ISSN 1063-7710, Acoustical Physics, 2014, Vol. 60, No. 1, pp. 123–125. © Pleiades Publishing, Ltd., 2014.

PHYSICAL FOUNDATIONS
OF ENGINEERING ACOUSTICS

Plasma-Stirling Cooling Machine[1]

A. R. Aramyan[a], S. A. Aramyan[b], and Y. S. Martinez[c]

[a]*Institute of Applied Problems of Physics of National Academy of Sciences of Armenia, Hr. Nersessian Street 25, Yerevan, 0014 Republic of Armenia*

[b]*International Scientific and Educational Center of National Academy of Sciences of Armenia, Marshal Baghramian Ave. 24d, Yerevan, 0019 Republic of Armenia*

[c]*Instituto Tecnologico y de Estudios Superiores de Occidente, ITESO, Tlaquepaque, Jalisco, Mexico*

e-mail: aramyan.artur@gmail.com

Received April 18, 2013

Abstract—A new plasma-Stirling refrigerator is presented, without any complicated structural solutions and moving mechanical parts. The proposed Stirling cryogenic machine works on the basis of shock waves. The mentioned advantages make these refrigerators comparatively cheap and easy to manufacture.

Keywords: shock wave, thermoacoustic oscillations, plasma

DOI: 10.1134/S1063771014010035

INTRODUCTION

The rapid development of microelectronics caused the necessity to create and develop new cooling systems. In the manufacturing process of micro-refrigerators, Stirling refrigerators became very widespread [1]. But, with their high efficiency, these refrigerators have a complex construction. These complex structures have a very short useful life, due to intensive wear. Here, we present a new plasma-Stirling refrigerator, which does not contain any complicated structural solutions or moving mechanical parts. The mentioned advantages make these refrigerators comparatively cheap and easy to manufacture. The proposed Stirling cryogenic machine works using shock waves. The shock front leaves a rarefaction zone behind it, which is moving in the same direction and lasts ~ 300 times longer than the shock wave itself [2, 3]. Periodic impact of the rarefaction zone on the cooling chamber reduces the temperature in the chamber according to the adiabatic cooling effect.

THEORETICAL ANALYSIS AND ESTIMATIONS

A spark breakdown in a gas is proposed to be used as a generator of shock waves,. The problem of a shock-wave radiation in the breakdown of the gas can be considered as a problem of a strong explosion. In this case, the propagation of a spherical shock wave resulting from the instantaneous release of energy at a point is discussed. The assumption of a strong explosion means that the pressure P_1 of undisturbed gas ahead of the discontinuity is much lower than the pressure P_2 behind it.

The gas movement (according to [4]) is determined by two factors: the initial gas density ρ_1 and the released energy E. The displacement of the shock wave in time is the following:

$$R = \beta(Et^2/\rho_1)^{1/5},$$

where R is the distance of the wave from the center (the point of energy release); β is a numerical constant that depends on the adiabatic index of the gas and t is time. The value of β is determined by solving the equations of motion, and for the air it is equal to 1.033.

The speed of shock wave propagation relative to the undisturbed gas is

$$u_1 = \frac{dR}{dt} = \frac{2R}{5t} = \frac{2\beta E^{1/5}}{5\rho_1^{1/5}t^{3/5}}.$$

The pressure P_2, density ρ_2 and velocity v_2 of the gas behind the discontinuity can be expressed in a fixed coordinate system through their initial values P_1, ρ_1, v_1 using the general formulas for shock waves in a polytropic gas:

$$v_2 = \frac{2}{\gamma+1}v_1; \quad \rho_2 = \rho_1\frac{\gamma+1}{\gamma-1}; \quad P_2 = \rho_1 v_1^2\frac{2}{\gamma+1}.$$

From these expressions it is easy to obtain the dependence of the pressure in the shock wave on the distance from the point of explosion:

$$P_2 = \frac{0.32}{\gamma+1}\frac{E}{R^3}.$$

On Fig. 1 the values v/v_2, P/P_2 and ρ/ρ_2 are presented as functions of r/R for the air, obtained by solving the equations of the centrally symmetric adiabatic

[1] The article is published in the original.

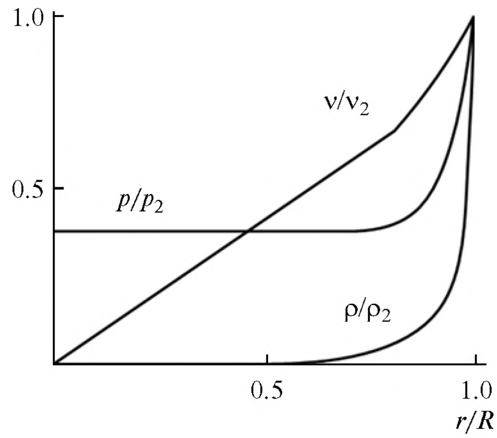

Fig. 1. Profiles of pressure, density and velocity for a strong point explosion in a gas.

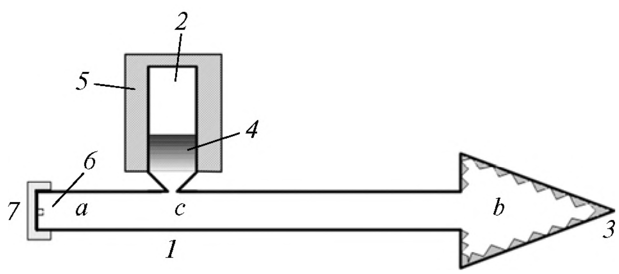

Fig. 2. Fridge principal scheme. *1*—pipe which the shock wave is running through, *2*—working volume, *3*—shock wave trap, *4*—regenerator, *5*—thermostat, *6*—shock wave generator, *7*—cooling water bath.

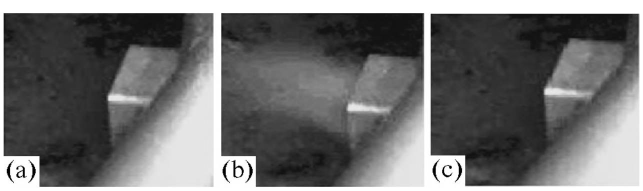

Fig. 3. Acoustic cannon side valve drawings during its work. a—before shooting, b—during the shot, c—after the shot.

motion of the gas in the entire region behind the shock wave.

Note the very rapid decrease in density towards the center of the explosion. This is due to the fact that on the surface of the shock wave the density exceeds the normal one in

$$\frac{\rho}{\rho_1} = \frac{\gamma + 1}{\gamma - 1} = \frac{1.4 + 1}{1.4 - 1} = 6,$$

times, i.e., almost all of the gas is concentrated on the surface of the shock wave.

To estimate the order of magnitude of the shock wave which was produced from the breakdown of the gas, let us find the pressure at a distance of 2 mm from the point of breakdown and the time of the shock wave propagation to that distance when the released energy is 0.1 J. The calculation of the formulas above gives us

$$P_2 = 1.2 \text{ MPa}, t = 6.2 \times 10^{-7} \text{ s}.$$

Since $P_2 \gg P_1 = 0.1$ MPa, the assumption of a strong explosion can be considered fair. The above assumption that the release of energy occurs in a point source instantaneously is also satisfied in the considered conditions.

So, it turns out that it is possible to generate quite powerful shock waves by means of electric discharges.

Let us discuss the principle of work of the fridge. On Fig. 2 the main scheme of the device is given. In the shock wave generator 6 shock waves rise in the point *a* and propagate through pipe 1 to the point *b* with a defined frequency. At point *b* in 3 (shock wave trap) shock waves are destroyed by giving their energy to the walls of 3. In pipe 1 the shock wave forms a rarefaction zone and before the gas can diffuse from 3 to pipe 1 and reach point *c*, the gas from 2 will reach 1 across 4 (regenerator). The gas in volume 2 freezes by adiabatic expanding. After a certain time *t* the gas pressure in pipe 1 is recovered. The pressure in volume 2 is also recovered.

In fact, it turns out that in point *c* the flow of gas changes its direction in time from 2–1 to 1–2. In the 2–1 case the gas is getting energy by passing through the regenerator, and in 1–2 case the gas is giving its energy to the regenerator.

This way, we are getting a Stirling's refrigerator [5]. By repeating the described process multiple times it is possible to get a refrigerator with high efficiency. The frequency of that repetition should correspond to the acoustic resonance frequency of the system. The repetition frequency of shock waves should also correspond to the resonance frequency. The proposed refrigerator's work principle is similar to a Prandtl–Glauert singularity [6]. The essence of this effect is as follows. A flying object at high (supersonic) speeds creates an area of high pressure in front of it and a low pressure area behind it. After the object has passed, the low pressure area begins to be filled with the surrounding air. This is a locally adiabatic process, where the air volume increases, and its temperature lowers. If the air humidity is high enough, the temperature can drop to a value that is lower than the dew point. Then, the water vapor contained in the air condenses into tiny droplets that form a small cloud.

The above mentioned mechanism also works with acoustic hail cannon. After the explosion, the gas is forced out with supersonic speed from the camera which causes a low pressure area in the camera. Afterwards, due to the pressure difference, the camera remains open, and the air fills the camera with a very high speed. In Fig. 3 frame-by-frame pictures of this process are given, which show that the rapid flow of air leads to the cooling of some areas of the air itself. The freezing occurs in the form of a small cloud, which means that the air is so frozen that it passes to the dew temperature and the water molecules contained in air begin to condense (Fig. 3b).

CONCLUSIONS

We can draw the following conclusion. If we create a shock wave that moves at supersonic speed, then we will have a rarefaction zone behind it. By virtue of Prandtl–Glauert singularity this rarefaction zone is filled with surrounding gas and the nearby surroundings freeze adiabatically. If this is done in a tube, the shock wave runs through the pipe and the role of the environment is carried out by any volume mounted on the pipe wall. Then, due to the rarefaction zone, the gas from this volume will move to the pipe, thus creating an adiabatic cooling in the volume. And if we add a regenerator at the connection point of this volume with the pipe and repeat the mentioned process at the acoustic resonance frequency, we will get a Stirling's refrigerator.

It is necessary to note that the journal "Acoustical Physics" has already published many works on acoustical thermometry (see, for example, the recent paper [7]). However, problems connected with thermoacoustic engines and refrigerators [5], seemingly, have not been reported yet. The list of relevant papers can be easily found in Internet (see http://www.akzh.ru/rubrics_en.htm) [8].

REFERENCES

1. A. M. Veprik and S. V. Riabzev, *Proc. Low Power Cryocooler III Workshop*, Venlo, Netherlands, 1999.
2. Y. Miyake, K. Bando, and T. Akasaki, Exper. Thermal and Fluid Sci. **5**, 781 (1992).
3. A. A. Vardanyan, G. A. Galechyan, V. G. Perepelkin, and I. P. Chunchuzov, Techn. Phys. **56**, 1524 (2011).
4. Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Dover, New York, 2002).
5. G.W. Swift, *Thermoacoustics: A Unifying Perspective for Some Engines and Refrigerators* (Acoustical Society of America, Sewickley, 2002).
6. E. Truckenbrodt, *Fluidmechanik*, Band 2, 4th Auflage (Springer-Verlag, 1996).
7. A. A. Anosov, R. V. Belyaev, V. A. Vilkov, A. S. Kazanskii, N. A. Kuryatnikova, and A. D. Mansfel'd, Acoust. Phys. **59**, 482 (2013).
8. V. G. Shamaev, A. B. Gorshkov, and A. V. Zharov, Acoust. Phys. **59**, (2013) (in press).