Study of aerosol behavior under resonant vibrations in the vicinity of an open end of a pipe

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Annotation. The aerosol movement at an open end of a pipe at the resonant frequency was experimentally studied. The aerosol flow in an external wave field was visualized. The numerical value of the Rayleigh correction for an open end of an experimental plant was obtained. A good agreement between the numerical and experimental values was demonstrated.

1. Introduction
Interest in the study of nonlinear gas vibrations in pipes in the vicinity of resonances is relevant due to the widespread occurrence of the process in modern applications. Under such vibrations, various nonlinear effects occur, e.g. a pulsejet at the open end, vortex structures, thermo-acoustic effects, etc. When studying theoretically the resonance gas vibrations in the open pipe, considerable difficulties emerge because of the mentioned effects in the nonlinear wavefield at the pipe outlet section [1]. In this regard, both theoretical and experimental evaluations of parameters associated with the gas and aerosol outflow from the open end of the pipe are important.

2. Experimental plant
Experimental plant (Fig. 1) is a vibration generator 1 Model TIRAvib S 5220/LS with a power amplifier BAA 1000-ET made by TIRA Company. A flat piston with the diameter of \( R = 0.05 \) m was installed on the table of the vibration generator, it produced vibrations inside the cylinder connected to the vertical quartz pipe 3 with the length of \( L_0 = 0.918 \) m. Control and monitoring over the vibration stand were carried out with a computer by means of the piezo-electric IEPE accelerometer 2 Model 4513 made by Bruel & Kjaer Company and controller of VR9500 type made by Vibration Research Corporation. Di-ethyl-hexyl-sebacate [2] was used as an operating medium. The aerosol was created from it using the aerosol generator ATM 225 made by TOPAS Company. The process of the aerosol deposition was recorded with the camera 4 Canon EOS 650D with the lens EF-S 18-55 mm IS II Black installed perpendicularly on a tripod. Black screen 5 was installed behind the pipe for a clear and sharp picture.
Figure 1. Scheme of the experimental plant: 1 – vibration stand, 2 – accelerometer, 3 – pipe, 4 – video camera, 5 – screen.

The experiment was carried out under conditions of the full filling of the pipe with the aerosol to the edge of the open end. Sinusoidal vibrations were produced in the pipe at the resonant frequency of $\nu = 90.3$ Hz with the piston shift amplitude of $l = 0.75$ mm. The video recording was started synchronically.

3. Results and discussion
The experimental results are shown in Fig. 2.

Figure 2. Pictures of the aerosol outflow from the open end of the pipe at the resonant frequency of $\nu = 90.3$ Hz with the piston shift amplitude of $l = 0.75$ mm, where a – $t = 0$ sec., b – $t = 0.8$ sec., c – $t = 1.1$ sec.
The experiment was started with the value of \( t = 0 \) (Fig. 2a) when the aerosol fully filled the pipe without vibrations. At the experiment beginning, the aerosol is released into the external environment under the influence of the gas flow in the area of the open end of the pipe (Fig. 2b). Herewith, the time during which the aerosol starts moving is less than 1 sec. During the time of 1.1 sec. (Fig. 2c), a stable parabolic profile with the linear speed of 0.029 m/sec. is formed. Then, its character is changed due to the formation of vortices in the jet (Fig. 3.) [3].

![Image](image-url)

**Figure 3.** The video segment of the aerosol release from the open end of the pipe at the resonant frequency of \( \nu = 90.3 \) Hz with the piston shift amplitude of \( l = 0.75 \) mm at the moment \( t = 1.5 \) from the experiment beginning.

It can be assumed that the outflow shape retains its form over the distance of the Rayleigh correction. Experimental measurement shows that \( \sigma_1 = 0.64 \) and respectively \( \sigma_1 R = 0.032 \) m.

It is known that a sound wave is reflected at the open end of the circular pipe if the pipe diameter is small compared to the wavelength [4]. Concurrently, the resonant frequency is decreased as a result of the pipe length increasing by a value of \( \sigma_1 R \). This value is usually called the Rayleigh correction for the open end of the pipe. The \( \sigma_1 \) value for the pipe with the endless flange has been determined by Rayleigh within the limits [5]

\[
\frac{1}{4} \pi R < \sigma_1 < \frac{8}{3\pi} R
\]

(1)

\( R \) – pipe radius, \( \sigma_1 \) - coefficient that determines presence or absence of the flange.

More accurate calculations carried out by Rayleigh depend on the minimum energy argument and give a value for \( \sigma_1 = 0.82 \).

The introduced correction that must be added to the pipe length \( L_0 \) to take into account the open end in the form

\[
L = L_0 + \sigma_1 R
\]

(2)

should be taken into account in theoretical calculations in the area of an open pipe [5, 6], where the gas outflow may be considered as jet and \( L_0 \) is a pipe length, \( L \) is a calculated length.

Calculations for the open pipe without the flange were given in [4], they gave an accurate solution of the acoustic problem based on the Wiener–Hopf equation

\[
\alpha = 1.226, \ \omega = 4\pi
\]

(3)

Generalization of the \( \sigma_1 R \) correction for the canonical shape without the flange was proposed by Chester [7], where
\[ \sigma_1 R = \frac{1}{2} \alpha R \left( \frac{\omega}{4 \pi} \right)^{3/2} \]

(4)

\[ \alpha = 1 + 0.5 \left( \frac{\omega}{4 \pi} \right) - 0.3641 \left( \frac{\omega}{4 \pi} \right)^{3/2} + 0.3864 \left( \frac{\omega}{4 \pi} \right)^2 - 0.2957 \left( \frac{\omega}{4 \pi} \right)^{5/2} \]

(5)

ω – solid angle.

For this experimental plant, using the equations (4-5), we obtain the values for the coefficient \( \sigma_1 = 0.6133 \) and \( \alpha = 1.226 \), thus the Rayleigh correction \( \sigma_1 R = 0.03 \) m.

The theoretical estimate obtained is in good agreement with the experimental results [8-10].

4. Conclusion

The gas flow in the area of the open end of the pipe at the resonant frequency under high-intensity vibrations was studied. It was found that the aerosol retains its parabolic shape while outflowing from the pipe at the distance of 0.032 m for 1.1 sec. from the experiment beginning. A good agreement between the theoretical and experimental values of the Rayleigh correction was found.

References

[1] Ilgamov M A, Zaripov R G, Galiullin R G, Repin V B 1996 Appl. Mechanics Reviews 49 137
[2] Gubaidullin D A, Zaripova R G, Tkachenko L A, Shaidullin L R 2018 High Temperature 56 146
[3] Gubaidullin D A, Kashapov N. F, Zaripov R. G, Tkachenko L A, Shaydullin L R 2017 J. Phys.: Conf. Ser. 789 012017
[4] Levine H and Schwinger J 1948 Physical Review 73 383
[5] Rayleigh J W S 1945 The Theory of Sound (Dover Publications) 480
[6] Zaripov R G, Tkachenko L A, Shaidullin L R 2017 J. of Engin. Physics and Thermophysics. 90 1463
[7] Chester W Math. Phys. 1983 34 412
[8] Zaripov R G, Tkachenko L A, Shaidullin L R 2015 J. of Engin. Physics and Thermophysics. 88 871
[9] Shaydullin, L.R. 2016 IOP Conf. Ser.: Mater. Sci. Eng. 134 012022
[10] Gubaidullin D A, Zaripova R G, Tkachenko L A, Shaidullin L R 2017 High Temperature 55 469