PROCEEDINGS OF ECOS 2026 - THE 39^{TH} INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
28 JUNE - 03 JULY, 2026, CONSTANȚA, ROMANIA

Experimental and numerical investigation of the Ranque-Hilsch vortex tube phenomenon

Wojciech Kostowski[a], ***Michał Majchrzyk***[b], ***Marcel Barzantny***[c], ***Daniel Adamecki***[d], ***Barbara Mendecka***[e], ***Daniele Chiappini***[f], ***Paweł Bargiel***[g], ***Erwin Maciak***[h], ***Michał Fratczak***[i]

[a] *Silesian University of Technology, Gliwice, Poland, wojciech.kostowski@polsl.pl CA*
[b] *Silesian University of Technology, Gliwice, Poland, michal.majchrzyk@polsl.pl*
[c] *Silesian University of Technology, Gliwice, Poland, marcel.barzantny@polsl.pl*
[d] *Silesian University of Technology, Gliwice, Poland, daniel.adamecki@polsl.pl*
[e] *Niccolo Cusano University, Rome, Italy, barbara.mendecka@unicusano.it*
[f] *Niccolo Cusano University, Rome, Italy, daniele.chiappini@unicusano.it*
[g] *Silesian University of Technology, Gliwice, Poland, pawel.t.bargiel@gmail.com*
[h] *Silesian University of Technology, Gliwice, Poland, erwin.maciak@polsl.pl*
[i] *Silesian University of Technology, Gliwice, Poland, michal.fratczak@polsl.pl*

Abstract:

The paper presents progress of the ongoing research project aimed at an experimental and numerical investigation of the Ranque-Hilsch phenomenon occurring in a vortex tube supplied with compressed media. The experimental work is based on the main test rig equipped with mass flowmeters, pressure, temperature and composition sensors, flow controllers, as well as supply system for pressurized gasses (air, nitrogen, helium, CO2). Moreover, auxiliary test rigs have been built for experiments concerning flow visualization and the operation with pressurized water. The experimental part also comprises the design and manufacturing of several vortex tube items with small modifications to address some appearing technical issues. Several series of measurements are presented. The numerical part comprises a series of steady-state and transient CFD models aiming to mirror the laboratory test conditions, with selected measurement values used as boundary conditions for the numerical model. Eventually, the validation procedure is discussed in detail, as it required multiple steps at the experimental side to achieve a good agreement between the measurements and the numerical results.

Keywords:

Ranque-Hilsch phenomenon, Vortex tube, Temperature separation, Mass separation, Gas mixtures

1. Introduction

The Ranque-Hilsch vortex tube (RHVT) is a device entirely devoided of moving parts that facilitates the separation of a pressurised inlet gas stream into two distinct, decompressed streams of varying temperatures, which exit via the hot and cold outlets [1, 2]. Despite the considerable time that has elapsed since its discovery by Ranque in the 1930s, and the device's apparent mechanical simplicity, the fundamental fluid dynamics and the physical mechanisms governing the energy and mass separation remain highly complex and are not entirely understood.

Historically, the scientific community has proposed several conflicting hypotheses to explain the Ranque-Hilsch phenomenon. These include the local compression and expansion hypothesis, the radial temperature gradient hypothesis, the multi-circulation hypothesis, the acoustic hypothesis, the Görtler vortices hypothesis, and the friction hypothesis [1–6]. While a substantial part of research has focused on thermal separation, the mechanisms underlying mass and species separation within non-homogenous gas mixtures have been neglected. Understanding these species stratification mechanisms opens new opportunities to integrate the RHVT into various industrial applications, such as separating gas network zones with different hydrogen contents or improving refrigeration cycles [7–9].

This work presents the recent progress in the ATHLETE research project. Because of the multidisciplinary character of the project, which encompasses both extensive experimental and numerical investigations, the article is divided into specific sections that detail the progress across these different aspects. This is the third progress paper in the project sequence [10, 11]. The primary focus at the current state of the project is the investigation of gas mixtures separation including three specific gases, this is: helium (He), carbon dioxide (CO_2), and nitrogen (N_2) as well as energy separation occurring in each of these gases seperately. To reduce undesired heat exchange caused by the high thermal conductivity of the initially applied aluminum vortex tube, the physical model was slightly modified, and a new tube was prepared using polyetheretherketone (PEEK). Furthermore, to obtain more reliable empirical data, a high-precision stepper motor was applied to ensure the exact placement of the hot-end regulation valve. This automated control significantly reduced measurement inconsistencies, thereby facilitating the validation of Computational Fluid Dynamics (CFD) results. Additionally, a new computational unit based on GPU calculations was incorporated to accelerate the complex numerical simulations.

2. Experimental setup development

Following the preliminary investigation phases, the experimental test rig underwent major structural and functional modifications. These upgrades were designed to (1) reduce or compensate for any identified measurement inaccuracies, (2) minimise unwanted heat transfer, and (3) enable a more precise investigation of multi-component gas mixtures. In addition, a separate test rig for experimental flow visualisation was assembled. A detailed explanation of the vortex tube flow visualisation investigation is presented by the project team in [12].

2.1. Upgraded vortex tube design

In the earlier stages of the project, the Ranque-Hilsch vortex tube (RHVT) prototypes were predominantly manufactured from aluminium. While this material allowed for straightforward machining, its high thermal conductivity facilitated unwanted heat transfer between the hot and cold sections of the device. This phenomenon negatively influences the effect, obscuring the observation of the fundamental thermal separation process.

To isolate the physical separation mechanisms from the conductive properties of the casing, a new vortex tube was designed and manufactured from polyetheretherketone (PEEK). This material is characterised by good resistance to high temperatures and a low thermal conductivity of 0.27 W/(m·K).

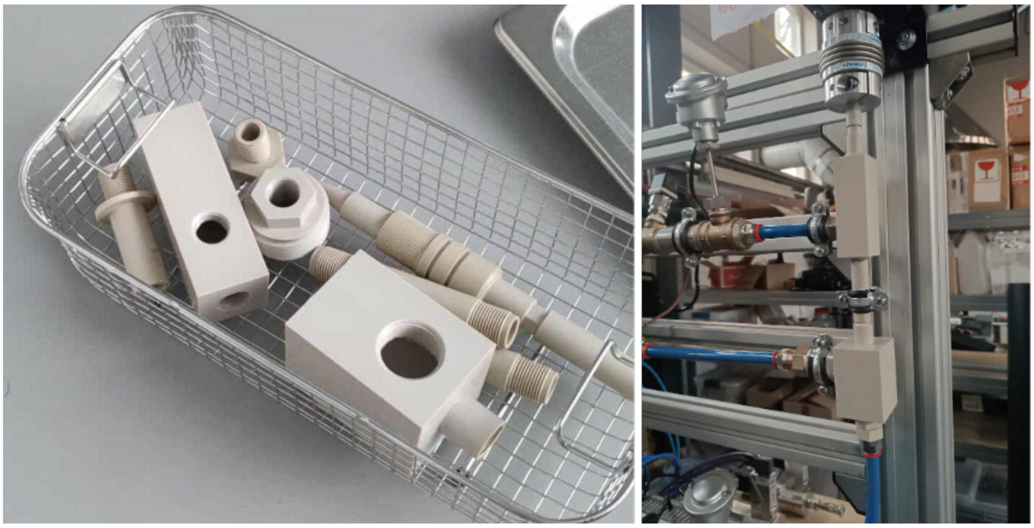

Figure 1: The polyetheretherketone (PEEK) vortex tube – disassembled and mounted at the test rig.

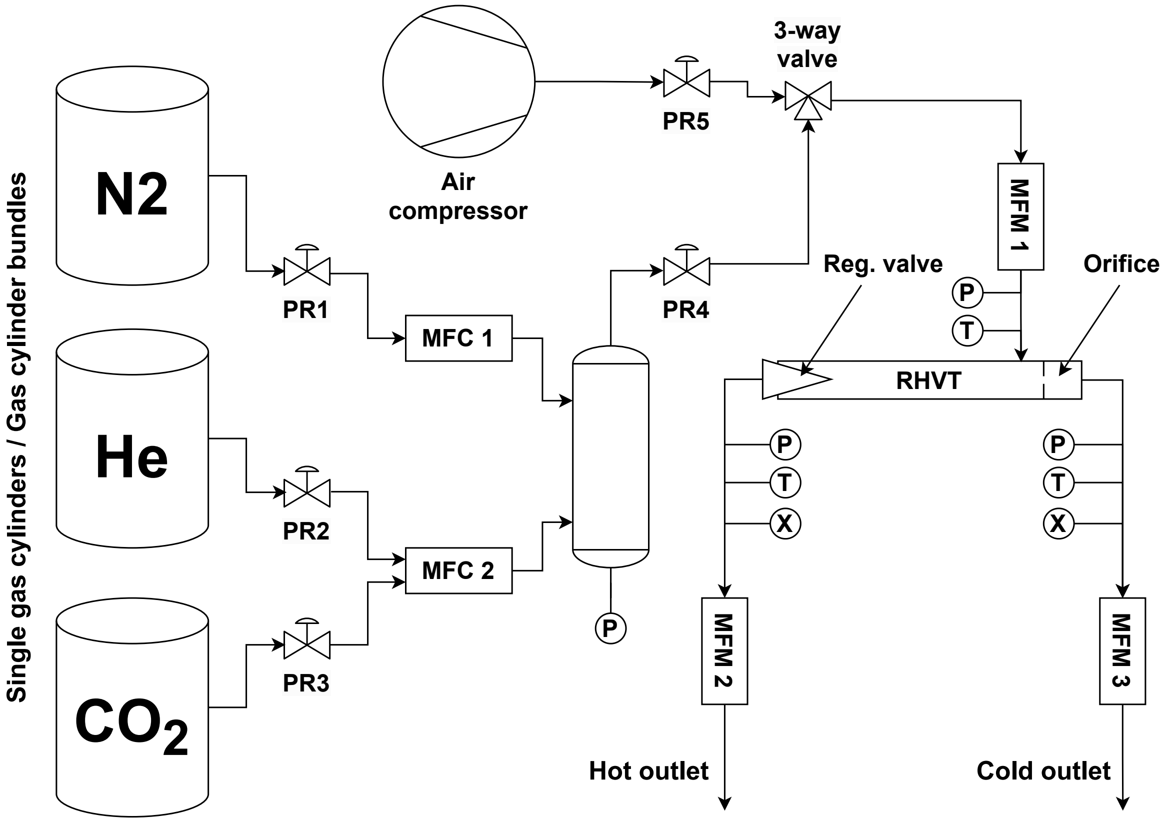

Figure 2: RHVT mass and temperature separation test rig schematic. PR – pressure regulators, MFC/MFM - mass flow controller/meter, P, T, X – measurement of pressure, temperature, concentration.

As shown in Figure 1, the new construction significantly reduces thermal bridging across the tube's body, ensuring that the measured temperature gradients are a direct result of the fluid dynamics and the Ranque-Hilsch effect, rather than the thermal inertia of the device or the test rig.

2.2. Gas mixing unit

To fulfil the project's objective of investigating gas mixtures, the laboratory setup was expanded to include a bespoke gas mixing system. The overall layout is illustrated in Figure 2 and Figure 3.
The upgraded supply section is capable of drawing from three single gas cylinders or three cylinder bundles, each fitted with a dedicated pressure regulator to ensure a stable initial feed. The precise proportioning of the gas mixture is governed by a system of two Mass Flow Controllers (MFCs). These controllers dose the constituent gases into a mixing tank, which provides a uniform blending

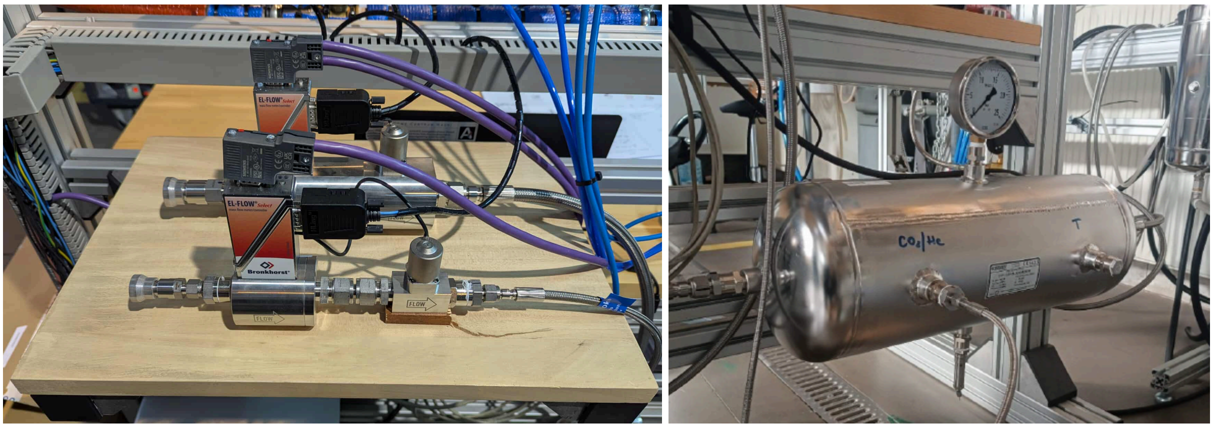

Figure 3: RHVT test rig – mass separation part, mass flow controlers and mixing tank.

Figure 4: The RHVT test rig in the laboratories of SUT (left side) and regulation valve positioning system (right side).

and dampens any pressure pulsations. Subsequently, a pressure reducer located downstream of the tank establishes the exact operating pressure before the mixture enters the vortex tube. To guarantee a high-level leak tightness and maintain the integrity of the gas composition, the entire pneumatic circuit was assembled using robust Swagelok connections.

2.3. Automation and precision control

A major enhancement to the experimental methodology was achieved by the modernisation of the rig's automation system, specifically regarding the control of the hot-end conical valve. Previously, manual valve adjustments made it difficult to reproducibly achieve the same valve opening angle between measurement series, resulting in noticeable measurement errors and inconsistencies between test runs.

To rectify this, the manual control mechanism was replaced with a high-precision stepper motor coupled with a reduction gearbox, depicted in Figure 4. This automated actuator is integrated into the rig's control system, allowing for exact, repeatable positioning of the control cone. This modification has drastically reduced the mechanical hysteresis and human error associated with valve operation, leading to a marked improvement in the overall reliability and accuracy of the experimental data.

2.4. Phase-change investigation

One of the notable potential application areas for the RHVT lies within the refrigeration sector. Thermodynamic models, such as those proposed by Maurer [13] and Keller [14], demonstrate the viability of utilising the RHVT as a replacement for a conventional expansion valve. Implementing the device in this configuration results in an enhancement of the system's Coefficient of Performance (COP). Consequently, a primary objective initially formulated within the ATHLETE project was to adapt the experimental test rig to investigate high-pressure carbon dioxide (CO_2), which is widely anticipated to be a leading natural refrigerant in modern HVAC systems.

However, such an application of CO_2 necessitates highly specific pressure conditions. It is generally postulated that the process requires the CO_2 to be compressed to a range of 130–140 bar, followed by expansion to approximately 30 bar. During this rapid expansion, a phase transition of the CO_2 occurs, and the RHVT facilitates the separation of the liquid phase from the gaseous stream. Unfortunately, owing to financial constraints and inherent technical limitations, specifically, that CO_2 in standard

Table 1: Numerical settings in ANSYS Fluent

Methods				
Gradient	Pressure	Density	Momentum	Energy
Least Squares	Second Order	Second Order	Bounded Central Differencing	Second Order
Controls				
Pressure	Density	Body Forces	Momentum	Energy
0.3	1.0	1.0	0.7	1.0

commercial gas cylinders is stored in a liquid state near the saturation boundary at a pressure of merely 50–60 bar, contingent upon ambient temperature, adapting the main measurement apparatus for these parameters proved unfeasible.

Therefore, the team has decided to launch two alternative experimental campaigns: (1) process visualisation using gases and liquids (completed and published), and (2) process visualisation and investigation using alternative 2-phase media (in progress). Visualisation using liquids yielded an intriguing discovery: the occurrence of cavitation within the vortex tube [12]. This empirical finding, coupled with a comprehensive review of the literature regarding two-phase flows in RHVTs, prompted the project team to conceptualise an alternative research trajectory. It was determined that the phase-change mechanics within the RHVT could be effectively simulated and observed under significantly lower pressure conditions by employing air highly saturated with water vapour.

To realise the 2nd experimental campaign, a separate, dedicated test rig based on the barbotage principle was designed. In this setup, a stream of compressed air is injected below the surface of a water reservoir and subsequently extracted from the headspace above the liquid level. This moisture-saturated air stream is then introduced into the vortex tube, with both the hot and cold outlets equipped with specialised collection systems to capture any condensed water. This auxiliary test rig is currently under construction and represents a collaborative effort between the Faculty of Energy and Environmental Engineering and the Faculty of Automatic Control at the Silesian University of Technology.

3. Numerical investigation

The latest numerical computation are being performed on a new workstation in ANSYS Fluent 2025 R2 with a GPU acceleration. The previously validated model had to be reconstructed as the capabilities of the Fluent on the GPU acceleration are severely limited. It was decided that Large Eddy Simulation (LES) model out of all available models is the most appropriate one as it solves large eddies and is more accurate for the highly turbulent and unstable flow occuring in the vortex tube. The SIMPLE algorithm was chosen for pressure-velocity coupling due to its robustness and computational efficiency. Moreover, the Rhie-Chow distance based interpolation scheme was applied for the flux calculation ensuring stable solution. In light of the project's research plan, which is currently focused on the upcoming series of gas mixture measurements, the numerical studies are one step behind their experimental counterpart. The ongoing computations focuses on the thermal separation of different individual gases such as: helium, nitrogen and carbon dioxide. The mesh was refined as part of a sensitivity analysis of the mesh's impact on the final results, which concluded that a mesh comprising 3 million elements is the optimal choice for obtaining accurate results within a reasonable timeframe. The pressure outlets and mass inlet were set as the boundary conditions based on the experimental data gathered during the last campaign. The computational domain itself was extended to include the locations where physical measurements were taken, with the aim of accurately modelling the fluid flow at the test rig. The main settings used in the ANSYS Fluent are presented in Table 1.

The preliminary computational results with a nitrogen as working agent are showed in Fig. 5. This case addresses similar flow character compared to the air operating RHVT and above all demonstrates an accurate representation of the phenomenon using a computational model running on a new GPU unit with a limited amount of numerical schemes and turbulent models. The nitrogen case shows a

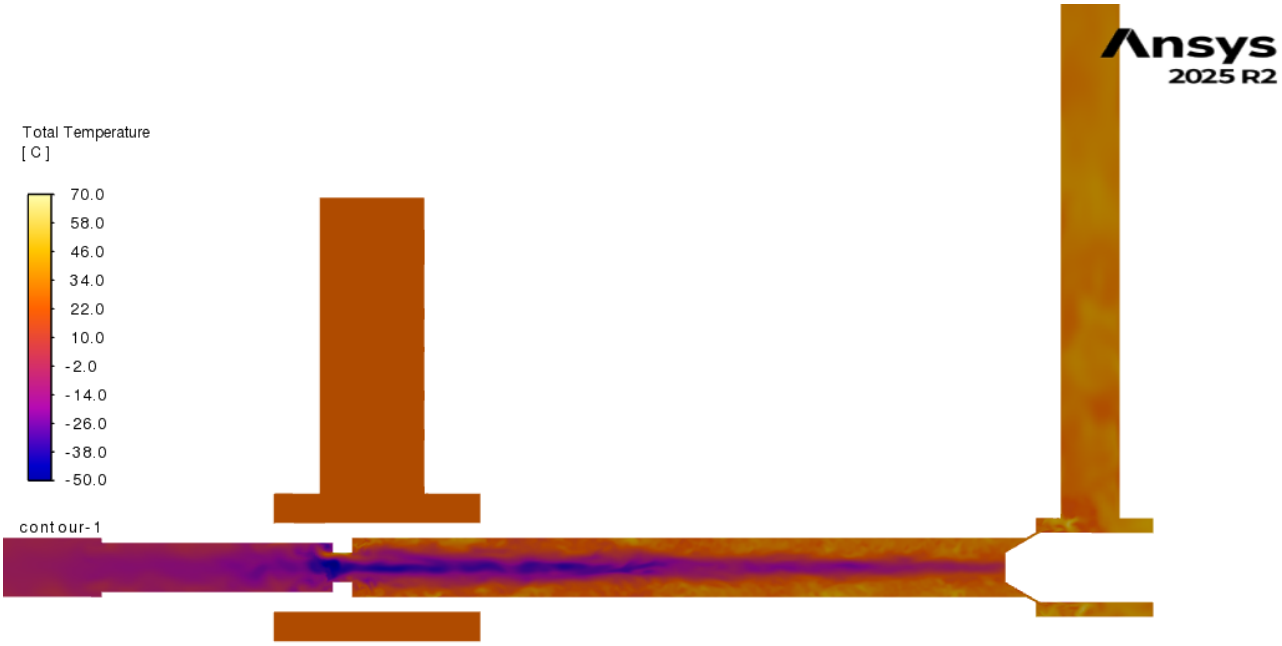

Figure 5: Counter of total temperature for the nitrogen simulation

similar potential of energy separation compared to air. The numerical model was easily validated due to the relatively low cost of nitrogen and the vastly greater computing power of the new workstation. These activities were aimed at ensuring a reliable CFD model during the final stages of the project, during which the mechanism of mixture separation will be investigated.

4. Methodology for gas mixtures and mass separation

The primary objective of this experimental phase is to determine the feasibility and extent of mass separation within the Ranque-Hilsch vortex tube. To observe this phenomenon, the rig has been adapted to handle multi-component gas mixtures under fully automated, continuous flow conditions.

4.1. Working fluids and experimental plan

The experimental matrix focuses on evaluating the separation of species with differing molecular weights. Nitrogen (N_2) serves as the primary carrier gas, into which a controlled fraction of a lighter gas (helium, He) and a heavier gas (carbon dioxide, CO_2) is introduced. The specific volumetric concentrations are established as 90% N_2 with 10% He, and 90% N_2 with 10% CO_2.

To comprehensively assess the stratification mechanisms, the mixtures will be introduced to the vortex tube at six distinct inlet overpressure levels: 2 bar, 2.1 bar, 2.5 bar, 3 bar, 4 bar, and 6 bar. Achieving a steady-state flow condition is paramount; therefore, the duration for each pressure point is designated as either 5 or 10 minutes.

Furthermore, a comprehensive experimental campaign utilising single gases is planned to thoroughly elucidate the influence of individual gas properties on the overall performance of the RHVT. This phase will commence following the successful integration of the high-capacity gas cylinder bundles, thereby establishing a fundamental baseline for subsequent investigations into multi-component gas mixtures.

4.2. Mathematical model and high-capacity gas supply

The requirements for continuous operation necessitated an estimation of the expected mass flow rates to determine the necessary gas supply. Given a strict logistical constraint of a maximum of 16 cylinders per gas type, a mathematical model based on the ideal gas law (a further development of the simplified flow model explained in [10]) was employed. The nozzle outlet pressure was determined iteratively to satisfy the flow equations.

The core of the model determines the mass flow rate $\dot{m}$ through the nozzles:

$$\dot{m} = A\psi\sqrt{\frac{p_1}{RT_1}} \tag{1}$$

where A is the internal cross-sectional area, p_1 and T_1 are the inlet pressure and absolute temperature, and R is the specific gas constant. The flow number ψ is contingent upon the critical pressure ratio β_{crit}:

$$\beta_{crit} = \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa-1}} \tag{2}$$

For subcritical conditions, where the pressure ratio $\beta = p_2/p_1$ exceeds β_{crit}, the flow number is evaluated as:

$$\psi_s = \sqrt{\frac{2\kappa}{\kappa - 1}\left(\beta^{\frac{2}{\kappa}} - \beta^{\frac{\kappa+1}{\kappa}}\right)} \tag{3}$$

where κ represents the adiabatic exponent. Subsequently, the total number of required cylinders is calculated by dividing the total mass of the mixture required for the given test duration by the capacity of a single cylinder.

4.3. Results of the Measurement Plan

The mathematical methodology yielded specific material requirements, confirming the viability of the test matrix. For the mixture of 90% N_2 and 10% He, the calculated mass flow rate ranged from 19.9 kg/h at 2 bar to 60.35 kg/h at 6 bar. Completing the measurements across all six pressure levels theoretically consumes 1.53 cylinders for the 5-minute variant and 3.05 cylinders for the 10-minute variant.

For the mixture of 90% N_2 and 10% CO_2, the mass flow rate varied from 21.25 kg/h at 2 bar to 64.32 kg/h at 6 bar. The 5-minute test sequence requires 1.32 cylinders, whereas the 10-minute sequence requires 2.64 cylinders. These estimations confirm that the planned experimental matrix is well within the 16-cylinder limitation, ensuring that the supply system can sustain the required flow rates without risk of depletion during the steady-state phases.

4.4. Automated flow and concentration measurement

To ensure high accuracy and repeatability, the entire mixing and measurement process is fully automated. The mass flow meters installed in the system feature advanced capabilities, allowing their calibration curves to be dynamically adjusted in real-time according to the specific gas mixture flowing through them. This prevents the measurement drift that typically occurs when using standard air-calibrated flow meters for variable gas blends.

At the outlets of the vortex tube, the composition of the separated streams is continuously monitored using a set of specialised gas sensors. Carbon dioxide concentrations are measured using Non-Dispersive Infrared (NDIR) sensors, while helium concentrations are tracked using Thermal Conductivity Detectors (TCD). This automated, dual-sensor approach guarantees reliable, real-time data logging of the species separation across the entire operational envelope.

5. Preliminary results and discussion

Preliminary measurements were conducted to evaluate the performance of the laboratory test rig. Although the use of individual gas cylinders restricted the maximum fluid flow rates, the results demonstrate the system's functional capabilities and highlight existing technical constraints.

5.1. Separation of the N_2/CO_2 mixture

The initial phase of the experimental campaign encompassed the analysis of a gas mixture comprising 90% nitrogen (N_2) and 10% carbon dioxide (CO_2). According to theoretical postulates, the

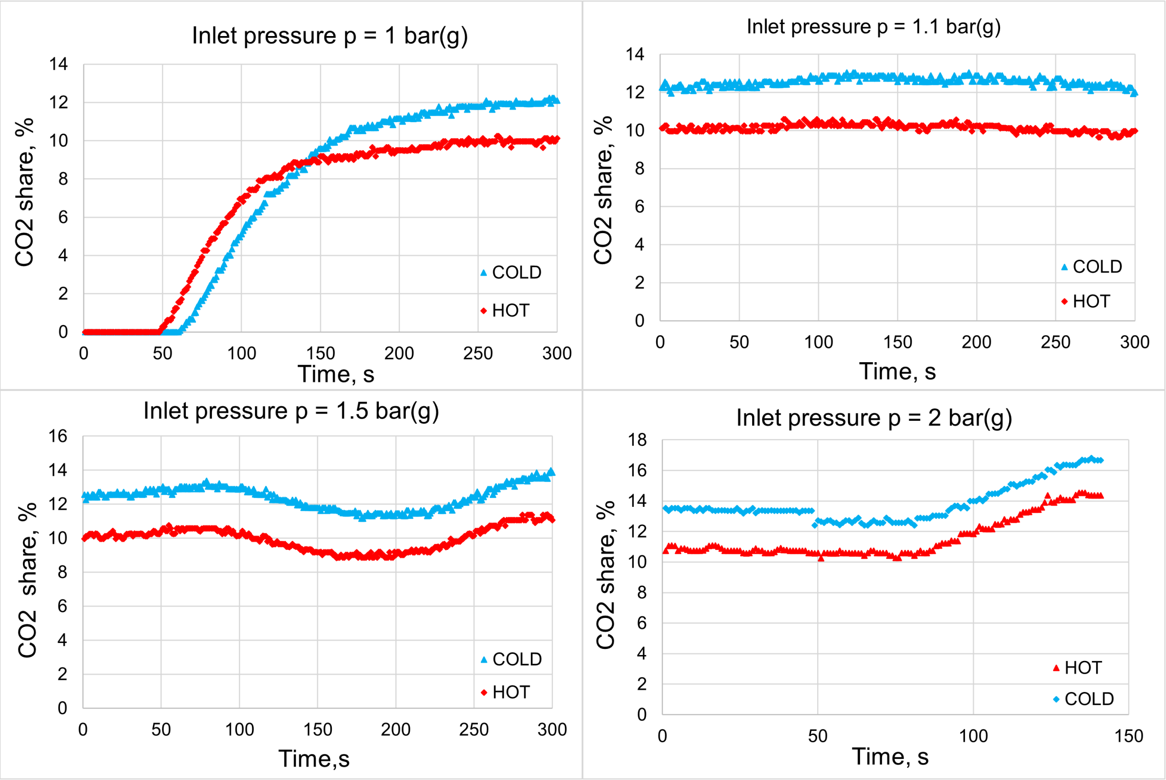

Figure 6: Concentration of CO_2 in the hot and cold outlet streams for a 90% N_2 and 10% CO_2 mixture. The results are inconsistent with the expectations of a higher CO_2 concentration at the hot outlet.

heavier gas should undergo distinct separation, directing itself predominantly towards one of the outlet streams. However, a phenomenon contrary to these expectations was observed; consequently, the separation attempt for this specific mixture was deemed unsuccessful. At an inlet overpressure of 1 bar, the CO_2 concentration settled at 9–10% in the hot stream and 11–12% in the cold stream. Increasing the pressure to 1.1 bar resulted in concentrations of 9.5–10.5% (hot stream) and 12–12.5% (cold stream). The trial conducted at an overpressure of 2 bar was characterised by significant flow instability, with the CO_2 content reaching 14–14.5% and 16–16.5%, respectively. The primary cause for this lack of distinct mass stratification was the relatively small difference in molar masses between carbon dioxide (44.01 g/mol) and the carrier gas, nitrogen (28.01 g/mol).

5.2. Separation of the N_2/He mixture

In contrast to the tests involving carbon dioxide, the experiment utilising a lighter gas (a mixture of 90% N_2 and 10% He) proved successful. A notably higher percentage of helium was observed in the cold stream. Crucially, the difference in helium concentration between the cold and hot streams remained stable at approximately 5–6% and exhibited no sensitivity to variations in the inlet overpressure. At an overpressure of 1 bar, following a complete flow stabilisation, approximately 8% He was measured in the hot stream, whilst the value in the cold stream was approximately 14%. Furthermore, at an overpressure of 1.1 bar, values of 6–7% (hot stream) and 12–13% (cold stream) were recorded. It should be noted, however, that for this specific pressure variant, a full steady state might not have been completely achieved prior to the depletion of the supply mixture. The successful separation of these components stemmed from the vast disproportion in their molar masses, reaching nearly 600% (4.003 g/mol for He compared to 28.01 g/mol for N_2).

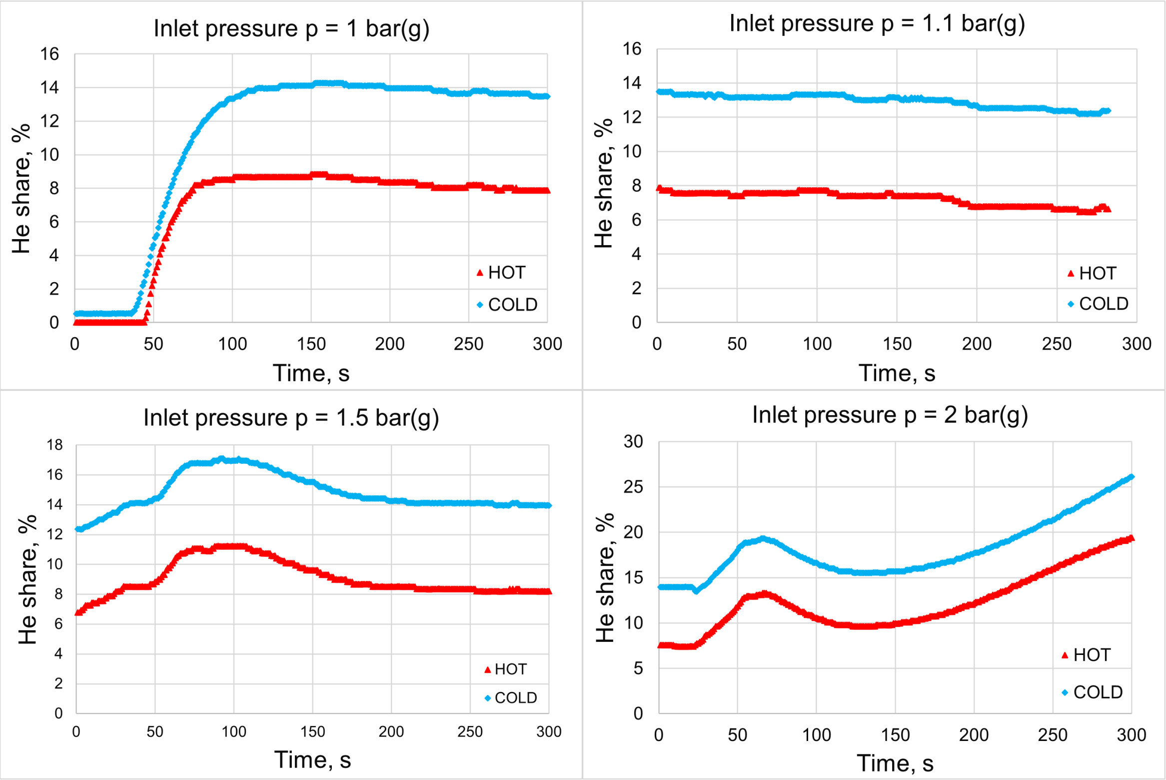

Figure 7: Helium concentration in the hot and cold streams as a function of time for a 90% N_2 and 10% He mixture. The results demonstrate a stable separation efficiency of approximately 5–6% across different inlet overpressures.

5.3. Hardware challenges and measurement uncertainty

During the execution of the measurement campaign, several technical challenges were identified that impacted the experimental procedures. In the initial phase of each test, the gas analyser recorded erroneous fractions of the individual components. This discrepancy originated from the presence of atmospheric air or remnants of the working fluid from previous trials lingering within the mixing tank. Moreover, the limited reserve of gases in the individual cylinders (particularly nitrogen) precluded the long-term maintenance of a stable, high supply pressure, which was particularly noticeable during the trials at 1.5 bar and 2 bar. To rebuild the pressure within the tank, it was necessary to employ interventional methods, such as temporarily closing the inlet valve to the vortex tube. Additionally, the minor fluctuations in mass fractions observed on the recorded characteristics are attributed to the inherent measurement uncertainty of the utilised sensors and analyser systems.

6. Conclusions and outlook

The primary objective for the immediate future of the research project remains the comprehensive investigation of multi-component gas mixtures within the Ranque-Hilsch vortex tube. Having successfully concluded the preliminary experimental phase utilising single gas cylinders, the empirical campaign will now transition to continuous, steady-state operations employing high-capacity cylinder bundles. This operational scale-up will facilitate the execution of the complete experimental matrix detailed in this work, encompassing all designated inlet overpressure variants for both the N_2/He and N_2/CO_2 mixtures.

A critical focus of this forthcoming experimental phase will be to rigorously evaluate whether the mass and species separation mechanisms within the vortex tube align with the hypotheses and phenomenological descriptions currently documented in the scientific literature. By observing the stratification of species with significantly different molar masses under sustained, stable flow conditions, the study aims to provide concrete evidence regarding the driving forces of this separation. Concurrently, the research team will further advance the validation process bridging the empirical experimental data and the numerical Computational Fluid Dynamics (CFD) models. By leveraging the robust, steady-state datasets generated from the upcoming high-capacity trials, the numerical boundary conditions will be strictly calibrated. This iterative validation loop will ultimately enhance the predictive accuracy of the CFD simulations, enabling a much deeper, three-dimensional understanding of the complex fluid dynamic phenomena and species stratification occurring within the device.

Acknowledgments

This research work was possible thanks to the support of the National Science Centre of Poland, which financed the research project NCN-Opus nr 2021/43/B/ST8/03320 (UMO-2021/43/B/ST8/03320) ‘ATHLETE’.

Nomenclature

Latin symbols

A	internal cross-sectional area, m^2
D	inner diameter, m
M_z	molar mass, $\mathrm{kg/kmol}$
$\dot{m}$	mass flow rate, $\mathrm{kg/s}$
m_b	mass capacity of a single gas cylinder, kg
n	number of nozzles
p	pressure, Pa
R	specific gas constant, $\mathrm{J/(kgK)}$
T	absolute temperature, K

Greek symbols

β	pressure ratio
κ	isentropic (adiabatic) exponent
ψ	flow number / nozzle flow coefficient

Subscripts and superscripts

1	inlet conditions
2	outlet conditions
crit	critical state
s	subcritical / isentropic conditions

References

[1] G. Ranque *et al.*, “Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air,” *J. Phys. Radium*, vol. 4, no. 7, pp. 112–114, 1933.

[2] R. Hilsch, “Die expansion von gasen im zentrifugalfeld als kälteprozess,” *Zeitschrift für Naturforschung A*, vol. 1, no. 4, pp. 208–214, 1946.

[3] Y. Xue, M. Arjomandi, and R. Kelso, “A critical review of temperature separation in a vortex tube,” *Experimental Thermal and Fluid Science*, vol. 34, no. 8, pp. 1367–1374, 2010.

[4] M. Kurosaka, “Acoustic streaming in swirling flow and the ranque—hilsch (vortex-tube) effect,” *Journal of Fluid Mechanics*, vol. 124, pp. 139–172, 1982.

[5] K. Stephan, S. Lin, M. Durst, F. Huang, and D. Seher, “An investigation of energy separation in a vortex tube,” *International Journal of Heat and Mass Transfer*, vol. 26, no. 3, pp. 341–348,

1983.

[6] D. Webster, “An analysis of the hilsch vortex tube,” *Refrigerating engineering*, vol. 58, no. 2, p. 163, 1950.

[7] D. Majidi, H. Alighardashi, and F. Farhadi, “Lpg mass separation by vortex tube cascade and its economics,” *Applied Thermal Engineering*, vol. 148, pp. 1139–1147, 2019.

[8] J. Yun, Y. Kim, and S. Yu, “Feasibility study of carbon dioxide separation from gas mixture by vortex tube,” *International Journal of Heat and Mass Transfer*, vol. 126, pp. 353–361, 2018.

[9] K. Christensen, M. Heiredal, M. Kauffeld, and P. Schneider, “Energy savings in refrigeration by means of a new expansion device. report of energy research programme,” *Journal*, no. 1223/99, p. 0006, 2001.

[10] W. Kostowski, P. Bargiel, M. Barzantny, D. Adamecki, M. Majchrzyk, B. Mendecka, and E. Maciak, “Experimental setup design for multi-purpose Ranque-Hilsch vortex tube investigation,” in *36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023)*, pp. 781–791, Curran Associates, Inc., 2023.

[11] M. Barzantny, M. H. Hamede, S. Merbold, C. Egbers, M. Majchrzyk, and W. Kostowski, “The ranque hilsch phenomenon: Experimental visualization of the flow structure,” in *Proceedings of the German Association for Laser Anemometry (GALA e.V.)*, (Karlsruhe, Germany), GALA e.V., 2024.

[12] M. Barzantny, M. H. Hamede, M. Majchrzyk, S. Merbold, C. Egbers, and W. Kostowski, “Experimental investigation of the flow characteristics driving the ranque–hilsch phenomenon,” *International Journal of Heat and Mass Transfer*, vol. 253, p. 127543, 2025.

[13] T. Maurer, “Patent de 197 48 083 a1,” *Entspannungseinrichtung*, 1999.

[14] J. Keller and M. Göbel, “Die thermodrossel: eine anlage zur entspannung komprimierter flüssigkeiten unter wärmeabgabe,” *KI. Luft-und Kältetechnik*, vol. 33, no. 2, pp. 57–60, 1997.