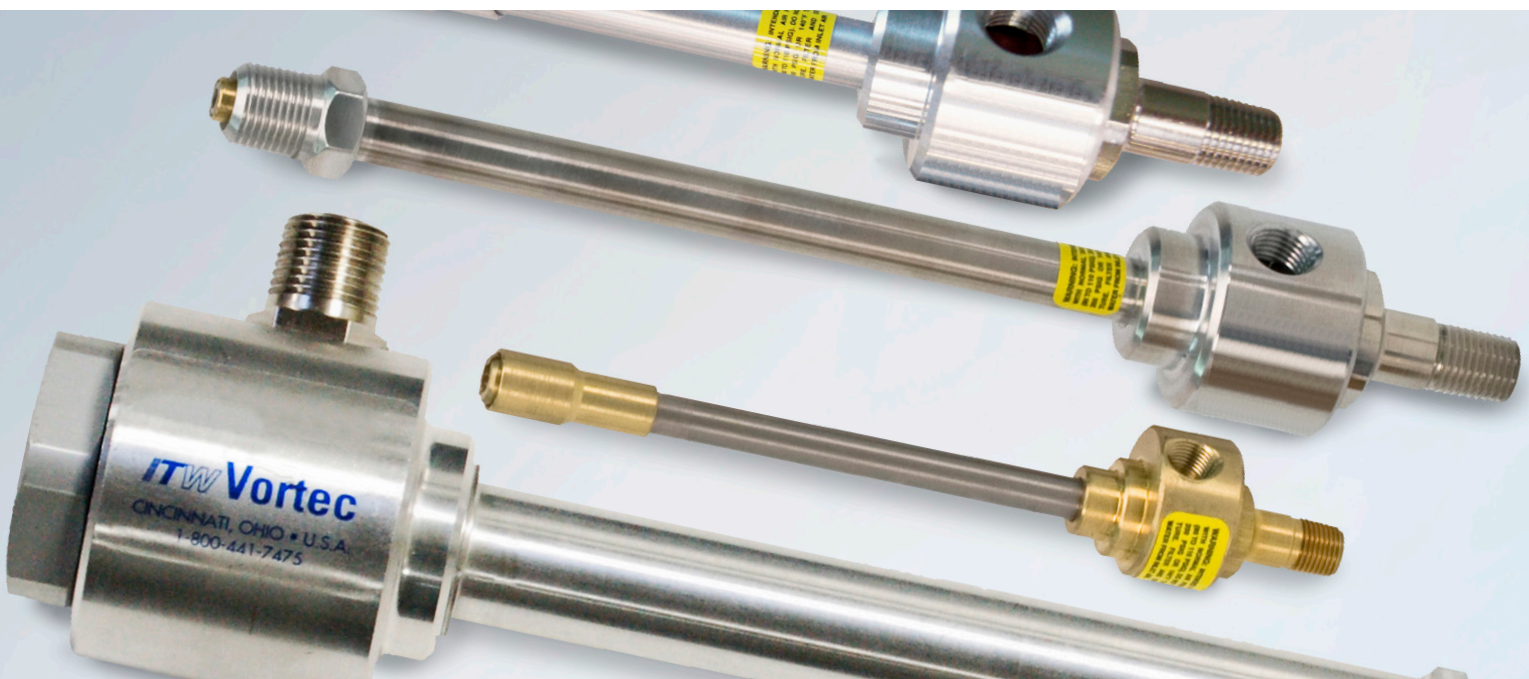


Vortex Tube Short Course

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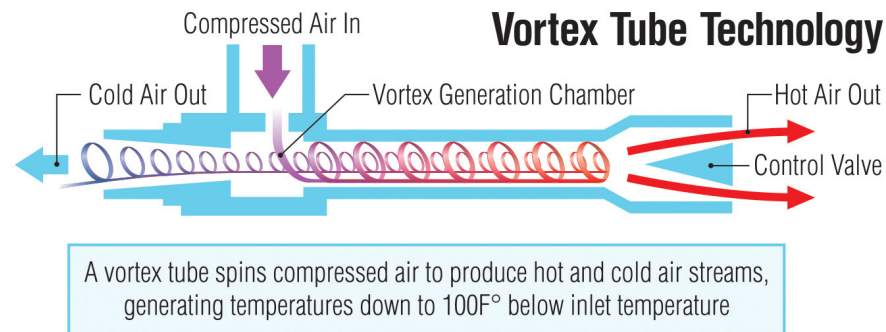
The vortex tube has been around for decades, yet occasionally it is still misunderstood by engineers and maintenance personnel, resulting in improper use with less than ideal results. This article explains the basic operation of the vortex tube and guides the user how to apply it effectively to make the best use of its cooling and heating abilities. Attention given to the model selected, how it is adjusted for the application, the quality of the compressed air supply and the conditions downstream of the vortex tube can make the difference between a successful application and a failed one.

History of the vortex tube

Vortex tube effects were first observed by a French scientist, George Ranque in 1933. He presented a paper on the vortex tube to a scientific society in 1933 but it was met with disbelief and disinterest. Thereafter, the vortex tube disappeared for several years until Rudolf Hilsch studied it and published his findings in 1947. Hilsch's paper stirred so much interest that most people thought that he had invented the device, so it was popularly called the Hilsch tube. In 1961 an engineer at General Electric, Charles Darby Fulton, started a company in Cincinnati, Ohio called Fulton Cryogenics. This was the first company to study the vortex tube in depth and develop it for specific industrial applications. In 1968, Fulton Cryogenics became Vortec Corporation which expanded and improved the vortex tube product line to cover a broad range of applications in industrial and commercial markets. In 1991, Illinois Tool Works acquired Vortec, opening up access to many technological methods to study the inner workings of the vortex tube.

Air Movement in a vortex tube

The schematic below shows a basic vortex tube with common names labeling certain important features.



High pressure (compressed) air enters the inlet and flows into the annular space surrounding the generator. As it contacts the generator nozzles, the air loses some of its pressure, expands and begins to spin in the generator where it gains near sonic velocity. The nozzles are oriented so that the air is injected tangentially to the circumference of the generation chamber. All of the air leaves the generation chamber and goes into the hot tube. Centrifugal force keeps the air near the inside wall of the hot tube as it moves toward the valve at the hot end.

By the time the air reaches the hot end valve, its pressure is less than the nozzle exit pressure but greater than atmospheric pressure.

The position of the hot end valve determines how much air leaves at the hot end. It controls the pressure at the hot end, before the valve. For hot/cold temperature separation, it must allow only a portion of the air to escape. The remaining air is forced to the center of the hot tube creating a counter-current flow where, still spinning, flows back to the cold outlet. The air flows the entire length of the hot tube, through the center of the vortex generation chamber and to the cold outlet.

Recall that the original stream of air in the hot tube did not occupy the center of the tube because of centrifugal force. Therefore it created an ideal path for the inner stream to follow. This, combined with the above mentioned pressure difference between the hot end valve and the cold outlet, is the reason there are two distinct spinning air streams, one spinning inside the other but moving in opposite directions in the hot tube.

Vortex tube performance

As the hot end valve position is changed, the proportions of hot and cold air change, but the total flow remains the same. Therefore the amount of air exiting the cold end can be varied over a wide range for a given size vortex tube. The volume of the cold air is called the "cold fraction".

Good vortex tube design avoids mixing the cold inner stream (the cold fraction) with the warm or hot outer air stream. If a vortex tube is operating at a high cold fraction, the passage through the center of the generator must be large enough to handle the cold air flow. If it is not, it will cause some of the cold air to be deflected away and mix with the hot air stream, thus wasting refrigeration. At low cold fractions, the desired result is a small stream of very cold air. If the generator passage is too large it will allow entrainment of some of the surrounding warm air and raise the cold outlet temperature.

Therefore for any given vortex tube of a fixed total flow, there is an ideal opening size for every cold fraction. Practically, a vortex tube user will want one of two modes of operation: either maximum refrigeration (occurring at about 70% cold fraction) or lowest possible cold temperature (occurring at about 20% cold fraction). Accordingly, Vortec offers vortex tubes with "H" (high cold fraction) generators designed for maximum refrigeration or with "L" generators designed to produce the lowest possible temperature.

Temperature separation effects in the vortex tube

Recall that the air in the vortex tube has a complex movement. An outer ring of air is moving toward the hot end and an inner core of air is moving toward the cold end. Both streams of air are rotating in the same direction, but flowing concurrently (in opposite directions). Most importantly, both streams of air are rotating at the same angular velocity. This is because the intense turbulence at the boundary and throughout the two streams locks them into a single air mass as far as rotational motion is concerned.

The proper term for the inner stream is a "forced vortex". This is different from a "free vortex" in that its rotational motion is controlled by some outside force other than the conservation of angular momentum. In this case, the outer hot air stream forces the inner cold air stream to rotate at a constant angular velocity.

In a bathtub whirlpool a free vortex tube is formed as water goes down the drain. As the water moves inward, its rotational speed increases to conserve angular momentum. Linear velocity of any particle in the vortex is inversely proportional to its radius. Thus in moving from a radius of one unit to a drain at a radius of $\frac{1}{2}$ unit, a particle doubles its linear velocity in a free vortex. In a forced vortex with constant angular velocity, the linear speed decreases by half as a particle moves from a radius of one unit to a drain at a radius of $\frac{1}{2}$ unit.

So for the situation above, particles enter the drain with four times the linear velocity in a free vortex compared with a forced vortex. Kinetic energy is proportional to the square of linear velocity, so the particles leaving the drain of the forced vortex have $\frac{1}{16}$ the kinetic energy of those leaving the drain of the free vortex in this example. Where does the energy ($\frac{15}{16}$ of the total available kinetic energy) go? Therein lies the secret of the vortex tube. The energy leaves the inner core as heat which is transmitted to the outer core. The inner core gets cold and the outer core gets hot.

The air in the cooling inner stream had to travel through the outer (heating) stream first. Why doesn't it heat the same amount it cools with no net cooling effect? Keep in mind that the rate of flow in the outer stream is always larger than that of the inner stream, since part of the outer stream is being discharged at the hot end valve. If the energy (btus) leaving the inner stream equal the energy (btus) gained by the outer stream, the temperature drop of the inner stream must be more than the temperature gain of the outer stream because its mass flow rate is smaller. This is why hot air temperature increases as cold fraction increases and why cold air temperature decreases as cold fraction decreases.

Effects of inlet temperature

As the temperature of the compressed air increases or decreases, so does the temperature of the cold and hot air streams produced. If the compressed air temperature increases from 70°F in the morning to 80°F in the afternoon, then the cold air temperature will increase by 10 F degrees during that period also.

Inlet vs. outlet pressure

The vortex tube performance table (or cold fraction chart) shows the cold and hot temperature differentials achievable at various cold fraction settings and inlet pressures. The table seems to imply that temperature drops and rises at a specific cold fraction are related to the compressed air inlet pressure. That is not entirely true. The temperature differential is related to the absolute pressure ratio between the inlet air and the cold outlet. The performance table is based on the assumption that the cold outlet air is at atmospheric pressure. Take for example a vortex tube operating at 90 psig (104.7 psia absolute) and with the cold air exhausting to atmosphere (0 psig or 14.7 psia). This results in a pressure drop ratio of 7.1 to 1 between the inlet and the outlet. Now if the inlet pressure remains the same but the cold air flow is restricted so that outlet pressure increases to 15 psig (29.7 psia), then the pressure drop ratio falls to (104.7/29.7) 3.5 to 1. Therefore it is important not to restrict the flow of cold air out of the vortex tube by installing undersized tubing, fittings, valves, etc.

Numbers on White Bar: Temperature Drop Numbers on Blue Bar: Temperature Rise

Cold Fraction	10		20		30		40		50		60		70		80		90		
	PSIG/BAR	F°	C°	F°	C°	F°	C°	F°	C°	F°	C°	F°	C°	F°	C°	F°	C°		
20/1.4		63	35	62	34	60	33	56	31	51	28	44	24	36	20	28	15	17	9
		7	4	15	8	25	14	36	20	50	28	64	36	83	46	107	59	148	82
40/2.8		91	51	88	49	85	47	80	44	73	41	63	35	52	28	38	21	29	14
		9	5	21	11	35	19	52	29	71	39	92	51	117	65	147	82	220	122
60/4.1		107	59	104	58	100	56	93	52	84	47	73	41	60	33	45	25	29	16
		10	6	24	13	40	22	59	33	80	44	104	58	132	73	168	93	236	131
80/5.5		119	66	115	64	110	61	102	57	92	51	80	44	66	36	49	27	31	17
		11	7	25	14	43	24	63	35	86	48	113	63	143	79	181	101	249	138
100/6.9		127	71	123	68	118	66	110	61	99	55	86	48	71	39	53	29	33	18
		12	8	26	14	45	25	67	37	91	51	119	66	151	84	192	107	252	140
120/8.3		133	74	129	72	124	69	116	64	104	58	91	50	74	41	55	31	34	19
		13	8	27	14	46	26	69	38	94	52	123	68	156	87	195	108	257	142
140/9.7		139	78	135	75	129	72	121	67	109	61	94	52	76	42	57	32	35	20
		14	8	28	16	47	27	71	39	96	53	124	69	157	88	196	109	259	144

Table Baseline:

- Compressed Air Temperature: 70°F / 21°C
- Pressure Dew Point: -25°F / -32°C
- Compressed Air Pressure: 100 psig (6.9 bar)
- Backpressure: Temperature drops and rises in the chart are based on zero (0) backpressure on the hot and cold outlets of the vortex tube. Backpressure exceeding 5 psig (0.3 bar) will reduce the performance of the vortex tube.

Supply Air Pressure

As important as it is not to restrict the cold air flow out of a vortex tube, it is just as important not to restrict the flow of air into a vortex tube. The components in the air supply system (pipe, hoses, tubing, valves, fittings, regulators, etc.) must be sized so as not to restrict the flow of compressed air and create excessive pressure drop. Just one component in an otherwise properly sized compressed air system can create excessive pressure drop, resulting in low air pressure at the vortex tube inlet. Although vortex tubes will create temperature separation with air pressures as low as 15 psig (1 bar), most performance specifications are stated with 100 psig (6.9 bar) air pressure measured at the vortex tube inlet connection.

Humidity effects

A vortex tube does not separate humidity (water vapor) between the hot and the cold air. The absolute humidity of both the cold and hot air streams is the same as the entering compressed air. Moisture will condense and/or freeze in the cold air if its dew point is higher than its temperature. Condensation will not normally occur at moderate cold air temperatures. However when temperatures are low enough to cause condensation, it will appear as "snow". The snow may have a sticky quality if there is oil vapor in the air supply. The snow may gradually collect inside and block the cold air passages.

If water vapor in the compressed air supply is an issue, the resulting condensation and snow can be avoided by careful selection of a compressed air dryer. The dryer must be selected based on the lowest anticipated cold air temperature. For most enclosure cooling applications a refrigerative dryer with a pressure dew point of 35 to 40°F can be used. For vortex tube and cold air gun applications where extreme cold air temperatures may be required, a regenerative desiccant-type dryer with a pressure dew point of -40°F may be needed.

The air supply

As the saying goes, “garbage in=garbage out”. This is true with vortex tubes also. If dirty, oily or wet compressed air is supplied to the vortex tube you will get the same quality of air out and more importantly, poor performance. Over time the contaminants in the air supply will wear or clog the internal passages, resulting in decreased cooling performance. It is very important to properly filter and dry the compressed air supply to remove contaminants before they reach the vortex tube.

ISO 8573.1:2001 is the international compressed air quality standard. Part one of the standard defines the compressed air quality that a manufacturer specifies for his product. There are three contaminants that the standard classifies: solid particulate, water vapor and oil. Each contaminant is defined by up to six classes. For example: Class 3.4.2 means that (1)10,000 ppm of .5 to 1 micron and 500 ppm of 1 to 5 micron sized solid particulate is allowed per cubic meter of compressed air; (2) the air must be dried to a pressure dew point of 37°F or lower; and (3) there can be no more than .1 mg per cubic meter of oil vapor in the air. ITW Vortec’s line of compressed air filters and coalescing filters satisfy the first and third requirements. A refrigerative type drier may be needed to satisfy the second requirement (see the previous section “Humidity effects”).

For vortex tubes, Cold Air Guns or other cold fraction adjustable vortex tube products where the user may adjust the product to produce minus 5°F air or less, an ISO 8573.1:2001 air quality Class 3.3.2 is recommended. For fixed cold fraction enclosure cooling products, an air quality Class 3.4.2 is recommended. For more information about ISO air quality classes, see page ten of: <http://cdn.norgren.com/pdf/Clean%20Compressed%20Air.pdf>

Benefits of vortex tubes, compared to other cooling methods, include:

- ✓ unsurpassed reliability
- ✓ no moving parts
- ✓ adjustable over a wide temperature range
- ✓ no maintenance
- ✓ small and lightweight
- ✓ low cost
- ✓ ability to endure harsh environments
- ✓ no spark or explosion hazard
- ✓ no RF interference created
- ✓ instantaneous cooling and heating

When selected and applied correctly, successful vortex tube applications include cooling a wide variety of items such as electronics, gas samples, personnel working in hot environments, cutting tools and work-pieces, molded parts, heat sealed products, industrial sewing machine needles, composite and rubber materials, thermal sensors, industrial robots and many more. Although heating applications are not as prevalent as cooling applications, vortex tubes are being used with great results for drying paints and inks, shortening adhesive cure times and warming personnel working in cold environments.