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The Ranque Hilsch phenomenon: Experimental visualization of the flow structure.

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Abstract

In this study, experimental investigations are conducted employing visualization techniques with the objective of elucidating the flow structure within the Ranque-Hilsch vortex tube. As part of the research project, a test rig has been constructed. The primary component of the rig is a transparent vortex tube made of acrylic glass. Three different working fluids are planned for use in the experiments: air, water, and silicone oil. The objective of the research is to leverage the unique properties of each fluid to achieve the desired outcome across a broader range of input flow parameters. In the current stage of the project, we are utilizing air as the working fluid, with the other working fluids to be investigated in subsequent stages. The flow input during the tests was planned for pressures of up to 4 bar (g) and flow rates up to 70 kg/h, but after preliminary results changed to very low pressures: up to 0,2 bar (g). The test rig was equipped with a laser and a high-speed camera setup to capture the flow with high spatial resolution.

Introduction

The Ranque-Hilsch phenomenon was first identified in the 1930s [1], inside the vortex tube an inlet mass flux of given thermal state is separated into two streams where one is brought into a higher thermal state and the other into a lower than the initial one. Despite the considerable time that has elapsed since then, and the numerous published studies, the physics of the phenomenon remain poorly understood. Previous visualization experiments have not provided a definitive answer to the fundamental question: How does it work?

The vortex tube is a relatively simple device, consisting of four principal elements: a vortex chamber (tube), inlet nozzles directed tangentially to the vortex chamber, a cone-shaped control valve, which distributes the amount of hot flow exiting the tube (referred to as the "hot outlet"), and an orifice, through which the cold stream exits (referred to as the "cold outlet"). Figure 1 illustrates the configuration of these elements.

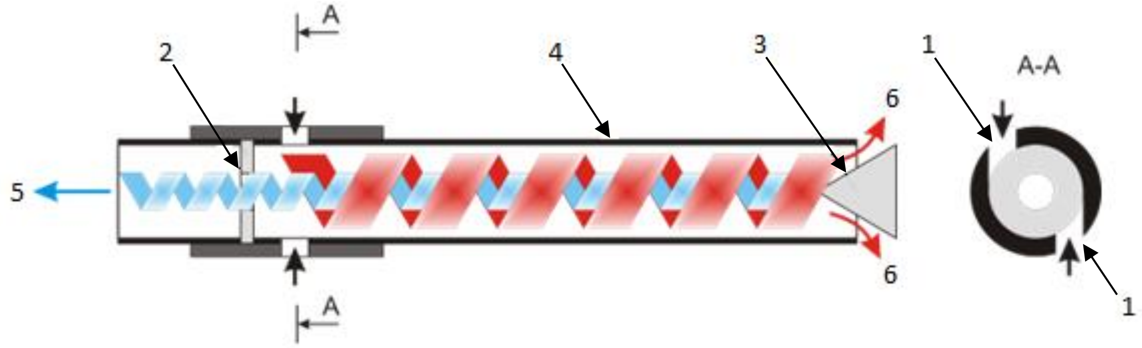

Figure 1 Vortex Tube construction and hypothetical flow structure [2].
1 – inlet nozzles, 2 – outlet nozzle(orifice), 3 – cone shaped control valve,
4 – vortex chamber (tube), 5 – cold outlet, 6 – hot outlet

The working principle is to separate the pressurized inlet stream into two streams with different thermal parameters. The increased pressure of the inlet stream generates high speed and strong swirling flow in the nozzles. As a result of a complex turbulent flow, the temperature decreases at the cold outlet and increases at the hot outlet. Therefore, the basic research issue of the Ranque Hilsch phenomenon is to identify the mechanism responsible for temperature stratification. There are six hypotheses describing the Ranque Hilsch phenomenon, these include: Local Compression/Expansion Hypothesis[1], Radial Temperature Gradient Hypothesis [3], Mult circulation Hypothesis [4], Acoustic Hypothesis [5], Goertler Vortices Hypothesis [6] and the Friction Hypothesis [7].

The temperature separation effect defines the Ranque Hilsch phenomenon in a blackbox approach, but the flow structure inside the Ranque Hilsch Vortex Tube (RHVT) is the key to explain the detailed physical mechanism of the process. The majority of research into the Ranque-Hilsch phenomenon is focused on quantifying the energy separation process, with the visualization of the flow structure being a secondary objective. Moreover, there is frequently a lack of correlation between experimental and numerical approaches. Consequently, the flow structure is simplified to an extent that is not representative of the actual phenomenon. Consequently, experimental research on the flow structure is of paramount importance, as it reveals intriguing characteristics of the flow that can be employed to assess and subsequently validate numerical models. This enables us to gain insight into the inner workings of the RHVT. There are different approaches to visualize of the flow structure inside the RHVT. The most common approach is numerical modelling by computational fluid dynamics (CFD). A major obstacle in an experimental visualization is the high rotational speed achieved by the gas medium. Studies using water as a working fluid improved the visual insight, but the state of knowledge is still unsatisfactory. Arbuzov et al. [8] created a system using Hilbert visualization technique. The outcome of the experiment was a footage of a vortical double helix. Liew et al. [9] conducted a LDA (Laser Doppler Anemometry) experiment tracking water droplets. Xue et al. [10] prepared a system working on water with hydrogen bubble injection. In effect a rotational axis of the flow was recorded. Additionally it was possible to track a particle moving from the cold to the hot end. In another approach Xue et al.[11] used Particle Image Velocimetry (PIV) to capture the vortex flow and the behavior of the inner vortex. As a result, the velocity profile was investigated and the precession of the vortex core was observed, which agrees with numerical results.

Research plan

The motivation to address the research gap resulting from insufficient explanations in the existing literature prompted the formulation of a specific research plan that employs a phenomenological approach. The aim of the underlying study project is to reveal the flow pattern and vortex behavior inside the RHVT by means of experimental investigation, to foster the fundamental understanding of the physical processes inside the RHVT. The results of these investigations unveil the behaviors and give evidence for the six working hypotheses mentioned.

In the present study the experimental procedure for the visualization inside the RHVT is elaborated to enable the physical understanding of the flow phenomena. The decision to employ the visualization technique was made at the outset. All potential avenues were considered, and the concave shape of the pipe walls and the anticipated fast and complex dynamic of the flow were taken into account. It was determined that this technique would be the most effective means of achieving the desired research goal of the study. The flow was seeded with aerosol particles using an aerosol generator, and a laser sheet was induced in a specific position of the pipe. Finally, a camera was positioned facing the laser sheet to capture the light reflection of the flowing aerosol particles. This allowed for the visualization of the flow structure and the formation of the internal vortex.

However, this approach required the use of air as working medium, what, as mentioned before, could become a major problem. The experimental facility is designed for pressures up to 6 bar(g), while in the present study including the aerosol generator for flow visualization, limits the inlet pressure. Therefore, the focus was set on pressures of up to 0,2 bar(g), which meant studies on the verge of occurrence of the phenomenon. The possibility of carrying out tests with a liquid medium has also been established.

Finally, a plan was drawn up to carry out the experimental part: (i) First, a preliminary study of the possibilities of visualizing the phenomenon in the vortex tube using an aerosol generator. This means determining whether it is possible to visualize this way, and then determining locations along the length of the pipe where important details in the flow can be observed. (ii) Second, carrying out detailed flow studies at the designated locations, and post-process them for analysis of the results. (iii) Third, after the tests with pressurized air have been completed, the test rig will be rebuilt and adapted for visualization with liquid mediums.

Experimental setup

Constructing the test rig was the first step towards carrying out experimental studies. The basic element of the rig was a transparent vortex tube made of acrylic glass. The design has already been tested at an earlier stage of the ATHLETE[1] research project and has not been changed except for the set of nozzles and material for the transparent version. The designed RHVT is shown in Figure 2.

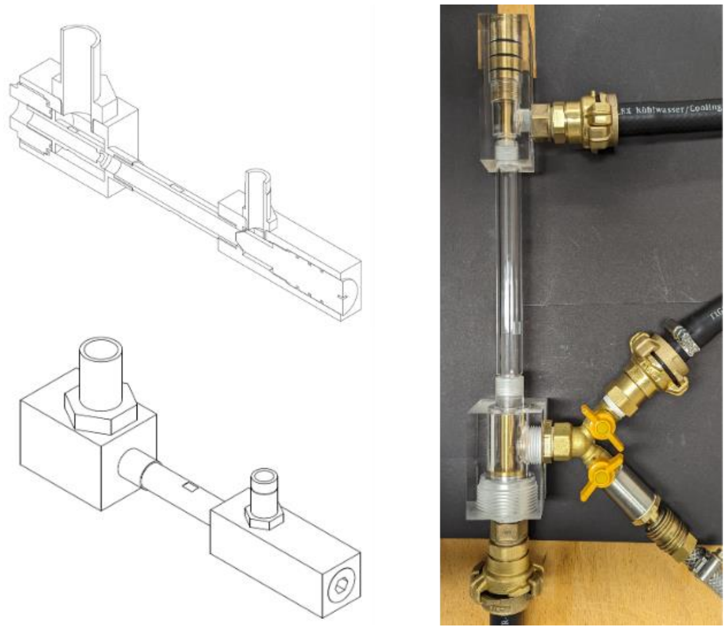

Figure 2 The vortex tube used for the study. ISO projection, cross-section, and the device prepared for operation.

The new nozzle element was equipped with 4 nozzles, each of them with 3.0 mm^2 cross section area. Three tube lengths were employed for testing purposes: 100, 180 and 240 mm. The lengths were selected based on a review of pertinent literature in regard to the L/D ratio [12].

It was hypothesized that an increase in the length of the tube would result in an increase in the instability of the phenomenon.

In order to meet the assumptions of the specified research plan, a test rig was assembled (Figure 4)Figure 4 Experimental setup: a) Version “v1”, b) Version “v2”. The rig was equipped with:

1) Transparent Vortex Tube,
2) Topas ATM230 Aerosol Generator, working with Di-Ethyl-Hexyl-Sebacat (DEHS), generating polydisperse aerosol mainly below 1 µm,
3) a) Laser, class 3b enclosed in a safety enclosure, power of 75 mW, wavelength of 532 nm (green),
   b) Laser, class 4 with 450mW
4) a) Canon EOS M50 camera with a EF-M 32 mm lens mounted on a tripod.
   b) VEO-640L High-speed camera with 100mm Macro lens

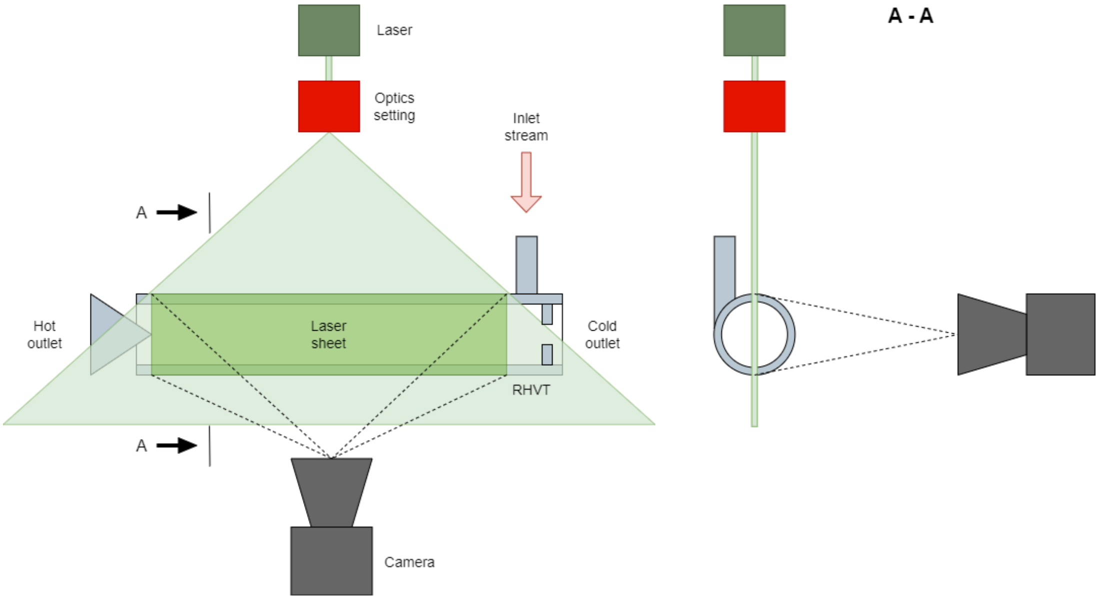

Figure 3 Schematic of the experimental setup.

In addition, two K-type thermocouples were used to measure the temperatures at the outlets of the vortex tube and a pressure sensor (Jumo Midas C08) was installed at the inlet to the device. The camera allowed recording up to 100 fps in 1280x720 resolution, or 2560x1440p at 25 fps setting.

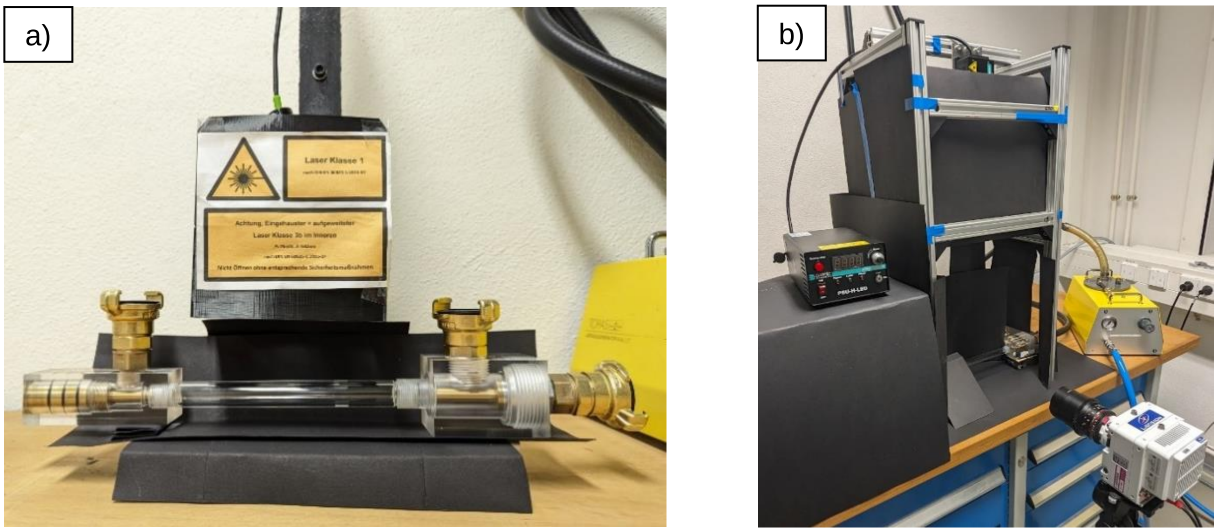

Figure 4 Experimental setup: a) Version “v1”, b) Version “v2”.

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[1] Research Project NCN-Opus nr 2021/43/B/ST8/03320 (UMO-2021/43/B/ST8/03320) “ATHLETE” financed by the National Science Centre of Poland

Following the completion of the preliminary tests, the test rig was rebuilt and adapted to work with a high-speed Phantom VEO-640L camera (2560x1440 resolution) in order to more accurately capture the flow dynamic with higher temporal resolution. The lens used in this case was a 100 mm / 3.1 Macro Photo. The basis of the new design (version “v2”) was a construction of aluminum profiles, covered in black cardboard for Laser safety reasons as shown in Figure 4b. A different laser with a higher intensity was required for this configuration in order to achieve a higher acquisition rate. The Dantec Dynamics RayPower 450 laser device was employed with a power of 450 mW and a wavelength of 532 nm (green).

Measurement procedure

The first part of the planned experiments focused on developing an appropriate calibration method to obtain repeatable measurement results. The first tests showed that there are relatively large light refractions on the surface of the tube. We were able to avoid this effect by manipulating the laser settings. The camera was positioned perpendicular to the device at a distance depending on the resolution, from 15 to 40 cm (Vortex Tube to lense). Furthermore, to facilitate the planned use of a high-speed camera, an attempt was made to select the optimal resolution of the recordings. This would allow for the optimization of data acquisition and analysis in future tests. This ultimately led to the discovery that the most informative recordings and the most intriguing behavior of the flow structure are observed at the hot outlet. Therefore, for a better process understanding, the vortex tube has been symbolically divided into three experimental sections: (1) the hot outlet (Valve section), (2) the middle part (Mid section) and (3) the cold outlet (Orifice section).

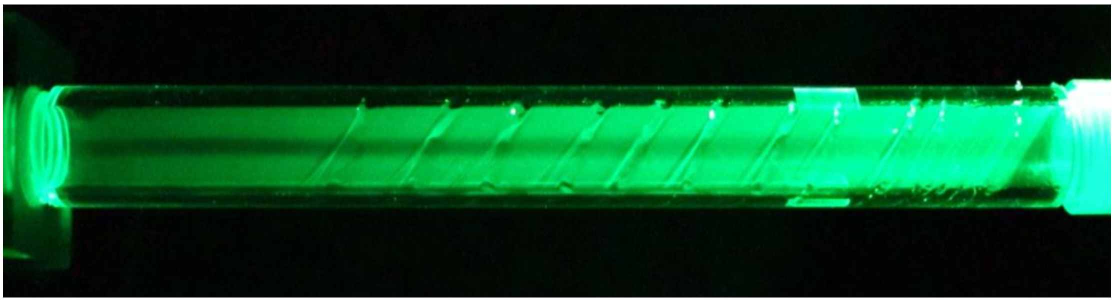

Figure 5 Vortex tube flow visualization using the test rig V1.
The concentrating aerosol depicts the outer vortex.

The initial observation was the concentration of the aerosol at the outer edges of the pipe, which resulted in the formation of an area of much darker color. The time required to reach this state was very short: up to 10 seconds, depending on the inlet pressure. This has been hypothesized to be an internal vortex moving towards the cold outlet. However, there was uncertainty due to the low pressure at the outlet of the particle generator. A series of tests were conducted to ensure the pressure at which the temperature difference becomes noticeable, and to determine whether there is a flow through both outlets. The results of the tests demonstrated for all tube lengths that:

I. at both outlets a flow is observed,
II. a temperature difference of 0,1°C already exists for an inlet pressure of 0.02 bar(g) and at the max inlet pressure of 0,2 bar(g) increases to: 3°C – 100 mm tube; 3,7°C – 180 mm tube; 5,2°C – 240 mm tube ,

thereby confirming the statement about the internal vortex.

Further experiments demonstrated that, due to the high rotational speed and the presence of nozzles, the aerosol drips. It can be observed that the plough moves in a regular shape and at a regular angle of inclination towards the hot outlet Figure 5. Moreover, experiments were conducted to ascertain the boundaries of the observed laser plane (due to the occurrence of refractions), to examine the sensitivity of the phenomenon to the change of the opening angle of the control cone and to perform an injection into the internal vortex (the attempt was unsuccessful). Additionally, a regulation cone (valve) in the form of a camera cap made of acrylic glass was planned. This design would enable the observation of the cross-section of the flow and the potential motions of the internal vortex in another plane.

Preliminary testing and its conclusions resulted in the creation of a specific approach to further research. The main findings may be summarized as follows:

(i) Recordings were limited to 20 seconds, the inlet pressure range to the RHVT was limited to 0.1 bar (g). This was done because the amount of aerosol dripping at higher pressures made it impossible to make good recordings.

(ii) The recording resolution has also been minimized to 1920x400 pixels, resulting in sharper images.

(iii) The frame rate was set to 800 frames per second, but was subsequently reduced to 400 fps in order to save data space, thereby allowing for the storage of more recordings. This allowed us to get a deeper insight into the structure of the flow.

(iv) (For tubes with a length of 100 and 180 mm, the valve section and the orifice section were considered. The resolution allows these two recordings to cover the mid-section as well. The mid-section was recorded separately only for the 240 mm tube.

(v) The data was recorded in the form of .cine files (the default format of the camera software: Phantom Camera Control Application). The recordings were then converted to TIFF images to prepare for post processing.

Results and discussion

Two distinct methodologies for conducting experiments have been delineated. Firstly, the pressure was gradually increased and the formation of the internal vortex was observed. Secondly, separate recordings were made for eight pressure settings, ranging from 0 to 0.1 bar (g), with an increment of 0.0125. This allowed to observe the behavior of the inner core depending on the inlet pressure and the length of the pipe.

The obtained measurement results demonstrate a high degree of agreement with the available literature data. Of particular interest is the observation of the behavior of the inner core, which appears to have great scientific value. As previously stated in the introduction, Xue et al. [10] research led to the visualization of the internal core's rotational axis. The visualization indicated a deviation of the rotational axis from the axis of symmetry of the tube. In the course of their research, this observation was made using an experimental setup in which water was used and the visualization method was based on the injection of hydrogen bubbles into the flow. Additionally, difficulties in repeating such behavior with the use of air were also identified. Our studies have demonstrate that air exhibits similar behavior to water, hence, the rotational axis of the internal core deviates from the axis of symmetry of the pipe as shown in Figure 6.

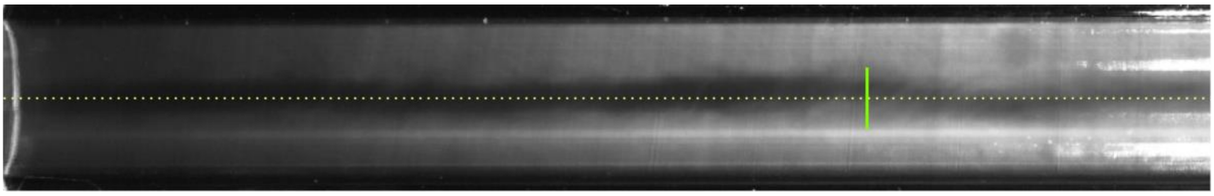

Figure 6 Visualization of flow in the RHVT, 180 mm tube (valve section). Marked: axis of symmetry (yellow line), location used for further investigation (green line).

These observations are done for each tube length. In the case of a 100 mm tube, the displacement is least visible. For the 180 mm pipe, it is already significant, similarly for the 240 mm pipe. This phenomenon is best observed for inlet pressure above 0,05 bar(g). The results presented in this study is obtained on the 180mm tube and inlet pressure 0,06 bar(g). To obtain further insight, the image intensity of the visualization is analyzed. For the selected region of flow, as illustrated in Figure 6, the space-time evolution of the light intensity gray scale is presented in Figure 7. The selected location is 80 mm from the hot outlet of the vortex tube (left of the figure). The results presented in the graph demonstrate the variability of the internal vortex over 1,500 frames, which corresponds to 3.75 seconds of recorded footage.

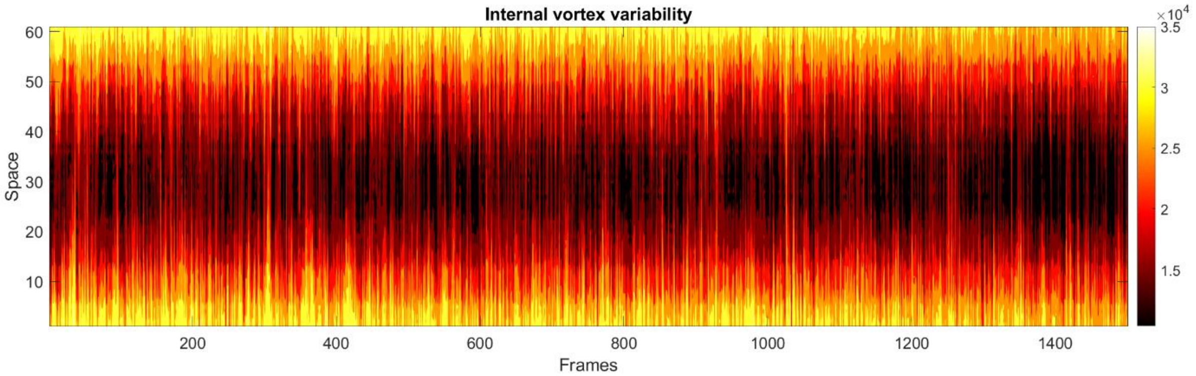

Figure 7 Internal vortex variability in the RHVT.

Figure 7 illustrates that the upper and lower boundaries of the inner vortex are not temporally fixed, but rather, their thickness varies over time. It is of particular importance to note that this variability is primarily related to the movement of the core in relation to the axis of symmetry. Xue et al. [11] also obtained comparable results by examining the behavior of the core in the cross-section of the vortex tube. The compatibility of the behavior of the inner core for air and water tests has been confirmed in this case as well. This is of particular interest as studies using air have been considered unpromising and difficult to carry out. Studies using water, which is an incompressible fluid, allowed good results to be achieved. However, in the case of the RHVT, it is difficult to determine the exact causes of the phenomenon, since the stratification of temperature is minimal. Our studies showed that air, which is a compressive fluid, allows significant results to be achieved in flow visualization. Moreover, air (or simply gases) is a predefined working factor in vortex tube installations, and should be considered as the optimal medium for studying the phenomenon.

Conclusion and Outlook

At the current state of knowledge, it can be said that particle-based visualization of the Ranque-Hilsch phenomenon still remains a challenge for typical values of inlet pressure due to the nature of the flow. The reasons for the occurrence of the Ranque-Hilsch phenomenon remain unclear. Nevertheless, the studies conducted have demonstrated the feasibility of experimental studies using air as a working fluid. Moreover, the results obtained to date are highly promising and consistent with the results presented in the literature. The failure to answer the research question indicates the need for further development of these studies. Furthermore, concurrent studies employing water can facilitate a more expedient comprehension of the phenomenon and the utilization of alternative forms of visualization. For the planned investigation using water and silicone oil, it is planned to seed the fluid with Kalliroscope particles [13], which are tiny particles having very small Stokes numbers and following the flow precisely.

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