GAS LIQUEFACTION USING A RANQUE-HILSCH VORTEX TUBE: DESIGN CRITERIA AND BIBLIOGRAPHY

by

Kenneth George Hellyar

B.S.Ch.E., University of Massachusetts, Amherst (1969)

M.S., University of California, Berkeley (1971)

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Signature of Author: Signature redacted
Department of Chemical Engineering

Certified by: Signature redacted
Professor R. C. Reid, Thesis Supervisor

Accepted by: Signature redacted
Chairman, Departmental Committee on Graduate Theses

Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
September 21, 1979

Professor George C. Newton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Newton:

In accordance with the regulations of the Faculty, I herewith submit a thesis entitled "Gas Liquefaction Using A Ranque-Hilsch Vortex Tube: Design Criteria and Bibliography" in partial fulfillment of the requirements for the degree of Chemical Engineer in Chemical Engineering at the Massachusetts Institute of Technology.

Respectfully submitted,

Signature redacted

Kenneth George Hellyar

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DESIGN CRITERIA AND BIBLIOGRAPHY

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Kenneth George Hellyar

Submitted to the Department of Chemical Engineering on September 21,1979, in partial fulfillment of the requirements for the degree of Chemical Engineer.

ABSTRACT

The Ranque-Hilsch vortex tube is a device, with no moving parts, that produces two gas streams of different temperatures, from a high pressure inlet gas. One outlet stream is colder than the inlet and the other hotter than the inlet, with the relative temperatures being determined by the ratio of mass flow of any two streams, and the geometrical parameters of the vortex tube. The energy efficiency is much less than for more conventional refrigeration cycles, with the result that the vortex tube is used in situations requiring a device of high reliability and where high pressure gas is readily available. Since natural gas is often available at high pressures at the well-head, the possibility of using a vortex tube in liquefaction and separation processes using natural gas was reviewed. Particular emphasis was placed on design and operating criteria, and performance results reported in the literature. The separation of propane and higher molecular weight hydrocarbons from natural gas is feasible, but the liquefaction of methane and ethane using the vortex tube alone does not appear to be feasible.

An extensive bibliography of nearly 250 references is appended. This is a source of information on the historical development of the vortex tube as well as numerous applications not reviewed here.

Thesis Supervisor: Professor Robert C. Reid
Professor of Chemical Engineering

...even the purest truth comes on for trial, in time, in the market. That is, whatever abstract treasure you find when in delight you dive into the deepest mysteries of nature someone else sometime later will put to use in the world. And since such truths have real uses, what may happen to a people who have no use for such truths?

Elting E. Morison,

From Know-How to Nowhere

to

Professor Glenn C. Williams

and

Professor Robert C. Reid

PREFACE

My interest in the vortex tube began, while an undergraduate, when I bought an old issue of the Scientific American which told how to make a vortex tube (Stong, 1958). As a junior, I built and tested a vortex tube made from iron pipe, wrote up a report and gave an oral presentation. Further involvement came from correspondence resulting from the publication of my letter to the editor of the American Scientist ("The Hilsch Tube," American Scientist, p. 177, March/April 1971). During my first semester at M.I.T., Professor Robert C. Reid asked me if it would be possible to use the vortex tube in processes using natural gas. The result was a report which I submitted to him on December 21,1973. That report was slightly revised, updated and retyped in September 1979, and now appears as this Thesis.

Both Professor Glenn C. Williams and Professor Robert C. Reid have provided encouragement and assistance during my entire stay at M.I.T. They gave of their most valuable possession, their time, and have made it possible for me to submit this thesis. For shortcomings and errors contained herein, I alone am responsible.

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1 Introduction

The vortex tube, invented by Georges Ranque (1931) and brought to prominence by the work of Rudolf Hilsch (1946), is shown schematically in Figure 1. Gas under pressure is fed into the stem of the "T" shaped device and exits from both "arms" of the "T". The "stem" is tangential to the inner wall of the "arms". After leaving the inlet nozzle, the gas flows as a vortex down the hot tube. By adjusting a valve at the end of the hot tube, a fraction of the inlet gas is made to flow through an orifice or diaphragm in the hot tube. Gas entering the cold tube through the orifice originates mainly from the center of the vortex. The net effect is to separate a high pressure stream of gas into two low pressure streams, one hotter and the other colder than the original gas stream. This is the original design of the vortex tube and is often called a "counterflow" vortex tube. Other types of vortex tubes are possible but will not be considered here (see Torocheshnikov et alii, 1958; Lewellen, 1971; and Linderstrom-Lang, Risö Report No. 248, 1971).

Temperature data (Hilsch, 1947) for the gas streams from a vortex tube are plotted on an enthalpy-entropy diagram in Figure 2. Starting with inlet gas at the conditions represented by point 'a' (pressure of 4 atmospheres and temperature of 300 K), an isentropic expansion to a final pressure of one atmosphere would result in a final temperature of about 200 K. For an isenthalpic expansion to one atmosphere,

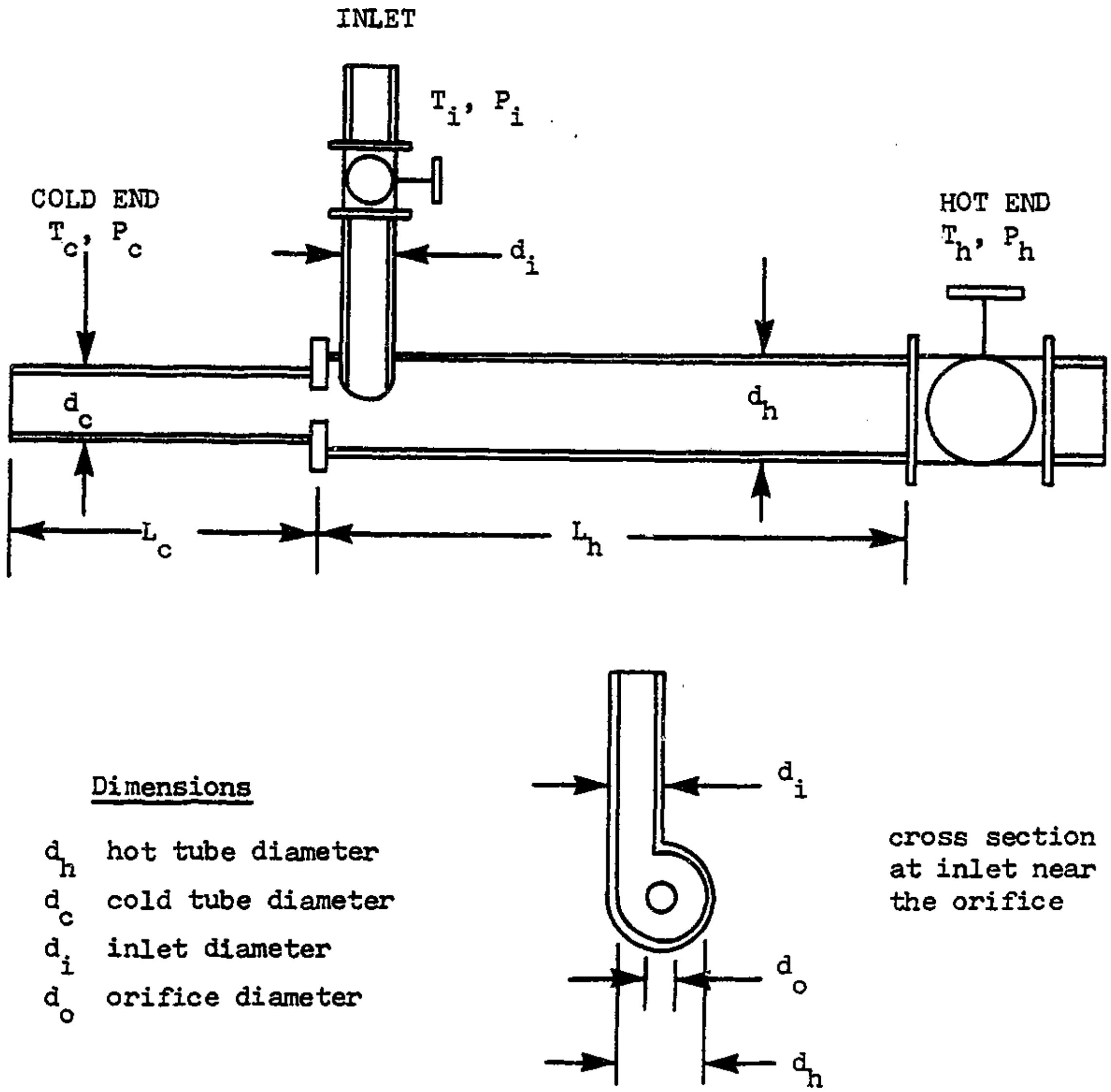

FIGURE 1. Schematic of the Ranque-Hilsch vortex tube.

such as occurs across a Joule-Thomson valve, there would be almost no temperature drop. The two slant dashed lines originating at 'a' represent the expansion of a gas in a Ranque-Hilsch vortex tube into two gas streams at different temperatures. The cold stream exits at 264 K and the hot stream at 315 K. Since the vortex tube operates essentially adiabatically, mixing the two gas streams together would result in a final gas mixture at the same temperature as resulted from the isenthalpic expansion. Although the vortex tube is not as efficient as an expansion machine, the fact that it rejects a fraction of the mass flow at a higher temperature (enthalpy) than the inlet gas means that is is potentially more efficient than a Joule-Thomson expansion process.

This thesis will be limited to reviewing gas liquefaction and separation processes employing the vortex tube, some of the criteria available for designing and operating a vortex tube, and a very brief discussion of the mechanism underlying the vortex energy separation effect. The historical development of the vortex tube, its use in airborne thermometry, cooling of aircraft and missile electronic components, cooling of suits for pilots and in industrial applications, use as a mass separation process, and similarities with the proposed gaseous fission rocket are not discussed here. A literature survey was conducted, with nearly 250 references listed in the bibliography, containing many topics not commented upon in this report.

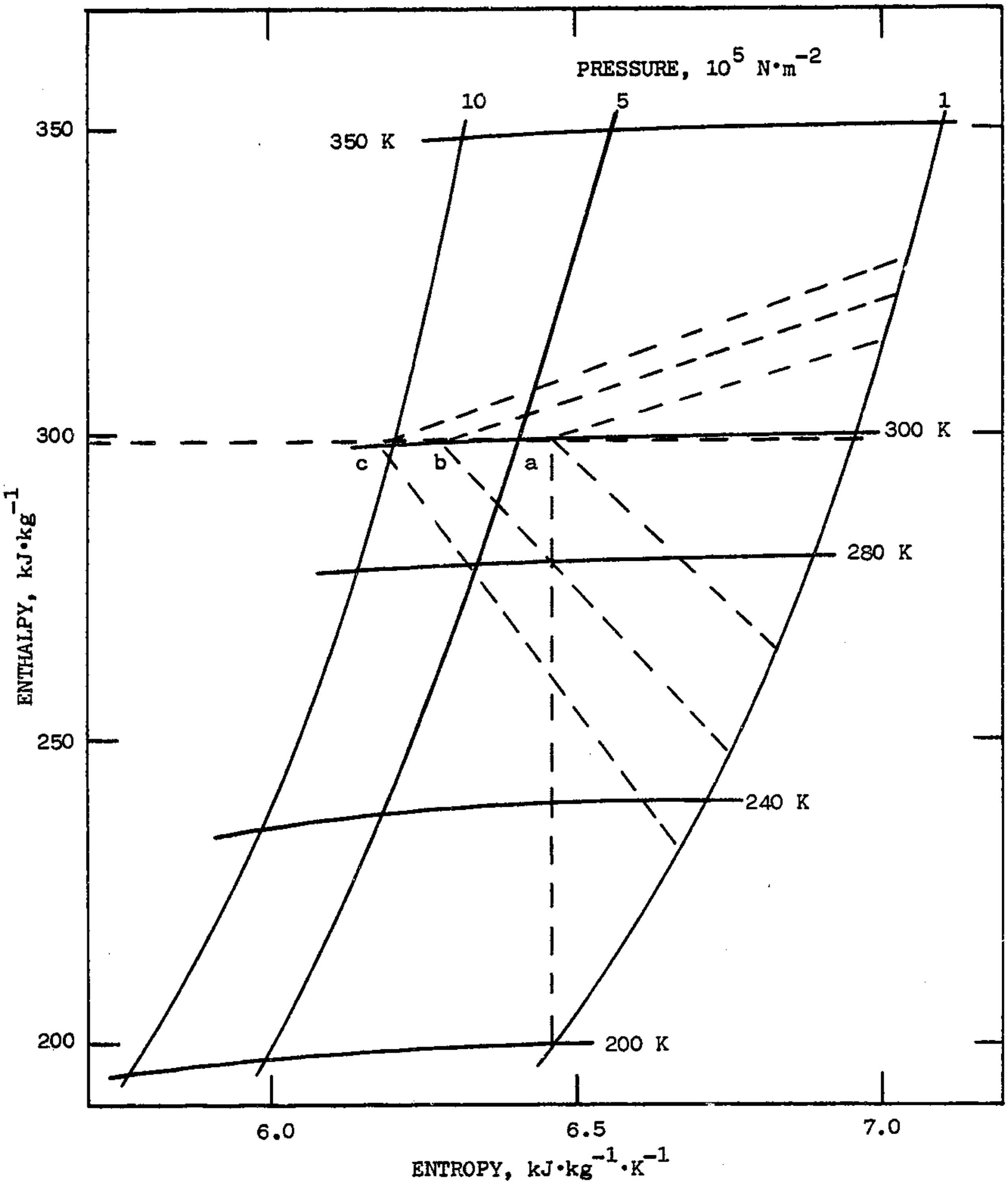

FIGURE 2. Performance data for a vortex tube (Hilsch, 1947) plotted on a Mollier diagram for air; tabulated data for air from Chemical Engineers' Handbook, 5th ed., p. 3-152.

Point	T_h	T_c	T_i-T_c	T_h-T_i	P_i
a	315	264	36	15	4
b	322	248	52	22	7
c	329	232	68	29	11

Data is for tube No. 3 having the following dimensions:

d_h = 17.6 mm

d_i = 4.1 mm

d_o = 6.5 mm

The ratio of mass flow out cold end to the total inlet mass flow was 0.3. Total gas flow at 11 atm was reported to be 97.0 m^3/hr.

TABLE 1. Performance data for a vortex tube (Hilsch, 1947). Points a, b, and c are plotted on Figure 2.

2 Liquefaction and separation processes employing the vortex tube

Since the vortex tube is not a very efficient refrigerator, the device has shown promise only in those cases where its simplicity of design is of primary importance or where compressed gas is available 'free'. One such case found in the petroleum industry involves the processing of natural gas. Natural gas wells may have a considerable pressure head and there is need for simple automatic processes to remove water and condensates from well-head gas. For petroleum companies in the western world, the principle sources of information concerning their vortex processes are the patent literature (Atkinson, 1954; van Dongen, 1957; Hendal, 1959; and Auer et alii, 1959) and articles by Metcalfe (1966) and Fekete (1967 and 1970). For the Russian gas industry, several articles have appeared in the literature (Raiskii, 1967; Krasovitskii et alii, 1969; Leites et alii, 1971; and Bazhenov et alii, 1976).

In Figures 3 and 4, two flow sheets redrawn from the articles authored by Fekete are shown. Figure 3 differs significantly from Figure 4, and highlights differences in concept and practice. The first flow sheet, Figure 3, was a proposal for a potential application of the vortex tube in gas-processing. In this process the cold stream from the vortex tube contained condensate and LP-gas. These were removed from the cold gas stream in the separator vessel shown. In the

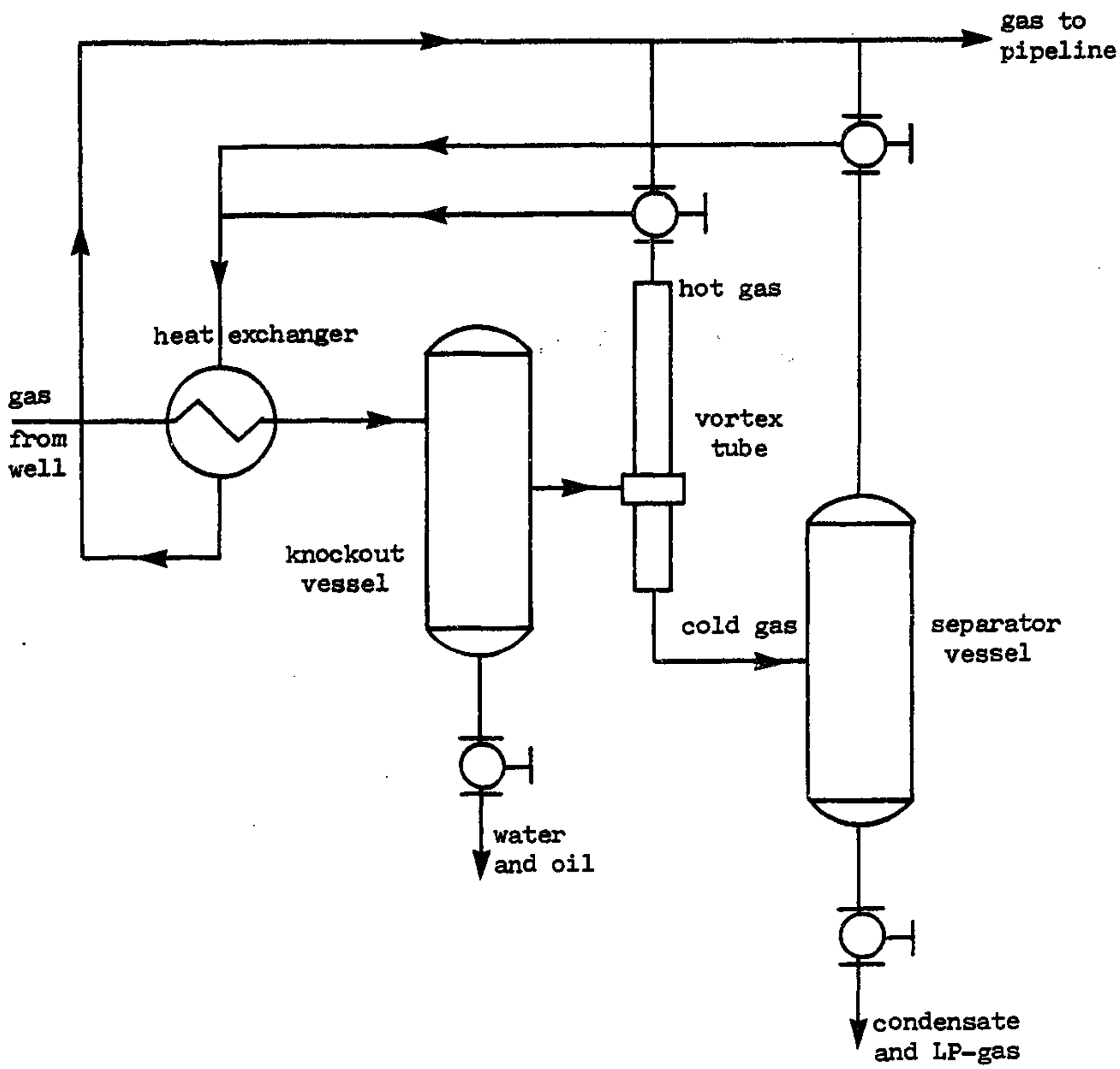

FIGURE 3. Proposed gas separator process using the vortex tube (Fekete, 1967).

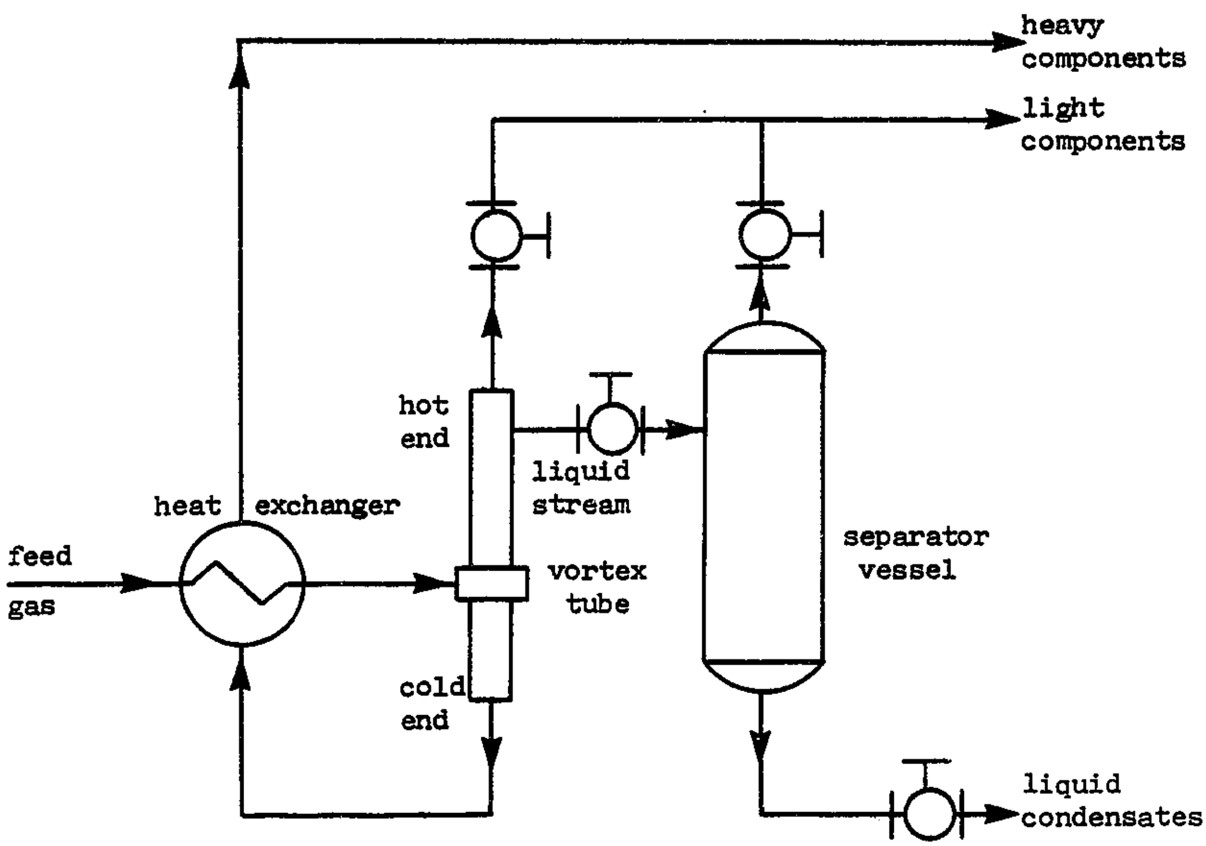

FIGURE 4. System used to field test vortex tube (Fekete, 1970). See also Table 2.

process field tested, Figure 4, the condensates appeared in the hot stream from the vortex tube. In addition to hot gas, a liquid stream is removed from the vortex tube, at the hot end, through a separate outlet, with the liquid being fed into a separator vessel. In the first process, it was proposed that the inlet feed gas be heated to break gas hydrates using the hot gas stream from the vortex tube. Alternatively, the cold gas stream from the separator vessel could be used to precool the feed and condense out water and oil. In field tests it was found that the hot gas stream did not provide enough heat to crack the hydrates, so this was performed in a fired heater. The Joule-Thomson effect and the effect of condensation in the hot tube was great enough to cool the 'hot' gas to about 20°F above the inlet temperature. As shown in Figure 4, the cold stream from the vortex tube was used to precool the feed to the vortex tube. Some other data from this field test are listed in Table 2.

TABLE 2. Field test of a vortex tube at an HNG-Petrochemicals gas-processing plant in 1969; see Figure 4.

Gas stream	Molecular weight
feed	35.0 g/g mol
gas, hot tube	34 to 38 g/g mol
liquid, hot tube	60 to 65 g/g mol

Feed contained 74% ethane, .4% methane, with the remainder higher molecular weights.

Inlet pressure was 600 psi (recirculated with a 15,000 hp compressor) and outlet pressure of 150-200 psi.

1967	Tenneco gas well in the Mississippi delta; a low-temperature field-gas separator of a high-pressure gas well.
1968	reworked gas well with a high water content
1969	HNG-Petrochemicals gas-processing plant (Figure 4 and Table 2)
1969	a Chocolate Bayou recycling plant near Houston dehydrating gas to meet pipeline specifications
1969	pipeline regulating station near Moorland, Woodward County, Oklahoma

TABLE 3. Gas-processing using the vortex tube (Fekete, 1970).

Fekete claims success in removing condensables, including water. He further states that, "the experiments show that if the quantity of condensables is less than 1% and may be dissolved by the gas, the separation is problematic." No design data were given for the vortex tube used, although it was claimed that it "differs in principle and in design from Ranque's early concept." It apparently differs in principle because the author claims liquids are removed from the gas due to centrifugal forces, rather than condensation, and differs in design because it is a "controlled-flow vortex tube." Details are probably contained in a patent awarded to him (Fekete, 1970).

Metcalfe (1966) reports that the vortex tube has been used commercially to cool high temperature gas reactors for shut-down. The compressors which would normally feed the reactor compressed gas are used to compress air for a vortex tube and the cold gas stream from the vortex tube is discharged through the reactor.

Figure 5 is a flow sheet for a Russian gas-processing pilot plant using a vortex tube to separate condensables from natural-gas (Leites et alii, 1971). The plant was planned to remove heavy hydrocarbons from natural-gas and thereby stabilize the gas for use in chemical processes such as the production of acetylene and the synthesis of ammonia where the presence of heavy hydrocarbons might cause soot formation in the reactors. Leites et alii report that the 'impurities' leave in the cold stream. They give data on the heat transfer coefficient in the spiral heat exchanger as a function of time, indicating fouling by the formation of gas hydrates. The heat exchanger is periodically cleaned by passing hot gas through it.

The amount of condensates appears to be a little less than that reported by Fekete for the depropanizer. Some equilibrium expressions are derived for the solubility of the lighter gas components in the condensate. Finally, Leites et alii give some design and operating

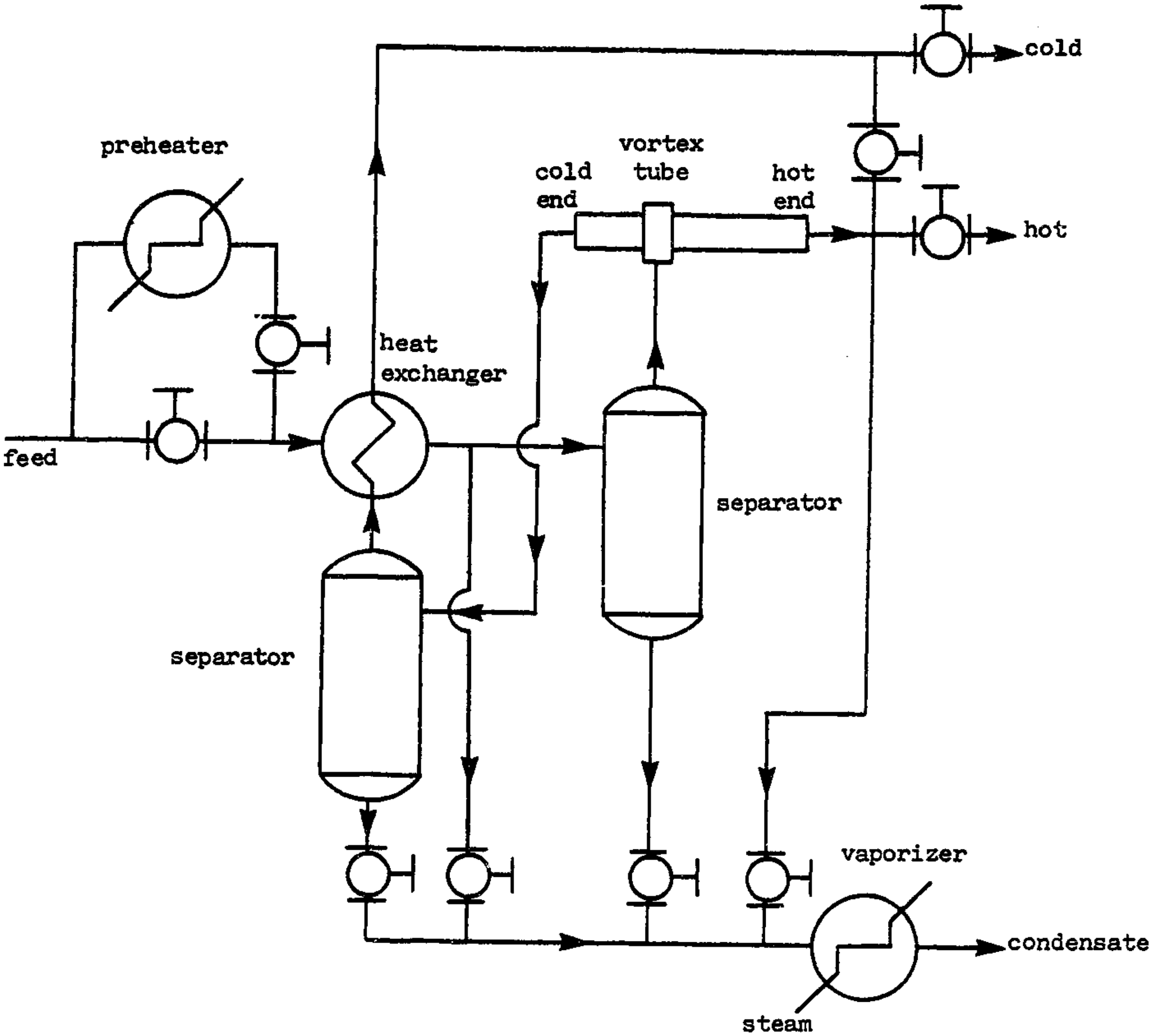

FIGURE 5. Flow diagram of a Russian plant for removing higher hydrocarbons from natural gas (Leites et alii, 1970).

TABLE 4. Data for Russian gas-processing plant shown in Figure 5.

DESIGN DATA

Vortex tube:

hot tube, diameter	70 mm
hot tube, length	1900 mm
cold tube, length	1400 mm
orifice, diameter	37 mm

orifice diameters of 35 and 40 mm were also tested

nozzle contained a single rectangular slit, 20mm x 10 mm, with the length along the axis of the tube; equivalent diameter is 13.3 mm

Heat exchanger:

spiral type heat exchanger with heat transfer area of 100 square meters

feed gas enters on the shell side and cold gas from the vortex tube enters on the tube side

OPERATING DATA

Feed:

1,000 to 5,000 m^3/hr ("normal conditions") of natural gas containing 2 to 40 g/m^3 of condensates (-70°C)

inlet pressure	10 to 40 atm
outlet pressure	2 to 9 atm

maximum temperature drops at cold flow rate/total flow rate of 0.2

P_i/P_c	T_i-T_c
4.0	70
3.5	59 - 60
3.0	53 - 54
2.5	39 - 40

data for the vortex tube, which seems to indicate that a very large vortex tube follows essentially the same design correlations as the smaller research vortex tubes. Plant details are given in Table 4.

To date there have been no reports of studies for the total liquefaction of natural-gas feed using the vortex tube. DiCuia and Pasik (1968) have studied the liquefaction of oxygen and nitrogen and found that precooling of the feed was necessary.

3 Design of the vortex tube

It is not yet possible to design a vortex tube from just the equations of fluid mechanics and thermodynamics. However, there are qualitative correlations, supported by some theoretical models, which will predict the principle design parameters and operating conditions near the experimentally determined optimum. It is also possible to predict qualitatively what performance change could be expected from a change in inlet gas temperature or pressure. In one instance a larger vortex tube was designed by simply scaling up a smaller research model (Otten, 1958).

It is convenient to consider the geometrical parameters necessary to design a vortex tube in terms of a characteristic length, which will be taken as the hot tube diameter just downstream of the orifice (d_h) (for symbols and their relation to the vortex tube, see also Figure 1). The principle remaining parameters are then: the cold tube diameter (d_c), the inlet gas nozzle diameter (d_i), the cold gas orifice diameter (d_o), and the lengths of the hot tube (L_h) and the cold tube (L_c). In more sophisticated designs additional factors msst be considered, such as the number and shape of the inlet gas nozzles, the vortex chamber shape, angle of divergence of the hot tube if conical rather than cylindrical, and the use of diffusers and vanes in the vortex tube.

The adjustable operating parameters are best considered as ratios. The pressure variable is expressed as the ratio of the inlet pressure (P_i) to the outlet cold gas pressure (P_c). In most cases it is the cold gas stream that is of greater interest, and this stream generally leaves the vortex tube at atmospheric pressure. Lorenz et alii (1961), Martynovskii and Voitko (1961) and Alimov et alii (1974) have studied the vortex tube at low pressure, where the cold gas stream leaves at a pressure of less than one atmosphere. The ratio of the inlet pressure to the hot gas pressure (P_h) could be specified, but generally a more useful parameter is the cold mass flow ratio Φ_c, the ratio of mass flow out the cold tube to the total inlet mass flow. The cold mass flow ratio is controlled by a valve on the end of the hot tube, which regulates the pressure in the hot tube. The dependent variable, the temperature of the outlet streams, may be expressed as the difference between the hot (T_h) or cold (T_c) exit temperatures and the inlet temperature (T_i). Gulyaev (1965) has studied the Ranque effect at inlet temperatures of 80 K. These temperature changes may be put in dimensionless form by dividing by either the inlet temperature or the isentropic temperature change. Most performance plots giving the lowest attainable temperature are expressed in terms of $\Delta T_c = T_i - T_c$, while the ratio $\Delta T_c / \Delta T_{isentropic}$ is most useful when considering the efficiency of the vortex tube, the maximum cooling per unit mass of inlet feed.

The vortex effect is also dependent to a small extent on the gas properties as expressed by the Prandtl number. This is in addition to any Joule-Thomson effect that may be present. This is discussed again later.

The vortex tube may be operated with the hot tube held at either adiabatic or isothermal conditions.

Figure 6 represents the general form of a performance plot most often seen for the vortex tube (Hilsch, 1947; Westley, 1957). Many plots do not include data for cold flow ratios below 0.1 or above 0.9, since the flow may become erratic and the temperature may reverse, with hot gas exiting through the cold tube (Martynovskii and Alekseev, 1956 and 1957).

A. Inlet nozzle

The pressure drop across the inlet nozzle generally exceeds the critical ratio of about 2 (nozzle inlet pressure/nozzle outlet pressure) for flow through a sharp edge orifice. Therefore, for an inlet gas of a given composition and temperature, the flow rate is proportional to the inlet pressure and the cross-sectional area of the nozzle and is independent of the downstream pressure, as discussed in most fluid mechanics texts. Hilsch (1947) gave the formula,

$$G = \text{constant} \cdot A \cdot P_i$$

where P_i = the inlet pressure, atmospheres

A = the area of the nozzle, mm^2

G = the rate of air flow, kg/hr

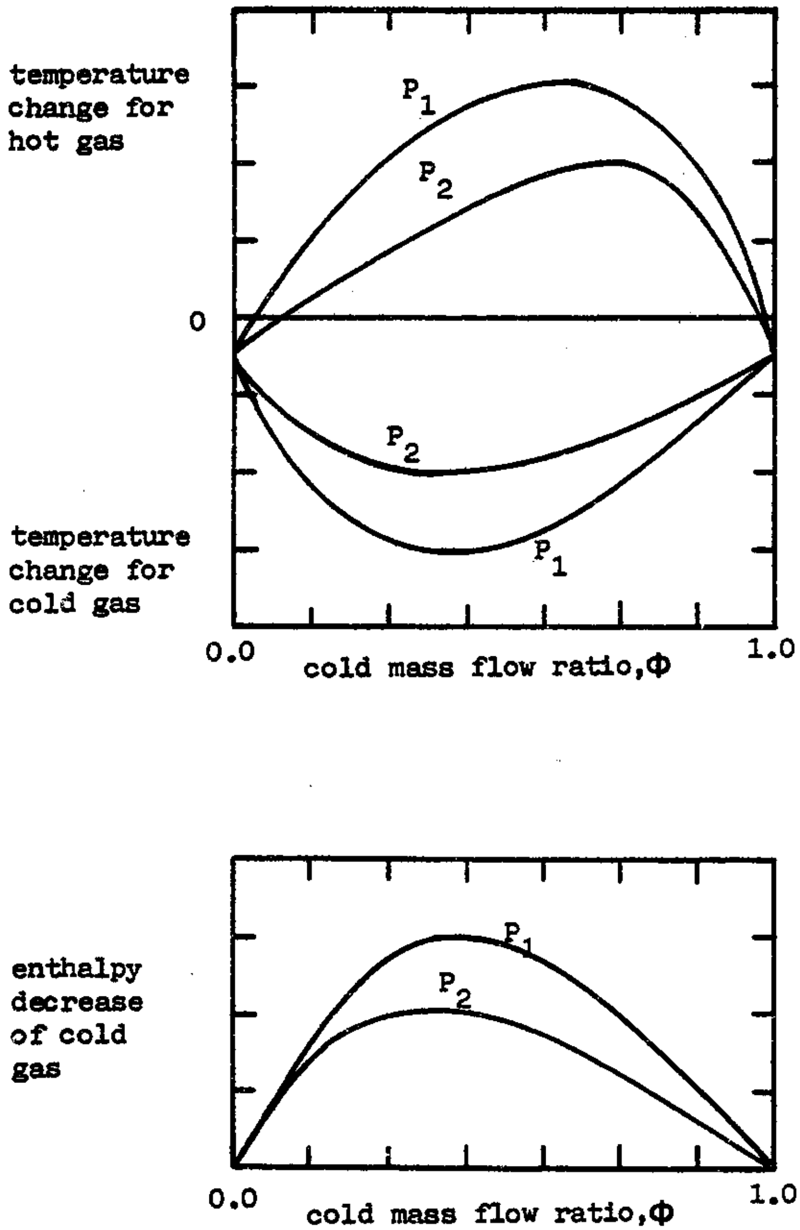

FIGURE 6. Generalized performance plots for a vortex tube operating at two different inlet pressures, where P_1 is greater than P_2.

The constant has a value of about 0.80 kg/(hr·mm^2·atm). Gulyaev (1966) has derived an expression for the flow rate in the vortex tube in which the gas properties and orifice coefficients for both the nozzle and the cold gas orifice are expressed explicitly.

In some vortex tube designs the inlet gas enters tangentially to the inner tube wall through multiple nozzles that have rectangular rather than circular openings. In these cases, the nozzle diameter is interpreted as the hydraulic diameter of the opening, given by the formula,

$$d_i = \frac{4(\text{total cross-sectional area})}{\text{total perimeter}}$$

Some other papers express the inlet nozzle parameter either in terms of a ratio of the area of the nozzle to the tube cross-sectional area, or as the ratio of some other hydraulic parameter to the tube diameter.

Experimentally, the optimum inlet nozzle diameter has been found to be about $0.25d_h$ (see, for example, Linderstrom-Lang, Risö Report No. 248, p. 91, 1971). Figure 7 (redrawn from Westley, 1957), shows the effect of different inlet nozzle diameters, at the optimum cold gas flow ratio and cold gas orifice diamter, on the maximum temperature drop. The temperature drop ratio used for the plot is $(T_i-T_c)/T_i$. The temperature drop ratio for a d_i/d_h of 0.266 will probably increase with the pressure ratio (P_i/P_c) until it reaches an asymptotic value

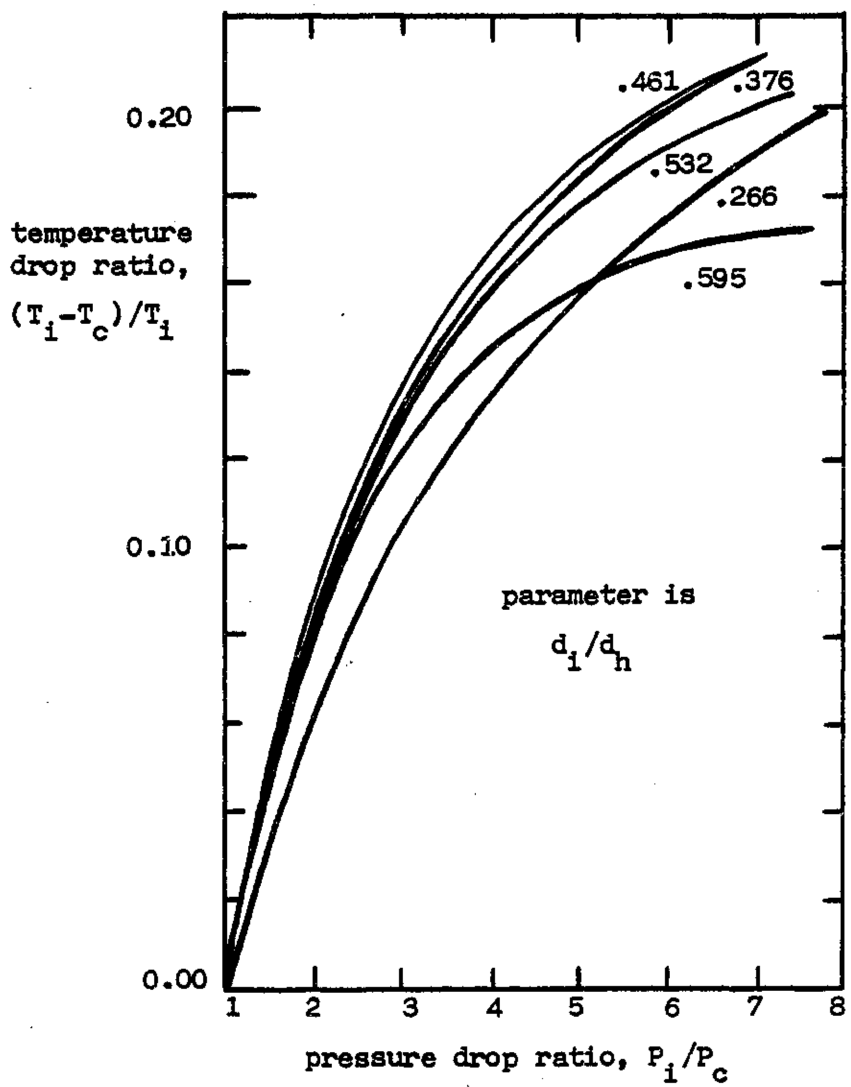

FIGURE 7. The temperature drop ratio as a function of the pressure drop ratio for optimum values of orifice diameter and gas flow rates, with the ratio of inlet tube to outlet tube diameters as the parameter (Fig. 47 from Westley, 1957).

greater than that for the other diameter ratios. There is probably little increase in the temperature drop ratio for values of P_i/P_c greater than 11 or 12.

B. Cold gas orifice

Experimentally, the optimum cold gas orifice diameter has been found to be about $0.4d_h$ to $0.5d_h$. The optimum diameter is a function of the gas flow rate through the orifice, hence it is a function of the pressure drop across the orifice and the cold gas mass flow ratio. If the orifice is too large, warm gas from the outer edge of the vortex is drawn through the orifice with the colder inner gas. However, if the orifice diameter is too small, there is a significant pressure drop across the orifice, and hence a smaller pressure drop across the inlet gas nozzle.

Westley (1957) has investigated the temperature drop for the full range of mass flow ratios and pressure ratios from 1 to 9 and has published 30 plots, each for a different setof d_i/d_h and d_o/d_h ratios. The ratio d_o/d_h was varied from 0.167 to 0.667, while the ratio of d_i/d_h was varied from 0.266 to 0.595. Data for two cases are reproduced in Figures 8 and 9. For both plots the inlet nozzle diameter is the same. The plot in Figure 8 is for a ratio of d_o/d_h of 0.250 and the plot in Figure 9 for a ratio of 0.667. The sharp peak at low cold mass flow ratios is typical for small values of the cold gas orifice diameter. With a larger orifice, the maximum temperature drop occurs

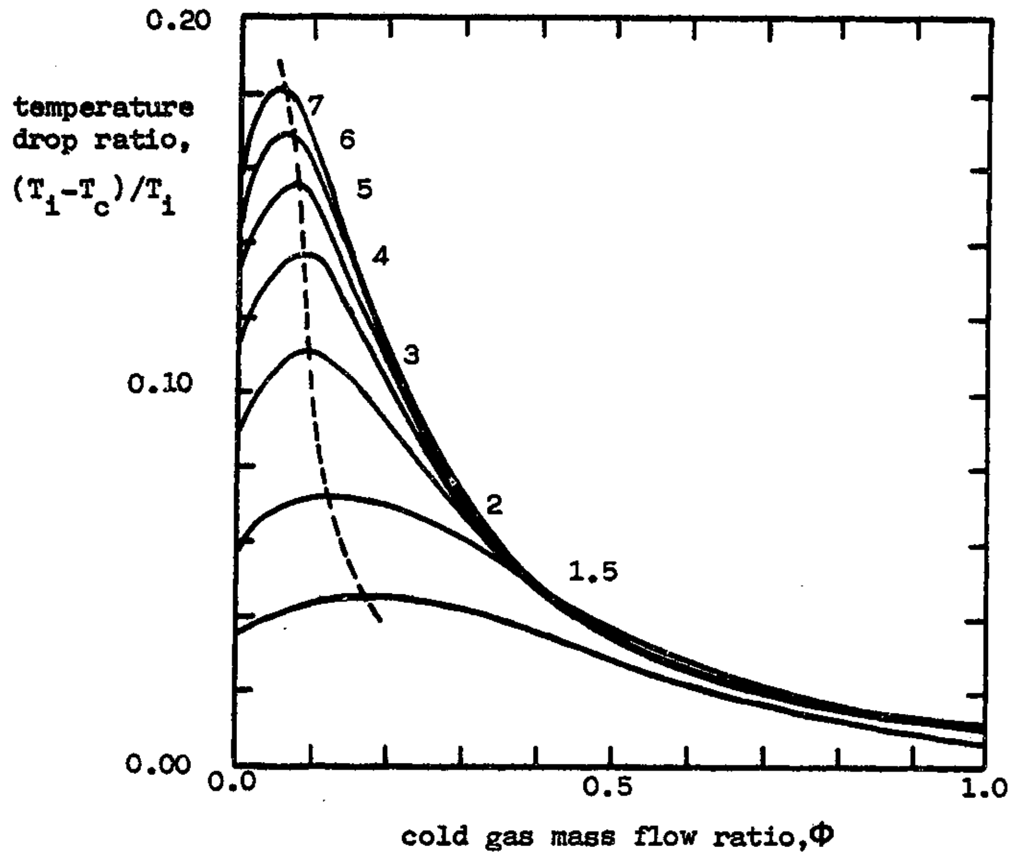

FIGURE 8. Temperature drop ratio as a function of cold gas mass flow ratio, with the pressure drop ratio as the parameter; $d_o/d_h = 0.250$ and $d_i/d_h = 0.461$ (Fig. 25 from Westley, 1957).

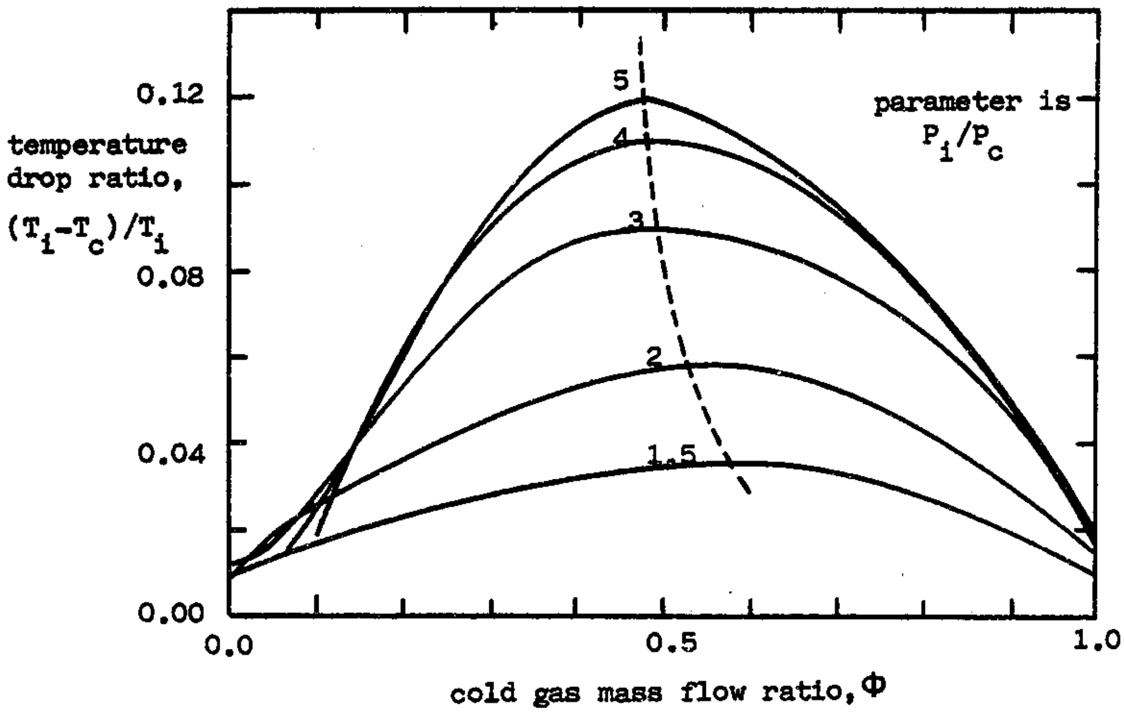

FIGURE 9. Temperature drop ratio as a function of cold gas mass flow ratio, with the pressure drop ratio as the parameter; $d_o/d_h = 0.667$ and $d_i/d_h = 0.461$ (Fig. 30 from Westley, 1957).

at higher mass flow ratios, but is not as great as at smaller orifice diameters. The data from plots like those in Figures 8 and 9 can be combined, as in Figure 10. The optimum cold outlet orifice diameter for this particular inlet nozzle diameter is nearly constant for the entire range of inlet pressure ratios. Westley presents five plots like Figure 10, with the results tabulated below.

TABLE 5. Optimum orifice diameters.

	Optimum d_o/d_h	
d_i/d_h	P_i/P_c=1.5	P_i/P_c= 7
.266	.34	.38
.376	.37	.38
.461	.40	.40
.532	.41	.37
.595	.36	.32

C. Length of hot and cold tubes

The earlier vortex tubes generally had hot tubes with lengths of about $50d_h$. However, from the work of Westley (1957) it appears that the only requirement is that the tube exceed $10d_h$. Lewellen (1971) states that, "as long as the tube wall is insulated the temperature separation in the tube should be unaffected by L_h/d_h as long as some minimum length is exceeded."

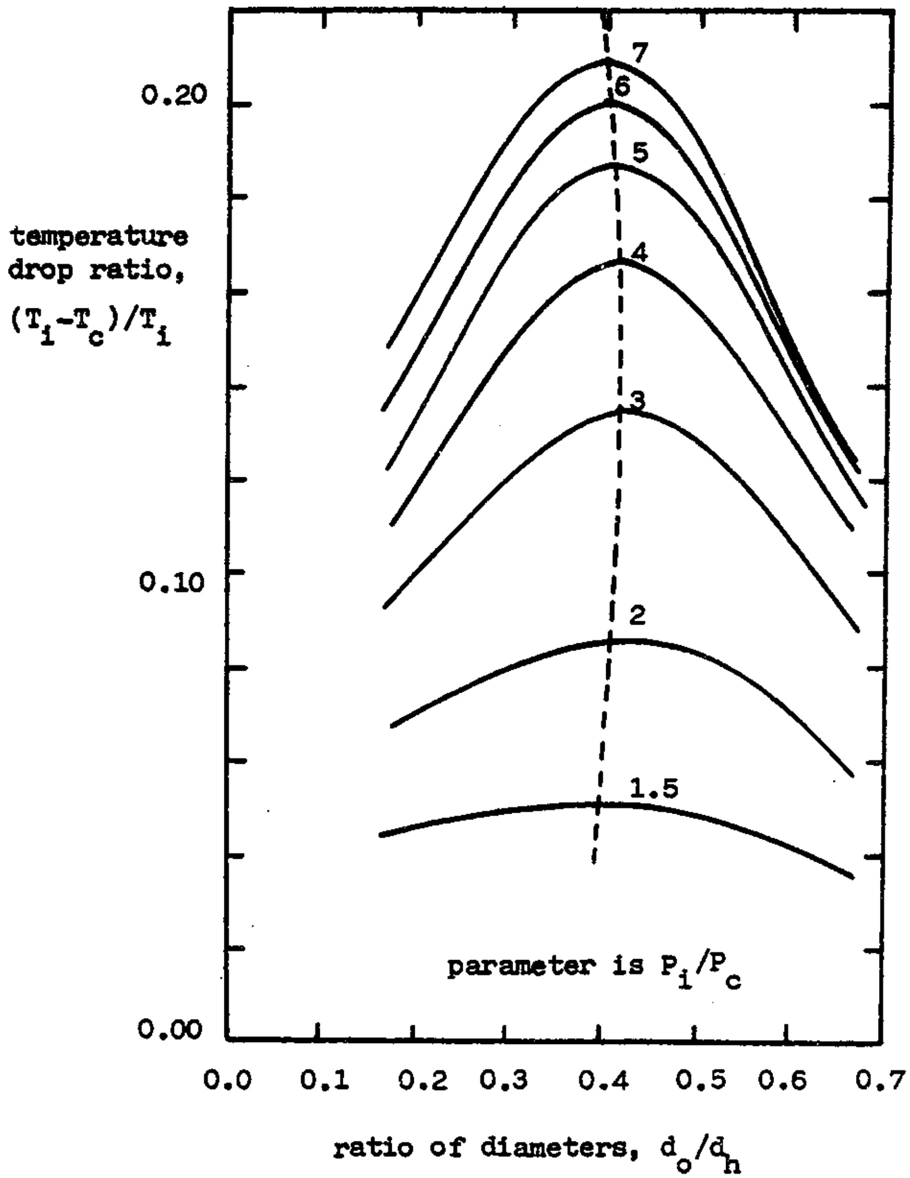

FIGURE 10. Temperature drop ratio as a function of ratio of orifice diameter to hot tube diameter, with pressure ratios as the parameter; $d_i/d_h = 0.461$ (Fig. 44 from Westley, 1957).

Gulyaev (1965 and 1966) also found that the minimum length for a cylindrical hot tube was about $10d_h$. If the hot tube is conical, rather than cylindrical, the minimum length must be increased, to about $13d_h$ for a tube with an angle of divergence of 2^o to 3^o. Otten (1958) has also shown that the vortex tube performance could be improved by using a conical tube. He reports an additional temperature drop of nearly 20^oC at a cold mass flow ratio of about 0.1, 10^oC for a ratio of about 0.5, and almost no effect at ratios larger than 0.9. Metenin (1964) has reported that conical tubes with a length of only $3d_h$ perform satisfactorily if a diffuser is added to the end of the hot tube.

Otten (1958) has shown that a water-jacketed vortex tube maintained at 15^oC may have a cold gas stream 10^oC colder than an uncooled tube (apparently exposed to ambient air) at a cold mass flow ratio of 0.8, but almost no effect at ratios of 0.4 or less. Heffaer (1959) has also investigated water-jacketed vortex tubes.

The length of the short tube has generally not been considered to be of importance. However, there are some reports that if the tube is made long enough so the vortex tube is symmetrical about the orifice, then a reversal of flow is possible at low flow rates (Dubinskii, 1955; Martynovskii and Alekseev, 1956 and 1957; and Linderstrom-Lang, p. 82, 1971). Torocheshnikov et alii (1958) show a symmetrical counter-flow tube which has no diaphragm or orifice. Both the hot and cold tubes are of equal length and both contain valves at the outer end. By adjusting the valve, hot or cold gas may be made to flow out either end.

D. Vortex chamber design

Most vortex chambers are circular with a single circular nozzle inlet. Martynovskii and Alekseev (1956) experimented with three different chamber configurations, including one called a "Hilsch whorl", and concluded that a circular chamber with two nozzles was the most efficient. Metenin (1961) uses six tangential nozzles and latter (1964) one nozzle leading into an Archimedian spiral. Leites et alii (1970), use a single rectangular nozzle on their large industrial vortex tube. Westley (1957) used multiple rectangular nozzles entering into a circular chamber. As long as the gas enters tangentially in a fairly smooth manner, it does not appear that elaborate nozzle or orifice chamber designs will significantly improve the vortex tube performance.

E. Pressure and temperature of the inlet gas

As was shown in Figure 7, the maximum temperature drop approaches an asymptotic value as the inlet pressure increases. This is more clearly illustrated in Figure 11, where the maximum temperature drop is plotted as a function of the pressure drop ratio for the optimum cold gas flow and the optimum inlet nozzle diameter and cold gas orifice diameter. The temperature drop approaches an asymptotic value of 0.22. For an inlet gas at 300 K, this corresponds to a maximum temperature drop of about 66 K. In Figure 2 data was shown for the vortex tube of Hilsch. With an inlet pressure ratio of 11, the temperature drop was 68 K.

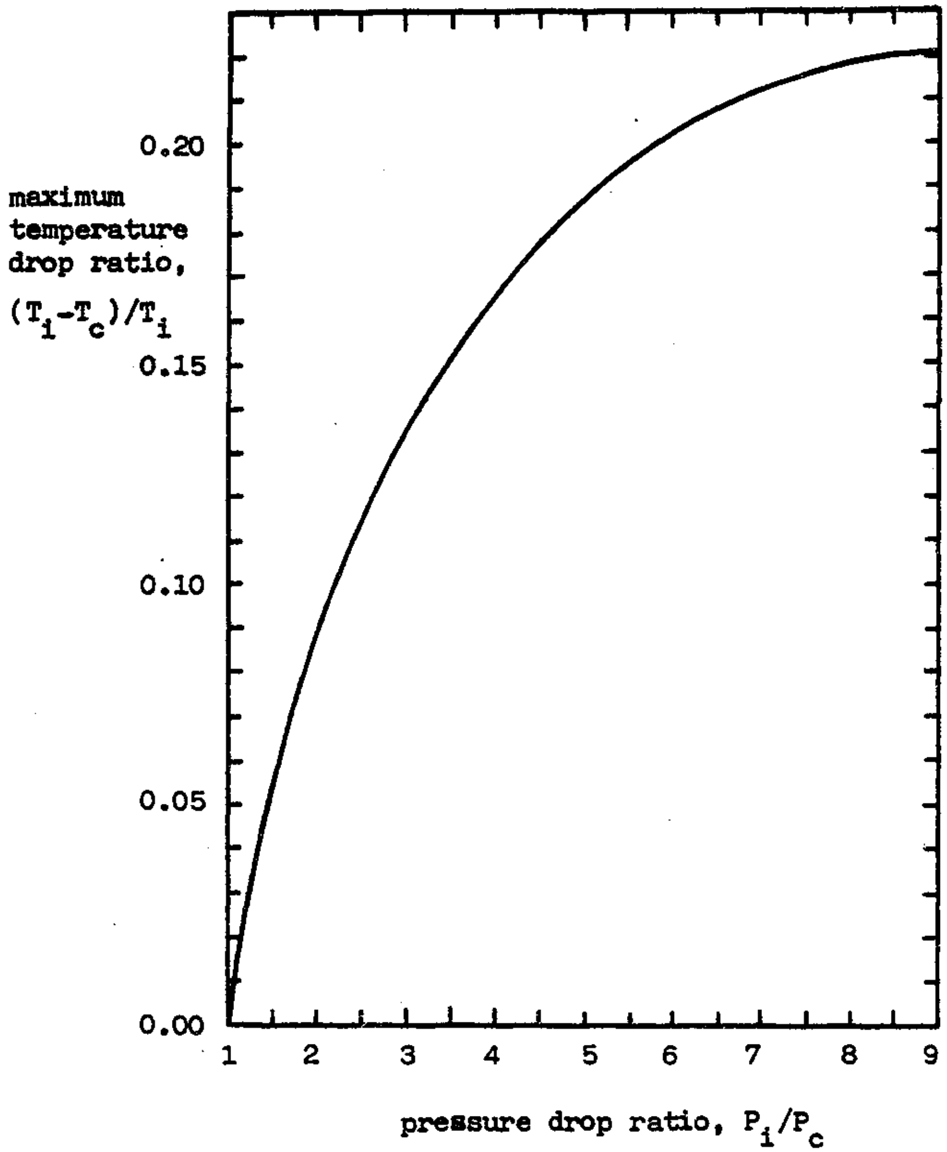

FIGURE 11. Maximum temperature drop ratio as a function of the pressure drop ratio; at optimum values of d_c, d_i and gas flow ratios (Fig. 49 from Westley, 1957).

Lewellen (1971) presents a very simplified analysis in which he predicts an asymptotic value of about 0.185, and writes, "although this is somewhat lower than Westley's asymptotic value of 0.22 it is close enough to suggest that the model is basically sound." Complete agreement could be obtained by a 10% change in the Prandtl number used in his model. This will be discussed more fully in the section on a theoretical mechanism for the Ranque-Hilsch effect.

As mentioned earlier, Gulyaev (1965) has investigated the Ranque effect for helium at 80 K, and has concluded that the cold gas temperature is approximately equal to a constant times the inlet temperature, or

$$\frac{T_i - T_c}{T_i} = \text{constant (for a given } P_i/P_c \text{ and } \Phi_c)$$

At the optimum conditions this constant should be the same as the asymptotic value mentioned above. He also noted that the ratio

$$(T_i - T_c)/(T_i - T_c)_{isentropic}$$

was nearly independent of the inlet gas temperature, but varied from a value of about 0.2 at a cold gas flow ratio of 0.8 to about 0.5 at cold gas flow ratios around 0.2 to 0.3.

It should be noted that the gas flow rate through a nozzle at a supercritical pressure ratio is proportional to the inlet pressure and to $T^{-1/2}$. Also, as a gas is cooled, the Joule-Thomson effect generally becomes more significant.

F. Gas properties

While most of the experimental work done with the vortex tube has been with air as the gas medium, a few other gases have been studied. Some temperature values from Martynovskii and Alekseev (1956) are listed in Table 6.

TABLE 6. Temperature drops for four different gases.

Gas	T_i-T_c [1]	Prandtl[2] number	Heat capacity[3] ratio
air	38.0	0.73	1.403
CH_4	40.0		1.31
CO_2	34.6	0.78	1.304
NH_3	30.0	0.85	1.310

1. The cold gas flow ratio was 0.3 in all four cases. $P_i/P_c = 5.0$
2. Bird, Stewart and Lightfoot, Transport Phenomena (1960), p. 256.
3. Perry (ed.), Chemical Engineers' Handbook, 3rd ed., p. 233. C_p/C_v data at 15°C except air, which is at 17°C.

The fact that air did not show a greater temperature drop than methane was explained by the fact that it contained some water.

Otten (1958) presents a "Correction factor for T_i-T_c" as a function of C_p/C_v. The cooling effect is considered to be proportional to the absolute inlet temperature. The ratio of the specific heats are used in connection with a plot giving the standard performance of a vortex tube operating with air. Otten also notes that if the ratio of specific heats varies with pressure or if the Joule-Thomson effect is important, "appropriate gas table should be used."

We might wonder what effect gas properties would have on a curve such as shown in Figure 11. Nonidealities in gas behavior will probably introduce a Joule-Thomson effect. Figure 11 is for air with an inlet temperature of about 70°F, where the Joule-Thomson cooling is small. (As previously noted, the temperature drop ratio is not a function of temperature, so temperature does not have an effect as long as the degree of nonideality of the gas does not change significantly over the temperature range involved.) As shown in Table 6, the maximum temperature drop appears to be inversely proportional to the Prandtl number, which may be the most significant measure of the influence of gas type.

Recently, Soni and Thomson (1975) have conducted a parametric study of the Ranque-Hilsch tube, leading to optimal design criteria similar to those given here.

4 Mechanism underlying the vortex energy separation effect

Ever since Georges Ranque first presented his explanation as to why the vortex tube 'works' (Ranque, 1933), and Brun (1933) criticized his experiments, there has been no generally accepted explanation for the mechanism underlying the vortex effect. There have been numerous theoretical and experimental papers published during the last thirty years, but our understanding of the processes taking place in a supersonic, turbulent, vortical flow is not yet sufficient to solve the fluid mechanical equations describing the vortex tube operation. The principle papers presenting theoretical analyses are those of Fulton (1950), Hartnett and Eckert (1956), Deissler and Perlmutter (1958 and 1959), Lay (1959), Suzuki (1960), Gulyaev (1965), Lewellen (1971), and Linderstrom-Lang (Risø Report No. 248, 1971). Together, these provide an adequate qualitative model which explains most of the phenomena observed with the vortex tube.

Fulton (1950) states that, "The theory Ranque gives in the patent, later rejected, is as follows: The rotating gas spreads out in a thick sheet on the wall of the tube and the inner layers of this sheet press upon the outer layers by centrifugal force and compress them, thus heating them. At the same time the inner layers expand and grow cold." It would be expected that most of the energy transfer between the two streams would occur in the vortex chamber, and not in the hot tube if this explanation were indeed correct.

In his address before the Societe Francaise de Physique, Ranque proposed another mechanism. It is summarized as follows: a short distance down the hot tube, the inlet gas forms an almost free vortex in which the angular velocity varies inversely as the square of the radius. Friction between the gas layers transforms this into a forced vortex in which the angular velocity is proportional to the radius. This causes the inner rotating gas to slow down, while the outer gas accelerates. This amounts to a flow of work from the central gas region to the outer gas layers. As the center gas does work, it cools, and there is a flow of heat to it from the hotter outer gas layers. However, the flow of work is greater than the flow of heat, so the central gas, which may have cooled somewhat due to the initial gas expansion, remains cool.

Fulton (1950) seems to have been the first to express the theory presented by Ranque, and supported by Hilsch, in a mathematical formulation. Martynovskii and Alekseev (1956) refer to this as "Fulton's hypothesis," and show that the ratio of the cold gas temperature drop to the isentropics temperature drop remains about constant, in agreement with tre hypothesis. It was pointed out earlier that Lewellen predicted the maximum temperature drop, at optimim conditions, using a model for the fluid mechanics, which was essentially that of the Fulton hypothesis. Deissler and Perlmutter (1960) have also concluded that "the most important factor affecting the total temperature of a fluid element in a compressible vortex is the turbulent shear work done on or by the element." They point out that turbulence is important for two effects: it causes the effective Reynolds number to remain low (where energy separation can take place), and the fact that "there is an additional energy separation in the turbulent case due to the expansion and contraction of the eddies as they move radially in the pressure gradient."

It is the case with most rotating flows that they can be considered as being composed of a primary flow and a secondary flow. Most studies have concentrated on the primary flow, the high velocity tangential component. As Bruun (1969) has shown, the radial and axial components are of the same magnitude, and result in many of the characteristics of the secondary flow, such as temperature reversal.

In Fulton's analysis he found the ratio of the work flux to the heat flux was equal to twice the laminar Prandtl number. Since that analysis, both the Reynolds number and Mach number have also been used as parameters. Lewellen (1971) pointed out some difficulties in obtaining a turbulent Prandtl number. (Fulton wrote, "Is the turbulent Prandtl number equal to the laminar Prandtl number? . . . they should be . . ."). There is little convincing evidence that the Prandtl number is the most important parameter, but it seems likely that it is significant, because the vortex effect is probably due to a form of viscous work. Experiments with gases having different Prandtl numbers also support this.

Finally, Linderstrom-Lang provides the following analogy (1971), "It is helpful for the understanding of the functioning of the vortex tube, . . . , to recognize that the tube may be viewed as a generalized type of heat exchanger with total enthalpytransported and conserved. A special feature of the transport is that equilibrium between the two streams does not imply temperature equality but a total temperature difference determined by the pressure gradient (the tangential velocity). The system therefore resembles chemical separation units such as distillation columns."

5 Conclusions and recommendations

1. Liquefaction of a small fraction of the gas feed appears to be possible. Studies are needed to define how much gas can be liquefied and which end of the vortex tube it is likely to emerge. Studies of two phase flow in the vortex tube are needed.

2. Data are available for estimating the general design and operating parameters. However, any installation where efficiency is of particular importance still requires that the vortex tube be optimized by experiments. Studies of the design and operating parameters where the inlet and cold gas outlet pressures are high are needed to see if the correlations developed for pressures in the range of 1 to 10 atmospheres are still valid. Staging vortex tubes in a cascade appears to be an obvious way to improve the efficiency of a liquefaction process where feed gas is available at very high pressures.

3. Theoretical developments are limited by our understanding of turbulent vortical flow. Further developments in understanding the mechanism of turbulent heat transfer may make it possible to develop a more rigorous mathematical theory giving more quantitative predictions.

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The march of Providence is so slow, and our desires so impatient, the work of progress is so immense, and our means of aiding it so feeble, the life of humanity is so long, and that of the individual so brief, that we often see only the ebb of the advancing wave, and are thus discouraged. It is history that teaches us to hope.

Robert E. Lee

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