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Measurement of the Thickness of Thin Foam Films by Laser Interferometry

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ABSTRACT:*Foams are involved in many industrial processes, including foods and beverages, firefighting, subsoil environmental remediation and enhanced oil recovery. In these applications, foam stability and dynamics depend on the permeability of the thin liquid films to gases. An important parameter in the description of the foam permeability is the thickness of the thin liquid films. The foam film permeability is can be measured using (laser) light interferometry. In this paper, we survey the principles of this technique and compute the expressions for the thickness for a free standing foam film. The foam film is consists of five layers: a core aqueous layer with two surfactant monolayers, each consisting of consisting of hydrocarbon tails and polar head-groups sub-layers. From its reflection intensity coefficient for perpendicularly incident light.*

Keywords:foam film, thickness, interferometry, intensity

I. INTRODUCTION

Foam is a dispersion of a gas phase in a continuous liquid phase, stabilized by a surfactant. Applications involving foams in modern industrial processes have grown considerably in the last few decades. Hence, foam is matter of interest in many physical, biological and technological researches, including food and beverage technology, medical research (breathing), environmental remediation and petroleum engineering and research [1-3]. Use of foams in petroleum engineering includes enhanced oil recovery, well treatments and drilling operations [4]. The efficiency of the foam depends strongly on the stability and dynamics of foam films. As depicted in fig. 1, we can represent a foam film by a thin aqueous layer bound by monolayers of adsorbed surfactant molecules; the main function of the surfactant molecules is to stabilize the foam film [5]. The adsorption of surfactants onto the gas liquid interfaces can inhibit the flux of gas through the foam film [6-9]. The permeability of the foam films to gases limits the stability of the foam [10,11]. One of the key parameters in determining the film permeability to gases is the thickness of the foam film which results from the equilibrium between the film surfaces. Therefore, knowing the thickness of the foam films helps the better understanding of the physical properties of the foam. In this paper, first the formulas to calculate the thickness of a uniform homogenous liquid film by interferometry will be presented in details. Next, considering the structure of the foam films, these formulas will simplified. These formulas can be used both for horizontal and vertical (free standing) films.

II. MODEL DESCRIPTION

Below we present the equations for computing the fraction of a light wave reflected by a flat interface between two dielectric media, with different refractive indices; these are the Fresnel equations. It proceeds by considering the boundary conditions at the interface for the electric and magnetic fields of the light waves. In fig 2, the xy plane in the interface plane. The x axis is the projection of the rays on the plane boundary and the y axis is perpendicular to the plane of drawing. According to the electromagnetic theory of the light the incident, reflected and transmitted waves of light can be written as [12,13]:

$$E_0^d = A_0 exp(i\tau_0^d)\ , E_0^r = R_0 exp(i\tau_0^r)\ , \ E_1^d = A_1 \exp(i\tau_1^d) \quad (1)$$

Where,

$$\tau_0^d = \omega\left(t - \frac{x \sin\theta_0 + z\cos\theta_0}{v_0}\right),\ \tau_0^r = \omega\left(t - \frac{x\sin\theta_0 - z\cos\theta_0}{v_0}\right),$$

$$\tau_1^d = \omega\left(t - \frac{x\sin\theta_0 + z\cos\theta_0}{v_1}\right) \quad (2)$$

In these equations t is the time, ω is the circular frequency of the light wave, $\theta_0$is the angle of incident light and $v_0$and $v_1$are the velocity of the ray in the first and second media respectively. The vector of the amplitude of the incident, reflected and transmitted light waves (electric field strength),A_0,R_0 and A_1 , have two components: (a) a component lying in the plane of reflection (or incident, i.e., plane xz) and (b) a component perpendicular to the plane of reflection i.e., plane xy. For the reflected wave these two components are given by [12,13]:

$$R_{0,P} = \frac{n_1\cos\theta_0 - n_0\cos\theta_1}{n_1\cos\theta_0 + n_0\cos\theta_1} A_{0,P} = \frac{\tan(\theta_0-\theta_1)}{\tan(\theta_0+\theta_1)} A_{0,P} \quad (3)$$

$$R_{0,P} = \frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1} A_{0,s} = -\frac{\sin(\theta_0-\theta_1)}{\sin(\theta_0+\theta_1)} A_{0,s} \quad \text{(4)}$$

n_0 and n_1 are the refractive indices of two media. For the ratio of reflected and incident amplitudes:

$$r_P = \frac{R_{0,P}}{A_{0,P}} = \frac{n_1 \cos\theta_0 - n_0 \cos\theta_1}{n_1 \cos\theta_0 + n_0 \cos\theta_1} = \frac{\tan(\theta_0-\theta_1)}{\tan(\theta_0+\theta_1)} \quad \text{(5)}$$

$$r_s = \frac{R_{0,s}}{A_{0,s}} = \frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1} = -\frac{\sin(\theta_0-\theta_1)}{\sin(\theta_0+\theta_1)} \quad \text{(6)}$$

The intensity of reflected light is given for both components by:

$$I_P^r = r_P^2 \quad \text{(7)}$$

$$I_s^r = r_s^2 \quad \text{(8)}$$

III. RESULTS AND DISCUSSION

We assume a homogenous film in which the refractive index n_f is constant in the whole thickness ε_{eq} (Fig. 3). For a thin film for two components of the reflected light we obtain the following equations [12]:

$$r_P exp(i\delta_P) = \frac{r_P' + r_P'' \, exp(-i\Delta\varphi)}{1 + r_P' r_P'' \, exp(-i\Delta\varphi)} = \frac{r_P' exp(i\Delta\varphi) + r_P'' \, exp(-i\Delta\varphi)}{exp(i\Delta\varphi) + r_P' r_P'' \, exp(-i\Delta\varphi)} \quad \text{(9)}$$

$$r_s exp(i\delta_s) = \frac{r_s' + r_s'' \, exp(-i\Delta\varphi)}{1 + r_s' r_s'' \, exp(-i\Delta\varphi)} = \frac{r_s' exp(i\Delta\varphi) + r_s'' \, exp(-i\Delta\varphi)}{exp(i\Delta\varphi) + r_s' r_s'' \, exp(-i\Delta\varphi)} \quad \text{(10)}$$

$$\Delta\varphi' = \frac{2\pi\varepsilon_{eq}}{\lambda_0} 2n_f \cos\theta \quad \text{(11)}$$

$$\Delta\varphi = \frac{\Delta\varphi'}{2} = \frac{2\pi n_f \varepsilon_{eq}}{\lambda_0} \cos\theta \quad \text{(12)}$$

Multiplication of equations (9) and (10) by the complex conjugate expression $r_P exp(-i\delta_P)$ and $r_s exp(-i\delta_s)$ respectively gives:

$$I_P^r = r_P^2 = \frac{r_P'^2 + r_P''^2 + 2r_P' r_P'' \cos\Delta\varphi'}{1 + r_P'^2 r_P''^2 + 2r_P' r_P'' \cos\Delta\varphi'} \quad \text{(13)}$$

$$I_s^r = r_s^2 = \frac{r_s'^2 + r_s''^2 + 2r_s' r_s'' \cos\Delta\varphi'}{1 + r_s'^2 r_s''^2 + 2r_s' r_s'' \cos\Delta\varphi'} \quad \text{(14)}$$

Where r_P' is calculated from equation (9) and,

$$r_P'' = \frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2} = \frac{\tan(\theta_1-\theta_2)}{\tan(\theta_1+\theta_2)}$$

$$r_s'' = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} = -\frac{\sin(\theta_1-\theta_2)}{\sin(\theta_1+\theta_2)}$$

The intensity of the incident light is assumed to be one and the amplitudes r_P and r_s are taken with positive signs.

$$(I_P^r)_{max} = \frac{r_P'^2 + r_P''^2 + 2r_P' r_P''}{1 + r_P'^2 r_P''^2 + 2r_P' r_P''} = \left(\frac{r_P' + r_P''}{1 + r_P' r_P''}\right)^2 \quad \text{(15)}$$

$$(I_P^r)_{min} = \frac{r_P'^2 + r_P''^2 - 2r_P' r_P''}{1 + r_P'^2 r_P''^2 - 2r_P' r_P''} = \left(\frac{r_P' - r_P''}{1 - r_P' r_P''}\right)^2 \quad \text{(16)}$$

$$(I_s^r)_{max} = \frac{r_s'^2 + r_s''^2 + 2r_s' r_s''}{1 + r_s'^2 r_s''^2 + 2r_s' r_s''} = \left(\frac{r_s' + r_s''}{1 + r_s' r_s''}\right)^2 \quad (17)$$

$$(I_s^r)_{min} = \frac{r_s'^2 + r_s''^2 - 2r_s' r_s''}{1 + r_s'^2 r_s''^2 - 2r_s' r_s''} = \left(\frac{r_s' - r_s''}{1 - r_s' r_s''}\right)^2 \quad (18)$$

Since $\cos 2x$= 1- $2sin^2 x$then equation (13) and (14) can be rearranged to:

$$I_P^r = r_P^2 = \frac{(r_P' + r_P'')^2 - 4r_P' r_P'' \sin^2\Delta\varphi}{(1 + r_P' r_P'')^2 - 4r_P' r_P'' \sin^2\Delta\varphi} \quad (19)$$

$$I_s^r = r_s^2 = \frac{(r_s' + r_s'')^2 - 4r_s' r_s'' \sin^2\Delta\varphi}{(1 + r_s' r_s'')^2 - 4r_s' r_s'' \sin^2\Delta\varphi} \quad (20)$$

When light is normally incident on the film ($\theta_0 = 0$,as in Fig. 4), Fresnel's formula can be rewritten in a simplified form:

$$r_P' = \frac{n_1 - n_0}{n_1 + n_0} = -r_P'' \quad (22)$$

$$r_s' = \frac{n_1 - n_0}{n_1 + n_0} = -r_s'' \quad (23)$$

Both components of the amplitude of the reflected light have the same magnitude but different signs; this means that one component is shifted by π with respect to the other.
Therefore in this section we confine ourselves to one component and drop the subscripts, s and p.

$$I_r = r^2 = \frac{(r' + r'')^2 - 4r' r'' \sin^2\Delta\varphi}{(1 + r' r'')^2 - 4r' r'' \sin^2\Delta\varphi} \quad (24)$$

Now if we put $r' = r'' = r_f$ which means that the film is placed between two optical media having a high reflectivity at the boundaries of the optical medium and film (Figure4). Thus, considering film as a homogenous layer with the refractive index of n_f and assuming no light absorption into the film, the following formula will be obtained:

$$\frac{I_r}{I_0} = \frac{4r_f^2 \sin^2\Delta\varphi}{1 - 2r_f^2 \cos 2\Delta\varphi + r_f^4} \quad (25)$$

Where,
I_r: Intensity of light reflected by the film
I_0:Intensity of the incident light (which is normally is assumed to be one)

r : Reflection coefficient for the amplitude for a single interface between the film with refractive index n_f and the surrounding medium with refractive index n_0.
For perpendicularly incident light:

$$r_f = \frac{n_f - n_0}{n_f + n_o} \quad (26)$$

$\Delta\varphi$ is the phase difference between light at the front face and back face of the film which in the case of normal beam is equal to:

$$\Delta\varphi = \frac{2\pi n_f \varepsilon_{eq}}{\lambda_0} \quad (27)$$

Where λ_0 is the wavelength in vacuum.
Replacing cos2$\Delta\varphi$ = 1-2$sin^2\Delta\varphi$ and R= r_f^2 in equation (25) we lead to:

$$I_r = I_0 \frac{4R \sin^2\Delta\varphi}{(1-R)^2 + 4R\sin^2\Delta\varphi} \quad (28)$$

I_r Has the minimum value when sin Δφ = 0 . Therefore,I_{min} = 0 when:

$\Delta\varphi = \frac{2\pi n_f \varepsilon_{eq}}{\lambda_0}$ = pπ, where p∈ Z. Then in this case the thickness of the film is equal to:

$\varepsilon_{eq} = \frac{p}{2n_f}\lambda_0$ ……………………………………………………………………………………. (29)

I_r has the maximum value when sin Δφ = 1 . Therefore, $I_{max} = \frac{4R}{(1+R)^2}$ when:

$\Delta\varphi = \frac{2\pi n_f \varepsilon_{eq}}{\lambda_0} = (4p+1)\frac{\pi}{2}$ Where p$\in Z$.Then in this case the thickness of the film is equal to:

$\varepsilon_{eq} = \left(\frac{4p+1}{2n_f}\right)\lambda_0$ ……………………………………………………………...……………. (30)

I we define $\Delta = \frac{I_r - I_{min}}{I_{max} - I_{min}}$ and substitute the parameters in this formula we will get:

$$\Delta = \frac{\frac{4R\sin^2\Delta\varphi}{(1-R)^2}}{\left(1+\frac{4R\sin^2\Delta\varphi}{(1-R)^2}\right)\left(\frac{4R}{(1+R)^2}\right)}$$

$\Delta = \frac{(1+R)^2 \sin^2\Delta\varphi}{(1-R)^2 + 4R\sin^2\Delta\varphi}$ ……………………………………………………..……………… (31)

$$\Delta(1-R)^2 + 4R\Delta\sin^2\Delta\varphi = (1+R)^2\sin^2\Delta\varphi$$

$$\sin^2\Delta\varphi\left(\frac{(1+R)^2}{(1-R)^2} - \frac{4R\Delta}{(1-R)^2}\right) = \Delta$$

$$\sin^2\Delta\varphi\left(\frac{(1+R)^2 + 4R(1-\Delta)}{(1-R)^2}\right) = \Delta$$

$\sin^2\Delta\varphi\left(1 + (4R(1-\Delta)/(1-R)^2)\right) = \Delta$

$$\sin^2\Delta\varphi = \frac{\Delta}{1 + (4R(1-\Delta)/(1-R)^2)}$$

$$\sin\Delta\varphi = \sqrt{\frac{\Delta}{1 + (4R(1-\Delta)/(1-R)^2)}}$$

$$\Delta\varphi = \sin^{-1}\sqrt{\frac{\Delta}{1 + (4R(1-\Delta)/(1-R)^2)}}$$

$\varepsilon_{eq} = \frac{\lambda_0}{2\pi n_f}\sin^{-1}\sqrt{\frac{\Delta}{1+(4R(1-\Delta)/(1-R)^2)}}$ …………………………………………….……….. (32)

The thickness calculated by equation (32) is the equivalent thickness of the film which is slightly thicker than the actual film thickness. Moreover, a foam film consists of three homogenous layers, a core aqueous layer with the thickness of ε_w sandwiched by two surfactant monolayers with the thickness of ε_w. We assume a uniform thickness for the foam film and neglect the curvature in the corners (Figure 5). These three layers have different refractive indices (refractive index of surfactant monolayer is larger than that of solution). A surfactant monolayer itself consists of a head group with the refractive index of n_{pg} and a hydrocarbon chain with the refractive index of n_{hc} which in fact indicates that the film can be considered to have five layers. Therefore, equation (32) should be corrected to calculate the thickness of core aqueous layer. The following correction derived by Duyvis [14]:

$\varepsilon = \varepsilon_{eq} - 2\varepsilon_{hc}\left(\frac{n_{hc}^2 - n_w^2}{n_w^2 - 1}\right) - 2\varepsilon_{pg}\left(\frac{n_{pg}^2 - n_w^2}{n_w^2 - 1}\right)$ ……………………………………………….. (33)

ε_{eq} is the equivalent thickness calculated by equation (32), ε_{hc} is the thickness of the hydrocarbon chain of the surfactant molecule and ε_{pg} is the thickness of head group of the surfactant molecule. Thus the thickness of the aqueous layer is calculated by:

$$\varepsilon_w = \varepsilon - 2\varepsilon_m \quad \ldots\ldots (34)$$

Where $\varepsilon_m = \varepsilon_{hg} + \varepsilon_{hc}$ is the thickness of a surfactant monolayer.
Equation (33) can be used to measure the thickness of very thin foam films in the range of few nanometers. The accuracy of these equations is reported to be less than ±0.1nm [5,15].

IV. FIGURES

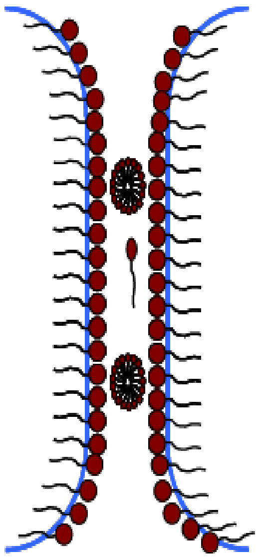

Figure 1 Schematic of a foam film (lamellae), sandwich model, an aqueous layer with adsorbed surfactant monolayers.

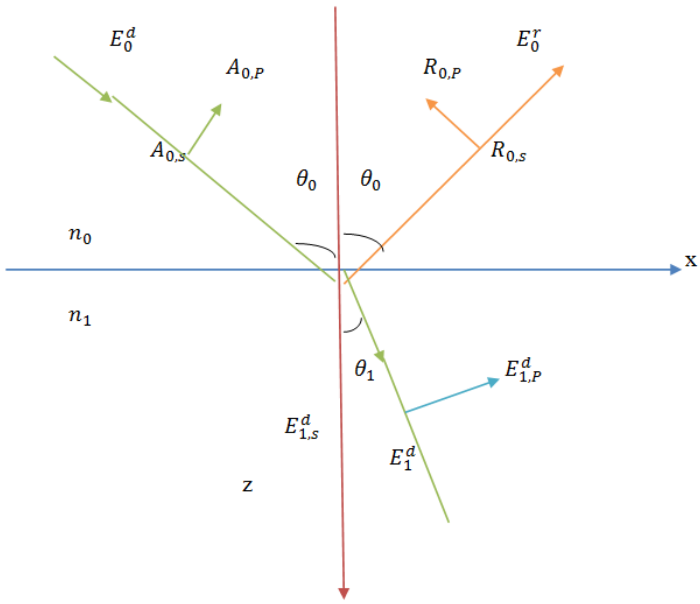

Figure 2 Reflection and refractive of light at plane boundary between two media.

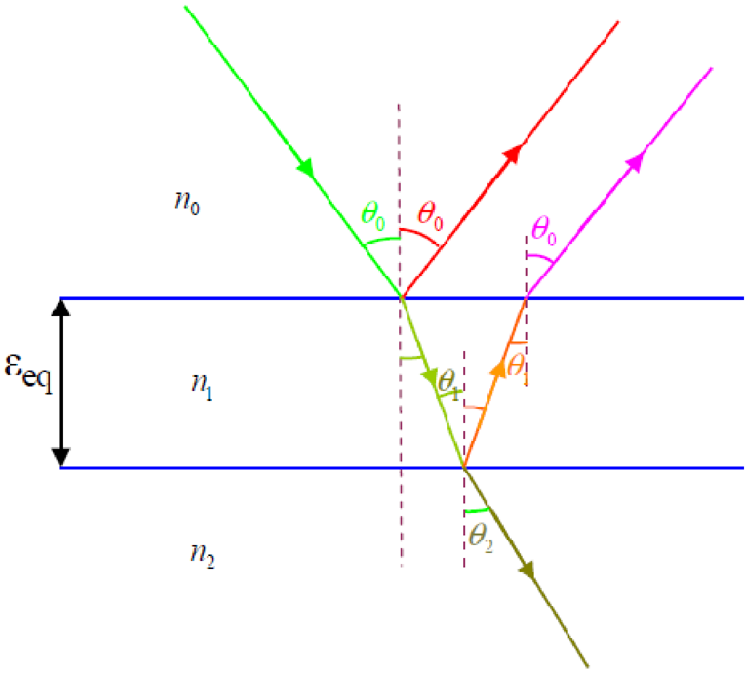

Figure 3 Reflection and refractive of light by one thin film.

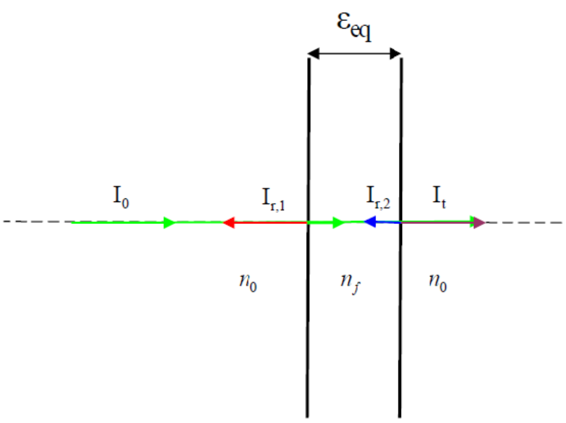

Figure 4 Schematic of a uniform liquid film.

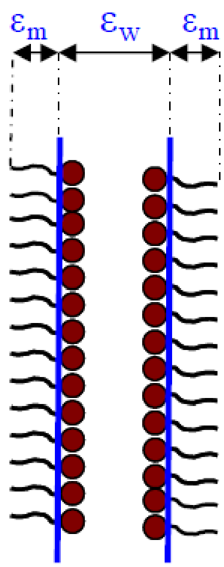

Figure 5 Schematic of foam without considering the Plateau border.

V. CONCLUSION

In this paper a method to measure the thickness of the thin foam films was reviewed and considering the structure of the film the related formulas were presented in some detail. First a formula was derived for the thin homogenous liquid film and then the derived equation was corrected for surfactant monolayers. The calculated thickness is very useful in investigating the stability of foam films and the study of interaction between adsorbed surfactant molecules.

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