

# Estimation of Local Equilibrium Foam Model Parameters as Functions of the Foam Quality and the Total Superficial Velocity

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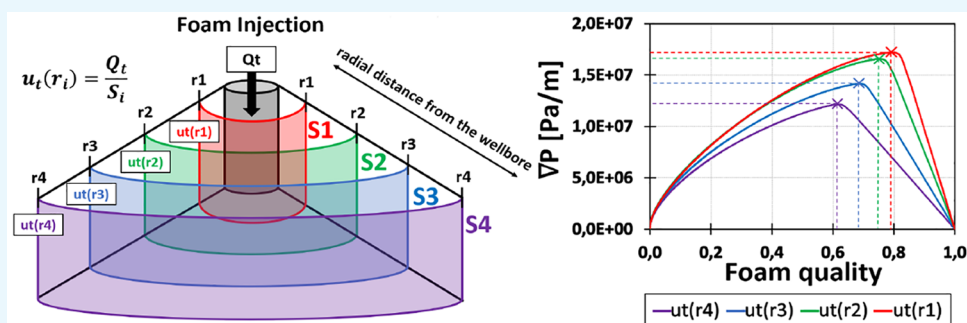
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**ABSTRACT:** In this paper, the behavior of foam in a porous medium is studied in order to understand the effect of the fluid velocity on foam properties. This aspect is crucial during foam injection, as due to radial effects the foam velocity largely decreases around the injection well. The foam properties are detailed through the use of a new local equilibrium foam model parameter estimation approach using an improved new shear function and based on the most widely used STARS model developed by the Computer Modeling Group (CMG). A new mode of calculation of the STARS model parameters is then presented in order to allow both a semiautomated fitting of several quality scan pressure curves and a consideration of the role of the total velocity. The approach is tested through column experiments done at various velocities and gas fractions. Furthermore, the proposed model is also tested on literature results in order to validate it for very different experimental conditions. This study and the fitted results are then used to understand, on both our column experiments and the literature data, the existence of two shear effects and their origins.

## INTRODUCTION

Foam injection in porous media was commonly used with several objectives such as diversion of acid or gas for improved oil recovery (IOR)<sup>1–3</sup> and mobilization or solubilization of contaminants for in situ environmental remediation (ISER).<sup>4–6</sup>

Foam in porous media is formed by gas bubbles separated by liquid films called lamellae. Foam behavior is inherently linked to the porous media characteristics (pore size, distribution, etc.) through a creation and destruction dynamic of lamellae.<sup>7</sup> These lamellae are in situ generated throughout snap-off, lamellae division and are left behind when they collapse due to gravity drainage, gas diffusion, and capillary suction.<sup>8</sup> Foam could be stabilized by amphiphilic molecules called surfactants, which reduced the interfacial tension at the bubble gas–liquid interface (i.e., lamellae). Therefore, lamellae dynamics and displacement create a resistance to the gas flow, which reduces gas relative permeability (i.e., mobility) and increases the apparent viscosity of the foam that diverts flow from large pores to smaller ones.

Several experiments demonstrated that foam flow in porous media is composed of two distinct regimes, the high and the low quality regimes.<sup>9,10</sup> The foam quality represents the gas

fraction in the liquid/gas mixture, which is injected. On one hand, in the low quality regime when the foam quality increases, the pressure gradient or apparent viscosity of the foam increases. In this regime, bubble trapping and mobilization dominate the foam flow with a possible shear thinning effect. On the other hand, in the high quality regime when the foam quality increases, the pressure gradient or the apparent viscosity of the foam decreases. In this regime gas bubbles are separated by thin lamellae, which are unstable, and the flow is dominated by lamellae breaks and the concept of limiting capillary pressure  $P_c^*$ .<sup>11</sup>

Foam models are usually divided into two groups, the population balanced (PB) model and local equilibrium (LE) model. The explicit PB models describe lamellae generation and destruction happening at the pore scale. This type of model is generally not viable for large scale simulation due to

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its expensive computational cost and its number of parameters. This is why LE models are widely used for large scale reservoir simulation thanks to their implicit approach, which consists of a single empirical formula to control the gas phase mobility. Thus, it could be easily integrated to a two phase flow generalized Darcy model using relative permeability models.<sup>12,13</sup> Parameters of the LE model are estimated from foam flooding experiment data through different kinds of methods<sup>14–16</sup> during a steady state foam flow. One of the most commonly used LE foam models, named STARS, comes from the Computing Modeling Group (CMG). This model approaches foam behavior by modifying the gas relative permeability with a “mobility factor” (FM). The FM factor can be calculated as a function of several variables where each of them expresses a particular foam behavior. Cheng et al.<sup>15</sup> give a detailed description of these variables that can compose the FM function.

For ISER applications, the radial effect needs to be considered to qualify the foam behavior as the foam is injected in a wellbore. For this purpose, numerical simulations with an LE foam model are generally used. Although the foam behavior has been shown to vary with the total superficial velocity,<sup>9,10,17</sup> to our knowledge no studies considered STARS model parameters varying with the distance from the well. This is the major objective of this paper, where the foam parameters are modeled for the whole range of quality scans including  $u_t$  variations. In order to do so, a reformulation of the shear effect was necessary to take under consideration both the role of the foam quality and  $u_t$  on the whole quality scan. This new approach was supported by new 1-D foam flooding experiments and was then extended to other experiments available in the literature. The link between the parameters and  $u_t$  allowed us then to expand the approach to the study of radial effects during foam injection.

## FOAM MODEL

**STARS Foam Model.** STARS, from the Computing Modeling Group (CMG), is a commercial reservoir simulator including a texture-implicit local equilibrium (LE) foam model. In this model, the foam behavior is introduced by multiplying the gas relative permeability  $k_{rg}$  by a mobility reduction factor FM. Thus, a new foam equivalent relative permeability  $k_{rg}^f$  is obtained. The factor FM is presented within the generalized Darcy expression of the gaseous phase in eq 1.

$$u_i f_g = -\frac{k k_{rg}^f}{\mu_g} (\nabla P_g - \rho_g g) \quad \text{with} \quad k_{rg}^f = k_{rg} \times \text{FM} \quad (1)$$

where  $u_i$  is the total superficial velocity ( $u_i = u_g + u_w$ ),  $f_g$  the foam quality with  $f_g = \frac{u_g}{u_i}$ ,  $k$  the intrinsic permeability,  $k_{rg}$  the relative permeability of the gas phase without foam, and  $\mu_g$  the gas dynamic viscosity. The gas pressure gradient  $\nabla P_g$  and water pressure gradient  $\nabla P_w$  are linked through the capillary pressure expression  $P_c(S_w) = P_g - P_w$ . Furthermore, if 1-D experiments are conducted horizontally, the gravitational contribution for each phase can be neglected during the foam model parameter estimation process.

FM is dimensionless and composed of a given number of dimensionless subfunctions shown in eq 2. These subfunctions describe the foam behavior against a given factor such as water saturation, surfactant concentration, oil saturation, non-Newtonian behavior, foam generation, salinity, etc.

$$\text{FM} = \frac{1}{1 + f_{mmob} \times \prod_{i=1}^n F_i} \quad (2)$$

The parameter  $f_{mmob}$  represents the highest mobility reduction factor reachable for wet foam.  $F_i$  subfunctions are defined within the range ( $0 \leq F_i \leq 1$ ). From this definition the foam at a given quality  $f_g$  and total superficial velocity  $u_t$  obtains its maximum gas mobility reduction when all  $F_i$  subfunctions are equal to 1. In this paper two subfunctions are considered, the water saturation dependence or dry out subfunction  $F_{dry}$  and the shear rate dependence subfunction  $F_{shear}$ . Then, eq 2 is reduced to

$$\text{FM} = \frac{1}{1 + f_{mmob} \times F_{dry} \times F_{shear}} \quad (3)$$

$F_{dry}$  is the water saturation dependence subfunction which is continuous and increases with  $S_w$  as presented in eq 4.

$$F_{dry} = 0.5 + \frac{\arctan(\text{epdry}(S_w - \text{fmdry}))}{\pi} \quad (4)$$

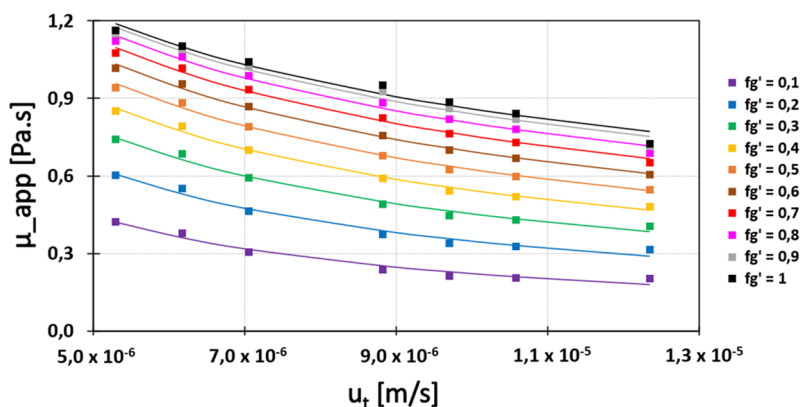
$F_{dry}$  contains two parameters:  $\text{fmdry}$  and  $\text{epdry}$ .  $\text{fmdry}$  is defined as the critical water saturation under which foam collapses and is often confused with  $S_w^*$ , the water saturation at the transition point where the foam strength is maximal.  $S_w^*$  is often linked to the limiting capillary pressure  $P_c^*$  in the literature,<sup>15,18</sup> the pressure above which the capillary pressure dries out lamellae and leads to their rupture.  $\text{epdry}$  controls the abruptness of the foam collapse. A large value of  $\text{epdry}$  implies a sharp dry out of the foam as soon as the water saturation approaches the  $S_w^*$  value. Due to the sharp pressure gradient decrease at this point,  $S_w^*$  and  $\text{fmdry}$  values are very close and could be confused. The role of  $\text{epdry}$  on the distinction between  $\text{fmdry}$  and  $S_w^*$  and how  $\text{epdry}$  can be used to calculate  $\text{fmdry}$  from  $S_w^*$  are presented within the **Fitting Method** section.

$F_{shear}$  (also called  $F_{cap}$ ) is the shear rate dependence subfunction using the local capillary number  $N_{Ca}$  as presented in eq 5.

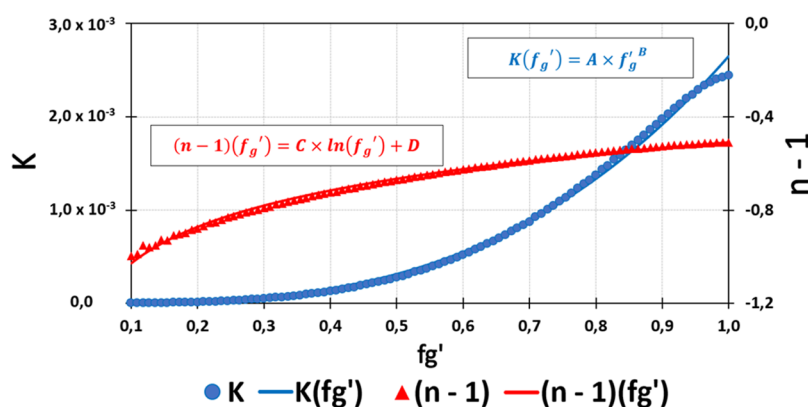
$$\text{if } N_{Ca} > \text{fmcap}, F_{shear} = \left( \frac{\text{fmcap}}{N_{Ca}} \right)^{\text{epcap}}; \text{ otherwise, } F_{shear} = 1 \quad (5)$$

The parameter  $\text{epcap}$  controls how foam rheology is dependent on the shear rate. A positive value of  $\text{epcap}$  corresponds to a shear-thinning behavior.  $\text{fmcap}$  is a parameter used to normalized the  $F_{shear}$  value within the range  $[0, 1]$ .  $N_{Ca}$  is a dimensionless number in fluid mechanics which compares viscous and capillary forces. A high  $N_{Ca}$  value implies higher viscous effects and, thus, a high shear rate. The expression of the capillary number remains controversial in the literature,<sup>9,14,19,20</sup> and its use differs from one to another parameter optimization process; it has been used with two significations.

On one hand, the  $F_{shear}$  subfunction is used to modify the value of the maximum apparent viscosity of the foam for different superficial velocities. As an example, in the experiments of Zeng et al.<sup>19</sup> the capillary number  $N_{Ca}$  was defined using the total superficial velocity and the surface tension between the gaseous and the aqueous phases. The transition foam quality  $f_g^*$  observed on a single quality scan was determined, and several experiments at this  $f_g^*$  with various total superficial velocities  $u_t$  were performed. It seems that a fixed  $f_g^*$  point for all  $u_t$  values was assumed. Zeng et al.<sup>19</sup> also



**Figure 1.** Apparent viscosity  $\mu_{app}$  plotted against the total superficial velocity  $u_t$  from the Alvarez et al. experimental data. Each group of colored squares corresponds to various values of  $f_g' = f_g/f_g^*$ . In this plot, note that  $f_g' \in [0, 1]$  and that the  $f_g'$  increase is constant between each color. Final fits using  $K(f_g')$  and  $(n-1)(f_g')$  functions are also plotted with colored lines to validate eq 8.



**Figure 2.** Obtained  $K$  and  $(n-1)$  values from the first set of the SLSQP plotted against  $f_g'$  with blue circles and red triangles, respectively.  $K$  and  $(n-1)$  functions of  $f_g'$  using parameters  $A$ ,  $B$ ,  $C$ , and  $D$  were fitted using a second set of the SLSQP and presented with blue and red lines, respectively.  $A = 2.6462 \times 10^{-3}$ ,  $B = 3.0713$ ,  $C = 2.2530 \times 10^{-1}$ , and  $D = -5.0865 \times 10^{-1}$ .

used a very low  $epdry$  value to obtain a curved shape able to capture experimental points within the low quality regime. This technique would be limited for a case with an abrupt foam collapse. In addition, using a low  $epdry$  with the assumption that  $S_w^* = fmdry$  seems not relevant with regard to the literature.<sup>16</sup>

On the other hand, the  $F_{shear}$  subfunction is used to catch experimental points within the low quality regime of the quality scan, which are often underestimated using the subfunction  $F_{dry}$  alone.<sup>14,21</sup> The capillary number is defined using the pressure gradient, which requires iterations for convergence. Furthermore, to keep  $F_{shear}$  within the range  $[0, 1]$ , the  $fmmob$  value is increased from the first value obtained through  $F_{dry}$  alone<sup>14</sup> to compensate the  $F_{shear}$  modification (see Figure S1 in the Supporting Information).

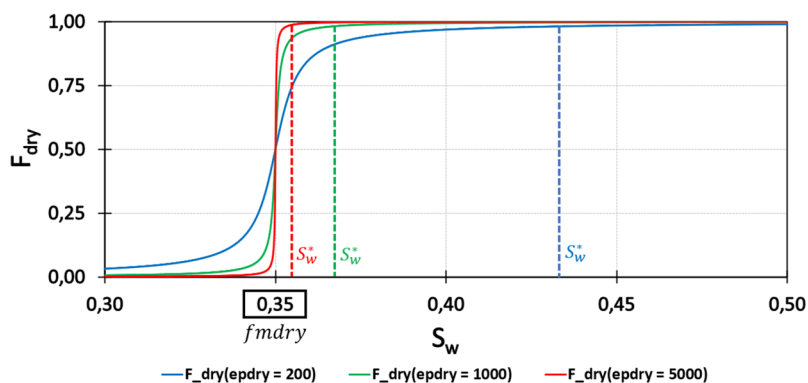
**Modified Foam STARS Model and Assumptions.** For ISER applications, foam is injected through wells leading to a fast decrease of the total superficial velocity  $u_t$  with the radial distance. In turn, it modifies the foam properties with distance from the injection point.<sup>17</sup> It therefore appears that for real field applications the STARS model parameters must be  $u_t$  dependent functions. Because  $F_{shear}$  uses a description within FM, we present below an approach which takes  $u_t$  variations into account with an improved shear dependence expression. Note that only the low quality regime is studied below ( $0 \leq f_g$

$\leq f_g^*$ ) as the  $F_{dry}$  subfunction used to describe the high quality regime (foam collapse) has already been detailed previously.

In their paper, Alvarez et al.<sup>9</sup> provide numerous experimental results of foam injections with pressure contour plots. These data show a foam quality value at the transition  $f_g^*$  increasing with  $u_t$ , which was never taken into account within LE foam models to our knowledge. As the  $f_g^*$  value is a function of  $u_t$  in this case with  $f_g^*(u_t) \in [0.5, 0.9]$ , we defined the relative position from the  $f_g^*$  point within the low quality regime as  $f_g' = f_g/f_g^*$ .  $f_g'$  is a shared and comparable parameter for all  $u_t$  quality scans (various injected foam qualities for a fixed  $u_t$  value).  $f_g^*$  values were estimated with a correct accuracy thanks to the amount of data for various  $u_t$  values close to the transition points. Using the apparent viscosity definition presented eq 6, we plotted  $\mu_{app} = f(u_t)$  curves for various values of  $f_g'$  within the low quality regime on Figure 1.

$$\mu_{app} = \frac{kVP}{u_t} \quad (6)$$

Colored squares on Figure 1 show that there is a dependency of  $\mu_{app}$  both on  $u_t$  and on  $f_g'$ . In fact,  $\mu_{app}$  is a nonlinear function of  $u_t$  with coefficients changing with  $f_g'$ . This led us to consider the curves  $\mu_{app} = f(u_t)|_{f_g'}$  for various fixed  $f_g'$  values. We opted for an Ostwald–de Waele type law using the total superficial velocity  $u_t$  presented hereafter:



**Figure 3.**  $F_{shear}$  plotted against  $S_w$  for  $epdry = [200, 1000, 5000]$  with blue, green, and red curves, respectively.  $fmdry$  was set to 0.35 for the example and is indicated with a black rectangle on the  $S_w$  axis. Estimated  $S_w^*$  values are given using colored dotted straight lines for the three different  $epdry$  values.

$$\mu_{app} = K \times u_t^{(n-1)} \quad (7)$$

with  $K$  the consistency factor and  $(n - 1)$  the flow behavior exponent. The classical Ostwald–de Waele law uses the shear rate as  $\mu_{app} = K\dot{\gamma}^{n-1}$ , and we simplified the relation using the total superficial velocity, which is still a good indicator of the shear rate as the steady state is reached for all experiments. A first set of fits were made using a sequential least-squares program (SLSQP). We present on Figure 2 the obtained  $K$  and  $(n - 1)$  values plotted against  $f_g^*$  for all velocities with blue circles and red triangles, respectively.

Using the obtained  $K$  and  $(n - 1)$  shapes against  $f_g^*$ , two functions  $K(f_g^*)$  and  $(n - 1)(f_g^*)$  were set and are presented in Figure 2. The expression of the apparent viscosity as a function of  $f_g^*$  and  $u_t$  is presented below:

$$\mu_{app} = A \times (f_g^*)^B \times u_t^{C \times \ln(f_g^*) + D} \quad (8)$$

with  $A$ ,  $B$ ,  $C$ , and  $D$  the determined constants of  $K$  and  $(n - 1)$  functions of  $f_g^*$ . A second set of the SLSQP were done to determine  $A$ ,  $B$ ,  $C$ , and  $D$  values (see Figure 2).  $K(f_g^*)$  and  $(n - 1)(f_g^*)$  fitted curves are given Figure 2 with blue and red lines, respectively. Equation 8 fit accurately the original experimental data set, providing the expected apparent viscosity variations as presented Figure 1 with colored lines. It is clear, however, that these expressions are not constants as has been used up to present. In this formulation,  $K$  and  $(n - 1)$  depend on foam quality, which has not been shown previously to our knowledge.

**Fitting Method Using  $F_{dry}$  and the New Function  $F_{shear}$ .** In this section we present a fitting method to determine  $F_{dry}$  (eq 4) and  $F_{shear}$  (eq 13) parameters, and this method needs several quality scans ( $\nabla P(f_g)$  curves for various  $u_t$  values). It appeared from several optimization processes that the  $D$  parameter used for the  $F_{shear}$  subfunction was not essential for the fit. Thus,  $D$  was set to zero by default to decrease the number of parameters within  $F_{shear}$ . For the fitting process, the generalized Darcy equations for gas, eq 9, and water, eq 10, are simplified to the following expressions without capillary pressure nor gravity effects:

$$u_t f_g = k \lambda_{rg} FM \nabla P \quad \text{with } \lambda_{rg} = \frac{k_{rg}}{\mu_g} \quad (9)$$

$$u_t(1 - f_g) = k \lambda_{rw} \nabla P \quad \text{with } \lambda_{rw} = \frac{k_{rw}}{\mu_w} \quad (10)$$

Note here that for simplification we use the absolute value of the pressure gradient  $\nabla P$ .  $\lambda_{rg}$  and  $\lambda_{rw}$  are the gas and water mobilities, respectively. We used the Brooks and Corey<sup>12</sup> relative permeability model for the two phases. As shown in eq 11 and eq 12,  $k_{rg}^0$  and  $k_{rw}^0$  are the end point relative permeabilities for gas and water, respectively,  $S_{g,r}$  is the gas residual saturation,  $S_{w,r}$  is the water residual saturation, and  $n_g$  and  $n_w$  are the Brooks and Corey model exponents for gas and water, respectively.

$$k_{rg} = k_{rg}^0 \times (1 - Se)^{n_g} \quad \text{with } Se = \frac{S_w - S_{w,r}}{1 - S_{w,r} - S_{g,r}} \quad (11)$$

$$k_{rw} = k_{rw}^0 \times (Se)^{n_w} \quad (12)$$

Equations 9 and 10 and the relation  $f_g = \frac{u_g}{u_g + u_w}$  were used to express  $f_g$  (eq 14) and  $\nabla P$  (eq 15). In order to do so, and for consistency with eq 14 and eq 15, the  $F_{shear}$  subfunction is expressed with  $S_e$  and not  $f_g$ :

$$F_{shear} = A \times (S_e')^B \times u_t^{C \times \ln(S_e')} \quad \text{with } S_e' = \frac{1 - Se}{1 - Se^*} \quad (13)$$

$$f_g = \frac{\lambda_{rg} FM}{\lambda_{rg} FM + \lambda_{rw}} \quad (14)$$

$$\nabla P = \frac{u_t f_g}{k \lambda_{rg} FM} \quad (15)$$

The fit is done in several steps, as a direct fit does not converge. Five parameters must be optimized to fit the model:  $f_g^*$ ,  $\nabla P^*$ ,  $A$ ,  $B$ , and  $C$ . We assume that  $epdry$  is constant, and we use it as an input set by the user. This parameter can influence the curvature within the low quality and, thus, interfere with  $F_{shear}$  parameters  $A$ ,  $B$ , and  $C$  optimization. As a consequence, a few order of magnitude of  $epdry$  must be tested to find the best one; however, the sharpness of the transition point indicates the order of magnitude of  $epdry$ . At first a simple polyfit method around the transition point is done using experimental values to provide ( $f_g^*$ ,  $\nabla P^*$ ) input values and  $A$ ,  $B$ , and  $C$  were set to 1. Then, several optimization steps were done through

python scripts using the `scipy.optimize.fmin_slsqp` method (sequential least squares programming) on a shared routine presented in Figure S2 in the Supporting Information.

The  $S_w^*$  values are obtained through the eq 16 using eq 10 and eq 12

$$S_w^* = \left( \frac{u_t(1 - f_g^*)\mu_w}{k_{rw}^0 k \nabla P^*} \right)^{1/n_w} \times (1 - S_{g,r} - S_{w,r}) + S_{w,r} \quad (16)$$

During the parameter optimization processes observed in the literature the *fmdry* estimation and distinction from  $S_w^*$  is not always clear. In fact the *fmdry* value corresponds to the  $S_w$  value at which  $F_{dry} = 0.5$  and the  $S_w^*$  value corresponds to the transition point, where the pressure gradient is maximal. These two values may be very close for large *epdry* values, but the signification of a large value is left to user appreciation. This is why, as  $S_w^*$  is known from eq 16, a method to calculate *fmdry* is defined below.

We present in Figure 3 a plot of  $F_{dry}$  against  $S_w$  for a fixed *fmdry* and various *epdry* values. For this plot, we considered that the  $S_w^*$  value is obtained for  $F_{dry} = 0.995$ , which corresponds to the beginning of the foam collapse very close to the transition point (0.5% error). Based on these assumptions, we defined the distance between  $S_w^*$  and *fmdry* as  $\delta S_w = S_w^* - fmdry$ , which was calculated as follows using eq 4:

$$\delta S_w = \frac{\alpha}{epdry} \quad \text{with } \alpha = \tan(\pi \times 0.495) \quad (17)$$

This equation thus allows *fmdry* to be estimated after  $S_w^*$  calculation, assuming *epdry* is known. Equation 17 provides an accurate *fmdry* value for *epdry* values above or equal to 200.

The parameter *fmmob* is calculated at the transition point ( $f_g = f_g^*$  and  $\nabla P = \nabla P^*$ ) using the eq 19 with the assumption that  $F_{dry} = 1$  at the transition and  $F_{shear} = A$  at this point.

$$fmdry = S_w^* - \frac{\alpha}{epdry} \quad (18)$$

$$fmmob = \frac{\left( \frac{k\lambda_{rg} \nabla P}{u_t f_g} - 1 \right)}{F_{dry} F_{shear}} \quad (19)$$

Then, it is possible to solve eq 14 and eq 15 using  $S_w$  variations within the interval  $[S_{w,r}, 1 - S_{w,r}]$ . A detailed flowchart of the optimization process is given in Figure S2 in the Supporting Information.

## RESULTS AND DISCUSSION

We will first demonstrate our fitting method results using experiments presented in this paper and two other experimental data sets from the literature. Then, we will discuss our new  $F_{shear}$  subfunction integration to the STARS foam model and the radial effect consequences on a field foam injection for ISER application.

**Experimental and Parameters Fitting Results. Saponin Column Results.** We applied the previous fitting method with  $f_g^*$  and  $\nabla P^*$  parameters as  $u_t$  functions using data from experiments presented in this paper. Numerical values obtained from the experiments are provided in Table 1. For these experiments, saponin, an environmentally friendly surfactant, has been used with foam regeneration.

**Table 1. Summary of the Flooding Experiments Presented in This Paper**

column no.	$k$ [m <sup>2</sup> ]	$u_t$ [m/s]	$\nabla P$ [Pa/m]
C <sub>1</sub> ( $f_g = 0.3$ )	$6.97 \times 10^{-11}$	$1.3393 \times 10^{-4}$	$3.0944 \times 10^5$
	-	$1.0881 \times 10^{-4}$	$2.5439 \times 10^5$
	-	$8.3704 \times 10^{-5}$	$2.0795 \times 10^5$
	-	$5.8592 \times 10^{-5}$	$1.3671 \times 10^5$
C <sub>2</sub> ( $f_g = 0.5$ )	$3.29 \times 10^{-11}$	$1.3393 \times 10^{-4}$	$5.2251 \times 10^5$
	-	$1.0881 \times 10^{-4}$	$3.9888 \times 10^5$
	-	$8.3704 \times 10^{-5}$	$2.8820 \times 10^5$
	-	$5.8592 \times 10^{-5}$	$1.8602 \times 10^5$
C <sub>3</sub> ( $f_g = 0.7$ )	$6.00 \times 10^{-11}$	$1.3393 \times 10^{-4}$	$3.3361 \times 10^5$
	-	$1.0881 \times 10^{-4}$	$2.5077 \times 10^5$
	-	$8.3704 \times 10^{-5}$	$1.8675 \times 10^5$
	-	$5.8592 \times 10^{-5}$	$1.2733 \times 10^5$
C <sub>4</sub> ( $f_g = 0.8$ )	$4.97 \times 10^{-11}$	$1.3393 \times 10^{-4}$	$2.0214 \times 10^5$
	-	$1.0881 \times 10^{-4}$	$1.5549 \times 10^5$
	-	$8.3704 \times 10^{-5}$	$1.1578 \times 10^5$
	-	$5.8592 \times 10^{-5}$	$7.9358 \times 10^4$
C <sub>5</sub> ( $f_g = 0.9$ )	$4.97 \times 10^{-11}$	$1.3393 \times 10^{-4}$	$1.4297 \times 10^5$
	-	$1.0881 \times 10^{-4}$	$1.1418 \times 10^5$
	-	$8.3704 \times 10^{-5}$	$6.5719 \times 10^4$
	-	$5.8592 \times 10^{-5}$	$4.1530 \times 10^4$

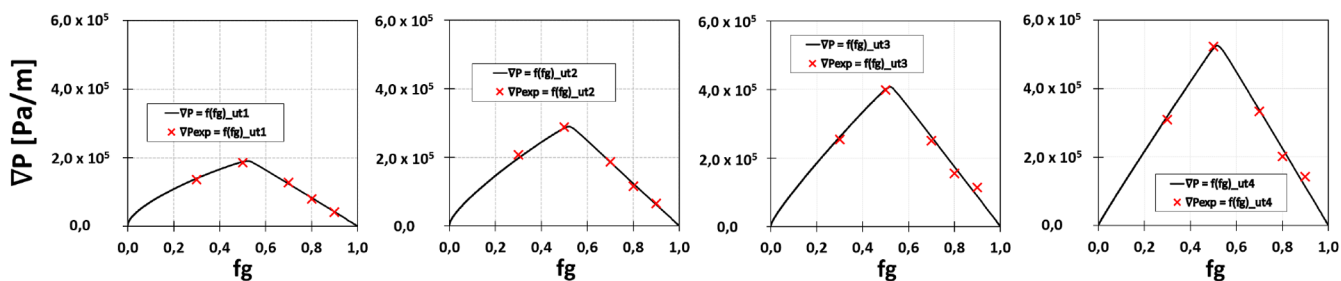
Experimental data results and data fit to each quality scan are given in Figure 4. These fits use  $f_g^*(u_t)$  and  $\nabla P^*(u_t)$  fitted curves and the three parameters  $A$ ,  $B$ , and  $C$  presented Figure 5.

Quality scan  $f_g^*$  values are located around  $f_g = 0.5$ , and the influence of  $u_t$  on this parameter seems to be negligible. This is confirmed by the  $f_g^*(u_t)$  plot in Figure 5. Thus,  $f_g^*(u_t)$  could be interpreted as a constant in this case. The pressure gradient at the transition  $\nabla P^*$  is quite linear against  $u_t$  within the tested range. The *epdry* value was tested with various orders of magnitude, and *epdry* =  $10^4$  provides the best global fit.

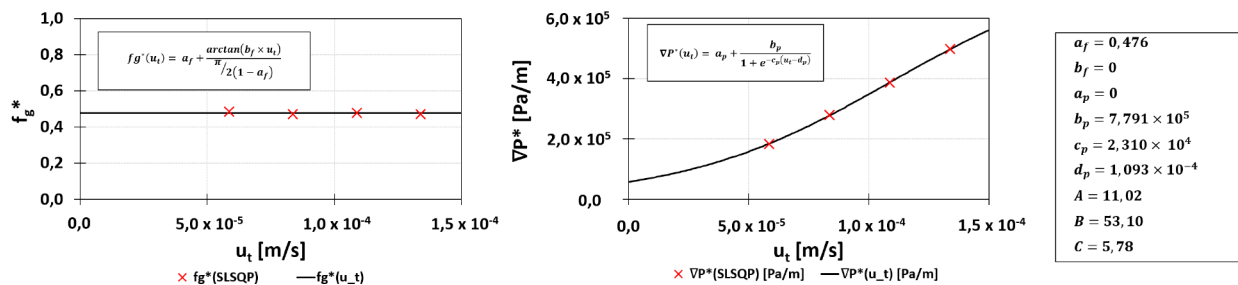
*Alvarez et al. Experiments, 2001.* We applied our fitting method to the Alvarez et al.<sup>9</sup> data. As Figure 6 shows, the resulting fit are quite good. The model illustrates a significant change of  $f_g^*$  with the total interstitial velocity  $u_t$  provided in the different subplots. The pressure gradient  $\nabla P$  also changes for each velocity, increasing with  $u_t$ . The model also clearly shows the linear and rapid decrease of  $\nabla P$  for high  $f_g$  after the collapsing point. On the contrary, thanks to the formulation of  $F_{shear}$  presented above, the model captures a clear nonlinear behavior for low quality foam, below  $f_g^*$ .

$f_g^*(u_t)$  and  $\nabla P^*(u_t)$  fitted curves and the  $A$ ,  $B$ , and  $C$  constants are given in Figure 7. They illustrate a different behavior than our previous experiments: all parameters are changing with  $u_t$ . The parametric equations used to fit the  $u_t$  relationships allow a good fit. It must be noticed that the equation itself is the same as for the previous experiments, only the parameters are changing. The pressure gradient at the transition  $\nabla P^*$  tends to a plateau for high  $u_t$  values.

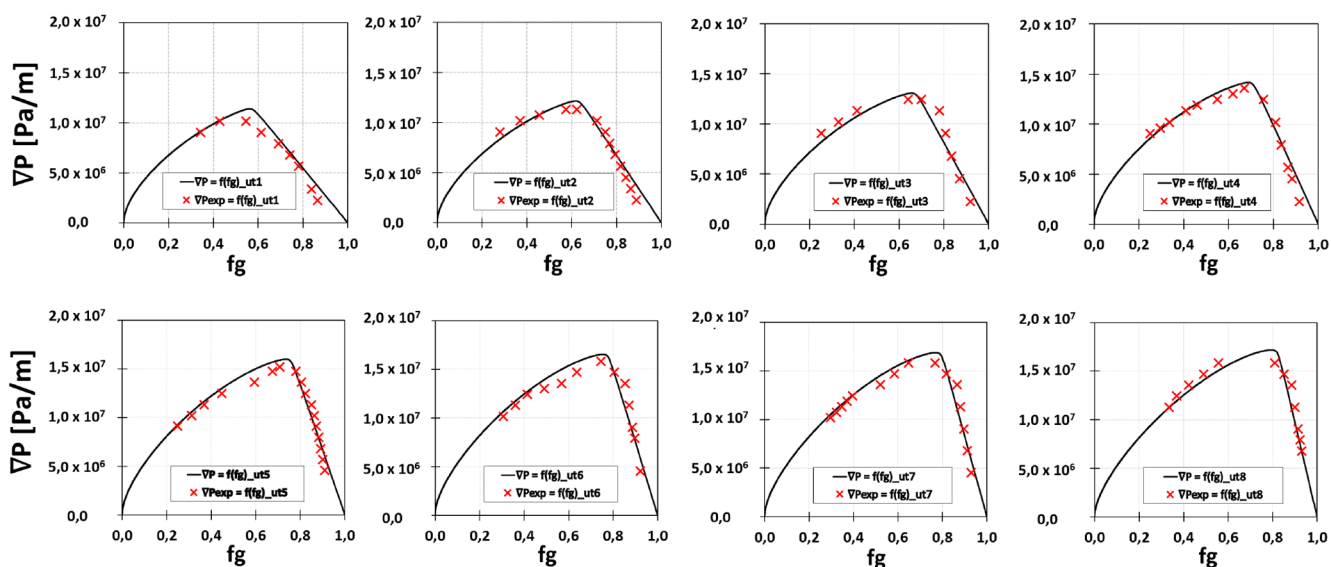
*Osterloh et al. Experiments, 1992.* These experiments were done at similar velocities to experiments presented in this paper, in lower permeability unconsolidated sand-packs at high temperatures (Figure 8). Under the given conditions, the curves are quite specific in the sense that the  $f_g^*$  values are very high. There are no obvious reasons for these high values, and  $f_g^*$  shows only very slight variations with  $u_t$ . The pressure gradient also increases slightly with  $u_t$ . The high  $f_g^*$  may explain why the experimental points are present only in the high range



**Figure 4.**  $\nabla P = f(f_g)$  curves fit to experiments presented in this paper. These curves are obtained through parameter functions of  $u_t$  and the optimization schema presented Figure S2 in the Supporting Information.  $epdry$  was set to  $10^4$  for all  $u_t$  values.



**Figure 5.** Parameters  $f_g^*$  and  $\nabla P^*$  coming from the optimization process plotted against  $u_t$  with their dedicated curve fits and expressions. Red crosses come from the optimization process, and straight black lines represent fitted  $f_g^*(u_t)$  and  $\nabla P^*(u_t)$  subfunctions. Parameters  $A$ ,  $B$ , and  $C$  from the  $F_{shear}$  function are also given. This figure gathers all the information needed to cover all foam injection cases within the range of  $u_t$  studied.



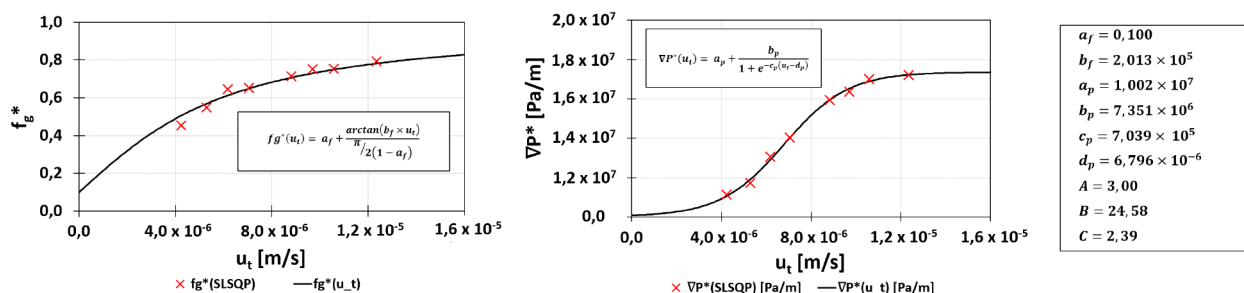
**Figure 6.**  $\nabla P = f(f_g)$  curves fit to the Alvarez et al.<sup>9</sup> experimental data. Red crosses represent experimental points and were determined using  $u_g = f(u_w)$  curves with pressure contours. Black curves are obtained through parameter functions of  $u_t$  and the optimization schema presented in Figure S2 in the Supporting Information. We set  $epdry = 10^4$  for all  $u_t$  values.

of  $f_g$ . It outlines, as in the Alvarez et al.<sup>9</sup> experiments, that the curves at low quality, below  $f_g^*$ , are not linear. However, here, due to the small number of experimental data at low  $f_g$ , the fit may be rather approximate.

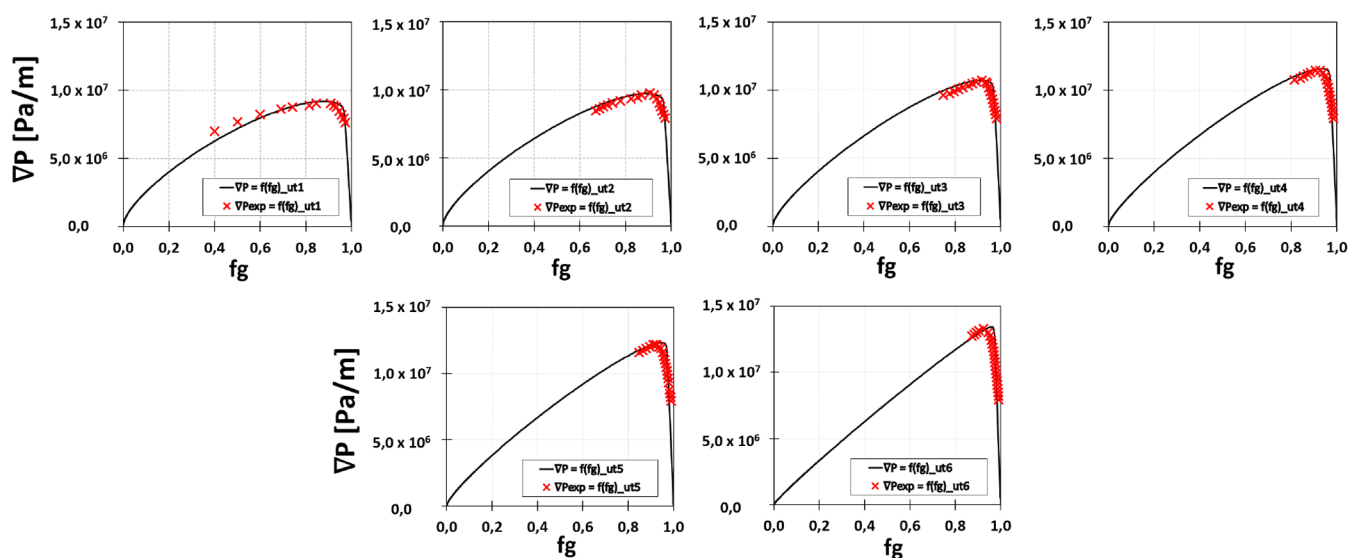
Concerning the evolution of the parameters with  $u_t$  (see Figure 9), the parametric equations again fit quite well the experimental points. As said above, the  $f_g^*$  value slightly increases but then rapidly remains stable. The pressure gradient also increases with a behavior closer to the one observed by Alvarez et al.<sup>9</sup> and seems to tend to a plateau.

**Modified  $F_{shear}$  Subfunction within the STARS Foam Model.** In the Foam Model section, two shear effects were cited: one for the variation of THE  $\nabla P^*$  value with  $u_t$  and one for the foam quality variation within the low quality regime. To our knowledge, we first gather these two effects: the variation of  $\nabla P^*$  is provided by linking the model parameter values with  $u_t$  and the shear effect in the low quality region is embedded by the  $F_{shear}$  function (equivalent to  $F_{cap}$ ).

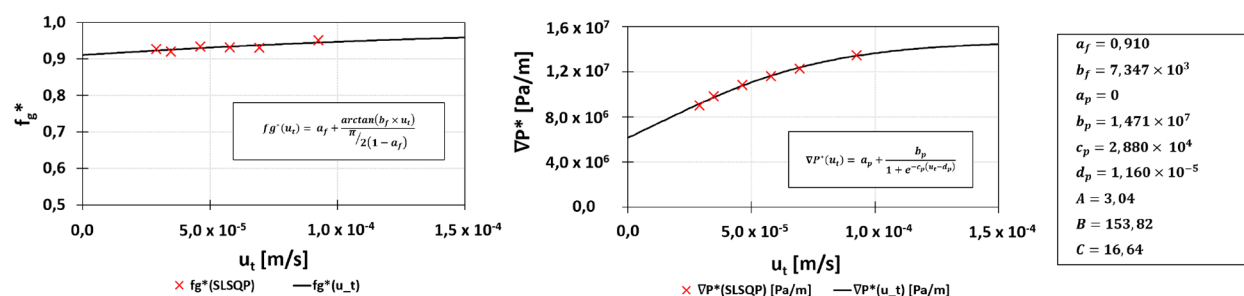
One significant contribution is the new definition of the  $F_{shear}$  function that is here linked to the Ostwald law and thus gains physical meaning. Indeed this modifies the formula and



**Figure 7.** Parameters  $f_g^*$  and  $\nabla P^*$  coming from the optimization process plotted against  $u_t$  with their dedicated curve fits and expressions. Red crosses come from the optimization process, and straight black lines represent fitted  $f_g^*(u_t)$  and  $\nabla P^*(u_t)$  subfunctions. Parameters  $A$ ,  $B$ , and  $C$  from the  $F_{shear}$  function are also given. This figure gathers all information needed to cover all foam injection cases within the range of  $u_t$  studied.



**Figure 8.**  $\nabla P = f(f_g)$  curves fit to the Osterloh et al.<sup>10</sup> experimental data. Red crosses represent experimental points and were determined using  $u_g = f(u_w)$  curves with pressure contours. Black curves are obtained through parameter functions of  $u_t$  and the optimization schema presented in Figure S2 in the Supporting Information. We set  $epdry = 2 \times 10^4$  for all  $u_t$  values.



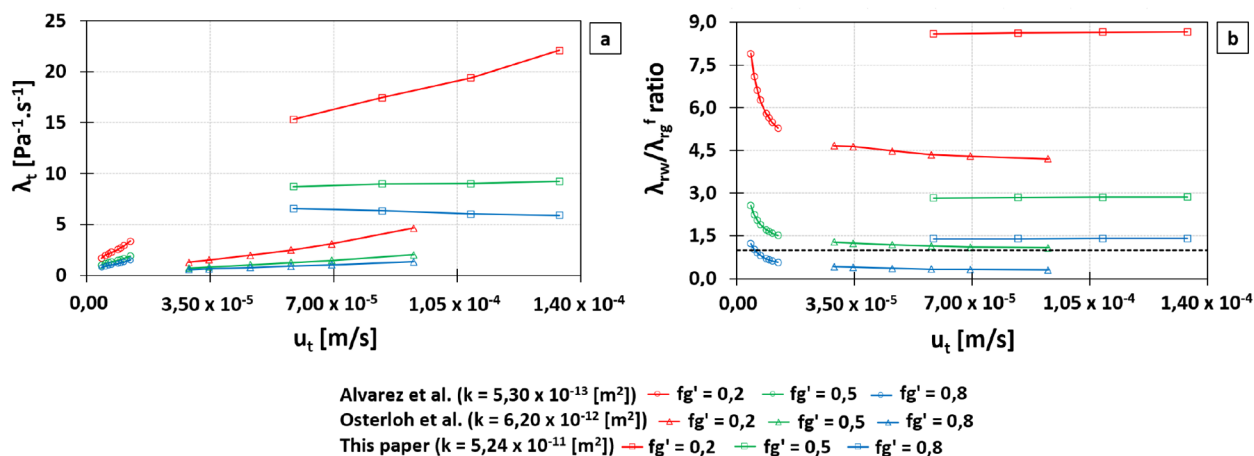
**Figure 9.** Parameters  $f_g^*$  and  $\nabla P^*$  coming from the optimization process plotted against  $u_t$  with their dedicated curve fits and expressions. Red crosses come from the optimization process, and straight black lines represent fitted  $f_g^*(u_t)$  and  $\nabla P^*(u_t)$  subfunctions. Parameters  $A$ ,  $B$ , and  $C$  from the  $F_{shear}$  function are also given. This figure gathers all the information needed to cover all foam injection cases within the range of  $u_t$  studied.

leads to a value of  $F_{shear}$  higher than one, but this is compensated by fitting the other parameters valid for the whole range of  $u_t$  values. However, the low quality shear behavior is also dependent on the  $u_t$  value as shown in Figure 1.

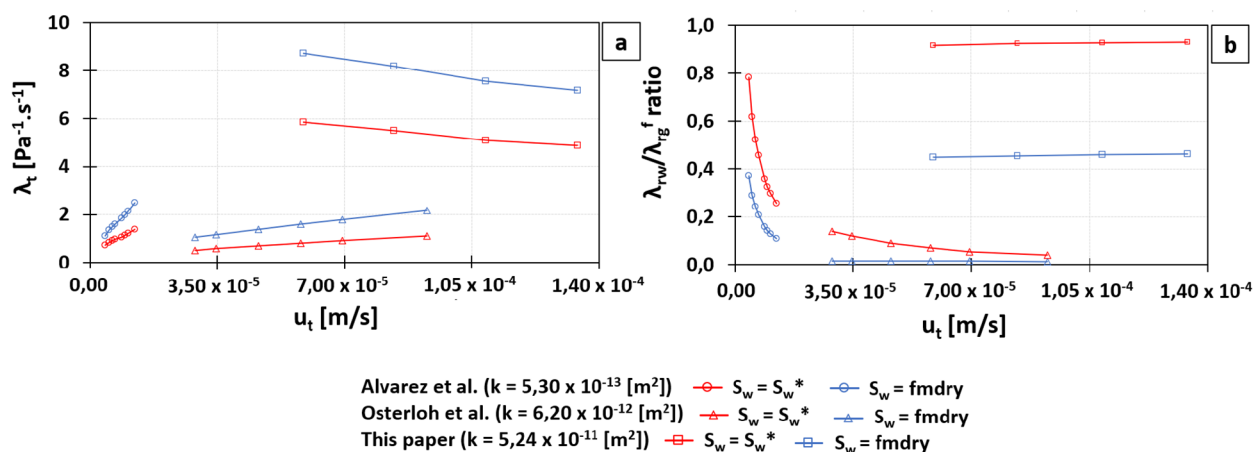
Our results show that a typical shear thinning occurs with  $u_t$  variation. This effect is evidenced at the transition point. Moreover, in the low quality regime another shear effect is present: at  $f_g = 0.5$  the pressure gradient is higher than the average of  $f_g = 0$  and  $f_g = 1$  (i.e., Newtonian behavior);

therefore, the foam quality effect is a shear thickening below  $f_g^*$ . The Ostwald law parameters show that the intensity of this effect is also dependent on  $u_t$ .

**Radial Effect on the Total Superficial Velocity and  $u_t$  Functions.** All experiments demonstrated the need to consider the total superficial velocity effect on the foam behavior. Indeed, foam is always injected around a well bore, which leads to a rapid decrease of the total superficial velocity with the distance from the injection point. Interestingly, the variation of the pressure gradient with velocity is more



**Figure 10.** (a) Total mobility  $\lambda_t$  plotted against  $u_t$  for all experiments studied in this paper. Plots were done for three  $fg'$  values within the low quality regime. Permeability values are also given for the three studied cases. (b) Mobility ratios  $\lambda_{rw}/\lambda_{rg}^f$  plotted against  $u_t$  for all experiments studied in this paper. Plots were done for three  $fg'$  values within the low quality regime. The dotted black line corresponds to the value  $\lambda_{rw}/\lambda_{rg}^f = 1$  when both mobilities are equal.



**Figure 11.** (a) Total mobility  $\lambda_t$  plotted against  $u_t$  for all experiments studied in this paper. Plots were done for  $S_w = S_w^*$  and  $S_w = fmdry$ . Permeability values are also given for the three studied cases. (b) Mobility ratios  $\lambda_{rw}/\lambda_{rg}^f$  plotted against  $u_t$  for all experiments studied in this paper. Plots were done for  $S_w = S_w^*$  and  $S_w = fmdry$ .

pronounced in the presence of environmentally friendly surfactants (our experiments). This may suggest that the foam strength will decrease with distance from the well and the radius of action of the foam may be smaller than expected from lab experiments. Lee et al.<sup>22</sup> introduced the fact that the relative reduction in mobility generated by the presence of foam may depend on the permeability medium. In order to analyze this effect, the variations of the total mobility for the different experiments are illustrated in Figure 10.

In order to understand the origin of the total mobility variations, the equations of the phase mobilities must be detailed. Indeed, even though foam is composed of two phases (liquid and gas), in the proposed model of the original STARS one reproduces the steady state foam behavior only through the modification of the gas phase equation. The following two equation system use the generalized Darcy approach:

$$\begin{cases} u_g = u_g^f = -\lambda_{rg}^f k \nabla P \\ u_w = u_t(1 - f_g) = -\lambda_{rw} k \nabla P \end{cases} \quad (20)$$

with  $u_g$  and  $u_w$  as the gas and liquid superficial velocities and  $\lambda_{rg}^f = \frac{k_{rg}^{FM}}{\mu_g}$  and  $\lambda_{rw} = \frac{k_{rw}}{\mu_g}$  their mobilities, respectively. The total velocity is given by

$$u_t = -(\lambda_g^f + \lambda_w) k \nabla P \quad (21)$$

It appears from eq 21 that both fluid mobilities are implied to express  $\nabla P$  vs  $u_t$  with foam. Remember here that  $F_{dry}$  is equal to one or closer within the low quality regime; thus, FM is only influenced by the  $F_{shear}$  subfunction. At first, as it is the objective of foam injection, Figure 10a shows that increasing the foam quality within the low quality regime reduces the total mobility  $\lambda_t$ . Second, it appears that the total mobility is influenced by  $u_t$  for all foam qualities in the Alvarez et al. experiments, i.e., at low velocities and permeability like in a deep reservoir. However, for the Osterloh et al. data and our experiments, this effect exists only at very low quality and is not supposed to be used in a field injection. Thus, curiously, in high permeability media, although the foam parameters are influenced by  $u_t$ , the total mobility in this regime is constant for



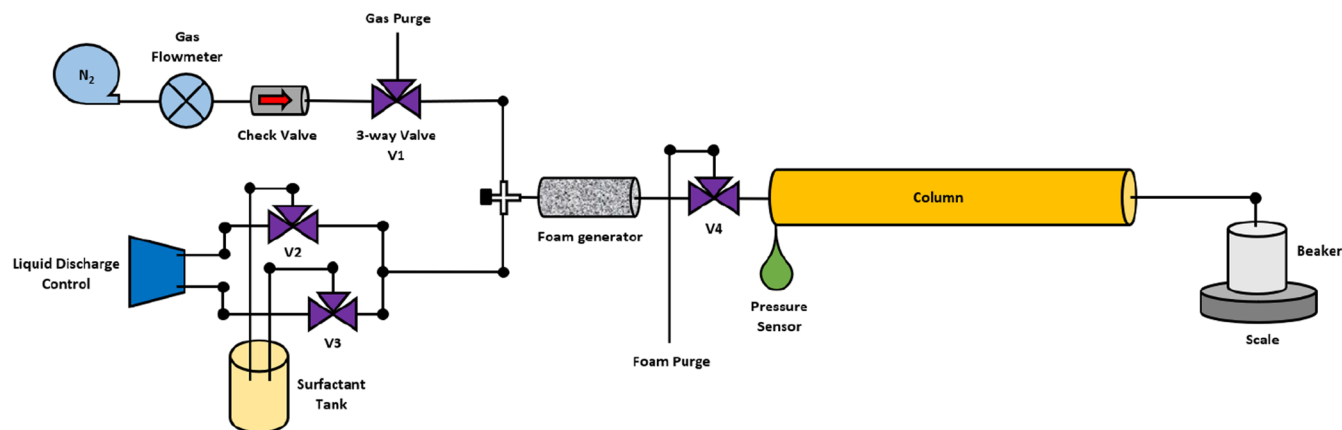


Figure 12. Schematic of the experimental apparatus.

one  $f_g$  value. This may arise from the fact that at  $f_g$  lower than  $f_g^*$  the role of water becomes prevalent.

The role of the mobilities of each phase is shown in Figure 10b, which presents the ratio of the water to the gas mobilities for the same conditions as previously. Again the Alvarez et al. experiments show different behavior than the others, with a ratio rapidly decreasing with velocity, while the other experiments show almost no  $u_t$  dependence. Moreover, for almost all experiments the ratio is above 1, showing, as we outlined above, that the role of water in the total mobility is the most important. So, in this regime, the mobility being linked to water behavior is not dependent on the total velocity.

In addition, we present in Figure 11a,b similar plots using the transition point and the  $S_w = f_{mdry}$  point to have a view on the high quality regime. Even if the high quality regime was not as detailed as the low quality regime, the fit in this area is still good. Figure 11a shows an increase of  $\lambda_t$  from  $S_w^*$  to  $f_{mdry}$  as expected. Our experimental results show a decrease of the total mobility with  $u_t$  when the two others from the literature present an increase. We can notice here that this increase is more pronounced for the Alvarez et al. experiments, which have the lowest permeability. The mobility ratios (Figure 11b) are constant against  $u_t$  in our experiments and decrease with  $f_g$  within the high quality regime for the other experiments.

## CONCLUSION

In summary, we propose an approach to obtain the parameters of a modified STARS foam model type in an in situ environmental remediation context with a radial effect. This modified model presented here takes under consideration both the role of the foam quality and  $u_t$  on foam behavior by using an Ostwald–de Waele derived law as an  $F_{shear}$  subfunction. This new approach, applied to various  $u_t$  values and quality scans, demonstrates its ability to reproduce foam behaviors. Instead of using only one point to make the  $u_t$  dependence (often the  $f_g^*$  one) as shown in the literature, we proposed here to cover all the low quality regime of each quality scan to enhance the model. This model provides an accurate scan of all studied cases in this paper following each  $\nabla P = f(f_g)$  shapes in both quality regimes. Moreover, a semiautomated process was set to estimate parameters of  $u_t$  functions using experimental data of multiple and dissimilar cases. In order to have an accurate fit, a certain amount of data is needed, especially in the low quality regime, to capture precisely the foam behavior. We also showed that the same mathematical formulation of the

relationships between the model parameters and  $u_t$  can be used for each experimental set whatever the studied case, only modifying the values of the subparameters. The subparameter values seem to depend on both the medium and the surfactant, with no simple relationship with these factors at present.

## EXPERIMENTAL SECTION

Several new 1-D foam flooding experiments at various total superficial velocities  $u_t$  and foam qualities  $f_g$  were carried out to complement previous experiments through the literature.<sup>9,10</sup>

**Material and Methods.** All the experiments were carried out in unconsolidated sand packs (MI 0.4/0.9  $S_iO_2$  99.1%). Sand packs had a diameter of 4.5 cm and a length of 27.7 cm. The permeability to water was calculated from a Darcy test for each column before flooding experiments. An average permeability of  $5.24 \times 10^{-11} \text{ m}^2$  with a standard deviation of  $1.37 \times 10^{-11} \text{ m}^2$  was obtained for the 5 columns. Saponin, which is naturally derived from plants, was used as a nonionic, biodegradable, and renewable surfactant in an environmental burden reduction context.<sup>23</sup> Tap water was used as the liquid phase, and the critical micelle concentration of the saponin (CMC) was previously determined through the pending water drop test<sup>24</sup> with a value of 0.062 wt %. Nitrogen ( $N_2$ ) was used as the gas phase during the experiments.

**Experimental Setup.** A schematic of the apparatus is presented in Figure 12. The same column was used for each experiment (sand was replaced in it) and placed in a horizontal position with injection from the left. A pressure tap was located next to the injection point within the porous medium, and the pressure was recorded by an Idroscan AEP transducer with a range of 0–5 bar and a resolution of 1 mbar. A foam generator was used in order to improve the gas and liquid mixture before the entry into the porous medium. This component has an internal diameter of 3.4 cm and a length of 12.5 cm and was filled by 2 mm glass beads.

The liquid and gas were coinjected at defined proportions before entering the foam generator. The gas injection was controlled by a Bronkhorst gas thermal mass flow meter with a range of 0.4–20 mL/min. The liquid discharge control was performed by a dual syringe injector (60 mL volume) linked to a stepper motor. This device avoids syringe reloading and, thus, injection discontinuity by a simultaneous charge and discharge of syringes. A beaker was used to collect the effluent, and a scale was used to check the liquid flow equality between inlet and outlet. This equality coupled to the stabilization of

the pressure value indicates that the steady state regime was reached.

**Experimental Procedures.** All experiments were carried out at room temperature (20 °C) with an atmospheric outlet pressure. Each column was filled with sand and tap water following the same procedure, which consists of alternated small additions of water and sand interspersed with tamp operations. The porosity was deduced from the total water volume added to fill the column and its dimensions.

The foam generator was placed vertically (inlet downward), and tap water was injected with the foam purge active (see 3-way valve V4, Figure 12) to release the air, and then the foam generator was placed horizontally, after which the foam purge was closed and the column was connected to the apparatus keeping the water flow to avoid air bubbles into pipes. Then, a Darcy test was done to estimate the water permeability of the sample.

After this step, the column and the foam generator were filled with surfactant solution at 10 CMC at one pore volume to prevent adsorption of the surfactant by the porous media during foam injection. The liquid discharge control and the gas flow meter were set to the desired flow value, using the gas purge. As soon as the gas flow was stabilized, the gas purge was closed to start foam injection into the foam generator, keeping the foam purge activated. When the steady state was reached into the foam generator, the foam injection started in the column for a minimum of 3 VP of both fluids.

We assume that the steady state is reached when the pressure drop held constant over time. The bubbles dynamic (creation, deformation, and destruction) leads to pressure oscillations even in the steady state. The outlet liquid flow rate was compared to the inlet one, and their equality helped to confirm that steady state was reached. The same column was used for a new injection at the same foam quality with a lower total superficial velocity. When the effluent of the foam purge was stabilized, the next flooding experiment was started by switching it.

At least 20 flooding experiments were done combining different total superficial velocities and foam qualities. Table 1 summarizes the experimental conditions of each test and their average pressure gradient responses once steady state has been reached.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.1c04899>.

Figure S1 presents the  $F_{shear}$  subfunction used to cover the low quality regime by modifying the  $fmmob$  value, and Figure S2 presents the detailed flowchart of the fitting method presented in this paper (PDF)

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### Notes

The authors declare no competing financial interest.

## ■ NOMENCLATURE

$\lambda_f^f$	Relative mobility of the gas phase in the presence of foam (Pa·s) <sup>-1</sup>
$\lambda_t$	Total mobility (Pa·s) <sup>-1</sup>
$\lambda_{rg}$	Relative mobility of the gas phase (Pa·s) <sup>-1</sup>
$\lambda_{rw}$	Mobility of the water (Pa·s) <sup>-1</sup>
$\mu_g$	Dynamic viscosity of the gas phase (Pa·s)
$\mu_w$	Dynamic viscosity of the water (Pa·s)
$\mu_{app}^f$	Apparent viscosity of the foam (Pa·s)
$\nabla P$	Pressure gradient (Pa·m <sup>-1</sup> )
$\rho_g$	Density of the gas phase (kg·m <sup>-3</sup> )
$epcap$	Parameter that captures shear thinning behavior in the low quality regime
$epdry$	Parameter that controls the abruptness of foam collapse
$f_g$	Foam quality
$f_g^*$	Normalized position within the low quality regime
$f_g^*$	Foam quality at the transition point
$F_i$	additional factors from the STARS (CMG) model
$f_{cap}$	The smallest capillary number expected to be encountered
$FM$	Mobility factor from the STARS (CMG) model
$fmdry$	Critical water saturation value at which foam starts to collapse
$fmmob$	Reference gas-mobility-reduction factor for wet foams
$g$	Gravitational force (m·s <sup>-2</sup> )
$k$	Permeability (m <sup>2</sup> )
$k_{rg}$	Relative permeability of the gas phase
$k_{rg}^0$	Brooks and Corey constant for the gas phase
$k_{rw}$	Relative permeability of the liquid phase
$k_{rw}^0$	Brooks and Corey constant for the water
$n_g$	Brooks and Corey gas phase exponent
$n_w$	Brooks and Corey water exponent
$N_{Ca}$	Capillary number
$RF$	Resistance factor
$S_e$	Effective water saturation
$S_w$	Water saturation
$S_w^*$	Critical water saturation value at which foam starts to collapse
$S_{g,r}$	Residual gas saturation
$S_{w,r}$	Residual water saturation
$u_g$	Superficial velocity of the gas phase (m·s <sup>-1</sup> )/(m·d <sup>-1</sup> )
$u_t$	Total superficial velocity (m·s <sup>-1</sup> )/(m·d <sup>-1</sup> )
$u_w$	Superficial velocity of the water (m·s <sup>-1</sup> )/(m·d <sup>-1</sup> )

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