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Analysis of the work of experimental equipment on the principle of the vortex tube

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Abstract: The authors focused on 3 different constructions of experimental equipment based on the principle of countercurrent Ranque-Hilsch Vortex Tube (RHVT). With the help of experimental devices, the separating effect of air can be demonstrated by means of a vortex effect. The constructions of the experimental facilities are based on the relationships published by the authors Takaham and Sonim. Based on the air inlet pressure and the hot outlet area, the outlet temperature of the hot and cold air fractions will be monitored. The temperature difference is evaluated and the suitability of the proposed parameters of the experimental equipment is assessed.

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1 Introduction

Over time and with the development of technology, it is possible to see the improvement of many technological processes. The reason for their improvement are various causes such as economic burden, or savings or the improvement of the technological process itself for the possibility of applying better equipment. There are many ways to achieve this.

Sometimes chance and sometimes curiosity leads to the discovery of something new. By focusing on only one crucial element, an unexpected result is achieved.

Such a case is also the examination of the vortex effect in the vessel or tube.

The vortex effect is used, for example, to separate solid particles in cyclone separators, or to better mix liquids and the like. A special case is the use of a vortex effect to separate the hot and cold components of the gas in a tube with a tangential supply of compressed gas. It was first to discover this phenomenon in 1930, and in 1934 he obtained a US patent from G.J. Ranque [1]. Later, the German physicist R. Hilsch dealt with this phenomenon and published his research in 1947 in a publication [2]. Since then, the vortex tube is also known as The Ranque-Hilsch Vortex Tube (RHVT).

With the publication of these researches, massive (intensive) experimental and analytical research has been launched in an effort to obtain as many results as possible for a detailed description of the ongoing events in RHTV.

2 Vortex tube

The vortex tube or RHVT is a mechanical device separating a compressed gas stream into two streams with low and high temperatures, known as the temperature (or energy) separation effect [3].

Generally, the vortex tube can be classified into two types. One is the counter flow type (often referred to as standard type) and another is parallel or uni-flow type.

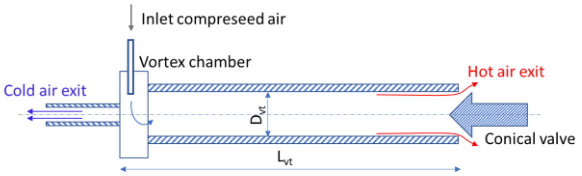

Figure 1 Schematic diagram of the vortex tube (counter flow type)

The studies focused on the influence of the tube geometry and the energy redistribution of the supplied gas depending on the inlet pressure and the respective tube dimensions. One of the parameters discussed is the tube length ratio (L_{vt}) to its average (D_{vt}) L_{vt}/D_{vt}.
Saidi[4] when examining the ratios of the parameters of the length and diameter of the tube, for cooling, suggests the optimal ratio 55.5 (3 inlets). They noted that ratio should be between $20 < L_{vt}/D_{vt} < 55.5$ in RHVTs. Soni [5] argue in his work that for the work of RHVT it is sufficient if the ratio is:

$$\frac{L_{vt}}{D_{vt}} \geq 32 \qquad (1)$$

L_{vt}- length of vortex tube, (m)
D_{vt}- diameter of the vortex tube, (m)

Many authors have researched this relationship, and they are mentioned in e.g. in literature.[6]
Thakare et. al. [7] in their review study they described very clearly the possibilities of using different numbers and types of input nozzles, which are analyzed not only experimentally but also using CFD simulations. From a number of experiments that have been performed, it has been found that it is better to use a vortex tube on the counter-current principle [1, 2]. The first to deal with the correct placement of the individual parts and to determine their effect on the performance of the tube was Hilsch [2].
The effect of the correct positioning of the control pyramid and the shape of the inlet nozzle for the compressed gas was discussed by Linderstrøm-Lang [8].
In 1955 Westley [9] experimentally optimized the geometry of a vortex tube. He found that the optimal solution would be the relationship between the inlet surface, the length of the tube, the cross-section of the vortex tube, the area of the cold outlet and the inlet pressure. He recorded the ratios as follows:

$$\frac{A_c}{A_{vt}} \cong 0.167 \qquad (2)$$

$$\frac{A_{in}}{A_{vt}} \cong 0.156 + \frac{0.176}{\tau_p} \qquad (3)$$

$$\tau_p = \frac{p_{in}}{p_c} \qquad (4)$$

A_c – flow area at cold outlet, (m^2)
A_{vt} – area of vortex tube, (m^2)
A_{in} – area of inlet nozzle (m^2)
$\frac{p_{in}}{p_c}$ – inlet pressure ratio p_{in} and cold outlet p_c

In the 1960s, Takahoma [10] determined another ratio for the correct vortex tube geometry. He found that if the Mach number reaches 0.5~1 at the input, the geometry of the vortex tube should be as follows.

$$\frac{D_{in}}{D_{vt}} = 0.2 \qquad (5)$$

$$\frac{A_{in}}{A_{vt}} = 0.08{\sim}0.17 \qquad (6)$$

$$\frac{A_c}{A_{in}} = 2.3 \qquad (7)$$

D_{in}- diameter of the inlet nozzle, (m)

This arrangement makes it possible to achieve a greater heating and cooling effect.
In 1969, Soni [7] published a study describing the results of working with 170 different vortex tubes and describing the optimal performance that should be achieved if these geometric ratios are observed:

$$\frac{A_{in}}{A_{vt}} = 0.084{\sim}0.11 \qquad (8)$$

$$\frac{A_c}{A_{vt}} = 0.08{\sim}0.145 \qquad (9)$$

$$\frac{L_{vt}}{D_{vt}} = 45 \qquad (10)$$

It can be shown that all the geometric ratios of RHVTs described so far have the same features as the ratios described by Westley and Takaham. In 1974, Raiskii [8] focused on these ratios and used them experimentally.

2.1 Design of experimental equipment

For the design of the experimental device, a counter-current vortex tube (Figure 1) was chosen, the dimensions of which were determined on the basis of equations (1) and (5) - (6).
The design of the vortex tube diameter and length was based on Equation (1) and available tube diameters. A metal tube with an inner diameter of 25.4 mm and in the second and third cases a plastic tube with an inner diameter of 22 mm and 14 mm were chosen as the material for the first tube.
The inlet nozzle is an important component of RHVT. Its location and number of input was the subject of independent research (studies) both experimentally and with the help of mathematical simulations.

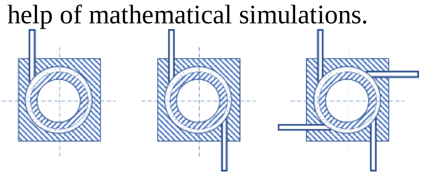

Figure 2 Vortex chamber with input nozzles

The design was based on relations (1) and (8). In the first case, 4 inputs were selected, and the effects of connecting 1-4 inputs were monitored. In the second case, only one input was used. The nozzles pointed to the inner edge of the chamber at an angle of inclination to the tube of 5°.

Another important parameter of RHVT is the output of the cold gas fraction. The design was based on the relationship (9) and the relevant tube diameter.

For the length of the cold outlet tube, a relation was used according to which the length of the cold outlet should be equal to 2.5 times the diameter of the vortex tube:

$$L_c = 2.5\, D_{vt} \tag{11}$$

L_c- length of cold tube, (m)

No less important parameter of the RHVT is the control pyramid, which was placed on the threaded slider. A type of non-bevelled pyramid with an angle of 45° was used. In practice, pyramid surfaces with an angle ranging between 40-60° are used, the optimal angle of the pyramid is 50° according to some authors.

Table 1 Table of dimensions of experimental devices

	Model 1 [mm]		Model 2 [mm]		Model 3 [mm]	
	calculated	used	calculated	used	calculated	used
D_{vt}	25.4	25.4	22.0	22.0	14.0	14.0
D_{in}	5.08	5.0	4.4	5.0	2.8	3.0
D_c	7.704	7.7	6.67	8.0	4.25	6.0
L_{vt}	812.8	1240	704.0	780	448.0	448
L_c	63.5	63.5	55.0	80.0	35.0	32.0
$\frac{L_{vt}}{D_{vt}}$	32.0	48.82	32.0	35.45	32.0	32.0

In Table 1 are calculated and used dimensions of experimental devices. The dimensions used are in accordance with the main condition of relation (1).

Table 2 Table of ratios of main parameters of devices

	Takahama Soni	Calculated	Model 1	Model 2	Model 3
$\frac{D_{in}}{D_{vt}}$	0.2	0.2	0.197	0.227	0.214
$\frac{A_c}{A_{vt}}$	0.08-0.145	0.092	0.0919	0.123	0.184
$\frac{A_c}{A_{in}}$	2.3	2.3	2.372	2.37	4.0
$\frac{A_{in}}{A_{vt}}$	0.084-0.11	0.04	0.0387	0.052	0.0459

Table 2 compares the recommended values according to Takaham [7] and Soni [5], according to which the calculations of the parameters of the experimental equipment were performed. The comparison ratios of the main dimensions of the devices were observed. It was not possible to keep only the ratio of the inlet area and the area of the hot part of the tube A_{in}/A_{vt}, The ratio was below the lower limit of the recommended value.

3 Experimental methods and the results of measurements

In the analysis of the work of the proposed experimental equipment, the temperature of the incoming air and the outgoing fractions were monitored.

K-type thermocouples were used to monitor temperatures. The values obtained were recorded using a Comet MS3 data logger. A Testo 880 thermal imager was used for the overall evaluation of surface temperatures and a Testo 452 touch thermometer was used for verification.

3.1 Experimental device No.1

Experimental device No.1 was constructed of steel components. The aim of the measurement was to determine the behavior of the device in the separation of cold and hot fraction depending on the inlet pressure and the position of the cone on the hot side.

Figure 3 Experimental device No.1

The measurement was performed at air pressures from the compressor of 0.15-0.45 MPa. The ambient temperature was 1°C and the relative humidity 60%. The barometric pressure was 101.4 kPa. The effect of the size of the outlet surface on the hot side of the tube as a function of the change in inlet air pressure was monitored. The change of area was performed by means of a threaded slider connected to the outlet cone on the hot side.

Table 3 Table of measured temperatures on equipment No.1

Pressure (MPa)	$t_{in.\,air.}$ (°C)	Area of hot inlet [cm^2]							
		0.9		1.4		2.2		3	
		C	H	C	H	C	H	C	H
0.15	5.3	3.6	7	5	6.9	6.2	8.9	7	9.7
		3.2	6	3.9	6.9	5.6	8	6.4	8.4
0.2	8	10.5	13.5	10	13	9.9	12	8.3	11.5
		9.3	13	9.2	12.7	8.6	11.9	8	11.1
0.3	10.4	10	15	10.5	17.5	11	17.5	12.5	18
		8.5	14.8	9.3	17.1	10.1	17.2	11.2	17.3
0.45	13.2	12.1	22	12.4	21	12	19.9	11.8	18.5
		10.9	21.2	10.4	20.1	10.7	19	10.3	18

$t_{in,\,air,}$- *temperature of inlet air, (°C)*
red values - measured values, (°C)
black values - verification measurement, Testo 452, (°C)
C- cold air, H- hot air

Based on the obtained results, it can be stated that the desired effect of separation of hot and cold gas fractions was achieved.

By comparing the temperatures at the hot and cold outlets, it is possible to observe an increase in the temperature difference from the pressure of 0.3 MPa. The size of the outlet area on the hot side had a negligible effect.

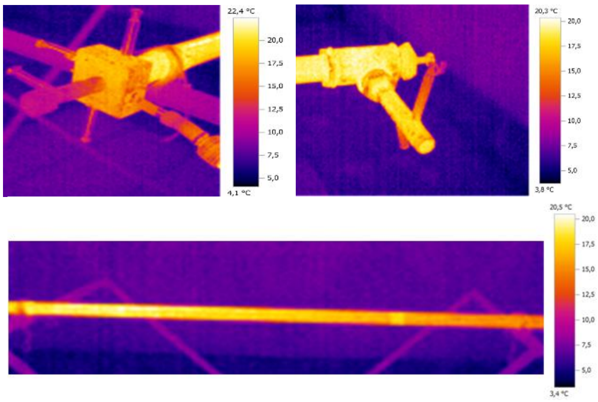

Figure 4 Experimental device No.1- surface temperature

From the point of view of the length of the device, it can be stated that by shortening the tube, the heat losses are reduced and the temperature of the hot fraction is increased. Reduction of heat losses can also be achieved by changing the material of the tube. The high temperature losses from the surface of the tube are also proved by the images from the Thermal Imager in Fig.4. Due to the change in the length of the tube produced, compared to the calculated value, no large differences between the hot and cold fractions were obtained. As the surface area of the tube has increased, the heat losses to the surroundings in particular have increased.

3.2 Experimental device No.2

Experimental device No. 2 was constructed of a plastic tube of the PP type in order to reduce heat losses. The aim of the measurement was to determine the behavior of the device in the separation of cold and hot fraction depending on the position of the cone on the hot side at the selected inlet air overpressure.

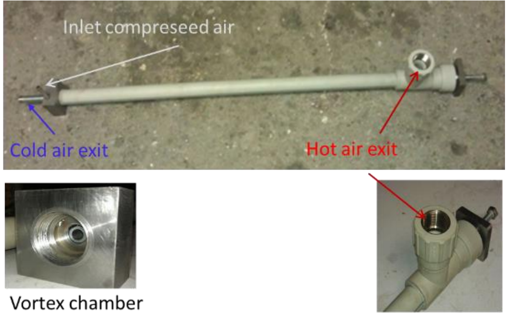

Figure 5 Experimental device No.2

Figure 5 shows a manufactured experimental device that had only one inlet nozzle for air supply. Even in this case, the length of the tube body was about 10.8% longer and met the basic condition according to Equation (1).

When measured, the average ambient air temperature was 16.5 ° C and the relative humidity was 50%. The temperature of the air entering the device was in the range of 15 - 21 ° C. The increase in the temperature of the air entering the tube was caused by the operation of the compressor. The measurement was performed at a constant overpressure of 0.45 MPa. The aim was to monitor the effect of the size of the outlet surface on the hot side of the tube on the temperature difference of the exhaust gases.

Table 4 Table of measured temperatures on equipment No.2

Area of hot inlet (cm^2)									
0.17		0.33		0.55		0.96		1.35	
C	H	C	H	C	H	C	H	C	H
13.2	25	15.3	25.8	18.7	28.2	21.3	28.2	22.8	29
9.8	26.2	11.4	26.7	14.8	28.1	18	28.2	19.1	28.5

From the obtained results it is possible to observe an increase in temperature on the hot side with increasing outlet area of the cone. Control measurements of the temperatures of the exiting fractions show a difference in the cold fraction which could have been caused by incorrect placement of the thermocouple at the outlet.

3.3 Experimental device No.3

Experimental device No. 3 was constructed, similarly to the second case, from a plastic tube of the PP type. The aim of the measurement was to determine the behavior of the device in the separation of cold and hot fraction depending on the position of the cone on the hot side at the selected constant overpressure of the incoming air.

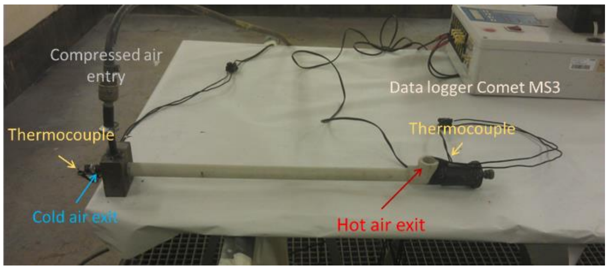

Figure 6 Experimental device No.3

Figure 6 shows the measuring set of experimental device No.3. In this case, the calculated tube length was observed and at the same time, the condition according to Equation (1) was satisfied.

The ambient temperature was 19.5°C with a relative humidity of 50 %. The barometric pressure was 100.8 kPa. The measurement was performed only at an overpressure of 0.45 MPa and a change in the size of the area of hot air coming out. The area change was performed using a threaded slider connected to the outlet cone. The temperature of the air entering the device was in the range of 19.5 - 21°C. The increase in the temperature of the air entering the tube was also caused in this case by the work of the compressor.

Table 5 Table of measured temperatures on equipment No.3

Area of hot inlet (cm^2)									
0.1		0.14		0.27		0.40		0.64	
C	H	C	H	C	H	C	H	C	H
13	37	15.2	33.7	16.2	30.5	13.8	32.4	17	32.5
10.3	37.8	11.7	35.5	12.1	35.6	12.8	33	14.8	33.5

The results obtained from the measurement at constant pressure again confirmed the suitability of the device for the separation of hot and cold gas fractions.

Control measurements of the temperatures of the exiting fractions again show differences that would need to be analyzed in more detail. The unsuitability of the type of thermocouple used is also assumed.

From the comparison of the temperatures on the hot side, it is possible to observe a decreasing tendency with an increasing cross-section on the hot side. The temperature on the cold side of the tube behaved similarly, which had an increasing character.

Comparing the results from measurements on the created experimental equipment, the most suitable construction No.3 appears, which proved the best separation capabilities using the vortex effect. Device No.2 and 3 was designed on the basis of experience from measurements on device No. 1. For this reason, the measurements focused mainly on higher pressures. The measurements were limited mainly by the power of the compressor.

4 Conclusions

The experimental device on the principle a vortex tube system has been designed and constructed in order to make a performance test.

To observe the effect of various parameters on performance several vortex tubes have been constructed throughout this work. These vortex tubes have been tested at various parameters to make a comparison between them. From the measurements it is possible to draw the following conclusions:

- The length of the tube has a great influence on the processes of separation of hot and cold gas fraction.

- The material of the tube plays an important role in increasing the performance of the hot component or can reduce heat loss to the environment from the surface of the tube.

- Increasing the cross-section at the outlet of the hot component decreases its temperature.

Many studies have been published on the relationship between individual RHVT parameters, and not all design parameters are unambiguous according to these authors. The studies are specifically focused and all authors agree that research in this area is still unfinished.

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