Reflection of acoustic waves from the boundary of contaminated fog

IOP Conf. Series: Journal of Physics: Conf. Series **1058** (2018) 012054 doi:10.1088/1742-6596/1058/1/012054

Reflection of acoustic waves from the boundary of contaminated fog

D A Gubaidullin, Yu V Fedorov, R R Zaripov
Institute of Mechanics and Engineering - Subdivision of the Federal State Budgetary Institution of Science ”Kazan Scientific Center of the Russian Academy of Sciences”, 2/31 Lobachevsky str., Kazan 420111, Russia
Kazan (Volga Region) Federal University, 18 Kremlyovskaya str., Kazan 420008, Russia

E-mail: gubaidullin@imm.knc.ru

Abstract. The problem of oblique incidence of an acoustic wave from pure air to the boundary of a vapor-gas mixture with droplets of liquid and solid particles is considered. Dependencies of the reflection coefficient of an acoustic wave on the volume content of inclusions and the angle of incidence of a wave are given. The influence of phase transitions is studied.

1. Introduction

The study of the reflection of acoustic waves from the vapor-gas medium is actual. This is mainly due to natural phenomena, such as a layer of fog, dusty gas in the atmosphere and atmospheric clouds. It is also possible to use various gas-droplet mixtures (fogs) to hide various objects from radars, for example ships. Such media are unusual, since they are characterized by the dispersion of the speed of sound. The dynamics of wave processes in such media was presented in well-known monographs [1, 2, 3]. Numerical and experimental analysis of the processes occurring in such media was considered in [4, 5]. A more interesting medium is a polydisperse medium, because such medium more accurately describes models of real medium. The influence of polydispersity on the propagation of sound in complex media was considered in [6, 7]. The problem of reflection of an acoustic wave from a fog boundary without phase transformations was considered in [8]. In this work the effect of phase transformations on the reflection of an acoustic wave from the boundary of a two-fraction vapor-gas-droplet mixture with polydisperse inclusions is studied.

2. Mathematical model.

We consider two mediums and denote them by numbers 1 and 2. Suppose that there is a planar interface between them, which coincides with the x-axis. The acoustic wave falls from the medium 1 to the interface of the medium 2. The angle at which the wave falls is measured from the normal (z axis) of the interface between the two media and denoted by θ_1 (Fig. 1). In this case, the reflection coefficient can be represented in the form [9]

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (1)$$

$$Z_i = \frac{\rho_i C_i}{\cos\theta_i}, i = 1, 2, \theta_2 = \arcsin\left(\frac{C_2}{C_1}\sin\theta_1\right)$$

Here R - a reflection coefficient, ρ - density, C - speed of sound, subscripts 1 and 2 refer to mediums 1 and 2.

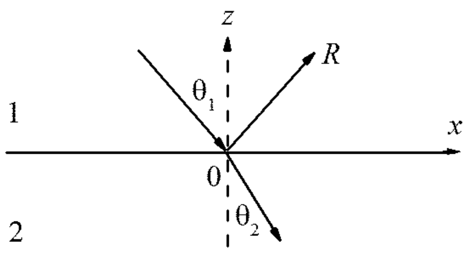

Figure 1. Scheme of the media.

It can be seen from formula (1) that to determine the reflection coefficient it is necessary to know the density and speed of sound in mediums 1 and 2. Analysis shows that the effect of phase transformations on the velocity in aerosol is more pronounced at low frequencies [2]. Thus, to study the effects of phase transformations on the reflection coefficient, we will use the equation for equilibrium velocity in the medium. The equation for the equilibrium speed of sound in a vapor-gas-droplet mixture with two fractions of inclusions has the form [10]

$$C_2 = C_1\left(\frac{\gamma_e}{m_1\gamma_1}\right)^{1/2}, m_1 = 1 + m_a + m_b \tag{2}$$

$$\gamma_e = \frac{m_2 R_V^*(1 - k_V R_V^*) + L}{(m_2 - 1)R_V^* + L - L_1 R_V^*/\gamma_1}, R_V^* = \frac{R_V}{R_1}, L = \gamma_1(\gamma_1 - 1)k_V l_0^{*2},$$

$$m_2 = 1 + \frac{m_a c_{2a}}{c_{p1}} + \frac{m_b c_{2b}}{c_{p1}}, L_1 = k_V(\gamma_1 - 1)(2l_0^*\gamma_1 - R_V^*) - 1, l_0^* = \frac{l_0}{C_1^2}$$

$$R_1 = k_V R_V + (1 - k_V)R_G, \gamma_1 = k_V\gamma_V + (1 - k_V)\gamma_G$$

Here, subscripts V refer to the vapor component of the carrier phase, G - to the gas component, a - to the first fraction, b - to the second fraction, γ - ratio of specific heat, k -the mass concentration of the vapor or gas, m - mass concentration, R - constant value of vapor or gas, c_p - specific heat, l_0 - specific heat of vaporization, C_1 - speed of sound in the carrier phase (gas).

3. The results of calculations.

Let us consider the fall of a low-frequency acoustic wave to the interface between two mediums. Let the wave fall from the side of air to the boundary of the vapor-gas mixture with droplets of water and ash particles at some angle. From the formulas (1) and (2) we obtain:

$$R = \frac{\rho_2 C_2/\cos\theta_2 - \rho_1 C_1/\cos\theta_1}{\rho_2 C_2/\cos\theta_2 + \rho_1 C_1/\cos\theta_1}, \theta_2 = \arcsin\left(\frac{C_2}{C_1}\sin\theta_1\right) \tag{3}$$

Calculations were obtained using formulas (2) and (3), the density of this mixture was determined as $\alpha_1\rho_1 + \alpha_{2a}\rho_{2a} + \alpha_{2b}\rho_{2b}$.

Fig. 2 shows the results of the reflection coefficient in dependence on the volume content of the drops of the first fraction, when acoustic wave falls at different angles. Here, the initial concentration of vapor $k_{V\,0}$ = 0.01, the volume content of particles of the second fraction α_{2b} = 0.005. Under normal incidence θ_1 = 0 of an acoustic wave, the curve $|R^2(\alpha_{2a})|$ is

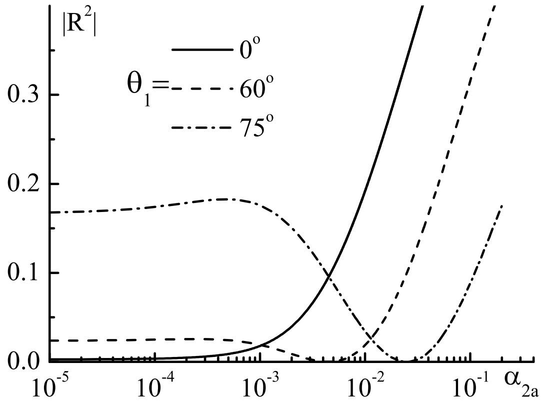

Figure 2. Dependencies of the reflection coefficient on the volume content of the inclusions.

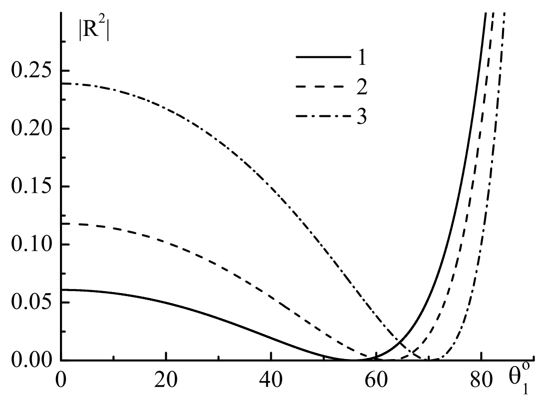

Figure 3. Dependencies of the reflection coefficient on the angle of incidence of the wave

monotonic, and if the angle of incidence of the wave grows up to 60° and to 75°, the curve $|R^2(\alpha_{2a})|$, as we can see, is not monotonic. Thus, when the wave falls at an angle θ_1 = 60° the curve $|R^2(\alpha_{2a})|$ practically does not change at volume drops $\alpha_{2a} < 10^{-3}$ and assumes a certain constant value. Then the curve decreases, which reaches a minimum at $\alpha_{2a} \approx 4.5 \cdot 10^{-3}$ and takes a zero value. In this way, an acoustic wave passes through the boundary completely for a given volume content. When the wave falls at an angle θ_1 = 75° a similar behavior of the reflection coefficient curve is observed. The only significant difference between them, is that the total passage of the wave through the boundary occurs with the volume content of the droplets $\alpha_{2a} \approx 2.5 \cdot 10^{-3}$.

Fig. 3 shows the reflection coefficient in dependence on the incidence angle of acoustic wave θ_1. The volume content of particles of the second fraction α_{2b} = 0.001, initial vapor concentration $k_{V\,0}$ = 0.01. Curves: 1 - α_{2a} = 0.0023, 2 - α_{2a} = 0.005, 3 - α_{2a} = 0.013. Here we should be noted, that the reflection coefficient does not depend monotonically on the angle of incidence of the wave. At the different value of the incidence angle the reflection coefficient reaches a minimum value, where the reflection coefficient becomes zero. The value of the angle at which the acoustic wave passes completely across the boundary depends on the volume content of the inclusions. For the case, when the volume content of the droplets α_{2a} = 0.0023 the wave is completely absorbed at θ_1 = 55°.The value of the angle, at which the wave passes without reflection across the boundary, increases with an increase in the volume content of the inclusions. To find out at which values of the incidence angles of the wave and the volume content of the inclusions, the incident wave will not be reflected from the interface of the two media, we turn to the analytical
expression [11, 12]

$$\theta_1^* = \arcsin\sqrt{\frac{\rho_2^2 C_2^2 - \rho_1^2 C_1^2}{C_2^2(\rho_2^2 - \rho_1^2)}} \tag{4}$$

where $\theta_1{}^*$ - is the critical angle of incidence of the wave, under which the condition for the complete passage of the wave across the boundary is satisfied.

Fig. 4 shows calculations of the dependences of the critical angle on the volume content of the inclusions, in which the incident wave is not reflected from the interface between the two media. Here, the curves in the form of lines correspond to different values of the vapor concentration obtained with the help of formula (4), and the points are constructed according to theoretical data [13]. As can be seen from the figure 4, the curve obtained by formula (4) agrees well with theoretical data [13].

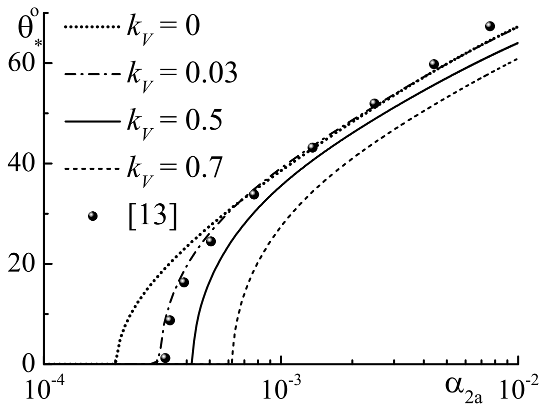

Figure 4. Dependencies of the critical angle of incidence on the volume content of the inclusions

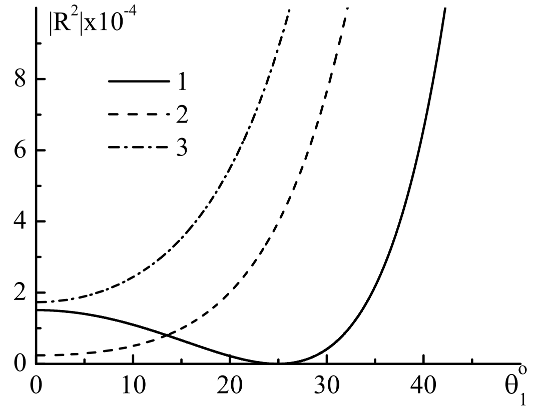

Figure 5. Dependencies of the reflection coefficient on the angle of incidence of the wave

Fig. 5 shows the reflection coefficient in dependence of the incidence angle of acoustic wave θ_1. Here $\alpha_2 a = 10^{-4}$, $\alpha_{2b} = 10^{-4}$, curves 1 - $k_{V0} = 0$, 2 - $k_{V0} = 0.01$, 3 - $k_{V0} = 0.05$. As can be seen from the figure, when there are no phase transformations, the reflection coefficient depends non-monotonically on the angle of incidence of the wave. And for given volume contents of inclusions the wave passes without reflection at θ_1 = 25°. For curves $|R^2(\theta_1)|$ with allowance for phase transitions, a monotonic dependence is observed.

Conclusions

The fall of a low-frequency acoustic wave from pure gas at different angles to the boundary of a vapor-gas mixture with droplets of water and ash particles is considered. The effects of the initial vapor concentration, the volume content of inclusions and the angle of incidence of the wave on the reflection coefficient were analyzed. It is shown, that the dependence of the reflection coefficient on the volume content is monotonic, in the case of a normal incidence of the wave, and in the case of an oblique incidence of the wave, a nonmonotonic dependence is observed. It is illustrated that for certain volume contents of inclusions and the angle of incidence of the wave the reflection coefficient assumes zero values. Namely, the incident wave passes without reflection through the interface between two media.

References

[1] Nigmatulin R I 1989 *Dynamics of multiphase media* (Moscow: Nauka)
[2] Gubaidullin D A 1998 *Dynamics of two-phase gas-vapor-droplet media* (Kazan: Kazan mathematical society)[3] Temkin S 2005 *Suspension acoustics: An introduction to the physics of suspension* (New York: Cambridge University Press)
[4] Bezrukov N A and Chernookulsky A V 2015 *Proceedings of the Russian Academy of Sciences. Physics of the atmosphere and ocean* 52 577
[5] Baudoin M, Coulouvrat F and Thomas J L 2011 *J. Acoust. Soc. Am.* 130 1142
[6] Gumerov N A and Ivandaev A I 1988 *PMTF* 115
[7] Gubaidullin D A and Ivandaev A I 1993 *PMTF* 75
[8] Shagapov V Sh and Sarapulova V V 2014 *Izvestiya Atmospheric and Oceanic Physics* 50 602
[9] Brekhovskikh L M and Godin O A 1989 *Acoustics of Layered Media* (Moscow: Nauka)
[10] Gubaidullin D A and Fedorov Yu V 2012 *High Temperature* 50 616
[11] Gubaidullin D A and Fedorov Yu V 2018 *Acoustical Physics* 64 164
[12] Gubaidullin D A and Fedorov Yu V 2017 *Doklady Physics* 62 478
[13] Shagapov V Sh and Sarapulova V V 2015 *Applied Mechanics and Technical Physics* 56 119