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Experimental arguments in favour of heat transfer in compressible fluids by Pressure Gradient Elastic Waves

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ABSTRACT

The results of extensive scientific research show that sound has an effect on thermal processes in gases. The Ranque and Hartmann-Sprenger effects belong to this class of phenomena. Existing conventional theories cannot explain the heat transfer processes in devices based on these effects.

The concept of Pressure Gradient Elastic Waves provides a physical description of heat transfer in these processes. Pressure Gradient Elastic Waves are waves of sound type. These waves arise in compressible fluids (in gases) as a result of the existence of a pressure gradient within the volume of the gas, and in the presence of initial density fluctuations (under the influence of sound). Under these conditions the pressure forces act on micro volumes having density fluctuations along the pressure gradient vector. However the resultant forces act on fluctuations of rarefaction and on fluctuations of compression in opposite directions. The compression front of Pressure Gradient Elastic Wave propagates in the direction of increasing pressure, while the rarefaction front propagates in the opposite direction i.e. in the direction of reducing pressure. Thus these waves carry energy from the low pressure zone to the high pressure zone. This heat transfer manifests itself in the heating of the wall bounding the high pressure zone and in the cooling of the low pressure region.

The article presents the results of experiments performed by the author on a short vortex chamber and on Sprenger heat tubes. The maximum possible extent of heating and cooling are estimated. It is shown that conventional theories, previously used to explain the Ranque and Hartmann-Sprenger effects, fundamentally cannot explain the results obtained.

1. Introduction

Much research has been published on the effect of sound on thermal processes in gases (on heating [1], on drying [2] and on cooling [3]). The temporary lack of an adequate understanding of the physical basis of these processes has resulted in them being attributed to a sequence of physical paradoxes. The Ranque [4] and Hartmann-Sprenger [5,6] temperature effects must be attributed to the same class of phenomena. Different concepts have been proposed to explain these effects. Adiabatic pressure reduction during the acceleration of the jets in the nozzles has been considered a source of gas cooling in devices utilizing these effects. 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 according to this concept. However until now there were no theories that adequately described thermal processes occurring in devices utilizing these effects [7,8].

More recently the temperature separation phenomenon in a short vortex chamber [9–11] was discovered. In this device compressed air was pumped at room temperature from the side peripheral wall toward the centre of the vortex chamber. These experiments revealed that the highest temperature of the periphery was 465 °C and the lowest temperature of the central zone was −45 °C. These results cannot be explained on the basis of the concepts outlined above.

The temperature separation modes in all of the above devices are always accompanied by a loud noise. H. Sprenger [6], M. Goldshtik [12], and M. Kurosaka [13] have all emphasized that sound affects the temperature separation process inside vortex tubes. Moreover, despite the fact that the gas flow conditions in the vortex tubes and in the Hartmann sound generator are radically different, Sprenger suggested [6] that the thermal effects in both devices have the same physical nature. Based on the work described in this paper (the analysis of temperature effects in the devices described above) it is concluded that Sprenger's assumption is correct. How-

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ever his assertion that the rotation of the gas in a vortex tube is not necessary is not supported. Instead it is found that rotation is necessary to create a pressure gradient.

In Refs. [9–11] the concept of Pressure Gradient Elastic Waves (PGEW) was been proposed and demonstrated. A PGEW is a special kind of elastic wave arising in compressible fluids (gases) with a pressure gradient, in the presence of initial density fluctuations. The most important property of PGEWs is that they transfer energy from a region of low pressure to a region of high pressure. This heat transfer is not dependent on the temperature gradient.

The concept of PGEWs is new and unexpected and has yet to be accepted and verified by the scientific community at large.

Nevertheless, the results of experiments, which cannot be explained on the basis of existing conventional theories, confirm the concept of PGEWs.

2. Pressure Gradient Elastic Wave

2.1. Fundamentals

This section briefly describes the concept of PGEWs. In doing so it utilizes the following four broadly accepted fundamentals:

- *Any effect on a gas, leading to appearance of a pressure gradient, can be modeled by the field of volume forces.*
- *A zone of density fluctuation in a gas can be represented as a micro-volume on whose boundaries pressure forces act.*
- *Pressure forces are "rapidly acting" forces having the rate of change faster than the sound velocity.*
- *Any disturbance associated with the gas density fluctuations generates an elastic wave (the Huygens' Principle for gases).*

Consider a rapid density fluctuation arising in a gas in the presence of a pressure gradient. The density of a gas changes from $\rho_s(r)$ to $\rho_s(r) \pm \Delta\rho$ *where* $\pm\Delta\rho$ is the amplitude of the fluctuations. Considering the balance of forces on the boundaries of a micro volume (the area fluctuations), it is seen that the pressure gradient creates a resultant force acting on this area of fluctuation. The expression for the acceleration $\boldsymbol{u}(r)$, which determines the magnitude of additional force acting on the area of initial density fluctuation, is given in Ref. [10].

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

where $\boldsymbol{u_f}(r)$ is the acceleration, which characterizes the volume forces (for example, for the rotation with constant angular velocity ω, $\boldsymbol{u_f}(r) = \omega^2 r$). The greater the value of the pressure gradient (defined by the acceleration $\boldsymbol{u_f}(r)$), and the greater the amplitude $\Delta\rho$ of the initial density fluctuation, the greater is the magnitude of this resultant force acting on the area of fluctuation. If the value of $\Delta\rho$ is positive (compression) then the force acts in the direction of increasing pressure and further compresses the zone of initial compression. If $\Delta\rho$ is negative (rarefaction) then the force acts in the direction of decreasing pressure and reduces the pressure generated by the field further extending the zone of initial rarefaction. The pressure forces are "rapidly acting" forces. The initial fluctuation develops with the speed of sound. During this process the rapidly acting pressure forces act on the zone of fluctuation, creating a secondary density disturbance.

In accordance with Huygens' Principle (as mentioned above) the secondary density disturbance in the zones of initial fluctuation must create a secondary elastic wave. This wave is described by the wave equation and propagates with the speed of sound. The principle of wave superposition makes it possible to consider this wave separately. In addition to the above, unique properties are revealed. This allows us to highlight this secondary wave in a *separate kind of elastic wave in gases* – the **Pressure Gradient Elastic Wave**.

As can be seen from the above arguments the existence of PGEWs follows naturally from established physical principles and does not require additional evidence. However, in the recent paper [14] the propagation of sound inside a gas centrifuge is modelled. It is concluded that the elastic waves in a gas having a pressure gradient exhibit unique characteristics, dramatically different from the properties of sound waves under normal conditions. This article can serve as a theoretical confirmation.

2.2. Properties of Pressure Gradient Elastic Wave

The PGEW properties listed below arise from the expressions published in articles [9,10] and are based on the two necessary conditions: the existence of initial 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 pressure gradient.
- The compression front and rarefaction front of PGEWs propagate in opposite directions: the compression front propagates to the direction of pressure increasing and the rarefaction front to the direction of pressure decreasing. The compression front carries the real heat and the rarefaction front carries the real cold.
- In a limited volume, PGEWs cannot be reflected and move in the opposite direction when it reaches the wall due to the waves interference. 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.
- The PGEW 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 could enable heat transfer, which is independent of the temperature gradient. That is, it could potentially enable the development of a new type of heat pump.

3. The results of the experiments (a critical review)

In this section conventional explanations for the Ranque and Hartmann-Sprenger temperature effects are discussed.

The experimental installations used were described in detail, along with the characteristics of sensors and their accuracy in Refs. [9,10].

3.1. The thermodynamic processes

3.1.1. Micro-cooling cycles

Micro-cooling cycles have been proposed as the source of heating and cooling in vortex tubes (the Ranque effect). Hot and cold micro-volumes are formed as a result of various processes inside vortex layer and then the micro-volumes are separated.

The temperature separation phenomenon, discovered and investigated in short vortex chamber [9,10], disproves this concept. Fig. 1 shows schematically the modified (simplified) vortex chamber. This simplified vortex chamber differs from the full installation in that outlet header has been removed. Air enters to the chamber tangentially through the nozzles mounted on the cylindrical side wall 2.

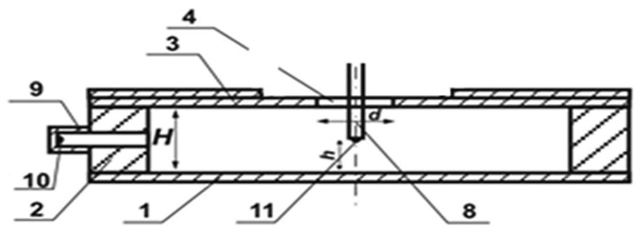

Fig. 1. Schematic overview of modified experimental vortex chamber (cross-section front view). 1-lower disc; 2-cylindrical side wall; 3-upper disc; 4-outlet diaphragm; 8-central rod; 9-plugged branch pipe; 10-"hot" thermocouple; 11-"Cold" thermocouple; *d*-outlet diaphragm diameter.

A powerful air flow moves from the periphery to the centre of the vortex chamber. The air escapes from the chamber through diaphragm 4 directly to the environment. 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. The experiments were performed with different diaphragm diameters. Maximal temperature separation takes place with d = 30 mm. During the maximal separation mode the temperature at the periphery reached +465 °C, and at the center −45 °C. With larger and smaller diaphragm 4 diameters, thermal separation still occurs, but it is weaker.

Fig. 2 represents the experimental file in which maximal heating of the branch pipe was reached [10]. During the test, the pressure was increased to 7 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 4.5 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 7 bar.

If "hot" micro-volumes are present inside the vortex chamber, they cannot move to the periphery due to the powerful radial air flow towards the centre. Consequently, the concept of micro-cooling cycles cannot explain the heating inside this apparatus.

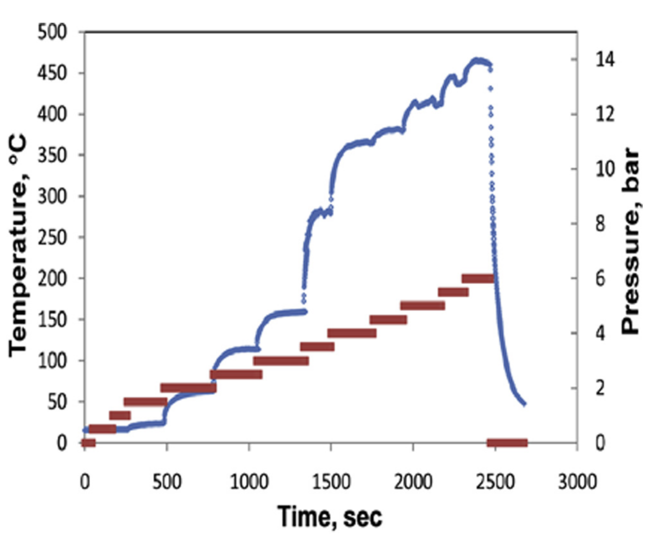

Fig. 2. The readings of temperature ("hot" thermocouple) and inlet pressure during the experiment on the vortex chamber with outlet diaphragm *d* = 30 mm. At the chart, the pressure is the gauge pressure (the ambient pressure is equal to null).

3.1.2. Heating process

The friction (Hartmann-Sprenger effect) and the interaction of vortexes (Ranque effect) are based on the concept of heating of gas micro volumes due to some thermodynamic cycle. It has been stated above that displacement of the hot micro-volumes to the periphery (when and if they are produced in a vortex layer) is impossible inside the vortex chamber Fig. 1. Nonetheless, heating takes place.

Moreover, the highest possible heating of a gas can be estimated. The compressor used during the experiments described in Refs. [9,10] compresses air from pressure P_1 = 1 bar to P_2 = 7 bar. Since, in the compressor, the temperature of the compressed air is aligned with the ambient temperature we will consider the process of isothermal compression at $T \sim 300$ K. It is easy to determine the physical work of compression for this process. If all this energy (during a hypothetical process) is transformed into heat, the air temperature will increase only by 166 K. During the experiments described in Ref. [9] and during the numerous experiments with Hartmann-Sprenger tubes described in Refs. [5,6], significantly higher temperatures were obtained. That is, the level of possible maximal theoretical heating of air is substantially lower than the actual heating observed during the experiments. Thus, the thermodynamic gas conversion cannot explain the observed heat, and therefore other processes must be responsible for this heating.

3.1.3. Cooling processes

From the standpoint of conventional theories cooling in the devices described can only result from the energy of compressed air and the processes of the gas cooling can only be adiabatic (polytropic) pressure relief and/or the throttle effect (the Joule–Thomson effect).

The experiments carried out on the short vortex chamber [9], allow us to estimate the maximal possible cooling due to these effects and to compare it with the measured value. It is assumed that the separate air jet during pressure relief converted by the way of only cooling processes and namely this jet cools the cold thermocouple 11 Fig. 1. The acceleration of air in the inlet nozzle will be considered as an adiabatic process and its movement in the vortex layer as a throttle process. When the pressure at the nozzle inlet was equal to 7 bar the pressure at the nozzle outlet was equal to 4.6 bar [9]. The adiabatic cooling of the air with this pressure drop amounts to no more than 34 K. The calculation of the air throttle cooling from 5 bar to 1 bar is presented in Ref. [6] and the value is equal to 0.3 K. Thus, the maximal possible cooling of the air can be assumed to be no more than 35 K. But in the real experiment with an inlet pressure of 7 bar the thermocouple 11 (Fig. 1) has recorded a temperature reduction of 65 K. Consequently, conventional thermodynamic processes cannot explain the cooling of a gas in the devices considered.

3.2. Elastic waves

There are two types of elastic waves in gases: shock waves and sound-type waves (sound, ultrasound, and infrasound), propagating at the speed of sound. Many authors refer to these waves for the explanation of the temperature effects under consideration.

3.2.1. Sound-type waves

The amplitude and frequency of sound-type waves 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 away from the sound source. The sound wave transfers energy which is obtained from the source. Of course wave absorption leads to the release of this energy which leads to an increase in the temperature of the gas (never to cooling). However the amount of heating is very small. Thermocouples installed close to even very powerful sound sources do not show any significant change of temperature. This occurs due to the fact that the increase in temperature in compression zones is compensated by the decrease in temperature in rarefied zones. So sound waves cannot cool gases and the degree of heating by its influence is negligible.

3.2.2. Shock waves

The Shock waves (SW) propagate with supersonic velocity. Their appearance is associated with the emergence of a new mass (explosion) or with supersonic motion. A SW can carry a significant amount of energy. It is always a compression wave. Rarefaction shock waves do not exist. The energy and velocity of the SW are reduced during its propagation. When the SW velocity becomes equal to the velocity of sound it is converted into sound wave. So a SW cannot cool a medium and the extent of its influence on heating must be considered for each device separately.

a) Pressure measurements on the short vortex chamber [9] gave a non-obvious result. The value of the pressure ratio on a nozzle P_{out}/P_{in} in all the operation modes is greater than the critical value for air i.e. 0.53. For example when the inlet pressure is equal to 7 bar the outlet pressure value is 4.6 bar and the ratio of the pressures $4.6{:}7 \approx 0.66$. This result demonstrates that the possible velocity values of input jets are subsonic and that **shock waves in the vortex chamber cannot arise**. This conclusion can be extended to vortex tubes (Ranque effect) because the gas inlet to the devices is similar to the same short vortex chambers.
b) In the Hartmann-Sprenger tubes (HST) the bottom of the cavity mounted opposite to the nozzle can heated to significant temperatures. During the experiment [5], using a helium jet, the cavity temperature reaches ~1100 °C, and the starting heating rate (from 27 °C to 300 °C) reaches in 1.7 ms.

The cavity of a Hartmann-Sprenger tube is characterized by a flow penetration depth L_p which depends on the parameters of the jet and on the geometry of the HST. The gas is motionless when the depth is greater than L_p. There is no doubt that the "over-compressed" jet in the space between the nozzle and the cavity generates the SW, and that these SWs penetrate into the cavity. However it is important to emphasize that if the depth of the jet penetration L_p lies in the range $L_p < L$ then the shock wave does not reach the bottom of the cavity. The degenerate SW ("zero gap" [15, Chapter 3] when the velocities of a gas before and after the break are equal) is transformed into a zone of compression in the sound wave. This fact is confirmed by experimental data [16] in which the pressure at the bottom of the cavity was measured by a high-speed sensor. The recorded change in pressure has a periodic "saw tooth" shape with zones of compression and rarefaction, which are typical of powerful sound waves that are studied by nonlinear acoustics. Thus, within the cavity, SW energy is released at the top of the tube; and **the shock waves cannot heat the bottom of the cavity**, where the temperature is highest.

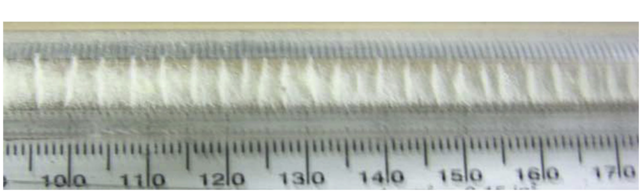

Fig. 3. Photo of periodic structure inside the transparent cavity of Hartmann sound generator.

Photograph of the periodic structures Fig. 3 confirms the absence of the shock wave within the cavity HST. The photograph was made using a HST with a transparent cavity that had been manufactured from a Plexiglas tube (cavity diameter 14 mm; cavity depth 375 mm). The cavity tube was mounted horizontally. The air jet enters the cavity along the axis and a fine powder was fed into the cavity. An interesting phenomenon was observed during the injection of the air jet into the cavity. The particles of the powder were rearranged to periodic structures. The photograph shows the steady state.

The periodic structures which the particles create within the cavity are formed as a result of a standing wave similar to that formed inside the familiar Kundt's tube. The photograph shows the situation where the particles are grouped in the nodes of the standing wave. The presence of periodic structures inside the HST cavity, in which a gas jet entered, **conflicts with the idea that the SW has reached the bottom of the HST cavity**. This observation underlines the fact that the depth of the jet penetration is small and that the sound wave propagates through the quiescent gas in most of the cavity volume. Hence we have additional confirmation that in a HST the energy is transferred only by the PGEW.

c) Furthermore, as described in Ref. [6], significant HST cavity bottom heating is detected during subcritical conditions when the **formation of a SW is impossible**.
d) An additional argument, which casts further doubt on the responsibility of SWs for cavity heating, are the operation modes when a SW exists but there is no heating. Indeed a SW always arises when the pressure ratio at the nozzle exceeds the critical value. However, as with sound, heating occurs only within a narrow range of distances between the nozzle and the HST cavity.

3.3. New experiments

In addition to the discussion in sections above, "conventional" theories cannot be invoked to explain the results of the experiments included in this section.

3.3.1. Cooling of the cold thermocouple 11

In the set-up in Fig. 1 the air comes out from the vortex chamber directly to the environment. The central (axis) zone of the vortex chamber is characterized by negative pressure in all flow modes which creates a back-flow. This flow has been well studied both theoretically and experimentally (for example [12,17]). The axial velocity in this area is directed vertically downward to the vortex chamber. The radial velocity is directed from the center to the periphery. In reality, at the central zone of the chamber, the pressure was negative and air (20 °C) is drawn in from the environment. Only this air blows over the central rod and over cold thermocouple 11. Nevertheless this thermocouple showed steady cooling (Fig. 4) [10] which increases with increase of input pressure.

Thus, it is clear that there is a cooling process during which air from the external environment, while driving along the central rod, is cooled, without participation in the main vortex motion and without having experienced a pressure relief. **None of the conventional processes can explain this cooling**.

3.3.2. The polyethylene tubes rupture

The polyethylene tubes connected the pressure transducers with the side wall during the tests with the short vortex chamber, Fig. 1. These tubes were repeatedly intruded by pressure from inside due to heating. It is reasonable to assume that the tubes were broken by pressure at the points of maximal heating. The air was motionless inside these tubes and if any process heats

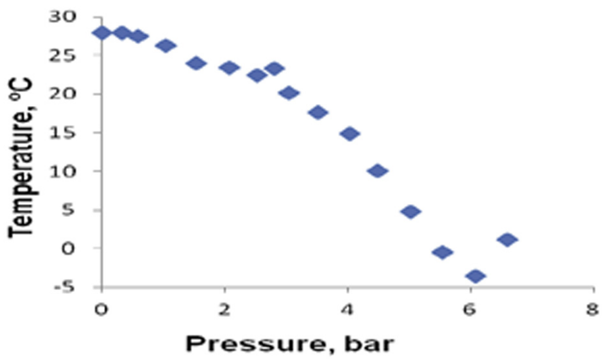

Fig. 4. The temperature measured by "cold" thermocouple 11 (Fig. 1) as function of inlet pressure.

the air at the periphery of the vortex chamber the point of maximum heating should be immediately adjacent to the outer surface of the side wall.

However, the broken holes were always located at a distance of 100–150 mm from the side wall, at a place where the tube was flexed, Fig. 5. **It is impossible to explain the observed heating of the tubes using the previously known physical processes.**

3.3.3. Heating of additional cavities

When an additional cavity was installed near the Hartmann sound generator (HST) and air supplied to the nozzle an unexpected effect was observed. In of some operating modes the bottoms of both cavities were heated including the one into which the air jet had not entered. Fig. 6 shows a photograph of one of the experimental set-ups used for the study of this effect.

The HST cavity – 1 was manufactured so that while practically unheated, but it generated a very loud whistle. The main air flow exited through one or both outlet ends of channel – 4. When injecting air through the nozzle – 2 the thermocouples installed on the plugged bottoms of all additional cavities – 3 showed an increase in temperature. The degree of heating depends both on the mode of the air jet (having room temperature) and on the geometric placing of parts of the assembly. The additional cavities heating rate is substantially less than for the cavity mounted opposite to the nozzle of HST. Optimization of the construction is not yet complete but at the time of writing a temperature of 280 °C has been recorded at the bottom of the additional cavity. The greater the heating of additional cavities, the greater was the cooling of the exiting air.

Furthermore, there is no air movement inside the additional cavities. This fact was confirmed by special experiments using an additional transparent cylindrical cavity – 3 filled with fine powder

Fig. 5. The broken piece of polyethylene tube.

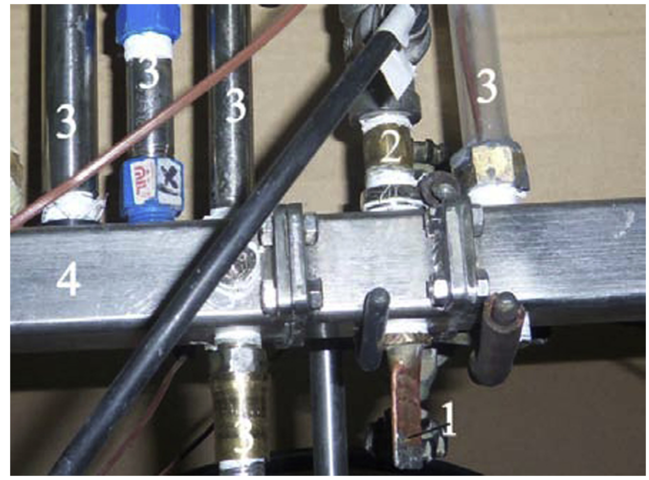

Fig. 6. Experimental assembling: 1 Cavity opposite the nozzle; 2 Input to the nozzle; 3 Additional cavities; 4 Air channel.

and aligned horizontally. In all HST operating regimes the powder filled the volume of the additional cylindrical cavity and/or formed plates or clumps corresponding to strips in the Kundt's tube (similar to the photograph in Fig. 3). To summarize:

The Hartmann generator creates a powerful sound;
The air stream moves inside the canal – 4;
The movement of air is absent inside of additional cavities;
The bottom of additional cavities is heated to significant temperatures and at the same time the outgoing air is cooled.

We find it difficult to find an adequate explanation of this effect based on the conventional thermodynamic concepts.

4. Explanation of the results of experiments based on the PGEW concept

It is impossible to draw definite conclusions about the processes described in Refs. [1–3] due to the lack of full descriptions of the equipment and of the air flows. However, it is important to emphasize that the following characteristics are common in these processes: the processes occur in gases and; the exposure of sound has a resonant character i.e. magnitude of the effect depends on the sound frequency. These circumstances allow us to say, with a high probability, that the basis of these processes is heat transfer by PGEW.

The PGEW concept completely and clearly explains the Ranque and Hartmann-Sprenger thermal effects as well as the effects described in this article. All these processes take place in gases (compressible fluids) and are accompanied by a loud sound. In all cases the pressure gradient exists in a gas volume in which the temperature separation takes place. Therefore it is seen that all three requirements necessary for PGEWs are fulfilled. The resultant PGEW transfers heat from the low pressure zone to the wall which located in the zone of high pressure.

In the vortex tubes and in the vortex chambers the pressure gradient is created by rotation with the minimum pressure zone in the center and with maximum pressure zone at the periphery i.e. at the side wall. Consequently heat is transferred from the centre to the peripheral side wall.

During the demonstration of the Hartmann-Sprenger effect the minimum pressure zone is located in the region of maximum velocity of the air jet and the maximum pressure zone is located near the plugged end of the cavity, installed in front of the nozzle.

Additional cavities use the sound generated by the Hartmann sound generator. In this device a dynamic pressure gradient exists. The minimal pressure zone is located at the region of maximum velocity of the air jet or in the center of air flow moving over the cavity. The zone of maximal pressure is located near the plugged end of the additional cavity.

The intensity of the heat transfer by PGEW is determined using the magnitude of pressure gradient, the amplitude and frequency of initial sound fluctuations of density, the characteristics of gas and the geometry of the working volume. Both the rate of heat transfer by PGEWs and the rate of heat (cold) removal inside the specific apparatus influence on the value of the obtained temperatures.

5. Conclusion

1. An analysis of the experiments of the temperature effects in gases showed that the "conventional" theories cannot fundamentally explain the obtained experimental results, namely:
   - In the vortex chamber, a powerful air flow is pumped from the periphery to the center; therefore the hot micro volumes cannot heat the side wall, because they cannot move in the opposite direction to the air flow.
   - Shock waves are not responsible for the heating. Shock waves are absent in the vortex chamber and in the vortex tubes (Ranque effect) and do not reach the bottom of the cavities (Hartmann-Sprenger effect).
   - The maximal temperatures of heating and cooling were calculated as a result of the thermodynamic transformations of a compressed air. The temperatures achieved in the experiments are much higher than calculated maximal temperatures.
2. We find it difficult to offer any adequate explanation (based on "conventional" thermodynamic concepts) for the results of following experiments:
   - The air was sucked from the room to the central area of the vortex chamber. This air blew over the thermocouple mounted on the end of the central rod. However this thermocouple showed stable cooling which increased with increasing of inlet pressure.
   - The polyethylene tubes were repeatedly intruded by pressure from inside at the points of maximal heating. If any process heats the air at the periphery of the vortex chamber the point of maximum heating should be right next to the outer surface of the side wall. However, the broken holes were always located at a distance of 100–150 mm from the side wall, at a place where the tube was flexed.
   - There is no air movement inside the additional cavities, mounted near the Hartmann sound generator. Nevertheless, the temperature 280 °C was recorded at the plugged bottom of the additional cavities. And the higher was the cavities heating, the higher was the cooling of outgoing air.
3. The proposed concept of Pressure Gradient Elastic Waves (PGEWs) adequately describes all of the experimental results. A PGEW is a kind of sound-type of elastic waves (i.e. it propagates with the speed of sound). PGEWs arise in gases (compressible fluids) under conditions with a pressure gradient. The resulting pressure forces act on the regions of sound density fluctuations and create a secondary disturbance. The emerging secondary waves (PGEW) have a unique property: the fronts of compression and expansion move in opposite directions. PGEWs transfer heat from the low pressure zone to a wall, located in the high-pressure zone.

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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] E. Brocher, J.P. Ardissone, Heating Characteristics of a new type of Hartman-Sprenger tube, Int. J. Heat Fluid Flow 4 (2) (1983) 97–102.
[6] H. Sprenger, Beobachtungen an Wirbelrohren (Observation of the Vortex Tube), Z. Angew. Math. Phys. 2 (1951).
[7] V. Bondarenko, S. Koshevoy, The geometric optimization of the gas-dynamic generator of cold on the basis of the Hartmann-Sprenger tube for application in neon helium mixture purification technology, Refrig. Tech. Technol. 4 (2006) (Russian).
[8] Y. Xue, M. Arjomandi, R. Kelso, A critical review of temperature separation in a vortex tube, Exp. Thermal Fluid Sci. 34 (8) (2010) 1367–1374.
[9] Y. Beliavsky, Experimental investigation of a temperature separation effect inside a short vortex chamber, in: Proceedings of the 9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Malta, July 2012, pp. 1482–1487.
[10] Y. Beliavsky, The pressure gradient elastic wave: energy transfer process for compressible fluids with pressure gradient, J. Mech. Eng. Autom. 3 (1) (2013) 53–64.
[11] Y. Beliavsky, The influence of sound on heat transfer in gases, Electron. J. Tech. Acoust. 6 (2014).
[12] M. Goldshtik, Vortex Flows, Nauka, Novosibirsk, 1981, pp. 305–311 (Russian).
[13] M. Kurosaka, Acoustic streaming in swirling flow and the Ranque-Hilsch (vortex-tube) effect, J. Fluid Mech. 124 (1982) 139–172.
[14] S. Bogovalov, V. Kislov, I. Tronin, Waves in strong centrifugal fields: dissipationless gas, Theor. Comput. Fluid Dyn. 29 (2015) 111–125.
[15] R. Mises, Mathematical Theory of Compressible Fluid Flow, Academic Press, New York, 1958.
[16] D.J. Bouch, A.D. Cutler, Investigation of a Hartmann-Sprenger Tube for Passive Heating of Scramjet Injectant Gases, AIAA, 2003, p. 1275.
[17] I.I. Smulsky, Aerodynamics and Processes in the Vortex Chambers, Nauka, Novosibirsk, 1981 (Russian).