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The Pressure Gradient Elastic Wave: Energy Transfer Process for Compressible Fluids with Pressure Gradient

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Abstract: The temperature separation was discovered inside the short vortex chamber (H/D = 0.18). Experiments revealed that the highest temperature of the periphery was 465 °C, and the lowest temperature of the central zone was -45 °C (the compressed air was pumped into the chamber at room temperature). The objective of this paper is to proof that this temperature separation effect cannot be explained by conventional heat transfer processes. To explain this phenomenon, the concept of PGEW (Pressure Gradient Elastic Waves) is proposed. PGEW are kind of elastic waves, which operate in compressible fluids with pressure gradients and density fluctuations. The result of PGEW propagation is a heat transfer from area of low pressure to high pressure zone. The physical model of a gas in a strong field of mass forces is proposed to substantiate the PGEW existence. This physical model is intended for the construction of a theory of PGEW. Understanding the processes associated with the PGEW permits the possibility of creating new devices for energy saving and low potential heat utilization, which have unique properties.

Key words: PGEW (Pressure Gradient Elastic Waves), temperature separation, Ranque effect, vortex chamber, heat transfer, energy saving, low potential heat utilization.

1. Introduction

The concept of PGEW (Pressure Gradient Elastic Waves) was proposed in Ref. [1] to explain the temperature separation inside a short (H/D = 0.18) 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 (wile the inlet air had the room temperature ~20 °C).

The goal of this work is to convince readers that only the concept of Pressure Gradient Elastic Waves can explain current experimental results. Pressure Gradient Elastic Waves are kind of elastic waves, which operate in compressible fluids with pressure gradient and density fluctuations.

The concept of PGEW is quite unexpected and is received today with incredulity. Indeed, if the phenomenon can be explained by existing theories, a new one is not needed.

It is reasonable to assume that the same physical phenomenon is the basis for air flow temperature separation in the examined vortex chamber [1] and in the vortex tubes (Ranque effect [2]). Today two current concepts are proposed to explain the effect of temperature separation inside vortex tubes. The theory based upon heat transfer processes, which transfer heat from the axis area to the periphery and the concept of the flow separation into two streams hot and cold. Such heat transfer seems quite possible inside the vortex tubes with a ratio of L/D = of 10/1 to 30/1. However it had a weak points and current critical review [3] emphasized that future research will benefit.

But these hydrodynamic theories, which are proposed to explain the Ranque effect, cannot explain the temperature separation inside the examined short vortex chamber (H/D = 0.18) [1].

Internationally known physicists H. Sprenger [4], M.A. Goldshtik [5] and M. Kurosaka [6] have

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emphasized that the sound effects on the temperature separation process inside vortex tubes. Their opinion can be summed up by Goldshtik's words: "The theory of vortex tube has to include the influence of the sound waves".

The paper is organized as follows: Section 2 describes the experiments and discusses its results; section 3 focuses on the statement of the physical model; section 4 gives the proofs of PGEW existence; section 5 includes the conclusions.

2. The Experiment

2.1 Experimental Equipment

The experimental installation used was described in detail, along with the characteristics of sensors and their accuracy in Ref. [1]. The pressure, measured by transmitters and expressed in bars, is a gauge pressure (atmospheric pressure = 0).

Please note the two thermocouples shown in Fig. 1. The "cold" thermocouple, 11, was attached to the end of the central rod. The "hot" thermocouple, 10, was mounted on the plugged end-cap of the branch pipe.

2.2 Results

Fig. 2 represents the data file of the experiment [1] in which maximal heating of the branch pipe was carried out, with the hot thermocouple temperature reaching 465 °C. During the test, the pressure was increased to 6 bar in increments of 0.5 bar. The pressure was kept constant while the temperature was increased and stabilized. For example, at a pressure of 3.5 bar, a sharp rise in temperature was observed with significant heating capacity. The individual experimental points, which were fixed every second, can be seen. The highest temperature was observed at 6 bar.

The modified vortex chamber (Fig. 3) was used for further experiments. The chamber was different in that the discharge collector (Fig. 1) was removed. The central rod was mounted at the chamber axis.

The air flow emerged from the chamber (Fig. 3) in the form of a cone. The cone was close to the axis only

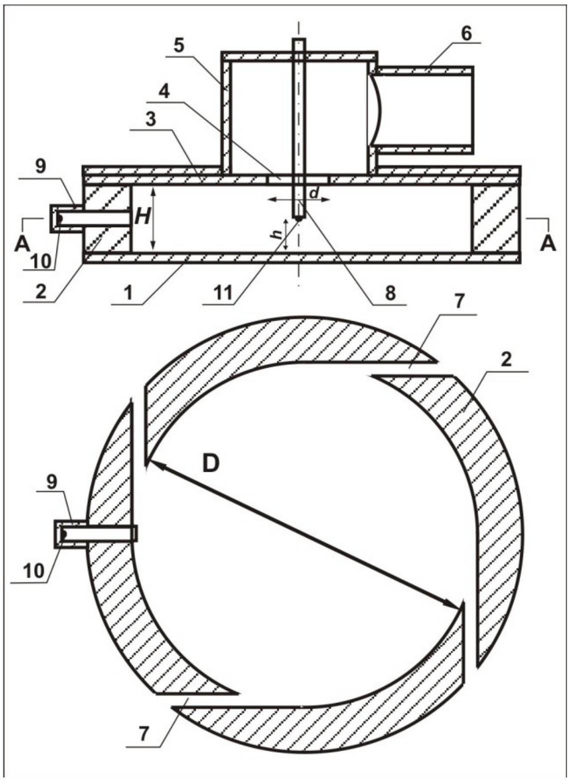

Fig. 1 Schematic overview of experimental vortex chamber. Top: cross-section front view; Bottom: cross-section top view. The experimental setup stands of the following components: 1—lower disc; 2—cylindrical side wall; 3—upper disc; 4—outlet diaphragm; 5—discharge collector; 6—outlet connection; 7—tangential nozzles; 8—central rod; 9—plugged branch pipe; 10—"hot" thermocouple; 11—"cold" thermocouple; *D*—vortex chamber diameter (140 mm); *H*—vortex chamber height (25 mm); *d*—outlet diaphragm diameter; *h*—distance between central rod and lower disc [1].

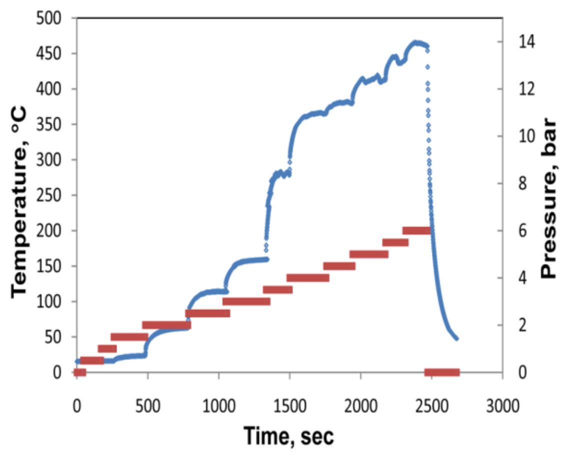

Fig. 2 The experimental file of the vortex chamber with outlet diaphragm *d* = 30 mm. The readings of inlet pressure and temperature ("hot" thermocouple) were recorded every second.

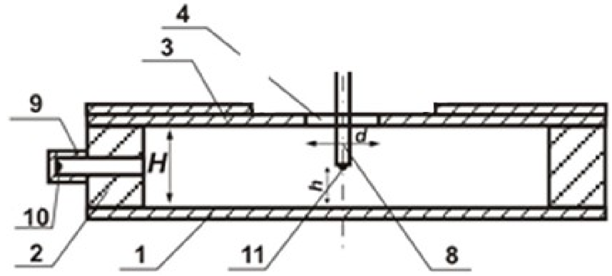

Fig. 3 Schematic overview of modified experimental vortex chamber (cross-section front view). 1—lower disc; 2—cylindrical side wall; 3—upper disc; 4—outlet diaphragm; 8—central rod; 9—plugged branch pipe; 10—“hot” thermocouple; 11—“Cold” thermocouple; *H*—vortex chamber height (25 mm); *d*—outlet diaphragm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

at high pressures (for the outlet diaphragm diameter of 30 mm at pressures higher than 5.5 bar). In the other modes, the outlet flow cone had an open form close to the top of the outer surface of the chamber (perpendicular to the axis) [5]. The central (axis) zone inside the vortex chamber (Fig. 3) is characterized by negative pressure in all flow modes, which creates a back flow. The air is sucked out from the outside of the chamber along the central rod, twists, and escapes from the chamber with the main vortex stream.

Nevertheless, Fig. 4 shows the cooling of the “cold” thermocouple as a function of input pressure (d = 30 mm and h = 22 mm).

During maximal heating (d = 30 mm) [1], large amounts of heat were released at the periphery of the vortex chamber. Not only the branch pipe was warmed up, but the entire massive side wall was heated. The polyethylene tubes connecting the pressure transducers with the side wall and lower disc were also broken by the heat and pressure.

Fig. 5 shows one of the broken pieces of polyethylene tube. The tube fast connector was mounted on the outer surface of the side wall. The cylindrical canal inside the side wall and the closed part of the tube were oriented along the radius of the chamber. It is very interesting that the broken holes were located not near the vortex chamber side wall but at a distance of 10-15 cm from it, at a place where the pipe was flexed.

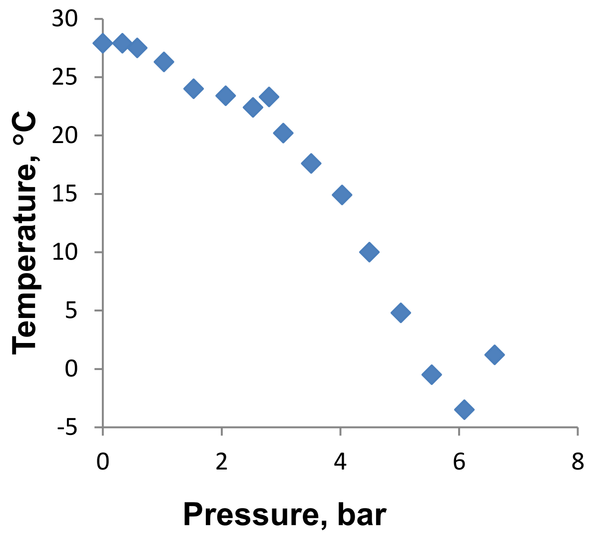

Fig. 4 The temperature measured by “cold” thermocouple (Fig. 3) as function of inlet pressure.

Fig. 5 The broken piece of polyethylene tube.

With the introduction of air, the process was accompanied by much loud noise. The analysis of the audio spectrum was performed with the LabView software. The audio spectrum (can be seen in Fig 6) is obtained by the microphone placed at a distance of 1 m from the vortex chamber. We see three distinct peaks (horizontal lines): the basic tone of ~3 kHz, the first overtone of the double-frequency of ~6 kHz, and the second harmonic of the triple frequency ~9 kHz. The sound intensity (color scaled) of the basic peak ~3 kHz (black line) exceeds 160 dB. The amplitude of the overtone peaks is less, but also considerably higher than the baseline noise level. So, it seems that there is a standing sound wave inside the vortex chamber.

Observation indicates (Fig. 7) that the effect of temperature separation correlates with the acoustic intensity (loudness).

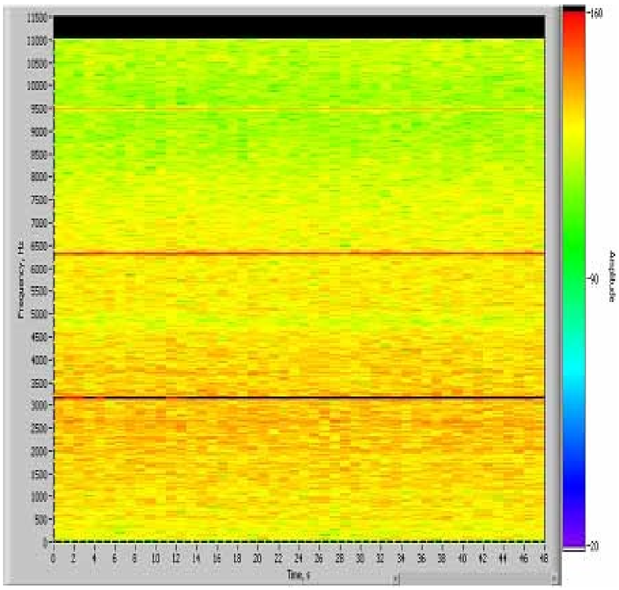

Fig. 6 The audio spectrum, obtained from the vortex chamber (Fig. 1, *d* = 30 mm, *P* = 5 bar).

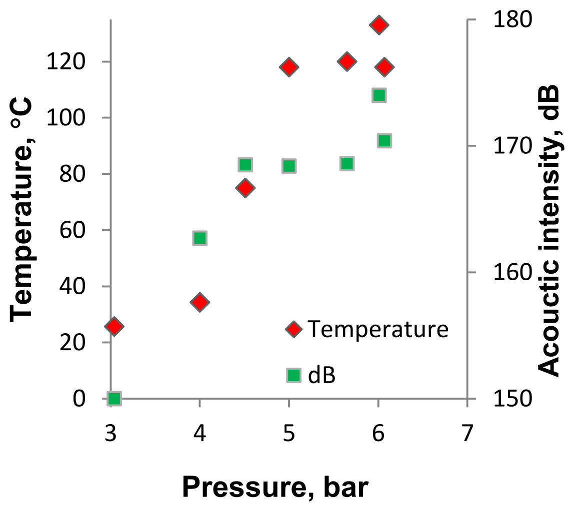

Fig. 7 The heating of "hot" thermocouple and acoustic intensity as functions of inlet pressure.

2.3 Discussion

The theory of heat transfer, which is proposed to explain the Ranque effect in vortex tubes, cannot explain the temperature separation inside the short vortex chamber examined. Indeed, it is impossible for convective heat transfer processes to take place from the central area to the periphery. If the "hot" micro-volumes are present inside the vortex chamber, they cannot move to the periphery due to the powerful radial flow towards the centre.

Physicists with whom the author has discussed this phenomenon usually agree with the previous statement. But they oppose the following suggestions: (1) the concept of flow separation into a hot stream and a cold stream, and the influence of (2) shock waves, (3) powerful acoustic waves, or (4) pulsations.

The concept of flow separation into two streams, one hot and one cold, means that these two streams do not mix. The hot stream is heated by friction and jet impacts. The cold stream is cooled by adiabatic expansion and reduction processes.

But this concept cannot explain why the heating of the plugged branch pipe and the cooling of the central rod depend so dramatically on the diameter of the outlet diaphragm. The hydrodynamic process of flow temperature separation must be stronger when the flow velocity increases. So the maximal temperature magnitudes must occur with the outlet diaphragm diameter of 40 mm, when the hydraulic resistance of the vortex chamber is minimal. But at 40 mm there is minimal temperature separation, while dramatically high maximal heating occur with the diaphragm diameter of 30 mm.

The concept of flow separation (into hot and cold streams) is also unable to explain the following questions: What is a stream that warms the bottom of the branch pipe up to 465 °C (See Fig. 2), unless there is practically no movement of air inside the cavity? How does the distance between the central rod and lower disk affect the temperature inside the branch pipe (See Ref. [1], Fig. 4)? Why does the level of heating inside the branch pipe depend on the symmetry of the position of the central rod axis displaced from the common axis [1]?

The experiment (Fig. 4, executed on the installation shown in Fig. 3) demonstrates cooling of thermocouple, mounted on the end of central rod. We know that all the air exits the vortex chamber through the thin ring-shaped space (~1-2 mm thickness) near the diaphragm. In the central zone of the vortex chamber (near the central rod), there is negative pressure. The back flow of air from the outside of the chamber (having a temperature of ~23 °C) blows on the "cold" thermocouple mounted on the central rod. There are no "cold" jets, which would cool the thermocouple, coming from the vortex flow. But the cooling occurs. So, the concept of flow separation into hot and cold streams is unsuitable to explain the examined temperature separation effect.

Pulsations are certainly present. It is the turbulent air pulsations that are the source of powerful sound in the vortex chamber. Of course fast pulsation creates compressed and rarefied zones with increased and decreased temperatures respectively. But usually the process of creation of turbulent pulsations is simultaneously accompanied by the process of their dissipation, and the resultant total temperature change is null. The pulsations move with the common flow. In the vortex chamber the powerful radial flow towards the centre prevents any movement of micro-volumes in the opposite direction, so temperature separation due to pulsations is impossible.

The shock waves inside the vortex chamber can be created only if the air jet velocities exceed the velocity of sound. The hydrodynamic investigations of the vortex chamber show [1] that in all operating modes the jet velocities are lower than the sound velocity. Therefore, the vortex flow inside the chamber was not accompanied by shock wave propagation.

Even if there were shock waves in the device, the following must be considered: The rarefaction shock wave does not exist, so the cooling effect stays out of consideration. The reflection of the shock waves from the cylindrical side wall would lead to a concentration of waves and an increase in temperature at the centre. However, we observe the opposite effect (cooling).

Powerful acoustic waves are an important factor in the temperature separation process. But the propagation of a sound wave cannot change the air temperature. If the mass of a gas inside a disturbance zone is constant, even a single fluctuation of compression must be accompanied by a fluctuation of rarefaction. These two phases constitute a unified wave which propagates from the point of creation. Separate compression and rarefaction sound waves do not exist.

Consider the "sound" disturbance. The energy density of the disturbance (the increment of energy per unit volume) is given by the equation (for example, Ref. [7], Chapter 1):

$$\in = \Delta\varepsilon + u\mathrm{k} = w0\,\Delta\rho + \frac{a^2}{2\rho_0}(\Delta\rho)^2 + \frac{\rho_0 v^2}{2} \quad (1)$$

In this equation, $\Delta\varepsilon$ is the increment of the specific internal energy of the disturbed gas; $u\mathrm{k}$ is the kinetic energy density of oscillating motion, $u\mathrm{k} = \frac{\rho_0 v^2}{2}$, $w0$ is the specific enthalpy, $w = \varepsilon + \frac{P}{\rho}$, v is the velocity and index 0 refers to the unperturbed state. During the derivation of expression (1), the increment of the specific internal energy of the disturbed gas with accuracy up to second order with respect to $\Delta\rho$ was considered. The processes in the gas were taken to be isentropic.

The second and the third terms (the kinetic energy density) of the sum in Eq. (1) are equal and are members of the equation of the second order quantity. In the process of calculating the total energy of the acoustic disturbance (via the integration of Eq. (1)), the first term of the sum cancels due to the fact that the density variations in compression zones are compensated by the density variations in rarefied zones.

Of course the sound wave (including the powerful sound waves studied in Nonlinear Acoustics) 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. So, the influence of powerful acoustic waves cannot explain the temperature separation inside the examined short vortex chamber.

Consider Fig. 5 carefully. The polyethylene tubes are repeatedly torn out by pressure and heating. Clearly, the broken hole is the place of maximal heating. There is no movement of air inside these tubes, and if any kind of heating takes place inside the vortex chamber, the hole has to appear near the chamber wall (near the fast connector). On the other hand, if shock waves or sound waves are responsible for heating the tube, the maximum heating should take place at the far end of the tube (The tube is a perfect wave conductor due to the wave reflection from the tube walls).

It seems that the heat leaves the vortex chamber through the cylindrical channel linearly along the radius and is absorbed by the tube wall in the place where it is flexed.

Therefore there is no known physical process which would provide such warming of the tube.

The Pressure Gradient Elastic Waves concept is suggested to explain the experimental results. The author believes that a special kind of elastic wave (PGEW) exists in nature.

3. Pressure Gradient Elastic Waves

The current chapter focuses on the statement of the physical model, which is intended for the construction of a theory of Pressure Gradient Elastic Waves.

3.1 The Physical Constitutive Model

In order to introduce the concept of Pressure Gradient Elastic Waves, a simplified model is considered: gas in a strong field of mass forces. Powerful forces affect the gas molecules creating a pressure gradient, even within a small volume. In the first stage, we shall not specify the nature of these forces (noting that such forces are strong gravity or electromagnetic field acting on the ionized gas).

We can take the initial assumptions:

- Steady state conditions;
- The gas is a perfect fluid;
- The substance is homogeneous with respect to temperature;
- The forces over the entire volume are directed to one side (we assume that they are directed downwards);
- We shall consider this problem in a one-dimensional approximation (The direction of unit vector is directed to pressure increase).

We obtain the pressure gradient expression from the Euler equation for a steady-state volume element.

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

Here $\boldsymbol{u}_f(r)$ is the acceleration, which characterizes the field of forces. $\rho_s(r)$ is the gas density, which depends on the pressure.

$$\rho_s(r) = \frac{k}{a^2}P(r) \tag{3}$$

Here a is the sound velocity, and k is the adiabatic index

For a limited volume filled with perfect fluid, we can obtain from Eq. (2) an expression for the pressure at the point r.

$$P(r) = P_0 \exp\left(\frac{k}{a^2}\int_{r_0}^{r} u_f(r)dr\right) \tag{4}$$

Here P_0 is the pressure on the upper wall (the point r_0).

In cases where inside the volume concerned acceleration $\boldsymbol{u}_f(r)$ is constant (having magnitude G, Eq. (4) is transformed into the expression

$$P(r) = P_0 \exp\left(\frac{Gk(r - r_0)}{a^2}\right)$$

Regarding the elastic waves propagation, we assume that

- Elastic waves have no effect on the movement of a mass inside a volume;
- The processes associated with the propagation of elastic waves are adiabatic processes;
- Fast-acting processes, whose speed exceeds the local sound velocity, we will assume as immediately operating processes. This group includes the high-speed force of the field, creating a pressure gradient, and the forces of pressure. Pressure is associated with an average velocity of molecules, which depends on temperature and is always higher than the local sound velocity.

Consider an elongated volume (Fig. 8) with a square cross section filled with gas. The volume is mounted vertically. The system is closed (the mass of a gas is constant), but not isolated (the field of the forces affects every molecule of a gas in the volume). The system is in steady state—no mass moving.

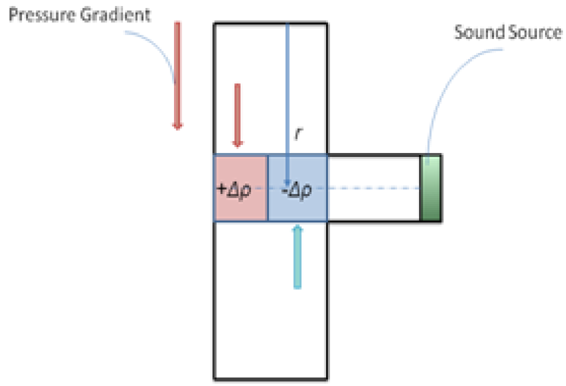

Fig. 8 Volume filled with a gas inside a field of forces, creating pressure gradient.

The sound source is installed in the volume (Fig. 8). The sound source creates a standing wave inside with a perfect flat front. (Here the "sound" combines the elastic oscillations regardless of their frequency). The sound source is chosen so that the length of the generated sound wave is equal to the width of the volume. A density fluctuation created by sound source will called starting fluctuation (starting disturbance) and consider only the area in front of the sound source. In reality, the pressure in the sound wave has sinusoidal varies. However, for simplicity, we assume that the half-periods of the standing waves are characterized by the magnitude of sound pressure fluctuation ΔP, which is added to the existing pressure. We assign a coordinate r of the zone of starting sound fluctuations (the distance will be measured from the top cover). This zone is divided into two parts, one with increased and one with decreased pressure. Inside the compressed zone, the gas density and temperature are increased, while in the rarefied zone, these characteristics are reduced. Within the starting sound fluctuations zone, the pressure, density and temperature are interrelated by adiabatic equations. Thus, the gas density in the area of the starting sound fluctuations changes from $\rho(r)$ to $\rho(r) + \Delta\rho$ ($\pm\Delta\rho$ defines the amplitude of fluctuations). However, the magnitude of the pressure on the disturbance zone boundaries remains unchanged. If we consider the balance of forces on the borders of the starting sound fluctuations in the presence of a pressure gradient, it is seen that new forces arise which further act on the gas inside these zones. These forces are the resultant forces of pressure forces and forces of the field which create the pressure gradient. With regard to Eq. (2), we obtain an expression for the acceleration $\boldsymbol{u}(r)$:

$$\boldsymbol{u}(r) = \boldsymbol{u_f}(r)\frac{\Delta\rho}{\rho_s(r)+\Delta\rho} \qquad (5)$$

This acceleration determines the magnitude of the additional resultant force which acts on the starting density fluctuations zone.

If inside the closed volume (Fig. 8) the acceleration $\boldsymbol{u_f}(r)$ has negligible variation and may be replaced by constant G, Eq. (5) is transformed into the expression

$$\boldsymbol{u}(r) = \boldsymbol{G}\frac{\Delta\rho}{\rho_s(r)+\Delta\rho}$$

When $\Delta\rho$ is positive (the fluctuation of compression), the resulting force is directed downwards in the direction of increasing pressure while when $\Delta\rho$ is negative (the fluctuation of rarefaction), the resulting force is directed upwards in the direction of low pressure.

We consider that the fast-acting pressure forces act immediately in comparison with the "slow" sound velocity. Starting sound fluctuations develop with the sound velocity. Throughout (during approximately the period of the sound wave), fast-acting forces create a secondary disturbance of the gas density in the area of the fluctuation.

3.2 Justification of the Real Existence of Pressure Gradient Elastic Waves

In accordance with Huygens principle, a secondary wave occurs at each point in space that the primary wave has reached. With regard to elastic waves in gases, this principle can be represented as follows: Two types of gas disturbances are the same—the disturbance caused by the pressure forces and the disturbance caused by the wave source (for example, by the sound transmitter). In Ref. [8], the wave equation is derived based on only two obvious assumptions: the existence of a gas disturbance associated with small density fluctuations, and the existence of the positive derivative $\frac{dP}{d\rho}$. We can assume that this is a mathematical justification of the Huygens principle discussed above.

Evolvement of the starting density fluctuations in the gas (Fig. 8) under a pressure gradient causes the appearance of fast-acting pressure forces. The forces have an additional effect on the starting fluctuations area and create a secondary disturbance.

In accordance with the above principle, this secondary disturbance undoubtedly creates a secondary elastic wave which we denote Pressure Gradient Elastic Wave. Using the superposition principle of the wave, we can consider PGEW separately from the starting sound wave.

3.3 Propagation of the Pressure Gradient Elastic Wave

The starting "sound" disturbance triggers the Pressure Gradient Elastic Waves emerging. This starting "sound" disturbance creates a density fluctuation $\Delta\rho$ which determines the appearance of the force (by relation (5)) that creates the Pressure Gradient Elastic Wave. The magnitude of gas density inside the disturbance zone with a pressure gradient depends on the location of the starting disturbance,

$$\rho(r) = \rho_s(r) + \Delta\rho, \tag{6}$$

where $\rho_s(r)$ is the initial density distribution (3). The amplitude of the density fluctuations $\Delta\rho$ is related to the amplitude of the pressure fluctuations ΔP by Poisson's adiabatic relation. The force, which created Pressure Gradient Elastic Waves, always exists when $\Delta\rho \neq 0$ (See Eq. (5)).

The waves produced by elastic disturbances (including PGEW) move with the sound velocity. The pressure and the forces creating the pressure gradient are sharp-acting forces (i.e., faster than the sound velocity). Thus, the resulting force creating the Pressure Gradient Elastic Waves affects the area of the fluctuations as long as the wave propagates. If, from the starting point with coordinate r, the Pressure Gradient Elastic Wave moves to a distance dr, this force will do the work which is added to the wave energy ($d\ni$ is the increment of work per unit of volume).

$$d\ni = \rho(r)u(r)dr \tag{7}$$

We obtain next expression taking into account Eq. (5) for the acceleration $u(r)$, caused by the action of the resultant force in the disturbed area, and also taking into account Eq. (6) for PGEW.

$$d\ni = \Delta\rho(r)u_f(r)dr \tag{8}$$

where $u_f(r)$ is the acceleration of the force field.

Furthermore, the energy density of the Pressure Gradient Elastic Waves is the sum of the energy of the starting disturbance (the first term of the sum in Eq. (1)) and the physical work $\ni$ (integrated Eq. (8)). The equations above can equally be applied to compressed wave and rarefied wave, taking into account the appropriate sign (plus or minus) of the increment.

3.4 The Compressed Wave

Above, we have considered the increment of the density fluctuations $\Delta\rho$ as a constant that is right for the starting "sound" fluctuation. In Pressure Gradient Elastic Waves, $\Delta\rho(r)$ and $\Delta P(r)$ are subjected to change during the propagation of the waves. The "sinking" compressed wave moves in the direction of increasing of pressure and density ($\Delta\rho$ is positive). The force, which created the pressure gradient, "pushes" a compressed front of PGEW. The work done by this force at every path segment is added to the energy of the compression zone. This zone experienced an additional press up, as a result of which the $\Delta\rho(r)$ and $\Delta P(r)$ are increased.

However, there is a factor that can act in reverse. Consider the situation where a compressed front of Pressure Gradient Elastic Waves is shifted, but its energy remains constant (i.e., energy changes can be neglected). We suppose two extreme positions: First, the magnitudes of $\Delta\rho$ and ΔP remain constant, and second, the geometric dimensions of the compressed wave front are not changed.

In the first instance, the dimensions of the compressed wave front have to decrease. Taking into account that energy is an additive thermodynamic function; the mass of a gas covered by the compressed wave front has to remain constant. Such a changing of the dimensions (changing of wavelength) is possible only if the downstream layers of the compressed wave front move with a higher velocity than the upstream layers. The density change during elastic wave propagation has an effect on the temperature, which can be determined from the adiabatic equation

$$T_1 = T_0 \left(\frac{\rho_1}{\rho_0}\right)^{k-1} = T_0 \left(1 + \frac{\Delta\rho}{\rho_0}\right)^{k-1} \quad (9)$$

where k is the adiabatic index and the index 0 refers to the undisturbed state.

Consider two adjacent thin layers in the compressed wave front, each with the same value of $\Delta\rho$, but due to the pressure gradient, the initial values ρ_0 are different. The value ρ_0 inside the upstream (in the direction of increasing pressure) layer is larger. So the temperature T_1 (due to (9)) (and the value of the local sound velocity) in upstream layer is therefore less than in the downstream layer, which is moved after it. Thus, the compression (reduction in size) of the dense front of Pressure Gradient Elastic Waves definitely takes place; however, it is not obvious that the magnitude of this compression is fully consistent with of the energy conservation law.

In the latter case, if the geometric dimensions of the compressed wave front have not changed (in addition, the mass covered by the wave is increased), the amplitudes $\Delta\rho$ and ΔP should decreased.

It is likely that there is a combination of all the factors listed above.

The above considerations suggest that the propagation of the compressed wave front of PGEW may have physical limitations. For example, its amplitude can be damped. Most likely, for small values of $\Delta\rho$, the propagation of the compressed wave front of Pressure Gradient Elastic Waves is impossible.

3.5 The Rarefied Wave

The "floating" rarefied wave front propagates in the direction of decreasing pressure and density ($\Delta\rho$ is negative). The force of pressure expands the rarefied wave front of PGEW, performing negative physical work, with an increase ($-\Delta\rho$ and $-\Delta P$) in magnitude and a temperature decrease.

The arguments presented above can be repeated for the rarefied wave. The main difference is that during the displacement, the rarefied wave front covers a smaller mass of the gas. These circumstances lead to an increase of the amplitudes ($-\Delta\rho$ and $-\Delta P$). The magnitudes of the local sound velocities also contribute to the expansion of a rarefied wave packet. In other words, the physical limits for the rarefied front of PGEW propagation are absent. For any small starting density fluctuation, a "cold" wave of PGEW will continue to exist and develop.

The above general results for the evaluation of the Pressure Gradient Elastic Waves propagation correlate with the results obtained in Ref. [7]. In Ref. [7], it is shown that the propagation of shock waves in the atmosphere for the downward direction is different compared to the upward direction. Moving down is characterized by deceleration and dissipation, and moving up has unlimited development, up to breaking the atmosphere. One of the main factors of this difference is the change of air density (of the mass involved to the process) along the vertical due to the gravitational pressure gradient.

The experimental results in Ref. [1] also confirm the above conclusions. The cooling, produced by Pressure Gradient Elastic Waves in the axial zone of the installation, is observed in all modes of operation for all sizes of the outlet diaphragms, for the entire pressure range. The process of heating the branch pipe's end cap, which was mounted on the side wall of the vortex chamber, is a more volatile phenomenon (At low pressures, the heating is usually not present).

3.6 The Dynamic Systems

Above, we assumed that the pressure gradient was created by a field of mass force (similar to gravity),

Table 1 The properties of Pressure Gradient Elastic Waves.

The normal "sound" waves	Pressure Gradient Elastic Waves
The "sound" waves always arise in compressible fluids when there is a sound source, creating density fluctuations.	Three conditions are necessary for Pressure Gradient Elastic Waves arising: (1) The substance must be a compressible fluid; (2) A pressure gradient must exist inside a space or a volume filled with a compressible fluid; (3) Density fluctuations must be present. These fluctuations may be a result of sound.
The source of the "sound" determines the characteristics of the "sound" wave (frequency and amplitude). All the energy of the "sound" wave is received from the source of the "sound".	Pressure Gradient Elastic Waves created by external forces, which create a pressure gradient in a gas.
The sound waves propagate out in the direction of the sound source. In the case of a point "sound" source placed in homogeneous infinite space, the surface of the front of the acoustic wave is an expanding sphere (full solid angle).	Pressure Gradient Elastic Waves propagate along the vector of the pressure gradient.
The process of "sound" waves propagation is periodically process. The reason of this is the fact that "sound" source always pulsates or carries out oscillatory motion.	The oscillations are absent in Pressure Gradient Elastic Waves since they do not exist in the field of force, which generates the pressure gradient.
In "sound" wave the compression and rarefaction zones alternate and move together in the same direction.	The compressed front of the Pressure Gradient Elastic Waves is directed toward the higher pressure zone, while the rarefied front is directed in the opposite direction toward the lower pressure zone.
The process of "sound" waves propagation in a gas is an isentropic process.	The process of Pressure Gradient Elastic Waves propagation is adiabatic (no heat supply or removal), but is not an isentropic process. The force field did the work. It compresses or expands the density fluctuation area.
The energy of "sound" waves in gases consists of two components: the potential energy, which is due to the magnitude of the relative elastic strain; a component of the kinetic energy of the oscillatory movement. Adiabatic compression and rarefaction have to change the gas temperature in the wave disturbance areas. However, since in the "sound" waves these zones alternate, the net effect is zero.	The component, which is due to the kinetic energy of the oscillatory movement, is absent in the energy of Pressure Gradient Elastic Waves since there are no oscillations in the PGEW. The energy of the PGEW consists of two components: the energy of starting "sound" disturbances, including the component associated with the change in temperature of the disturbance area, and the energy equivalent of the work done by pressure force, which moves the wave front.
Inside a bonded space, the "sound" waves are reflected from the walls.	Inside a bonded space, Pressure Gradient Elastic Wave is absorbed by the walls. The PGEW reflection and its movement in the opposite direction is impossible. This is prevented by the force, creating a pressure gradient. As the result of Pressure Gradient Elastic Waves absorption, the entire energy of the wave is transferred to the walls in the form of heat or cold. The PGEW cannot pass through an extremum point, thus if the function of the pressure gradient has an extremum, it is dissipated in this place.
The "sound" wave transfers the energy obtained from the sound transmitter. Their absorption usually has very small changes the thermodynamic characteristics of the system.	Pressure Gradient Elastic Waves take energy over all space, and carry it to the direction of increasing pressure. The heat transfer increases the temperature in the high pressure zone and reduces it in the low pressure area.

which affects every molecule of a gas. However, the pressure gradient in the volume of a gas can be created dynamically by rotation, acceleration and deceleration. We assume that Pressure Gradient Elastic Waves exist inside systems where the pressure gradient is created in a dynamic way.

The forces of inertia are introduced for convenience in the consideration of dynamic systems. These forces allow us to use the static equation for the description of the dynamic systems. We extend the idea of the inertial forces to the idea that there are "mass" forces. We assume that the introduction of inertial forces adequately simulate the dynamic action on the gas volume as a whole and on each molecule of gas in this volume. Let us remember that the introduction of the "field" of inertial forces, which creates a pressure gradient, is a simplified model. The accuracy of using such a model must be confirmed by experimental results.

For example, consider a closed volume (pipe) filled with gas (Fig. 8) mounted on a centrifuge which rotates with constant angular velocity ω. The axis of the pipe is installed along the radius of the rotation. The pressure gradient is created by the field of centrifugal forces. The centrifugal acceleration creating the pressure gradient (according to Eq. (2)) in this case is

$$u_f(r) = \omega^2 r$$

The pressure $P(r)$ and the pressure gradient $gradP(r)$ at radius r are given by equations

$$P(r) = P_0 \, exp\left(\frac{k\omega^2(r^2 - r_0{}^2)}{2a^2}\right)$$

$$gradP(r) = k\left(\frac{\omega}{a}\right)^2 r\, P(r)$$

where P_0 is the pressure at radius r_0 near the wall, close to the centre of rotation.

3.7 Characteristic Property of Pressure Gradient Elastic Waves Propagation

We single out the main differences between this kind of elastic wave from conventional "sound" waves (here the term "sound" combines the elastic oscillations regardless of their frequency). To compare the properties, two types of waves are presented in Table 1.

4. The Proof of Pressure Gradient Elastic Waves Existence

At the date of writing this work, the direct experimental demonstrations of the Pressure Gradient Elastic Waves existence are not yet available. Below, indirect proofs of PGEW existence are given:

(1) The Pressure Gradient Elastic Wave is the phenomenon which determines the Ranque' effect and the work of all the vortex tubes [2-3]. The explanation of the operation of these devices, based on the concept of PGEW, removes all the "weaknesses" in the pre-existing theories;

(2) The Pressure Gradient Elastic Wave operates inside the Hartmann sound generator [9]. In these devices, the pressure gradient is created by gas jet impact. PGEW heats the end of the cavity mounted opposite to the nozzle. During the experiment, using a helium jet, the end cavity temperature reaches ~1000 °C;

(3) The results of experimental investigations of the temperature separation in the short vortex chamber [1] raise a lot of questions, whose answers can only be obtained on the base of the PGEW concept. The existing "hydrodynamic" theories (as proposed for the vortex tubes) cannot answer, for these questions.

All the experimental results (present paper and Ref. [1]) can be explained by Pressure Gradient Elastic Waves. The configuration of the vortex chamber with air flow features affect the frequency and amplitude of the generated sound waves. The outlet diaphragm diameter *d* = 30 mm forms a sound frequency close to the natural resonance frequency of the vortex chamber. At this diaphragm diameter, optimal resonance conditions were observed. The amplitude of density fluctuations is maximal and this creates a powerful Pressure Gradient Elastic Waves. Other diaphragm diameters and changing the central rod position changes the generated sound frequencies. When this happens, the initiating sound wave moves from a resonance condition, its amplitude decreases and the PGEW will also decrease or not exist.

5. Conclusions

The experimental investigation of temperature separation effect inside a short vortex chamber is executed. The analysis showed that the results of these experiments cannot be explained on the basis of existing hydrodynamic concepts proposed to explain the temperature separation inside the vortex tubes (Ranque effect).

The concept of Pressure Gradient Elastic Waves is proposed to explain the results of the experiments. PGEW is a special kind of elastic waves, which operate in compressible fluids (gases) with pressure gradients and density fluctuations.

The paper presents the physical model of a gas in a strong field of mass forces to substantiate the PGEW existence. Using this model a theory of PGEW can be created. Systems with PGEW are non-equilibrium systems. Thus, it describing will require tools from Non-Equilibrium Thermodynamics.

The propagation of PGEW and their main properties is discussed in the article. The emergence of PGEW inside the volume results in the heat transfer from the area of low pressure in the high pressure zone. Understanding the processes associated with the PGEW permits the possibility of creating new class of technical devices [10] (for example, heat pumps) with unique properties. The fields of its application are: energy saving and low potential heat utilization.

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