ACOUSTICS OF MARINE HYDROCARBON SEEPS

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Abstract

Gas and oil seepages in shallow submarine environments produce buoyant hydrocarbon plumes that are detected as sonar targets within the water column. The present report describes acoustic methods of evaluation of parameters of gas vents. Using the equations describing bubble gas transfer and motion the occurrence of anomalies in concentrations of gas inclusions has been predicted. A passive method for diagnostics of gas vents has been proposed. A rising bubble plume forms an effective acoustic waveguide that possesses normal modes. The “birthing wails” of the bubbles as they depart from the vent is accompanied by generation of broadband noise. The noise frequency spectrum has several peaks related to the lowest-mode frequencies of the bubble plume. Explicit expressions for the frequencies of these modes have been derived. The model is extended to prediction of seep intensity on the base of the measured sound spectral density and the solution of the Helmholtz equation.

Introduction

Natural hydrocarbon seeps are found in varying intensity along most continental shelves. These seeps emit gas, oil, or a mixture of both from seafloor vents. Free bubbles rise from the sea bed into the water columns and form a flare. Bubble flare are registered by standard shipboard sonar as hydroacoustic anomalies in back scattering and are seen as dark curtains on sonar paper chart records [1]. Few published quantitative observations of the bubble emission size distribution for hydrocarbon seeps exist. This research seeks to provide the necessary theoretical background to allow modeling of gas bubble streams and to solve inverse problem of evaluation of parameters of gas vents on the base of the data of echo-sounding.

Seep bubbles are often observed escaping from the seabed as a stream of nearly pure CH_4 bubbles. The bubble CH_4 is highly supersaturated with respect to the bulk ocean and rapidly outflow from the bubble, causing bubble dissolution. The mass flow for any gas (CH_4, N_2 and O_2) is described by [2, 3]

$$\dot{N}_i = 4\pi R^2 k_{Bi}(R, \nu_i, D_i)(c_i - P_{Bi}/H_i)\,, \qquad (1)$$

where N_i is the number of moles in the bubble, R is the bubble radius, c_i is the aqueous concentration, P_{Bi} is the partial pressure in the bubble, H_i is the Henry’s low constant. The gas transfer rate k_{Bi} is strongly dependent on R, the ratio of molecular diffusivity D to advective transport and effect of surfactants. The internal bubble pressure $P_B = \sum P_{Bi}$ is primary a function of hydrostatic pressure $P_B = P_0 + \rho_w g z = P_0(1 + z/h)$, where ρ_w is the water density, g is the gravitational constant, z is the water depth (positive with increasing depth) and h is the characteristic depth where hydrostatic pressure is doubled ($h \approx 10$ m).

As the bubble rise, its radius changes due to mass flux and decrease in the hydrostatic pressure. The equation describing variation in bubble radius can be derived from the ideal gas law, and if isothermal, is in differential form [2]

$$\dot{R} = \sum_i k_{Bi} \frac{\mathbb{R}T}{P_0} \frac{[c_i - (P_{Bi}/H_i)]}{1 + (z/h)} - \frac{R}{3} \frac{(\dot{z}/h)}{1 + (z/h)}\,. \qquad (2)$$

While the CH_4 outflows the bubble, dissolved air inflows, slowing the rate of bubble dissolution. For the case when air inflow has negligible effect on R Eq. (2) can be rearranged to yield

$$\dot{R} = k_B \frac{\mathbb{R}Tc_0}{P_0} \frac{[(c - c_0)/c_0 - (z/h)]}{1 + (z/h)} - \frac{R}{3} \frac{(\dot{z}/h)}{1 + (z/h)}\,, \qquad (3)$$

here c_0 is the equilibrium concentration for CH_4 under atmospheric pressure and we omitted index.

Newly formed bubbles rapidly accelerate to their terminal rise velocity $v_B(R)$, as determined by the balance between the buoyancy and drag forces. Thus the final differential equation needed to describe bubble evolution has the following form

$$\dot{z} = -v_B = -\left(\frac{2}{9}\right) g \frac{R^2}{\nu}\,. \qquad (4)$$

The explicit expression for the velocity corresponds to dirty bubbles and small Re, here ν is the viscosity. For the same case Eq. (3) takes the form

$$\dot{R} = -\frac{2}{\pi}\left(\frac{2}{9}\right)^{1/3} \left(\frac{D^2 g}{\nu}\right)^{1/3} \frac{c_0}{\rho_g} \frac{(z/h)}{1 + (z/h)} - \frac{R}{3} \frac{(\dot{z}/h)}{1 + (z/h)}\,, \qquad (5)$$

where we neglect difference between aqueous and equilibrium concentrations.

“Car-jam” effect in rising bubble plume

Equations (4) and (5) now together define the vertical motion of the bubble, and its change in radius and composition with time. Using these equations the occurrence of anomalies in concentrations of gas inclusions can be predicted. The inhomogeneity of bubble rise velocity with depth results in that the growth of bubble concentration occurs at the horizon with minimal velocity. One can draw a close analogy to the effect, arising in the theory of transport flows, when at braking "car-jam" occurs and, on the contrary, at acceleration decreasing of concentration takes place.

The bubble distribution, as a function of position **r**, time t and radius R — $f(\mathbf{r},R,t)$, satisfies a kinetic-type transport equation

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial z}(\dot{z}f)+\frac{\partial}{\partial R}(\dot{R}f)=0\,. \qquad (6)$$

We transform governing equations (4-6) into non-dimension form by introducing $t'=t/\tau^*$, $\tau^*=(3\pi/2)(3/4\pi)^{1/9}(c_0/\rho_g)^{-2/3}(\nu^5h^3/D^4)\approx 137s$, $R^*=(162/\pi^3)^{1/9}(c_0/\rho_g)^{1/3}(D^2\nu^2h^3/g^2)\approx 1.9\cdot 10^{-4}\,\mathrm{m}$, $z'=z/h$, $R'=R/R^*$. A steady state solution of kinetic equation (6) satisfies to

$$\frac{\partial}{\partial z'}(R'^2 f)+\frac{\partial}{\partial R'}\left[\left(\frac{z'}{1+z'}-\frac{1}{3}\frac{R'^3}{1+z'}\right)f\right]=0\,. \qquad (7)$$

It may be shown [4] that Eq. (4, 5) have an integral

$$\frac{R'^3}{3}(1+z')-\frac{z'^2}{2}=Const\,, \qquad (8)$$

so that on substituting (8) in (4, 5) exact solutions can be obtained. The characteristics of kinetic equation (7) are simply the bubble dynamic equations. Bubbles trajectories in the space of depths $z'=z/h$ and sizes $R'=R/R^*$ are shown in figure 1.

The formal solution of kinetic equation can be expressed as a linear integral along characteristic curves. Integrating yields

$$f(z',R'(z'))=\frac{(1+z')}{(1+z_0')}f(z_0',R_0')\,, \qquad (9a)$$

$$\frac{R'(z')^3}{3}(1+z')-\frac{z'^2}{2}=\frac{R_0'^3}{3}(1+z_0')-\frac{z_0'^2}{2}\,. \qquad (9b)$$

If at the seabed $z'=z_0'$, the bubble size distribution emitted by vents is $f(z_0',R_0')$, then the size distribution at depth z' $f(z',R')$ will be defined by expression (9a), where $R'(z')$ and R_0' are coupled by trajectory equation (9b).

Let us suppose that emitted size distribution is a sharp function located near an average radius $\bar{R}_0'$. We than can approximate it by δ-function: $f(z_0',R_0')=n\delta(R_0'-\bar{R}_0')$, and obtain at the depth z' the following number of bubbles

$$f\left(z',\left[R_0'^3\frac{(1+z_0')}{(1+z')}-\frac{3}{2}\frac{z_0'^2-z'^2}{(1+z')}\right]^{1/3}\right)=$$

$$=\frac{(1+z')}{(1+z_0')}n\delta(R_0'-\bar{R}_0')\,, \qquad (10)$$

or, if we return to the natural variable R'

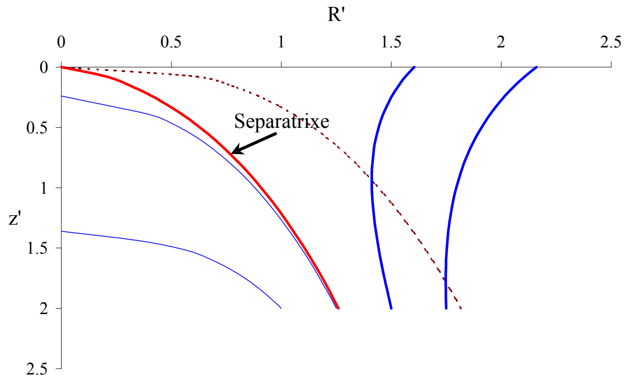

Figure 1. Bubble rise trajectories in the space of depths z' and sizes R'. Separatrixe is shown by the heavy line. The dashed line corresponds to the states where dissolution rate is equal zero ($\dot{N}=0$).

$$f(z',R')=n\delta\left(\left[R'^3\frac{(1+z')}{(1+z_0')}-\frac{3}{2}\frac{z'^2-z_0'^2}{(1+z_0')}\right]^{1/3}-\bar{R}_0'\right)\times$$

$$\times\frac{(1+z')}{(1+z_0')}=n\frac{\bar{R}_0'^2}{\bar{R}'(z')^2}\delta(R'-\bar{R}'(z'))\,, \qquad (11)$$

where $(\bar{R}'(z')^3/3)(1+z')-z'^2/2=(\bar{R}_0'^3/3)(1+z_0')-z_0'^2/2$. Since the bubble radius, and as a consequence of Eq. (4) the terminal rise velocity depend on the depth, it appears that bubble concentration is quit inhomogeneous with depth.

Let us now analyze the degree of space inhomogeneity for bubble distribution. Consider $R'_{cr}=R'_{cr}(z_0')=(3/2)^{1/3}[z_0'^2/(1++z_0')]^{1/3}$ - the characteristic size coinciding with the bubble radius at seabed for the separatrixe trajectory. This trajectory is defined by Eq. (8) when *Const*=0 (see Figure 1) and separates the domain of bubble states (trajectories) rising along which bubble will inevitably dissolve and will not reach the surface and those providing bubble-mediated CH_4 transport to the surface. For $z_0'>>1$ ($z_0>>10\,\mathrm{m}$) we have

$$f(z',R')=\frac{\bar{R}_0'^2(2/3)^{2/3}(z'/z_0')^{2/3}}{z_0'^{1/3}\left[(z'^2/z_0'^2)+\bar{R}_0'^3/R_{cr}^3(z_0')-1\right]^{2/3}}\times$$

$$\times n\delta(R'-\bar{R}'(z')) \qquad (12)$$

We see that rising bubbles with $\bar{R}_0'<R'_{cr}$ diminish monotonically its size till the horizon of dissolution $z_s'=z_0'\left[1-\bar{R}_0'^3/R_{cr}^3(z_0')\right]^{1/2}$, and correspondingly the rise velocity decreases monotonically. As a result bubble concentration will increase, as bubbles approach to stopping horizon in accordance with classical "car-jam" effect. Power singularity in Eq. (12) will not be realized in reality as the solution is to remain finite. Really, as the rise velocity decreases till the value comparable with random (turbulent) pulsation, one should account additional (diffusion-

like) terms [5] in the kinetic equation (6), which will lead to smoothing this singularity.

Bubbles with radii $\bar{R}_0{}' > R'_{cr}$ will always attain the surface. Those with initial radii $1 < (\bar{R}_0{}'/R_{cr}{}')^3 < 2(1 + 1/z_0{}')$ will decrease their sizes at the initial stage till rising at depth $z_m{}' = \sqrt{1 + z_0{}'^2[\bar{R}_0{}'^3/R_{cr}^3(z_0{}') - 1]} - 1$, where their radius $R_{\min}{}' = R'(z_m{}') = (3z_m{}')^{1/3}$ and rise velocity are minimum and, correspondingly, concentration is at most. During their further rising bubble radius growths, as well as the velocity, but concentration decreases.

Finally, bubbles with radii $(\bar{R}_0{}'/R_{cr}{}')^3 > 2(1 + 1/z_0{}')$ growth monotonically as they ascending to the surface, the rise velocity increases and concentration decreases.

Interpretation of echo-sounding records of bubble plumes

The range-gated backscattering intensity measured by sonar provides estimates of the scattering cross section per unit volume of the bubble clouds. The active sonar equation has the form

$$10\lg M_v = RL - SL + 2TL_b + 2TL - 10\lg\left(\frac{U}{4\pi}\right),$$

where M_v is the scattering cross section per unit volume (m^{-1}), RL – is the system receive response (dB re 1Pa), SL – is the system source level (dB re 1Pa), $U = (\Phi/3)\left\{\left[r + (L/4)\right]^3 - \left[r - (L/4)\right]^3\right\}$ – is the insonified volume (m^3), Φ – is the ideal beam pattern, solid angle, L – is the pulse length in water (m), TL – is the one way transmission loss (dB), TL_b – One way bubble transmission loss (dB).

Bubble contribution to the back scattering is defined by

$$M_v^b(x,y,z) = \int_0^\infty \sigma_s^b(R) f(x,y,z,R)\,dR$$

where $f(x,y,z;R)$ is the bubble size distribution and $\sigma_s^b = 4\pi R^2\left[(f_R/f)^2 + \delta^2\right]^{-1}$ is the bubble scattering cross section, $f_R = \sqrt{3\gamma P_0(1 + z/h)\rho_0^{-1}R^{-2}}$ is the natural frequency, f is the sound frequency, δ – is the damping constant.

Current methods of evaluation of echo-sounding records are based on the assumption of dominant contribution of the resonant bubbles in the back-scattering cross section (at the sonar frequency *f*, a bubble of the given size $R_r(z') = R_r(0)\sqrt{1 + z'}$ is in resonance with the exciting sound wave at depth z', where $R_r(0)$ is the resonant radius at atmospheric pressure). The interpretation of the observations

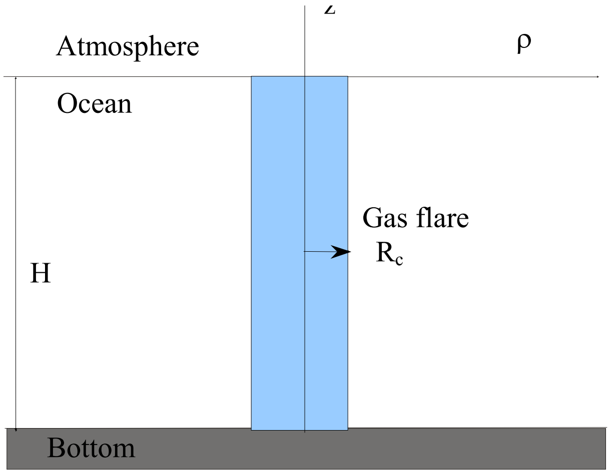

Figure 2. Geometry of a model gas plume: bubbly medium in the form of a cylinder with radius R_c and length H surrounding by water is considered as waveguide.

depends on the dynamics of, and gas flux from, individual bubbles.

In evaluating the sonograph ‘pictures’ of bubble clouds the population of resonant bubbles can be determined at different depths. These define a set of ‘initial values’ on the trajectories of dynamical system (4), (5) that describe growth and dissolution of rising bubbles. The exact solutions of these equations (reversed in time) make it possible to determine bubble population and spectra near the sea bottom.

If the emitted size distribution of bubbles is narrow and $R_0' < R_{cr}'$, all bubbles will dissolve at about the same depth, i.e. in a thin layer. Any substances carried by the bubbles, e.g. sediments, contaminant particles, bacteria, etc will be deposited in this layer. For oily bubbles this implies a subsurface oil layer. This leads to great increase of the acoustic scattering cross section of the layer and sonograph image will dominate by the dark patch, which can not begin with dark resonant bubbles lines.

Noise spectrum of gas flare

A passive method for diagnostics of gas vents can be suggested. A rising bubble plume forms an effective acoustic waveguide that possesses normal modes. The “birthing wails” of the bubbles as they depart from the vent is accompanied by generation of broadband noise. The noise frequency spectrum has several peaks related to the lowest-mode frequencies of the bubble plume. Explicit expression for the frequencies of these modes have been derived for the bubbly medium in the form of cylinder with radius R_c and length H

$$\omega_n^* = \frac{c_m}{R_c}\left|\ln\left(\frac{R_c(\pi n)}{H}\right)\right|^{-1/2}, \qquad (13)$$

here n is the mode of number, $c_m^2 = \left(c^{-2} + \beta\rho_0 / P\right)^{-1}$ is effective Wood's sound speed in bubble mixture,. $f(R)$ is the bubble size distribution and $\beta = (4\pi/3)\int f(R)R^3 dR$ is the void fraction.

An extension of the approach [6] is presented to prediction of seep intensity on the base of the measured sound spectral density and the solution of the Helmholtz equation. The quantity measured experimentally is the sound spectral density SD defined by

$$\mathrm{SD} = 10\lg\left(\frac{4\pi\left|\hat{P}_T(\omega)\right|^2}{T\left(P_{ref}^2/\Gamma\text{ц}\right)}\right) \qquad (14)$$

where $\hat{P}_T$ is the Fourier transform of the measured pressure, T is the duration of each sampling interval, and P_{rel} - the reference pressure ($P_{rel} = 1\mu Pa$). Since the problem is linear we have $\left|\hat{P}_T\right|^2 = \left|\hat{P}_B\right|^2 \left|P\right|^2$, where P – is the solution of Helmholtz equation for forcing by an imposed pressure field of unit amplitude and time dependence $\exp(-i\omega t)$ at the base of column of bubbly liquid, and P_B is the noise pressure due to the process of bubble formation at the base of column. With the assumption that the acoustic emission is incoherent we have

$$\left|\hat{P}_B\right|^2 = \dot{n}T\left|<\hat{p}_B>\right|^2, \qquad (15)$$

in which $<\hat{p}_B>$ denotes the averaged contribution of each bubble and $\dot{n}$ is the number of bubbles generated per unit time given by- $\dot{n} = \dot{V}\big/\left[(4/3)\pi R_m^3\right]$. Here $\dot{V}$ is the total volume flow rate and R_m is a characteristic radius of the bubbles coinciding with the magnitude of maximum bubble size distribution. At frequencies much below the natural frequencies of the bubbles we have

$$\left|\hat{P}_B\right|^2 = 2\rho_0^2\dot{n}T\frac{R_m^6}{R_c^2}\frac{\dot{n}_N^2}{9\pi}, \qquad (16)$$

where $\dot{n}_N$ - is the number of bubbles generated per unit time in each vent. An interpretation of the argument used to obtain this result is that the base of the column has been divided into N incoherent «pistons», each one of which acts on the column over the area $\pi R_c^2/N$.

In examining the power spectra of the noise field near the gas flare the lowest peak can be interpreted as corresponding to the lowest-mode frequency resonance of the bubble column Eq. (13). Evaluating on the base of the echo-sounding data cross section of the plume and thus R_c one can find void fraction at the bottom $\beta(H) = (4/3)\pi R_m^3 v_B^{-1}(N/\pi R_c^2)\dot{n}_N$, where v_B is the bubble rise velocity. The use of measured values of SD Eq. (14) and solution of the Helmholtz equations allows one to determine noise intensity at the bottom Eq. (16) which is expressed in terms of $(N/\pi R_c^2)$ - the distribution of vents over the bottom and ($\dot{n}_N$) – the number of bubbles generated per unit time in each vent. Thus the inverse problem of evaluation of parameters of gas vents by acoustical methods has the solution as we have two equations for two variables.

Conclusions

We have shown that the acoustical methods can be effective in evaluation of parameters of marine seeps. Bubble-mediated transport for a natural hydrocarbon seep is a complex process dependent on many parameters. The present analysis is strictly valid only for dirty bubbles and small Reynolds numbers. The obtained simple analytical dependences apply only qualitatively to intense seeps. The purpose of the present study was to gain only a first insight into the problem by finding analytically the active and passive acoustical response of marine seeps.

Acknowledgments

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References

[1] Report R/V M.Keldysh Cruise 11 A, “Gas hydrate accumulation in Okhotsk Sea,” IO AS, Leningrad 1988.
[2] V.K. Goncharov, N.Yu. Klement'eva, “Modeling the dynamic and conditions of sound scattering by gas bubbles floating up from deep-water oil and gas deposits,” Phys. Acoust., vol. 42, pp. 371-377, 1996.
[3] I. Leifer, R.K. Patro, “The bubble mechanism for methane transport from the shallow sea bed to the surface: A review and sensitivity study,” Continental Shelf Research, vol. 22, pp. 2309-2428, 2002.
[4] A.O. Maksimov, “Time variation of back scattering from the ascending bubble plume,” in Marine technologies, IPMT FEBRAS, Vladivostok, vol. 2, pp. 167-175,. 1998.
[5] A.O. Maksimov, E.V. Sosedko, “Dynamic of dissolution of ascending gas bubbles in random flows,” in Marine technologies, IPMT FEBRAS, Vladivostok, vol. 4, pp. 193-202, 2001.
[6] M. Nicholas, R.A. Roy, L.A. Crum, H. Oguz, A. Prosperetti, “Sound emissions by a laboratory bubble cloud,” J. Acoust. Soc. Am., vol. 95, pp. 3171-3182, 1994.