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Influence of the nozzle shape on sound generation in a jet-driven Helmholtz oscillator

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Abstract. The excitation of pressure fluctuations by an air jet in the model of a Helmholtz oscillator, consisting of a cylindrical chamber with a nozzle in the front cover and an outlet opening in the rear one was studied. The influence of the shape of the nozzle in combination with the length of the chamber and the diameter of the outlet opening was considered. The amplitude-frequency spectra when changing the configuration of the oscillator and the Reynolds number in the allowable range was analyzed. The formation of the reverse flow area in a cylindrical nozzle and its influence on the intensity of the interaction of the jet with the flooded chamber volume are considered. The advantage of a nozzle with a profiled inlet providing a continuous flow in the nozzle and a top-hat profile of velocity at the nozzle exit are determined. The jet-driven Helmholtz oscillator can be used as a downhole emitter for intensifying oil production.

1. Introduction

To increase oil recovery in productive formations, the method of wave action by pressure fluctuations on the bottomhole formation zone is used. When pumping technical fluid into the formation, flowing hydrodynamic emitters are used, which are installed in injection wells. All liquid flows through these emitters, and part of the energy of the pressure is converted into the energy of elastic vibrations during deformation of the flow in the profiled channel of the emitter.

The highest efficiency of energy conversion is provided by the configuration of the channel, made according to the scheme of the jet-driven Helmholtz oscillator (JDHO). Structurally, the JDHO is a cylindrical chamber with two flat covers. There are through openings in the covers. The opening in the front one – the nozzle – serves to supply fluid to the chamber, and the hole in the back one serves to remove the spent fluid from the chamber. A stream of liquid inside the chamber develops along the axis, in the interval between the openings in the covers.

From a physical point of view, JDHO is a combination of two relatively independent devices: a jet generator (JG) and an acoustic resonator (AR) [1]. The jet generator consists of a nozzle, a jet of liquid and a sharp annular edge of the outlet opening. It is known that such a JG "nozzle - jet - sharp edge" is capable of producing small pressure fluctuations at discrete frequencies f_n in local space when the jet interacts with a sharp edge [2]. A jet generator is placed inside the chamber of the acoustic resonator. The acoustic resonator is a cylindrical chamber with two openings. When one of the discrete frequencies f_n coincides with the natural frequency of oscillations (NF) f_0 of the acoustic resonator, resonance occurs ($f_R \approx f_0$), where f_R is the resonance frequency. At the same time, harmonic-type acoustic waves are emitted from the outlet opening.

Historically, JDHO evolved from a flow-obstacle-generating system capable of producing pressure fluctuations of small amplitude in the surrounding space [3] when a stream flows at a certain speed W onto an obstacle in the form of a rod [4], which leads to the formation of the Karman vortex street behind the obstacle (see the corresponding section in the Van Dyke album). The frequency of vortex formation f in the wake behind a rod of diameter D smoothly changes in accordance with the Strouhal number ($Sh_D = f \cdot D/W$) over a wide range of parameters D and W.

The development of jet sound sources is the "nozzle-jet-wedge" generating system with an active element in the form of a flat jet, the speed of which is conveniently controlled by adjusting the pressure drop ΔP on the nozzle ($W^2 = 2\Delta P/\rho$), where ρ is the density of the liquid. It turned out that the wedge value should be proportional to the jet thickness, and the jet length L ($Sh_L = f \cdot L/W$) [5] is the size that determines the generation frequency f. The generation frequency f is intermittent and is related to the feedback one that determines the tone frequency f_T.

In the axisymmetric JG "nozzle - jet - hole" with a round nozzle, the outlet opening must be proportional to the nozzle, and the jet length L ($Sh_L = f \cdot L/W$) is also the size that determines the generation frequency f. The theory of sound generation in JG "nozzle - jet - opening", proposed by Kruger and Schmidtke [6], explains the discrete frequency of generation by the formation of a chain of vortex disturbances on the jet shell (Kelvin – Helmholtz vortices).

Kelvin-Helmholtz vortices are formed with stable periodicity in the mixing layer of a free stream flowing out of the hole into the flooded space. The vortex intensity is determined by the velocity gradient dW/dy in the mixing layer [7], where dy is the transverse coordinate, in other words, the velocity distribution in the cross section of the jet at the outlet of the hole.

The formation of a velocity diagram with gently sloping edges provides a low velocity gradient in a thick mixing layer and a low vortex formation intensity. A rectangular velocity diagram at the exit of the hole with a sharp change in velocity at the jet boundary provides a high velocity gradient in a thin mixing layer and a high vortex formation intensity. The authors of [7] reported on the influence of the shape of the nozzle on the formation of Kelvin – Helmholtz vortices. In the case of a profiled nozzle with a rectangular velocity diagram at the outlet opening, a chain of vortices begins to form directly in the plane of the nozzle exite. Lengthening the profiled nozzle with a cylindrical section leads to smoothing (rounding) of the velocity diagram at the edges and a thickening of the mixing layer. As a result, the velocity gradient becomes less sharp, and the onset of vortex formation shifts further from the nozzle exit.

In [8], the influence of the shape of the velocity diagram on the flat nozzle exit in the jet system "nozzle – jet – wedge" on the generation spectrum was studied. A significant difference is noted in the amplitude-frequency spectra of generation in the case of using two nozzles: forming jets with a rectangular and parabolic exit velocity profile.

The combination of JG with an acoustic resonator allows pressure fluctuations of significant amplitude in the surrounding space. A resonator with a single neck can be excited by a sliding fluid stream flowing along the plane of the throat and touching the sharp edge of the throat [9], or by a sliding jet also touching the sharp edge of the throat [10]. An ordinary referee whistle works in a similar way [11].

In [12], a detailed study of both the influence of the configuration of individual elements of the device and their mutual arrangement on the generation amplitude in the air flow is presented. Unfortunately, in his many experiments, the author used a cylindrical nozzle of constant length equal to its diameter (one gauge). The author compared a cylindrical nozzle with a profiled one, but did not notice a noticeable advantage in a profiled nozzle.

In our work, we present the results of experiments with the JDHO model, in which the cylindrical nozzle had a different length, or the rounding of the input edge.

2. Model, methodology and experiment

The model JDHO was a cylindrical chamber 1 (figure 1), limited on both sides by covers. A through round opening was made in the center of the front cover 2 — a nozzle 3, and a round outlet opening 5 was made in the center of the rear one 4. A measuring microphone 6 was mounted in the front cover and there was an opening 7 for measuring the static pressure in the chamber. The camera was made from pieces of plastic pipe. The nozzle is designed to accelerate the flow of air before feeding it into the chamber. The outlet opening is designed to remove exhaust air from the chamber.

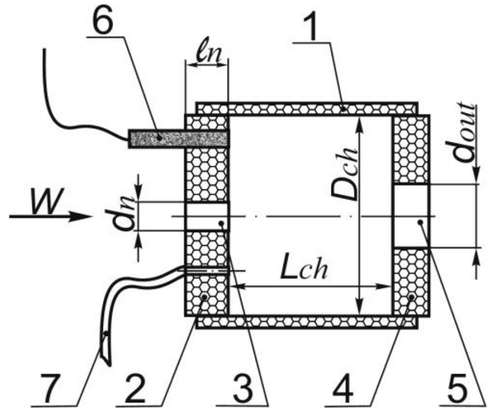

Figure 1. The scheme of the model of the jet-driven Helmholtz oscillator.

The experimental test stand was a vacuum chamber connected to a vacuum pump. The model JDHO was mounted on the lid of the camera, with an outlet inside the camera. Air was sucked into the nozzle from the laboratory. Installation of the model, measuring equipment and the algorithm for processing the measurement results are described in detail in [13-14]. The jet length ℓ_{JET} corresponded to the chamber length L_{CH} and was determined by the interval between the lids (L_{CH}/d_N=0.5-3.5), where d_N is the nozzle diameter. The outlet opening was made with a diameter of d_{OUT} from 10 to 30 mm (d_{OUT}/d_N =1-2.5) and a length of 10 mm.

Microphone RFT MV 201 Robotron measured the pressure fluctuation in the chamber with a frequency above 20 Hz. The static pressure in the chamber was measured by the strain gauge pressure transducers PD 150-DV250 and PD 150-DV2500 OVEN in the corresponding pressure variation intervals. The signals from the microphone and pressure transducer were fed into the E14-140 14 module of an analog-to-digital converter (ADC) with a sampling frequency of 10 kHz and then to a personal computer (PC). For registration and signal processing, the program Power Graph 3.3.8 (PG) was used. The total error of the acoustic measuring system when recording the signal frequency was about 0.4%. The error of the PD is declared by the manufacturer within 1.5%.

The Strouhal numbers ($Sh_L = f \cdot L_{CH}/W$) and Reynolds numbers ($Re_L = L_{CH} \cdot W/\nu$), where ν is the kinematic viscosity of air, in this work were calculated from the ideal jet velocity $W^2 = 2\Delta P/\rho$. Air was considered to be an incompressible fluid at a speed of 70 m/s [15]. The generation amplitude is considered to be the one of the pressure fluctuations inside the cavity chamber, measured with a microphone.

3. Results and analysis

The results of experiments with the JDHO model are presented in figure 2, where it is seen that the generation amplitude curves have a pronounced upper extremum, in the region $L_{CH}/d_N \approx 2$, and a decrease or increase in the length of the chamber leads to a decrease in the generation amplitude. The optimal length of the cylindrical nozzle is $\ell_N/d_N \approx 2$.

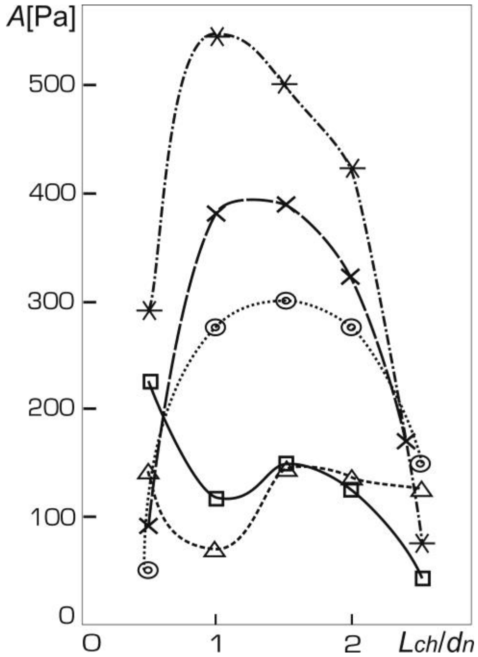

Figure 2. The influence of the nozzle length ℓ_N and the rounding of the input R_N on the generation amplitude A at different chamber lengths L_{CH}/d_N and d_{OUT}/d_N=1.33 in JDHO.
Δ – $\ell_N = d_N$; □ – $\ell_N = 1.37\ d_N$; x – $\ell_N = 2\ d_N$; ʘ – $\ell_N = 2.9\ d_N$; * – $R_N = d_N/2$ ($\ell_N = 1.37\ d_N$)

From consideration of figure 2, it becomes obvious that in the manufacture of the JDHO model, the length of the cylindrical nozzle is important to ensure a high generation amplitude. As one can see, the nozzle length should be approximately two diameters ($\ell_N \sim 2\ d_N$).

The velocity profile at the nozzle exit varies with its length, since the jet inside the nozzle accelerates and contracts to the minimum cross section, approximately one gauge distant from the entrance plane (ℓ/d = 1). Further, the jet gradually expands and carries adjacent air layers into its motion, forming a region of reduced pressure inside the nozzle. Inside the nozzle, a reverse flow area (RFA) is formed, communicating with the chamber volume behind the nozzle exit. The shape of the RFA determines the velocity profile at the nozzle exit and the intensity of the interaction of the jet with the surrounding air.

As experiments show, the presence of a RFA in the nozzle leads to a decrease in the generation amplitude in the device, since the thickness of the mixing layer increases and the velocity gradient at the jet boundary decreases. A nozzle with a profiled inlet provides an uninterrupted flow along the walls and forms a stream with a top-hat velocity distribution over the cross section at the outlet.

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