.5}$  is also always larger in that case. However, the inertial resistance coefficient increases much less with  $\phi_{\text{eff}}^{-5.5} k_{\text{eff}}^{-0.5}$  after polymer treatment.

## Conclusions

Experimental results presented in this paper show clearly that Disproportionate Permeability Reduction (DPR) due to nonionic polyacrylamide polymer adsorption is very strong for gas/water systems. Irreducible water saturation obtained after gas drainage depends on the presence of adsorbed polymer. Its value increases when adsorbed polymer is present. This effect, due to capillary trapping and water retention in the polymer depends on the way the core is treated (gas drainage occurring directly after polymer injection or after having removed the non adsorbed polymer from the core).

Inertial effects may be important when injecting gas. These effects are increased by the presence of irreducible water saturation that reduces effective porosity and permeability. For the sandstone samples used in the present work, a correlation between  $\beta$  and  $\phi_{\text{eff}}^{-5.5} k_{\text{eff}}^{-0.5}$ , as proposed elsewhere [17,18], has been found to be physically relevant. Inertial resistance coefficient can be reduced by the presence of adsorbed polymer. It has been observed that the rate of increase of  $\beta$  with  $\phi_{\text{eff}}^{-5.5} k_{\text{eff}}^{-0.5}$  is significantly smaller after polymer treatment. However, this effect is in competition with the increase of irreducible water saturation which increases  $\beta$ . These results are promising for practical field applications

## Nomenclature

$A$  = core surface ( $\text{m}^2$ )  
 $d_p$  = particle diameter (m)  
 $k$  = absolute permeability ( $\mu\text{m}^2$ ).  
 $k_r$  = relative permeability  
 $L$  = core length (m)  
 $M$  = molar mass ( $\text{kg.mol}^{-1}$ )  
 $P$  = pressure (Pa)  
 $Q_1$  = inlet flow rate ( $\text{kg.m}^{-3}$ )  
 $R$  = perfect gas constant ( $\text{J.mol}^{-1}.\text{K}^{-1}$ )  
 $R_{Kg}$  = gas permeability reduction.  
 $R_{Kw}$  = water permeability reduction.  
 $S$  = fluid saturation  
 $T$  = temperature (K)  
 $v$  = Darcy velocity ( $\text{m.s}^{-1}$ )  
 $x$  = distance (m)  
 $X$  = Forchheimer variable (Eq. 6)  
 $Y$  = Forchheimer variable (Eq. 7)  
 $\beta$  = inertial resistance coefficient ( $\text{m}^{-1}$ )  
 $\phi$  = porosity.  
 $\lambda$  = constant (Eq. 9)  
 $\mu$  = dynamic viscosity ( $\text{Pa.s}$ ).  
 $\rho$  = fluid density ( $\text{kg.m}^{-3}$ )

## Subscripts

$1,2$  = core inlet, outlet  
 $\text{eff}$  = effective

g = gas phase  
i = fluid phase  
w = water  
wi = irreducible water

#### Superscripts

(1) = original core  
(2) = cleaned core  
(3) = full core

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