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The influence of sound on heat transfer in gases

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A large amount of experimental data illustrating the influence of sound on temperature processes has accumulated in industry and technology research. The Ranque effect, the Hartmann–Sprenger effect and the temperature separation inside a short vortex chamber (performed by the author) also belong to this class of phenomena. None of these effects can be explained by conventional heat transfer processes. The concept of Pressure Gradient Elastic Waves (PGEW) is proposed and proved. The concept gives a physical description of the heat transfer in these processes. A PGEW is a special type of elastic wave arising in compressible media (gas) with a pressure gradient in the presence of density fluctuations (sound). The most important property of this kind of elastic wave is that it transfers energy from a low pressure zone to a high pressure one.

Keywords: PGEW (Pressure Gradient Elastic Waves), temperature separation, Ranque effect, Hartmann–Sprenger effect, vortex chamber, heat transfer, energy saving, low potential heat utilization.

INTRODUCTION

A large amount of experimental data illustrating the influence of sound on temperature processes have accumulated in industry and technology research. A temporary lack of an adequate understanding of the physical basis of these processes is forcing us to refer these phenomena to a sequence of physical paradoxes. Below are examples of a large number of research papers of this type. In [1] the results of the experiments on the influence of sound on the process of heat exchange between the air and the particulate material layer are published. It is shown that the coefficient of heat transfer is maximal under the influence of sound with a frequency of 50–200 Hz (depending on the flow rate). In [2] the results of experiments on the effects of sound on the drying process are presented. In [3] the effect of sound on the cooling process was studied. The temperature of the heating element is reduced when subjected to sound with frequencies of 30–100 Hz. Maximum cooling was observed at a frequency of 60 Hz.

It is not possible to draw unambiguous conclusions about the processes described in these publications due to the absence of a complete description of fluid flows. The common characteristics of these processes are that:

- processes occur in gases;
- the resonant character of sound effects is emphasized; that is, the dependence of the intensity of the process on the sound frequency is observed.

The temperature effects of Ranque [4] and Hartmann–Sprenger [5] should be attributed to the same class of phenomena.

The temperature separation inside vortex tubes (Ranque effect) is always accompanied by a loud noise. Internationally known physicists H. Sprenger [6], M.A. Goldshtik [7], and M. Kurosaka [8] have emphasized that sound affects the temperature separation process inside vortex tubes. Their opinion can be summed up in Goldshtik's words: "The self-oscillating and acoustic phenomena, always accompanying the operation of the vortex tube, should play a large role in the theory of the Ranque effect". The gas rotating inside vortex tubes creates a pressure gradient with the maximum pressure at the periphery near the cylindrical wall and with the minimum at the central area near the tube axis. The heating zone is located at the periphery, and a cooling zone in the centre.

In the Hartmann–Sprenger tubes (the Hartmann sound generator) the pressure gradient is created by the gas jet impact. The bottom of the cavity mounted opposite to the nozzle is heated to significant temperatures. The pressure has maximal magnitude at this point (the kinetic energy of the jet transforms into potential energy). During the experiment [5], using a helium jet, the end cavity temperature reaches ~1000°C. In this device, the minimum pressure area is the area between the nozzle and the cavity, where the jet velocity is maximal. It is possible to achieve a significant reduction of the gas temperature by removing heat from the outer wall of the cavity and by outputting the gas from the space between the nozzle and the cavity. The gas-dynamic generator of a cold [9] is arranged according to this principle. This device operates at cryogenic temperatures.

Different concepts were proposed to explain these effects (the Ranque and Hartmann–Sprenger effects). The adiabatic pressure reduction during the acceleration of the jets in the nozzles was considered a source of gas cooling in these devices. The heating process was explained by the viscous friction of gas jets or (in the Hartmann–Sprenger effect) by shock waves. The micro-refrigeration processes (or interaction of vortexes) were also considered. Hot and cold micro-volumes obtained from these processes were then separated. But, until now there were no theories that adequately described thermal processes occurring in these devices [9, 10].

We can identify the following general characteristics of the devices using the Ranque and Hartmann–Sprenger effects:

- gases are working substances;
- the operation is accompanied by a loud noise;
- the pressure gradient exists inside the devices;
- the heating zone is a zone of high pressure;
- the cooling zone is a zone of reduced pressure;
- the maximum temperature effect always coincides with the maximum sound intensity.

1. TEMPERATURE SEPARATION INSIDE THE SHORT VORTEX CHAMBER

The author discovered the temperature separation phenomenon in a short vortex chamber [11, 12]. The phenomenon includes all of the above features including the resonant character of the process. Compressed air is pumped at room temperature from the side peripheral wall toward the centre of the vortex chamber. Experiments revealed that the highest temperature of the periphery was 465°C and the lowest temperature of the central zone was – 45°C

The analysis performed showed that the results of these experiments cannot be fundamentally described based on the concepts mentioned above. Actually:

a) The flow regime in the vortex chamber eliminates the possibility of shock wave formation [11];

b) The thermocouple placed in the central area of the vortex chamber Fig. 1 [12] showed stable cooling, which increased with increases in the inlet pressure. But there was air suction from the room (~20°C) to the central zone of the chamber, where pressure was negative. Exactly this air (and only it) cooled the thermocouple. Hence, this air had time to cool down without participating in the main vortex motion and without experiencing the pressure drops;

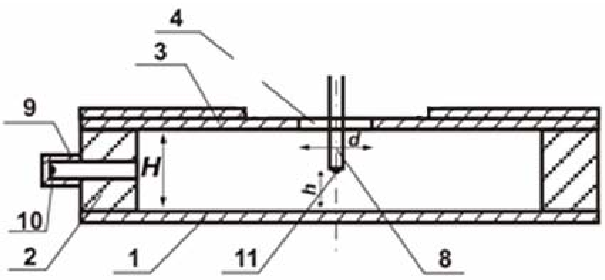

Fig. 1. Schematic overview of modified experimental vortex chamber (cross-section front view). 1 – lower disc; 2 – cylindrical side wall; 3 – upper disc; 4 – outlet diaphragm; 8 – central rod; 9 – plugged branch pipe; 10 – “hot” thermocouple; 11 – “Cold” thermocouple; *H*-vortex chamber height (25 mm); *d* – outlet diaphragm diameter (30 mm); *h* – distance between central rod and lower disc.
The vortex chamber diameter was equal to 140 mm

c) If hot micro-volumes were formed in this vortex flow, the possibility of their displacement to the periphery was completely excluded. (It is inconceivable that when the spiral of a thermal fan is turned on the heat will be transferred in the opposite direction to the air flow). Nevertheless in this device, heat was transferred to the periphery toward the powerful air flow

d) The level of gas heating possible due to the viscous friction is substantially lower than the actual heating during the tests. At solid body friction, the kinetic energy of the entire mass is accumulated in a thin layer, which is deformed under friction and heats up. Such accumulation in a gas is impossible. It is impossible to imagine a process whereby a micro-volume warms as a result of deceleration and then re-accelerates without reducing the temperature and slowing down again, and so on. The single deceleration is the real process.

The highest possible heating of a gas micro-volume can be estimated if we imagine that all the energy of the compressed gas which has accumulated in the compressor is transformed into heat. Since in the compressor the temperature of the compressed gas is aligned with the ambient temperature, we will consider the process of isothermal compression. The work of the isothermal compression from state 1 to state 2 for a unit mass of an ideal gas is determined by the relation:

$$l_{1-2} = \frac{RT}{\mu} \ln \frac{P_2}{P_1}$$

where P is a pressure; T is a temperature; μ is a molar mass; R is the universal gas constant.

The compressor used in the experiments compresses air from the pressure P_1=1 bar to P_2=7 bar at the temperature $T \sim 300\ K$. Using for the air the values μ = 29 kg/kmol and R = 8314 J/(kmol K), we obtain l_{1-2}= 167 kJ/kg. If all this energy (during a hypothetical process) is transformed into heat, the air temperature (c_p=1.006 kJ/kg K) will increase only by 166 K. In the experiments [11, 15] (as well as in many experiments with Hartmann–Sprenger tubes) significantly higher temperatures were obtained.

2. THE ENERGY OF THE SOUND-TYPE WAVES IN GASES

With the term «wave of sound type» we can unite the elastic waves propagating at the velocity of sound regardless of the oscillation frequency of the wave source. Then we can say that there are only two types of elastic waves in gases:

- waves of sound type,
- and shock waves.

The shock waves [13] propagate with supersonic velocity. Their appearance is associated with the emergence of a new mass (explosion) or with supersonic motion. The shock wave carries a significant energy; it is always a compression wave. Rarefaction shock waves do not exist. The energy and velocity of the shock wave are reduced during its propagation. When the shock wave velocity becomes equal to the velocity of sound, it is converted into a wave of sound type.

The amplitude and frequency of the sound-type wave are determined by the characteristics of vibrations or pulsations of the sound source. In a sound wave, the zones of compression and expansion alternate and spread in the direction moving away from the sound source. In gases, these waves are always longitudinal; that is, the gas molecules oscillate along the direction of wave propagation.

There exist sounds associated with a single disturbance. The oscillations are absent in the source of such a sound: for example, the breakdown of a spark, thunder, the bursting of a balloon, a single clap, and so on. But in this case, the sound wave should consist of one period – the compression zone and the rarefaction zone. Indeed, if the source (or sink) of mass is absent in the volume of the gas, any development of compression fluctuation must be accompanied by simultaneous development of rarefaction fluctuation. So the total change in mass of gas in the disturbance region is equal to zero.

The pressure in the sound fluctuation zone is expressed as a sum $P = P_0 + \Delta P$, where P_0 is the undisturbed value of pressure before the arrival of a wave, and ΔP is the wave amplitude characteristic, which determines the intensity of the sound. In the wave of sound type $P_0 >> \Delta P$. Indeed, the loudest sounds at 170 dB (jet engine, noise grenade) are characterized by an excessive pressure of $\Delta P \sim$ 0.063 bar. For this reason, in the derivation of relations describing the wave processes, the values of the second order of smallness ($\sim \Delta P^2$) are neglected.

However, during the calculation of the sound wave energy, the values of the second order of smallness are taken into account namely. The energy associated with an acoustic disturbance that propagates through a quiescent gas includes two components: the component associated with the variation of the internal energy and the component associated with the kinetic energy of oscillatory motion. In the compression zone the gas velocity is directed toward the wave propagation, and in the rarefaction zone the velocity is directed in the opposite direction.

If v is the characteristic velocity of oscillatory motion ($v << a$, where a is the sound velocity), the kinetic energy density of oscillating motion g_k is the value of the second order of smallness $g_k = \frac{\rho_0 v^2}{2}$, where ρ_0 is the density of unperturbed gas. The increment of the specific internal energy of the disturbed gas $\Delta\varepsilon$ is equal to (for example, [13], Chapter 1)

$$\Delta\varepsilon = w_0 \Delta\rho + \frac{a^2}{2\rho_0}(\Delta\rho)^2 .$$

Here w is the specific enthalpy, $w = \varepsilon + \frac{P}{\rho}$, and the index 0 refers to the unperturbed state.

The energy density of the sound disturbance (the increment of energy per unit volume) is given by the sum $E = \Delta\varepsilon + g_k$,

$$E = w_0 \Delta\rho + \frac{a^2}{2\rho_0}\left(\Delta\rho^2\right) + \frac{\rho_0 v^2}{2} . \quad (1)$$

During the derivation of expression (1), the increment of the specific internal energy of the disturbed gas with accuracy up to the second order with respect to $\Delta\rho$ was considered. The processes in the gas were taken to be isentropic. The gas was considered to be ideal.

The first term in equation (1) is much larger than the second and third terms; however, the sound wave energy formulas generally include only the second and third terms. This is because in the process of calculating the total energy of the acoustic disturbance (via the integration of Eq. (1)), the first term of the sum is cancelled due to the fact that the density variations in compression zones $+\Delta\rho$ are compensated by the density variations in rarefied zones $-\Delta\rho$.

Of course the sound wave transfers the energy which is obtained from the source. The wave absorption leads to the release of this energy, which leads to an increase in the temperature of the gas (never to cooling), but the amount of heating is very small. The thermocouples installed near even very powerful sound sources do not show the real change of temperature.

Although the first term in (1) is not considered in the majority of sound processes, it should be emphasized that this component exists in reality and there are processes where it manifests itself. In a standing wave of sound type, the position of the zones of compression and rarefaction has been fixed. The thermocouples installed in the zones of compression and rarefaction show increases and decreases in temperature, respectively. If metal plates are placed in these areas and collected in a pile (sandwich), it is possible to obtain heat and cold from this system. Thermoacoustic heat pumps [14] are designed in this way. In this system, if first a standing wave is created and then heat and cold are provided to the appropriate plates from an external source, the wave amplitude (the sound volume) will increase. (An additional increase in temperature in the compression zone increases ΔP, which is characterized the amplitude.)

Are there any other processes (other than the process mention above), which can reveal the first term of the formula for sound wave energy (1) defining the real heating and cooling? The arguments presented below allow us to answer this question in the affirmative.

3. ELASTIC WAVES IN COMPRESSIBLE FLUID WITH AN ANISOTROPIC ON PRESSURE

Echo-location in the ocean is a widely known example of the propagation of sound type waves, both towards the increase in pressure and in the opposite direction. But in the articles devoted to these anisotropy problems, only the temperature anisotropy is considered. Pressure changes sharply in the ocean with depth. But due to the fact that water is practically incompressible, its density is almost constant and the mass involved in the wave process does not change (the medium is density isotropic).

In book [13] (Chapter 12), the influence of the pressure gradient in the atmosphere on the shock wave propagation is considered. It seems that the urgency of this problem was caused by the need to simulate the explosion of the atomic bomb. It is shown that the movement of the shock wave in the atmosphere in the upward and downward directions is different in nature. Downward movement is characterized by inhibition and extinction and upward movement is characterized by unlimited development until it breaks through the atmosphere. The main reason for this difference is the change in air density (mass), which is involved in a wave process. This is caused by the gravitational pressure gradient.

In the Earth’s atmosphere, the gravitational effects of air density changes can manifest themselves at very long distances. The absorption of sound-type waves occurs at much shorter distances. Therefore, the influence of the gravitational pressure gradient on the propagation of sound waves in the atmosphere can be ignored. But in technical devices the pressure gradient values can be substantial. For example, in a vortex chamber with an outlet diaphragm of 30 mm [11] at a pressure value of 7 bar at the inlet to the nozzle, the pressure on the side wall was equal to 4.5 bar. Accordingly, the average value of the pressure gradient over the volume of the vortex chamber was significant: $\frac{\Delta P}{\Delta r}$ = 0.6 bar/sm.

Consider an elongated volume (Fig.2) [12] filled with gas and placed in the field of mass forces, creating a pressure gradient within the volume. Note that these forces are, for example, strong gravity or electromagnetic field acting upon the ionized gas. The pressure gradient may also be created dynamically. For example, volume (Fig. 2) can be fixed on the centrifuge (along the radius of rotation). In this case, the pressure gradient is created by the field of centrifugal forces. We assume that any effect on the gas leading to the appearance of the pressure gradient can be modeled by the field of mass forces acting on each gas molecule.

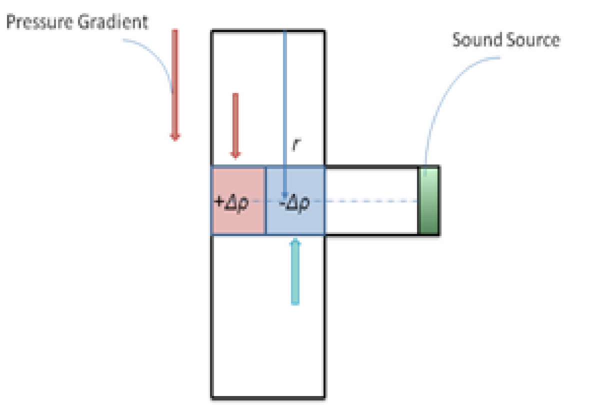

Fig. 2

Volume filled with a gas inside a field of forces, creating pressure gradient

So, a pressure gradient is created in the volume (Fig. 2). This thermodynamic system is closed and is in an equilibrium state (the volume is temperature homogeneous; the mass and volume of the gas are constant; the gas does not move). The heat exchange with the external space is absent, but the system is not isolated (the field of force acts on each molecule in the gas volume.)

- We assume that the gas is perfect.
- We shall consider the problem in the one-dimensional approximation (the unit vector directed in the direction of increasing pressure).

An expression for the pressure gradient obtained in [12] from consideration of the elementary volume is

$$grad\ P = \rho_s(r)\bar{u}_f(r), \tag{2}$$

where $\bar{u}_f(r)$ is the acceleration that characterizes the field of mass forces; $\rho_s(r)$ is the gas density at the point r, which depends on the value of pressure; and $\rho_s(r) = \frac{k}{a^2}P(r)$ (a is the sound velocity; k is the adiabatic index; and the index s refers to the initial (starting) state (before the arrival of the disturbance).

$$P(r) = P_0 \exp\left(\frac{k}{a^2}\int_{r_0}^{r} u_f(r)dr\right).$$

(3)

The exponential dependence (3) for pressure at point r is derived from the expression (2), where P_0 is the pressure at the upper wall (point r_0).

Sound source produces inside the volume (Fig. 2) a sound wave. Consider the area of sound density disturbance in the gas, consisting of half period of compression and of half period of rarefaction. For simplification, we assume that the compression zone and rarefaction zone have an average value of the sound pressure fluctuations ± ΔP.

So, in the zone of initiation of sound fluctuation, the density of the gas has changed from $\rho_s(r)$ to $\rho_s(r) \pm \Delta\rho$ ($\pm \Delta\rho$ determine the amplitude of the fluctuations). However, the pressure values on the boundary of the disturbance zone remain unchanged and shaped by the existing pressure gradient. If we consider the balance of forces on the borders of the elementary volume, which coincide with the boundaries of the initial sound fluctuations, we can see that under a pressure gradient the forces arise, which additionally act on the gas in this region. These forces are the pressure forces. These forces are generated by the field of force, which creates a pressure gradient. Using the expression (2), we obtain the relation for the acceleration $\bar{u}(r)$, which determines the magnitude of additional force acting on the area of initial density fluctuation:

$$\bar{u}(r) = \bar{u}_f(r) \frac{\Delta\rho}{\rho_s(r) + \Delta\rho}. \tag{4}$$

The greater the value of the pressure gradient (defined by the acceleration $\bar{u}_f(r)$) and the greater the amplitude $\Delta\rho$ of the initial density fluctuation, the greater the magnitude of this force. If the value of $\Delta\rho$ is positive (fluctuation of compression), the force is directed downwards in the direction of increasing pressure. This force is added to the pressure force, and further presses the zone of initial compression. If $\Delta\rho$ is negative (the fluctuation of rarefaction), the force is directed upward toward the low pressure area. This force reduces the pressure generated by the field and further extends the zone of initial rarefaction.

4. PRESSURE GRADIENT ELASTIC WAVE

Any disturbance associated with density fluctuation inside a compressible fluid creates an elastic wave. This formulation of Huygens' Principle for gases was confirmed mathematically in the book [15]. The wave equation was obtained on the basis of the obvious condition of the existence of a positive derivative $\frac{d\rho}{dP}$ and under the assumption of the existence of a disturbance associated with a small density fluctuation.

The pressure forces are "rapidly acting" forces. The pressure in the gas is determined by the average velocity of molecules. This velocity is greater than the sound velocity (strictly speaking, the sound propagation in the gas is determined just by the forces of pressure). The initial sound fluctuation develops with the sound velocity. During the whole of this time, the rapidly acting pressure forces act on the zone of fluctuation, creating a secondary density disturbance.

Based on the formulated above Huygens' Principle, we can claim that the above-described secondary density disturbance in the zones of initial sound fluctuation must create a secondary elastic wave. This wave is described by the wave equation (see [15]) and propagates with the velocity of sound. It certainly contributes to the total interference pattern. However, the principle of wave superposition makes it possible to consider this wave separately. In addition to the above, the unique properties are revealed. This allows us to highlight this secondary wave in a *separate third type of elastic wave in gases* – the **Pressure Gradient Elastic Wave** (PGEW) [11, 12]. The PGEW properties listed below are derived from the above relations and are based on both of the two necessary conditions: the existence of a sound starting density fluctuations and the existence of a pressure gradient.

- Regardless of the direction in which the initial sound wave propagates, the PGEW is always directed along the vector of the pressure gradient.
- In the PGEW the compression front and rarefaction front propagate in opposite directions: the compression front propagates in the direction of increasing pressure and the rarefaction front in the direction of decreasing pressure.
- The forces generated by the pressure gradient continue to affect the perturbation zone while the PGEW propagates. These forces further compress the compression wave and further expand the rarefaction wave.
- In a limited volume, PGEW cannot be reflected and move in the opposite direction when it reaches the wall. The forces that created this wave prevent the wave displacement in the opposite direction. Consequently, when PGEW reaches the walls, it transfers its own energy to the wall. For the same reason, the PGEW cannot pass through the zone of the extremum of the pressure gradient (for example, through the centre of rotation) and is dissipated in this region.
- There are no oscillations in the PGEW, since the oscillations are absent in the field of force, which generates this wave. As a result, the formula of PGEW energy does not include the term associated with the kinetic energy of oscillatory movement.
- As the compression front and the rarefaction front of the PGEW move in opposite directions, the first term in the formula of the wave energy (1) will not be compensated. Consequently, the compression front carries the real heat and the rarefaction front carries the real cold.
- The most important property of the PGEW is that in a limited volume it cools the wall (or region) positioned in the low pressure zone and heats the wall positioned in the high pressure zone.

The feeding of heat transfer agents to the respective zones allows us to realize the heat transfer, which is independent of the temperature gradient. That is, it will permit the creation of a new type of heat pump [16].

5. THE PROPAGATION OF THE PRESSURE GRADIENT ELASTIC WAVE (STATEMENT OF THE PROBLEM)

The energy transfer process by PGEW is irreversible and is a non-equilibrium process. The PGEW arises under the influence of an external force field, which creates a pressure gradient with a constant influence of density fluctuations (the starting sound wave). To describe the processes associated with PGEW it is necessary to use the mathematical apparatus of nonequilibrium thermodynamics. Nevertheless, numerous experiments [11, 12] showed that in all modes the constant values of temperature and pressure are established sufficiently fast. Consequently, the idea of local equilibrium can be used for this system.

The considered volume in the initial state (before the sound is turned on and the PGEW appears) is anisotropic in pressure and density and isotropic in temperature. As a first approximation, the calculation should be carried out at the temperature corresponding to the starting conditions. (PGEW absorption in a gas can be ignored when considering a small volume). However, when the PGEW emerges, a new stable state is established sufficiently rapidly, and is characterized by a reduced temperature in the area of low pressure and high temperature near the wall where the pressure is maximal. This steady state is characterized by equilibrium of the two heat flows. On the one hand, PGEW transfers energy from the zone of low pressure and heats the wall in the zone of high pressure. On the other hand, the competing processes of conventional heat transfer (diffusion, convection, and thermal radiation) transfer the heat in the reverse direction – from the hot wall to the cold zone. If the movement of a gas presents in the volume, it contribute significantly to the steady temperature distribution. The heat-exchange through the walls with heat transfer fluids also influence on this characteristic.

5.1. Waves of sound type

Naturally, PGEWs arise under pressure gradient conditions when any density fluctuations (pulsations, gas turbulent eddies) take place. However, in my opinion it is mainly sound that is the necessary "trigger" of a powerful PGEW.

The propagation of sound-type waves in a gas in the presence of a pressure gradient has its own features. These features are associated to the fact that the mass of the gas in the sound disturbance is not constant. (It should be noted that in [17] the problem of sound propagation in a gas for the hypothetical case of density anisotropy at constant pressure was considered.)

Any wave beam can be decomposed into two components: along the vector of the pressure gradient and perpendicular to this vector. The movement of the sound wave in the perpendicular direction takes place as usual, in a layer with a constant gas density. But the movement along the pressure gradient vector has two essential features. First, additional forces caused by the pressure gradient act on the sound density fluctuations. The forces act on the compression and rarefaction half-periods in the opposite directions. Secondly, the zone of sound disturbance moves through a space having a different density (the mass and/or the volume of a gas in the fluctuation are not constant). Certainly, the forces generated by the pressure gradient will reduce the disturbance of compression in sound waves propagating toward lower pressures and will reduce the rarefaction disturbance in sound waves which propagate toward higher pressures. In these conditions the sound will actually transfer heat toward higher pressures and transfer cold toward lower pressures (the integral of the first term in equation (1) gives a non-zero result). But in the first approximation, this contribution can be ignored in comparison with the PGEW arising throughout the volume at each sound density fluctuation regardless of the direction of sound propagation. The devices in which PGEWs arise usually have small dimensions (for example, a good thermal separation takes place with the vortex tube having a diameter of 5 mm). At small distances, the complete suppression of the compression zones or of the rarefaction zones in the sound wave has a low probability.

5.2. PGEW

The energy carried by the PGEW includes only the energy of adiabatic compression (rarefaction). This compression (rarefaction) takes place under the influence of forces defined by the pressure gradient. The magnitude of these forces is determined by the acceleration according to formula (4). This force acts on the mass of gas in the zone of disturbance. At the initial moment, the $\Delta\rho$ magnitude in the expression (4) characterizes the starting disturbance of density and is determined by "the sound pressure level" (sound loudness). With the displacement of the zone of wave density fluctuation, the magnitude $\Delta\rho$ changes due to compression (rarefaction).

At a first approximation, the energy that is carried by the PGEW can be estimated by assuming a value of pressure force as a constant and by calculating the isentropic work of compression (rarefaction) in the initial sound fluctuation. These forces are applied to the mass of a gas in the region corresponding to half of the length of the initial sound wave. This mass we will be assumed to be a constant too. As the density $\rho_s(r)$, we will use the average value in this area. The magnitude of $\Delta\rho$ can be assumed to be a constant for the entire volume. The duration of this force pressure corresponds to the duration of existence of the PGEW front. That is, it is the duration of wave propagation at the velocity of sound from the point of origin to the point of absorption. For the compression front, the point of absorption is the wall located in the zone of maximum pressure. For the rarefaction front, the point of absorption is the wall located in the zone of minimum pressure or the dissipation region. The summation (integration) has to be conducted over the entire volume and over the duration, considering the frequency of the initial sound wave (the frequency of the sound's initial density fluctuations).

This approximation will allow the power of heat transfer by means of the PGEW to be estimated. But it fails to identify the observed effects. For example, at low inlet pressures [11], the heating is usually completely absent and at the same time there is noticeable cooling. A more detailed approach should consider the fact that the PGEW passes through the volume with changes in the gas density.

When sound-type waves propagate in a medium with a constant density, the frequency and wavelength do not change. Similarly, the mass involved in the disturbance zone does not change. Is it possible that on the basis of this fact we can assume that the geometric dimensions of the density fluctuation zone remain unchanged during the PGEW disturbance propagation? It cannot be argued. Similarly, it cannot be argued with respect to the mass of a gas in the zone of disturbance.

Most likely, the real process of PGEW propagation is a simultaneous change in both the volume and the mass of the disturbance. The pressure force compresses the compression zone (performing work of isentropic compression), reducing its size and increasing the pressure, density, and temperature. But, being displaced toward higher values of density, the compression zone transfers disturbance on a large mass. The energy is an additive function. Therefore, the conservation of energy when the PGEW is transferring the disturbance on the large mass leads to a decrease of the amplitude and to a decrease the pressure, density, and temperature. We see that in the compression front, these factors have opposite trends.

The influence of external field on the rarefied front of the PGEW reduces the resultant pressure force. This rarefaction zone is additionally expanding (performing the work of isentropic expansion). Herewith, the size of the rarefaction zone is increased, and the pressure, density, and temperature are decreased. By shifting toward lower values of density, the rarefaction zone transfers disturbance to the smaller mass. This factor increases the amplitude of the rarefied front of PGEW, which further increases the cooling. It is seen, that both the above-mentioned factors are complementary and mutually reinforcing.

CONCLUSIONS

1. A large amount of experimental data illustrating the influence of sound on temperature processes have accumulated in industry and technology research. A temporary lack of an adequate understanding of the physical basis of these processes is forcing us to refer these phenomena to a sequence of physical paradoxes. The investigation of the temperature separation phenomenon in the short vortex chamber [11] (performed by the author) confirmed this conclusion. The experimental results obtained cannot be explained by conventional heat transfer processes.

2. The concept of Pressure Gradient Elastic Waves (PGEWs) is proposed and proved. A PGEW is a special type of elastic wave arising in compressible fluids (gases) with a pressure gradient in the presence of the initial density fluctuations (in the presence of sound). This concept allows us to provide an adequate description of the physical processes of heat transfer taking place in the conditions described above. These processes include:

- the Ranque effect (the temperature separation in vortex tubes);
- the Hartmann–Sprenger effect (the heating of a cavity of a Hartmann sound generator and obtaining a cold using this effect);
- the temperature separation in the short vortex chamber (performed by the author) [11], [12].

3. The most important property of PGEWs is that they transfer energy from the low pressure zone to the region of high pressure. This heat transfer is not dependent on the temperature gradient; that is, the heat transfer can flow from cold to hot regions. A new class of heat pumps (refrigerators, heaters, etc.) can be created on the basis of PGEW. The field of application of these devices is energy savings and low potential heat utilization.

4. The activities under this project are continuing. Currently additional experimental proofs of PGEWs concept are obtained (will be published).

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