DOI https://doi.org/10.32782/1994-4691-2026-1-77-4
UDK 621.565.9

FEASIBILITY ASSESSMENT OF A VORTEX TUBE FOR EXHAUST AIR ENERGY RECOVERY IN A PNEUMATIC CYLINDER

ОБҐРУНТУВАННЯ МОЖЛИВОСТІ ЗАСТОСУВАННЯ ВИХОРОВОЇ ТРУБИ ДЛЯ РЕКУПЕРАЦІЇ ЕНЕРГІЇ ВІДПРАЦЬОВАНОГО ПОВІТРЯ ПНЕВМОЦИЛІНДРА

A. Rogovyi[1], Dr. Sc., Professor ORCID: 0000-0002-6057-4845
M. Stryzhak[1*], Ph.D., Associate Professor ORCID: 0000-0003-3335-4086
D. Savenkov[1] ORCID: 0009-0008-8654-627X
D. Dyomin[1] ORCID: 0009-0003-0314-1191
R. Hasanov[1] ORCID: 0009-0002-4436-3359

[1]*National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine*
*e-mail: Mariana.Stryzhak@khpi.edu.ua

Abstract. This article discusses an approach to improving the energy efficiency of pneumatic actuators by recovering energy from exhaust air using a vortex tube based on the Rank-Hirsch effect. Based on a review of the literature, the selection of the pipe's geometric parameters is justified, and a three-dimensional CAD model of the pipe is constructed, adapted to the conditions of supply from the exhaust line of a pneumatic cylinder. The methodology includes numerical simulation of the airflow in ANSYS CFX under steady-state boundary conditions corresponding to the characteristic parameters of the exhaust flow. The results confirm the formation of a cold axial core and a hot peripheral flow zone, with maxima of static entropy and turbulent kinetic energy localized immediately behind the nozzle rim. The obtained data indicate the fundamental possibility of using the cold flow for localized cooling of components in technological systems without the use of additional energy.

Keywords: pneumatic actuator, vortex tube, energy recovery, energy efficiency.

Introduction.

Pneumatic actuators form the basis of modern automation systems and flexible manufacturing complexes. Their widespread integration into a wide variety of industrial processes is due to their high specific power, fast response time, reliability, and fire safety. However, a significant drawback of pneumatic systems remains their low overall efficiency, which typically does not exceed 15% [1, 2]. Given the high cost of producing and preparing compressed air, the task of energy conservation and fully utilizing the performance of compressed air is critically important for industry.

Literature Review.

Various scientific approaches to improving the energy efficiency of pneumatic systems are currently being actively developed [3]: preventing compressed air leaks, maintaining an optimal pressure level in the system, correctly selecting the sizes of actuators, and so on. One such approach is the use of computational fluid dynamics methods for a detailed analysis and optimization of pneumatic actuator operating processes, which allows for the identification of hidden sources of losses that are inaccessible to classical calculation methods [4].

At the same time, there is another source of irreversible energy and exergetic losses in the operating cycle of a pneumatic actuator that is less frequently studied: the free expansion of compressed air into the atmosphere during the exhaust phase [5, 6]. A quantitative exergetic assessment of the efficiency of a pneumatic actuator with controlled piston braking and

compressed air recovery, which confirms the significant potential for reducing losses specifically during the exhaust phase, is presented in [7].

At the moment the exhaust line of the air distributor opens, the cylinder's working chamber is still under residual pressure. When this pressure is directly vented, up to 40-60% of the potential energy expended by the compressor during the intake stroke is lost [8, 9]. Such direct dissipation of energy into the environment is inefficient, since the exhaust flow possesses sufficient energy potential to perform useful work.

In this regard, a promising approach to energy conservation is the reuse of energy from the exhaust air [10]. Specifically, this is achieved by recovering air from the exhaust chamber and returning it to the intake system [11] using a check valve configuration.

Reference [12] describes a system that involves storing the air exiting the cylinder in a special receiver and subsequently reusing it in subsequent cycles, which has enabled savings of up to 23%. In [13], a scheme is proposed that cuts off the air supply once the required pressure level is reached, allowing air to be retained in the chambers without additional supply – this approach yielded savings of up to 71%.

The paper [14] describes an approach in which, instead of the traditional venting of air, it is redirected between the cylinder chambers or even returned to the network. As a result, savings of up to 87% are achieved, making such switching solutions among the most promising for energy-saving applications.

Overall, active research into energy recovery from exhaust flows indicates the promise of this approach to improving the energy efficiency of pneumatic actuators. The use of a vortex tube, device based on the Rank-Hilsch effect [15, 16], deserves special attention.

The phenomenon of energy separation of a swirling gas flow into a cold axial component and a hot peripheral component was first described in 1933 [15] and subsequently investigated in [16], where a characteristic design of a counter-flow cylindrical tube with a tangential nozzle inlet was proposed. Compressed air is accelerated through a ring of tangential nozzles to a high (transonic) velocity, resulting in the formation of vortex motion within the pipe, with energy transfer from the axial to the peripheral layers occurring primarily due to viscous shear. This causes an increase in the total temperature at the periphery of the flow and a decrease in the near-axis zone; accordingly, hot (through a conical valve) and cold (through a restricting diaphragm) flows are extracted at opposite ends of the tube.

The practical value of using a vortex tube lies in the ability to "passively" utilize the exhaust flow (Fig. 1). The tube is installed in the exhaust line of a pneumatic cylinder and requires no additional power consumption or complex mechanisms; it is fire-safe (since it uses only the exhaust air flow without electrical voltage) and is highly reliable.

The cold component, which forms in the axial zone of the tube, can be directed to dissipate heat from the electronic components of the pneumatic actuator, which are typically located in close proximity to the actuator and are sensitive to overheating, or to cool the tool (Fig. 1). The hot component, in turn, is discharged into the atmosphere according to the basic design, just like exhaust air without the use of a vortex tube; that is, it does not degrade the performance characteristics of the pneumatic system. However, the elevated temperature of this flow opens up additional potential for auxiliary applications. This could involve heating components of distribution equipment to prevent the freezing of moist compressed air at low temperatures, which is a common problem in industrial pneumatic systems during the winter.

A schematic diagram illustrating the proposed approach is shown using the example of a drilling machine feed drive (Fig. 1). Pneumatic cylinder 1, together with control box 2, drives the machine's spindle; when the valve switches to reverse operation, the exhaust air from the cylinder's working chamber is not vented to the atmosphere, as in a traditional circuit, but is directed to the nozzle inlet of the vortex tube 4. The swirled flow in the tube is divided into a cold axial component and a hot peripheral component: the cold flow is drawn off through the "cold" outlet 5 and, via a flexible hose 3, is directed directly into the cutting zone for

localized cooling of the drill bit; the hot flow is diverted through the “hot” outlet 6. This integration method requires no additional power sources or changes to the cylinder control circuit, since the vortex tube merely intercepts a flow that would otherwise be discharged into the atmosphere anyway.

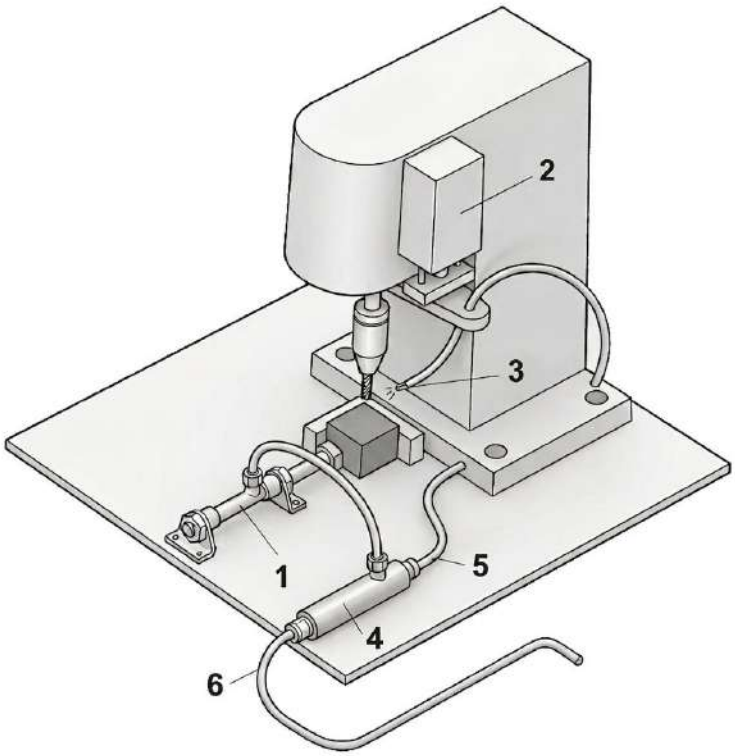


Fig. 1. Schematic diagram of a drilling machine’s pneumatic drive with an integrated vortex tube for drill bit cooling: 1 – pneumatic cylinder; 2 – control box; 3 – hose with cooled air; 4 – vortex tube; 5 – “cold” outlet of the tube; 6 – “hot” outlet

The efficiency of the energy separation of the flow into hot and cold components depends significantly on the pipe’s geometric parameters. The ratio of length to inner diameter L/D_1, according to data from various sources, is optimal in the range of 20-55 [17–19], although the flow separation process occurs primarily near the pipe inlet [17]. The ratio of the cold orifice diameter to the pipe diameter $d_c/D_1 = 0,5$ is recognized as optimal in a number of independent experimental studies [20–22], while some studies recommend a slightly higher value – up to 0.7 [23]. The number and shape of the tangential nozzles (typically, $N = 4\text{K}\,6$) [24, 25] and the opening angle of the conical valve at the hot outlet, whose optimum varies within the range of $45\text{K}\,80°$ depending on the total pressure ratio [26–28], also have a significant influence on the characteristics.

Despite nearly ninety years of research into this effect, there is still a lack of high-precision experimental data with a quantitative assessment of measurement uncertainty. One of the most comprehensive modern studies of this kind [29] presents the characteristics of a counter-flow vortex tube ($L/D_1 = 20$, $d_c/D_1 = 0,5$, $N = 6$, $\varphi = 80°$) for a feed pressure of 3.0–7.0 atm, demonstrating maximum separation efficiency under these conditions.

At the same time, the vast majority of existing studies focus on supplying the vortex tube from a continuous source of compressed air at mainline pressure. The issue of its application under conditions of cyclic, pulsating supply directly from the exhaust line of a pneumatic cylinder (performing a technological operation), without additional supply from the main line and at a high cycle frequency (approximately 20 cycles/min), remains virtually unexplored. At the same time, this particular configuration offers significant energy-saving potential: it

allows for the recovery of exergy from a flow that would otherwise be irretrievably dissipated into the atmosphere, without requiring additional consumption of compressed air or electricity.

The practical significance of the proposed approach lies in the fact that the cold flow obtained at the outlet of the vortex tube can be used for heat dissipation from the electronic components of a hybrid pneumatic actuator. For technological systems, the ability to obtain "free" coolant from the exhaust flow without using additional energy is of practical value and serves as the motivation for the chosen research direction.

Research Methodology.

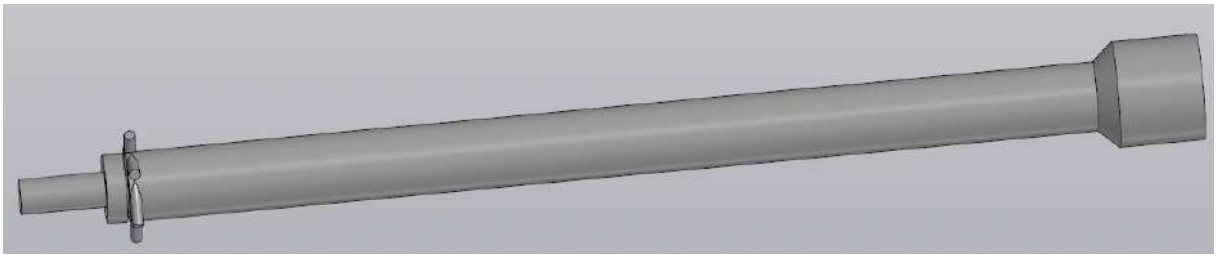
The objective of this work is to assess the fundamental feasibility of using a Rank-Gilsh vortex tube to recover energy from the exhaust air of pneumatic systems through a numerical study of the energy separation process under steady-state boundary conditions characteristic of the operating parameters of pneumatic actuator exhaust air.

To achieve this objective, an analysis of literature data on the geometric parameters of vortex tubes was conducted. Based on the recommendations obtained, a three-dimensional CAD model of a counter-flow vortex tube was constructed. Numerical simulation of the flow was performed in ANSYS CFX using the SST k-ω turbulence model. Based on the calculation results, the temperature, entropy, and turbulent kinetic energy fields were analyzed to assess the nature of the flow's energy separation.

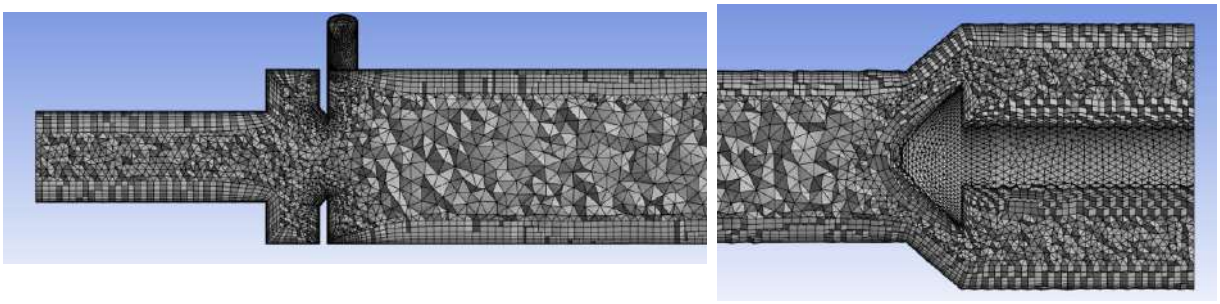
Since the objective of this work is to assess the fundamental feasibility of using a vortex tube, a design was adopted whose characteristics have been thoroughly investigated and experimentally verified in [29]. Using a geometry close to the optimal one according to the criteria of flow energy separation allows minimizing the influence of design factors on the simulation results and focusing on investigating the possibility of obtaining a cold flow under



a



b



c

Fig. 2. Three-dimensional model of the internal geometry of the flow section of the vortex tube: a – longitudinal cross-section; b – external view; c – mesh partition

supply parameters characteristic of pneumatic systems. Pipe geometric parameters: inner pipe ?diameter D_1 = 23 *mm*; length-to-diameter ratio L/D_1 = 20; ratio of the "cold" orifice diameter to the pipe diameter d_c/D_1 = 0.5; number of tangential nozzles N = 6 with the ratio of the total throat area of the nozzle ring to the cross-sectional area of the pipe A_1/A = 0.22; the opening angle of the conical valve at the "hot" outlet φ = 80°; the ratio of the valve's outer diameter to the pipe diameter d_c/D_1 = 1.51. Based on these parameters, a three-dimensional geometric model of the flow section of the vortex tube was constructed (Fig. 2).

The computational domain was meshed in ANSYS Meshing using an unstructured tetrahedral mesh with local refinement in the nozzle rim region, the axial region, and near the walls. To verify the correctness of the numerical solution, a mesh independence check was performed; based on its results, subsequent calculations were carried out on a mesh for which changes in the governing flow parameters were negligible.

The model was simulated using the ANSYS CFX software package under steady-state conditions for a compressible turbulent air flow. The Reynolds equations were closed using the SST k-ω turbulence model, which is traditionally used to simulate swirling high-velocity flows in vortex tubes due to its ability to accurately reproduce turbulence anisotropy in the near-axis region. The energy equation was solved jointly with the equations of motion to accurately reproduce the effect of energy separation in the flow [11].

At the inlet to the nozzle ring, parameters corresponding to the actual cylinder exhaust conditions were specified: total pressure p_1, temperature T_{01} = 293 *K*. At the hot and cold outlets, the static pressure was set equal to atmospheric pressure $p_c = p_h$ = 1 *atm*, and the fraction of the cold flow ε was controlled by the cross-sectional area of the nominal throttling element at the hot outlet. The process is assumed to be adiabatic; heat transfer through the cylinder walls is neglected, and there is no sliding.

The solution was performed using second-order discretization schemes; convergence was verified by the level of inconsistency (no worse than 10^{-5}) and the stabilization of the integral temperature values at the outlets. The calculation results yielded fields of static (Figs. 3, 4) and total (Fig. 5) temperature, static entropy (Fig. 6), and turbulent kinetic energy along the pipe's longitudinal cross-section (Fig. 7), which were used to analyze the mechanism of energy separation in the flow and to assess the degree of irreversibility of the processes in the considered geometry.

Results.

The calculations yielded the spatial distribution of key flow parameters along the longitudinal cross-section of the vortex tube (Figs. 3–7).

Fig. 3 shows the pattern of energy separation characteristic of the Rank–Hilsch effect: in the nozzle inlet region, the flow has a relatively low temperature (about 260 *K*). However, immediately after passing the nozzle rim, a pronounced field inhomogeneity forms: the axial region at a short distance from the inlet remains relatively cold (green zone on the contour), while the peripheral region heats up rapidly.

Further along the length of the pipe, the field evens out toward a high-temperature state (approximately 330 *K*), which corresponds to the conversion of the kinetic energy of the swirling flow into thermal energy due to viscous shear; this mechanism is described in [15, 16, 29]. Compared to Fig. 4, which shows a smoother, nearly monotonic heating along the length of the pipe from the inlet to the hot outlet, the total temperature field emphasizes the localized, rather than distributed, nature of the initial separation, where the main "jump" occurs within the first few pipe diameters from the nozzle rim, which is consistent with the conclusion in [17] regarding the concentration of the energy separation process near the inlet ($3 < L/D_1 < 5$).

The temperature contours in Fig. 4 and Fig. 5 reveal a characteristic periodic, "nested" structure of isolines in the form of elongated ovals that alternate sequentially along the pipe axis. This reflects not merely a monotonous decay of vorticity, but a wave-like, quasi-periodic

nature of temperature redistribution, which is a typical feature of the interaction between the vortex core and the wall-adjacent shear flow in counter-flow vortex tubes.

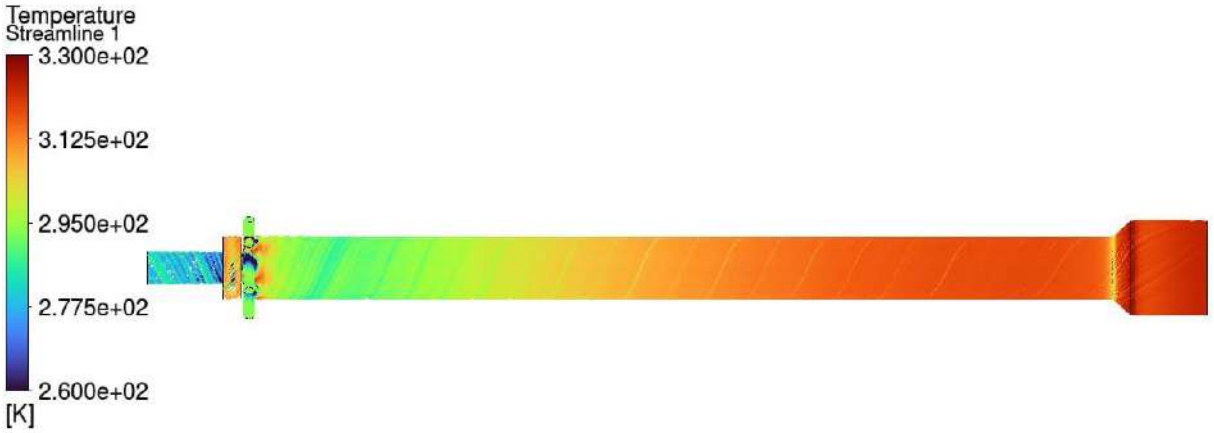


Fig. 3. Distribution of static temperature along the flow line in the longitudinal cross-section of a vortex tube

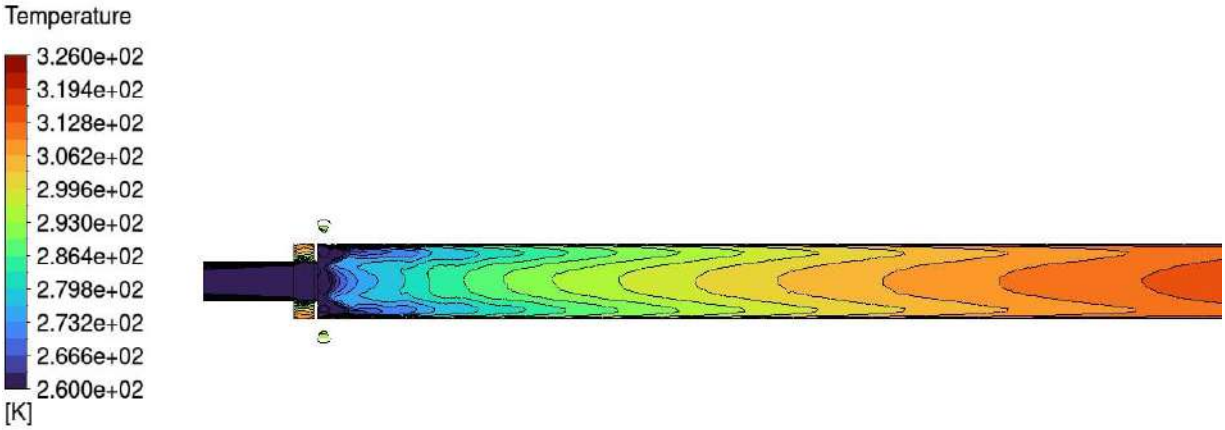


Fig. 4. Static temperature field in the longitudinal cross-section of a vortex tube

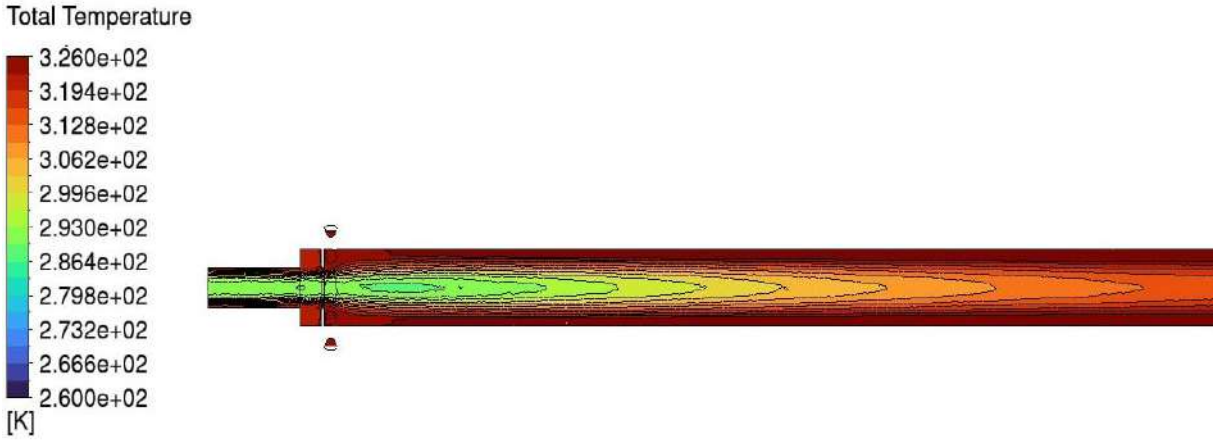


Fig. 5. Total temperature field in the longitudinal cross-section of the vortex tube

The number and scale of these structures gradually decrease along the length, indicating a gradual dissipation of flow vorticity and a transition from intense vortex motion immediately downstream of the nozzles to a practically axisymmetric, weakly vortical flow closer to the "hot" outlet.

The static entropy field (Fig. 6) clearly delineates the zone of maximum irreversibility of the process: peak values (up to 120.8 $J/(kg \cdot K)$ relative to the adopted reference) are observed

directly in the nozzle inlet zone and immediately beyond it, where a sharp acceleration of the flow occurs through the tangential nozzles and a vortex core forms. Further downstream, the entropy drops rapidly and stabilizes at a relatively uniform level (approximately 350…450 *J*/(*kg*·*K*) over most of the pipe's length, indicating a transition from intense generation of irreversibilities in the inlet zone to a quasi-equilibrium, low-dissipative flow regime further along the length. This result demonstrates a pronounced spatial localization of the source of irreversibility along the pipe coordinate.

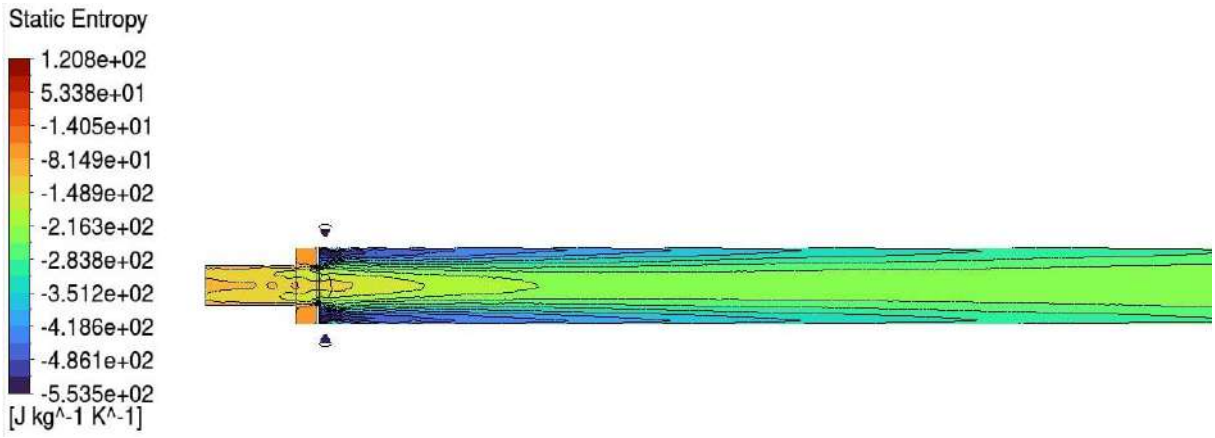


Fig. 6. Static entropy field in the longitudinal cross-section of a vortex tube

Fig. 7 confirms the conclusions made above: the maximum turbulent kinetic energy (up to 1,890 m^2/s^2) is concentrated in a narrow zone immediately behind the nozzle rim, where an intense shear layer forms between the high-velocity peripheral flow and the slower axial core. Further along the length of the tube, the level of turbulent kinetic energy decreases in a wave-like manner, with a gradual attenuation of the oscillation amplitude, which correlates with the structure of the temperature contours in Figs. 4-5 and confirms the "top-down" energy transfer mechanism through a cascade of turbulent vortices, which gradually decays with increasing distance from the vortex generation zone.

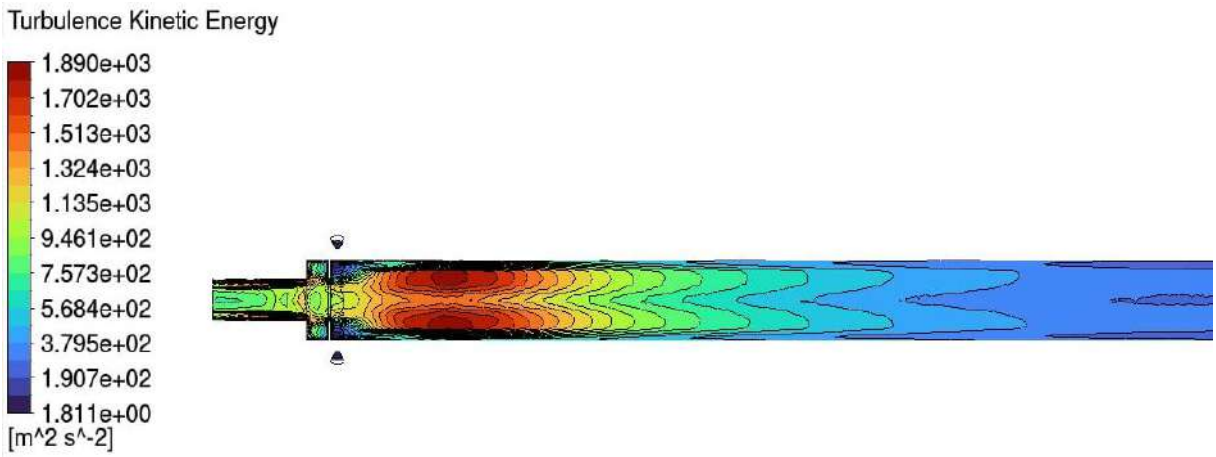


Fig. 7. Turbulent kinetic energy field in the longitudinal cross-section of a vortex tube

The results of the numerical simulations confirm that a stable zone of reduced temperature forms in the pipe in the near-axis region of the flow (the minimum values in the calculated fields correspond to a range of approximately 260–270 *K*, Figs. 3–5). This result opens up the practical possibility of using a cold flow, drawn from the corresponding outlet of the vortex tube, for heat removal from the electronic components of a hybrid pneumatic actuator located directly adjacent to the actuator mechanism. Unlike traditional cooling systems (fans, Peltier elements, liquid circuits), which require an additional power source, the

proposed approach utilizes a pneumatic flow, contains no electrical voltage, and is fire-safe, which is particularly relevant for electronics cabinets, mobile systems, and robotic systems.

Conclusions.

Based on an analysis of existing approaches to improving the energy efficiency of pneumatic actuators, it has been established that a vortex tube based on the Rank–Hilsch effect is a promising but under-researched means of recovering energy from the exhaust flow of pneumatic cylinders, capable of providing effective cooling without the use of additional energy.

Based on a review of the literature, the choice of the vortex tube's basic geometry was justified, and this geometry was adapted for conditions of supply from the exhaust cavity of a pneumatic cylinder. Numerical flow simulation confirmed the qualitative correspondence of the obtained physical picture to the classical mechanism of energy separation in a swirled flow: the formation of a cold axial core and a hot peripheral zone, with maxima of static entropy (up to 120.8 $J/(kg \cdot K)$ and turbulent kinetic energy (up to 1890 m^2/s^2) localized in a narrow zone immediately behind the nozzle rim.

The spatial coincidence of the zones of maximum entropy and turbulent kinetic energy generation immediately behind the nozzle rim indicates that the majority of the irreversible losses of the flow's mechanical energy are concentrated in the initial section of the pipe (within a few diameters from the inlet), while the remainder of the length primarily serves a transport function, followed by a significantly slower decay of the residual vortex.

The obtained results are based on constant (in magnitude) boundary conditions at the inlet, corresponding to a single characteristic operating mode, without pulsating pressure and flow rate values throughout the entire operating cycle. Therefore, they should be regarded as confirmation of the fundamental applicability of the chosen geometry and the qualitative correctness of the physical picture of the energy separation process. Investigating this issue in a transient setting with time-dependent boundary conditions that reproduce the actual exhaust profile is a direction for future work.

The results obtained confirm the fundamental feasibility of using a cold flow from a vortex tube, powered by the exhaust energy of a pneumatic cylinder, to cool the electronic components of a hybrid drive, which determines the practical focus of future research.

References

1. Radgen, P., Blaustein, E. Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential, and Policy Actions. Stuttgart: Fraunhofer Institute for Systems Technology and Innovation, 2001. Available at: https://publica.fraunhofer.de/entities/publication/60fbadfb-caf9-4e21-bd6e-5095fbff1964 (accessed July 18, 2026).

2. Beater, P. Pneumatic Drives: System Design, Modeling, and Control. Berlin: Springer-Verlag, 2007, 330 p. Available at: https://link.springer.com/book/10.1007/978-3-540-69471-7 (accessed July 18, 2026).

3. Saidur, R., Rahim, N. A., Hasanuzzaman M. A review on compressed-air energy use and energy savings. *Renewable and Sustainable Energy Reviews*, 2010. 14(4). 1135–1153. https://doi.org/10.1016/j.rser.2009.11.013

4. Rogovyi, A., Strizhak, M., Korohodskyi, V., et al. Optimization of pneumatic actuator processes by means of computational fluid dynamics. *AIP Conference Proceedings*, 2026. 3496(1). 060001. https://doi.org/10.1063/12.0044441

5. Cai, M., Kawashima, K., Kagawa, T. Power assessment of flowing compressed air. IEEE/ASME *Journal of Fluids Engineering*, 2005, 128(2), 402–405. https://doi.org/10.1115/1.2170129

6. Gryboś, D., Leszczyński, J. S. Exergy analysis of pressure reduction, back pressure and intermittent air supply configuration of utilization/expansion stage in compressed air systems. *Energy*, 2023. 285. 129419. https://doi.org/10.1016/j.energy.2023.129419

7. Rogovyi, A., Strizhak, M. Exergy-Based Energy Efficiency Analysis of the Pneumatic Drive with Controlled Braking and Compressed Air Recuperation. *Problemele Energeticii Regionale*, 2026. 70(2). 65–77. https://doi.org/10.52254/1857-0070.2026.2-70.06

8. Dindorf, R. Estimating Potential Energy Savings in Compressed Air Systems. *Procedia Engineering*, 2012. 39. 204–211. https://doi.org/10.1016/j.proeng.2012.07.026

9. Gryboś, D., Leszczyński, J. S. A Review of Energy Overconsumption Reduction Methods in the Utilization Stage in Compressed Air Systems. *Energies*, 2024. 17(6). 1495. https://doi.org/10.3390/en17061495

10. Harris, P., Nolan, S., O'Donnell, G. E. Energy optimisation of pneumatic actuator systems in manufacturing. *Journal of Cleaner Production*, 2014. 72. 35–45. https://doi.org/10.1016/j.jclepro.2014.03.011

11. Rogovyi A., Romasevych Y., Stryzhak M. et al. Transient Energy Conversion and Compressed Air Recovery in Pneumatic Systems: Optimization and CFD-Based Analysis. *Actuators*, 2026. 15(3). 135. https://doi.org/10.3390/act15030135

12. Hepke, J., Weber J. Energy saving measures on pneumatic drive systems. SICFP2013, 2013, 475–483. https://doi.org/10.3384/ecp1392a47

13. Yang, A., Pu, J., Wong, C.B., Moore, P. By-pass valve control to improve energy efficiency of pneumatic drive system. Control Engineering Practice, 2009. 17(6). 623–628. https://doi.org/10.1016/j.conengprac.2008.10.013

14. Rihong, Z., Qungui, D. Dynamic Simulation and Optimization of Cushioning Performance in High Speed Pneumatic Cylinders. International Journal of Simulation: Systems, *Science & Technology*, 2016, 17(17). 17.1–17.6. https://doi.org/10.5013/IJSSST.a.17.17.17

15. Ranque, G. Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air. Le Journal de Physique et le Radium, 1933, 4, 112–114. Available at: https://www.scirp.org/reference/referencespapers?referenceid=624309 (accessed July 18, 2026).

16. Hilsch, R. The Use of the Expansion of Gases in a Centrifugal Field as Cooling Process. *Review of Scientific Instruments*, 1947. 18. 108–113. https://doi.org/10.1063/1.1740893

17. Raiskii, Yu. D., Tunkel, L. E. Influence of vortex-tube configuration and length on the process of energetic gas separation. *Journal of Engineering Physics*, 1974. 27. 1578–1581. https://doi.org/10.1007/BF00863014

18. Martynovskii, V. S., Alekseev, V. P. Investigation of the vortex thermal separation effect for gases and vapors. Soviet Physics. *Technical Physics*, 1956. 1(10). 2233–2243.

19. Gao, C. M., Bosschaart, K. J., Zeegers, J.C.H., de Waele, A.T.A.M. Experimental study on a simple Ranque-Hilsch vortex tube. *Cryogenics*, 2005. 45(3). 173–183. https://doi.org/10.1016/j.cryogenics.2004.09.004

20. Saidi, M. H., Valipour, M. S. Experimental modeling of a vortex tube refrigerator. *Applied Thermal Engineering*, 2003. 23(15). 1971–1980. https://doi.org/10.1016/S1359-4311(03)00146-7

21. Nouri-Borujerdi, A., Bovand, M., Rashidi, S., et al. Geometric parameters and response surface methodology on cooling performance of vortex tubes. *International Journal of Sustainable Energy*, 2016. 36(9). 872–886. https://doi.org/10.1080/14786451.2015.1127233

22. Promvonge, P., Eiamsa-ard S. Investigation of vortex thermal separation in a vortex tube refrigerator. *Science Asia*, 2005. 31. 215–223. https://doi.org/10.2306/scienceasia1513-1874.2005.31.215

23. Liu, X., Liu, Z. Investigation of the energy separation effect and flow mechanism inside a vortex tube. *Applied Thermal Engineering*, 2014. 67(1-2). 494–506. https://doi.org/10.1016/j.applthermaleng.2014.03.071

24. Behera, U., Paul, P. J., Kasthurirengan, S., et al. CFD analysis and experimental investigations toward optimizing the parameters of the Ranque-Hilsch vortex tube. *International Journal of Heat and Mass Transfer*, 2005. 48(10). 1961–1973. https://doi.org/10.1016/j.ijheatmasstransfer.2004.12.046

25. Eiamsa-ard, S., Promvonge, P. Review of Ranque–Hilsch effects in vortex tubes. *Renewable and Sustainable Energy Reviews*, 2008. 12(7). 1822–1842. https://doi.org/10.1016/j.rser.2007.03.006

26. Pise, A. T., Devade, K. D. Investigation of the refrigeration effect using a short divergent vortex tube. *International Journal of Earth Sciences and Engineering*, 2012. 5(1). 378–384.

27. Aydin, O., Baki, M. An experimental study on the design parameters of a counterflow vortex tube. *Energy*, 2006. 31(14). 2763–2772. https://doi.org/10.1016/j.energy.2005.11.017

28. Markal, B., Aydin, O., Avci, M. An experimental study on the effect of the valve angle of counter-flow Ranque-Hilsch vortex tubes on thermal energy separation. *Experimental Thermal and Fluid Science*, 2010. 34(7). 966–971. https://doi.org/10.1016/j.expthermflusci.2010.02.013

29. Chowdhury, N. H. K., Povey, T. High-accuracy experimental study of the performance characteristics of an optimized Ranque-Hilsch vortex tube. *Applied Thermal Engineering*, 2024. 251. 123385. https://doi.org/10.1016/j.applthermaleng.2024.123385

Дата першого надходження статті до видання 25.08.2026
Дата прийняття статті до друку після рецензування 23.09.2026
Дата публікації (оприлюднення) статті 04.11.2026
Стаття поширюється на умовах ліцензії відкритого доступу(CC BY 4.0)

ОБҐРУНТУВАННЯ МОЖЛИВОСТІ ЗАСТОСУВАННЯ ВИХОРОВОЇ ТРУБИ ДЛЯ РЕКУПЕРАЦІЇ ЕНЕРГІЇ ВІДПРАЦЬОВАНОГО ПОВІТРЯ ПНЕВМОЦИЛІНДРА

А.С. Роговий[1], М.Г. Стрижак[1], Д.А. Савенков[1], Д.Р. Дьомін[1], Р.С. Гасанов[1]
[1] *Національний технічний університет "Харківський політехнічний інститут"*

Анотація

У статті розглянуто проблему підвищення енергоефективності пневматичних приводів шляхом рекуперації енергії відпрацьованого повітря за допомогою вихорової труби Ранка-Хілша. Пневматичні виконавчі механізми залишаються широко затребуваними в промислових системах автоматизації завдяки високій питомій потужності, швидкодії та пожежобезпечності; проте їхній загальний ККД рідко перевищує 15 %, переважно через те, що стиснене повітря, яке залишається в камері циліндра в момент вихлопу, стравлюється в атмосферу. Хоча кілька стратегій рекуперації енергії, зокрема накопичення в ресивері, відсікання подачі та перепускання між камерами циліндра, продемонстрували економію енергії до 87 %, потенціал термічної рекуперації самого вихлопного потоку досі залишається відносно малодослідженим. Вихорова труба є пасивним засобом реалізації цього потенціалу, розділяючи вихлопний потік на холодну та гарячу складові без додаткових витрат енергії; практичну схему інтеграції проілюстровано на прикладі пневмоприводу свердлильного верстата, де холодний потік спрямовується в зону різання для локального охолодження свердла.

Як зразок було прийнято базову геометрію вихорової труби, раніше експериментально валідовану в літературі, щоб відокремити вплив параметрів живлення від впливу геометричної оптимізації. Тривимірну CAD-модель розрахункової області було побудовано та дискретизовано в ANSYS Meshing із локальним згущенням сітки біля соплового кільця, в пристінній області та в осьовому ядрі. Стисливу турбулентну течію моделювали в ANSYS CFX у стаціонарній постановці з використанням моделі турбулентності SST k-ω; на вході задавали повний тиск і температуру, репрезентативні для вихлопу циліндра, а на обох виходах – статичний атмосферний тиск.

Розраховані поля підтверджують класичний механізм енергетичного розділення на основі ефекту Ранка-Хілша: формується холодне осьове ядро та гаряча периферійна зона, при цьому пікові значення статичної ентропії (до 120,8 Дж/(кг·К)) і кінетичної енергії турбулентності (до 1890 м²/с²) зосереджені у вузькій області одразу за сопловим кільцем, після чого спостерігається поступове хвилеподібне згасання закрутки вздовж труби. Цей просторовий збіг свідчить, що основна частина незворотних втрат припадає на перші кілька діаметрів труби від входу, тоді як решта її довжини виконує переважно транспортну функцію.

Результати, отримані за стаціонарних репрезентативних граничних умов, слід розглядати як підтвердження якісної можливості реалізації запропонованого підходу. На практиці продемонстроване зниження температури холодного потоку (приблизно до 260-270 К) підтверджує доцільність використання вихорової труби як пасивного джерела охолодження без витрат енергії, що особливо актуально для компактних і мобільних робототехнічних систем.

Keywords: пневмопривод, вихорова труба, рекуперація енергії, енергоефективність.