

A MONTE CARLO MODEL FOR THE DETERMINATION OF THE VOLUME FRACTIONS OF CRUDE OIL, WATER AND NATURAL GAS USING THE DUAL ENERGY γ -RAY TRANSMISSION

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The extraction of petroleum from its geological reservoirs involves the piping of crude oil, water and natural gas from the wells as a multiphase mixture. Knowledge of the mass flow rate of each component is required to control production.

In this work, this multiphase flow has been pictured as a coarse-grained component system, water as drops and natural gas as bubbles, both are carried out through the crude oil along the pipeline. According to this picture, a Monte Carlo model for grain size dependent gamma-ray attenuation has been constructed and applied to determine the volume fractions of oil, water and natural gas in pipelines by using gamma-ray transmission technique.

Keywords: *grain-size, volume fractions, Monte Carlo method.*

INTRODUCTION

Considerable importance attaches to the presence of water in crude oil. Since, water leads to difficulties in refinery. i.e ; corrosion of equipment, uneven running on distillation unit, blockages in heat exchangers and adverse effects on product quality, besides, flooding of distillation units and excessive accumulation of sludge in tank, It is necessary to know its volume fractions in order to choose the suitable time and method for its separation.

Due to the natural appearance of water and natural gas in the crude oil as droplets and bubbles the beer's law of γ -ray attenuation in a homogenous mixture

cannot be used and the influence of the grain-size has to be considered in the attenuation law [1,2].

Several authors [3,4,5] studied the effect of the grain-size experimentally. They used mass flow rate measurement in the determination procedure of multiple coarse-grained components. Techniques for sensing one or more of the components include electrical, nuclear, x-ray transmission, radio frequency resonator and microwave methods [6,7,8].

Others [1.2.9.10] have investigated this problem theoretically suggesting online testing methods, which are characterized by their economical and low time consuming feature.

This work describes a Monte Carlo treatment of γ -ray attenuation in mixtures containing multiple-coarse-grained components such as the mixture contains water and natural gas as grained components and oil as a homogeneous residual. The mean values of the modified attenuation coefficients of the different coarse-grained component materials, for the used γ -ray energies, have been computed over the expected ranges of variation of volume fractions. By introducing these values in the attenuation equations of the used γ -ray energies, the volume fraction of various components can be determined. A comparison of Monte Carlo predictions with the true volume fractions indicates that this method is accurate enough and should be recommended in testing the crude oil composition.

MONTE CARLO MODELING

The Determination of the Mean Modified Gamma-Ray Attenuation Coefficient

In this model, it will be assumed that crude oil represents a triple component material that consists of unified homogeneous residual constituent (oil) and two coarse-grained components (water and natural gas) of uniform spheres of radii r_w and r_g respectively.

Neglecting the particle-size effects in the γ -ray attenuation, the ratio $t(r_w = 0, r_g = 0)$ of the γ -ray intensities have any discrete energy E_γ after penetrating the water-natural gas-oil mixture or oil respectively. The following equations are achieved:

$$t(r_w = 0, r_g = 0) = I / I_{oil} = \exp(-v_w \Delta\mu_w L) \exp(-v_g \Delta\mu_g L), \quad (1)$$

with

$$I_{oil} = I_o \exp(-\mu_o L),$$

$$\Delta\mu_i = \mu_i - \mu_o, \quad i = w, g \quad (2)$$

where v_i denotes volume fractions of component materials $i = w, g$; μ_o and μ_i stand for the linear γ -ray attenuation coefficient of the oil and i^{th} component respectively. L is the transmission length, and I_o is the intensity of the original γ -ray beam.

In order to account for particle-size effect, it is assumed that the particles of each component material are distributed uniformly over the flow volume in a way that, for each of them, the mean distance to its neighbors within the flow volume is constant. On the basis of the picture of idealized imaginary disks arrayed along the transmission path of a photon between source and detector [2], the radii r_w and r_g of the particle materials are correlated as follows:

$$r_g = r_w (v_g / v_w)^{1/3} \quad (3)$$

Consequently, the probability of photon collisions with the different component materials in an imaginary disk can be obtained as follows:

For $r_g \geq r_w$ the probabilities of p_g and p_w that a photon will strike the particle of natural gas and water respectively when penetrating a disk are:

$$P_g = 3/2 v_g (1 + \delta / 2), \quad (4)$$

$$P_w = 3/2 (v_w / r_w) (r_g + \delta / 2), \quad (5)$$

with, δ as seen in Figure 1. is given by

$$\begin{aligned} \delta &= (L - 2r_g n) / n \\ n &= L / 2r_g \end{aligned} \quad (6)$$

As seen in Figure 1. where n : is the number of imaginary disks along the transmission length. On the other hand, for $r_g \leq r_w$ the probabilities of p_g and p_w are:

$$P_g = 3/2 (v_g / r_g) (r_w + \delta / 2), \quad (7)$$

$$P_w = 3/2 v_w (1 + \delta / 2), \quad (8)$$

with, δ as seen in Figure 1. is given by

$$\begin{aligned} \delta &= (L - 2r_w n) / n \\ n &= L / 2r_w \end{aligned}$$

The component material involved in a collision with a photon can be determined by selecting a random number ξ from a sequence of positive real numbers distributed uniformly on the interval (0, 1) [11]. If this random number ξ lies in the range $0 \leq \xi \leq P_g$, natural gas particle is selected; if $P_g \leq \xi \leq P_g + P_w$, water particle is selected; and if $P_g + P_w \leq \xi \leq 1$, the residual component (oil) is selected.

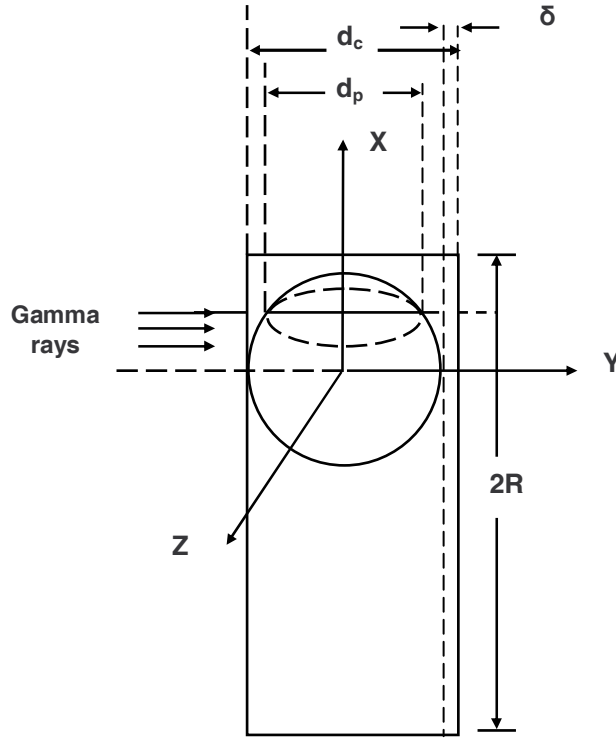


Figure 1. Coordinate system for particle p in an imaginary disk, $p = w$ or g

In order to account for particle-size effects in attenuation of γ -ray as it penetrates the conveyor flow, the weight factors for the forced photon penetrating the selected components along the transmission length, may be estimated [2] as follows:

$$W_{\text{natural gas}} = \exp(-\mu_g d_g) \exp(-\mu_o(d_c - d_g)) \quad (9)$$

$$W_{\text{water}} = \exp(-\mu_w d_w) \exp(-\mu_o(d_c - d_w)) \quad (10)$$

$$W_{\text{oil}} = \exp(-\mu_o d_c) \quad (11)$$

where d_c is the thickness of each disk, d_g and d_w are the distance that a photon can travel across natural gas and water particle respectively. These can be obtained from a random number ξ_1 according to the coordinate system for a particle material in an imaginary disk as shown in Figure 1.

The coordinates of the penetrating γ -ray of a particle are given by

$$\begin{aligned} x &= r_p \sqrt{1 - \xi_1} \\ y &= -r_p \sqrt{1 - \xi_1} \quad \text{and} \quad z = 0 \end{aligned}$$

The distance (d_p) that a photon can travel across a particle may be given by

$$d_p = 2|y|$$

The thickness of each disk (d_c) may be given by

$$d_c = 2r_p + \delta$$

If the probability is considered for n -disks along the photon path, the residual mixture oil, natural gas and water particles were penetrated o , g and w times, respectively. Then the total weights for photon penetration in each of the constituents are given by:

$$W_{oil} = \prod_{i=1}^o W_i \text{ (oil)} \quad (12)$$

$$W_{natural\ gas} = \prod_{j=1}^{n-(o+w)} W_j \text{ (natural gas)} \quad (13)$$

$$W_{water} = \prod_{l=1}^{n-(o+g)} W_l \text{ (water)} \quad (14)$$

The total penetration weight in passage the k^{th} photon through n -disk without interaction is given by:

$$W_k = W_{oil} \times W_{natural\ gas} \times W_{water} \quad (15)$$

The Monte Carlo method estimates the value $t^*(r_g, r_w)$ [12] as:

$$t^*(r_g, r_w) = 1/N \sum_{k=1}^N W_k \quad (16)$$

where N is the number of histories.

If the residual mixture consists of carrier medium such as oil and natural gas fine-grained while water is still in droplet form. The linear γ -ray attenuation coefficient of the residual mixture may be computed as:

$$\mu_{rm} = \mu_o + (v_g \times (\mu_g - \mu_o)) / (1 - v_w) \quad (17)$$

The probability p_{w1} that a photon will strike the particle of water is:

$$P_{w1} = 3/2 v_w (1 + \delta / 2), \quad (18)$$

The component material involved in a collision with a photon can be determined by selecting a new random number ξ_2 . If $P_{w1} \leq \xi_2 \leq 1$, the residual component is selected, but if the previous inequality is not satisfied, the water particle is selected.

$$W_{rm} = \exp(-\mu_{rm} d_c) \quad (19)$$

$$W_{water} = \exp(-\mu_w d_w) \exp(-\mu_{rm} (d_c - d_w)) \quad (20)$$

If a probability is considered for n disks along the photon path, the residual mixture rm and the water particles, were penetrated for k and $n-k$ times respectively. Then the total weights for photon penetration of both of them respectively without interaction will be given by:

$$W_{rm} = \prod_{i=1}^k W_i (rm) \quad (21)$$

$$W_{water} = \prod_{l=1}^{n-k} W_l (water) \quad (22)$$

The total penetration weight in passage the k^{th} photon through n -disk without interaction is given by:

$$W_k = W_{rm} \times W_{water} \quad (23)$$

Thus the value of the of $t^*(r_w, 0)$ in this case is given by

$$t^*(r_w, 0) = \exp(-v_g \Delta\mu_g L) \times 1/N \sum_{k=1}^N W_k \quad (24)$$

If the residual mixture consists of carrier medium such as oil and water fine-grained while natural gas is still as bubbles. Then the linear γ -ray attenuation coefficient of the residual mixture may be computed from equations (17 – 24) by substituting w for g to get

$$t^*(r_g, 0) = \exp(-v_w \Delta\mu_w L) \times 1/N \sum_{k=1}^N W_k \quad (25)$$

From equations 16, 24 and 25 the modified linear γ -ray attenuation coefficient of water and natural gas particle is given by:

$$\mu_w^*(r_w, r_g, v_w, v_g, E\gamma) = \mu_w(E\gamma) - (1/L v_w) \ln [t^*(r_g, r_w) / t^*(r_g, 0)] \quad (26)$$

$$\mu_g^*(r_w, r_g, v_w, v_g, E\gamma) = \mu_g(E\gamma) - (1/L v_g) \ln [t^*(r_g, r_w) / t^*(r_w, 0)] \quad (27)$$

The mean values of the modified γ -ray attenuation factors $t^*(r_g, r_w)$, $t^*(r_w, 0)$ and $t^*(r_g, 0)$ have been predicted using Monte Carlo procedure described by [2]. Due to the

complicated dependence of γ -ray attenuation on v_w and v_g , the mean values $\overline{\mu_w^*}(r_w, r_g, E_\gamma)$ and $\overline{\mu_g^*}(r_w, r_g, E_\gamma)$ of the true linear attenuation coefficients $\mu_w^*(r_w, r_g, v_w, v_g, E_\gamma)$ and $\mu_g^*(r_w, r_g, v_w, v_g, E_\gamma)$ respectively for the γ -ray energies used, are computed over the expected ranges of variation of v_w and v_g .

For the given values of r_w, r_g, E_γ and the given ranges N_w and N_g of v_w and v_g respectively. The mean values of the modified γ -ray attenuation coefficients of the component materials water and natural gas over the given range of volume fractions can be obtained as follows:

$$\overline{\mu_w^*}(r_w, r_g, E_\gamma) = \frac{\sum_{j=1}^{N_w} \sum_{l=1}^{N_g} \mu_{wj}^*(r_w, r_g, v_w, v_g, E_\gamma)}{N_w \times N_g} \quad (28)$$

$$\overline{\mu_g^*}(r_w, r_g, E_\gamma) = \frac{\sum_{j=1}^{N_w} \sum_{l=1}^{N_g} \mu_{gl}^*(r_w, r_g, v_w, v_g, E_\gamma)}{N_w \times N_g} \quad (29)$$

b-The Computation of the Volume Fractions the Two Coarse-Grained Materials Water and Natural Gas:

Introducing $\overline{\mu_w^*}(r_w, r_g, E_\gamma)$ and $\overline{\mu_g^*}(r_w, r_g, E_\gamma)$ given by equations 28 and 29 respectively into the following equation to get $\overline{\Delta\mu_j^*}$

$$\overline{\Delta\mu_j^*} = \overline{\mu_j^*}(r_w, r_g, E_\gamma) - \mu_o(E_\gamma), \quad j = w, g \quad (30)$$

Substituting for $\overline{\Delta\mu_j^*}$ from the above equation (30) into equation (31) one gets the value of $t^*(r_g, r_w)$

$$t^*(r_g, r_w) = \exp(-v_w \overline{\Delta\mu_w^*} L) \exp(-v_g \overline{\Delta\mu_g^*} L) \quad (31)$$

From equation (31) one can get

$$j_k(r_w, r_g) = a_k v_g + b_k v_w \quad (32)$$

with the help of:

$$a_k = \overline{\Delta\mu_g^*}(r_w, r_g, E\gamma_k) - \mu_o(E\gamma_k), \quad (33)$$

$$b_k = \overline{\Delta\mu_w^*}(r_w, r_g, E\gamma_k) - \mu_o(E\gamma_k), \quad (34)$$

$$j_k(r_w, r_g) = -1/L \ln[t^*(r_g, r_w)] \quad (35)$$

$$v_w + v_g + v_o = 1$$

If γ -ray of two energies ($k = 1, 2$) were used, then equation (32) may be written as follows:

$$j_1(r_w, r_g) = a_1 v_g + b_1 v_w \quad (36)$$

$$j_2(r_w, r_g) = a_2 v_g + b_2 v_w \quad (37)$$

The values of $j_1(r_w, r_g)$ and $j_2(r_w, r_g)$ may be obtained either from the Monte Carlo procedure or from the experiment. The solution of equations (36) and (37) with respect to the volume fraction given:

$$v_w = \frac{j_2(r_w, r_g) b_1 - j_1(r_w, r_g) b_2}{a_2 b_1 - b_2 a_1} \quad (38)$$

$$v_g = [j_1(r_w, r_g) / b_1] - (a_1 / b_1) v_w \quad (39)$$

or

$$v_g = (r_g / r_w)^3 v_w \quad (40)$$

COMPUTATIONS

Equations (28) and (29) were calculated for different r_w , v_w , v_g and the corresponding r_g values according to equation(3). Using r_w , ranging between 0.5 to 3 cm, in steps of 0.5 cm. The v_w and v_g values varied between 1 to 10% in steps of 1%.

The obtained values of the mean modified absorption coefficients of natural gas and water were substituted in equation (30) to get $\overline{\Delta\mu_j^*}$, which in turn were substituted in equation (31) to get $t^*(r_g, r_w)$. Mathematical manipulation of equation (31) led to equation (32), which was calculated for different energies leading to the volume fractions of the crude oil components.

RESULTS AND DISCUSSION

A triple-component system is used for the purpose of checking the present Monte Carlo method. It consists of: (i) Water as a coarse-grained material with $\mu_w(r_w=0) = 0.1932 \text{ cm}^{-1}$ and 0.1107 cm^{-1} . (ii) Natural gas as a coarse-grained material with $\mu_g(r_g = 0) = 0.0001558 \text{ cm}^{-1}$ and $0.00009386 \text{ cm}^{-1}$. (iii) Crude oil as a residual material with $\mu_o = 0.1863$ and 0.112 cm^{-1} for 0.059 and 0.356 Mev photon energies, respectively. The mass absorption coefficient of crude oil, water and natural gas were calculated using Xcom program [13]. Knowing the densities and compositions of crude oil and natural gas, the linear absorption coefficient were calculated.

Figures 2. and 3. give the Monte Carlo predictions of the mean values of the modified linear γ -ray attenuation coefficients $\overline{\mu}_w^*(r_w, r_g, E\gamma)$ and $\overline{\mu}_g^*(r_w, r_g, E\gamma)$ for different values of r_w and r_g at the energies 0.059 and 0.356 Mev.

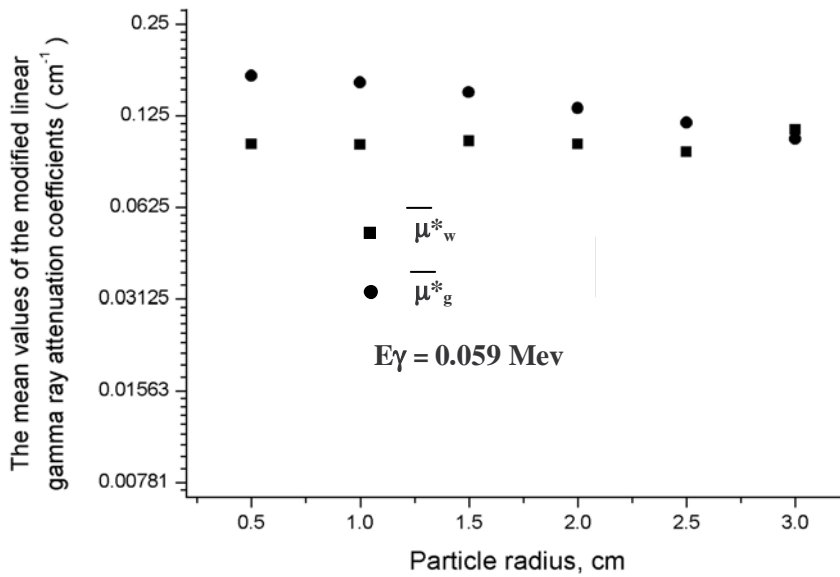


Figure 2. Modified linear gamma-ray attenuation coefficient Vs particle radius, for 0.059 Mev photon energy.

The Monte Carlo prediction of ν_w and ν_g is in agreement with the true values over the given range of ν_w and ν_g . The error between the given and the prediction values of ν_w and ν_g is in order 1%. The results show that, the accuracy of the method depends on two parameters: (i) the number of photon histories used in Monte Carlo

calculation and (ii) the radius r_w and r_g of the particle materials. While the first parameter influences the accuracy much smaller than the second parameter, the accuracy increases by decreasing the radii of the particles, which leads to increasing the homogeneity of the mixture.

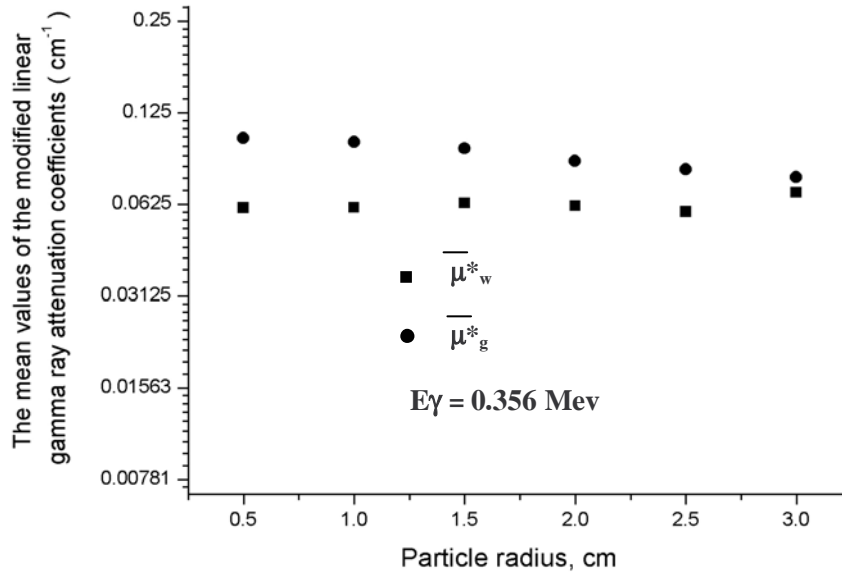


Figure 3. Modified linear gamma-ray attenuation coefficient Vs particle radius, for 0.356 MeV photon energy.

SUMMARY AND CONCLUSIONS

In the present work, a method for Monte Carlo prediction of volume fraction in multiple coarse-grained component conveyor flows has been established and applied on crude oil mixture. The linear γ -ray attenuation coefficients of materials involved are modified in order to account for grain-size effects in γ -ray attenuation.

Due to the complicated dependence of γ -ray attenuation on the volume fraction of various components in attenuating medium, the mean values of the modified γ -ray attenuation coefficients are computed over the expected ranges of variation of the volume fraction. To test the accuracy of this model in determining the volume fraction of coarse-grain mixture, the mean values of the obtained results of the modified attenuation coefficient are used to determine the volume fraction. Since the obtained results were found to be in good agreement with the assumed values it is recommended to be used in determining the coarse-components in crude oil, which under circumstances can be harmful.

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استخدام طريقة مونت كارلو لتعيين الحجم النسبي لمكونات خليط من زيت البترول الخام به ماء وغاز باستخدام طاقتين مختلفتين لأشعة جاما

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أثناء استخراج البترول الخام من الآبار يتم معه استخراج كميات من الماء والغاز وبذلك يصبح البترول الخام خليط من مكونات عديدة. لذلك كان من الضروري التعرف على معدل الحجم المناسب لكل مكون من المكونات الثلاثة لكي يتسنى التحكم والسيطرة على عملية الإنتاج.

في هذا البحث يتم التعامل مع مثل هذا الخليط على أنه خليط من مكونات حبيبية. حيث ينظر للماء على أنه قطرات وللغاز على أنه فقاعات وكلاهما محمول خلال زيت البترول الخام المتدفق في خطوط الإنتاج. وبناء على هذا الفرض، تم تطبيق طريقة مونت كارلو باستخدام طاقتين مختلفتين لأشعة جاما آخذين في الاعتبار معاملات الامتصاص الخاصة بمكونات الخليط لتعيين الحجم النسبي لمكونات خليط متدفق خلال خطوط الإنتاج مكون من زيت البترول الخام بالإضافة إلى ماء وبعض الغاز.