IJE TRANSACTIONS B: Applications Vol. 39, No. 02, (February 2026) 444-453

International Journal of Engineering

Journal Homepage: www.ije.ir

Feasibility Analysis of Hartmann-Sprenger Effect for Quasi-Isothermal Pressure Reduction of Natural Gas

A. M. Schipachev, E. S. Ovchinnikov*, Y. A. Laptenok, A. A. Alexandrov

Department of Transport and Storage of Oil and Gas, Oil and Gas Faculty, Empress Catherine II Saint Petersburg Mining University, St. Petersburg, Russian Federation

PAPER INFO

Paper history:
Received 13 April 2025
Received in revised form 18 May 2025
Accepted 28 May 2025

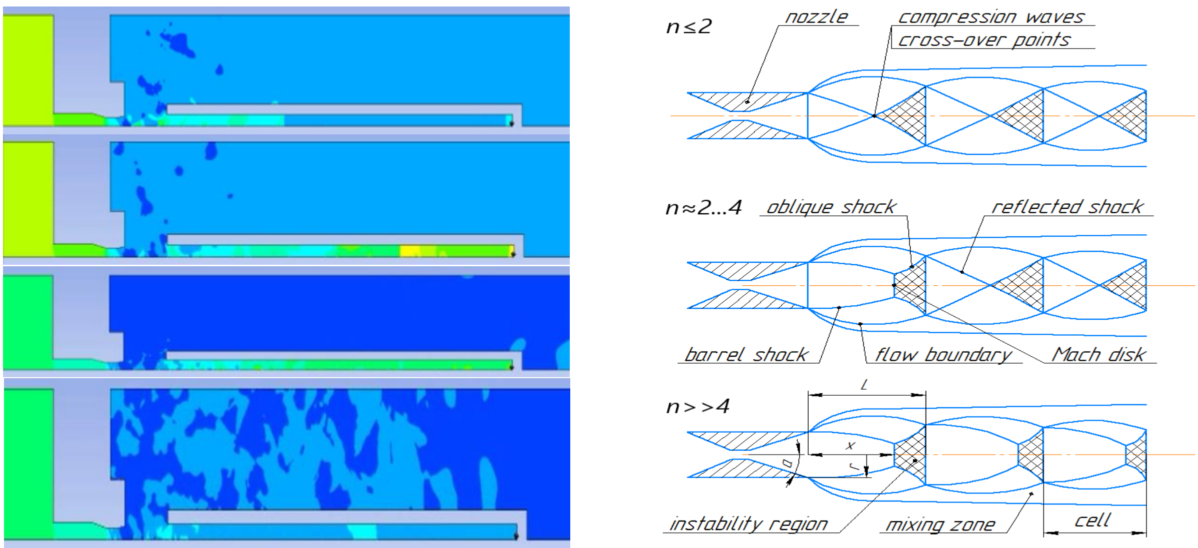
Keywords:
Hartmann-Sprenger Effect
Quasi-isothermal Pressure Reduction
Gas Distribution System
Energy Separation
Pressure Energy Recovery
Resonator

ABSTRACT

Transporting gas over long distances requires high pressure, which must be reduced before the gas is distributed to consumers. This pressure reduction occurs at pressure reduction facilities, where the gas pressure is reduced by using the gas flow energy to overcome the local resistance. According to the Joule-Thomson law, the gas is simultaneously cooled. This leads to the risk of freezing of the valves, precipitation of gas hydrates and disruption of the continuity of the metal. To prevent this from happening, an additional supply of thermal energy is required. This leads to low energy efficiency of the reduction process. Of course, the optimal solution to this problem would be direct conversion of gas pressure energy into thermal energy. This paper presents a brief review of the literature and an analysis of the Hartmann–Sprenger effect efficiency in terms of quasi-isothermal reduction of pressure at gas transportation system. Scientists identify the following factors that influence the occurrence and existence of the effect: pressure drop across the nozzle, geometry and location of the resonator. Regarding practical application concerns, attention is paid to the level of generated vibrations and noise, the possibility of cleaning the resonator cavity from contamination, and the thermal and strength properties of the materials used. Taking into account these provisions, the implementation of a pressure regulator based on the Hartmann-Sprenger effect seems possible.

***doi**: 10.5829/ije.2026.39.02b.12*

Graphical Abstract



*Corresponding Author Email: egor.owchinnikov@yandex.ru (E. S. Ovchinnikov)

Please cite this article as: Schipachev AM, Ovchinnikov E. S, Laptenok YA, Alexandrov AA. Feasibility Analysis of Hartmann-Sprenger Effect for Quasi-Isothermal Pressure Reduction of Natural Gas. International Journal of Engineering, Transactions B: Applications. 2026;39(02):444-53.

NOMENCLATURE			
ΔT	Maximum temperature increase along the length of the resonator from the open end to the closed end (K)	m	The mass flow rate of moisture entering the resonator (kg/s)
$\bar{T}$	Average temperature (K)	h	Absolute humidity of gas (kg/m^3)
k	Adiabatic index	q	Volumetric flow rate of gas through the device (m^3/s)
n	Degree of deviation	S_r, S_f	The cross-sectional area of the resonator and the flow part of the device (m^2)
p_n, p_a	The pressures in the nozzle outlet section and the surrounding space (MPa)	S_{min}	The minimum required area of the hole at the bottom of the resonator (m^2)
x	The position of the Mach disk (m)	μ	Orifice flow coefficient
L	Length of the first cell (m)	g	Acceleration of gravity (m/s^2)
M	Mach number	ρ	Density of condensate inside the resonator (kg/m^3)
r	Nozzle outlet radius (m)	Δp	The maximum amplitude of pressure oscillations in the resonator cavity (MPa)
a	Nozzle half-opening angle (deg)	p_f	Average pressure in the flow (MPa)

1. INTRODUCTION

For long-distance transportation, in order to reduce costs, gas is supplied to the gas transportation system under high pressure, since hydraulic losses decrease and gas consumption increases. However, end consumers do not require such high pressure, and for this purpose, the gas pressure is gradually reduced (1).

To reduce the gas flow pressure at pressure reduction stations (PRS), local resistance is used, represented by a throttling valve of the pressure regulator. It causes pressure energy expenditure as the flow passes through it. However, due to the pressure reduction, according to the Joule-Thomson law, the temperature of the flow also decreases, which can provoke the precipitation of gas hydrates, freezing of pipeline fittings and a violation of the continuity of the metal (2, 3), which negatively affects the safety of operation (4). To prevent this bad consequences, additional heating is carried out. As a rule, heaters burn approximately 0.3% of the transported gas volume to restore the temperature of the flow.

This method of reduction has low energy efficiency, since the pressure energy obtained from gas pumping units is simply lost to overcome local resistance, and additional thermal energy is required to further restore the flow temperature. Considering that the Russian gas transportation system includes more than 350 thousand reduction points, the volume of energy lost is quite significant.

Current goals of the oil and gas industry are the creation of new and improvement of existing technologies for the operation of the hydrocarbon transportation system (5), rational use of all types of natural energy resources (6-8). The role of the environmental impact of production in the formation of the development strategy of the gas transportation system is also growing (9).

Obviously, for the purposes of saving fuel gas and reducing the anthropogenic impact of the gas transportation system, it will be more efficient to heat the gas by converting previously lost pressure energy into heat.

For these purposes, it is possible to install expander-generator units (10, 11). The gas energy is spent on the rotation of the expander rotor, which in turn transmits torque to the electric generator. The resulting electricity is then converted into thermal energy (12). However, this option is not optimal due to the complication of the technological scheme of the reduction point, the complexity of the equipment and the need for additional maintenance, additional removal of pressure energy for the rotation of the expander, which will require more significant heating (13, 14).

Of great interest is the Hartmann-Sprenger resonance effect. Danish scientist Julius Hartmann conducted experimental research (1916-1918) on the topic of generating sound waves by an air flow. When a supersonic air flow was fed into a Pitot tube, he recorded the occurrence of pressure fluctuations in the tube cavity when it was placed at a certain distance from the point where the jet was flowing out. The scientist called the positions in which pressure fluctuations occurred "zones of instability" (15). In 1954, Herbert Sprenger continued his research and, with a significant lengthening of the resonator, discovered that high temperatures were generated at its bottom, up to 1000 °C (16).

2. PROCESS PHYSICS

The gas flow, entering a cavity closed at one end, initiates oscillations with a frequency equal to the natural frequency of the gas column in the separation region, maintained by the energy of the oncoming flow. Compression or expansion waves propagate from the oscillating interface into the cavity, then meet the closed end and reflect back. As a result of the superposition of compression waves, shock waves are formed, propagation of which is accompanied by irreversible heat release. At the closed end of the resonator, cumulative heat accumulation occurs and the gas is heated (17). The process is accompanied by the generation of high temperatures and low cooling capacity.

The Hartmann-Sprenger effect cycle can be broken down into the following stages (Figure 1):

1. Filling: The resonator cavity is filled with an oncoming flow of gas under pressure.
2. Compression: Upon reaching the closed end of the resonator cavity, the gas is compressed and temperature increases.
3. Expansion: The compressed gas moves towards the open area of the resonator due to the pressure gradient.
4. Evacuation: Gas under pressure leaves the resonator. A vacuum zone is formed in the cavity and the process is repeated cyclically.

Below are the main stages of the effect cycle in regurgitation mode, obtained using mathematical modeling.

When conducting experiments with Hartmann tubes, Sarohia and Back identified three mechanisms for the occurrence of resonance (18, 19):

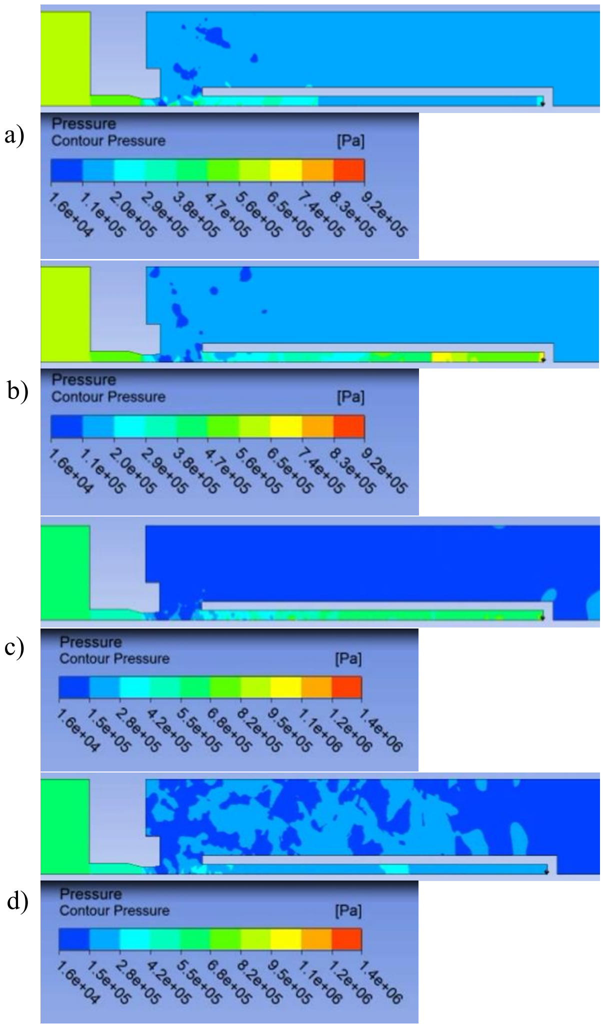


Figure 1. The Hartmann–Sprenger effect cycle: a) filling; b) compression; c) expansion; d) evacuation

1. Instability mode: The regime exists at subsonic speeds. Due to the formation of vortices at the nozzle outlet, the flow is unable to generate strong shock waves in the resonator, so no significant heating of the gas is observed.

2. Regurgitation mode: In this mode, the resonator periodically ingests and releases portions of gas. The flow structure can have diamond-shaped or barrel-shaped cells, depending on the pressure difference on the nozzle. This mode shows itself best with long resonators, since it requires sufficient space so that strong shock waves can form as a result of the compression waves superposition. This mode does not allow achieving significant temperatures and heating rates.

3. Screech mode: This mode requires a relatively high flow pressure before the nozzle. A Mach disk (normal compression shock) forms at the resonator inlet and oscillates at the highest frequency compared to the other modes. However, the shock waves become weaker. In this mode, it is possible to achieve maximum temperatures, since the hot gas locked in the tube exchange less heat with the cold flow flowing around the resonator. The mode is optimal when working with relatively short resonators; it is depending on geometric and flow parameters modes which can switch.

3. APPLICATION

The main part of the research of the Hartmann-Sprenger effect thermal performance, considers it from the negative side and is aimed at its suppression, for example, when heating up the elements of the supersonic aircraft design. With the beginning of the construction of new gas pipelines with pressures over 10 MPa, cases of heating up the dead-end risers of valve units when filling the pipelines with gas began to occur more often (20). To eliminate the effect, the risers are usually connected by a bypass to eliminate dead-end zones. When the effect occurs, the heating temperature can reach 1600 K (21), the heating rate can reach 160 K/ms (22). This allows the effect to be effectively used in rocket engine ignition systems (23). Brocher and Betton (24) proposed using the heat produced by the resonator to generate electricity by using magnetohydrodynamic generators. In this way, approximately 21% of the flow energy can be converted into electricity. Hartmann-Sprenger tube can be also used for preheating the gas before feeding it into the engine combustion chamber (25). Kadaba et al. (26) used the Hartmann-Sprenger effect to implement a refrigeration machine due to a large temperature gradient with the environment. High temperatures allow the effect to be used for thermal desorption or to create a high temperature difference to generate electricity using thermoelectric elements.

4. GENERAL PART

Many researchers have managed to achieve high temperatures in their studies of the Hartmann-Sprenger effect. The temperature obtained when working with hydrogen was 811 K (27); with nitrogen – 870 K (18); with helium – 1000 K (25, 28); with air – 800 upto 1600 K (21, 23), etc. The theoretically possible heating rate is $3\cdot10^6$ K/s (29).

The temperature is distributed as follows: the first 30% of the resonator length at the input remains cold, and the last 10% at the dead end heats up to maximum values (21).

Shapiro derived the dependence of the ratio of the maximum temperature increase along the length of the resonator from the open end to the closed end ΔT to the average temperature $\overline{T}$ on the adiabatic index k (Equation 1):

$$\frac{\Delta T}{\overline{T}} \cong 2\left(k+1\right) \quad (1)$$

The formula contains a number of assumptions such as: ideal gas, oscillation frequency equal to a quarter of the acoustic wave, flow velocity equals the speed of sound in the medium, no energy loss through the tube walls. According to the formula, methane can be heated to temperatures 4.5 times higher than the average, but in practice the value does not always exceed 2 times.

The possibility of the effect occurring and the temperature values depend on the geometry, the pressure difference across the nozzle, the resonator position relative to the nozzle, the gas composition, the oscillation mode, the structure of the flow jet (23), and also the materials.

The thermal effect is greatest when the gas accumulates heat inside the cavity without the possibility of mass exchange with the external flow. Depending on the requirements for the resonator (acoustic effect, thermal effect), the tuning will differ. Thermal effect requires large amplitude of pressure oscillations at the resonant frequency of the tube.

5. FLOW DESTABILIZATION

Hydrodynamic/thermodynamic instability criteria are of great interest to scientists (30). Rayleigh pointed out that the inflection point of the velocity profile is a necessary condition for instability creation (31). So preventing a stable flow state is essential in terms of oscillations and resonance occurence. Destabilizing devices are used for this purpose. Some of these include axial rods, annular nozzles, and reflecting surfaces near the boundary of the jet.

Brocher and Duport (32) investigated the effect of various destabilizing devices on subsonic flow and found the existence of a critical speed below which the oscillations are irregular and have a small amplitude, while when this threshold is exceeded the amplitude of the oscillations increases sharply. The importance of using various destabilizing devices is due to the fact that they allow resonant oscillations to emerge even at subsonic speeds (33).

For example, Hartmann and Trudsø (34) showed that streamlined bodies in the form of thin cylinders (pins) introduced along the nozzle axis, induce oscillations even at subsonic speeds. Installing a pin along the nozzle axis also helps empty the resonator by lowering the pressure in the jet center and, accordingly, lowering the incoming flow pressure on the inlet section of the resonator. As a result the amplitude of pressure oscillations inside the resonator increases (35). Annular nozzles contribute to a more stable existence of the effect, since they significantly increase the working range of pressure drops, due to automatic regulation in case of operation in off-design modes (22). Also, a pin can be installed in the center of the resonator cavity. Due to narrowing of the resonator effective cross-sectional area, pin allows concentrating compression shocks, and the amplitude of oscillations also increases. As a result, the heating rate increases (19).

6. RESONATOR PARAMETERS

The researchers experimented with different geometric shapes of resonant tubes to enhance the thermal effect, adapting them to real-world application conditions. Geometric modifications include different types of cavity shapes: stepped resonators, contour cavities of various shapes, such as logarithmic and exponential. Sobieraj and Szumowski (36) presented various non-traditional resonator shapes. In their study, they note that although the cavity edge shape significantly affects the acoustic/thermal phenomena and oscillatory modes (change of mode between screech and regurgitation), the shape of the edge at the nozzle outlet has almost no effect on the process.

McAlevy and Pavlak (37) investigated both conventional and conical resonators and it appeared that the internal geometry is not important for the initiation or maintenance of the oscillations. The effect is determined by the events at the resonator input.

An important parameter that determines the occurrence of the effect and the values of the obtained temperatures is the ratio of the diameter of the resonator inlet section and the cross-sectional size of the underexpanded jet. The resonator inlet section should ensure that the flow is ingested by the tube, rather than flowing around the cavity. The energy should enter the resonator. However, the size of the inlet section also has its own optimal value, exceeding which will create flow recirculation zones at the resonator inlet, and then exclude the possibility of the effect occurring. Hartmann suggested that the diameter of the resonator inlet should equal the outlet diameter of the nozzle. Based on the study of stroboscopic shadowgraphs, Palmé (38) suggested that the diameter of the resonator inlet should equal the maximum diameter of the underexpanded jet. In another study, Monson and Binder (39) obtained an optimal value for the ratio of the cavity diameter to the jet diameter of 1.27. Most often, recommendations are found for the values of this ratio in the range of 1.0-2.5 (26–28). However, it is necessary to remember that, depending on the conditions, the optimal value may be outside this range; for example, there are studies with a value of 6.0 (40).

Significant thermal effect can be achieved by increasing the length of the cavity as it allows the gas to stay inside the resonator longer and be exposed to shock waves longer, which intensifies the effect (28). It is also worth noting that each specific case has its own optimal length of the resonator tube. With an increase in length, a further increase in the heat exchange area and the resonator mass will lead to a decrease in the temperature and heating rate. With a decrease in length, the heating efficiency decreases due to an increase in heat exchange between the hot gas in the resonator and the cold gas of the flowing stream and an increase in transverse heterogeneity in the jet (21). Researchers give recommendations on the ratio of the resonator length to the diameter of its inlet in the range of 15 - 37 (21, 40), but for certain conditions there are recommendations with values both smaller (7.5 (27)) and bigger (about 70 (26)).

One of the ways to intensify the thermal effect is to use resonators of various shapes. Most often, the following resonators are used to increase the temperature: cylindrical resonators with a transition to conical (23); stepped (21, 22); conical with a cone angle of 3°-4° (27); with an expansion at the end (41); a resonator in a resonator (26). According to studies, stepped resonators reached higher temperatures and showed a higher heating rate compared to other types (42–44). Also, stepped and conical resonators allow to obtain heating at low oscillation frequencies compared to heating in a cylindrical resonator at relatively high oscillation frequencies (21). Explanation is that in conical and stepped resonators the flow parameters are smoothed along the length due to the change in the cross-sectional area along the resonator length, which allows to intensify the heating process at low frequencies. Neemeh et al. (45) considered a resonator of such an exotic shape as a logarithmic spiral and determined more effective heating than in cylindrical and conical resonators, however, it is impossible not to note the complexity of the shape for practical purposes. From this point of view, cylindrical and conical resonators are more preferable. Resonators with an expansion at the end allow to increase heating due to the formation of a stagnation zone due to additional resistance to gas removal in a narrow neck and cumulative accumulation of heat. One must not forget about the resonator inner walls roughness; in resonators of short length it was possible to obtain a higher temperature due to additional heating from the friction force (28).

It is also recommended to operate at oscillation frequencies higher than natural ones for more uniform resonator heating along the length (46).

Another problem in terms of practical application is the relatively large length of the resonators, which does not allow replacing traditional pressure regulators without making additional changes to the design of the reduction point. An obvious solution in this case is to split the flow into several nozzle-resonator pairs, but no studies have been found in this area. There are studies of installations with several Hartmann "whistles" or installations using one accelerating device for two resonators (47).

7. FLOW PARAMETERS

The composition of the gas has a direct effect on the thermal performance. The heating temperature and its growth rate are higher for monatomic gases than for diatomic gases. The reason for this is the higher irreversibility of shock waves that occur in monatomic gases (28). Theoretically, monatomic gases can be heated to temperatures exceeding the ambient temperature by 3 times, and diatomic gases by 2 times (29). Thus, monatomic helium is heated from 300 K to 600 K in 1.7 ms, and diatomic hydrogen in 49 ms (22). The molecular mass of gases is inversely proportional to the heating temperature and its growth rate (27). The gas humidity and occurrence of nonequilibrium condensation reduce the temperature at the muffled end of the resonator.

Studies demonstrate that:

- The pressure fluctuation amplitude within the resonator is directly proportional to the nozzle inlet pressure (27);
- The resonator gas temperature exhibits a direct dependence on the nozzle exit Mach number (28).

This suggests a recommendation to operate at large pressure differences on the nozzle, providing high Mach numbers. However, it is also impossible to infinitely increase the pressure difference due to the existence of optimal differences for each medium. Exceeding the optimal values will lead to a decrease in heating efficiency, and in the future the effect will terminate (25). For different nozzle geometries and resonator positions there are optimal pressure differences providing required structure of the underexpanded jet at the resonator inlet.

Also, depending on the gas composition, there is an optimal degree of deviation n ($n = p_n/p_a$). When working with nitrogen and a sonic nozzle, the value is 4.5 (27). For oxygen or air – 4.0 ... 8.0 (48), 5.5 ... 6.0 (41). Heating also depends on the resonator operating mode (18). For example, temperatures in the screeching mode were higher than in the regurgitation mode.

8. RESONATOR POSITIONING

The location of the resonator relative to the accelerating device is important for the occurrence and maintenance of the Hartmann-Sprenger effect, since it determines the maximum temperature and also affects the rate of its growth. Depending on the degree of deviation n, the structure of the underexpanded jet changes and, accordingly, the optimal position of the resonator changes. Effect stable existence requires positioning of the resonator inlet near the first or second "instability" zone coaxially with the nozzle. Kastner and Samimy (49) and Raman et al. (50) revealed that as the nozzle-to-resonator distance grows, higher jet Mach numbers are needed to achieve the same oscillation amplitude. The explanation is that the length of the structural cell increases with an increase in the Mach number, and accordingly the distance must increase so that the resonator inlet cross section is in the corresponding instability region.

Sarpotdar et al. (51) found a correlation between the active distance – the distance at which the tube resonates – and the shock cell length. Increasing the degree of deviation resulted in an increase in the shock cell length. Increasing the shock cell length increased the active distance. Also, the transition to the screech mode from the regurgitant mode required an increase in the pressure in front of the nozzle when the resonator was moving away from the nozzle (18).

Murugappan and Gutmark (52) found a relation between the resonator position and the change in operating modes. They observed a change from the screech mode to the regurgitation mode at nozzle-resonator distance of 5.6 mm. When the ratio of the resonator cavity inlet diameter to the jet diameter was >1, the regurgitation mode was maintained over a large range of distances. When the diameter ratio was <1, the screech mode was observed.

Depending on the degree of deviation n, the structure of the jet changes (Figure 2). For $n \leq 2$, the jet cells will have a diamond-shaped form; for $n = 2 \ldots 4$, the first compression shock will have the form of a barrel with a Mach disk; for $n > 4$, the formation of Mach disks can be repeated in the cells many times. However, further growth in the thickness and diameter of the first Mach disk at excessive values of n can block the appearance of subsequent Mach disks.

At high degree of deviation n, when the diamond-shaped cells are truncated and become barrel-shaped, the tube resonates regardless of the distance from the nozzle (53). The experimental results indicated that variations in the distance had negligible effect on the oscillation frequency as long as the resonator depth remains constant. However, minor differences in frequency with distance do occur.

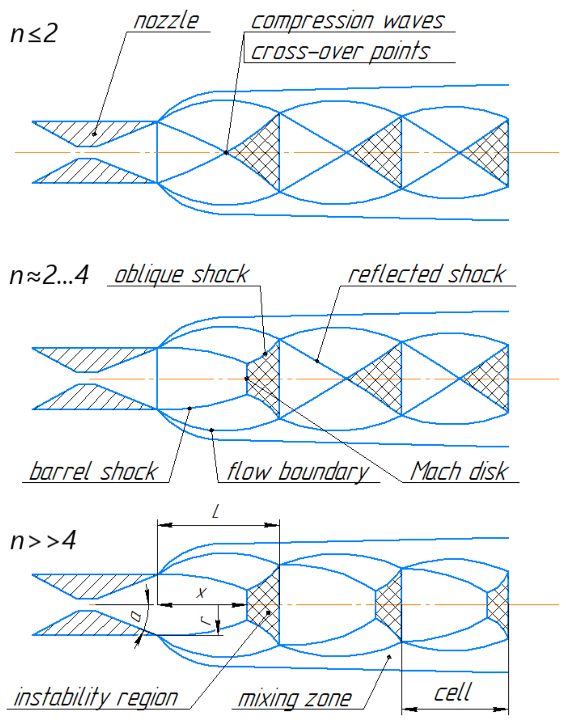


Figure 2. Structures of underexpanded jet flow at various degrees n of deviation from the design

There are several ways to determine the structure of the jet and the position of its "instability" zones. The first method is to use schlieren photography, but this method is quite laborous. The second method is to determine the flow structure analytically. In the case of barrel-shaped shock waves, it is necessary to determine the position of the normal shock wave (Mach disk); for diamond-shaped shock waves, the boundaries of the "instability" zone are found by determining the intersection point of the inclined shock waves. In their study, Brocher and Maresca determined the optimal positioning of the resonator relative to the converging nozzle. The optimal ratio of the nozzle-resonator distance to the diameter of the latter was: for the subsonic regime - about 1; for the supersonic regime for a diatomic gas - about 2; for a monatomic gas - about 3 (28). If we consider nozzles with a diffuser, then for flows with barrel-shaped shock waves, the position of the Mach disk x is calculated as discussed by Shelukhin (54) (Equations 2-4):

$$x = 0.8L \quad (2)$$

$$L = 1.558 \cdot x' \quad (3)$$

$$\frac{x'}{r} \sim \sqrt{n\left(1+kM^2\cos a\right)-1} \quad (4)$$

where M – Mach number at the nozzle outlet section. For flows with a diamond-shaped shock wave structure, the convergence point of the oblique shock waves is positioned approximately at the cell's midpoint. For nozzles with a more complex geometry, the flow structure can be determined by numerical methods.

9. PRACTICAL RECOMMENDATIONS

The simplest way to increase thermal efficiency is to reduce the heat exchange surface (55), use thermal insulation (17, 22), and use materials with low thermal conductivity (27). However, this can only be recommended for use if the goal is not to increase the temperature of the flow around the resonator.

To be able to practically implement a pressure regulator based on the Hartmann-Sprenger effect, the device must meet a number of conditions. The generated noise and vibrations must not exceed regulation values and affect the safety and reliability of the operation of production facilities. The device must stably cope with condensate and other contaminants, as they could lead to the impossibility of the existence of the effect. Also, it is necessary to optimize the dimensions of the devices to be able to implement them in pressure regulation points without rebuilding them, the reliability of the regulator is also important.

Brocher and Maresca (56) concluded that the predominant heat transfer mechanism in the resonance tube involves mass exchange between the incoming cold jet flow and the heated gas within the tube. For the purpose of removing hot gas (17) and for cleaning the resonator cavity from accumulating mechanical impurities and condensate (57), it is possible to create an opening at the bottom of the resonator. According to experiments, the optimal value of the ratio of the area of the opening at the bottom of the resonator to the area of its cross-section is 0.12 (17).

To determine the minimum area of the hole for removing accumulated condensate, it is necessary to know the mass flow rate of moisture entering the resonator along with the gas flow (57) (Equation 5):

$$m = h \cdot q \frac{S_r}{S_f} \quad (5)$$

Using the known liquid mass flow rate, we can calculate the minimum required orifice area at the resonator bottom to prevent condensate accumulation (Equations 6-7):

$$S_{\min} = \frac{2m}{\mu\sqrt{2g\rho\Delta p}} \quad (6)$$

$$\Delta p = 2kMp_f \quad (7)$$

When operating a pressure regulator based on the principle of energy separation, the issue of generated vibrations and noise pressure, which can reach 100 dB or more at certain resonant frequencies (19, 58), will be important. Existing equipment at facilities often operates under dynamic loads and vibrations, and additional loads from the pressure regulator integration can negatively affect the reliability of operation and safety of operation.

To reduce the noice it's possible to use mufflers or operate under higher frequencies to reduce noise level (46).

Narayanan et al. (59) investigated how chamfer geometry (both internal and external) of the resonant cavity influences acoustic emissions in Hartmann whistles, demonstrating that internal chamfering significantly enhances sound pressure levels. It was found that the sound pressure level of cavities with inwardly beveled edges is higher than that of cavities without chamfers (60). A comparison of the results of the two studies suggests that in order to reduce the sound pressure level, it is better to use resonators with non-chamfered edges.

Thomas et al,. (61) examined the effect of the underexpanded jet shape on the sound pressure level. The following nozzle attachments were used: circle, ellipse, triangle, rectangle, and square. The sound pressure level increased with increasing underexpanded jet ratio for all diaphragm combinations. The highest sound intensity was demonstrated by a round jet. At high underexpanded jet ratios, a significant drop in the sound pressure level was observed for square, rectangular, and triangular jets. In non-circular jets a significant drop in sound intensity is observed, which makes them more preferable options in terms of reducing sound impact. This is confirmed by the results of other studies, for example, Jothi and Srinivasan (62) found that when replacing a round jet with a triangular and square one, the installation begins to operate 10 dB quieter.

Noise and vibration effects, of course, must be taken into account when using devices based on the Hartmann–Sprenger effect, but their magnitudes do not go beyond their usual values for such technological equipment and will not create significant obstacles for practical application (63).

It should be noted that the materials for manufacturing resonators must ensure their high strength, thermal conductivity, impermeability, and also a wall structure that does not absorb pressure fluctuations (27). This is an important condition for long-term trouble-free operation, since even in short experiments, researchers observed failures of resonant tubes (23, 27, 40).

Also for stable existence of the effect under conditions of changing flow rates and pressures it is necessary to adjust the distance between the resonator and the nozzle. For these purposes, it is proposed to take as a basis the system of adjusting the degree of valve opening of the conventional pressure regulator with the necessary modifications. This is a topic for further research.

10. CONCLUSION

Based on the analysis results, it can be said that the intensification of the Hartmann-Sprenger effect requires: operation at high pressure drops optimal for a specific geometry of the device; the size of the resonator inlet cross-section calculated for a certain underexpanded flow jet; the location of the resonator relative to the nozzle depending on the flow structure (approximately near the first or second instability zone); the use of resonators with a variable cross-sectional area; sufficient mass transfer between the hot gas of the resonator and the cold gas of the flowing around it. In practical terms, it is important to ensure a reduced level of acoustic impact and vibrations, removal of accumulations of mechanical impurities and condensate from the system, and the materials must be resistant to significant cyclic loads. Considering these findings, the development of a quasi-isothermal natural gas pressure regulator utilizing the Hartmann-Sprenger effect appears technically possible.

11. REFERENCES

1. Fetisov V, Shalygin AV, Modestova SA, Tyan VK, Shao C. Development of a numerical method for calculating a gas supply system during a period of change in thermal loads. Energies. 2023;16(1):60. https://doi.org/10.3390/en16010060
2. Perveitalov OG, Nosov VV, Schipachev AM, Alekhin AI. Thermally activated crack growth and fracture toughness evaluation of pipeline steels using acoustic emission. Metals. 2023;13(7):1272. https://doi.org/10.3390/met13071272
3. Vasiliev GG, Dzhaljabov AA, Leonovich IA. Analysis of the causes of engineering structures deformations at gas industry facilities in the permafrost zone. Journal of Mining Institute. 2021;249:377–385. https://doi.org/10.31897/PMI.2021.3.6
4. Zemenkova MYu, Chizhevskaya EL, Zemenkov YuD. Intelligent monitoring of the condition of hydrocarbon pipeline transport facilities using neural network technologies. Journal of Mining Institute. 2022;258:933–944. https://doi.org/10.31897/PMI.2022.105
5. Shammazov IA, Borisov AV, Nikitina VS. Modeling the operation of gravity sections of an oil pipeline. Bezopasnost' Truda v Promyshlennosti. 2024;1:74–80. https://doi.org/10.24000/0409-2961-2024-1-74-80
6. Aleksandrova TN, Lushina EA. Influence of an ionic composition of a sludge liquid phase on technological parameters of beneficiation. Tsvetnye Metally. 2024;8:13–20. https://doi.org/10.17580/tsm.2024.08.02
7. Litvinenko VS, Tsvetkov PS, Molodtsov KV. The social and market mechanism of sustainable development of public companies in the mineral resource sector. Eurasian Mining. 2020;1:36–41. https://doi.org/10.17580/em.2020.01.07
8. Smirnova EA, Saychenko LA. Hydrodynamic modeling and evaluation of partial substitution of cushion gas during creation of temporary underground gas storage in an aquifer. International Journal of Engineering, Transactions A: Basics. 2024;37(7):1221–1230. https://doi.org/10.5829/ije.2024.37.07a.02
9. Shammazov IA, Borisov AV, Aleksandruk BS, Lopatenko GV, S.Nikitina V. Algorithmic Models for Determining the Flow Patterns of Oil Pipelines in Gravity Sections. International Journal of Engineering, Transactions A: Basics. 2025;38(10):2476-85. https://doi.org/10.5829/ije.2025.38.10a.22
10. Abramovich BN, Bogdanov IA. Improving the efficiency of autonomous electrical complexes of oil and gas enterprises. Journal of Mining Institute. 2021;249:408–416. https://doi.org/10.31897/PMI.2021.3.10
11. Kuzmin AM, Buslaev GV, Morenov VA, Tseneva SN, Gavrilov NA. Improving the energy-efficiency of small-scale methanol production through the use of microturboexpander units. Journal of Mining Institute. 2022;258:1038–1049. https://doi.org/10.31897/PMI.2022.104
12. Condessa GÁ, Ismail KAR, Hunt JD, Ponce Júnior N, Velásquez RMG, Borges VL, Bindemann FT. Electricity generation potential from natural gas pressure reduction turbines in Brazil. Energy Efficiency. 2023;16(8):97. https://doi.org/10.1007/s12053-023-10176-8
13. Ladino-Moreno EO, García-Ubaque CA, Zamudio-Huertas E. Development of a Conservative Hamiltonian Dynamic System for the Early Detection of Leaks in Pressurized Pipelines. Civil Engineering Journal. 2024;10(4):994-1011. https://doi.org/10.28991/CEJ-2024-010-04-01
14. Khayam U, Hamdani YM, Rachmawati. Design of Modified UWB Microstrip Antenna for UHF Partial Discharge Sensor. Emerging Science Journal. 2024;8(5):1716-1731. https://doi.org/10.28991/ESJ-2024-08-05-03
15. Hartmann J. On a new method for the generation of sound-waves. Physical Review. 1922;20(6):719–727. https://doi.org/10.1103/PhysRev.20.719
16. Sprenger H. Uber thermische effekte in resonanzrohren. Mitteilungen aus dem Institut für Aerodynamik an der Eidgenössischen. 1954;21:719–730.
17. Masaaki K, Makoto S. Temperature separation produced by a Hartmann-Sprenger tube coupling a secondary resonator. International Journal of Heat and Mass Transfer. 1981;24(12):1951–1958. https://doi.org/10.1016/0017-9310(81)90117-4
18. Sarohia V, Back LH. Experimental investigation of flow and heating in a resonance tube. Journal of Fluid Mechanics. 1979;94(4):649–672. https://doi.org/10.1017/S0022112079001233
19. Bauer C, Hauser M, Haidn OJ. Investigation of stabilization effects in Hartmann-Sprenger tubes. Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan. 2016;14(30):95-100. https://doi.org/10.2322/tastj.14.Pa_95
20. Parfenov DV, Aginey RV. Experimental researches of the anomaly overheating of pipe impasse branches of valve stations when the trunk pipeline «Sakhalin-Khabarovsk-Vladivostok» is filling by gas. Pipeline transport: Theory and Practice. 2014;43–44(3–4):50–53.
21. Kuptsov VM, Ostroukhova SI, Filippov KN. Pressure fluctuations and heating of a gas by the inflow of a supersonic jet into a cylindrical cavity. Fluid Dynamics. 1977;12(5):728–733. https://doi.org/10.1007/BF01050487

22. Brocher E, Ardissone JP. Heating characteristics of a new type of Hartmann-Sprenger tube. International Journal of Heat and Fluid Flow. 1983;4(2):97–102. https://doi.org/10.1016/0142-727X(83)90008-5
23. Marchan RA. Small-scale supersonic combustion chamber with a gas-dynamic ignition system. Combustion Science and Technology. 2011;183(11):1236–1265. https://doi.org/10.1080/00102202.2011.589874
24. Brocher E, Betton M. Experiments with the hydraulic analogy of a shock-wave magnetohydrodynamic generator. Physics of Fluids. 1975;18:795–802. https://doi.org/10.1063/1.861242
25. Bouch D, Cutler A. Investigation of a Hartmann-Sprenger tube for passive heating of scramjet injectant gases. B 41st Aerospace Sciences Meeting and Exhibit. American Institute of Aeronautics and Astronautics. 2003. https://doi.org/10.2514/6.2003-1275
26. Kadaba PV, Bondarenko VL, Arkharov AM. Thermal characteristics of a Hartmann-Sprenger tube. International Journal of Refrigeration. 1990;13(5):309–316. https://doi.org/10.1016/0140-7007(90)90062-2
27. Phillips BR, Pavli AJ. Resonance tube ignition of hydrogen-oxygen mixtures: report No. NASA TN D-6354. Washington, D.C., USA: NASA. 1971.
28. Brocher E, Maresca C. Etude des phenomenes thermiques dans un tube de Hartmann-Sprenger. International Journal of Heat and Mass Transfer. 1973;16(3):529–538. https://doi.org/10.1016/0017-9310(73)90221-4
29. Brocher E. Heating rate of the driven gas in a Hartmann-Sprenger tube. AIAA Journal. 1975;13(10):1265–1266. https://doi.org/10.2514/3.60537
30. Schlichting H., Gersten K. Boundary-layer theory. Springer Science & Business Media. 2003.
31. Lord R. On the stability, or instability, of certain fluid motions. Proceedings of the London Mathematical Society. 1879;11(1):57–72. https://doi.org/10.1112/plms/s1-11.1.57
32. Brocher E, Duport E. Resonance tubes in a subsonic flowfield. AIAA Journal. 1988;26(5):548–552. https://doi.org/10.2514/3.9932
33. Wu J, Ostrowski P, Neemeh R. Subsonic jet-driven resonance tube. CASI Transactions. 1975.
34. Hartmann J, Trudsø E. Synchronisation of Air-jet Generators with an Appendix on the Stem Generator. København. 1951:39.
35. Brocher E, Maresca C, Bournay MH. Fluid dynamics of the resonance tube. Journal of Fluid Mechanics. 1970;43(2):369–384. https://doi.org/10.1017/S0022112070002422
36. Sobieraj GB, Szumowski AP. Experimental investigations of an underexpanded jet from a convergent nozzle impinging on a cavity. Journal of Sound and Vibration. 1991;149(3):375–396. https://doi.org/10.1016/0022-460X(91)90443-N
37. McAlevy RF, Pavlak A. Tapered resonance tubes - Some experiments. AIAA Journal. 1970;8(3):571–572. https://doi.org/10.2514/3.5710
38. Palmé M. Contribution à l'étude de la sirène de Hartmann. Il Nuovo Cimento. 1950;7(2):260–277. https://doi.org/10.1007/BF02784321
39. Monson H, Binder R. Intensities produced by jet-type ultrasonic vibrators. Journal of The Acoustical Society of America. 1953:25. https://doi.org/10.1121/1.1907193
40. Narayanan S, Behera B, Sundararajan T, Srinivasan K. Acoustic heating effects in Hartmann whistle. International Journal of Aeroacoustics. 2013;12(5–6):557–578. https://doi.org/10.1260/1475-472X.12.5-6.557
41. Neshin AM, Fedulova VI, Kesaev KhV, Kurpatenkov VD, Kuptsov VM, Sergienko AA, Semenov VV. Gas-dynamic igniter. Soviet. Union patent 1255818. 1985.
42. Marchese VP, Rakowsky EL, Bement LJ. A fluidic sounding rocket motor ignition system. Journal of Spacecraft and Rockets. 1973;10(11):731–734. https://doi.org/10.2514/3.61955
43. Marchese VP. Development and demonstration of flueric sounding rocket motor ignition (No. KD73-40). 1974.
44. Rakowsky EL, Corrado AP, Marchese VP. Fluidic explosive ignitor. Fluidics Quarterly. 1974;6:13–32.
45. Neemeh RA, Ostrowski PP, Wu JHT. Thermal performance of a logarithmic-spiral resonance tube. AIAA Journal. 1984;22(12):1823–1825. https://doi.org/10.2514/3.8860
46. Dulov VG, Maksinov VP. Thermal effect of the Hartmann-Sprenger resonator in the high-frequency mode. Bulletin of Saint Petersburg University. Mathematics. Mechanics. Astronomy. 2005;4:79–86.
47. Porumbel I, Cuciumita CF, Nechifor C, Kuncser R, Cuciuc T. Experimental measurements in Hartman oscillators. Transportation Research Procedia. 2018;29:339–355. https://doi.org/10.1016/j.trpro.2018.02.031
48. Kessaev K, Zinoviev V, Demtchenko V. Acoustic igniter and ignition method for propellant liquid rocket engine. U.S. patent 6272845. 2001.
49. Kastner J, Samimy M. Development and characterization of Hartmann Tube fluidic actuators for high-speed flow control. AIAA Journal. 2002;40(10):1926–1934. https://doi.org/10.2514/2.1541
50. Raman G, Mills A, Othman S, Kibens V. Development of powered resonance tube actuators for active flow control. Proceedings of the ASME Fluids Engineering Division Summer Meeting. 2003;2:533–546.
51. Sarpotdar S, Raman G, Cain AB. Powered resonance tubes: resonance characteristics and actuation signal directivity. Experiments in Fluids. 2005;39(6):1084–1095. https://doi.org/10.1007/s00348-005-0041-5
52. Murugappan S, Gutmark E. Parametric study of the Hartmann–Sprenger tube. Experiments in Fluids. 2005;38(6):813–823. https://doi.org/10.1007/s00348-005-0977-5
53. Smith T, Powell A. Experiments concerning the Hartmann whistle. 1964.
54. Shelukhin NN. Study of characteristics of supersonic underexpanded jet. Scientific notes of TsAGI. 1995;26(1–2):78–87.
55. Arkharov AM, Prorko VG, Bordarenko VL, Borisov YuYa, Desiatov AT, Filiyn NV, Yushin VP. Cooling effect at wave expansion of gas stream. Cryogenics. 1984;24(12):697–701. https://doi.org/10.1016/0011-2275(84)90042-0
56. Brocher E, Maresca C. Study of thermal phenomena in a Hartmann-Sprenger tube. International Journal of Heat and Mass Transfer. 1974;16:529–548.
57. Alemasov VE, Butorin EhA, Kravtsov JaI, Muslimov RKh, Karelin VA, Volkov JuV, Khusainova AA. Gear to treat productive stratum. RU2135736 (Patent).1999.
58. Pang Y, Zhang G, Gu H, Yuan D, Chen Y, Wu L, Lin C. Flow and sound field characteristics of a Hartmann whistle with flow-sound-separation feature. Applied Acoustics. 2022;201:109103. https://doi.org/10.1016/j.apacoust.2022.109103
59. Narayanan S, Srinivasan K, Sundararajan T. Aero-acoustic features of internal and external chamfered Hartmann whistles: A comparative study. Journal of Sound and Vibration. 2014;333(3):774–787. https://doi.org/10.1016/j.jsv.2013.09.019
60. Narayanan S, Srinivasan K, Sundararajan T, Ramamurthi K. Acoustic characteristics of chamfered Hartmann whistles. Journal of Sound and Vibration. 2011;330(11):2470–2496. https://doi.org/10.1016/j.jsv.2010.12.003

61. Thomas SK, Narava VSR, Srinivasan K. Role of non-circular jets in the performance of Hartmann whistles. Applied Acoustics. 2022;192:108736. https://doi.org/10.1016/j.apacoust.2022.108736

62. Jothi TJS, Srinivasan K. Acoustic characteristics of non-circular slot jets. Acta Acustica united with Acustica. 2008;94(2):229–242. https://doi.org/10.3813/AAA.918026

63. Belousov A, Lushpeev V, Sokolov A, Sultanbekov R, Tyan Ya, Ovchinnikov E, Shvets A, Bushuev V, Islamov Sh. Hartmann–Sprenger Energy Separation Effect for the Quasi-Isothermal Pressure Reduction of Natural Gas: Feasibility Analysis and Numerical Simulation. Energies. 2024;17(9):1–25. https://doi.org/10.3390/en17092010

Persian Abstract

چکیده

انتقال گاز در مسافت های طولانی نیاز به فشار بالایی دارد که قبل از توزیع گاز به مصرف کنندگان باید کاهش یابد. این کاهش فشار در تاسیسات کاهش فشار اتفاق می‌افتد، جایی که فشار گاز با استفاده از انرژی جریان گاز برای غلبه بر مقاومت موضعی کاهش می‌یابد. طبق قانون ژول تامسون، گاز به طور همزمان خنک می شود. این منجر به خطر یخ زدگی دریچه ها، رسوب هیدرات های گاز و اختلال در تداوم فلز می شود. برای جلوگیری از این اتفاق، منبع اضافی انرژی حرارتی مورد نیاز است. این منجر به راندمان انرژی پایین فرآیند کاهش می‌شود. البته راه حل بهینه برای این مشکل تبدیل مستقیم انرژی فشار گاز به انرژی حرارتی خواهد بود. این مقاله مروری کوتاه بر ادبیات و تحلیلی از بازده اثر هارتمن–اسپرنگر از نظر کاهش شبه همدما فشار در سیستم حمل و نقل گاز ارائه می‌کند. دانشمندان عوامل زیر را شناسایی می کنند که بر وقوع و وجود اثر تأثیر می گذارد: افت فشار در نازل، هندسه و محل تشدید کننده. با توجه به نگرانی های کاربرد عملی، توجه به سطح ارتعاشات و نویز ایجاد شده، امکان پاکسازی حفره تشدید کننده از آلودگی، و خواص حرارتی و مقاومتی مواد مورد استفاده می باشد. با در نظر گرفتن این مفاد، اجرای یک تنظیم کننده فشار بر اساس اثر هارتمن–اسپرنگر ممکن به نظر می رسد.