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MODELING OF PROCESSES IN GAS-DYNAMIC SECONDARY ENERGY GENERATORS

The rapid dynamics of physical processes complicate experimental studies, highlighting the need for mathematical modeling and numerical analysis. Gas-dynamic oscillations in simplified models help understand real system behavior. Gas-jet acoustic generators, with simple design and dynamic operation, provide favorable conditions for modeling, enabling detailed analysis of internal processes and secondary energy conversion efficiency.

***Keywords**: secondary energy sources, discharge pressure, gas-jet acoustic generators, Hartmann-Sprenger generator, mathematical modeling, three-dimensional model, two-dimensional model, Hartmann generator.*

Introduction

In modern scientific research, the issues of increasing energy efficiency and rationalizing the use of energy resources are gaining particular relevance. The constant growth of energy consumption, caused by the intensive development of civilization, necessitates the search for new approaches to energy supply. One of the key challenges is the imbalance between the growing costs of extracting primary fuel and energy resources and the aggravation of environmental problems caused by traditional technologies for their processing and use. In this context, research aimed not only at the introduction of alternative energy sources, but also at the development of technologies for the most effective use of secondary energy resources in industrial and municipal processes is of particular importance.

Literature Review

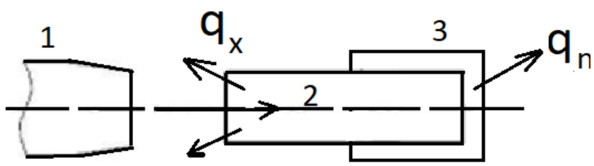
Along with the most common types of secondary energy resources, secondary energy resources of excess (discharge) pressure are of significant scientific interest. They represent the potential energy of gaseous or liquid media that are under pressure higher than atmospheric and are formed as a result of various technologicalz processes in industry [1, 4-18]. Current research in this area is aimed at developing technologies for the effective utilization of this energy, in particular its conversion into heat or cooling products, which allows optimizing energy consumption and increasing the overall efficiency of energy systems.

Among modern technological solutions, devices capable of simultaneously generating heat and cold using external excess pressure as an energy source attract particular attention. Such devices include gas-jet acoustic generators, which have become the subject of intensive scientific research in recent years. Their popularity is due to a number of advantages: cost-effective energy efficiency, the absence of moving parts in most design schemes, compactness, ease of operation, lack of vibration, high reliability and durability, as well as the ability to operate stably in a wide range of operating pressures and temperatures - both negative and positive. The use of such generators allows to increase the efficiency of air cooling processes under conditions of excess pressure.

The rapid development of modern computing technologies has significantly expanded the possibilities for studying complex physical processes. The rapidity and multicomponent nature of the phenomena occurring in gas-jet acoustic generators complicate their in-depth experimental study, which, in turn, stimulates the use of numerical modeling and mathematical programming. The study of the dynamics of gas-dynamic oscillations in such systems is an urgent task of modern science, since the development of the theory of nonlinear oscillations in real environments is accompanied by significant methodological difficulties.

Gasdynamic oscillations characteristic of the operation of gas-jet acoustic generators form a complex dynamic picture [1, 2], the analysis of which requires the use of mathematical modeling. The simplicity of design solutions combined with the rapidity of internal processes create favorable conditions for the development and testing of numerical models capable of accurately describing the internal dynamics of such systems and predicting their effectiveness in practical applications.

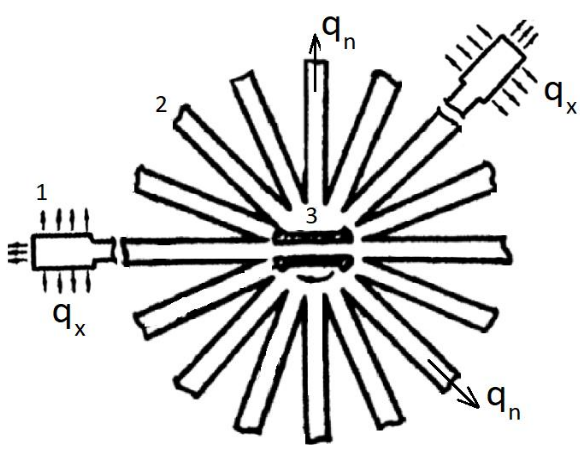
These are so-called energy distribution devices, which include devices with a resonant tube - Hartmann generators (see Fig. 1), as well as gas-jet acoustic generators (see Fig. 2) [4, 5]. Such devices incorporate the principle of aerodynamic resonance [6, 7, 10], as well as the phenomenon of thermal energy separation during nonlinear oscillations of gas in a tube closed on one side.



1 – nozzle; 2 – receiving tube;
3 – heat-dissipating surface
$q_п$ – heat from the cooling object;
q_x – heat of compression discharge.

Fig. 1. Hartmann generator

The design of such devices consists of a nozzle and a receiving tube or fan of tubes into which gas is supplied under pressure. For such devices, the operating mode must be pulsating, and the oscillation frequency must correspond to the natural oscillation frequency of the tube.



1 - heat-dissipating surface;
2 - fan of receiving tubes;
3 - gas distributor.
$q_п$ – heat from the cooling object;
q_x – heat of compression discharge.

Fig. 2. Gas-jet heat acoustic generator
with mechanical gas distributor

This operating principle allows for the effective use of Gas-jet heat acoustic generator for local air conditioning, cooling of process gases, or equipment requiring heat removal. The adiabatic efficiency level of such devices reaches 70. High-pressure gas periodically enters the gas distributor through special holes in the housing and is then directed into the energy exchange channel located along the axis of the device.

In this channel, intensive heat exchange processes occur, which cause a decrease in the gas temperature. The cooled gas rotates in the opposite direction through separate channels of the gas distributor and is discharged from the device. The created temperature difference on the heat exchange surface allows for effective heat removal by forced or natural means. High thermal power (up to a thousand kW [8]), which allows them to be used in industrial areas where large amounts of gas need to be processed: in pulsation devices in the bottomhole zone of the reservoir in oil and gas production, for gas-dynamic ignition of combustible gases; and also as a rotary wave cryogenic generator for small-scale production of liquefied natural gas, in aircraft construction, as a heating element of the anti-icing system in the air intake of an aircraft.

Research Aim

The aim of the work is to create a comprehensive generalized model of thermo-gasodynamic processes occurring in gas-jet refrigeration and heating acoustic generators. The research is aimed at obtaining detailed characteristics of the operation of generators under various operating conditions, as well as at identifying and justifying effective ways to increase their energy and operating efficiency at various frequency regimes.

Discussion of Results

To study in detail the dynamics of the gas wave in the receiving tube of the acoustic generator, a proven simplified two-dimensional CFD model based on principles similar to the design of the Hartmann generator was used. This model allows for a qualitative description of the complex wave processes that occur during the cyclic filling and emptying of the tube.

Since the studies are performed using a demo version of a commercial software package, which has limitations on the number of spatial grid elements and integration time step, it was decided to implement a simplified version of the three-dimensional model (see Fig. 3).

For numerical analysis of gas-dynamic processes in the receiving tube of the acoustic generator, a tube 1.5 m long, with an internal diameter of 8 mm and a wall thickness of 1 mm was selected [3]. Such dimensions correspond to typical geometric characteristics of experimental samples used in laboratory conditions and provide sufficient length for the development of wave processes and observation of the formation of thermal effects.

To ensure correct convergence of calculations and reduce the physical time of calculations, the model is presented in the form of a thin layer (slit) with a thickness of 1 mm, which corresponds to the conditions of two-dimensional consideration (see Fig. 4).

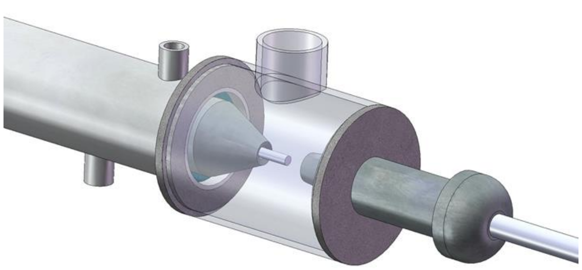


Fig. 3 Three-dimensional model of a Hartmann-Sprenger generator with an axial rod

This approach allows to achieve acceptable modeling accuracy with limited computational resources, while preserving the key features of the gas flow and pulsations.

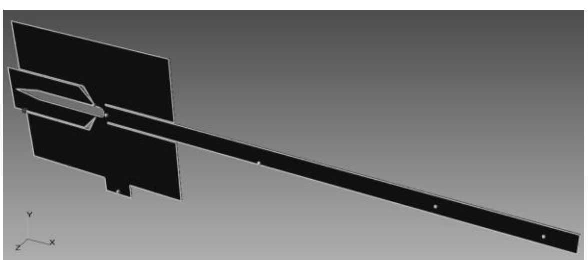


Fig. 4. A simplified three-dimensional model that approximates the two-dimensional problem

The initial thermodynamic parameters of the working medium (air) in the tube were: pressure – 0.11 MPa; temperature – 300 K. The gas at the inlet to the tube is supplied under an excess pressure of 0.25 MPa at a temperature of 300 K. The exhaust air is discharged into the low-pressure zone with the parameters: pressure – 0.1 MPa; temperature – 300 K.

To numerically solve the problem, a simplified quasi-two-dimensional model with a spatial grid of 100×150×1 was used (see Fig. 5), simulating a thin three-dimensional layer with a thickness of 1 mm.

This approach reduces computational costs while maintaining the accuracy of the reproduction of wave transport and zones of elevated pressure and temperature.

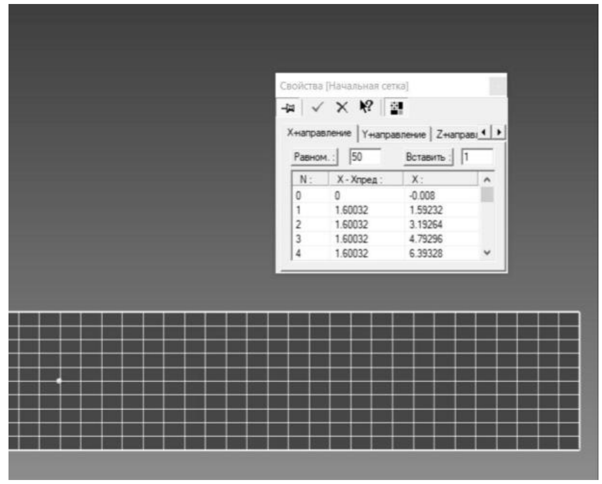


Fig. 5. Spatial grid for a two-dimensional model

The calculation was performed with a time step of 10^{-8}–10^{-7} s to correctly describe fast processes, in particular the formation of shock waves, rarefaction waves, and pulsation dynamics.

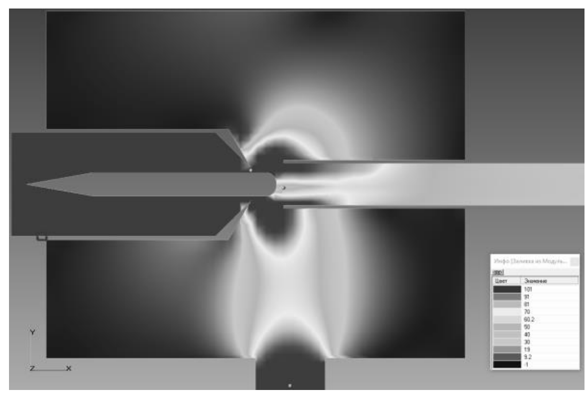


Fig. 6. Gas distribution in a receiving tube with a round-shaped rod

Numerical simulations have shown that when compressed gas flows out of a conical nozzle, its potential energy is converted into kinetic energy. The interaction of the flow with the blunt end of the axial rod forms a region of reduced pressure and temperature on the axis - a cavity, which determines the subsequent gas-dynamic regime in the receiving tube. At the stage of filling the tube with gas, the pressure in its volume gradually increases.

Simulation (Fig. 6 and 7) shows that already at t = 0.02 s a cavity is formed: the rounded end of the rod creates a distributed, smooth cavity, while the acute-angled one creates a localized one with a sharp drop in pressure and temperature.

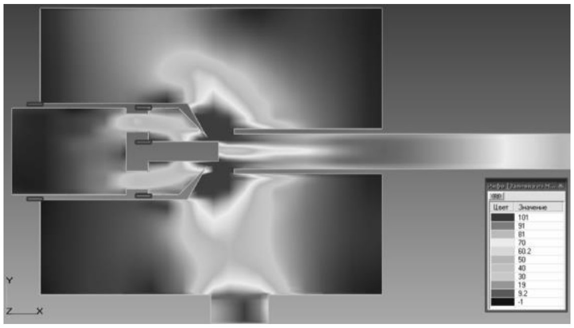


Fig. 7. Gas distribution in a receiving tube with a rod with a cut end

Conclusions

When the compression wave reaches the closed end of the tube, it is reflected, forming a return wave that travels towards the open end. As it passes through the cavity, the wave partially changes its structure and forms a return axial jet, a key element of the phase dynamics of an acoustic generator. Further interaction of the reflected wave with a new gas pulse causes turbulent mixing of the flows, and the excess pressure ensures the gas escapes into the low-pressure chamber.

This cyclic process of filling and emptying the tube is accompanied by successive shock-wave interactions. In a certain zone, the incoming wave transforms into a flat shock wave, behind the front of which the gas velocity is less than the local speed of sound, which causes an uneven pressure distribution.

The use of an axial rod modifies the jet structure at the inlet, promotes the formation of a reverse flow, and enhances the cumulative thermo-gasodynamic effects, which are important for increasing the efficiency of the generator.

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МОДЕЛЮВАННЯ ПРОЦЕСІВ У ГАЗОДИНАМІЧНИХ ГЕНЕРАТОРАХ ВТОРИННОЇ ЕНЕРГІЇ

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Окрім добре відомих методів утилізації вторинної теплоти, у дослідженні приділено увагу ще одному важливому різновиду вторинних енергоресурсів — енергії надлишкового або скидного тиску. Такий ресурс утворюється у процесах видобутку, транспортування та розподілу природного газу, а також широко зустрічається у хімічній, нафтовій, гірничій і харчовій промисловості. Незважаючи на значний енергетичний потенціал, утилізація скидного тиску залишається менш розвиненою у порівнянні з технологіями повторного використання скидної теплоти. Це зумовлює необхідність пошуку нових технічних рішень, що здатні забезпечити ефективне перетворення цього виду енергії в корисну роботу.

У статті показано можливості використання надлишкового тиску для забезпечення функціонування газоструменевого акустичного генератора Гартмана–Шпренгера, який здатний працювати у різних технологічних системах. Наголошено, що залучення такого ресурсу має подвійний ефект: по-перше, зменшує економічні втрати, пов'язані з невикористаною енергією, а по-друге — сприяє підвищенню екологічної безпеки завдяки зниженню рівня викидів парникових газів і шкідливих домішок у навколишнє середовище.

Особливий акцент зроблено на перспективності застосування газоструменевих акустичних генераторів, які відрізняються простотою конструкції, високою надійністю та ефективністю роботи. Завдяки цим характеристикам вони можуть бути використані у теплових і холодильних технологіях, системах локального кондиціонування та установках утилізації енергії скидного тиску. Висвітлено актуальність використання математичного моделювання та чисельного аналізу для дослідження складних газодинамічних процесів у подібних генераторах. Показано, що швидкоплинність фізичних явищ та складність їхньої експериментальної фіксації значно обмежують традиційні методи дослідження. Натомість математичне моделювання дозволяє створювати спрощені, але інформативні моделі, що відтворюють характер коливальних процесів, дають змогу аналізувати внутрішню динаміку генератора та оцінювати ефективність перетворення вторинної енергії у корисну роботу.

Таким чином, у роботі обґрунтовано важливість дослідження утилізації енергії скидного тиску, показано перспективність застосування газоструменевих акустичних генераторів та підкреслено роль математичного моделювання як ключового інструменту для аналізу їхньої роботи.

Ключові слова: *вторинні джерела енергії, скидний тиск, газоструменеві акустичні генератори, генератор Гартмана-Шпренгера, математичне моделювання, тривимірна модель.*