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Experimental Analysis on Heat And Mass Transfer and Separation Process Inside A DCVT Based on Pressure Distribution

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The types of vortex tubes (VTs) or air separators (professional separating, heating and cooling systems used in large engines like submarines, ships and etc) are usually determined based on the position of cold and hot exit areas. Based on these arrangements, there are three general types of vortex tubes including; Ranque-Hilsch (opposite directions), Parallel (same direction) and Double-Circuit (opposite directions with an extra injection at the center of hot valve). This study tries to present a comprehensive study on Double-Circuit vortex tube (DCVT). In this study the impact of pressure ratio (extra injection pressure/inlet pressure) on the separation quality is investigated. Based on the experimental results there are optimum values for the nondimensional pressure (P_{ex}/P_{in}) equal to and 0.2.

1. Introduction

Double-Circuit vortex tube (DCVT) is a special type of vortex tube which applies an extra inlet mass flow at the center of the throttle valve on the hot end of the main tube (Figure 1, Alekhin et al. ,2015). The first vortex tube was invented (completely in an accidental research) by Ranque (1933), after that this device was introduced and improved academically by Hilsch (1947) in several years later. After these two steps (the invention and the first improving), three types of this device are introduced as said before and the researches are continued on improving of the thermal performance of vortex tubes. Figure 2 shows the experimental setup of this study on the DCVT.

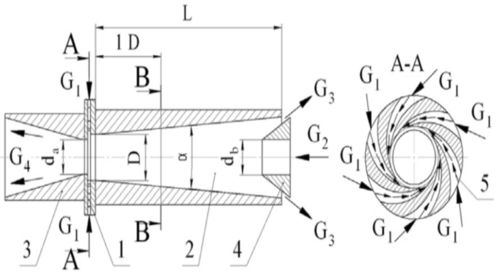

Figure 1: 1-main inlet nozzle; 2-energy separation chamber; 3-diffuser of cold flow; 4-nozzle of additional flow

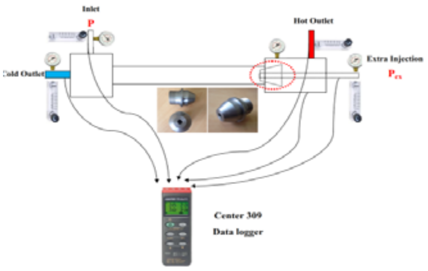

Figure 2: Schematic diagram of experimental setup

It can be said that there is a huge volume of papers on the RHVT and its performance despite severe lack in scientific reports on the DCVTs and PVTs. Here we want to present a brief review on the RHVT studies. Rafiee and Sadeghiazad (2017 and 2017a) designed a numerical or CFD method (based on DCVT model) for describing the interaction phenomenon between the flow and energy patterns in a DCVT. Sometimes there

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are some requests for special RH vortex tubes with indirect outputs (with the desired angles). So, industry needs the curved RHVTs with special angles. The details of the thermal efficiencies regarding the curved vortex tubes have been described based on different curvature angles by Rafiee *et al*., (2016). Dincer (2011) managed three innovative arrangements of the vortex tubes systems as the six RHVT cascade types, three-fold VT and the conventional VT considering different operational pressures. As said before, a vortex tube (convergent VT) has some essential structural parameters such as the main length for hot tube, the orifice diameter for exhausts and etc; these parameters are optimized in an experimental investigation by Rafiee and Sadeghiazad (2016a; 2016b; 2016c; 2017b; 2017c; 2017d) and Rafiee et al. (2015). The effect of geometrical factors of straight VT is analyzed by Rafiee and Sadeghiazad (2014a; 2015; 2017d; 2016d; 2016e; 2016f; 2016g), Pourmahmoud et al. (2014) and Rafiee et al. (2013). The interaction between the gas layers can be affected by the molecular weight, so, the type of operational fluid can be considered as an effective parameter on the thermal performance of a vortex tube, this effect is analyzed by Han et al. (2013), Thakare and Parekh (2015) and Pourmahmoud et al. (2013) via some gases such as R728, N_2, O_2, R161, CO_2, R32, R134a, R744, and R22. Rafiee and Rahimi (2013) focused on increasing the thermal separation efficiency of a RHVT via designing a new type of nozzles. They named this kind of nozzles as convergent nozzles and introduced a nondimensional parameter to define the correct way for using this kind of nozzles. As we know, the aim of all researches on optimization of the structural parameters for a vortex tube is enhancing the thermal capability of this device which leads to decreasing the costs in related industries. Beside the conventional methods, there are some different analyzing methods (such as "exergy considering", (Saidi and Allaf Yazdi, 1999; Ouadha et al., 2013; Rafiee and Sadeghiazad, 2014b) which can be considered as useful tools to accompany the old methods for optimizing the device (VT). The nozzle or injection slot has an internal diameter based on its shape. The effect of this matter is reported by Aydin and Baki (2006). There are some researchers which added a divergent main tube on their VT systems and reported different (sometimes opposite) results Rahimi et al. (2013) reported an optimum angle for the best efficiency, but, Chang et al., (2011) reported that the divergent tube destroys the separation in the VTs). Some researchers determined the CFD solution ways in their works Rafiee and Rahimi (2014) and Akhesmeh et al. (2008) by 3D models. Increasing the rotational speed can lead to the better separation, this matter can gain by applying the convergent nozzles reported by Pourmahmoud et al. (2012). Moraveji and Toghraie (2017) analyzed the effect of nozzle number, tube length and cold orifice diameter on VT performance using methane as working fluid.

2. Experimental process

In all VT types, the operating gas source is the pressurized gas supplied by a compressor or a high pressure cylinder (the pressure range is between 2 to 10 bar). The temperatures are recorded by a data logger (Center ^{R} 309 with 4 output channels, Range -200 C to 1370 C, Resolution 0.1 C) in all lines (main inlet, extra inlet, cold and hot exhausts for the DCVT). In the designed VT, the slots are set on a ring coupled on the entrance of the main tube (6 slots) with thermal welding. The pressure at the hot, cold, inlet and extra inlet is considered by the analog pressure gages. The rate of gas (air) is under control by the rotameters in all lines. In RHVTs we need a simple control valve without any complicated structures (just a conical shape with a certain angle and diameter at the end), but the situation is a little different in the case of DCVTs. In this kind, we need to apply a special valve with an orifice at the center of the valve (this orifice conducts the extra air to the main tube in the case of DCVT). Fig. 2 can help readers to imagine the general shape of this kind of control valve. The pressure fluctuations are controlled by a regulator on the line, so, we have a stable pressure at the inlets. Also, this setup can present any exact cold mass fractions, because of the valve's actions on the rotameters (in all lines). We adjusted the pressure at the inlet line by a valve on 1 MPa. The set-up is working (continually) for 10 to 15 minutes in each case to reach a stable condition (after adjusting the pressure at the inlets).

3. Basic concepts

The performance measurements on the VT systems (usually) are pointed and presented based on the temperature differences (there is no difference what kind of the VT is used, RHVT, PVT or DCVT). There are three definitions; first, the cold temperature difference or ΔT_{cold} (difference between inlet and cold sides), the total temperature difference or $\Delta \mathrm{T}$ (difference between hot and cold sides) and the hot temperature difference or ΔT_{hot} (difference between hot and inlet sides), these definitions are as bellow:

$$\Delta T_h = T_h - T_{inlet} \tag{1}$$

$$\Delta T_c = T_{inlet} - T_C \tag{2}$$

Beside the mentioned temperature differences, there is another scale for measuring the efficiency of a VT, named as the cold mass fraction. This factor (in fact the cold mass fraction manages the rate of cold flow as well as the cold temperature at the cold side) can be defined as bellow:

$$\alpha = \frac{Cold\ mass\ flow(m_c)}{Inlet\ mass\ flow(m_I)} \tag{3}$$

Furthermore, we need a nondimensional scale for a correct analyzing regarding the VT's performance, so, we present the isentropic efficiency as bellow:

$$\eta_{Isentropic} = \frac{\Delta T_c}{\Delta T_{Isentropic}} = \frac{T_{inlet} - T_C}{T_{inlet} - T_{Isentropic}} = \frac{T_{inlet} - T_C}{T_{inlet}\left[1 - \left(\frac{P_{atm}}{P_{Inlet}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

Here (in equation 4) we have these parameters; P_{inlet} or inlet pressure, ΔT_c or cold temperature difference, $\Delta T_{Isentropic}$ or isentropic temperature difference and P_{atm} or the surrounding pressure.

4. Result and discussion

The DCVT is created based on this fact that there is another input line in addition to the main entrance of the vortex tube. The main entrance is located on the vortex chamber (as seen in Figure. 2) and the additional or extra input is fixed at the center of the control valve. So, it seems that the pressure at the additional line has some serious and strong effects on the thermal performance of the DCVT. This effect is not analyzed and reported yet.

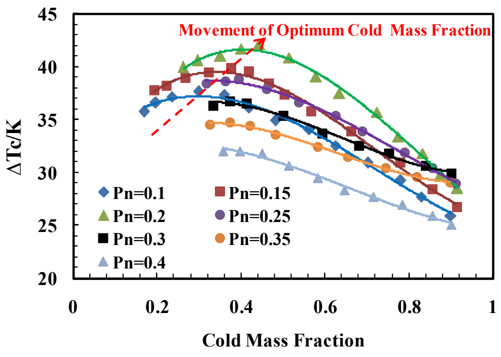

Figure 3: Effect of nondimensional pressure P_n on cooling performance of DCVT

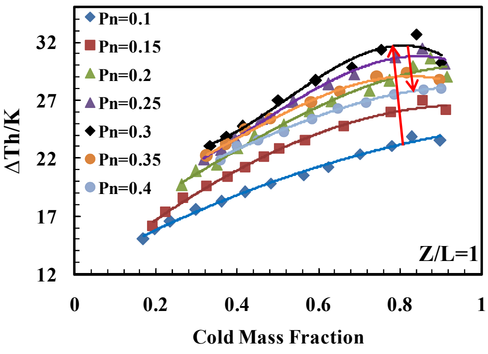

Figure 4: Effect of nondimensional pressure P_n on cooling performance of DCVT

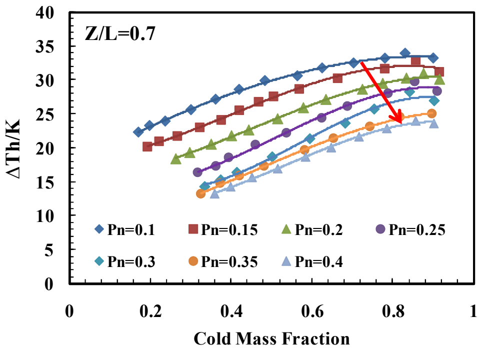

Figure 5: Effect of nondimensional pressure P_n (fixed inlet pressure and variable extra injection pressure) on heating performance of DCVT with D=35 mm, d_b=10 mm, d_a=13 mm, L=600 mm, D_n=0.77, N=6 and P=10 bar at Z/L=0.7

For this purpose we will present a nondimensional pressure as the ratio of extra injection pressure to the main inlet pressure or $P_n=P_{ex}/P$. The main injection pressure is fixed on 10 bar and the extra injection pressure will be varied in the range of 1 to 4 bar, so, P_n= 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 and 0.4. The effect of this nondimensional pressure on cooling and heating effectiveness of the DCVT (with D=35 mm, d_b=10 mm, d_a=13 mm, L=600 mm, D_n=0.77, N=6 and P=10 bar) will be studied in this section. Figure 3 shows that there is an optimum value for the nondimensional pressure P_n against the mass fraction axis. According to Figure 9, the cooling capability of the DCVT reaches a better situation and the DCVT works better than before when the nondimensional pressure is in the range of 0.1 to 0.2, and then, applying the greater values of P_n destroys the separation phenomenon and the cooling efficiency allays extremely. When the nondimensional pressure P_n increases from 0.1 to 0.2 the performance of the DCVT enhances 11.96% (4.5K). Because of an extra mass flow rate entering to the DCVT, it is expected that the structure of the optimum mass fraction on the cold mass fraction axis be changed, this fact is completely observable in Figure 3. When the nondimensional pressure P_n increases (from 0.1 to 0.2), the position of the optimum cold mass fraction is changed from 0.29 to 0.44 (red arrow on Figure 3). Another interesting result can be seen in Figure 3. The DCVT cannot work properly for the high values of the nondimensional pressure P_n at the range of 0.3 to 0.4 and the maximum cold temperature difference which occurs at the optimum mass fraction (approximately) will not happen (approximately) and the trend of ΔT_c continues along the mass fraction axis just like a straight line with a negative slope (cold temperature difference decreases continually). Finally when the nondimensional pressure P_n increases from 0.2 to 0.4 the cooling performance decreases 24.07%. According to the results of section 5.1 (Comparison between DCVT and RHVT with the same geometrical factors), a DCVT has lower heating efficiency compared to the cooling performance. It seems that this matter is because of the extra injection which is located at the center of the valve. This extra injection changes the energy pattern inside the main tube, especially near the valve (the location of hot exiting flow). So, this extra line and its features can have an extreme effect on the flow separation inside the DCVT. One of the most important thermophysical parameters of an inlet line is the pressure of the fluid. In this section we try to detect the extra injection pressure influence on the hot exit temperature (the hot exit place and the injection hole are in the same area at the end of the main tube).

As seen in Figure 4, the intensification in the nondimensional pressure (extra injection pressure) leads to an interesting improvement in heating capability of the DCVT. When the nondimensional injection pressure improves from 0.1 to 0.3 the heating performance of the DCVT elevates 37.23 % or 8.82K (the red arrow to top). The important thing is that this is the temperature of hot outlet and can be used directly for the heating purposes. But, this is not end of the performance and DCVT reactions against P_n increasing. After the performance improvement in the mentioned range, the pressure increasing has an opposite effect on the heating performance, so that, the heating effectiveness decreases for the nondimensional pressure P_n improvements in the range of 0.3 to 0.4 around 4.74 K or 14.49% (the red arrow to down). As a conclusion, a DCVT with low P_n is not appropriate to be used as a heating device and it should be forced by a high pressured extra injection line or P_n be greater than 0.2. At a same time we measured the temperature on the main tube at Z/L=0.7 for different nondimensional pressure P_n (As seen in Figure 5). It can be seen that the warm front will be weakened with increasing P_n, continuously, in other words, the increasing P_n pushes the warm front toward the hot exit and a DCVT can be used as an appropriate heating device by choosing an optimum nondimensional pressure P_n=0.3.

5. Conclusion

In this research, the experiments focus on the thermal performance of a special and interesting type vortex tube as the double circuit vortex tube (DCVT) based on different nondimensional pressure ratios (extra injection pressure P_{ex}/inlet pressure P) against the cold mass fraction. It should be said that the mentioned parameter its effects on the DCVT performance are not analyzed in previous researches. The aim of these tests is determining the possible optimum values regarding the mentioned parameter for the best thermal performance. The cooling capability of the DCVT reaches a better situation and the DCVT works better than before when the nondimensional pressure is in the range of 0.1 to 0.2, and then, applying the greater values of P_n destroys the separation phenomenon and the cooling efficiency allays extremely.

Reference

Akhesmeh S., Pourmahmoud N., Sedgi H., 2008, Numerical study of the temperature separation in the Ranque-Hilsch vortex tube, American Journal of Engineering and Applied Sciences, 3, 181-187, DOI: 10.3844/ajeassp.2008.181.187

Alekhin V, Bianco V, Khait A, Noskov A., 2015, Numerical investigation of a double-circuit Ranque-Hilsch vortex tube, International Journal of Thermal Sciences, 89, 272-282, DOI: 10.1016/j.ijthermalsci.2014.11.012

Aydin O., Baki M., 2006, An experimental study on the design parameters of a counter flow vortex tube, Energy, 31, 2763-2772, DOI: 10.1016/j.energy.2005.11.017

Bianco V., Khait A., Noskov A., Alekhin V., 2016, A comparison of the application of RSM and LES turbulence models in the numerical simulation of thermal and flow patterns in a double-circuit Ranque-Hilsch vortex tube, Applied Thermal Engineering, 106, 1244-1256, DOI: 10.1016/j.applthermaleng.2016.06.095

Bovand M., Sadegh V., Mohammad., Dincer, K., Tamayol Ali., 2014a, Numerical analysis of the curvature effects on Ranque-Hilsch vortex tube refrigerators, Applied Thermal Engineering, 65(1-2), 176-183, DOI: 10.1016/j.applthermaleng.2013.11.045

Bovand M., Valipour M.S., Eiamsa-ard S., Tamayol A., 2014b, Numerical analysis for curved vortex tube optimization, International Communications in Heat and Mass Transfer, 50, 98-107, DOI: 10.1016/j.icheatmasstransfer.2013.11.012

Chang K., Li Q., Zhou G., Li, Q., 2011, Experimental investigation of vortex tube refrigerator with a divergent hot tube, International journal of refrigeration, 34, 322-327, DOI: 10.1016/j.ijrefrig.2010.09.001

Dincer K., Baskaya S., Uysal B. Z., 2008, Experimental investigation of the effects of length to diameter ratio and nozzle number on the performance of counter flow Ranque-Hilsch vortex tubes, Heat Mass Transfer, 44, 367-73, DOI: 10.1007/s00231-007-0241-z

Han X., Li N., Wu. K., Wang Z., Tang L., Chen G., Xu X., 2013, The influence of working gas characteristics on energy separation of vortex tube", Applied Thermal Engineering, 61(2), 171-177, DOI: 10.1016/j.applthermaleng.2013.07.027

Hilsch R., 1947, The use of expansion of gases in a centrifugal field as a cooling process, Rev Sci Instrum. 18, 108-113.

Hitesh R., Thakare A.D., Parekh, 2015, Computational analysis of energy separation in counter-flow vortex tube" Energy, 5, 2-77.

Moffat R.J., 1985, Using Uncertainty Analysis in the Planning of an Experiment", Trans. ASME, J. Fluids Eng, 107, 73-178.

Moraveji A, Toghraie, D., 2017, Computational fluid dynamics simulation of heat transfer and fluid flow characteristics in a vortex tube by considering the various parameters, International Journal of Heat and Mass Transfer 113, 432-443.

Noor D.Z., Mirmanto H., Sarsetiyanto J., Soedjono D.M.E., Sri B.S., 2012, Numerical Study of Flow and Thermal Field on a Parallel Flow Vortex Tube", Engineering, 4, 774-777.

Ouadha A., Baghdad M., Addad Y., 2013, Effects of variable thermophysical properties on flow and energy separation in a vortex tube, International Journal of Refrigeration, 36(8), 2426-2437.

Piralishvili S.A., Polyaev V.M., 1996, Flow and thermodynamic characteristics of energy separation in a double-circuit vortex tube - an experimental investigation, Exp. Therm. Fluid Sci, 12, 399-410.

Pourmahmoud N., Hassanzadeh A., Rafiee S.E., Rahimi M., 2012, Three-dimensional numerical investigation of effect of convergent nozzles on the energy separation in a vortex tube, International Journal of Heat and Technology, 30(2), 133-140, DOI: 10.18280/ijht.300219

Pourmahmoud N., Rafiee S.E., Rahimi M., Hassanzadeh A., 2013, Numerical energy separation analysis on the commercial Ranque-Hilsch vortex tube on basis of application of different gases, Scientia Iranica, 20(5), 1528-1537.

Pourmahmoud N., Rahimi M., Rafiee S.E., Hassanzadeh A., 2014, A numerical simulation of the effect of inlet gas temperature on the energy separation in a vortex tube, Journal of Engineering Science and Technology, 9(1), 81-96.

Rafiee S.E., Ayenehpour S., Sadeghiazad M.M., 2016, A study on the optimization of the angle of curvature for a Ranque-Hilsch vortex tube, using both experimental and full Reynolds stress turbulence numerical modeling", Heat and Mass Transfer,52(2), 337-350.

Rafiee S.E., Rahimi M., 2013, Experimental study and three-dimensional (3D) computational fluid dynamics (CFD) analysis on the effect of the convergence ratio, pressure inlet and number of nozzle intake on vortex tube performance-Validation and CFD optimization Energy, 63, 195-204.

Rafiee S.E., Rahimi M., 2014, Three-Dimensional. Simulation of Fluid Flow and Energy Separation Inside a Vortex tube”, Journal of Thermophysics and Heat Transfer., 28, 87-99, DOI: 10.2514/1.T4198

Rafiee S.E., Rahimi M., Pourmahmoud N., 2013, Three-dimensional numerical investigation on a commercial vortex tube based on an experimental model-Part I: Optimization of the working tube radius", International Journal of Heat and Technology, 31(1), 49-56.

Rafiee S.E., Sadeghiazad M.M., 2014a, Effect of conical valve angle on cold-exit temperature of vortex tube, Journal of Thermophysics and Heat Transfer, 28(4), 785-794.

Rafiee S.E., Sadeghiazad M.M., 2014b, 3D cfd exergy analysis of the performance of a counter flow vortex tube, International Journal of Heat and Technology, 32(1-2), 71-77.

Rafiee S.E., Sadeghiazad M.M., 2015, 3D numerical analysis on the effect of rounding off edge radius on thermal separation inside a vortex tube, International Journal of Heat and Technology, 33(1), 83-90, DOI: 10.2514/1.T4198

Rafiee S.E., Sadeghiazad M.M., 2016a, Experimental and 3D CFD investigation on energy separation inside a convergent vortex tube air separator, Scientia Iranica, 23(4).

Rafiee S.E., Sadeghiazad, M.M., 2016b, Experimental and 3D-CFD study on optimization of control valve diameter for a convergent vortex tube, Frontiers in Heat and Mass Transfer, 7(1), 1-15.

Rafiee S.E., Sadeghiazad M.M., 2016c, Experimental study and 3D CFD analysis on the optimization of throttle angle for a convergent vortex tube, Journal of Marine Science and Application, 15(4), 388-404, DOI: 10.1007/s11804-016-1387-1

Rafiee S.E., Sadeghiazad M.M., 2016d, Three-dimensional computational prediction of vortex separation phenomenon inside the Ranque-Hilsch vortex tube, Aviation, 20(1), 21-31.

Rafiee S.E., Sadeghiazad M.M., 2016e, Heat and mass transfer between cold and hot vortex cores inside Ranque-Hilsch vortex tube-optimization of hot tube length, International Journal of Heat and Technology, 34(1), 31-38, DOI: 10.18280/ijht.340105

Rafiee S.E., Sadeghiazad M.M., 2016f, Three-dimensional CFD simulation of fluid flow inside a vortex tube on basis of an experimental model- The optimization of vortex chamber radius, International Journal of Heat and Technology, 34(2), 236-244.

Rafiee S.E., Sadeghiazad M.M., 2016g, Three-Dimensional Numerical Investigation of the Separation Process in a Vortex Tube at Different Operating Conditions, Journal of Marine Science and Application, 15(2), 157-165.

Rafiee S.E., Sadeghiazad M.M., 2017a, Improving the energetical performance of vortex tubes based on a comparison between parallel, Ranque-Hilsch and Double-Circuit vortex tubes using both experimental and CFD approaches, Applied Thermal Engineering, 123, 1223-1236.

Rafiee S.E., Sadeghiazad M.M., 2017b, Efficiency evaluation of vortex tube cyclone separator, Applied Thermal Engineering, 114, 300-327.

Rafiee S.E., Sadeghiazad M.M., 2017c, Experimental and 3D-CFD investigation on optimization of the air separator structural parameters for maximum separation efficiency, Separation Science and Technology, 52(5), 903-929.

Rafiee S.E., Sadeghiazad M.M., 2017d, Experimental and 3D CFD investigation on heat transfer and energy separation inside a counter flow vortex tube using different shapes of hot control valves, Applied Thermal Engineering, 110, 648-664.

Rafiee S.E., Sadeghiazad M.M., 2017e, Experimental and 3D CFD analysis on optimization of geometrical parameters of parallel vortex tube cyclone separator, Aerospace Science and Technology, 63, 110–122.

Rafiee S.E., Sadeghiazad M.M., 2017, Experimental and CFD analysis on thermal performance of Double-Circuit vortex tube (DCVT)-geometrical optimization, energy transfer and flow structural analysis, Applied Thermal Engineering, 128, 1223-1237, DOI: 10.1016/j.applthermaleng.2017.09.112

Rafiee S.E., Sadeghiazad M.M., Mostafavinia N., 2015, Experimental and numerical investigation on effect of convergent angle and cold orifice diameter on thermal performance of convergent vortex tube, Journal of Thermal Science and Engineering Applications, 7(4), 041006.

Rahimi M., Rafiee S.E., Pourmahmoud N., 2013, Numerical investigation of the effect of divergent hot tube on the energy separation in a vortex tube, International Journal of Heat and Technology, 31(2), 17-26, DOI: 10.18280/ijht.310203

Ranque G.J., 1933, Experiments on Expansion in a Vortex with Simultaneous Exhaust of Hot Air and Cold Air, Le J. de Physique et le Radium. 4, 112-114.

Saidi M.H, Allaf Yazdi M.R., 1999, Exergy model of a vortex tube system with experimental results, Energy, 24, 625-32.

Valipour M.S., Niazi N., 2011, Experimental modelling of a curved Ranque-Hilsch vortex tube refrigerator, Int. j. refrigeration, 34, 1109-1116, DOI: 10.1016/S1359-4311(03)00146-7