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HEAT TRANSFER IN COMPRESSIBLE FLUIDS BY PRESSURE GRADIENT ELASTIC WAVES. RESULTS OF EXPERIMENTS SUBJECT TO DISCUSSION.

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Abstract *Pressure Gradient Elastic Waves (PGEW) arise in compressible fluids when, at the same time, a pressure gradient (rotation, deceleration...) and density fluctuations (sound, turbulence) exist in a region of space. The appearance of PGEW in a closed volume leads to energy transfer, as a result of which the wall in the high-pressure zone heats up and the low-pressure zone cools.*

The report presents the results of experiments that substantiate the trueness and correctness of the PGEW concept. The emphasis is on interesting results that are subject to discussion and understanding.

The results of some experiments are published for the first time, these include:

Dependence of the degree of heating of the bottom of the cavity of the Hartmann-Sprenger tube on orientation in space

Key words: *Compressible media; Heat transfer; Pressure gradient; Density fluctuations; Pressure Gradient ElasticWave. .*

Articles and reports have accumulated many observations on the influence of sound on temperature processes in gases: heating [1], drying [2], cooling [3]. The common characteristics of these processes are that the processes occur in compressible media (gases) and have a resonant nature, that is, there is a dependence of the intensity of the process on the frequency of sound. The temperature effects of Ranque (Vortex Tubes) [4] and Hartmann-Sprenger [5] should be included in this class of phenomena. The temperature separation in these devices is always accompanied by a loud sound.

An additional common feature of these devices is the presence of a pressure gradient. Moreover, the heating area is in the high pressure zone, and the cooling area is in the reduced pressure zone.

The swirling of gas in vortex tubes creates a pressure gradient with a pressure maximum at the periphery near the cylindrical wall and a minimum in the central region near the tube axis. In Hartmann-Sprenger tubes (HST), a pressure gradient is created due to the deceleration of the gas jet. The bottom of the cavity installed opposite the nozzle is heated to significant temperatures, in this place the pressure is maximum (the kinetic energy of the jet turns into potential). In experiments [6] using a helium jet at the bottom of the cavity, a temperature of ~1000°C was achieved. The minimum pressure area is the zone between the nozzle and the cavity where the jet speed is maximum. By removing heat from the outer wall of the cavity and removing gas from the space between the nozzle and the cavity, a significant reduction in the temperature of the exiting gas is achieved.

Various concepts have been put forward to explain the temperature separation in these devices. A decrease in pressure during the acceleration of jets in the nozzles was considered as a source of gas cooling. Heating was caused by viscous friction of gas jets; micro-refrigeration processes (or interaction of vortices) were also considered, because of which cold and hot microvolumes were formed, which were then separated. Heating in the Hartmann–Sprenger effect) was explained by shock waves.

However, until now there have been no theories that adequately describe these temperature processes. A temporary lack of understanding of the physical basis of these processes forced us to attribute them to the realm of experimental paradoxes.

Concept of Pressure Gradient Elastic Waves

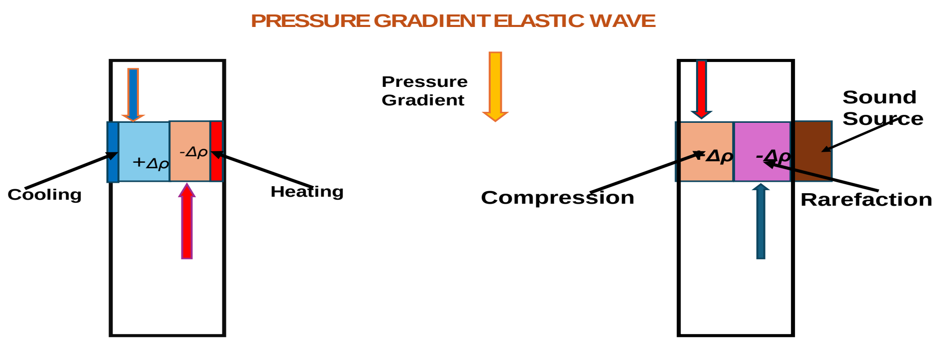
We carried out experimental studies of temperature separation in the devices mentioned above, as well as in a short vortex chamber (VC). The experimental results confirmed the conclusion that previously existing theories cannot explain temperature separation in gases. The concept of Pressure Gradient Elastic Waves is presented and justified [7 - 11].

PGEW is a sound type wave. PGEWs propagate at the speed of sound in accordance with the Huygens-Fresnel principle; these waves interfere, are reflected, and are absorbed. However, PGEWs differ from other sound-type waves in the nature of the forces that create PGEWs and the direction of propagation. PGEWs occur in a volume (space) when three conditions are simultaneously met: the volume is filled with a compressible fluid (gas); there is a pressure gradient in this volume; and starting density fluctuations (sonic or turbulent) are generated.

Justification for the existence of PGEW does not require the introduction of new physical entities and is based on classical thermodynamics, more precisely on nonequilibrium thermodynamics (systems with a pressure gradient that arises under the influence of external forces).

The simplest way to justify the existence of IOP is an analogy with the well-known phenomenon of natural convection.

Consider the thought experiment, Fig. 1.



a) b)

Fig. 1. An elongated volume filled with gas in the presence of a pressure gradient.

In Fig. 1 – two elongated volumes filled with gas, located in a force field that creates a pressure gradient (gravity, rotation...). The pressure gradient vector is directed from top to bottom in the direction of increasing pressure. In Fig. 1(a), plates are installed on the wall of the volume, which create heated and cooled microvolumes in the adjacent space. The theory of convection considers the balance of forces acting on the boundaries of a microvolume according to Archimedes' law. The resulting pressure force, displacing the microvolume, will arise when the density of the gas inside the microvolume differs from the density of the surrounding gas. Obviously, the cold microvolume (of higher density) will shift in the direction of increasing pressure (down), and the heated microvolume (of lower density) will shift in the opposite direction.

In Fig. 1(b), a sound source is installed on the wall of the volume, which created a sound density fluctuation with the formation of adjacent zones of compression and rarefaction. Acoustic processes are studied within the framework of classical thermodynamics, so we can reasonably consider the balance of pressure forces acting on the boundaries of these zones (just as in the phenomenon of convection). According to Archimedes' law, the resulting forces acting on the compression and rarefaction zones of the sound wave are not equal to zero, since the densities in these zones have shifted from their equilibrium values. These forces are directed along the pressure gradient vector. The force acts on the compression zone in the direction of increasing pressure, and on the rarefaction zone - in the opposite direction - in the direction of decreasing pressure. An important difference from the convection phenomenon discussed above is the adiabatic nature of sound processes. Therefore, the compression zone in the gas is heated, and the rarefaction zone is cooled.

Pressure in gases is determined by the average speed of molecules, which is higher than the speed of sound. Acoustic density fluctuations develop at the speed of sound. These zones are subject to faster pressure forces, creating an additional secondary density disturbance. This secondary disturbance (according to Huygens' principle) necessarily creates a secondary elastic wave. In accordance with the superposition principle, this wave can be considered separately. This is the **Pressure Gradient Elastic Wave**. PGEWs consist of a compression front and a rarefaction front. However, in accordance with the direction of the forces that create sound disturbances in density, the compression front of the PGEW is directed towards increasing pressure, and the rarefaction front of PGEW is in the opposite direction (towards decreasing pressure).

PGEWs occur at every point in the volume within which density fluctuations have occurred. This wave is a sequence of compression waves propagating in the direction of increasing pressure, and a sequence of rarefaction waves propagating in the opposite direction. In a limited volume the PGEWs heat the wall delimiting the high-pressure zone and cooled the wall (or region) of low pressure. In this volume, the PGEWs transfer energy from the low pressure zone to the high pressure zone.

The PGEW concept fully describes temperature effects in gases, including the Rank and Hartmann-Sprenger effects, as well as the results of all experiments.

Based on the PGEW phenomenon, a new type of heat pump can be created. The physics of the process allows us to reasonably predict that these new heat pumps will be more efficient than those existing today.

Short vortex chamber

The unexpected discovery of temperature separation in a short VC stimulated research of the effect, which led to understanding of the phenomenon and the promotion of the concept of PGEW [7].

Air was pumped into the VC with a height-to-diameter ratio H/D=0.18 at room temperature. In the maximum temperature separation mode, the temperature at the periphery reached 465°C, and the temperature in the central zone dropped to -45°C. The observed temperature separation is possible if heat is transferred from the center to the periphery. But in this VC, a powerful flow moves from the periphery to the center, and heat transfer due to the displacement of hot microvolumes in the opposite direction to the periphery is impossible.

The experimental setup is schematically shown in Fig. 2. The VC consists of: a lower disk (1), a cylindrical side wall (2), and an upper disk (3). On the cylindrical side wall (2) there are four tangential nozzles with a diameter of 5mm (7). The air jets entered the chamber at an angle of 20 degrees to the tangent. The rotating flow moved from the periphery to the center, then exited through the diaphragm (4) into the output manifold (5). The central rod (8) was installed coaxially with the output diaphragm (4). The plugged side pipe (9) was mounted on the outer surface of the cylindrical side wall (2). The cylindrical pipe (9) had a cavity with a diameter of 8 mm and a length of 32 mm. Experiments were performed with output diaphragms (4) with diameters (d = 20mm, 25mm, 30mm, 35mm, and 40mm).

Diagrams Fig.3 and Fig.4 show the dependence of the temperatures measured by two thermocouples (10) and (11) on the input pressure. The “cold” thermocouple (11) was mounted on the lower end of the central rod, and the “hot” thermocouple (10) on the plugged bottom inside the side pipe (9).

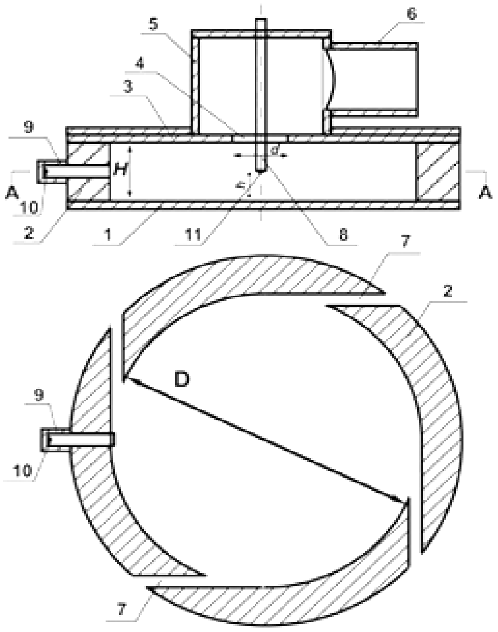


Fig. 2. Schematic representation of the experimental vortex chamber
Top: frontal section; Bottom: top view section.
Installation includes the following parts: 1. Lower disk, 2. Cylindrical side wall, 3. Upper disc, 4. Output diaphragm, 5. Output manifold, 6. Outlet pipe, 7. Tangential nozzles, 8. Central rod, 9. Plugged side pipe, 10. "Hot" thermocouple, 11. "Cold" thermocouple.
D – Vortex Chamber diameter (140 mm);
H – Vortex Chamber Height (25 mm);
d – Diameter of the output diaphragm; h – Distance between the central rod and the lower disk.

Fig. 3 shows the measurement results for a VC with an output diaphragm of 30 mm, Fig. 4 - for output diaphragm diameters of 20 mm, 25 mm, 35 mm and 40 mm

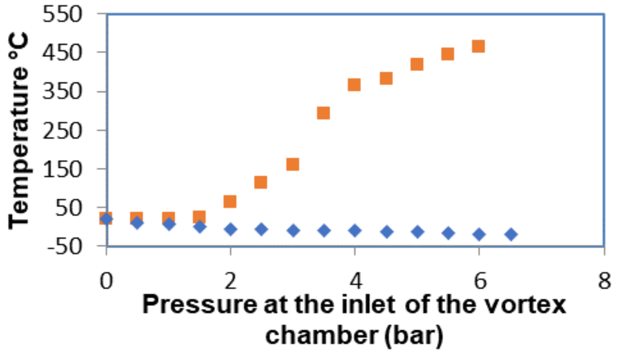


Fig. 3. Dependence of temperature on input pressure for an installation with an output diaphragm diameter d=30mm.

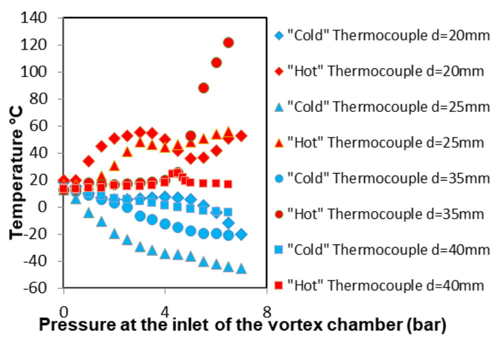


Fig.4. Dependence of temperature on input pressure for installations with output diaphragm diameters d= 20mm, 25mm, 35mm and 40mm.Рис.4.

The maximum temperature separation was obtained on a VC with an output diaphragm d = 30mm. The highest temperature recorded was 465°C at a pressure Pexp = 6 bar and the minimum temperature was 45°C at a pressure Pexp = 7 bar.

Experimental points on the diagrams characterize stationary values of temperatures and pressures. When the pressure changed, the temperature value was established after a certain period and then remained unchanged.

Previously existing theories (proposed to explain the Ranque effect) do not explain the heating of the periphery in this VC. Heat transfer due to the displacement of hot microvolumes from the center to the side wall is impossible. In addition, these theories do not explain the existence of the optimal value of the output diaphragm diameter d = 30 mm, at which the temperature separation is maximum.

The PGEW concept assumes that at d = 30 mm the chamber volume corresponds to the conditions of sound resonance. Indeed, the supply of air to the VC in all modes was accompanied by a very strong sound. Analysis of the sound spectrum, performed for a chamber with d = 30 mm, showed that at pressures above 1.7 bar a narrow peak appears at a frequency of ~3 kHz. The peak amplitude increased with increasing pressure and significantly exceeded the baseline noise level. With a further increase in pressure, a second peak appeared with a frequency of ~6 kHz.

Observations have shown that the level of temperature separation effect in VC increases in according to the sound intensity.

Pressure ratio (inlet/outlet) at nozzles in a short vortex chamber

Measuring the pressure on the VC (Fig. 2) gave an interesting and non-obvious result. The value of the pressure ratio on the nozzles Pout/Pin in all operating modes was greater than the critical value for air, that is, 0.53. For example, when the nozzle inlet pressure was 7 bar, the outlet pressure was 4.6 bar and the pressure ratio was 4.6 : 7 ≈ 0.66.

Diagram Fig. 5 shows the dependence of the measured values of the ratio **α** on the pressure at the inlet to the VC. The measurements were carried out for VC with different diameters of output diaphragms **d**.

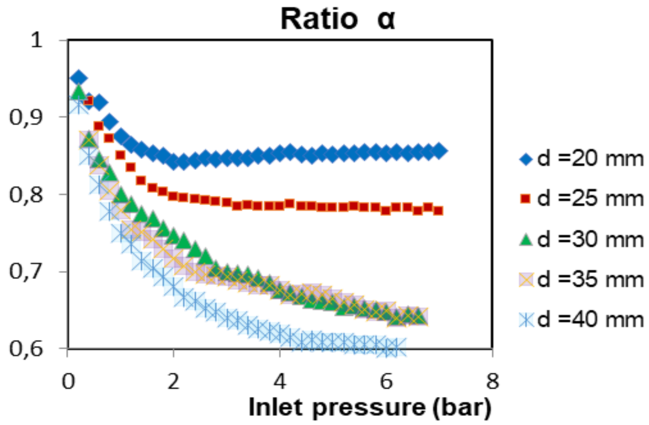


Fig. 5. Ratio α as a function of pressure at the entrance to the vortex chamber. Values of α are given for installations with output diaphragm diameters: D = 20 mm, 25 mm, 30 mm, 35 mm and 40 mm.

$$\alpha = \frac{Pside\ wall + 1}{Pinput + 1}$$

Pinput - inlet pressure (bar),
Pside - side wall pressure (bar)

The value of the ratio **α** determines the speed of the air jets entering the VC. It is important to point out that **α** is greater than 0.53 (the critical value for air) for all diaphragm diameters in all flow regimes. This circumstance means that the velocities of the jets at the entrance to the VC in all experiments were below the speed of sound. Consequently, the stream of the vortex flow was not accompanied by the propagation of shock waves inside the VC.

The jets emerging from the nozzles in the VC form the swirl of the vortex layer. The speed of these jets determines the tangential rotation speed of the layer, which in turn determines the pressure on the side wall. ***The revealed self-similarity is an experimental paradox and an interesting problem for theorists.***

Temperature distribution inside the vortex chamber

In the maximum heating mode (d = 30mm), significant thermal energy was released at the periphery of the VC. Not only the side pipe (9), but also the entire massive side wall heated up. The PVC side pipe was melted and ruptured by pressure. The polyethylene tubes connecting the side wall and peripheral areas of the lower disk to the pressure sensors were also repeatedly ruptured by pressure due to melting.

Diagram Fig. 6 shows the readings of thermocouples depending on the pressure at the inlet to the VC. Fig. 3 and Fig. 6 reflect the dependences obtained during the same experiment with d = 30 mm (at other diameters the heating effect is significantly less). For example, at inlet pressure Pexp=6 bar the following temperatures were recorded: on the side wall 60°C; at a point 50mm from the center 37°C; at a point 25mm from the center 33◦C. This cooling cannot be explained by a rapid decrease in pressure. In chambers with diaphragms d =25mm and 20mm, the pressure on the side wall and, accordingly, the pressure gradient is higher, the pressure relief is steeper, but the cooling of the flow is weaker.

To remove the assumption that the source of heating is cavity 10, an experiment was performed on a VC without a cavity, which practically repeated the results of Fig. 6.

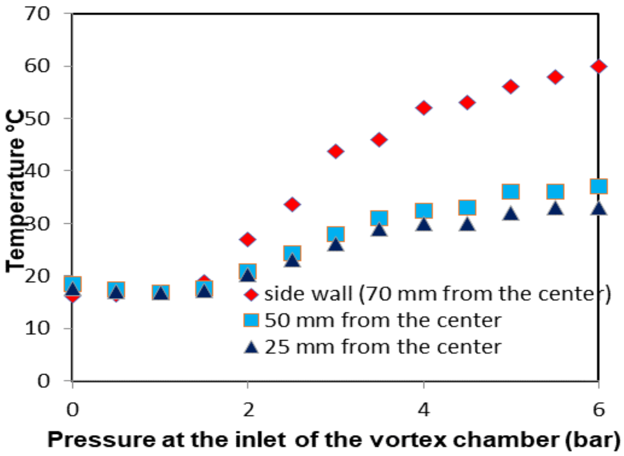


Fig.6. Temperatures inside the vortex chamber depending on the inlet pressure.
Thermocouples are installed: on the side wall (70mm from the center) and on the bottom disk (50mm and 25mm from the center).

Previously performed experiments showed that the cooling of air at the exit from a cylindrical nozzle is significantly less than adiabatic cooling with a pressure difference between the inlet and outlet. Thermocouples with a diameter of 0.7 mm at the exit from the 5 mm nozzles showed heating of the wall layer inside the nozzle, which is caused by friction. The temperature at the outlet from the VC usually decreased relative to the inlet temperature by no more than 5K.

Air entered the VC at a temperature below 18°C. At all pressures, the maximum temperature is the temperature of the wall layer of air. Shifting towards the center, the air cooled. At an inlet pressure of 6 bar, a displacement of 20 mm from the wall corresponds to a flow cooling of 23°C (Fig. 6).

Three questions arise.

What process heats the wall layer of air?

Why does the output diaphragm d=30mm produce significantly more heating than larger and smaller diameters? After all, the same energy is introduced into the VC by jets of air through the nozzles.

What process is responsible for cooling the flow in the VC?

The PGEW concept states that throughout the entire volume of the VC, sound and turbulent density fluctuations generate compression and rarefaction waves that propagate along the pressure gradient vector (along the radius of the VC) in opposite directions. Sound type PGEWs are practically not absorbed in gases at short distances. The compression waves reflected from the side wall are cancelled, as a result of interference, and release the heat brought into this area. Dissipation of rarefaction waves occurs in the center of the VC in the zone of minimum pressure with the release of cold.

The influence of the displacement of the central rod on the vortex chamber periphery heating

The effect of changing the distance **h** between the central rod 8 and the lower disk 1 on the temperature of the “hot” thermocouple (10) (Fig. 2) was recorded.

The diagram (Fig. 7) illustrates the experimental points of temperature (thermocouple 10) and pressure on the wall of the VC depending on the distance **h**. The experiment was carried out on an installation with an output diaphragm diameter d=30 mm at a constant input pressure Pexp = 4 bar. The first point (**h** = 0) reflects the position when the rod touched the lower disk. The central rod was displaced by 5mm, held in this position until the parameters stabilized, then the displacement continued. Above 25mm, the rod was displaced outside the VC. The final position h = 110 mm corresponds to the situation when the central rod has been completely removed from the holding collet. The maximum temperature of 212°C was recorded at h = 50 mm.

It is interesting that, along with the temperature of the “hot” thermocouple, the pressure value on the wall of the VC also changed synchronously. The identified dependencies are unexpected.

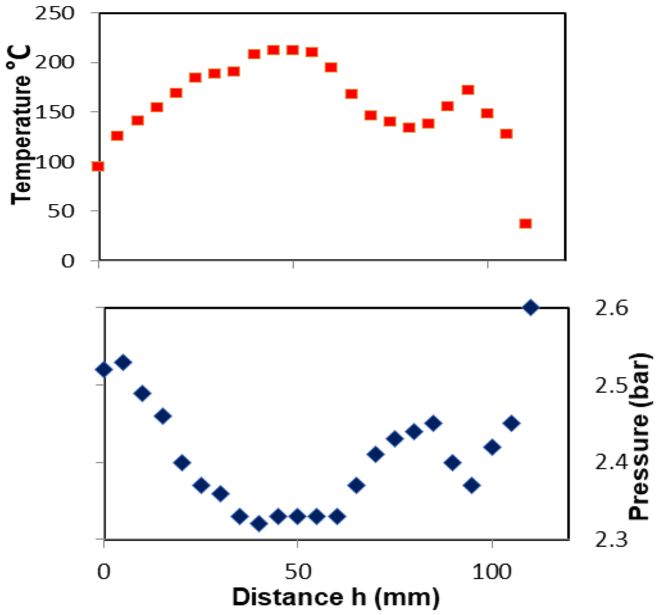


Fig. 7. Temperature (°C) measured by a "hot" thermocouple installed inside the plugged side pipe and pressure on the side wall (bar) depending on the distance h between the central rod and the lower disk

Indeed, the inlet pressure is constant, which means the speeds and air flow rates at the inlet to the AC are unchanged. Consequently, all characteristics of the vortex flow in the VK are constant**.**

Without invoking the concept of PGEW, it is impossible to explain how a change in distance h affects the temperature inside the side pipe. *The energy transferred by the PGEW is determined by the pressure gradient and the value of the starting density fluctuation (the amplitude of the starting sound wave). Changing the position of the central rod certainly changes the acoustic characteristics of the VC. To confirm the correctness of this assumption, it is necessary to repeat this experiment simultaneously with measuring the acoustic characteristics of the system.*

The influence of the position of the central rod on the side wall pressure (Fig. 7) is most likely explained by changes in the temperature of the wall air layers. It is known that heating the subsonic gas flow inside the pipe leads to an increase in its speed with a simultaneous decrease in pressure. Perhaps the same process occurs in a vortex flow. If the near-wall layers of the flow are in the same "constrained" state, then this allows us to explain the results obtained. An increase in the temperature of the near-wall layers leads to a decrease in pressure, which indicates a simultaneous increase in the kinetic energy of the vortex flow.

On the other hand, an increase in the tangential component of the near-wall flow velocity should increase the pressure on the side wall. ***Thus, the identified pattern needs explanation****.*

Vortex chamber without outlet manifold

The vortex flow in the VC forms a central zone of negative pressure. The dimensions of the vacuumized zone are formed by the output diaphragm. This zone reaches the lower disk and has a funnel shape. The measured pressure in the center of the lower disk 1 (Fig. 2) at all operating pressures for all diameters of the outlet diaphragms 4 was negative.

The maximum possible air-cooling temperatures are estimated under the assumption of two sequential processes - adiabatic cooling during jet acceleration inside the nozzle and then throttling cooling to atmospheric pressure. With a pressure at the inlet to the VC 7 bar, at the exit from the nozzles the pressure is 4.6 bar. The maximum adiabatic cooling with such a pressure decrease is 34 K. The throttling effect adds no more than 1 K to this value. The actual cooling, measured by cold thermocouple 11, was 65 K. That is, the actual cooling temperatures obtained significantly exceed the calculated (maximum possible) cooling.

Fig. 8 schematically shows a modified VC (outlet manifold is missing). The diagram (Fig. 9) shows experimental points corresponding to the readings of cold thermocouple 11 for various pressures at the inlet to the VC.

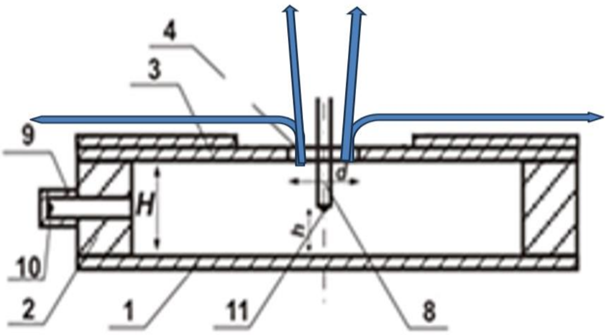


Fig. 8. Modified VC (schematic image; cross-section). 1-lower disk, 2-cylinder side wall; 3-upper disk; 4-output diaphragm; 8-central rod; 9-plugged side pipe; 10 - "hot" thermocouple. 11 - "cold" thermocouple.

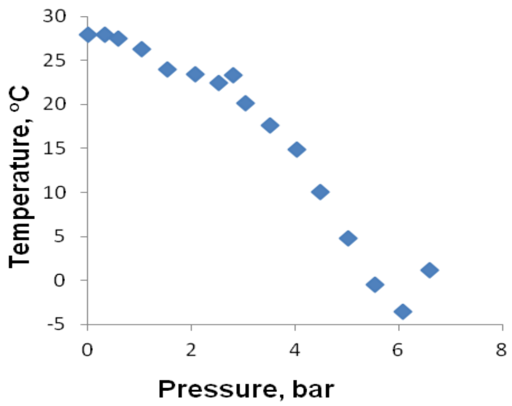


Fig. 9. Temperature measured by the "cold" thermocouple 11 depending on the input pressure

The vortex flow leaves the VC in a thin annular layer near the diaphragm 4. In the central zone around the rod 8, a flow is formed, which is well studied [12,13]. In all operating modes, the pressure in the center of the lower disk 1 was negative. Air (20°C) was sucked from the room into the VC along the central rod 8, reached the lower disk, turned around, and exited along with the main flow. It was this air that washed the central rod and thermocouple 11.

The density of the intake air changed slightly. However, thermocouple 11 showed a steady cooling (Fig. 9), which increased with increasing input pressure.

It was revealed that there is a cooling process in which the air from the external room is cooled while moving along the central rod without participating in the main vortex movement and without real pressure release. ***No conventional process can explain this cooling (without invoking the concept of PGEW).***

Goldshtick's paradox

The air leaves the VC (Fig. 8) upward along the axis in an annular layer near the diaphragm 4, maintaining the rotating. It seems obvious that the emerging jet should have the shape of a cone. Moreover, the greater the inlet pressure (flow through the VC), the stronger the cone is pressed to the axis.

However, there are only two states of the outgoing flow: vertical (narrow stream near the axis at high flow rates) and horizontal (perpendicular to the axis at low flow rates) [12], p. 255.

As the pressure at the inlet to the VC increases, the outgoing flow is rearranged from horizontal to vertical. When the pressure decreases, the outgoing flow is rearranged in the opposite way. At transition pressure, the restructuring occurs abruptly. Moreover, the regime is relatively stable. The restructuring can occur spontaneously, or it can be initiated by introducing an obstacle into the external flow, for example, by hand.

It is interesting and important that when the output flow jumps from horizontal to vertical, the pressure on the side wall sharply increases and the temperature values increase (thermocouples 10 and 11). When the flow changes in the opposite direction, the temperatures decrease.

The detected changes in parameters certainly indicate that not only the direction of the flow leaving the VC changes abruptly. Here we are dealing with two different types of vortex flow inside the VC. ***The question remains, how and why these two flows are formed? After all, the pressure at the inlet to the VC is constant, and the internal geometry of the VC is also unchanged****.*

Dependence of the heating level of the Hartmann-Sprenger tube cavity bottom on orientation in space

The outline of the Hartmann-Sprenger Tube (HST) device is shown in Fig. 10.

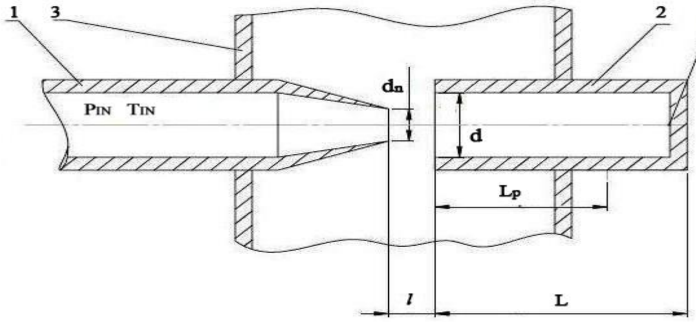


Fig. 10. The diagram of the Hartmann-Sprenger tube:
1 nozzle; 2 cavity; 3 channel walls;
4 thermocouple;
da - nozzle diameter;
d - cavity diameter;
l - gap between the nozzle and the cavity,
L - depth of cavity,
Lp - jet penetration depth;
Pin - input pressure;
Tin - inlet gas temperature.

The bottom of the cavity installed opposite the nozzle of the Hartmann sound generator is heated to significant temperatures [5]. In experiments [6] using a helium jet at the bottom of the cavity, a temperature of ~1100 ⁰C was reached. By removing heat from the outer wall of the cavity and removing gas from the space between the nozzle and the cavity, a significant reduction in gas temperature is achieved.

We investigated the HST in order to increase the efficiency of heat transfer, based on the fact that heat transfer in this device is carried out by PGEW. Understanding the physics of processes allowed us to increase the heat removal capacity by 3 times compared to the classical scheme Fig.10.

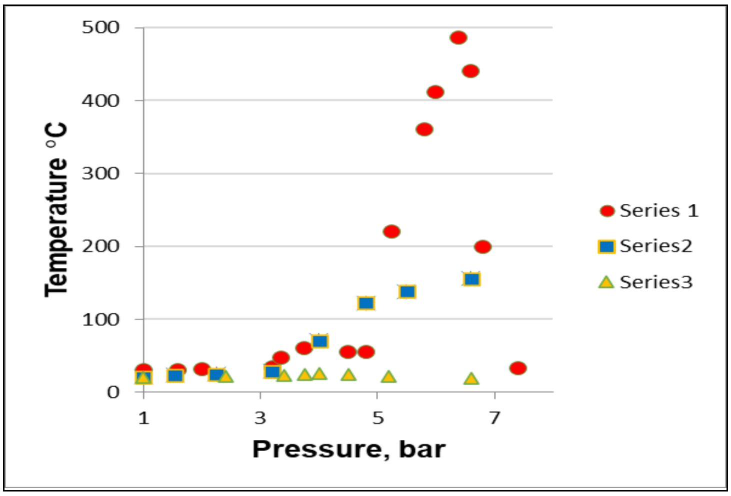


Fig. 11. The temperatures at the bottom of HST cavity at different pressure at the nozzle inlet

The heating level of the HST assembly depends on the pressure at the nozzle inlet and on the geometrical characteristics. The diagram (Fig. 11) shows the temperatures at the bottom of the cavity depending on the inlet pressure. Heating (Fig. 11) was obtained using a nozzle with a diameter of 5mm. Series 3 reflects a constant temperature on the channel wall (no cavity). In the experiments (series 1 and 2), a cavity with a diameter of 7 mm and a depth of 15 mm was used. The distance between the nozzle and the cavity was 7 mm (series 2) and 7.8 mm (series 1).

The additional experiments were performed on the HST assembly with maximum heating (series 1). The starting temperature was ~200⁰C. The cavity was heated from the outside with an electric heater. After turning off the heater, the damper was sharply detached and a stream of air entered the cavity. The final stationary temperatures completely repeated the results (Fig. 11).

It is evident that a heated object can be cooled by a stream of air. At the input pressures 5 bar and 7.5 bar that's exactly what happened, the cavity cooled sharply.

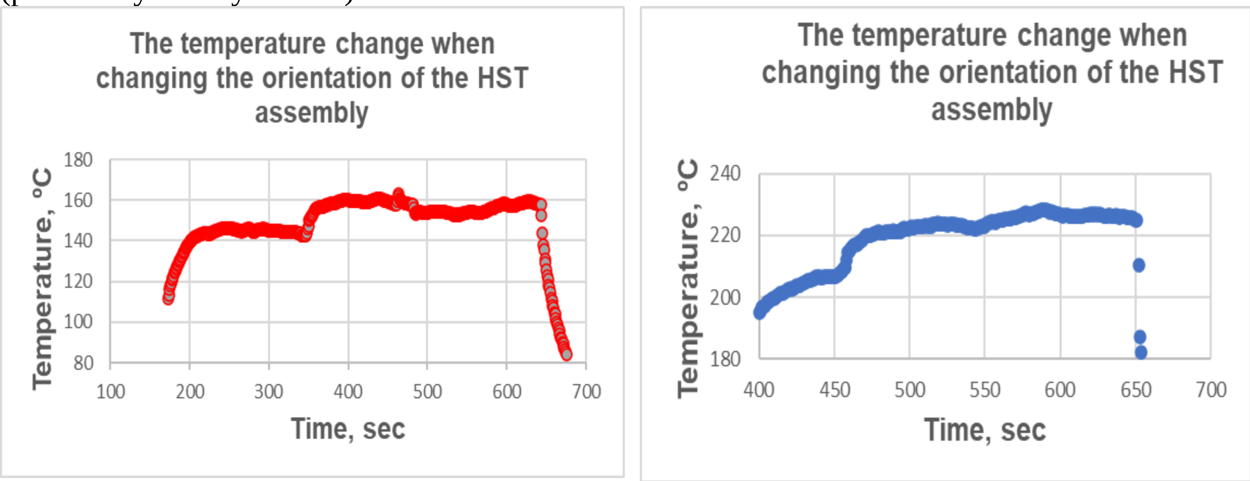
But at a pressure of ~6 bar – did it heat up sharply?

Without involving the concept of PGEW, it is impossible to explain why at 5 bar and 7.5 bar the cavity cools, and at 6 bar it heats up above 400⁰C. Moreover, it can be argued that at a pressure

of 6 bar the jet cools the bottom of the cavity in the same way as at other pressures. Consequently, the recorded maximum temperatures (Fig. 11) reflect the dynamic equilibrium between the cooling processes and the intensive heating process by PGEWs.

The temperatures shown above in all diagrams are characterized by stabilization time. These temperatures remain constant as long as the operating conditions remain unchanged. The steady-state temperature in all installations where PGEWs occur is the result of dynamic equilibrium. We believe that the main process competing with PGEW is forced convection created by the pressure gradient. The intensity of convection in HST assemblies significantly exceeds the intensity of natural gravitational convection, since the pressure gradient created by the jet significantly exceeds the gravitational pressure gradient. However, we have studied the degree of influence of natural (gravitational) convection on the level of heating HST assemblies.

In the experimental setup, the ability to smoothly rotate the HST assembly by 180 degrees around the horizontal axis without changing the air supply mode was realized. The diagram (Fig. 12) contains experimental points illustrating the temperature change at the bottom of the HST cavity (periodicity - every second).



a) б)

Fig. 12. Temperatures at the bottom of the HST assembly depending on the orientation in space

The diagram (Fig. 12 a) shows the change in the steady-state temperature of the HST assembly with a change in position relative to the horizontal axis. Assembly a) included a nozzle with a diameter of 2 mm, a cavity with a diameter of 3 mm, a length of 78 mm, and a distance between the nozzle and the cavity of 5 mm. The pressure at the nozzle inlet was maintained at 4.1 bar.

At the beginning, the jet from the nozzle was directed from top to bottom. This position corresponds to a temperature of 145°C. At 345 seconds, the assembly was rotated 180 degrees to a new vertical position. Now the jet from the nozzle was directed from bottom to top (the bottom of the cavity was at the top). The diagram shows that this rotation led to an increase in temperature to 160°C. At 485 seconds the assembly was rotated to a horizontal position. The temperature dropped to 154ºC. At 580 seconds, the assembly was again moved to a vertical position (cavity on top) and the temperature increased to 160°C. At 640 seconds the tap is closed.

In (Fig. 12b) experimental temperatures measured at an interval of 1 second for the assembly of the HST are placed, the difference is that the length of the cavity is 102 mm. Diagram b) also shows the change in the steady-state temperature of the HST assembly when its orientation relative to the horizontal axis changes. Throughout the experiment, the pressure at the nozzle inlet was maintained at 4 bar.

At the beginning of the experiment, the HST assembly was in a position where the jet from the nozzle was directed from top to bottom. In this mode, the steady-state temperature was 208°C. The beginning of rotation of the assembly to a horizontal position (90 degrees) corresponds to 460 seconds. At the same time, the temperature rose to 225°C. The 550th second of measurement corresponds to the beginning of the rotation, at which the assembly was rotated to a vertical position that differed from the original by 180 degrees. Now the jet from the nozzle was directed from bottom to top, and the bottom of the cavity was at the top. The diagram shows that this rotation led to a further increase in temperature to 230°C. At 650 seconds the air valve was closed.

The results of the experiments described above showed that rotating the HST assembly by 90 degrees from the "cavity below" position to the "horizontal" position increases the temperature increase by 8 ÷ 10% and rotating the HST assembly from the bottom position. The "cavity below" position is 180 degrees relative to the "cavity above" position increases the temperature increment by 15 ÷ 30%.

Such a significant effect of HST assembly orientation on the equilibrium temperature is unexpected. The pressure created by the deceleration of the jet in the cavity approaches the value of the initial pressure at the nozzle inlet. This value is many times greater than the pressure gradient created by gravity.

The understanding and explanation of this effect is based on two points:

1. IOP are "sound" type waves. At short distances (as in the HST assembly), these waves are practically not absorbed. In the HST cavity, compression waves move towards the bottom of the cavity, where, as a result of interference directly at the bottom, the reflected wave and the subsequent wave cancel each other out. It is in this zone of greatest pressure that heat is released.

2. The maximum pressure change is at the entrance to the cavity. Here the jet slows down and the pressure increases sharply. Deeper in the cavity the pressure increases slightly. Near the bottom, the magnitude of the dynamic pressure gradient is small. Therefore, the influence of adding (or decreasing) the gravitational component has a significant impact on the process.

Designations

PGEW – Pressure Gradient Elastic Wave;
VC – Vortex Chamber;
HST – Hartmann-Sprenger Tube;
P – absolute pressure, bar (atmospheric pressure is 1bar);
Pexp – relative (gauge) pressure (atmospheric pressure is zero), bar;
h – Distance between the central rod and the lower disk of the vortex chamber, mm;
d – Output diaphragm diameter, mm.

The investigation of the phenomenon of energy transfer in gases by Pressure Gradient Elastic Waves founded in 2014 - 2015 and in 2020 - 2022 by the Ministry of Energy of Israel

References

1. V. Ptitsyn, B. Fialkov, On the influence of gas flow pressure oscillations on heat transfer in the layer, Acoust. J. 15 (1969) 468 (Russian).
2. R. Soloff, Sonic drying, J. Acoust. Soc. Am. 36 (5) (1964) 961–965.
3. M. Dmitriev, L. Panov, Influence of low-frequency acoustic radiation on the temperature of the heated body, Technol. Des. Electron. Equip. (2008) 2 (Russian).
4. G.J. Ranque, US. Method and Apparatus for Obtaining from Fluid under Pressure Two Currents of Fluids at Different Temperatures, Pat. 1,952281, 1934.
5. Von Herbert Sprenger. Über thermische Effekte in Resonanzrohren, Mitteilungen aus dem Institut fuer Aerodynamik, Zurich, vol. 21, 1954, pp. 18-35.
6. Brocher E., Ardissone J.P., Heating Characteristics of a new type of Hartman-Sprenger tube, International Journal of Heat and Fluid Flow, Vol.4, No. 2, 1983, pp. 97-102.

7. Beliavsky Y. Experimental investigation of a temperature separation effect inside a short vortex chamber. Proc. of 9 Int. Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Malta, pp. 1482-1487, 2012.
8. Beliavsky Y. The Pressure Gradient Elastic Wave: Energy Transfer Process for Compressible Fluids with Pressure Gradient. J. of Mech. Engineering and Automation. 3: 1, 53-64, 2013
9. Beliavsky, The influence of sound on heat transfer in gase s, Electronic Journal "Technical Acoustics", 6, 2014
10 Beliavsky Y. Experimental arguments in favour of heat transfer in compressible fluids by Pressure Gradient Elastic Waves, Int. Journal of Heat and Mass Transfer, 107: 723–728. 2017
11. US Patent 9670938 B2. Method and devise for transfer of energy, Y. Beliavsky, 2013.
12. Goldshtik M.A. Vortex flows. Science, Novosibirsk 1981, Russian.
13. Smulsky I. Aerodynamics and processes in vortex chambers. Science, Novosib.,1981, Russian