Renewable and Sustainable Energy Reviews 52 (2015) 172–178

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of Ranque–Hilsch vortex tube experiments using air

Sudhakar Subudhi [a,*], Mihir Sen [b]

[a] Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, India
[b] Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA

ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form
2 June 2015
Accepted 25 July 2015
Available online 10 August 2015

Keywords:
Ranque–Hilsch vortex tube
Cold temperature drop
Hot temperature rise
Cold mass fraction
Optimum coefficient of performance
Optimum isentropic efficiency

ABSTRACT

This paper reviews the literature on Ranque–Hilsch vortex tube experiments using air as the working fluid. This is a simple device without any moving parts that uses vortex motion to separate a compressed gas flow into two streams of high and low temperature, respectively. After a brief introduction and background, the review focuses on the variables of interest and the important experimental results that have been obtained up to now. Another objective is to find curve-fitting equations using data from the literature which can provide a rough estimate of temperatures that are achieved, and which can be used in practice for preliminary vortex tube design. The review will conclude with comments on further directions that future studies on this device can take.

Contents

1. Introduction

Refrigeration is an important engineering process with many industrial and domestic uses. Though vapor compression and, to a lesser degree, vapor absorption continue to enjoy widespread use [1,2], alternative techniques are being looked at due to environmental considerations [3]. Among these techniques are gas cycle, desiccant, thermoelectric, magnetic, steam jet and thermoacoustic refrigeration. The Ranque–Hilsch vortex tube is also one of those techniques that has niche applications. The vortex tube is a device which produces hot and cold fluid streams from compressed air without the help of any moving parts. It was invented in 1933 by French physicist Georges Ranque [4,5], and improved by German physicist Rudolf Hilsch [6]. The interest in this device has increased over the years as indicated by the growing number of papers published as shown in Fig. 1.

There have been few reviews of the subject reported. Westley [7] provided a comprehensive bibliography of publications and studied the developments of vortex tubes through 1953. Yilmaz et al. [8] reviewed design criteria from experimental and theoretical investigations of vortex tubes until the year 2007. They classified the criteria of earlier investigators based on different parameters: vortex tube dimensions; area, type and number of inlet nozzles; cold mass fraction; inlet pressure and temperature; and fluid properties. Another review by Eiamsa-ard and Promvonge [9] was

* Corresponding author.
E-mail addresses: subudfme@iitr.ac.in (S. Subudhi), Mihir.Sen.1@nd.edu (M. Sen).

http://dx.doi.org/10.1016/j.rser.2015.07.103
1364-0321/

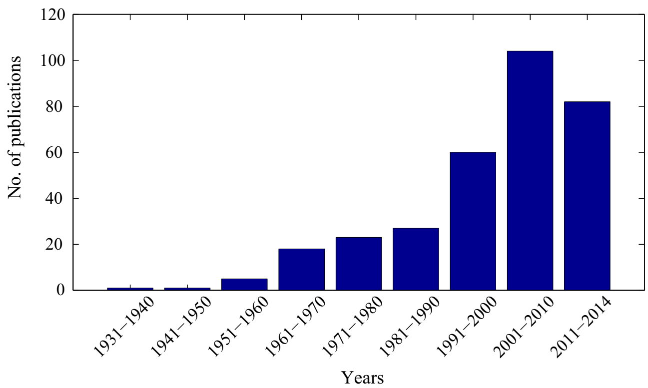

Fig. 1. Number of published papers on vortex tubes by decades.

very comprehensive. They looked at the experimental and computational studies done on the vortex tube through 2005 by separately summarizing the experimental and numerical studies.

A large number of experiments have been conducted so far on vortex tubes, and among them are the following. Hilsch [6] examined the effect of inlet pressure and geometrical parameters of the vortex tube by systematic experiments. Westley worked on determination of the optimum design of the vortex tube [10]. Takahama et al. [11–14] experimentally investigated the effect of size and geometry of the vortex chamber and the size and number of nozzles on energy separation. Soni [15,16] derived an empirical relation between the cold temperature drop and independent design parameters by using a regression analysis with the help of large number of test runs. Scheper [17], Hartnett and Eckert [18], Scheller and Brown [19], Lay [20,21], Vennos [22], Bruun [23], Linderstrøm-Lang [24], Ahlborn et al. [25–29], Gao [30], and Aljuwayhel et al. [31] analyzed the performance of the vortex tube by studying the temperature and/or velocity distributions in the vortex chamber. The model of Ahlborn et al. [25] predicts that the inlet velocity reaches the speed of sound for $X = 0.7$. Here X is the normalized pressure drop between the inlet and the cold exhaust port. No values of $X > 0.7$ could be obtained in these experiments and hence the flow always remained subsonic.

There are some studies by Stephan et al. [32,33] and Piralishvili and Fuzeeva [34] directed at a similarity relation for energy separation of geometrically similar vortex tubes. Guillaume and Jolly III [35] demonstrate that with equal inlet temperatures, a two-stage vortex tube (i.e., two vortex tubes operating simultaneously in series) produces a greater temperature separation than that produced by either one of the vortex tubes operating independently. Eiamsa-ard et al. [36,37] discuss the temperature separation and also the effects of cooling of a hot tube on the temperature separation and cooling efficiency in a counter-flow Ranque–Hilsch vortex tube. Valipour et al. [38,39] investigate the effect of geometrical parameters, i.e. diameter and length of main tube, diameter of outlet orifice, shape of entrance nozzle, on the cold temperature difference and efficiency, and also discuss the influence of uniform curvature of main tube on the performance of the vortex tube. Behera et al. [40] investigate the optimum cold end diameter and the length to diameter ratios and optimum parameters for obtaining the maximum hot gas temperature and minimum cold gas temperature through a computational fluid dynamics (CFD) analysis and experimental validation. Aydin and Baki [41] study the performances of counterflow vortex tubes as a function of the different geometrical parameters and three different working gases, air, oxygen and nitrogen, and it is found that the inlet pressure and the cold fraction are the important parameters influencing the performance. Skye et al. [42] discuss a comparison between the performance predicted by a CFD model and experimental measurements taken using a commercially available vortex tube to develop a design tool that can be used with confidence over a range of operating conditions and geometries. Hamoudi et al. [43,44] looked at the performance characteristics of a micro-scale vortex tube of diameter 2 mm by using a Reynolds number based on inlet tube hydraulic diameter and average velocity. Simões-Moreira et al. [45,46] find that the tube operating conditions that maximize flow parameters such as cold stream mass flow rate and cold stream differential temperature are mainly related to the inlet air pressure and hot orifice cross-section area. Simões-Moreira et al. [47] also discuss a thermodynamic air-standard cycle for vortex tubes to provide relevant thermodynamic analysis and tools for setting operating limits according to the conservation laws of mass and energy, as well as the constraint of the second law of thermodynamics. Xue et al. [48–53] investigated the flow structure at the interior of the vortex tube by flow visualization and measurements. They show the existence of multiple circulation regions within the vortex tube, and that the generation of the cold component of the flow is the result of expansion near the cold nozzle and the hot component is produced due to friction between the layers of flow.

There are also other experiments by Chang et al. [54], Dincer et al. [55,56], Im and Yu [57], Avci [58], Mohammadi and Farhadi [59], Liew et al. [60], Ramakrishna et al. [61], Agrawal et al. [62], and Liu and Liu [63]. They have all made experimental contributions to the study of vortex tubes by studying extensively the effect of different parameters on the temperature separation.

The present review has the following objectives. One is simply to bring the previous reviews up to date by including the papers published after 2007, while correcting some of the errors that crept in. Of a total of 470 papers on the Web of Science produced by the keywords “vortex tube,” 41.7% are dated 2008 or later. This is an indication of the great interest that this method of refrigeration has had in recent years, spurred no doubt by a desire to replace our current technology. Another goal is to combine the quantitative results obtained so far to enable rough predictions that can be used for practical design purposes. These predicted correlations are found by using the “fminsearch” solver of MATLAB that is based on the Nelder–Mead simplex method. The main focus will be exclusively on papers that report *experimental* results for two reasons: (a) experiments represent reality and take into account losses and other non-ideal flow conditions, and (b) though solutions of the complete laminar-flow governing equations can be obtained by computations, there is still no agreement on the basic principles on which the device operates. In addition, though the vortex tube has been used with other gases also, and sometimes with mixtures of gases for the purpose of separation, the review is only of experiments done with air. Dincer et al. [64] found that oxygen, carbon dioxide and nitrogen provide lower cold temperatures than air. Carbon dioxide is found to have lower hot and cold flow temperatures in compared the other fluids. The largest number of experiments have, of course, been done with air and, by keeping the working fluid fixed, its effect on the results is eliminated.

2. Background

A schematic of a vortex tube is shown in Fig. 2. Vortex tubes are also commercially available, and those designed for industrial applications

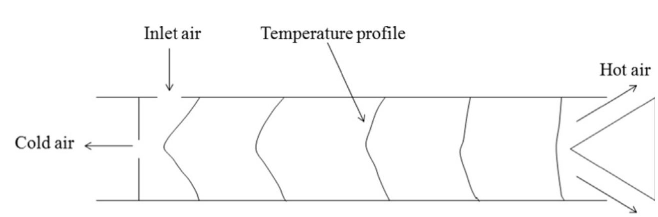

Fig. 2. Schematic of Ranque–Hilsch vortex tube.

produce a temperature drop of up to 70 °C. With no moving parts, no electricity and no Freon, a vortex tube can produce refrigeration of up to 1800 W using only filtered compressed air at 700 kPa. A control valve in the hot air exhaust adjusts temperatures, flows and refrigeration over a wide range. Vortex tubes are used for cooling of cutting tools (lathes and mills) during machining. The vortex tube is well-matched to this application: machine shops generally already use compressed air, and a fast jet of cold air provides both cooling and removal of the chips produced by the tool. This eliminates or drastically reduces the need for liquid coolant, which is messy, expensive, and environmentally hazardous. Hence, there is an increased interest in vortex tubes for this purpose.

Compressed air is pushed tangentially into a vortex chamber through one or more inlet nozzles. The air then proceeds down the tube, the flow consisting of a vortex with a forced vortex in the center and a free vortex in the periphery. At the far end of the tube (right side in the figure) there is an annular opening through which hot air exits. The tube must be long enough for temperature stratification to appear. The flow in the core of the vortex is blocked at this end, and so turns back and exits from the other side (left); this stream of air is cold.

Although there have been many studies, the exact mechanism of the temperature separation in vortex tube is still unclear. Different explanations have given by different researchers, and the following are some of them.

- *Compression and expansion*: Ranque [4] proposed that compression and expansion effects are the main reasons for the temperature separation in the tube. Simões-Moreira et al. [47] also pointed to compression phenomena as the driving force for temperature separation within the tube.
- *Viscous shear*: According to Hilsch [6], the air leaving through the orifice loses most of its kinetic energy by internal friction through expansion from a region of high pressure near the wall to a lower pressure near the axis. Hence, the air leaves through the orifice at the left with reduced temperature and the remaining part of air leaves to the right with increased temperature. Similarly, Aljuwayhel et al. [31] proposed that the energy separation is due to the work transfer caused by a torque produced by viscous shear acting on a rotating control surface that separates the cold flow region and the hot flow region. According to Ramakrishna et al. [61], temperature separation is due to the shear work transfer between the core and the periphery.
- *Angular motion*: According to Fulton [65], temperature separation is due to the transfer of energy between the air near the axis having higher angular velocity and the air at the periphery with lower angular velocity. Stephan et al. [32] suggest that the Görtler vortex produced by the tangential velocity on the inside wall of vortex tube is the driving force for the temperature separation.
- *Heat transfer*: Scheper [17] proposed that heat transfer from the vortex core outward due to static temperature gradients increases the stagnation temperature of the outer air stream which produces a hot flow at the right; meanwhile cold air flows through the orifice due to reduced stagnation temperature of the core. According to Linderstrøm-Lang [66], the energy separation is due to turbulent transfer of thermal energy in an incompressible flow.
- *Acoustic streaming*: Acoustic streaming processes are the mechanism for the energy separation according to Kurosaka [67].

Table 1
Independent and dependent parameters.

Independent		Dependent	
Cold orifice area	A_c	Cold air mass flow rate	$\dot{m}_c$
Hot annulus area	A_h	Hot air mass flow rate	$\dot{m}_h$
Tube cross-sectional area	A	Inlet air mass flow rate	$\dot{m}_i = \dot{m}_c + \dot{m}_h$
Inlet nozzle area	A_i	Cold mass fraction	$\mu_c = \dot{m}_c/\dot{m}$
Tube length	L	Outlet cold temperature	T_c
Inlet pressure	P_i	Outlet hot temperature	T_h
Inlet temperature	T_i	Inlet density	ρ_i
		Outlet cold density	ρ_c
		Outlet hot density	ρ_h

Of course, combinations of the above are possible. For example, Xue et al. [48,51] suggest that cold air stream is due to expansion near the cold nozzle and the hot stream is due to friction between the layers of flow. According to Ahlborn et al. [28], the combined process of formation of heating by the secondary stream formed due to primary vortex and the process of the conversion of kinetic energy into heat in the hot stream is the mechanism for the energy separation in the vortex tube.

3. Variables and definitions

Table 1 shows the independent and dependent variables involved in the vortex tube. Some of the independent parameters are geometrical, being those that depend on the mechanical design of the experiment such as cold orifice area A_c, hot annulus area A_h, tube cross-sectional area A, inlet nozzle area A_i, and tube length L. Others are the operating conditions like inlet pressure P_i (all pressures in this paper are absolute), and inlet temperature T_i. Both these sets of parameters can, in principle, be chosen by the experimenter. The dependent variables are values that cannot be independently chosen, but depend on the former. Since air is assumed to be the working fluid, its viscosity is fixed; the possible variation of viscosity due to temperature would be much smaller than the scatter in the data reported here so that a constant viscosity is a good approximation.

The following combinations of variables are of special importance.

Temperature changes: The cold temperature drop $\Delta T_c = T_i - T_c$ is the difference between inlet flow temperature and outlet cold flow temperature, and correspondingly the hot temperature rise $\Delta T_h = T_h - T_i$ is the difference between outlet hot temperature and inlet temperature.

Cold mass fraction: This is the ratio $\mu_c = \dot{m}_c/\dot{m}_i$, where m_c is the cold air mass flow rate and m_i is the inlet air mass flow rate. This depends strongly on the areas chosen for the two outlets.

Isentropic efficiency: Assuming the process in the vortex tube to be the isentropic expansion of an ideal gas, the isentropic cooling efficiency η_{is} is given by

$$\eta_{is} = \frac{\Delta T_c}{T_i - T_s}, \tag{1}$$

$$= \frac{\Delta T_c}{T_i\left[\left(\frac{P_i}{P_a}\right)^{(\gamma-1)/\gamma} - 1\right]}, \tag{2}$$

where T_s is the temperature after isentropic expansion, P_a is the standard atmospheric pressure, and γ is the specific heat ratio.

Coefficient of performance: The coefficient of performance COP is the ratio of the cooling rate obtained to the rate of work input to the device. It is given by

$$COP = \frac{Q_c}{W}, \tag{3}$$

$$= \frac{\mu_c c_p \Delta T_c}{\frac{\gamma}{\gamma-1} R T_i\left[\left(\frac{P_i}{P_a}\right)^{(\gamma-1)/\gamma} - 1\right]}, \tag{4}$$

Table 2
Data from the literature. Numbers in parenthesis in d_i column indicate number of nozzles used; no parenthesis means one nozzle; - indicates value not reported.

No.	Year	Ref.	D (mm)	L (mm)	P_i (atm)	d_i (mm)	d_c (mm)	$\mu_{c,opt}$	$\Delta T_{h,opt}$ (K)	$\Delta T_{c,opt}$ (K)	COP_{opt}	$\eta_{is,opt}$
1	1933	[4,5]	12	–	7	–	–	–	38	32	–	–
2	1947	[6]	4.6	230	7	1.1	2.2	0.23	13	45	0.0622	0.2074
3	1951	[17]	38.1	914	2	6.35	12.7	0.26	3.9	11.7	0.0479	0.1844
4	1956	[68]	9	450	6	2.3(2)	4	0.3	16.3	38	0.0584	0.1948
5	1957	[19]	25.4	1092	6.1	−(4)	9.53	0.506	15.6	23	0.0540	0.1067
6	1957	[18]	76.2	762	2.4	9.5(8)	0	0	3.5	40	–	–
7	1959	[20,21]	50.8	–	1.68	–	–	–	9.4	15.5	–	–
8	1968	[22]	41.3	1070	5.76	3.2(2)	15.9	0.35	−1	13	0.0244	0.0698
9	1969	[23]	94	520	2	21.5(2)	35	0.23	6	20	0.0718	0.3120
10	1983	[32]	17.6	352	6	4.1	6.5	0.3	18	38	0.0584	0.1948
11	1994	[25]	18	414	4	4.3	6.5	–	40	30	–	–
12	1996	[26]	25.4	600	3.7	–	–	0.4	9	27	0.0817	0.2042
13	2000	[29]	20	200	5	–	–	0.2	10	−55	0.0646	0.3229
14	2001	[35]	9.5	25.4	7	6.4	9.5	0.4	–	17.4	0.0320	0.0799
15	2003	[38]	18	1000	4	3.5(3)	9	0.6	–	43	0.1820	0.2830
16	2005	[36]	16	720	4.5	2	8	0.38	8	18	0.0424	0.1115
17	2005	[40]	12	120	5.4	3.17	6	0.41	26	24	0.0532	0.1298
18	2005	[31]	19	100	3	1	6	0.1	1.2	11	0.0100	0.0999
19	2006	[41]	18	750	6	6	5	0.2	15	50	0.0513	0.2563
20	2008	[44]	2	100	5	0.8	1.1	0.57	11.8	18.5	0.0618	0.1084
21	2010	[37]	16	720	4	2	8	0.3	4	17	0.0349	0.1163
22	2011	[55,56]	9	135	7.3	4.51	5	0.2	30	–	–	–
23	2011	[39]	19.05	400	4	–	9.5	0.24	5	21	0.0355	0.1481
24	2012	[57]	20	280	2	8.1	12	0.5	12	17	0.1304	0.2607
25	2014	[62]	10	175	4	2	4	0.6	–	26	0.1067	0.1779
26	2014	[63]	10	120	6	3.91	6	0.9	13.5	22.5	–	–

where $Q_c =$ rate of cooling, $W =$ rate of work input, c_p is the specific heat at constant pressure and R is the specific gas constant.

Optimum performance: Changing the independent parameters causes a change in ΔT_c. If the objective is to produce low temperatures, the optimum operating conditions can be taken to be when ΔT_c is the largest; the corresponding values of the variables are indicated by the subscript *opt*.

4. Experimental results

Some important parameters are mentioned in Table 2 for all studies to date for which the data have been reported. These are: diameter of the tube D, length of the vortex chamber L, inlet pressure P_i, inlet diameter d_i at the nozzle of the vortex tube, orifice diameter at cold outlet d_c, and finally the optimum values of cold mass fraction $\mu_{c,opt}$, hot temperature rise $\Delta T_{h,opt}$, and cold temperature drop $\Delta T_{c,opt}$. Not everyone reported the same data; in some papers, A_i and A_c were reported and were converted into d_i and d_c assuming circular cross-sections. In the performance studies of vortex tubes, the experiments have been conducted by varying some parameters and keeping other parameters constant. For example, the cold mass fraction is varied by varying inlet nozzle diameter, cold orifice area or hot annulus area for studies of temperature separations. Similarly, in some other investigations, temperature separations are analyzed by changing the L/D ratios. The hot annulus areas have not been provided in most of the papers, since the hot air stream is of lesser interest, and so they have not been included in Table 2.

4.1. Particular correlations

Fig. 3 shows the variation of optimum cold temperature drop with respect to inlet pressure at nozzle of the vortex tube. There is considerable scatter in the data, suggesting that P_i is not the only parameter on which $\Delta T_{c,opt}$ is dependent. The points are fitted

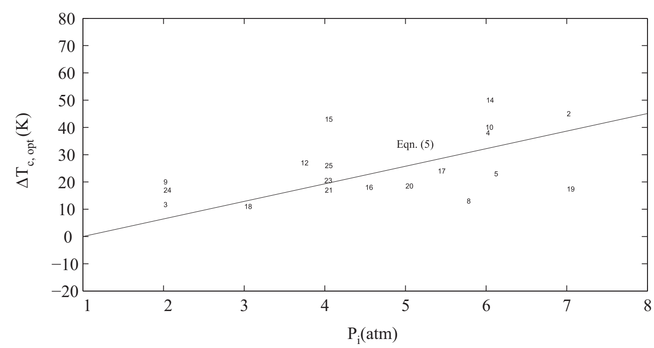

Fig. 3. Optimum cold temperature drop versus inlet pressure.

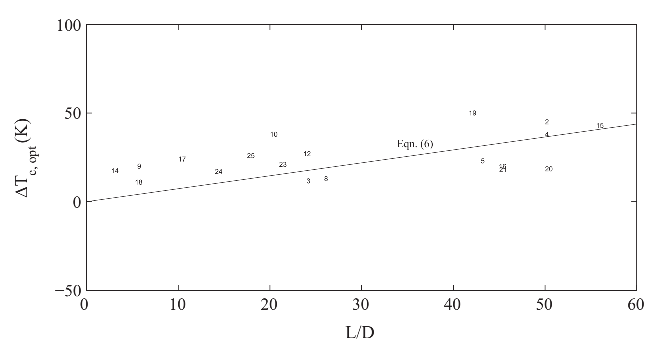

Fig. 4. Optimum cold temperature drop versus length–diameter ratio.

with the equation

$$\Delta T_{c,opt} = 6.4(P_i - P_a) \pm 77\%, \quad (5)$$

where $\Delta T_{c,opt}$ is in K, and P_i is in atms. 19 sets of experimental data are used, and the regression is a straight line that passes through $P_i = P_a$. This represents a linear increase in optimum cold temperature drop with increase of inlet pressure at the nozzle of the vortex

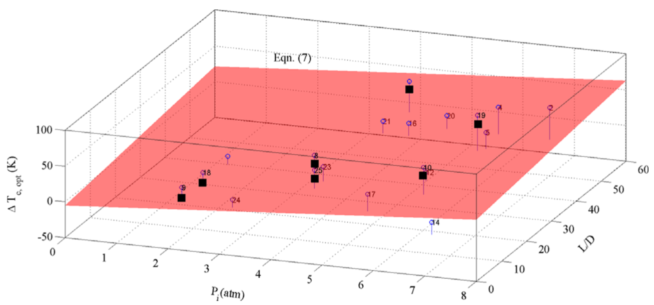

Fig. 5. Optimum cold temperature drop versus length–diameter ratio and inlet pressure in 3D plot.

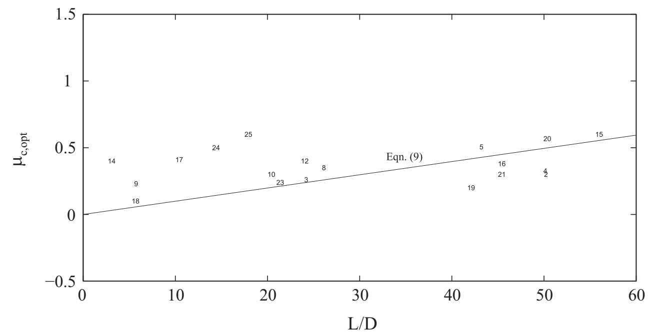

Fig. 7. Optimum cold mass fraction versus length–diameter ratio.

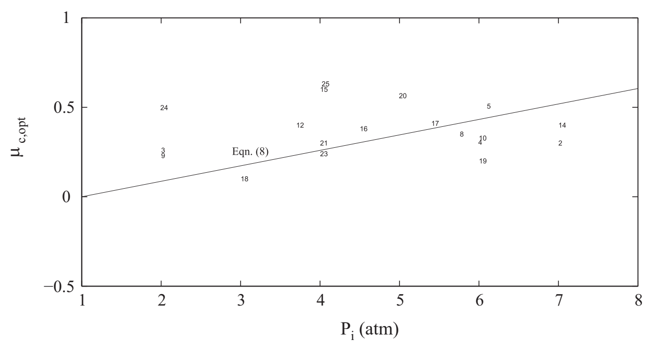

Fig. 6. Optimum cold mass fraction versus inlet pressure.

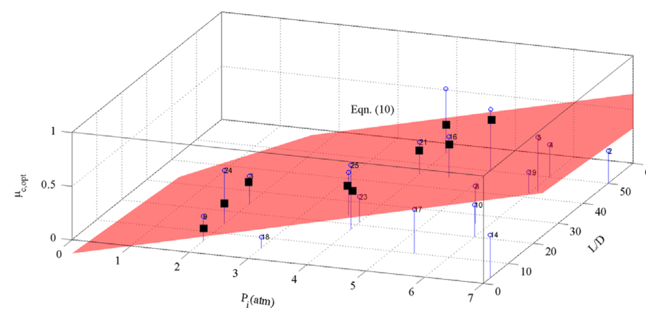

Fig. 8. Optimum cold mass fraction versus length–diameter ratio and inlet pressure in 3D plot.

tube. The error is the standard deviation of the scatter in the quantitative data.

Fig. 4 shows the variation of the optimum cold temperature drop with respect to length–diameter ratio of the vortex tube. The best-fit straight line that passes through the origin is

$$\Delta T_{c,opt} = 0.73\frac{L}{D} \pm 221\%. \tag{6}$$

The slopes of Eqs. (5) and (6) suggest that the temperature drop is more sensitive to a fractional change in pressure than to the tube length. This is why the scatter is more in Eq. (6) than in Eq. (5).

If the variation of $\Delta T_{c,opt}$ with respect to both P_i and L/D are considered, which are individually shown in the previous two figures, a 3D stem plot shown in Fig. 5 is obtained. The best-fit plane passing through $P_i = P_a$ and $L/D = 0$ is

$$\Delta T_{c,opt} = 5.2(P_i - P_a) + 0.44\frac{L}{D} \pm 51\%. \tag{7}$$

The filled squares represent the intersection of stems and the plane, so that it can be easily seen which points are above and which are below the plane.

Similarly, the measured optimum cold air fraction $\mu_{c,opt}$ can be considered. Figs. 6 and 7 show its variation with respect to $P_i - P_a$ and L/D, respectively, and Fig. 8 with respect to both. The corresponding linear best-fits are

$$\mu_{c,opt} = 0.086(P_i - P_a) \pm 140\%, \tag{8}$$

$$\mu_{c,opt} = 0.0099\frac{L}{D} \pm 350\%, \tag{9}$$

$$\mu_{c,opt} = 0.128(P_i - P_a) - 0.0021\frac{L}{D} \pm 120\%. \tag{10}$$

Again, the slope of Eq. (8) is larger than that in Eq. (9) and the scatter is less due to the greater importance of the inlet pressure compared to tube length.

Figs. 9 and 10 show the variation of the optimum coefficient of performance and the optimum isentropic efficiency, respectively, with respect to the optimum cold mass fraction of the vortex tube. The fits are

$$COP_{opt} = 0.17\mu_{c,opt} \pm 41\%, \tag{11}$$

$$\eta_{is,opt} = 0.41\mu_{c,opt} \pm 90\%. \tag{12}$$

These regression analysis of the experimental data show that the phenomena are not very well quantified by the linear fits proposed. The general trend is captured, but there may be considerable difference between predictions and actual experiments.

4.2. Overall correlation

The problem with the previous correlations is that they concentrate on one or two independent parameters when the process, of course, depends on all. Strictly speaking study of the data should begin with a dimensional analysis to first recognize the non-dimensional groups that play a role. Some of these non-dimensional design parameters are: A_c/A, A_h/A, A_i/A, and L/D. The input pressure and temperature can be nondimensionalized as $(P_i - P_a)/P_a$ and T_c/T_i. The Reynolds number is not included because it depends on the mass flow rate which is a dependent parameter once the geometry and pressures are prescribed.

Using these variables the available data, consisting of 15 sets of experiments, can be fitted with a power law. A_h/A have been left out since that information is not always available. Minimizing the squared error between the temperature-drop predictions and actual experimental measurements, the correlation comes out to be

$$\frac{\Delta T_{c,opt}}{T_i} = 0.045\left(\frac{P_i - P_a}{P_a}\right)^{0.32}\left(\frac{A_c}{A}\right)^{-0.36}\left(\frac{A_i}{A}\right)^{0.26}\left(\frac{L}{D}\right)^{0.12} \pm 24\%. \tag{13}$$

This, if no other information is available, is extremely useful for practical design. It is interesting to note that the scatter in this fit is

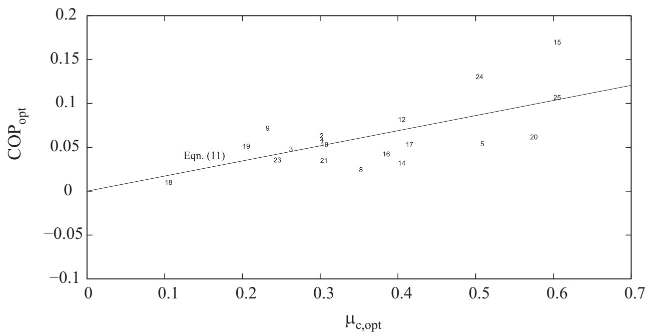

Fig. 9. Optimum coefficient of performance versus optimum cold mass fraction.

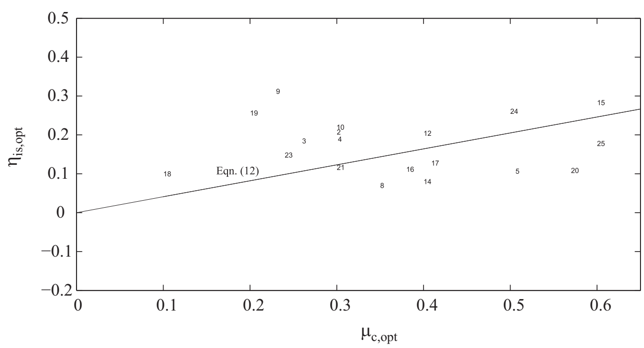

Fig. 10. Optimum isentropic efficiency versus optimum cold mass fraction.

much less than those in Eqs. (5)–(7), supporting the idea that all independent variables play a role in the process.

The other dependent values that can be calculated from measurements can be similarly correlated. Thus, it is possible to show that

$$\mu_{c,opt} = 0.42\left(\frac{P_i - P_a}{P_a}\right)^{-0.16}\left(\frac{A_c}{A}\right)^{0.51}\left(\frac{A_i}{A}\right)^{0.12}\left(\frac{L}{D}\right)^{0.35} \pm 44\%, \tag{14a}$$

$$COP_{opt} = 0.19\left(\frac{P_i - P_a}{P_a}\right)^{-0.50}\left(\frac{A_c}{A}\right)^{0.066}\left(\frac{A_i}{A}\right)^{0.32}\left(\frac{L}{D}\right)^{0.095} \pm 55\%, \tag{14b}$$

$$\eta_{is,opt} = 0.22\left(\frac{P_i - P_a}{P_a}\right)^{-0.37}\left(\frac{A_c}{A}\right)^{-0.36}\left(\frac{A_i}{A}\right)^{0.28}\left(\frac{L}{D}\right)^{0.12} \pm 24\%. \tag{14c}$$

The scatter is again less than those in Section 4.1. The equations in this section can also be used for design purposes.

5. Conclusions

The experimental literature on the Ranque–Hilsch vortex tube has been reviewed from invention to date. Only experimental studies with air as working fluid have been discussed, and all available results are displayed graphically. Best-fit correlations of the optimum performance of the device with respect to geometrical and operating parameters are presented. Among the parameters of interest are the cold temperature drop, cold mass fraction, coefficient of performance and isentropic efficiency. The equations presented here, especially Eq. (13), can be used for practical, preliminary designs of vortex tubes.

Further experiments need to be conducted for measurement of the performance variables as a function of all geometrical and experimental parameters. It has been mentioned that the role of the area of the hot stream A_h has not been sufficiently explored. Other aspects that need study are gas separation and dehumidification, both of which are possible applications of this device.

Acknowledgments

S.S. is grateful for a BASE Fellowship from the Department of Science and Technology, Government of India and the Indo-U.S. Science and Technology Forum (IUSSTF), and to the University of Notre Dame for its hospitality.

References

[1] Gosney WB. Principles of refrigeration. Cambridge, UK: Cambridge University Press; 1982.
[2] Dossat RJ. Principles of refrigeration. 3rd edition. . Englewood Cliffs, NJ: Prentice Hall; 1991.
[3] Steven Brown J, Piotr Domanski A. Review of alternative cooling technologies. Appl Therm Eng 2014;64(1–2):252–62.
[4] Ranque GJ. Expériences sur la détente giratoire avec productions simultanées d'un echappement d'air chaud et d'un echappement d'air froid. J Phys Radium 1933;4(7):112S–5S.
[5] Ranque GJ. Method and apparatus for obtaining from a fluid under pressure two outputs of fluid at different temperatures. US patent 1,952,281; 1934.
[6] Hilsch R. The use of the expansion of gases in a centrifugal field as cooling process. Rev Sci Instrum 1947;18(2):108–13.
[7] Westley R. A bibliography and survey of the vortex tube. Technical Report No. 9. Cranfield, UK: College of Aeronautics; 1954.
[8] Yilmaz M, Kaya M, Karagoz S, Erdogan S. A review on design criteria for vortex tubes. Heat Mass Transf 2009;45:613–32.
[9] Promvonge P, Eiamsa-ard S. Review of Ranque–Hilsch effects in vortex tubes. Renew Sustain Energy Rev 2008;12:1822–42.
[10] Westley R. Optimum design of a vortex tube for achieving large temperature drop ratios. Technical report no. 30. Cranfield, UK: College of Aeronautics; 1955.
[11] Takahama H. Studies on vortex tubes: (1) Experiments on efficiency of energy separation, (2) on profiles of velocity and temperature. Bull JSME 1965;8(31):433–40.
[12] Takahama H, Soga N. Studies on vortex tubes: 2nd report. Reynolds numbers. The effects of the cold air rate and partial admission of nozzle on the energy separation. Bull JSME 1966;9(33):121–30.
[13] Takahama H, Tanimoto K. Studies on vortex tubes: effect of the bend of a vortex chamber on energy separation. Bull JSME 1974;17(108):740–7.
[14] Takahama H, Yokosawa H. Energy separation in vortex tubes with a divergent chamber. ASME J Heat Transf 1981;103:196–203.
[15] Soni Y. A parametric study of the Ranque–Hilsch tube [PhD thesis]. University of Idaho, 1973.
[16] Soni Y, Thomson WJ. Optimal design of the Ranque–Hilsch vortex tube. ASME J Heat Transf 1975;97(2):316–7.
[17] Scheper GW. The vortex tube; internal flow data and a heat transfer theory. Refrig Eng 1951;59:985–9.
[18] Hartnett JP, Eckert ERG. Experimental study of the velocity and temperature distribution in a high-velocity vortex-flow. ASME J Heat Transf 1957;79:751–8.
[19] Scheller WA, Brown GM. The Ranque–Hilsch vortex tube. Ind Eng Chem 1957;49(6):1013–6.
[20] Lay JE. An experimental and analytical study of vortex flow temperature separation by superposition of spiral and axial flows: part I. ASME J Heat Transf 1959;81(4):202–12.
[21] Lay JE. An experimental and analytical study of vortex flow temperature separation by superposition of spiral and axial flows: part II. ASME J Heat Transf 1959;81(4):213–22.
[22] Vennos SLN. An experimental investigation of the gaseous vortex [PhD thesis]. Rensselaer Polytechnic Institute; 1968.
[23] Bruun HH. Experimental investigation of the energy separation in vortex tubes. J Mech Eng Sci 1969;11(6):567–82.
[24] Linderstrøm-Lang CU. Studies on transport of mass and energy in the vortex tube. The significance of the secondary flow and its interaction with the tangential velocity distribution. Technical report Riso report no-248. Riso: Danish Atomic Energy Commission; 1971.
[25] Ahlborn B, Keller JU, Staudt R, Treitz G, Rebhan E. Limits of temperature separation in a vortex tube. J Phys D: Appl Phys 1994;27:480–8.
[26] Ahlborn B, Camire J, Keller JU. Low-pressure vortex tubes. J Phys D: Appl Phys 1996;29:1469–72.
[27] Ahlborn B, Groves S. Secondary flow in a vortex tube. Fluid Dyn Res 1997;21(2):73–86.
[28] Ahlborn B, Keller JU, Rebhan E. The heat pump in a vortex tube. J Non-Equilib Thermodyn 1998;23(2):159–65.
[29] Ahlborn B, Gordon JM. The vortex tube as a classic thermodynamic refrigeration cycle. J Phys D: Appl Phys 2000;88(6):3645–53.
[30] Gao C. Experimental study on the Ranque–Hilsch vortex tube [PhD thesis]. Technische Universiteit Eindhoven; 2005.
[31] Aljuwayhel NF, Nellis GF, Klein SA. Parametric and internal study of the vortex tube using a CFD model. Int J Refrig 2005;28:442–50.

[32] Stephan K, Lin S, Durst M, Huang F, Seher D. An investigation of energy separation in a vortex tube. Int J Heat Mass Transf 1983;26(3):341–8.
[33] Stephan K, Lin S, Durst M, Huang F, Seher D. A similarity relation for energy separation in a vortex tube. Int J Heat Mass Transf 1984;27(6):911–20.
[34] Piralishvili SA, Fuzeeva AA. Similarity of the energy-separation process in vortex Ranque tubes. J Eng Phys Thermophys 2006;79:27–32.
[35] Guillaume DW, Jolly III JL. Demonstrating the achievement of lower temperatures with two-stage vortex tubes. Rev Sci Instrum 2001;72:3446–8.
[36] Promvonge P, Eiamsa-ard S. Investigation on the vortex thermal separation in a vortex tube refrigerator. ScienceAsia 2005;31:215–23.
[37] Eiamsa-ard S, Wongcharee K, Promvonge P. Experimental investigation on energy separation in a counter-flow Ranque–Hilsch vortex tube: effect of cooling a hot tube. Int Commun Heat Mass Transf 2010;37:156–62.
[38] Saidi MH, Valipour MS. Experimental modeling of vortex tube refrigerator. Appl Therm Eng 2003;23:1971–80.
[39] Valipour MS, Niazi N. Experimental modeling of a curved Ranque–Hilsch vortex tube refrigerator. Int J Refrig 2011;34:1109–16.
[40] Behera U, Paul PJ, Kasthurirengan S, Karunanithi R, Ram SN, Dinesh K, et al. CFD analysis and experimental investigations towards optimizing the parameters of Ranque–Hilsch vortex tube. Int J Heat Mass Transf 2005;48:1961–73.
[41] Aydin O, Baki M. An experimental study on the design parameters of a counterflow vortex tube. Energy 2006;31:2763–72.
[42] Skye HM, Nellis GF, Klein SA. Comparison of CFD analysis to empirical data in a commercial vortex tube. Int J Refrig 2006;29:71–80.
[43] Hamoudi AF. A investigation of a micro-scale Ranque–Hilsch vortex tube [Master's thesis]. University of Windsor; 2006.
[44] Hamoudi AF, Fartaj A, Rankin GW. Performance characteristics of a microscale Ranque–Hilsch vortex tube. ASME J Fluids Eng 2008;130 Art. No. 101206.
[45] Polisel RA, Rocha MS, Simões-Moreira JR. Parametric study of a Ranque–Hilsch or vortex tube. In: 19th international congress of mechanical engineering, Brasília, November 5–9; 2007.
[46] Pinto ML, Rocha MS, Simões-Moreira JR. Operating conditions of a Ranque–Hilsch or vortex tube. In: 21st Brazilian congress of mechanical engineering, Natal, Brazil, October 24–28; 2011.
[47] Simões-Moreira JR. An air-standard cycle and a thermodynamic perspective on operational limits of Ranque–Hilsch or vortex tubes. Int J Refrig 2010;33(4):765–73.
[48] Xue Y, Arjomandi N, Kelso R. Visualization of the flow structure in a vortex tube. Exp Therm Fluid Sci 2011;35:1514–21.
[49] Xue Y, Arjomandi M, Kelso R. Experimental study of the flow structure in a counter flow Ranque–Hilsch vortex tube. Int J Heat Mass Transf 2012;55:5853–60.
[50] Xue Y. The working principle of a Ranque–Hilsch vortex tube [PhD thesis]. Australia: School of Mechanical Engineering, University of Adelaide; 2013.
[51] Xue Y, Arjomandi M, Kelso R. Experimental study of the thermal separation in a vortex tube. Exp Therm Fluid Sci 2013;46:175–82.
[52] Xue Y, Arjomandi M, Kelso R. The working principle of a vortex tube. Int J Refrig 2013;36:1730–40.
[53] Xue Y, Arjomandi M, Kelso R. Energy analysis within a vortex tube. Exp Therm Fluid Sci 2014;52:139–45.
[54] Chang K, Li Q, Zhou G, Li Q. Experimental investigation of vortex tube refrigerator with a divergent hot tube. Int J Refrig 2011;34:322–7.
[55] Dincer K, Yilmaz Y, Berber A, Baskaya S. Experimental investigation of performance of hot cascade type Ranque–Hilsch vortex tube and exergy analysis. Int J Refrig 2011;34:1117–24.
[56] Dincer K. Experimental investigation of the effects of threefold type Ranque–Hilsch vortex tube and six cascade type Ranque–Hilsch vortex tube on the performance of counter flow Ranque–Hilsch vortex tubes. Int J Refrig 2011;34:1366–71.
[57] Im SY, Yu SS. Effects of geometric parameters on the separated air flow temperature of a vortex tube for design optimization. Energy 2012;37:154–60.
[58] Avci M. The effects of nozzle aspect ratio and nozzle number on the performance of the Ranque–Hilsch vortex tube. Appl Therm Eng 2013;50:302–8.
[59] Mohammadi S, Farhadi F. Experimental analysis of a Ranque–Hilsch vortex tube for optimizing nozzle numbers and diameter. Appl Therm Eng 2013;61:500–6.
[60] Liew R, Zeegers JCH, Kuerten JGM, Michalek WR. 3D velocimetry and droplet sizing in the Ranque–Hilsch vortex tube. Exp Fluids 2013;54:1416.
[61] Ramakrishna PA, Ramakrishna M, Manimaran R. Experimental investigation of temperature separation in a counter-flow vortex tube. J Heat Transf 2014;136 Art. No. 082801.
[62] Agrawal N, Naik SS, Gawale YP. Experimental investigation of vortex tube using natural substances. Int Commun Heat Mass Transf 2014;52:51–5.
[63] Liu X, Liu Z. Investigation of the energy separation effect and flow mechanism inside a vortex tube. Appl Therm Eng 2014;67:494–506.
[64] Dincer K, Bas KS, Kirmaci V, Usta H, Uysal BZ. Investigation of performance of a vortex tube with air, oxygen, carbon dioxide and nitrogen as working fluids (in Turkish). Eng Mach 2006;47(560):36–40.
[65] Fulton CD. Ranque's tube. Refrig Eng 1950;58:473–9.
[66] Lindstrøm-Lang CU. The three dimensional distribution of tangential velocity and total temperature in vortex tubes. J Fluid Mech 1971;45:161–87.
[67] Kurosaka M. Acoustic streaming in swirling flow and the Ranque Hilsch vortex tube effect. J Fluid Mech 1982;124:139–72.
[68] Martynovskii VS, Alekseev VP. Investigation of the vortex thermal separation effect for gases and vapors. Sov Phys-Tech Phys 1956;1(10):2233–43.