PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Experimental setup design for multi-purpose Ranque-Hilsch vortex tube investigation

Wojciech Kostowski[a], Paweł Bargiel[b] , Marcel Barzantny[c], Daniel Adamecki[d] , Michał Majchrzyk[e], Barbara Mendecka[f], and Erwin Maciak[g]

[a] *Silesian University of Technology, Gliwice, Poland, wojciech.kostowski@polsl.pl , CA*
[b] *MESco sp. z o.o., Bytom, Poland, pbargiel@mesco.com.pl*
[c] *Silesian University of Technology, Gliwice, Poland, marcbar945@student.polsl.pl*
[d] *Silesian University of Technology, Gliwice, Poland, daniel.adamecki@polsl.pl*
[e] *Silesian University of Technology, Gliwice, Poland, michal.majchrzyk@polsl.pl*
[f] *Niccolò Cusano University, Rome, Italy, barbara.mendecka@unicusano.it*
[g] *Silesian University of Technology, Gliwice, Poland, erwin.maciak@polsl.pl*

Abstract:

The paper presents design considerations for experimental investigation of the Ranque-Hilsch vortex tube effect (VT). The research aims to find physical mechanisms governing the thermal and mass separation of non-homogenous gases entering the VT. Also, an approach to study phase-change phenomena inside the VT will be undertaken to evaluate the applicability of the VT in refrigeration systems. For this purpose, it is essential to have a mutually validated experimental setup and numerical model.

The 1st generation test rig was based on a VT of 36 mm inner diameter and up to 1.62 m length. With inlet air supply at 3 bar abs, it was possible to achieve outlet temperature values from 0.1 C at the cold side to 42.3 C at the hot side, and the maximum air flow was 123 kg/h.

The 2nd generation should be reduced in size for two reasons. First, lighter and heavier gases (helium, carbon dioxide) will be supplied from pressurized cylinders and mixed with air or nitrogen. The flow rate should be minimized to enable a continuous operation from the pressurized cylinders. Second, to apply higher inlet pressure, it is required to reduce the flow channels to maintain the gas flow below the technical limit of about 60...100 kg/h.

The proposed test rig configuration is based on two supply options. In the first option, pure gases can be supplied from batteries (bundles) of pressurized cylinders, and then mixed to achieve the desired composition. The second option can be obtained by connecting the test installation to an air compressor, which is more suitable for test operation or for multiple-parameter measurements required to obtain boundary conditions for numerical modelling. Moreover, the test rig will be extended to include a multi-phase flow unit with a liquid dosing and separation equipment.

Keywords:

Ranque-Hilsch effect; Vortex Tube; Measurements; Gas flow; Mass separation.

1. Introduction

Ranque-Hilsch vortex tubes (RHVTs) is a device that allows separation of a pressurized and highly turbulent inlet stream into two distinct outlet streams of lower pressure and varying temperatures. Temperature and mass separation effects are unique and potentially useful phenomena occurring in RHVTs. The effect was discovered by Ranque [1] and then investigated by Hilsch [2], which is commemorated by the scientific community by the use of these surnames to denote both the effect and the device.

The effect of the inlet pressure on the temperature difference was observed and studied by Martynovskii and Alekseev. They observed that the temperature difference increases with the inlet flow pressure [3]. According to Crocker et al. [4], temperature increase at the hot side can be as high as 120 K. On the other hand, the temperature drop on the cold side is said to be up to 50 K with respect to the inlet temperature [5].

Significant number of papers has been published on temperature separation in RHTVs, contributing to our understanding of temperature separation phenomena occurring in vortex tubes (VTs). The current state of knowledge aimed to explain the phenomena occurring in VTs was presented by Xue et al. [6]. It was confirmed that when studying temperature separation in a RHTV, various factors such as pressure gradient, viscosity, secondary flow structure in the tube [7], and acoustic flow [8] should be considered. Furthermore, none of the above factors proved to be the real reason for the energy separation in his RHVT due to the complexity of the

 https://doi.org/10.52202/069564-0071

flow structure in the pipe. The various and sometimes conflicting conclusions of the investigation suggested the need for deeper and more thorough experimental and theoretical research work to better understand the complex processes inside the tube.

Regarding the mass separation phenomena in RHTVs, the reduced number of publications, with respect to the temperature separation can be found in literature. Most of studies focused on the VT application using compressed air. However, hydrocarbon processing (such as natural gas) is an example where knowledge of gas species distribution is important to keep dew point and hydrate formation conditions under control [9–11]. Practical applications for LPG processing have recently been reported by Majidi et al. [12]. Several experimental studies have been carried out by various investigators to investigate the potential for gas species separation in Ranque-Hilsch counter-flow vortex tubes. As one example, Yun et al. [13] performed an industry-oriented experimental study for CO2 separation from its mixture with air, observing the importance of the inlet pressure and the cold mass fraction. However, no qualitative conclusions leading to the explanation of the physical mechanisms were given.

The availability of such decoupling mechanisms presents a valid opportunity to integrate RHVT into various design systems to improve overall system efficiency. The potential areas of application are very wide and include, for example, improving the performance of refrigeration circuits [14, 15] or separating gas network zones with different hydrogen contents. Although a wide range of applications for RHVT can be presented [16-18], the mechanism of temperature and mass separation still lacks a fundamental scientific explanation [19, 20] as well as proper design of RHVT as a functional part of the system.

The current paper presents the initial part of a new research project, dedicated to the understanding and to possible applications of the highly interesting and still not fully explained Ranque-Hilsch phenomenon.

1.1. The ATHLETE project

The aim of the project is to carry out fundamental experimental and numerical research to improve the understanding of the Ranque-Hilsch phenomenon in a vortex tube (VT), comprising the thermal, mass and phase separation, and to demonstrate the potential of applicability in the most promising engineering areas of refrigeration and gas separation.

The project contains experimental and numerical research, and investigation on gas mixtures will be preceded by a fundamental research on pure compounds. The project will be concluded by a thermodynamic study of RHVT-based systems.

The main questions to be answered are:

1. does the difference in gas density cause a systematic mass stratification?
2. can the stratification mechanisms be confirmed by numerical modelling and flow visualization?
3. can the stratification mechanisms contribute to the performance of selected energy/process systems?

The specific project objectives comprise: O1: to build a functional CFD model of RHVT validated by experiments, O2: to elaborate a 0D (functional) representation of RHVT, O3: to demonstrate the benefits of integrating an optimized RHVT into energy systems using two specific case studies. Accordingly, five work packages (WPs) are proposed. Work packages WP1 and WP3 are related with experimental research for pure fluids and gas mixtures, respectively. Similarly, packages 2 and 4 aim to mirror the experimental results using a numerical model, which is supposed to provide a more detailed information on the flow structure. WP5 is aimed at a demonstration of benefits of the RHVT in two selected technical systems:

1.R744 (CO2)-based refrigeration cycle with an integrated RHVT;

2. Pressure let-down station for hydrogen rich natural gas, equipped with RHVT for separation of network zones of different hydrogen content.

1.2. Aim and novelty of work

The aim of this paper is to present the project development starting from the previous work of two team members, and then to explain the design of the experimental test rig which will be used to carry out the WP1 and WP3. Moreover, some technical issues influencing the experimental set-up and some modifications in the assumed plan of experiments are presented.

The novelty of work is related to the investigation of mass separation in the vortex tube, carried out within the ongoing ATHLETE project. Moreover, a detailed presentation of the test rig design, along with scale evaluation based on gas dynamics equation and preliminary measurements represents an original contribution as well.

2. First generation test installation

2.1. Installation layout and measurement methodology

The first generation test rig was built in the Laboratory of High Temperature Processes at the Silesian University of Technology. It was partially adapted from the previous test installation for the natural gas industry,

https://doi.org/10.52202/069564-0071

therefore, one flow measurement unit was composed of a distribution-type turbine flow meter Elster G65 with an integrated RTD Pt100 temperature sensor and an electronic volume corrector with built-in pressure transducer (0...600 kPa). A scheme and a photograph of the installation is presented in Fig. 1.

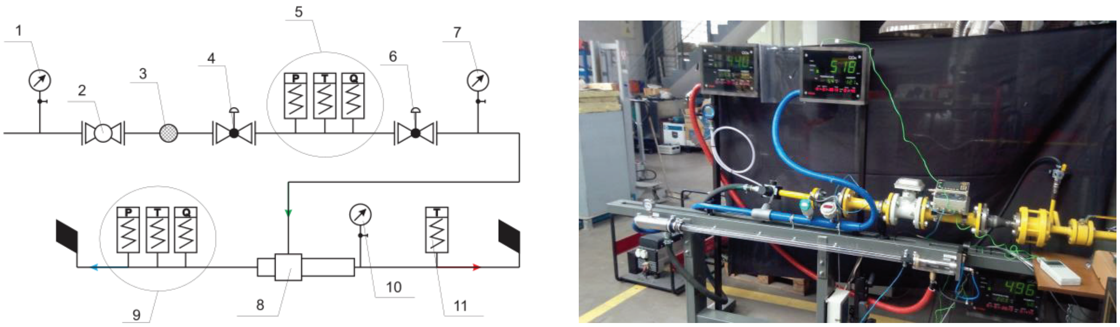


Figure 1. *Experimental setup of the 1st generation installation. 1, 7, 10: Manometers, 2. Inlet valve, 3. Filter, 4. Pressure regulator, 5, 9 Pressure, temperature and volumetric flow measurement, 6. Fine pressure regulator, 8. Vortex tube, 11: Temperature measurement.*

The vortex tube was designed by the team member Paweł Bargiel and manufactured by an external company. The main purpose of the designed experimental rig was to use it for the validation of the numerical approach, based on which the original analytical description of the VT was proposed.

The inner VT diameter was 36.0 mm. The construction was based on a set of 2 identical nozzles tangentially located to the core part of the tube. Each nozzle had a dimension of 4.4 × 7.2 (channel height × channel width) and they were positioned in parallel. The set of nozzles was integrated with an orifice of a constant diameter equal to 13 mm.

The main set of measurements was performed for the maximum inlet pressure possible to maintain at the vortex tube inlet, i.e. about 360 kPa abs. It was found that lower values of inlet pressure decreased the thermal effect. For the maximum pressure, two key variables were modified:

a) The Length/Diameter ratio L/D, ranging from 15 to 45. This parameter was modified by replacing the core part of the tube.
b) The cold mass fraction (CMF), ranging approx. from 0 to 0.9. This value, representing the ratio of the mass flow rate at the cold outlet to the total inlet flow, was modified by adjusting the conical valve located at the 'hot' outlet of the VT.

2.2. Selected results

Fig. 2 Presents the total (inlet) mass flow rate of air flowing into the vortex tube in terms of the length/diameter ratio and in terms of the cold mass fraction.

https://doi.org/10.52202/069564-0071

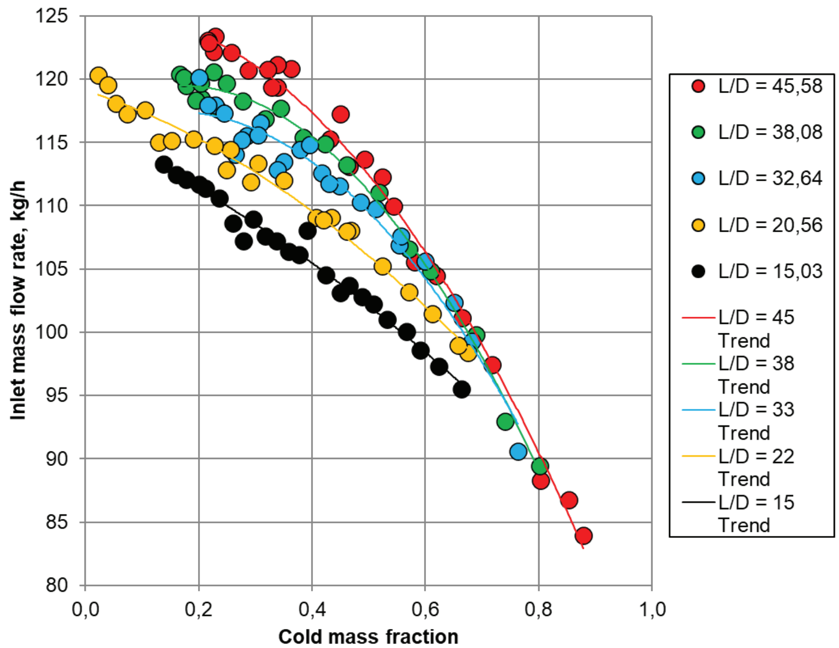


***Figure 2**. Total (inlet) mass flow rate of air through the vortex tube, inner diameter 36.0 mm; average inlet parameters: 363.5 kPa, 24.0°C.*

It can be seen that for the investigated design of the vortex tube, the total mass flow rate decreases with the cold mass fraction. However, from the point of view of the ATHLETE project, to properly design the new test installation it is essential to register the scale of the mass flow rate. In this case, inlet pressure of approx. 3.6 bar abs generates a flow exceeding 100 kg/h.

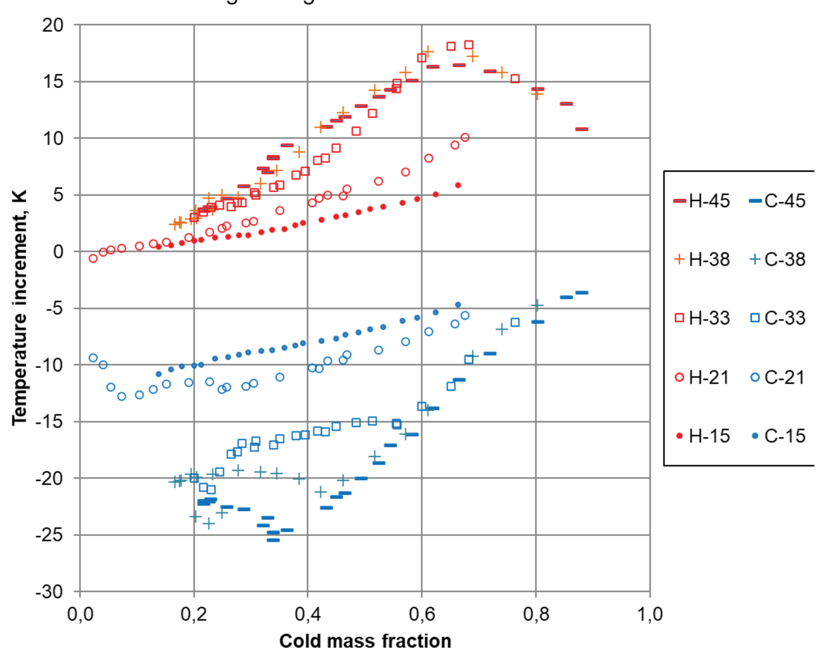


***Figure 3**. Thermal separation obtained in the 1st generation test rig with compressed air in terms of the Length/Diameter L/D ratio. Exact L/D values are given in Fig. 2. Pipe diameter (inner): 36 mm.*

Figure 3 presents the thermal performance of the studied vortex tube in terms of the length/diameter ratio. It can be observed that the increased L/D ratio improves the Ranque-Hilsch effect, however, there is no strict regularity for L/D > 33. Also, one cannot define a specific cold mass fraction corresponding to the maximum R-H effect. Maximum temperature drop at the cold outlet occurs for CMF = 0.3...0.4, while the maximum increment at the hot outlet corresponds to CMF = 0.6...0.7. For shorter vortex tubes (L/D = 15 and 21) no function maxima can be identified. Compared to similar reported studies [21], the function dependency for the hot outlet temperature in terms of the CMF is similar; different results are obtained for the cold outlet temperature. Here, a minimum value is obtained for most L/D ratios at CMF below 0.4, while Behera et al. [21] failed to obtain a minimum value as they only considered CMF ranging from 0.4 to 1.

Some more results of this work, including the numerical modelling, are shown by Bargiel et al. [22].

3. Second generation test installation

The first generation installation (related with a PhD programme) was designed to study the vortex tube operation using compressed air. To develop the idea according to the ATHLETE project assumptions, it is required to increase the scope of measurements which can be carried out at the experimental test rig. The most important modification is the adaptation to operation with compressed gases from gas cylinders, which in turn entails the reduction of the vortex tube size.

3.1. Preliminary assumptions

The initial concept of the ATHLETE research installation was based on the research questions formulated in the project application. The proposed scheme of the test rig is presented in Fig. 4.

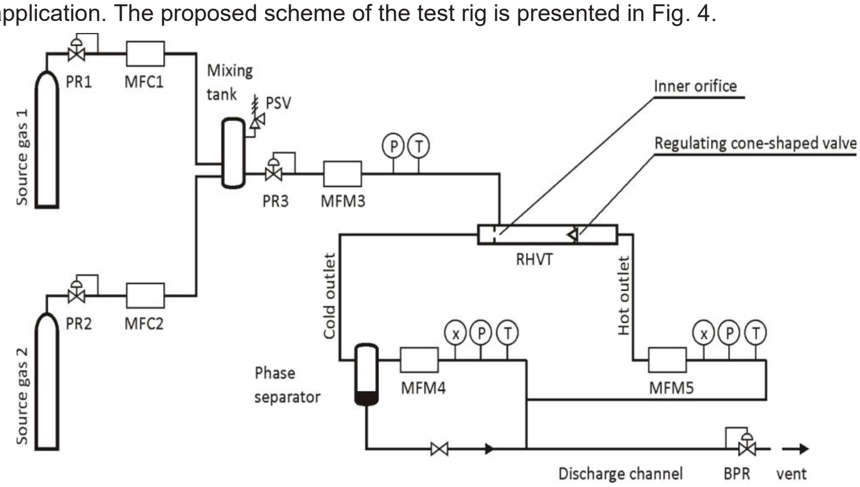


***Figure 4**. The initial concept of the ATHLETE project experimental set-up. {B]PR – [back] pressure regulators, MFC/MFM - mass flow controller/meter, p, T, x – measurement of pressure, temperature, concentration, PSV – pressure safety valve.*

In this configuration, it is possible to mix two source gases by means of two mass flow controllers supplying a specific quantity of gas to a mixing tank. Next, pressurized medium is supplied to the vortex tube, and its pressure is precisely adjusted in the regulator PR3. The discharge side of the VT is pressurized, its pressure is controlled by a back pressure regulator. This enables operation with carbon dioxide decompressed from supercritical conditions of approx. 140 bar to a back pressure of approx. 40 bar. Liquid phase of CO_2 is collected in a phase separator. The objective of this set-up is to investigate the mechanism of phase separation in the vortex tube.

3.2. Simplified flow model and preparatory measurements

To evaluate the mass flow rate of a compressed gas flowing through a vortex tube of given dimensions, it was proposed to combine a simple analytical approach with some preparatory measurements.

Within the analytical approach, the flow through a vortex tube was approximated by a flow through a set of two consecutive nozzles (Fig. 5):

 https://doi.org/10.52202/069564-0071

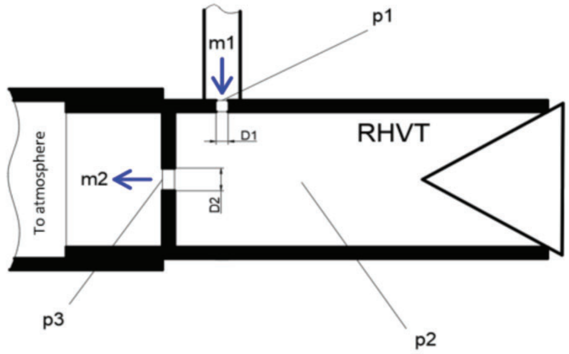


***Figure 5**. Simplified flow model for the estimation of the RHVT mass flow rate*

For the purpose of scale determination, it can be assumed that the hot outlet is completely closed. Results from the 1st generation installation show that, despite the increment in the total outlet cross section, opening the cone-shaped outlet valve does not cause any increment of the total inlet flow[1]. Accordingly, in the simplified model, mass flow rate through the inlet nozzles equals the flow rate through the orifice, provided that steady state is achieved.

For each nozzle, the outet-to-inlet pressure ratio $p_{\mathrm{out}}/p_{\mathrm{in}}$, henceforth denoted by β, generates a mass flow rate $\dot{m}$, which can be calculated as:

$$\dot{m} = C_D A \psi_s \sqrt{\frac{p_{\mathrm{in}}}{R T_{\mathrm{in}}}} \tag{1}$$

where C_D is the discharge coefficient (ideal nozzle = 1), A is the cross section area, R is the gas constant, and p_{in} , T_{in} are total (stagnation) inlet parameters. The flow coefficient ψ_s depends on the pressure ratio β, and it also determines the flow condition at the nozzle exit section (subsonic/sonic):

$$\psi_s = \begin{cases} \sqrt{\frac{2\kappa}{\kappa - 1}\left(\beta^{\frac{2}{\kappa}} - \beta^{\frac{\kappa+1}{\kappa}}\right)}, & \text{if } \beta > \beta_{\mathrm{crit}} \\ \sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}}\quad, & \text{if } \beta \leq \beta_{\mathrm{crit}} \end{cases} \tag{2}$$

The critical value of the pressure ratio for the ideal gas model is:

$$\beta_{\mathrm{crit}} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \tag{3}$$

This value ranges 0.48 to 0.54 depending on the isentropic exponent κ. Accordingly, if the nozzle inlet pressure is approx. 2 times higher than the outlet pressure, sonic flow is achieved. The derivation of ideal and real gas nozzle equations was presented i.a. by Rist [23].

In the studied case, two nozzles are connected in series. The first nozzle has p_1 as inlet, and the unknown value of p_2 as outlet pressure. The second nozzle has p_2 as inlet, $p_3 \cong p_{\mathrm{atmosphere}}$ as outlet pressure. The model has a set of simplifications:

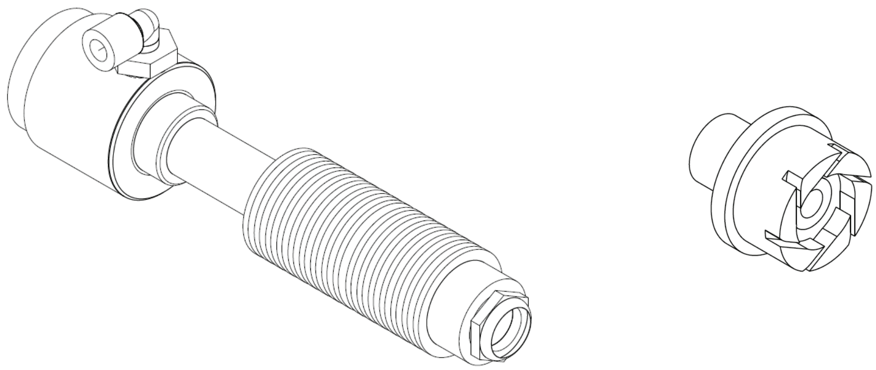
- Ideal gas model is used (acceptable for p < 4 bar);
- Stagnation parameters are approximated by static parameters;
- Outlet pressure is approximated by atmospheric pressure;
- The impact of the orifice geometry on the critical pressure value is neglected.

All these simplifications are attributed to the discharge coefficient C_D (which now includes flow contraction, the velocity coefficient and the above listed assumptions).

[1] This is an interesting paradox still to be investigated.

By setting the requirement of flow continuity $\dot{m}_{1-2} = \dot{m}_{2-3}$, the unknown internal pressure p_2 and the equalized flow rate $\dot{m}$ can be found within a simple numerical procedure.

The theoretically obtained value of the flow rate has been compared with the measured values for a commercially available small-scale vortex tube (Fig. 6). This VT is equipped with a suction chamber and a set of 6 identical nozzles. Each nozzle has a dimension of 0.9 × 3.1 mm (channel width × channel depth along the main VT axis). The set of nozzles is integrated with a divergent orifice with the smallest diameter of 4.7 mm.



a) b)

Figure 6*. a) A commercially available small-scale vortex tube used for system downscaling b) Set of nozzles in the commercially available vortex tube*

The commercially available small-scale vortex tube has been installed in the 1st generation test rig, however, due to the different scale of the object, only the inlet mass flow rate was measured. The objective of measurements was to define the range of mass flow rate which is critical for the selection of all process equipment, in particular the most expensive elements (flow meters, mass flow controllers and pressure regulators).

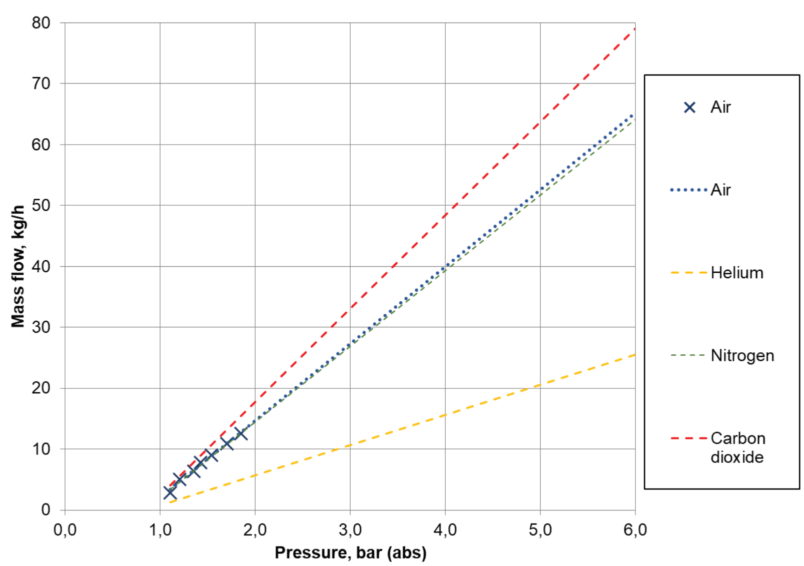


Figure *7. System scale evaluation based on air flow under variable inlet pressure. Points represent the measured values. Dashed lines represent an extrapolation to higher pressure values and a flow estimation for other gases using the calibrated analytical model.*

The measured values have been compared with the simple analytical model (Eq. (1)-(3)). Assuming that the discharge coefficient for the inlet nozzles is 0.98, the discharge coefficient for the orifice 0.854 provides the

 https://doi.org/10.52202/069564-0071

equality of the measured value and the calculated value. Accordingly, the simplified model is calibrated enough to be useful for the prediction of the flow range and the selection of process equipment. Values for other gases and for higher pressure have been calculated from the model, and the results are depicted in Fig. 7.

It can be concluded that if the designed vortex tube is kept at a similar scale, the range of flow 0...100 kg/s should be sufficient to analyze the flow of all technical gases foreseen in the project. Moreover, it was decided that heavier and lighter gases will be supplied at a maximum mass fraction of 10%, which should be sufficient to observe their possible stratification in the vortex tube.

3.3. Technical questions for the 2nd generation test installation

The conceptual design of the installation, depicted in Fig. 4, does not reveal technical details related to flow parameters. The selection of equipment and the estimation of the project budget was based on a single round of commercial requests which were sent to manufacturers of metering equipment, pressure regulators and tanks and to the suppliers of pressurized gases.

Within the first part of the project, a detailed, second round of commercial request was launched, followed by a series of meetings. In this way, the general idea was subject to verification with market reality, additionally suffering from consecutive global events, but most importantly, it was confronted with technical details. Several major conclusions could be drawn from this work are:

1. It is currently not possible to supply supercritical carbon dioxide from gas cylinders. Theoretically, the pressure of any gas in a cylinder can reach 300 bar or more, however, major suppliers of technical gases limit their offer here to a 2-phase fluid, with the saturation pressure resulting from ambient temperature (e.g. 57.3 bar @20°C);
2. Creating a closed-loop CO_2 system is technically possible, but it exceeds the budget of the current project. Also, there is no sufficient knowledge on how the vortex tube would operate and which part of the agent would condense. Accordingly, this idea represents an interesting field of future research.
3. It is essential to keep the topic of phase change inside the vortex tube within the scope of the project. To investigate a two-phase flow, an alternative strategy is required.
4. It was proposed to investigate the two-phase flow by dosing some liquid (e.g. water or ethyl alcohol) to the saturation level at the VT inlet, and then by measuring the liquefied quantity at VT outlet(s). A corresponding experimental installation is currently under design.
5. Using carbon dioxide as a heavy gas component is still possible and it enables to evaluate species separation (e.g. CO_2 from N_2). However, the CO_2 flow rate is technically limited by the evaporation rate in a gas cylinder, which is about 1 Nm^3/h. To ensure higher flow of CO2, a bundle of cylinders is needed.

The design of the experimental installation is presented in the subsequent section. The section of humidification and liquid separation is not included at this stage.

3.4. Current design of the installation

The key elements of the proposed installation are shown in Fig. 8.

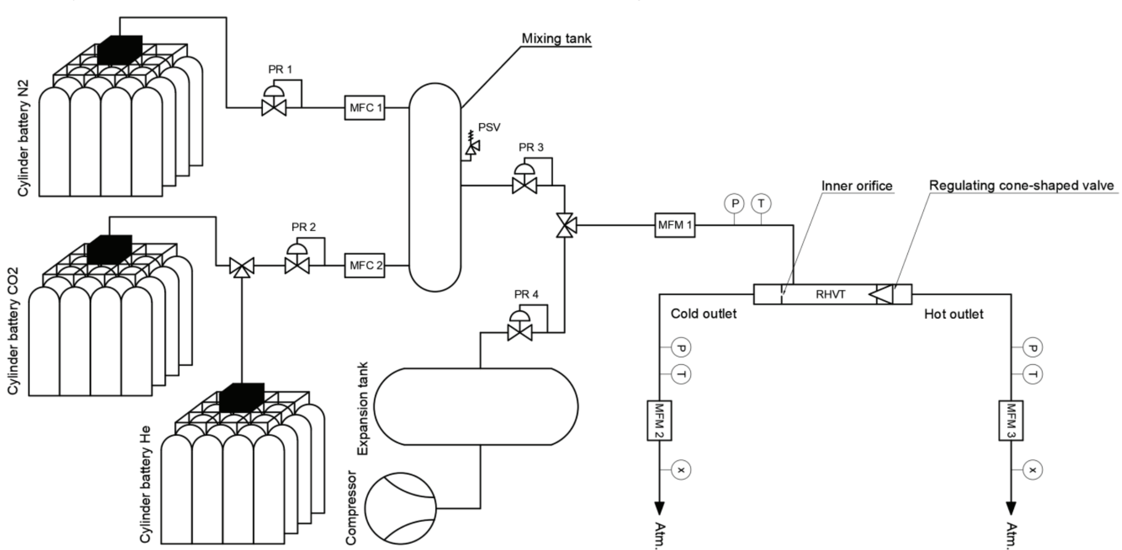


Figure 8. *The proposed test rig configuration for WP1 and WP3 measurements. Symbols are the same as in Fig. 4.*

The research installation is adapted to the supply of various gases. The first supply path leads from cylinder batteries (bundles), whereas the basic gas is nitrogen, obtain from a battery of 16 cylinders. Nitrogen can be mixed either with carbon dioxide CO_2 (a heavier gas CO2), or helium He (a lighter gas). Pressure of gases leaving the tank batteries is regulated by regulators PR1 and PR2. Next, a precisely determined mass of each gas is supplied to a mixing tank via mass flow controllers MFC1 and MFC2. The tank is protected by a pressure safety valve PSV. Currently, tank pressure of 16 bar is considered.

Next, the mixed gas leaves the tank and its pressure is adjusted again by a regulator PR3. The gas mixture passes through the mass flow meter MFM1. Here, a thermal flow meter with adjustable gas composition was selected. Once the gas pressure and temperature are measured, it enters the vortex tube and then leaves it through the hot and the cold outlet. Then, thermal parameters and mass flow rates are measured again by the same type of equipment. Finally, gas composition is measured at both ends. A dedicated gas composition measurement system will be developed based on commercially available calibrated gas sensors.

Another path for supplying the pressurised gas is obtained if an air compressor is used. In this case, compressed air passes through a tank and a local installation (this part of equipment was used in the 1st generation research). A newly adapted regulator PR4 will be installed for the reduced flow rate and increased pressure, compared with the 1st generation set-up.

The compressed air supply line is essential for multiple-parameter testing, where the use of pure gases is too expensive. Experimental results obtained with compressed air will be supplied as boundary conditions to multi-scenario numerical modelling. Only a reduced set of parameters obtained from the numerical modelling will be used for experimental work with pure gases.

https://doi.org/10.52202/069564-0071

4. Conclusions and further work

Results obtained from the 1st generation experimental set-up have been used to evaluate the scale of the system for the 2nd generation. In general, it is possible to maintain the previous maximum range of the mass flow rate at 100 kg/h maximum, however, the reduction of the vortex tube size enables the project team to work with higher supply pressures, reaching 6-10 bar depending on the final scale of the vortex tube.

The first stage of the project related with the detailed technical design of the experimental test installation revealed a series of problems, mostly related with the availability of pressurized carbon dioxide. To keep the desired flow capacity, it was decided to use bundles (batteries) of cylinders with pressurized gases instead of a single container, and to apply pressure regulators of higher capacity than that of standard cylinder regulators.

The current work within the project is performed in parallel in three areas:

1. Construction of an own vortex tube and its numerical model (twin); the construction is kept as simple as possible to enable an exact representation within the numerical model;
2. Completion of the experimental test rig, some elements (flow meters, temperature and pressure sensors, regulator PR4) have been purchased, other elements (mass flow controllers, pressure regulators PR1-PR3, tank) are at the selection stage and will be purchased in the upcoming weeks;
3. Design of the liquid phase dosing and separation system: this part of project is being carried out with a wider engagement of students within a dedicated Project-Based-Learning scheme, within a small grant obtained from the University.

Future work comprises advanced multi-scenario numerical modelling and optimization of the vortex tube, as well as elaboration of the gas composition measurement system and at attempt to flow visualisation.

The project team expects to obtain interesting and novel results, in particular in the topic of mass and phase separation, which is scarcely reported in subject literature.

Acknowledgments

This work was funded by the National Centre of Science, Poland (*Narodowe Centrum Nauki*) within the ATHLETE project entitled *Investigation of mass, thermal and phase separation in the Ranque Hilsch Vortex Tube: from fundamentals to technological concepts in energy and process engineering*, Grant No. UMO-2021/43/B/ST8/03320 which is carried out in co-operation of the Silesian University of Technology, Poland with Niccolò Cusano University, Italy).

Nomenclature

A area, m^2

C_D discharge coefficient

$\dot{m}$ mass flow rate, kg/s

p pressure, Pa

R gas constant, J/(kg K)

T temperature, K

Greek symbols

β pressure ratio

κ isentropic exponent

ψ_s nozzle flow coefficient

Subscripts

$()_{crit}$ critical

$()_{D}$ discharge

$()_{in}$ inlet

$()_{out}$ outlet

$()_{s}$ isentropic

References

[1] G. Ranque Experiences sur la détente giratoire avec productions simultanées d'un échappement d'air chaud et d'un échappement d'air froid J. Phys 8 (1933): 112-114.

[2] R. Hilsch The use of the expansion of gases in a centrifugal field as cooling process Review of Scientific Instruments 18.2 (1947): 108-113.

[3] V. S. Martynovskii and V. P. Alekseev Investigation of the vortex thermal separation effect for gases and vapors Soviet Physics-Technical Physics 1.10 (1956): 2233-2243.

[4] A. M. Crocker, S. M. White and F. Bremer Jr. Experimental results of a vortex tube air separator for advanced space transportation AIAA 4451 (2003): 20-23.

[5] B. K. Ahlborn and J. M. Gordon The vortex tube as a classic thermodynamic refrigeration cycle Journal of applied physics 88.6 (2000): 3645-3653

[6] Y. Xue et al. A critical review of temperature separation in a vortex tube Experimental Thermal and Fluid Science 34.8 (2010): 1367-1374

[7] Ahlborn, B., and Groves, S., 1997. "Secondary flow in a vortex tube". Fluid Dynamics Research, 21(2), p. 73

[8] Kurosaka, M., 1982. "Acoustic streaming in swirling flow and the Ranque-Hilsch (vortex-tube) effect". Journal of Fluid Mechanics, 124, pp. 139–172

[9] A. D. Gutak Experimental investigation and industrial application of Ranque-Hilsch vortex tube International Journal of Refrigeration 49 (2015): 93-98

[10] N. V. Poshernev and I. L. Khodorkov. Natural-gas tests on a conical vortex tube (CVT) with external cooling Chemical and Petroleum Engineering 40.3 (2004): 212-217

[11] V.L. Bondarenko, Y. M. Simonenko, and D. P. Tishko. Generation of Cold and Heat in Vortex Tubes during Pressure Reduction of Natural Gas. Chemical and Petroleum Engineering 56, 272–279 (2020)

[12] D. Majidi, H. Alighardashi, F. Farhadi, LPG mass separation by vortex tube cascade and its economics, Applied Thermal Engineering, 148 (2019): 1139-1147

[13] Jinwon Yun, Younghyeon Kim, Sangseok Yu, Feasibility study of carbon dioxide separation from gas mixture by vortex tube, International Journal of Heat and Mass Transfer, Volume 126, Part A, 2018, Pages 353-361

[14] Christensen, K., Heiredal, M., Kauffeld, M., and Schneider, P., 2001. "Energy savings in refrigeration by means of a new expansion device. report of energy research programme". Journal(1223/99), p. 0006

[15] Li, D., Back, J., Groll, E., and Lawless, P., 2000. "Thermodynamic analysis of vortex tube and work output expansion devices for the co2 trans-critical cycle". In Proceedings of the Fourth IIR-Gustav Lorentzen Conference on Natural Working Fluids at Purdue, Lafayette, IN, USA, pp. 25–28

[16] Bakhsheshi, M. F., Keenliside, L., and Lee, T.-Y., 2016. "Rapid and selective brain cooling method using vortex tube: a feasibility study". The American journal of emergency medicine, 34(5), pp. 887–894

[17] Khodorkov, I., Poshernev, N., and Zhidkov, M., 2003. "The vortex tube—a universal device for heating, cooling, cleaning, and drying gases and separating gas mixtures". Chemical and petroleum Engineering, 39(7-8), pp. 409–415.

[18] Chiappini, D., Mendecka, B., and Bella, G., 2021. "Sizing and optimization of a vortex tube for electric vehicle hvac purposes". In 15th International Conference on Engines & Vehicles, SAE International

[19] M. Attalla et al. An experimental study of nozzle number on Ranque Hilsch counter-flow vortex tube Experimental Thermal and Fluid Science 82 (2017): 381-389

[20] S. E. Rafiee and M. M. Sadeghiazad Three-dimensional numerical investigation of the separation process in a vortex tube at different operating conditions Journal of Marine Science and Application 15.2 (2016): 157-165

[21] Behera U. et al. CFD analysis and experimental investigations towards optimizing the parameters of Ranque-Hilsch vortex tube. International Journal of Heat and Mass Transfer 48 (2005) 1961-1973.

[22] Bargiel P. et al. Vortex Tube Operational Temperature Regime. ASME Journal of Energy Resources Technology. 142 (2020) / 082001-1

[23] Rist D. Dynamik realer Gase – Grundlagen, Berechnungen und Daten für Thermogasdynamik, Strömungstechnik und Gastechnik. Berlin-Heidelberg, Germany: Springer-Verlag; 1996. (in German).

https://doi.org/10.52202/069564-0071