Sept. 28, 1965 | C. D. FULTON | 3,208,229

VORTEX TUBE

Filed Jan. 28, 1965 | 2 Sheets-Sheet 1

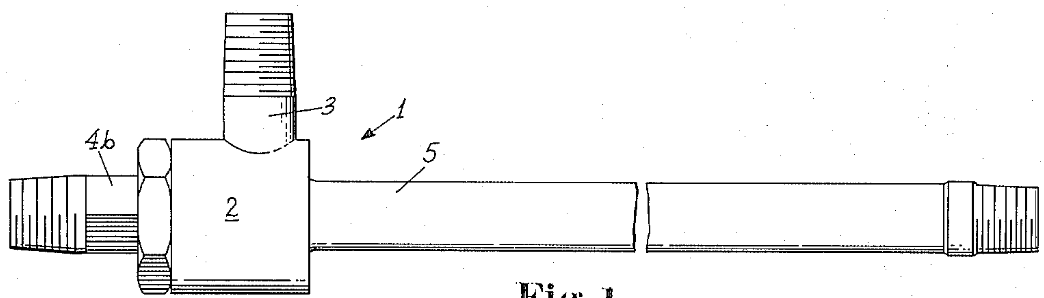

Fig. 1

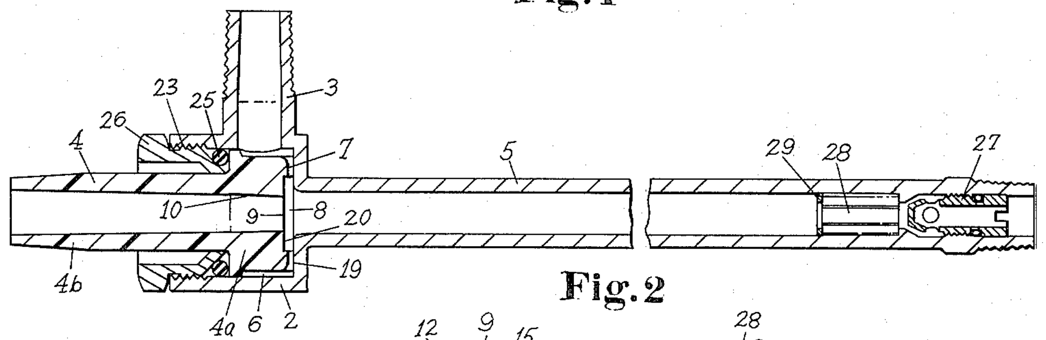

Fig. 2

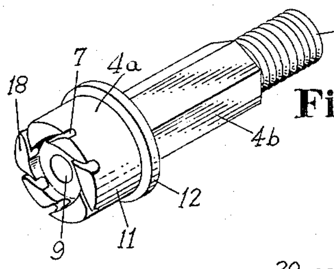

Fig. 3

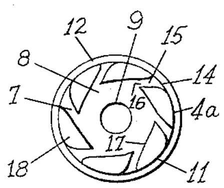

Fig. 4

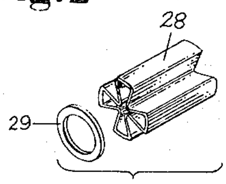

Fig. 6

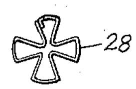

Fig. 7

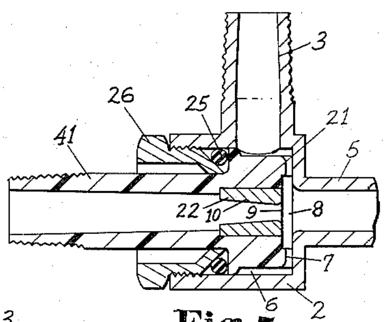

Fig. 5

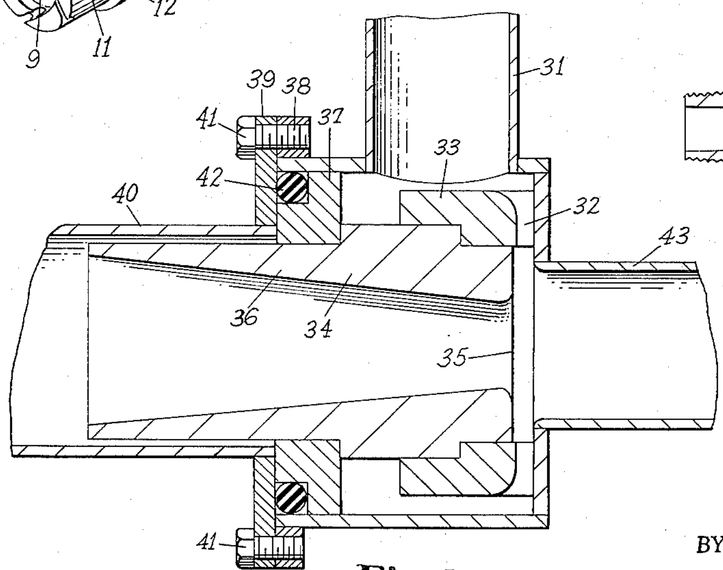

Fig. 8

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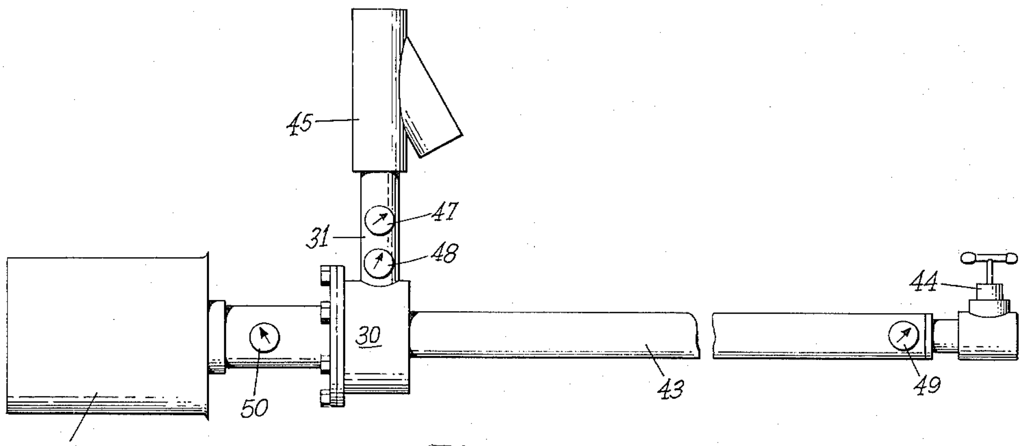

Fig. 9

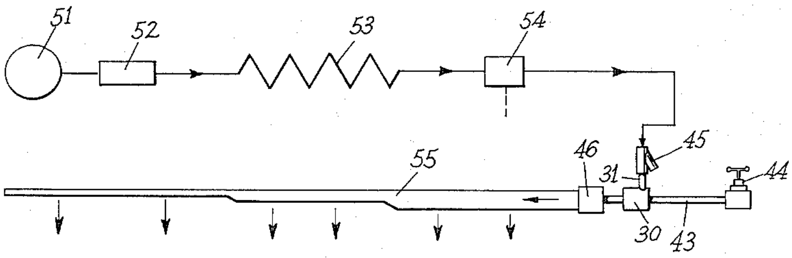

Fig. 10

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VORTEX TUBE

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Filed Jan. 28, 1965, Ser. No. 430,511
9 Claims. (Cl. 62—5)

This is a continuation-in-part of the copending application, Serial No. 240,381 filed November 27, 1962, now

The present invention relates to improvements in vortex tubes and relates more specifically to the design and construction of vortex tubes capable of emitting colder and hotter streams of gas, operating more efficiently, being more compact and more cheaply manufactured, and being more readily applied to useful purposes.

In approximately 1311, Georges Joseph Ranque of France developed a device or apparatus commonly referred to as a vortex tube, Ranque tube, Hilsch tube, or Ranque-Hilsch tube, the basic concept of which is shown in U.S. Patent No. 1,952,281. During the ensuing decade, little or no mention of this invention appeared in the scientific literature, nor did there arise any general interest in this unique phenomenon and achievement. In 1945, Rudolph Hilsch of Germany published an account of studies which he had made on vortex tubes. Thereafter there arose a worldwide interest in the subject and many treatises were published on the perplexing phenomenon offered by the vortex tube.

The great amount of interest attaching to the vortex tube is readily apparent upon witnessing a demonstration of this device in operation. Compressed air is fed into what resembles a T fitted with pipes on either side. Cold air thereupon issues steadily from one pipe and hot air issues steadily from the other. The cold stream of air is often visible as a light blue mist and forms frost on the pipe and on other objects which it touches. Temperature well below zero Fahrenheit are produced. At the other end of the device, the hot air stream, when the device is adjusted properly, reaches temperatures well above the boiling point of water. All of these results take place in an instrument having no moving parts and being extremely compact in size and in some cases no larger than a pencil. The simplicity of the vortex tube and its component parts enables it to be manufactured at a remarkably low cost. The absence of moving parts endows the device with extremely long life and trouble-free operation. Any gas whatsoever may be utilized in the device with substantially the same results. The device may be constructed of any size according to the quantity of gas flow which is desired. The physical phenomenon displayed by the vortex tube is unique and unparalleled by any other known phenomenon. Given a source of compressed air or other gas, the vortex tube affords the simplest and most direct known means of creating heat and cold.

The development of vortex tubes capable of operating with sufficient efficiency and economy would make it possible to revolutionize portions of such technological fields as refrigeration, air conditioning, cryogenics, instrumentation, and controls. The primary factor impeding the widespread utilization of the vortex tube has been its low thermodynamic efficiency—i.e., the high gas pressure required to create the desired temperature changes, the small fractions of the supplied gas delivered at the lowest and highest temperatures, and altogether a large expenditure for machinery, such as compressors, and for power. The improved vortex tube which is the object of this invention is capable of alleviating these difficulties by virtue of its increased efficiency and therefore of advancing the long-sought utilization of vortex tubes in the aforementioned technological fields.

Ranque taught certain embodiments of his invention including what are referred to as counterflow and uniflow types although it has since appeared that the counterflow type is superior for the emission of separate cold and hot gas streams. Ranque also taught various designs of tangential nozzles for producing the vortex while Hilsch employed a single nozzle leading into a spiral ramp.

The counterflow vortex tube comprises a long, slender tube with a diaphragm closing one end of the tube and a small hole in the center of the diaphragm, one or more tangential nozzles piercing the tube just inside the diaphragm, and a throttling valve at the far end of the slender tube. The function of the counterflow vortex tube is to receive a flow of compressed gas through the nozzles and to discharge a stream of cold, expanded gas through the small hole in the diaphragm, and a stream of hot, expanded gas through the valve. In the event the throttling valve is not employed, a vacuum is created in the center of the tube and atmospheric air is drawn in through the small hole, and no cold gas is emitted. The same results as are yielded by the use of the valve will be yielded by the use of a fixed orifice of proper size or by a connection of the tube to a chamber containing the same pressure as ordinarily exists in the hot tube ahead of the valve.

The coldest gas is produced when only a small fraction of the gas is emitted through the small hole. This condition is obtained by opening the valve rather wide. When this is done, the hot gas is then only warm. However, on the other hand, the hottest gas is obtained by closing the valve almost entirely. Nearly all the gas is then emitted through the small hole and is only cool. The fact that only a small fraction of the gas can be extracted at the lowest temperature is a source of inefficiency in the vortex tube. Another factor is that the amount of temperature depression obtained never approaches that of a perfect expansion engine. These two inefficiencies, taken together, amount to a large loss.

In the development of this invention it has been determined that the temperatures of the three streams of gas are related by the following improved energy balance:

$$f(T_i - T_c - JT) = (1-f)(T_h - T_i + JT)$$

where

T=temperature
i=inlet gas
c=cold gas
h=hot gas
f=cold fraction=mass flow of cold gas divided by mass flow of inlet gas
JT=Joule-Thomson temperature drop of gas on adiabatic throttling from inlet state to outlet pressure.

The value of JT is found in thermodynamic tables. It is 4 degrees F. in air throttled from 100 p.s.i.g. and 70 degrees F. to atmospheric pressure.

The above formula holds very accurately provided that the gas is dry and the vortex tube is insulated so as not to gain or lose heat to the atmosphere. The quantity f is measured with flow meters. By using the aforementioned formula, only two of the three temperatures need be measured. It is also possible to measure the 3 temperatures and compute f. A correction for the condensation and freezing of moisture, if present, can be incorporated into the formula. The efficiency or excellence of the vortex tube in performing its function is measured by how little gas pressure it requires and how much temperature difference it produces for a given cold fraction.

A thermodynamic formulation of the problem of optimizing the design of the counterflow vortex tube is that given the kind of gas, its pressure, temperature, and rate of flow, and a certain cold fraction to be delivered at a certain lower pressure, there exists a combination of geometric dimensions of all the parts of the vortex tube such that the cold gas will be delivered at the lowest possible temperature. The optimum design for the combination may be found as well as the temperature. The temperature of the hot gas is inherent in the energy balance and so long as the pressure of the hot gas is destroyed by throttling through the valve, that pressure does not enter into the optimization. If, however, the hot gas is to be removed under pressure and utilized in, for example, an ejector, the optimization takes on an additional dimension, namely the pressure of the hot gas, which must be taken into account.

At the present status of this technology and art, the optimization problem may be solved only by performing a very large number of parametric experiments where one dimension and another are changed step by step and the gas temperatures measured. At least fifteen important dimensions exist. This poses a problem of such intricacy that to achieve a thorough optimization even for one operating condition is very tedious and expensive. Should any condition be changed, a new optimization is required. For this reason, research is likely to continue on the vortex tube indefinitely.

Emphasis is more often placed on the cold gas because it is as a refrigerating means that the vortex tube has its greatest importance and number of potential uses. Heat or hot gas can ordinarily be obtained more economically by combustion or electricity. In fact if a compressor is used, it produces more heat than the vortex tube. The reason that refrigeration is usually the more valuable commodity resides in the greater rarity of vereversible processes over irreversible ones, as treated in the Second Law of Thermodynamics. Nevertheless, there are instances where the hot gas of the vortex tube is usable as a byproduct and there are others where the hot and cold streams are usable alternatively. Examples of the latter are found in laboratory apparatus which sometimes requires heating and sometimes cooling, and in the air conditioning of persons or spaces which sometimes require heating and sometimes cooling. There are also instances where it is desirable to use the vortex tube entirely for its heating effect. For simplicity, the following description will be given mainly in terms of the production of cold gas, but it will be understood that because of the aforementioned energy balance, the production of cold gas is always accompanied by the production of hot gas, and the improvements that will be described are equally applicable to both purposes.

The need for an improvement in the internal efficiency of the vortex tube has been mentioned. Another significant problem is that the vortex tube requires novel means of application in order to utilize what internal efficiency it does possess. Attempts to substitute the vortex tube into refrigerative procedures which suit the use of common vapor-liquid compression machines employing such refrigerants as dichlorodifluoromethane often lead to power consumptions of between six and ten times those of the vapor-liquid machines. This arises partly from the difference in the kinds of refrigerating duty that can be performed efficiently by an evaporating liquid and a warming gas. A solution to the latter problem is to devise means of changing the duty to suit the use of cold gas where possible.

However, in air conditioning applications, the vortex tube enjoys a particularly favorable position in that it produces dry, cold, pressurized, clean air directly at the point of use, and that air is used without any further heat exchangers, filters, dehumidifiers or fans. With a vapor-liquid machine, all of these auxiliaries are necessary including additional ducts, and they increase the cost while decreasing the efficiency and reliability.

The principles of thermodynamic efficiency show that as the cold gas grows colder, every degree of additional cooling is worth more than the preceding one. By worth is meant the power or work required to produce the same cold gas reversibly, according to the Second Law of Thermodynamics. For small amounts of cooling, the worth of the cold gas is proportional to the square of its temperature depression. Thus cold gas at 10 degrees F. below the environment is worth four times as much as at 5 degrees F. below the environment. For large amounts of cooling, the worth increases still faster. Therefore, if a vortex tube which gives 100 degrees F. of cooling is improved to give 110 degrees F. of cooling, the increase in efficiency is approximately 25 percent. A similar principle holds with respect to the hot gas. Small improvements in the vortex tube can therefore mount up to a large gain in overall efficiency.

In the practical application of the vortex tube, there has also arisen the need to render the vortex tube as compact as possible for any given capacity. This is true whether the vortex tube is of such capacity as to air condition a man in a suit, or to air condition an entire room or chamber. It is therefore, an object of the present invention to provide a vortex tube shortened to the greatest possible extent, without loss of effiicency or capacity.

It is an object of this invention to provide improvements in vortex tubes so that may emit colder and hotter gas and larger fractions of cold and hot gas with substantially increased efficiency and reduced economic expenditure for a greater range of applications.

It is an object of this invention to provide an improved vortex tube, and various components as well as the assembly of components, to produce an economic vortex tube having optimum efficiency.

A further object of this invention is to provide a novel generator-cold gas outlet component for a vortex tube capable of yielding optimum performance through the utilization of a more powerful vortex and the presentation of the vortex core and other components in conjunction with the generator.

Yet another object of this invention is to provide a vortex tube of improved freedom from leakage, reduced cost of manufacture, capability of performing with maximum efficiency over a wide range of capacities through the use of changeable inserts, and increased ability to utilize high gas pressures efficiently.

These and other objects of the invention which will be described hereinafter, or will be apparent to one skilled in the art upon reading this specification, are accomplished by that construction and arrangement of parts of which certain exemplary embodiments will now be described. Reference is made to the drawings wherein:

FIGURE 1 is a side elevational view of the counterflow vortex tube for the emission of the coldest and hottest possible gas streams corresponding to given available gas pressures and flows and desired cold and hot fractions;

FIGURE 2 is a longitudinal sectional view, presenting the structural components mounted in relationship to each other in the vortex tube;

FIGURE 3 is a perspective view of the generator-cold gas outlet component;

FIG. 4 is an end view of the generator-cold gas outlet component of FIG. 3, as seen from the generator end;

FIG. 5 is a partial longitudinal sectional view of a vortex tube illustrating another embodiment of the generator-cold gas outlet component having a cold gas orifice insert.

FIG. 6 is a perspective view of the counter-current control ring and brake of the present invention.

FIG. 7 is an end view of the brake.

FIG. 8 is a partial longitudinal sectional view of another embodiment of the vortex tube of the present invention.

FIG. 9 is a side elevational view of the vortex tube of FIG. 8, including instrumentation and muffler means; and

FIG. 10 is a diagrammatic representation of the vortex tube of FIGS. 8 and 9 used as an air conditioning means for an enclosed space or chamber.

Referring to the drawings and more particularly to FIGS. 1 and 2, there is illustrated an improved counterflow vortex tube (generally indicated at 1), for the emission of the coldest and hottest possible gas streams corresponding to given available gas pressures and flows desired cold and hot fractions. The construction illustrated is suitable for sizes ranging from the smallest possible unit to tube diameters of one inch or more.

The vortex tube comprises a body **2**, an inlet **3**, a generator *4a*, a cold gas outlet means *4b* and a hot gas outlet tube **5**.

Compressed gas from a compressor (not shown) is introduced through the inlet **3** into an annular plenum chamber **6** formed between the inner surface of the body **2** and the generator *4a*. Plenum **6** distributes the gas, still under full pressure, to a plurality of circumferentially spaced tangential nozzles **7** formed in the face of the generator *4a* as more fully shown in FIGS. 3 and 4. The vortex generator *4a* is a body of revolution except for nozzles **7**. The gas passes from the nozzles **7** into a vortex chamber **8**. Cold gas from the vortex chamber passes through the cold gas orifice **9**, through a cold gas diffuser **10** and into the cold gas outlet *4b*. The remainder of the gas from the vortex chamber **8** passes out through the hot gas outlet tube **5**.

Referring specifically to FIGS. 2, 3 and 4, it will be noted that the generator *4a*, the cold gas orifice **9**, the diffuser **10** and the cold gas outlet *4b* comprise a single integral unit, which may be referred to generally as the generator-cold gas outlet component **4**.

As most clearly shown in FIG. 3, the component **4** has a cylindrical end portion **11** and an annular flange **12**. The outer surface of the cylindrical portion **11** and the adjacent vertical surface of the flange **12** form, together with the inner surface of the body **2**, the plenum chamber **6**.

The generator-cold gas outlet component **4** is provided with a central longitudinal perforation. This perforation comprises the vortex chamber **8**, the cold gas outlet **9**, the tapered diffuser portion **10** and the axial bore of the cold gas outlet portion *4b*.

The cold gas outlet *4b* extends from the flange **12** and may be provided with any suitable exterior configuration. As shown in FIGS. 1 and 3, it may be provided with a hexagonal exterior surface so that it may be easily engaged by a suitable tool during installation. The end of the portion *4b* may be provided with external threads **13** for engagement with any suitable cold gas duct means (not shown).

The nozzles **7** are formed as slots in the face of the cylindrical end **11** of the component **4** and extend from the outer cylindrical surface of the vortex chamber **8**. As shown in FIG. 4, each nozzle **7** comprises a tapering, inwardly converging inlet section **14** merging into a straight tangential passageway **15**, having an opening **16** intersecting the round cylindrical outer surface **17** of the vortex chamber. Nozzles **7** are so positioned that the innermost portions of straight passageways **15** are approximately tangent to cylindrical surface **17**. In order to obtain optimum results, these portions should not reside outside of the tangent to surface **17** in order that there will not be created a step or indentation where the openings **16** terminate and surface **17** resumes. It is permissible that these innermost portions be slightly inside of the tangent to surface **17**.

The nozzles **7** may have substantially rectangular cross sections, and may be deeper than wide, giving an aerodynamic advantage of better tangency of injection. The cross sectional area of the nozzles may be adjusted by planing off the lands **18**, thus giving any precise desired air flow capacity.

Depending upon the material and method by which the component **4** is made, the nozzles may be formed by coining, machining or the like. In the preferred embodiment, however, the component **4** may be injection molded of nylon or other suitable plastic. This provides an inexpensive, and precision method of manufacturing the component **4** with all of its parts and functions, including a relatively heat insulating character. It will be understood by one skilled in the art, that the nozzles **7** and the vortex chamber **8** are made complete by cooperation of the component **4** and the inner, smooth, vertical surface **9** of the body **2**.

The function of nozzle **7** is to accelerate the gas to the maximum possible velocity, which is sonic velocity, and to inject the gas tangentially into the outer portion of the vortex chamber **8**. The inlet or mouth **14** of each nozzle should be not less than two times as wide as straight portion **15**. The contour or portion **14** should be smooth and polished and should merge gradually into portion **15**, which should be smooth and highly polished. The design of the nozzles follows well-known best practices in the design of converging nozzles for any fluid.

The number of nozzles that should be used is not definite but best results may be achieved when a plurality of not less than three are employed, and it has been found that six and eight nozzles are ordinarily preferable. In large vortex tubes, slight additional gains may be had by using as many as ten, twelve or more nozzles in the vortex generator. The optimum number of nozzles results from the opposing influences of nozzle wall friction, clogging and error of tangential injection into vortex chamber **8**. In the event too many nozzles are employed, they are so small that they can clog too readily and friction within them becomes excessive, although the gas is injected with almost perfect tangency. In the event too few nozzles are employed, too much gas is introduced that is not tangent, thus engendering excessive turbulence, mixing, shock waves, and other losses in the vortex.

The high-speed jets of gas emerging from the nozzles enter chamber **8** and create therein an intense vortex or rapidly revolving gas mass. In small vortex tubes this mass revolves at one million revolutions per minute or more. Chamber **8** is one of the features of this invention. The specification of chamber **8** is that it is a narrow cavity having a diameter substantially larger than that of the cold gas orifice **9** and substantially larger than the internal diameter of the hot gas outlet tube **5**. This results in what may be termed an enlarged vortex chamber. The axial width of chamber **8** is preferably made from one and one-half to two times the axial width of nozzle openings **16**. It can be made slightly wider without a substantial loss in performance provided that the flat surface **20** which terminates the vortex chamber on the cold end is located closely adjacent to the nozzle openings **16**. The preferred outer diameter of chamber **8** depends upon the absolute pressure ratio applied to the vortex tube as will be hereinafter described.

Results achieved utilizing chamber **8** as shown and described herein consistently yield from ten to twenty percent greater cold-air temperature depression (the quantity T_1-T_c at pressures between 80 and 140 p.s.i.g., with the cold air discharging at atmospheric pressure, than does the best-designed vortex tube without a chamber comparable to the enlarged chamber **8**.

The basic concept of chamber **8** is that it drives the main portion of the vortex at a faster rotatory speed than is possible otherwise and it, therefore, enables the cold gas to execute a more nearly reversible expansion to the outlet pressure. Converging nozzles **7** can produce no more than sonic velocity at their openings **16** and can utilize effectively no more than the well-known critical pressure ratio of the gas. That ratio is approximately equal to 0.528 for air. If the vortex tube is supplied with a greater pressure ratio than will produce sonic velocity, as it usually is, then the extra velocity, if it is achieved, cannot be achieved in the nozzles and must be generated in the outer portion of the vortex. Without the enlarged chamber 8, the outer portion of the vortex cannot generate more than a fraction of the extra velocity for two reasons: (a) if the emergent nozzle jets immediately accelerate through an additional pressure fall, they execute an unrestrained expansion which creates only a fraction of the extra velocity since part of the expansion is undesirably executed in the radial direction and also because the expansion overshoots and creates irreversible shock waves; and (b) the outer portion of the vortex cannot generate the extra velocity since it is a substantially forced vortex, one of constant angular velocity behaving as a solid body, because of the tremendous turbulent viscosity existing in it. The phenomena described in (a) are well known to nozzle designers and are sometimes overcome by employing a correctly contoured supersonic, diverging nozzle portion as in rocket motors, but the use of supersonic nozzles in the vortex tube would be undesirable for reasons disclosed hereafter. With respect to reason (b), should the vortex receive only sonic velocity, then since because of its forced nature it can possess velocities that only decrease with decreasing radius, it cannot be supersonic. To be supersonic, it would have to have a free-vortex outer portion where the received sonic velocity could be augmented to supersonic before the forced vortex is encountered. Such cannot occur in the turbulent, straight, uniform tube. However, in the sequestered outer portion of the vortex chamber 8, this desirable result for achieving supersonic velocity can be obtained and does occur.

In explanation, when air is supplied to a vortex tube at 100 p.s.i.g. and the core of the vortex is at atmospheric pressure, a common operating condition, the pressure at the nozzle exits is slightly less than 46 p.s.i.g., which value is found by applying the aforementioned critical pressure ratio. Because of nozzle friction, the actual pressure is usually in the range of 40 to 42 p.s.i.g., or, on the average, 41 p.s.i.g. If the vortex revolved as completely forced, were isentropic, and had sonic peripheral velocity, it would generate a peripheral pressure, due to centrifugal force, of only approximately 17 p.s.i.g. This is computed by integrating the pressure difference in the vortex, using well-known gas equations, with the result that the pressure ratio across the aforementioned kind of vortex is found to be equal to

$$\left(1-\frac{k-1}{2}\right)^{k/k-1}$$

where k is the well-known ratio of specific heats of the gas. For air, with $k=1.4$, the pressure ratio across the vortex would then be equal to 0.458. Although the vortex is not exactly isentropic, the result is approximately applicable. There would then be a mismatch of pressures of approximately 41−17 or 24 p.s.i. between the nozzle exits and the main vortex periphery. This pressure fall or drop will take place by unrestrained expansion, as described hereinbefore, with a partial realization of the theoretical velocity, such that the vortex will finally be driven at a slightly supersonic speed and will generate a peripheral pressure between 20 and 25 p.s.i.g. The remaining pressure mismatch, amounting to bewteen 16 and 21 p.s.i., is a total loss.

Calculations made in this manner show that a perfect match of nozzles and forced vortex exists, with air, up to an inlet pressure of approximately 55 p.s.i.g. With higher inlet pressures, the lossful phenomenon described begins to appear. It is large at 100 p.s.i.g. Still higher pressures are almost totally wasted.

Therefore, the need for a remedy begins at approximately 55 p.s.i.g. and increases thereafter. There are several reasons why supersonic nozzles are undesirable in the vortex tube. One is that experimental efforts to utilize them have failed to yield any benefit. This may be because the abrupt juncture of the supersonic jet with the vortex produces a shock wave that destroys the extra velocity. Another reason is the cost and difficulty of forming supersonic nozzles in a vortex tube. Still another is that even if they did function, they would require reshaping for different operating conditions.

The outer portion of the chamber 8 which is sequestered from the main turbulent vortex and not tightly coupled to it by the turbulent viscosity resolves the aforementioned difficulty. Furthermore, the narrowness of chamber 8 causes the air to spiral promptly inward therein and generate large Coriolis forces which speed it up. This establishes a substantially free vortex in chamber 8 and augments the entering sonic velocity efficiently to supersonic. In a free vortex, angular momentum is conserved and velocity is inversely proportional to radius. The supersonic air then enters the main, forced vortex and drives it at the maximum possible speed.

The minimum diameter of chamber 8 required to accomplish this function for any given operating pressure ratio can be computed by those highly skilled in the art with the aid of the aforementioned principles. No enlarged chamber 8 is needed below 55 p.s.i.g. with air discharging to the atmosphere. At 100 p.s.i.g., the diameter of chamber 8 should be at least 20 percent greater than that of the hot tube 5. At still higher pressures, chamber 8 should be still larger. However, at extremely high pressures and high supersonic velocities, the frictional losses rise rapidly and the efficiency of the vortex tube, like that of many devices, begins to fall.

Vortex tubes constructed which lacked enlarged chamber 8 but comprised multiple nozzles similar to those shown in FIGS. 3 and 4 yielded a rapidly appearing saturation at high pressures such that at pressures above 100 p.s.i.g. little further temperature depression was obtained. When an enlarged chamber 8 was added to the system, and provided with sufficient diameter as hereinbefore explained, the temperature depression continued to increase strongly with rising pressure, and efficiency was retained. Therefore, prior to incorporating enlarged chamber 8 into the structure, it was lossful to utilize the plurality of nozzles at high pressures and it was necessary to use Hilsch's single nozzle and spiral ramp, which partially performed the supersonic function. Now with the aid of enlarged chamber 8, it is preferable to use the multiple nozzles at all times because they provide better vortex tube performance, better vortex symmetry and concentricity, better nozzle jet tangency, simpler construction, more rational nozzle design, and the manufacturing advantages encompassed in the molding process which may be utilized for forming the vortex generator.

In the event chamber 8 is made larger than the minimum size required to match the pressures and velocities as described, the nozzles are driven into a subsonic state, but the main vortex continues to receive the maximum possible speed because the then augmented, transonic free vortex in chamber 8 executes the additional acceleration relinquished by the nozzles. The result is satisfactory unless chamber 8 is made so large that friction on its walls begins to exceed tolerable values. It is good practice to make chamber 8 somewhat oversize for the expected operating conditions.

A portion of the gas flows out through cold gas orifice **9**. The diameter of orifice **9** is critical and must be determined by experiment for each operating condition. For the production of small cold fractions, it should be less than one-half the inside diameter of the hot gas outlet tube **5**. For large cold fractions, the optimum is larger than one-half the inside diameter of the tube **5**.

FIGURE 5 illustrates an embodiment of the generator-cold gas outlet component 4 wherein a single such component 4 may be utilized for the production of either a large or a small cold gas fraction. Like parts have been given like index numerals. In this embodiment, the component 4 is provided with an enlarged perforation **21** extending from the chamber 8 to the central perforation of the cold gas outlet 4*b*. The perforation **21** is adapted to receive a cylindrical insert **22**. The cylindrical insert **22** has a central perforation comprising the cold gas orifice **9** and the diffuser **10**. Thus, by providing an insert **22** having a properly sized cold gas orifice **9**, the cold gas fraction of the vortex tube can be controlled without the necessity of providing a separate component **4** for each cold gas fraction desired. The insert **22** may be made of nylon or any suitable plastic and may be affixed within the perforation **21** in the component **4** by any suitable means including a press fit.

The optimum shape of the corner where surface **20** intersects orifice **9** is difficult to determine and depends somewhat upon the operating conditions and particularly upon the moisture content of the gas since deposition of ice may occur there. Under others, a small radius, as appears in FIG. 5 is best. Under still other conditions, a small snout or reentrant mouth is best. It is advisable to investigate the effect of the shape of this corner with respect to the particular operating conditions desired.

Upon passing through orifice **9**, the cold gas enters diffuser **10**. The diffuser **10** functions to convert the kinetic energy of the gas flowing through orifice **9** into pressure, thus enabling the gas to flow into cold outlet *4b* more readily. Thus diffuser **9** lowers the pressure in the vortex core, at any given cold fraction, and enables colder gas to be produced. It also permits a smaller orifice **9** to be employed for the production of a given cold fraction with the result that colder gas is selected from the vortex core. It is useful and effective primarily at high cold fractions where the velocity in the orifice is high and there is much kinetic energy to be converted. In order to perform the diffusing function most effectively, the divergent inner surface of the diffuser **10** should have a total included angle of between 8 and 16 degrees. However, a preferred valve is approximately 14 degrees.

The construction thus far outlined constitutes a great simplification in vortex tubes. As shown in FIGURE 2 it is only necessary to thread the interior surface of the body **2** as at **23**, place the component **4** within it, place an O-ring **25** against the flange **12** and thread in place a nipple **26** which has an inner conical nose portion acting to compress the O-ring both against the flange **12** and against the interior surface of the body **2**. A space between the interior bore of the nipple and the portion *4b* of the component **4** provides additional heat insulation.

The shape of the contour which merges chamber **8** into the hot gas outlet tube is not critical. A circular radius such as shown in FIG. 2 is satisfactory. It is not usually advisable that this radius be the largest possible radius that will produce a 90-degree corner; the radius is ordinarily made somewhat smaller so that a planar surface exists in the outer portion of chamber **8**.

The inside surfaces of all parts, the insert, the vortex generator, and the hot tube should be smooth, round and highly polished. The degree of smoothness and polish required in the tube **5** decreases toward its far end and becomes unimportant at that location.

A valve **27** ordinarily mounted at the terminal end of tube **5** may be of any convenient design and may be made alternatively in the form of a fixed orifice, porous plug, capillary tube, or any means that will create a sufficient obstruction to the movement of the desired fraction of hot gas out of the end of the vortex tube.

Recently developed uses for the vortex tube, such as its use as an air-conditioning device worn directly upon the person have made it mandatory to shorten the tube **5** in order that the instrument would be light and compact and not inhibit the movement of the wearer. Also, the use of the vortex tube in certain electronic and other instruments, and in various situations where space is at a premium, has made it necessary to shorten the tube. At the same time it was necessary to maintain the highest possible efficiency and capacity.

The size and efficiency of a vortex tube depend on many factors. Two opposing influences are at work upon

the air to determine the speed at which it rotates. On the one hand, after the nozzles have set the air into rotation, the force of angular momentum tends to increase the speed of rotation. That force results from the inward spiraling of a portion of the air and is the same force that causes a man spinning on his heel to revolve faster when he retracts his arms, and the vortex in a draining tub to rotate rapidly at the center. It is also called the Coriolis force. As stated above, due to the action of the sequestered portion of the enlarged vortex chamber, air from the nozzles increases in rotational speed as it spirals toward the vortex center. This increase in rotational speed continues until the air reaches a point spaced from the vortex center by a distance equal to the radius of the hot tube. From this point to the vortex center the rotational speed remains substantially constant to the vortex center. That portion of the vortex wherein the rotational speed of the air increases may be referred to as the augmented vortex portion. The remainder of the vortex wherein the rotational speed remains constant may be referred to as the inner vortex portion. If nothing acted against the Coriolis force, the peripheral speed of the inner vortex portion would become twice the speed of the adjacent part of the augmented vortex portion. The corresponding rotary speed is called the free speed. Under this condition, no cooling or heating would be obtained and the vortex tube would be useless. The available energy of the air would all be consumed in impact between the augmented vortex portion and the inner vortex portion. In mathematical parlance, the inner vortex portion would be improperly coupled to the augmented vortex portion; the mechanics and thermodynamics would be mismatched.

On the other hand, the friction of the air against the inside of the hot tube and any obstructions placed therein tends to slow down the rate of rotation of the inner vortex portion. The faster the inner vortex portion rotates, the more retarding friction arises. The slower it rotates, the more Coriolis force arises to urge it on. The interplay of these two forces results in an equilibrium speed at which the inner vortex portion actually rotates and the two forces are equal.

For maximum efficiency—that is, for the production of the coldest and warmest possible effluent air streams from the vortex tube—it is necessary for the peripheral speed of the inner vortex portion to be equal to the speed of the adjacent part of the augmented vortex portion. That is, the actual or equilibrium rotatory speed of the inner vortex portion must be one-half the free speed. At this condition, these vortex portions are properly coupled; there is no energy loss where these vortex portions blend; the mechanics and thermodynamics are matched. This condition is realized by applying precisely the correct amount of frictional force to limit the speed of the inner vortex portion. That is to say, the hot tube and any obstructions placed therein must be so designed that the rotating air will develop the precise amount of frictional or braking torque required. If the braking torque is less than this amount, the inner vortex portion will revolve too rapidly and there will be a loss of available energy where the vortex portions meet; if greater than this amount, the inner vortex portion will revolve too slowly and again there will be a loss of available energy where the vortex portions meet.

Therefore, it is necessary to apply precisely the correct amount of braking torque to the inner vortex portion. Hilsch achieved a fair approximation to this condition by using a very long tube (50 diameters) and sizing the nozzles to inject a certain amount of air such that the friction on the inside wall of the tube exerted approximately the correct amount of braking torque. If the nozzles were made too large, the torque was too small, if the nozzles were made too small, the torque was too large. Merkulov shortened the tube to 20 diameters or less, without loss of efficiency, by inserting a set of stationary blades that stop the rotation of the air at the extremity of the tube. The blades contribute the braking torque formerly provided by the far portion of the tube. Again an optimum exists: if the blades are advanced too close to the generator, excessive torque arises and efficiency fails.

Recently developed uses for the vortex tube have required that it be made even more compact. Thus an even more intensive braking action had to be created in a short length of tube but without upsetting the smooth and symmetrical flow and rotation of the air in the tube. Roughening the surface of the tube produces turbulence and mixing that offset any gain. Reducing the amount of air injected reduces the capacity. Enlarging the diameter of the tube requires a concomitant enlargement of generator and head, defeating compactness and increasing cost. Advancing the brake closer to the generator produces, as has been said, excessive torque.

The present invention contemplates the use of a brake and a countercurrent control ring which, placed directly ahead of the brake, permits the tube to be shortened further without loss of efficiency, reduction of capacity or other change of dimensions.

A form of brake which has been found very effective in shortening the hot gas tube **5** is indicated at **28** in FIGURES 2, 6 and 7. It is simply made by bending a strip of resilient metal into the form of a fermee cross, i.e., a figure having a cross section characterized by circumferential portions and radial portions. The material from which the brake is made may be phosphor-bronze strip. The brake is so made that it will maintain its position frictionally within the tube **5**. It is preferably used in connection with a metallic ring **29** located within the tube and ahead of the brake.

The illustrated and described combination of brake **28** and ring **29** has permitted a shortening of the hot gas tube **5** to a length far less than has hitherto been possible. Without desire to be bound by theory, it is believed that the reasons for the operation of the brake and ring **29** are as follows:

There exists in every vortex tube a strong axial countercurrent of warm, non-rotating air returning in the center of the tube from its far end toward the generator. This countercurrent is, within limits and under proper control, necessary and desirable to the scheme of operation of the vortex tube. It conveys much of the necessary braking torque to the forward portions of the vortex, where the torque is smoothly and uniformly applied to the fast-rotating air. The cause of this countercurrent is the difference in centrifugal force between the generator area, where the vortex is strong, and the extremity of the tube, where the vortex is weak. At the generator, centrifugal force causes a pressure difference amounting typically to 40 pounds per square inch between the center and the periphery of the vortex. At the extremity of the tube, this pressure difference is much less and depends upon the length of the tube and presence or absence of a brake and ring. A typical pressure difference there is 20 pounds per square inch. The result is that a strong axial circulation is created in the tube, with the air adjacent to the tube wall moving rapidly toward the region of lower pressure at the far end of the tube, and the air in the center of the tube moving rapidly from the far end of the tube, where the pressure is of an intermediate value, toward the generator and cold-air discharge orifice, where the pressure is the lowest anywhere in the vortex tube.

The current of air adjacent to the tube wall and moving rapidly away from the generator toward the far end of the tube was discovered by Ranque and has been observed by many others since. It may be called the Ranque nappe. It is quite thin, occupying perhaps only one-tenth of the cross-sectional area of the tube. That is because, driven by the steep pressure fall between the strong and weak portions of the vortex, it moves rapidly.

This leaves the inner nine-tenths of the cross-sectional area of the tube available for passage of the countercurrent.

An excessive countercurrent applies too much braking torque to the forward portion of the vortex where the cooling action is taking place, slowing the speed of rotation below the correct or optimum value. It also conveys warm air directly into the cooled region, where the warm air joins with the cooled air and flows out through the cold-air discharge orifice, thereby heating up the cold effluent from the vortex tube and reducing its efficiency. The ring **29** is an annular plate or washer obscuring the outer circumferential portion of the brake. This ring fits substantially against the inside wall of the tube **5**. It can be press-fitted in place by inserting it edgewise until it is near its intended position, then tilting it nearly broadside and driving it into final position, or it can be attached to the brake **28**. It will be understood by one skilled in the art that the ring **29** could also be formed as an integral part of the hot tube **5**.

The primary function of the ring **29** is to reduce the countercurrent to the optimal amount by constricting the area through which the countercurrent emerges. The countercurrent originates within and behind the brake out of the arrested Ranque nappe, which necks down and passes through the ring. The area through which the countercurrent can emerge is therefore the area of the hole in the ring less the amount of that area occupied by the Ranque nappe. For example, in a tube having a cross-sectional area of one square inch, if the Ranque nappe has a cross-section of $\frac{1}{10}$ square inch, there remains $\frac{9}{10}$ square inch through which the countercurrent can and will emerge if there is no ring. There would be an excessive countercurrent. If the ring has a hole of $\frac{6}{10}$ the area of the tube, then the area available to the countercurrent is $\frac{5}{10}$ square inch and the countercurrent will be $\frac{5}{9}$ as strong as before. In this way, by sizing the hole in the ring, the countercurrent is limited to the amount that gives best results, and the brake and ring may be advanced closer to the generator, the tube shortened, and the entire vortex tube rendered as compact, light and inexpensive as possible.

Another function and advantage of the ring is that it can take the place of the valve **27** otherwise employed to limit the amount of hot effluent air from the vortex tube. It has always been necessary to provide a valve or other restriction in the hot effluent stream, because otherwise little or no cold air is emitted from the vortex tube, all or virtually all of the injected air rushing out the hot tube because of centrifugal pressure in combination with the small cold-air discharge orifice. Customarily a valve is installed at the end of the hot tube, and this adds considerably to the cost. The ring can be so sized, in combination with its position in the tube, as to limit the effluent flow of hot air to the desired value and eliminate the valve, thus effecting a substantial saving in cost and complexity. In this case the ring performs both the countercurrent-limiting function and the hot-effluent-limiting function.

The combination of ring and brake thus described is simple, reproducible, easy to manufacture, low in cost, and productive of constant and optimal aerodynamic and thermodynamic results in a vortex tube. It permits the vortex tube to be shortened to the greatest possible extent, without loss of efficiency, and more than by any other known method.

The countercurrent should be so adjusted that none of it reaches the generator section. The countercurrent diminishes as it proceeds toward the generator because it is gradually entrained by the Ranque nappe. The Ranque nappe, in turn, is augmented as it proceeds toward the far end of the tube by the countercurrent that it entrains. With an excessive countercurrent, some of the countercurrent would remain at the generator section and flow out undesirably with the cold air, as was stated before. With an insufficient countercurrent, the countercurrent would all be entrained before it neared the generator. It is thought that optimal results occur when the amount of countercurrent allowed to emerge from the ring is such that the last of the countercurrent is entrained just before it reaches the generator.

The vortex tubes of this invention can be made in large sizes for the conditioning of the air in confined working spaces where the air is likely to be at an uncomfortable temperature. For example, a structure may be made large enough to air condition a portion or all of a mine entry.

In the manufacture of large vortex tubes where the cold gas and hot gas tubes may range up to or beyond 2 inches in diameter, the general principles outlined above can be employed; but, some modification of structure may be found useful. Referring to FIGURE 8, the body of a large sized vortex tube is indicated at **30**, having the compressed gas inlet **31**. As previously described, the nozzle openings **32** are formed in a circular element **33** and coact with the inside end surface of the body **30**. But, it is advantageous to restrict the axial length of the member **33** and to employ a more elongated member **34** which includes the cold gas orifice **35** and the tapered passageway or diffuser **36**. The flange **37** may be made separately; and elements **37** and **33** have shouldered interengagement as shown. In this particular embodiment a flange **38** is formed on the open end of the body **30**, and a co-acting flange **39** carries the cold gas outlet tube **40**. When the last mentioned flanges are held together as by bolts **41**, the body may be sealed by an O-ring **42** held in a shoulder in the first mentioned flange **37**. A hot gas tube **43** opens into the body **30**.

Referring to FIGURE 9, the hot gas tube **43** has been shown as having an adjustable valve **44** at its end in lieu of the valve **27** shown in FIGURE 3. Additional elements shown in FIGURE 9 include a strainer or filter **45** for the gas entering through the inlet **31**, and a muffler **46**, the purpose of which is to reduce the noise made by the movement of gas in the apparatus. The muffler may be of any desired type, but a simple open ended vessel containing a fibrous material held in place by perforated plates would serve the purpose.

Due to the large size of the apparatus of FIGURE 9 it may carry instrumentation such as a pressure gauge **47** and a thermometer **48** in the gas inlet; a thermometer at the far end of the hot gas tube and a thermometer **50** in the cold gas tube. It will be understood that the hot gas tube **43** will preferably contain a brake and a countercurrent control ring as previously described. By adjusting the valve **44** a smaller quantity of cold air at a lower temperature may be obtained, or vice versa.

In FIGURE 10, in which like parts have been given like numerals, there has been illustrated a system comprising a compressor **51**, a filter or strainer **52**, a means **53** for after cooling or pre-cooling the gas, and a water separator **54** for removing condensate from the air. A cooled air distributing system has been shown attached to the muffler **46** and may be of any type desirable for the confined space.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A vortex tube having a hollow casing with a cylindrical inner surface and a planar end portion, a hot gas outlet tube attached to and opening through said planar end portion, and a generator in said hollow casing, said generator comprising a cylindrical body of a diameter smaller than the internal diameter of said cylindrical inner surface of said hollow casing, an end portion of said body being characterized by a plurality of grooves tangential to and terminating in a circular vortex chamber having a diameter larger than the diameter of said hot gas tube, means for holding said body against said planar end portion of said hollow casing, and means providing a cold gas outlet from said vortex chamber of a smaller diameter than the diameter of said vortex chamber, said cold gas outlet having an interior opening tapering at least in part toward said vortex chamber.

2. The structure claimed in claim 1 wherein said cold gas outlet tube is made integral with said body and in which said body bears on the side remote from said grooves a flange having an external diameter substantially the same as the internal diameter of said hollow casing.

3. The structure claimed in claim 1 wherein said cold gas outlet tube is made integral with said body and in which said body bears on the side remote from said grooves a flange having an external diameter substantially the same as the internal diameter of said hollow casing, an O-ring lying against said flange, and a means engageable with the end portion of said hollow casing for compressing said O-ring against said flange and said hollow casing.

4. The structure claimed in claim 1 wherein said hot gas outlet tube is provided at its end remote from said casing with an adjustable valve and inwardly of said valve with a brake formed by folding strip metal into a cruciform configuration and inserting it within said hot gas outlet tube.

5. The structure claimed in claim 1 wherein the end of said hot gas outlet tube is provided with a brake characterized by vanes extending generally radially of said hot gas outlet tube and a ring member ahead of said brake.

6. The structure claimed in claim 4 including a ring located in said hot gas outlet tube ahead of and adjacent said brake.

7. In a vortex tube having a hot gas outlet tube terminating at one end at a vortex chamber, the combination of a brake characterized by substantially radially extending vanes located within said hot gas outlet tube at a point remote from said vortex chamber, and a ring element located adjacent said brake and between said brake and said vortex chamber.

8. The structure claimed in claim 5 including a muffler attached to the end of said cold gas outlet means remote from said vortex chamber.

9. The structure claimed in claim 8 employable for the air-conditioning of a confined space, said hollow casing having a laterally extending air inlet tube and an air filter attached to said inlet tube.

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