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INFLUENCE OF PHYSICAL-CHEMICAL PARAMETERS ON FOAM FORMATION AND DECAY

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Abstract. *In the oil industry the occurrence of foams can be beneficial, for example during the injection of gas to improve oil recovery. However, in other stages of oil production it can be harmful, as in the separation of phases, where the equipment is designed only for gas, water and oil, and the presence of foam may generate problems such as carry-over, carry-under, decrease of volume capacity and incorrect level measurement. Thus, it is important to know the behavior of foams structures with respect of some parameters to understand when it will occur. Knowing this, an experimental apparatus has been developed to assess the behavior of foam formation and decay observed in ISO14 oil + Sodium Lauryl Ether Sulphate + water mixture according to parameters of temperature (20-40°C), pressure (1-10 bar) and gas injected (nitrogen and methane). A simplified mathematical model for formation and decay will be suggested and validated with experimental data obtained.*

Keywords: *foam, formation, decay, oil industry*

1. INTRODUCTION

Foams are dispersed systems with small gas bubbles in a liquid continuous phase that may be stabilized by surfactants (Daltin, 2011). Foams can be found in several day-to-day situations, from solutions used for cleansing to safeguarding foams such as those used in fire extinguishers. However, in addition to valuable foams, undesired foams such as those that can be formed during oil/gas separation in petroleum industry can also be found.

In the oil industry, the occurrence of foams can be beneficial, such as gas injection in improving oil recovery. However, it can be harmful in other stages of oil production, as in the phase separation.

Although foams are thermodynamically unstable structures, they may not collapse due to some intrinsic properties such as: surface elasticity, viscous drainage and reduced gas diffusion between the bubbles. These properties can give rise to several problems caused by the formation of this structure in gravitational separators, such as: the reduction in the capacity of the separators due to the increase in the residence time required for complete separation and due to the large volume occupied by the foam. In addition, foaming contributes to incorrect measurement of the level of the separator interfaces, another very recurrent problem. Problems such as oil carry-over in the gas line can also occur, which can cause contamination of this line, in addition to hydraulic shim in the gas compressors, or even gas carry-under in the oil line causing, consequently, cavitation in the gas pumps (Shaban, 1995; Poindexter *et al.*, 2002; Zaki, Poindexter and Kilpatrick, 2002; Chen *et al.*, 2018).

There are some factors that can influence the formation of this type of foam, including: temperature, pressure, type of continuous fluid, type of injected gas, type of defoamer used, gas injection speed, among other factors. Therefore, it is necessary to study these factors in order to determine which ones can primarily influence the formation of foam by gas dispersion.

The aim of this work is to develop an experimental and theoretical study to evaluate the influence of several factors in the formation of dispersed foam. Among the factors to be analyzed are temperature, pressure and type of injected gas. To assess the impact of each of the parameters mentioned above, an experimental apparatus was built in order to measure the gas injection rate, as well as the height of the foam layer formed. In addition, some parameters will be evaluated, which can influence the formation and decay of the foam, which are varied within the following ranges: temperature (20-40°C), pressure (1-10 bar) and type of injected gas (nitrogen and methane). Thus, it can be verified their influence on the foamability and stability of the ISO14 mineral oil foam + Sodium Lauryl Ether Sulfate + Water.

In addition, this work aims to present a simplified mathematical model that will be validated with the results obtained experimentally. This model will be used to complement the experimental work proposed here.

2. METHODOLOGY

The experimental methodology applied to the project will be carried out in order to obtain relationships between the parameters to be analyzed (temperature, pressure and type of gas injected) and the formation and stability of the foam column. The desired data will be obtained through an experimental apparatus, composed of a foaming cell and several other equipment that will provide the control of the other variables.

2.1 Experimental apparatus and procedure

Figure 1 illustrates a simplified schematic drawing of the apparatus designed for foaming using the dispersed method.

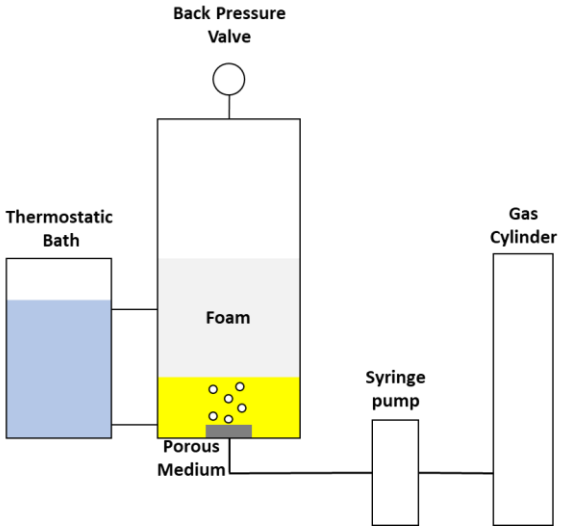


Figure 1. Simplified schematic apparatus.

Before starting the experiments, it will be necessary to inject the mixture oil + sodium lauryl ether sulfate + water through the injection line at the top of the test cell. Then, the cell will be pressurized with the test gas, up to the pressure of interest, with this, the influence of pressure on the tests can be evaluated. After this is done, the stabilization time of the gas-liquid mixture in the cell must occur. This time should be long enough for the gas to be solubilized in the liquid to be evaluated, and for the entire system to be in equilibrium. At the same time as this occurs, the thermal bath must be turned on at the desired temperature, and the system is expected to enter into thermal equilibrium. At this moment, the image acquisition must be started, it will allow the verification of the height of the foam column formed, as well as its decay time after the gas injection is turned off. In order for the pressure not to fluctuate during the experiment, the Back-Pressure valve must be set to the pressure of interest. Therefore, this equipment will regulate the pressure whenever it exceeds the established pressure. With all these parameters adjusted, the gas injection must then be started, which will cause the formation of the desired foam column. For this, the required flow rate in the syringe pumps must be adjusted. Gas flow must occur until such time as the height of the foam column becomes stable. From this moment on, the foamability of the fluid can be measured. Thus, the gas injection must be turned off and the time for the complete decay of the foam starts to be counted. With the given time and the intermediate foam volume measurements, a decay curve can be plotted in which the collapse slope will be analyzed to determine the stability of the foam formed.

2.2 Mathematical model for formation and decay

2.2.1 Formation

In this subchapter, an approach based on the work of (PILON; G. FEDOROV; VISKANTA, 2002) will be presented, who developed a mathematical model for the prediction of foam layer thickness as a function of time for the case of foams formed by gas injection (pneumatic test).

The model will be based on the following assumptions:

- The problem is one-dimensional and transient;
- Wall effects are negligible;
- The foam is isothermal;
- During transient formation, there will be no bursting on the foam surface.

The foam will grow until a time when the steady state will occur, at this time the height will be stable until the gas injection is stopped, thus the steady state height will be called H_∞. The time for this to happen will be called τ.

Thus, according to the assumptions made above, we will have the conservation of gas phase mass in the control volume, given as follows:

$$\frac{dm_g(t)}{dt} = \rho_g jA \tag{1}$$

where ρ_g is the density of gas phase, j is the superficial gas velocity, A is the cross-sectional area of the compartment, m_g is the mass of gas in the system and t is the time.

Also, it is possible to write the total mass of gas retained in the foam as a function of porosity as follows:

$$m_g(t) = \int_0^{H(t)} \rho_g \phi(z,t) A dz \tag{2}$$

We still know that the average foam porosity will be given by the following equation:

$$\bar{\phi}(t) = \frac{1}{H(t)} \int_0^{H(t)} \phi(z,t) dz \tag{3}$$

where $H(t)$ is the height of the foam column as a function of time, $\bar{\phi}(t)$ is the average porosity of the foam and $\phi(z,t)$ is porosity as a function of position and time.

After some mathematical manipulation it can be found the following equation:

$$H(t) = \frac{m_g(t)}{\rho_g A \bar{\phi}} \tag{4}$$

However, you can still integrate equation (1) as follows, then we obtain:

$$m_g(t) = \rho_g jAt \tag{5}$$

Substituting the expression found in equation (5) into (4), we obtain:

$$H(t) = \frac{\rho_g jAt}{\rho_g A \bar{\phi}} \tag{6}$$

Simplifying:

$$H(t) = \frac{jt}{\bar{\phi}} \tag{7}$$

This is the simplest option one can find to calculate the height of the foam layer as a function of time for foams formed through gas injection.

2.2.2 Decay

The decay model developed in this section is based on the model developed by (Fortkamp, 2014), but with some simplifications.

Based on visual observations of foam decay, the drainage rate can be modeled as being directly proportional to the foam height given the following expression (Fortkamp, 2014):

$$\dot{m}_g = m_0'' A \left[\exp\left(C_4 \frac{t}{\tau} \right) \right] \tag{8}$$

where $\dot{m}_g$ is the foam drainage rate, m_0'' is the proportionality term, A is the cross-sectional area, C_4 is an empirical constant, t is the time and τ the characteristic time.

However, it can be still writing the proportionality time as follows:

$$m_0'' = C_3 \bar{\rho} \sqrt{g H_f} \tag{9}$$

where C_3 is an empirical constant (equivalent to a coefficient of discharge or flow, i.e., related to the foam drainage velocity), $\bar{\rho}$ the mean density, g the gravity and H_f the foam height.

The variable τ can be defined as the ratio between the characteristic height and the characteristic velocity that will be defined later on:

$$\tau = \frac{H_c}{U_D} \tag{10}$$

To define the characteristic velocity, that is, the surface velocity of the liquid in the Plateau channels, Fortkamp used an analogy with porous media, determining such velocity from Darcy's Law for flows at low velocities. Thus, according to (Kaviany, 1995):

$$-\frac{dP}{dz} = \frac{\mu_L}{K} U_D \tag{11}$$

where $\frac{dP}{dz}$ is the hydrostatic pressure gradient, μ_L the liquid viscosity and K the porous media permeability.

Assuming the foam is in mechanical equilibrium, the hydrostatic pressure gradient can be written as follows:

$$\frac{dP}{dz} = -\bar{\rho} g \tag{12}$$

By substituting equation (12) into (11) an expression for the surface velocity can be obtained:

$$U_D = \bar{\rho} g \frac{K}{\mu_L} \tag{13}$$

It is still necessary to obtain a correlation for the foam permeability factor. Thus, the Carman-Kozeny model (Kaviany, 1995) can be used:

$$K = \frac{(1-\phi)^3 4r^2}{180\phi^2} \tag{14}$$

2.3 Results and discussions

2.3.1 Experimental data: Temperature

In order to evaluate the influence of the temperature parameter on the formation and decay of foams, several tests were carried out varying this parameter between 20 and 40°C. In addition, the parameters of foamability, collapse inclination and collapse time were calculated so that it was possible to evaluate these experimental points and further discussion of the results obtained.

The following figures, Figure 2 and Figure 3, show the experimental results obtained for the formation and decay of foams for nitrogen and methane, respectively:

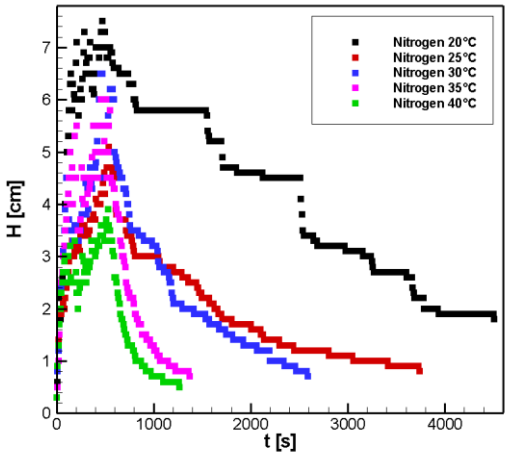


Figure 2. Experimental results for temperature influence with nitrogen gas

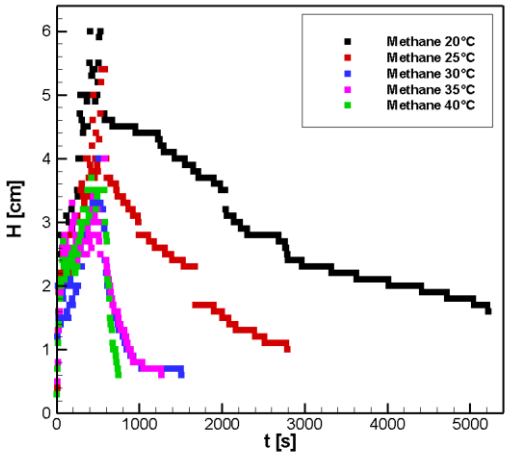


Figure 3. Experimental results for temperature influence with methane gas

Evaluating the graphs qualitatively, one can observe a very clear trend of increasing decay rate as temperature increases for both gases. This behavior was expected, as several other authors had previously verified such behavior, such as: (Buckingham, 1970; Indrawati *et al.*, 2008; Farajzadeh, Krastev and Zitha, 2009; Fortkamp, 2014; Kapetas *et al.*, 2016; Jackman *et al.*, 2018; Abd Rahim, Saaid and Umar, 2019; Delahaije, Lech and Wierenga, 2019) among several other authors.

This decrease in the stability of the foam column formed can be explained by several phenomena that occur in the foam structure due to an increase in temperature. However, the most common is due to the decrease in viscosity as a consequence of the increase in temperature. This decrease in viscosity generates an increase in the flow velocity through the Plateau borders, consequently the liquid film between the bubbles tends to become thinner in a faster way, which ends

up contributing to phenomena such as bursting and bubble coalescence. These phenomena are directly related to foam collapse, so there is an increase in decay speed, that is, a decrease in foam stability.

To quantitatively evaluate the results, the parameters of foamability, collapse slope and foam collapse time were calculated. These data will be presented in the following table:

Table 1. Quantitatively results for foam formation and decay: temperature

Experimental point	Foamability	Collapse slope	Collapse time	Experimental point	Foamability	Collapse slope	Collapse time
	Nitrogen				Methane		
P1	22.63	-0.0012	1990	**P16**	16.77	-0.0010	2240
P2	13.83	-0.0019	960	**P17**	15.03	-0.0019	810
P3	17.33	-0.0044	530	**P18**	9.83	-0.0119	190
P4	16.87	-0.0144	160	**P19**	9.47	-0.0090	160
P5	10.57	-0.0138	160	**P20**	10.53	-0.0279	60

Through the results presented in Table 1, two main points can be evaluated.

First, there is a trend towards reduced foamability for both nitrogen and methane with the exception of points P2 and P20. This reduction in foamability due to the increase in temperature can also be explained by the increase in the flow velocity through the Plateau borders. This is because the growth of a foam column is a competition between the phenomena that make this structure grow and those that cause the foam to decay. With the increase in temperature and consequently an increase in the drainage speed, the forces related to the decay of the foam end up standing out, so the foam ends up not growing as much as for lower temperatures, which goes against what was observed by (Fortkamp, 2014)

Furthermore, it can be observed that both the collapse slope and the collapse time tend to increase at higher temperatures. This is in line with what was qualitatively observed through the graphs, that is, the higher the temperature, the lower the foam stability, a fact that was also observed by several other authors in the literature.

2.3.2 Experimental data: Pressure

The influence of the pressure parameter was also evaluated through pneumatic foam formation and decay tests. In this case, six tests were performed for both gases and pressures ranging between 1 and 10 bar. The following figures, Figure 4 and Figure 5, show the results obtained through the experiments:

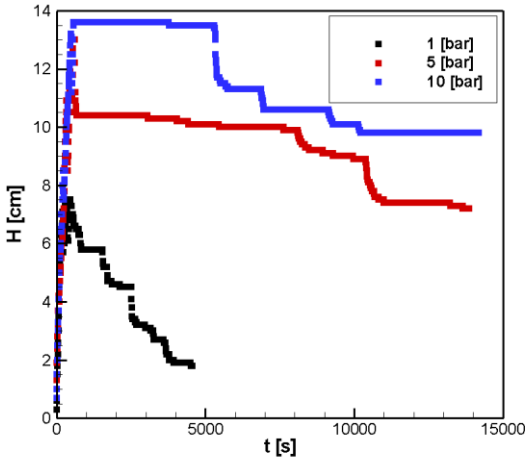


Figure 4. Experimental results for pressure influence with nitrogen gas.

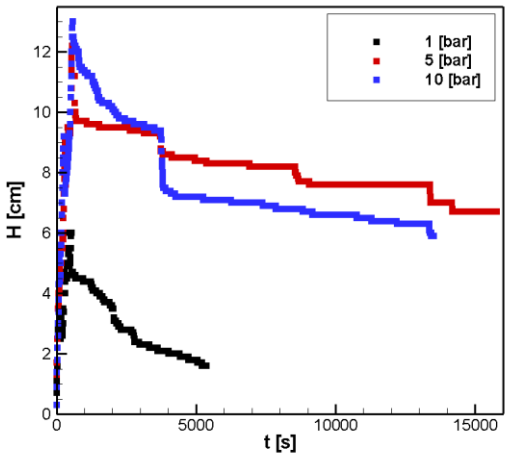


Figure 5. Experimental results for pressure influence with methane gas.

The influence of such parameter is quite controversial in the literature, as in addition to the influence of pressure in the system, the type of gas also influences the behavior of the foam during its decay.

For foams formed by nitrogen, a clear increase in stability can be observed with increasing pressure. This can be explained by several phenomena linked to pressure in the foam structure. Among these phenomena, the reduction of bubbles that form the foam can be highlighted. This reduction causes an increase in stability, as smaller bubbles are known to have longer life before collapse. Furthermore, a structure composed of smaller and more uniform bubbles tends to be more stable, because some phenomena such as Ostwald Ripening and bubble coalescence become less accelerated. It is still possible to link such an increase in stability to a decrease in the size of the Plateau borders. Due to a decrease in the bubbles present in the structure, the Plateau borders, consequently, have smaller dimensions, thus the flow through these channels becomes slower, which generates a decrease in the foam decay rate, that is, a significant increase of its stability.

However, evaluating the foam formed by methane, we have a slightly different behavior. An increase in stability between 1 and 5 bar can be observed, where the foam stability clearly increases with increasing pressure. However, when it is increased the pressure from 5 to 10 bar, a decrease in this stability can be observed. A similar behavior to this had already been observed by a number of authors listed in the article by (Szabries, Jaeger and Amro, 2019) for CO2 foams. This fact can be explained due to an increase in the solubility of the gas with increasing pressure, in which case the foam would tend to decay more quickly, as part of the gas present in this structure would solubilize in the liquid, causing some phenomena such as Ostwald Ripening and bubble coalescence become more accelerated, thus causing a decrease in stability.

2.3.3 Experimental data: type of gas

Finally, the influence of the type of gas injected on the formation and decay of foams was evaluated. For this, all experimental points were performed for both nitrogen and methane. The figures, Figure 6 and Figure 7, present the results obtained for a few cases the other results are presented in table 2:

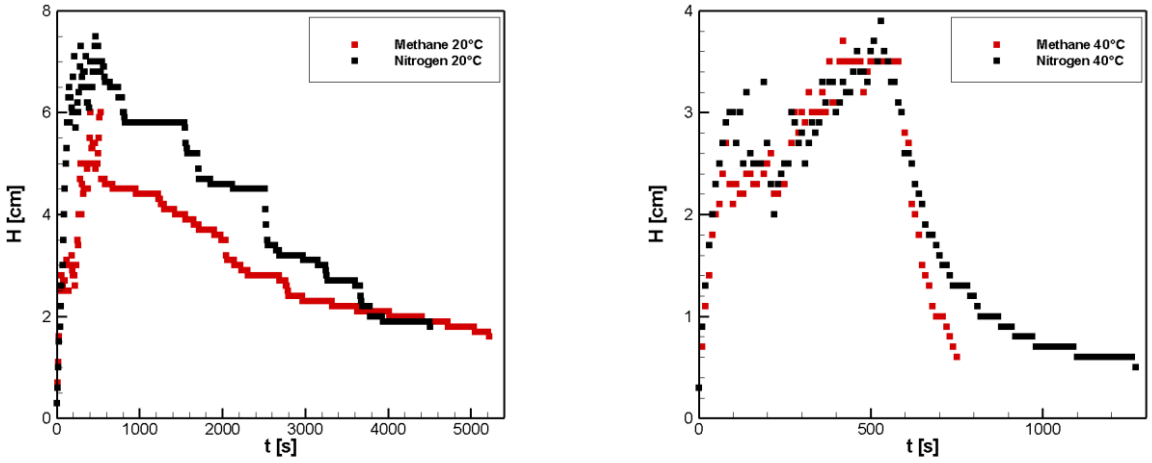


Figure 6. Experimental results for the influence of type of gas injected assessed for temperatures of 20 and 40°C.

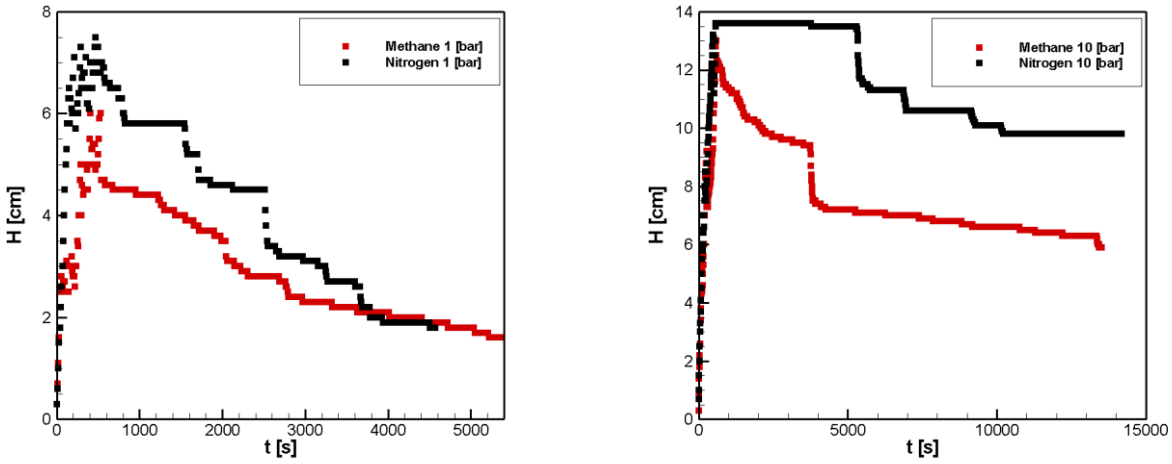


Figure 7. Experimental results for the influence of type of gas injected for pressures of 1 and 10 bar.

As can be clearly seen, there is a strong tendency for methane foams to grow less and decay faster compared to nitrogen. This can be explained by the greater solubility of methane. This characteristic of the gas ends up influencing several phenomena responsible for the formation and decay of the foam. First, gases with higher solubility will make it easier for phenomena such as Ostwald Ripening and bubble coalescence to happen, because the gaseous mass transfer ends up accelerating these processes. The increase in these phenomena will cause a decrease in the size of the foam column, as there is greater competition between the forces of growth and decay of this structure. Furthermore, such

phenomena will accelerate the foam decay process, as they will increase the size of the bubbles, causing Plateau borders to assume a larger shape and, consequently, there is an acceleration of the flow velocity through these regions. Furthermore, the increase in the aforementioned phenomena will contribute to a more prominent bursting phenomenon which will accelerate the decay of the foam formed. Such behavior has already been observed by (Hartland, Bourne and Ramaswami, 1993) where gases with greater solubility tended to form smaller foam columns and accelerate the decay process, so the results presented here are in line with those in the literature.

It is still possible to evaluate the influence of the type of gas through the calculation of Foaminess, this variable represents the amount of foam formed by the ratio of injected gas, that is, the higher the Foaminess, the more foam a certain type of gas can form using the same injection flow rate. The results of the Foaminess calculation will be presented in the following table:

Table 2. Quantitatively results of Foaminess: influence of type of gas injected.

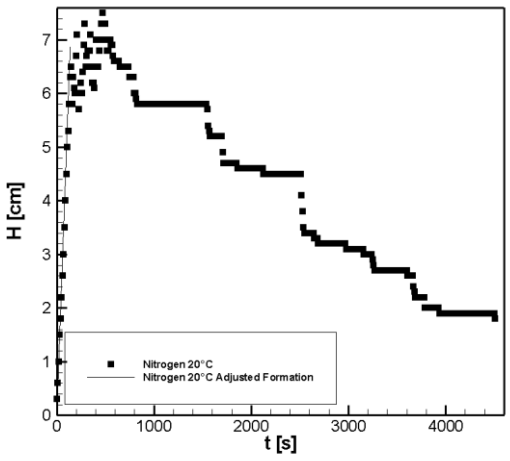
Experimental point	Steady-state foam volume	Gas rate	Foaminess	Experimental point	Steady-state foam volume	Gas rate	Foaminess
	Nitrogen				Methane		
P1	139.21	50	1,6705E+08	**P16**	104.65	50	1,2559E+08
P2	87.38	50	1,0485E+08	**P17**	94.44	50	1,1333E+08
P3	107.99	50	1,2959E+08	**P18**	63.81	50	7,6577E+07
P4	105.24	50	1,2629E+08	**P19**	61.65	50	7,3985E+07
P5	68.13	50	8,1760E+07	**P20**	67.94	50	8,1525E+07
P6	139.21	50	1,6705E+08	**P21**	104.65	50	1,2559E+08
P7	225.02	50	2,7002E+08	**P22**	223.05	50	2,6766E+08
P8	245.83	50	2,9500E+08	**P23**	226.59	50	2,7191E+08

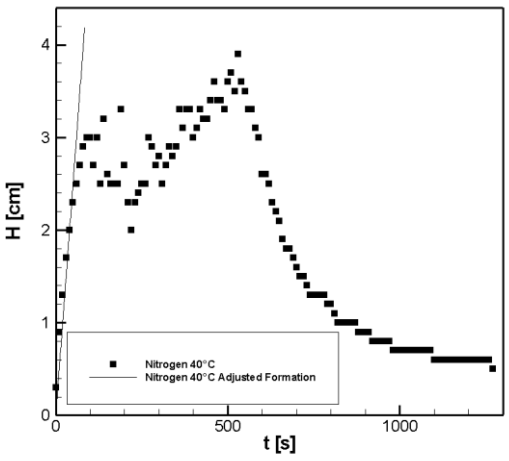
Using the table presented, it can be observed that, with the exception of point P2 and P17, the other pairs comparing nitrogen and methane, that is, P1 and P16, P3 and P18 and so on, all nitrogen points have higher Foaminess. This means that the quantitative results presented here are in agreement with the graphical analysis made earlier, and only reinforces the fact that foams formed by methane tend to grow less than those formed by nitrogen gas.

2.3.4 Mathematical model: Formation

In this subchapter, the results obtained through mathematical modeling based on (Pilon, G. Fedorov and Viskanta, 2002) will be presented.

The results obtained for formation are presented as follow:





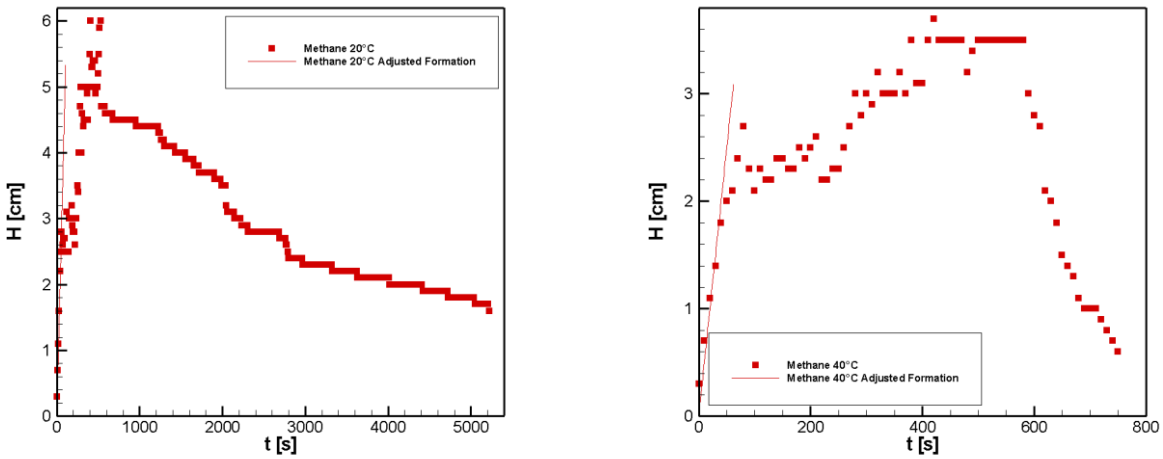


Figure 8. Formation mathematical model results with adjusted FiM.

Table 3. Quantitatively results for formation model.

	Temperature	FiM	Experimental height	Modeling height	Height error	Experimental time	Modeling time	Time error
	Nitrogen							
P1	20	0.8866	7.09	6.884	**2,909%**	210	138	**34%**
P2	25	0.8986	4.45	5.587	**25,547%**	430	112	**74%**
P3	30	0.9106	5.50	4.789	**12,933%**	430	96	**78%**
P4	35	0.9226	5.36	4.390	**18,104%**	380	88	**77%**
P5	40	0.9346	3.47	4.190	**20,753%**	450	84	**81%**
	Methane							
P16	20	0.8797	5.33	5.337	**0,139%**	400	107	**73%**
P17	25	0.8917	4.81	4.090	**14,961%**	540	82	**85%**
P18	30	0.9037	3.25	3.392	**4,369%**	420	68	**84%**
P19	35	0.9157	3.14	3.093	**1,506%**	190	62	**67%**
P20	40	0.9277	3.46	3.093	**10,615%**	380	62	**84%**

Through the tables it can be seen that the adjustment of the FiM variable in relation to the experimental data brings us a very interesting result regarding the error in height, but the errors in relation to time are still quite high. This happens because the formulation of the mathematical modeling is simplified, so some phenomena that occur during the foam formation step, such as bursting at the top of the column, are not taken into account, so the model reaches steady state foam column before it happens during the experimental procedure. In addition, the type of foam formed through the experiment is in line with what is classified in the article by (Pilon, G. Fedorov and Viskanta, 2002) as type 2 foam, that is, a foam that has oscillations between the value total height in steady state. As the model considers that the formation of the foam column is just a linear step, this is also linked to the observed time error, a fact that was also observed by Pilon in his article. Finally, it can be said that the model has a good correlation with the experimental data when observing the maximum height values in steady state, as well as having a good convergence regarding the behavior of the foam heights with increasing temperature, where this model is able to capture this foam layer shrinkage behavior due to viscosity reduction.

2.3.5 Mathematical model: Decay

The results regarding to mathematical modeling of foam decay based on (Fortkamp, 2014) will be presented.

In this model, two coefficients C3 and C4 needed to be adjusted. However, the C4 coefficient does not significantly influence the decay model for gas injection foams, so the value presented by (Fortkamp, 2014) in its global variables such as 5.0 x 10-3 was used to obtain the results. To obtain the C3 coefficient, several mathematical simulations were performed for each of the experimental points in order to optimize this coefficient. For each simulation, the root mean square error was evaluated. The acquisition of the optimized C3 coefficient was given by the smallest error acquired. The table below shows the results obtained from C3 as well as the RMSE and normalized RMSE:

Table 4. Adjusted C3 coefficient results and the RMSE.

	Temperature	C3	RMSE	Normalized RMSE
P1	20	3.40E-06	0.2731	4%
P2	25	5.40E-06	0.3834	8%
P3	30	1.01E-05	0.5351	9%
P4	35	3.19E-05	0.4418	8%
P5	40	2.85E-05	0.2355	7%
P16	20	2.50E-06	0.3552	6%
P17	25	6.50E-06	0.4849	10%
P18	30	2.22E-05	0.2589	7%
P19	35	2.80E-05	0.3885	11%
P20	40	7.40E-05	0.1979	6%
			Average error	7%

It can be seen that the average error of the normalized RMSE is 7%, which indicates a good correlation between the mathematical modeling and the experimental points used. The C3 coefficient was not globalized like the other coefficients, because in addition to the difference in temperature and type of gas, this variable is mainly related to the flow of liquid through the Plateau borders. Although the modeling is taking such variables into consideration, the C3 coefficient still has the function of correcting the errors presented by the model, a fact that was also observed by (Fortkamp, 2014). Some results obtained through the mathematical modeling will be presented in the Figure 9:

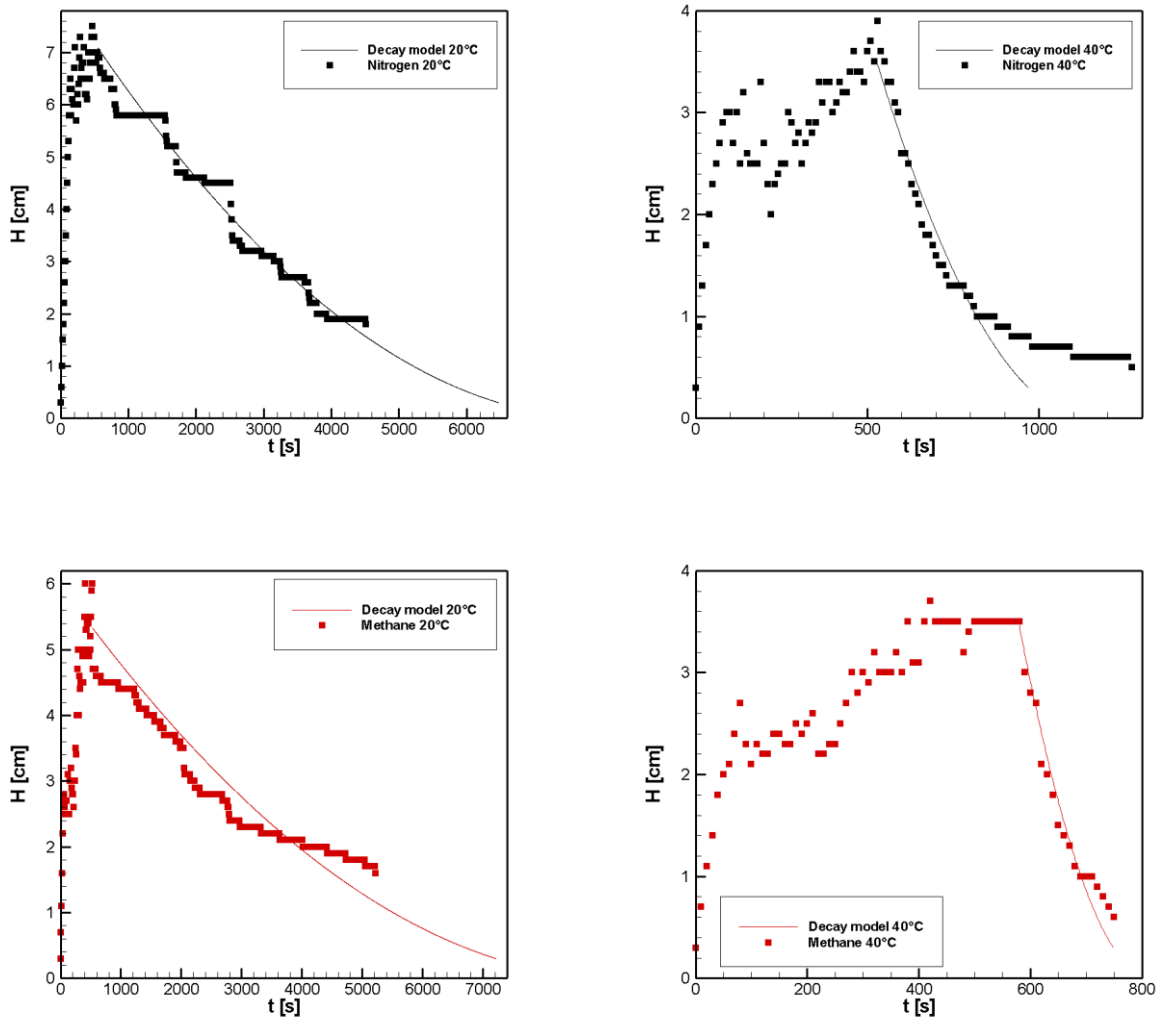


Figure 9. Decay model results for nitrogen and methane.

As can be seen, the decay model is very similar, in its behavior, to the results obtained experimentally. It is also possible to observe that generally the model predicts a more accelerated decay of the foam, because in the feeding of the models some simplifying hypotheses are used. Furthermore, it can be observed that the adjustment of variable C3 manages to maintain a good correlation between the experimental points and the mathematical model, but this indicates that the model still lacks some corrections to depend less on this adjustment variable. From a graphical analysis of the results, as well as the analysis related to the RMSE, it can be said that the results shown here are satisfactory.

3. CONCLUSIONS

The study presented by the present work showed the influence of several parameters (temperature, pressure and type of gas injected) on the formation and decay of foams formed by gas injection into a mixture of ISO14 mineral oil + sodium lauryl ether sulfate + water. Furthermore, a simplified mathematical modeling of formation and decay phenomena was presented and validated with the experimental results obtained. A good correlation can be observed between the data obtained both experimentally and through modeling when compared to the behavior of foams observed in the literature. Thus, it can be said that the results presented here are satisfactory.

4. REFERENCES

Abd Rahim, N. S., Saaid, I. M. and Umar, A. A. (2019) 'Evaluation of foam performance at different temperature for enhanced oil recovery process', *World Journal of Engineering*, 16(3), pp. 412–418. doi: 10.1108/WJE-06-2018-0210.

Buckingham, J. H. (1970) 'Effect of pH, concentration, and temperature on the strength of cytoplasmic protein foams', *Journal of the Science of Food and Agriculture*, 21(9), pp. 441–445. doi: 10.1002/jsfa.2740210901.

Chen, J. *et al.* (2018) 'Foaming of crude oil: Effect of acidic components and saturation gas', *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 553, pp. 432–438. doi: 10.1016/j.colsurfa.2018.05.097.

Daltin, D. (2011) *Tensoativos química, propriedades e aplicações*.

Delahaije, R. J. B. M., Lech, F. J. and Wierenga, P. A. (2019) 'Investigating the effect of temperature on the formation and stabilization of ovalbumin foams', *Food Hydrocolloids*, 91, pp. 263–274. doi: 10.1016/j.foodhyd.2019.01.030.

Farajzadeh, R., Krastev, R. and Zitha, P. L. J. (2009) 'Gas Permeability of Foam Films Stabilized by an α-Olefin Sulfonate Surfactant', *Langmuir*, 25(5), pp. 2881–2886. doi: 10.1021/la803599z.

Fortkamp, F. P. (2014) *Análise experimental e teórica da formação de espuma em misturas óleo-refrigerante*.

Hartland, S., Bourne, J. R. and Ramaswami, S. (1993) 'A study of disproportionation effects in semi-batch foams—II. Comparison between experiment and theory', *Chemical Engineering Science*, 48(9), pp. 1723–1733. doi: 10.1016/0009-2509(93)80131-9.

Indrawati, L. *et al.* (2008) 'Effect of processing parameters on foam formation using a continuous system with a mechanical whipper', *Journal of Food Engineering*, 88(1), pp. 65–74. doi: 10.1016/j.jfoodeng.2008.01.015.

Jackman, M. *et al.* (2018) 'Effect of temperature on foamability using a thermoresponsive polymer', *AIP Advances*, 8(7), p. 075320. doi: 10.1063/1.5017739.

Kapetas, L. *et al.* (2016) 'Effect of temperature on foam flow in porous media', *Journal of Industrial and Engineering Chemistry*, 36, pp. 229–237. doi: 10.1016/j.jiec.2016.02.001.

Kaviany, M. (1995) *Principles of Heat Transfer in Porous Media*. New York, NY: Springer New York (Mechanical Engineering Series). doi: 10.1007/978-1-4612-4254-3.

Pilon, L., G. Fedorov, A. and Viskanta, R. (2002) 'Analysis of transient thickness of pneumatic foams', *Chemical Engineering Science*, 57(6), pp. 977–990. doi: 10.1016/S0009-2509(02)00010-6.

Poindexter, M. K. *et al.* (2002) 'Factors Contributing to Petroleum Foaming. 1. Crude Oil Systems', *Energy & Fuels*, 16(3), pp. 700–710. doi: 10.1021/ef010224i.

Shaban, H. I. (1995) 'A study of foaming and carry-over problems in oil and gas separators', *Gas Separation & Purification*, 9(2), pp. 81–86. doi: 10.1016/0950-4214(95)93944-F.

Szabries, M., Jaeger, P. and Amro, M. M. (2019) 'Foam Analysis at Elevated Pressures for Enhanced Oil Recovery Applications', *Energy & Fuels*, 33(5), pp. 3743–3752. doi: 10.1021/acs.energyfuels.8b03088.

Zaki, N. N., Poindexter, M. K. and Kilpatrick, P. K. (2002) 'Factors Contributing to Petroleum Foaming. 2. Synthetic Crude Oil Systems', *Energy & Fuels*, 16(3), pp. 711–717. doi: 10.1021/ef010225a.

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