A Thermally Controlled Test Chamber for Centrifuge and Laboratory Experiments

by

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Introduction

It is well known that for certain experimental investigations the thermal environment in which the experiments are performed will have a significant effect on the results. It is also recognised that the response of instrumentation can also be affected by changes in the ambient temperature during the course of an experiment. Whilst these effects can be often be dealt with either by calibration or by performing the experiments in a constant temperature environment there may be instances where such measures are unfeasible or excessively time consuming. Such a situation often arises in the field of centrifuge model testing.

The environment of a centrifuge model is frequently observed to change during the course of a centrifuge test. These temperature changes can be due to diurnal temperature fluctuations or from the heat generated by the centrifuge rotating within its enclosure. These effects, while often considered minor for many experiments, can prove significant for tests on clay soils where thermally induced pore pressures may arise and for pollution migration experiments where temperature change can alter the fluid viscosity and reaction rates as well as generate convection currents.

For smaller centrifuge installations temperature fluctuations can be eliminated by air conditioning of the centrifuge enclosure. However, for larger centrifuges where large amounts of heat are generated, air conditioning can be prohibitively expensive. This paper describes a viable alternative in the form of a thermally controlled test chamber for use in laboratory or centrifuge experiments. The chamber has the added advantage that it is possible to maintain centrifuge models at very low temperatures for long periods to enable experiments involving cold regions engineering to be performed.

Design of Thermally Controlled Chamber

Previous experimental work in cold regions (e.g. Smith 1992) using passively insulated test chambers indicated that frozen models, for example, could only maintain reasonable thermal conditions over a few hours. For longer duration tests both passive and active measures to control temperatures were seen to be needed.

The thermally controlled chamber described below uses both active and passive measures of temperature control and has been successfully tested both on the laboratory floor and at enhanced acceleration levels at the Geotechnical Centrifuge Centre of Cambridge University.

Active cooling is provided by a stream of cold air delivered from a pair of vortex tubes. Vortex tubes are devices that expand a stream of high pressure gas into a stream of cold air and a stream of hot air (Otten, 1958), refer to Appendix A. The temperature of these air streams is a function of inlet/outlet pressure ratio across the device, inlet air temperature, and ratio of cold to total air vented (adjustable) termed the cold fraction.

The advantages of using vortex tubes in centrifuge applications have been discussed previously by Smith (1995). Commercially available devices typically operate at pressures of 690 kPa (100 psi) (max. 1725 kPa) and flow rates of up to 0.072 m^3/s (150 scfm). The devices used in this test were run at between 414-690 kPa (60-100 psi) and up to flow rates of 0.004 m^3/s (16 scfm), easily achievable using a standard laboratory air compressor. Flow rates are selectable by changing a 'generator' within the vortex tube.

The package is shown schematically in Figure 1 and consists of three main elements. These are labelled A-C in and are briefly described below.

A - Inner chamber:

This is the primary containment vessel within which the experiment is performed. In this particular case the containment vessel is a thick walled aluminium alloy chamber designed to withstand the very high pressures generated at enhanced acceleration levels on the centrifuge. It also provides a highly conductive pathway for heat ensuring a near isothermal boundary to the chamber.

B - Active air cooling ring

Cold air from two vortex tubes enter below the base of the inner chamber at J and passes through grooves in the distribution plate K and then up the annular gap (the air cooling ring) between the inner polypropylene ring L and the outer insulation ring M. The air then passes over the top insulation of the inner chamber to exit through the vent pipe at N. This exit vent incorporates a cowling arrangement to prevent the warm air stream through which the package is moving during a centrifuge test from disrupting the cool air flow. The space between ring L and the inner chamber, provides some degree of extra insulation but more importantly permits installation of instrumentation within a temperature controlled environment.

C - External passive insulation

External passive insulation is provided at the base by 140 mm of marine grade plywood, around the sides by injected foam continued within two steel rings and a lid fabricated from extruded Styrofoam sheets.

A cooling ring arrangement such as described in B above theoretically makes a very efficient use of the air stream supplied by the vortex tubes. If the air flow under centrifuge conditions remains laminar, then any external heat conducted in through the outer insulation is likely to be effectively convected away before it can cross the gap to the inner ring L assuming growth of the thermal boundary layer is sufficiently slow enough. In this circumstance, it is only required that the air stream have a temperature equal to that of the required inner chamber temperature and flow rate such that the boundary layer cannot develop across the gap, rather than requiring a temperature below that of the inner chamber and a flow rate sufficient to balance the heat gained through the external passive insulation. In practice, the flow in base and lid and to some extent the additional effect of free convection enhanced by a centrifuge g-field render this an ideal rather than a reality.

Chamber temperature control system

The temperature of the inner chamber for a given inlet air pressure and temperature can be set by adjusting the cold fraction of the vortex tube. Once the cold fraction has been set the outlet temperature from the vortex tube (and hence the inner chamber temperature) can be changed by adjusting either the inlet air pressure or temperature. For the system described here temperature regulation was provided by adjusting the inlet temperature of the air supply to the vortex tubes.

A digital on/off (Eurotherm) temperature controller with adaptive tuning was used to monitor the outlet temperature from one of the vortex tubes and to maintain this temperature constant by heating the inlet air temperature. Consequently it is necessary to ensure that the heated inlet air temperature at the start of the test is higher than the maximum temperature of the air likely to be supplied to the package at any time during the test. The air supply temperature is likely to follow ambient unless air supply lines are insulated.

Experimental Testing

Two tests are presented in which the performance of the chamber has been evaluated. The first (EC01) was performed at one gravity without temperature control and the second (EC02) was conducted both at one gravity and at an enhanced acceleration levels on the geotechnical centrifuge with temperature control. Data for each test is presented in the form of temperatures monitored at various locations within the test package by K-type thermocouples. The location of the thermocouples for both tests is shown in Figure 1.

Test EC01, Laboratory Evaluation

An overview of the test is shown in Figure 2. For this test iced water was placed in the inner chamber and the vortex outlet temperature was set to about 2^0C at a cold air flow rate of 0.004 m^3/s. The response of the thermocouple located in the cooled water (TC1) indicated that for the first four hours the system is achieving a steady state as the water temperature increases to that maintained by the cooled air stream.

The response of the thermocouple monitoring the ambient temperature (TC3) is closely followed by the response of the vortex tube outlet temperature (TC2). Since the temperature of the air supply will be dictated by the ambient air temperature then it is apparent that a temperature control system is required to maintain a constant inlet air temperature to achieve a constant outlet temperature from the vortex tubes.

Test EC02, Centrifuge Evaluation

For this test a temperature control system was utilised to maintain a constant inlet air temperature into the vortex tubes. The inner chamber was filled with water at an initial temperature of around 10 ‘C. No ice was added to the water as it was decided to investigate the feasibility of cooling the water in the inner chamber using only the cooled air flow produced by the vortex tubes. Consequently the system was set up and left for an extended period at 1 gravity. Figure 3 shows that after about 17 hours the water in the inner chamber is still cooling and only a temperature drop of some 3 - 4 °C has been achieved. Thus although the inner chamber can be cooled by the vortex tubes it would be more beneficial to select the vortex tube outlet temperature to maintain a desired inner chamber temperature unless only a small degree of cooling is required.

Prior to the centrifuge run the vortex tube outlet temperature was increased slightly to stabilise the temperature of the inner chamber. Figure 3 shows the response of selected transducers during the centrifuge runs. It is apparent that the ambient air temperature rises by some 12 - 13 °C during this period of testing. However the thermocouple output monitoring the vortex tube output and inner chamber temperatures remain unaffected by the increases in acceleration level.

After 24.5 hours the compressed air supply was turned off, resulting in a slow but steady increase in the inner tub temperature over the next 25 hours. This increase is initially due to temperature differential from inside to outside of about 10°C. In certain scenarios this could be of the order of 30°C or more with corresponding increase in rate of heat gain, demonstrating the need for control.

Theoretical Analysis

It is possible to derive a simple relationship between vortex output temperature and the equilibrium inner chamber temperature by assuming that the ultimate equilibrium temperature of the inner chamber is approximately equal to the average temperature of the air being circulated through the channels. It is thus possible to estimate the range of capabilities of the chamber. This analysis neglects any benefit from a boundary layer effect and is thus likely to be conservative.

Heat transfer may be assumed to occur as follows: Air at the inlet at temperature T_i (K) enters the package at a mass flow rate q (kg/s), flows around the air channels, absorbing heat from the exterior (at temperature T_e K) which is leaking into the package through the insulation, and exits at a temperature T_o (K). Assuming the external insulation has an overall heat transmissivity of X (W/K) and the air an average heat capacity of c_p. Then we can write the following approximate equations:

Heat leaking in through insulation = Heat gain by air flow

$$Xr(T_e - T_m) \approx qc_p(T_0 - T_i) \qquad (1)$$

where

$$T_m = \frac{T_i + T_o}{2} \qquad (2)$$

and

$$T_{av} = T_i + (T_o - T_i)(1 - \frac{r}{2}) \qquad (3)$$

where r denotes the proportion of the cooling duct system in which heat is gained (in many instances this will be equal to 1). Within the remaining (l-r) proportion, the duct air temperature is assumed to be equal to the external air temperature and so no further heat gain is possible. Hence $T_o = T_e$ for $r < 1$, and $T_o \leq T_e$ for $r = 1$. T_m is the mean temperature of the air into which heat is transferred and T_{av} is the average temperature of the entire air stream (from which heat will be transferred into the inner chamber).

X may be estimated from a knowledge of the dimensions and insulation properties of the package. For this case it has been estimated by calculation to be -3.2 W/K. The inlet temperature T_i and mass flow rate q may be taken as measured during the test or estimated from a knowledge of the vortex tube performance. After calculating c_p then T_{av} and T_O may be determined from equations (1) and (2). T_{av} is assumed to give the final equilibrium temperature of the inner tub.

Example calculations (performed by spreadsheet) are presented in Table 1. In addition calculations have been performed for distinct stages of each of the tests reported and predicted final equilibrium temperatures (labelled EQ) are given in Figs 2 and 3 for these stages. Stages boundaries are defined by a change in g-level, air supply pressure, or in the case of test EC01 a significant change in ambient conditions.

Air pressure kPa (psi)	Inlet air temperature (°C)	External temperature (°C)	Vortex Generator (scfm)	Cold fraction (%)	Cold air mass flow rate (g/s)	T_0 (°C)	T_{av} (°C)
414 (60)	17	18	16	89	5.3	9.5	5.7
414 (60)	24	21	16	85	5.0	12.0	8.0
414 (60)	24	21	25	86	8.0	10.6	8.0
690 (100)	40	40	25	75	10.6	12.8	8.0
690 (loo)	20	20	25	60	8.5	- 12.6	-20.0

Table 1 Predicted performance of package.

The first two entries in the table relate to tests EC01 (period 0 to 11 hours) and EC02 (period 22.75 to 23.5 hours) respectively and together with the plotted data in Figs 1 and 2 predict well the response of the package in experiments. The remaining entries are given to show the potential performance of the package. An increase in air flow rate leads to reduced temperature gain by the air cooling stream and thus a more thermally uniform air jacket. The system is capable of functioning with increased external temperatures and air feed temperatures and can if desired maintain significant sub zero temperatures within the package. In this latter case it is important that the vortex tube be supplied with dry air to prevent clogging by ice particles. Optimum performance is achieved when the air supply temperature to the vortex tube is kept as low as possible. If the external centrifuge pit/chamber temperature is high then this entails using insulated supply lines to the vortex tube.

Conclusions

A novel low cost temperature controlled test chamber has been presented. The system is based on providing both active and passive forms of insulation. The passive insulation is conventional low conductance lagging and the active insulation is a cooled air stream generated by commercially available vortex tube units. The active insulation allows the temperature of the chamber to be adjusted over a potentially wide range by altering the temperature of the cooled air generated by the vortex tubes. The chamber has been successfully tested on the laboratory floor and at enhanced acceleration levels on a geotechnical centrifuge.

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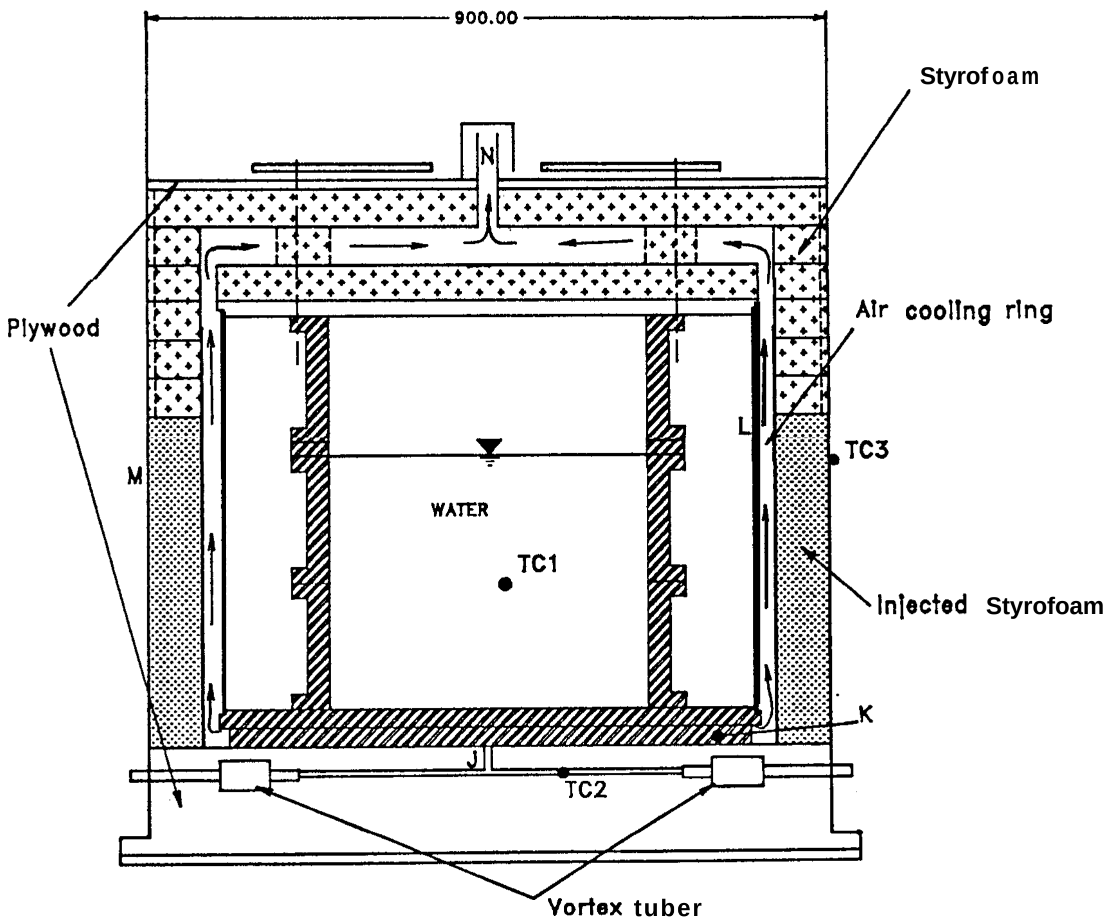


Figure 1: Schematic representation of the Chamber.

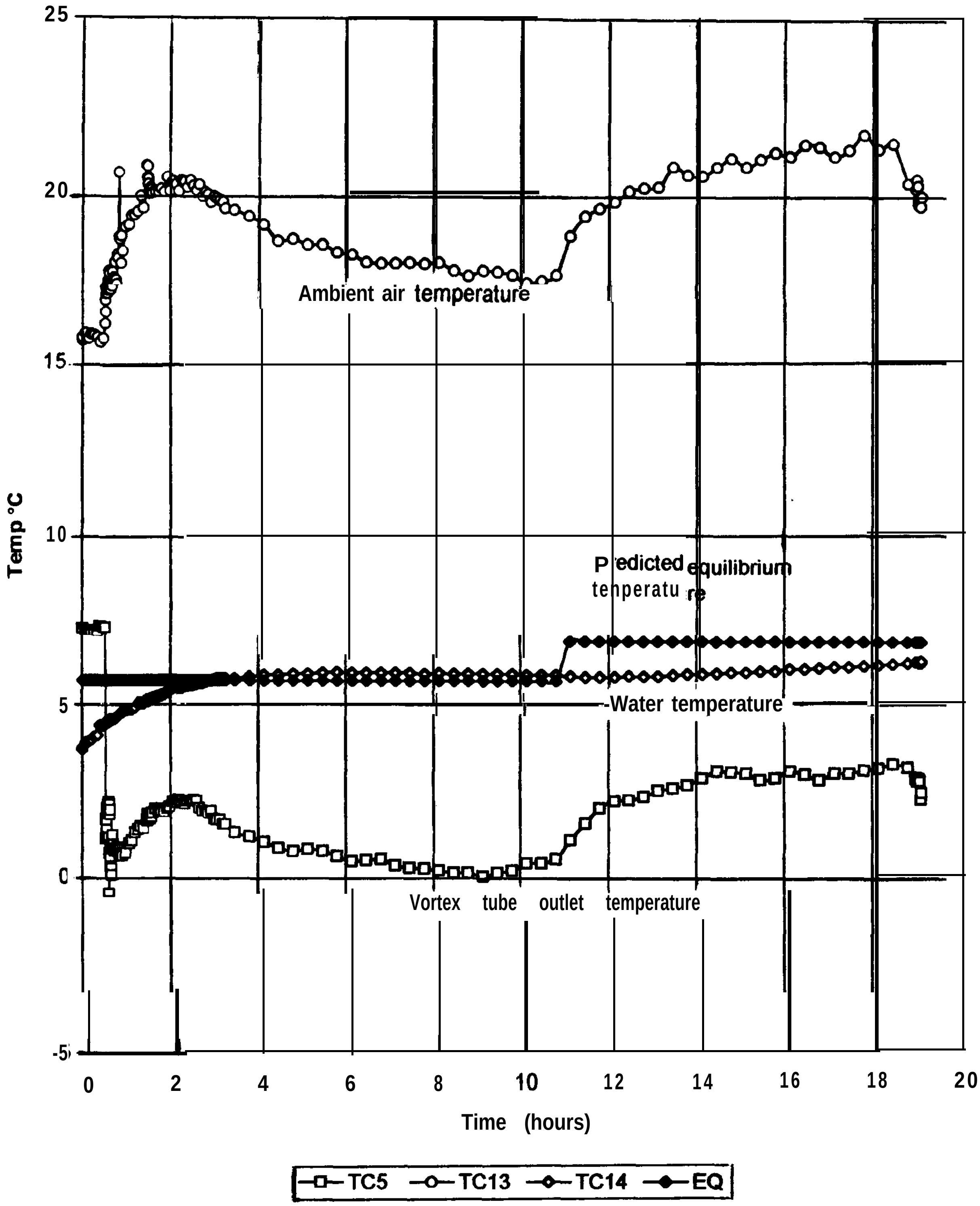


Figure 2: Selected thermocouple output for Test **EC01.**

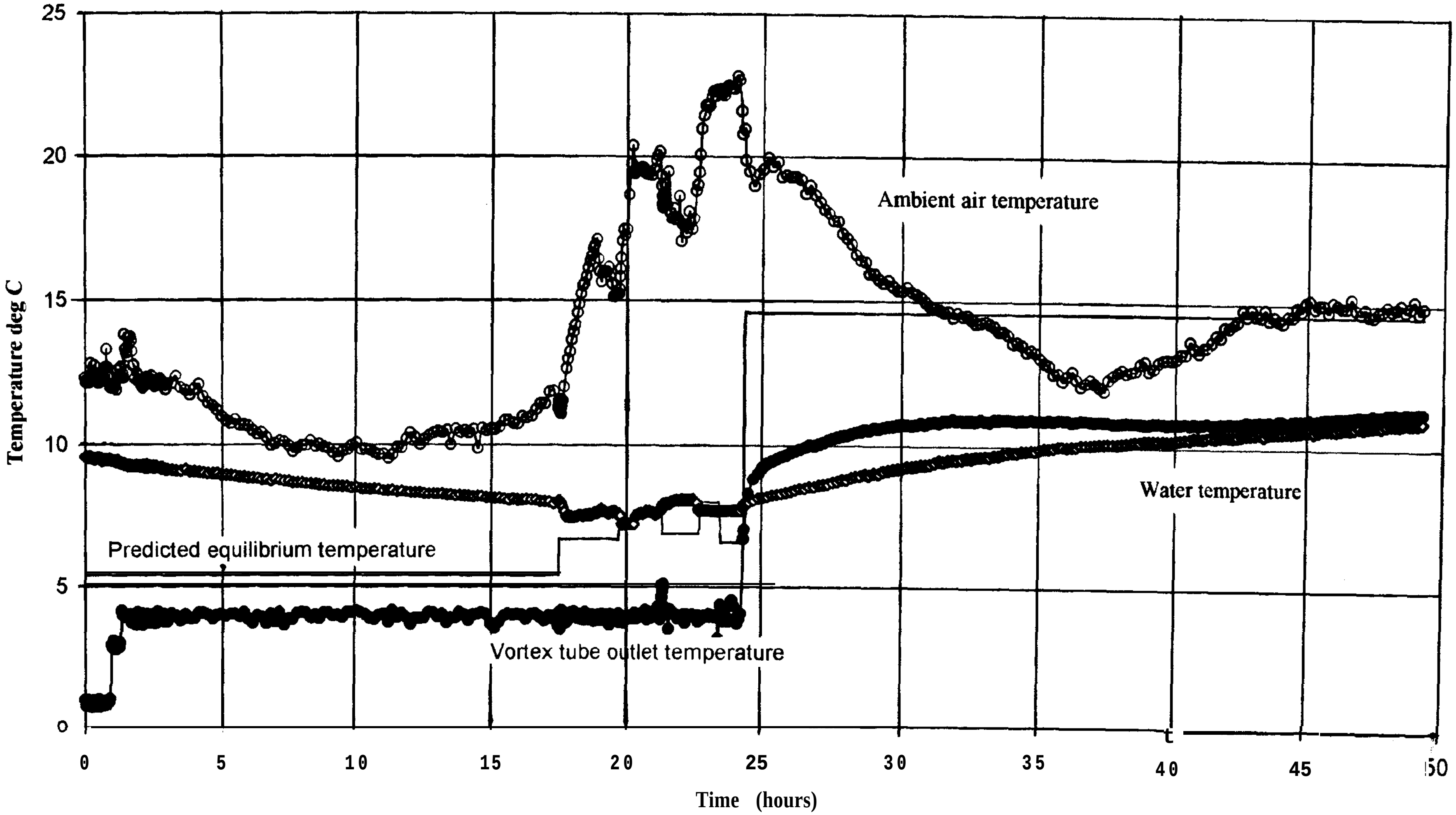


Figure 3: Selected thermocouple output for Test EC02.

APPENDIX A

A Short Course on Vortex Tubes and Application Notes

Contents

History

The Vortex Tube effects were first observed by Georges Ranque, a French physicist about 1930. He formed a small company to exploit the item but it soon tailed He presented a paper on the Vortex Tube to a scientific society in France in 1933, but it was met with disbelief and disinterest. Thereafter, the Vortex Tube disappeared for several years, until Rudolph Hilsch studied it and published his findings in the mid-1940s.

Hilsch's paper stirred much interest where Ranque's had not. So much so, in fact, that most readers thought Hilsch had invented the device, and it was popularly called the 'Hilsch Tube."

Since then, the Vortex Tube has become much better known to technical people. There has been a slow but steady increase in research and publication on the subject around the world. Well over 100 serious studies have been published in the world's scientific and engineering journals, scattered so that it is hard to assemble more than a fraction of them. Many popular articles and commentaries have been published. Many engineering schools and industrial and scientific groups are working on the Vortex Tube.

Today, Vortex Tubes serve in a wide variety of industrial applications, including cooling workers, cooling electrical and electronic equipment, and many process cooling applications.

Air Movement in a Vortex Tube

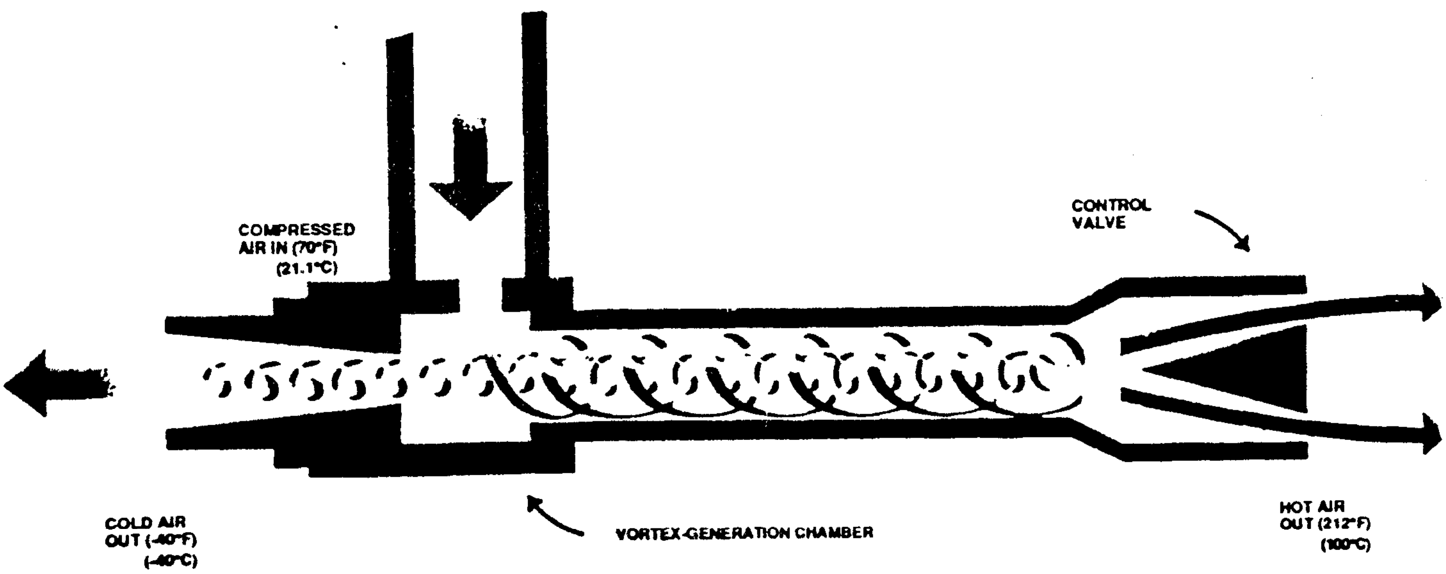
Below is a schematic drawing of a Vortex Tube showing the internal arrangement and the common names for certain important features.

High pressure air enters the inlet and enters the annual space around the generator. It then enters the nozzles where it loses part of its pressure as it expands and gains sonic or near-sonic velocity. The nozzles are aimed so that the air is injected tangentially at the circumference of the vortex generation chamber. All of the air leaves the vortex generation chamber and goes into the hot tube. It makes this choice (between hot and cold ends) because the opening to the hot tube is always larger than the opening to the cold tube (through the center of the generator). Centrifugal force keeps the air near the wall of the hot tube as il moves toward the valve at the end.

By the time the air reaches the valve it has a pressure somewhat less than the exit pressure at the nozzles, but more than atmospheric (assuming cold outlet is at atmospheric pressure). **It Is always true that the pressure just behind the control valve is higher than the cold outlet pressure.**

The position of the valve determines how much air leaves at the hot end. For hot-cold separation, it must allow only part of the air to escape. The remaining air is forced to the center of the hot tube where, still spinning, it moves back toward the cold outlet. It goes all the way through the hot tube, through the center of the vortex generation chamber, to the cold outlet.

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



PSIG, do not use a regulator to reduce the inlet pressure. Pressures higher than 250 PSIG must not be used. Pressures ower than 80 PSIG will still produce some cooling. However, oth the temperature drops and the flows are reduced due to he lower inbt pressures.

Line Sizes

Up to 35 SCFM, runs of pipe bss than 10 feet long may be 1/4" size ♦)(♦♒□♦♦ ● xassivo pressure drop. Up to 50 feet use 3/8" pipe, and use 1/2" pipe over 50 feet. Rubber hose of suitable pressure rating may he used. Consider 3/8" I.D. hose to be the same as 1/4" pipe, and 1/2" I.D. hose to be the same as 3/8" pipe. Remember that bwer transmission pressures will exhibit ● v8n greater pressure drops, so care must be taken to avoid large losses in the inbt air piping.

Compressor Size

In most large plants, the size of the compressor is adequate to handle many Vortex Tubes operating simultaneously. For smaller plants, estimate horsepower required bawd upon the rated capacity of the tubes. For a 100 PSIG system, it takes one horsepower to compress 4 SCFM of air.

Preparing the Air

Moisture

All compressed air systems will have condensed water in he lines unless a dryer is in use. To remove condensed water from the air, a filter-separator mud be used. Automatic drain types are recommended unless the area is always tended by a responsible employee who can empty the collection howl periodically. Place the filter-separator as near to the Vortex Tube as possible.

Dryers

Normally a dryer is not required for Vortex Tube applications. Occasionally, however, when very bw outlet temperatures are produced, icing will cause problems. Also, some applications may require the cold air stream to be completely free of condensed water or ice. A chemical dryer (Silica gel. heatless, or other type) can be used in the inlet line to eliminate condensed water or ice in the cold air stream. The dryer should be rated to produce an atmospheric dew point lower than the lowest expected cold outlet temperature.

Dirt

Because of the water in compressed air lines, there is always rust and dirt present. Vortec's filter-separators will actively remove these contaminants by using a 5 micron filter. Replacement filters are available at nominal cost, and it is necessary for the user to determine the frequency of replacement based on the conditions prevailing in his plant

Oil

Never use Vortex Tubas downstream of a lubricator. Oil in the air which has been introduced by the compressor lubrication system is usually not a problem for Vortec products, but occasionally older compressors produce very oily air. If the plant air is very oily, use an oil removal filter downstream of the filter-separator. The oil removal filter removes dirt, water. and oil aerosols with an effective filtration of 0.01 micron.

Settings

Maximum Refrigeration. Maximum refrigeration occurs when a Vortex Tube operates at 60 to 70 percent cold fraction. This is where the product of the mass of cold air and its temperature drop is the greatest. *Many* applications such *as* cooling electrical controls, liquid baths, and personal air conditioning use this maximum refrigeration setting. For maximum refrigeration, use H styb bushings.

Minimum Temperature. Some applications require the lowest possible cold output temperature. Examples are cooling glass, cooling hot parts, rnd using cold air to cool machining operations. These air spraying applications usually work better with very cold air, and results seem not to depend upon the refrigeration mte. For these applications, L style bushings and cold fractions in the 20 to 40 percent range are best.

Using The Cold Air

Back Pressure. One of the most common mistakes with Vortex Tubes is to restrict the cold outlet This will cause ● loss of performance. A small back pressure on the cold outlet to allow the air to move through piping or ducting is acceptable, but back pressure, measured at the tube. should be limited to less than 5 PSIG. Keep in mind the tube is responsive to the absolute pressure ratio applied and back pressures as low as 15 PSIG cut this ratio in half. Some pressure is available at the hot end, and it can be used so long as compensating adjustments in the control valve settings are made.

Insulation. As with any thermodynamic device, the proper use of insulation will improve Vortex Tube system performance. Avoid ducting the cold air through large thermal masses such as heavy piping, drilled holes in large blocks, etc. If possible, use plastic tubing or piping. Foam type insulation can also be quite helpful

Noise Mufflers

General. A common misconception is that a Vortex Tube emits a scream or whistle due to the Sonic speeds inside. Actually such noise is rarely observed, but me sound of escaping air is always present, and in Some cases it must be muffled. Ordinarily the cold air will be ducted into an enclosure or through Some pip8 or tubing. This abne may reduce its noise level to acceptable limits. Hot air escapes in Smaller amounts in most applications and may not be objectionable. Nevertheless, jets of escaping air can be quite objectionable if continued over a long period of time near a worker. h such situations mufflers are availabb. and should be used.

Cold Muffling. Mufflers used on the cold air must not be of a stuffed or porous type. Their small openings will quickly block with ice which has condensed and frozen in the cold air stream. Baffle type mufflers and silencers are best for the cold air. Avoid selecting any muffler which will apply high back pressures to the Vortex Tube.

Hot **Muffling. Nearly any** air silencer or muffler will work on the hot end. One should avoid selecting a muffler made from plastics or other materials with bw resistance to heat since hot end temperatures can easily exceed 200°F.

Maintenance

Since Vortex Tubes have no moving parts, they are highly reliable, and require little or no maintenance. Prolonged use with dirty or oily air can cause wear or dirt collection in the tube. Occasional disassembly, inspection, and cleaning are the only maintenance activities required.

ortex Tube Performance

As the valve position is changed, the proportions of hot nd cold air change, but the total fbw remains the same. hus, the amount of air exiting the cold end can be varied over wide range for a given Vortex Tube. The amount of this air is nown as the 'cold fraction."

As you can imagine, one of the secrets of good Vortex ube design is to avoid mixing of any of the cold inner stream he cold fraction) with the warm or hot outer stream. If a tube operating at a high cold fraction, the passage in the center of e generator must be large enough to handle the cold flow. If ot. it will cause some of the cold air to be deflected away and ixed in with the warm air stream, thus wasting refrigeration. t low cold fractions the desired resuk is usually a small stream f very cold air. An opening too large will invite entrainment of ome of the nearby warm air and raise the co&f outbt emperature.

Thus, for any given Vortex Tube of a fixed total flow apacity there is an ideal opening size for every cold raction. Practically, a Vortex Tube user will normally want ne of two modes of operation. Either maximum refrigeration which occurs at about 60% cold fraction) or lowest possible old temperature (which occurs at about 20% cold fraction). ccordingly, Vortec offers H (high cold fraction) bushings esigned with the optimum opening for maximum refrigeration nd L (bw cold fraction) bushings with the optimum smaller pening to create lowest possible cold temperatures.

Each of Vortec's standard tubes can also be fitted wkh enerators for different CFM capacities. Thus, we offer an H nd L bushing for each CFM capacity in a given tube. So e bushings must be selected based on two parameters, apacity and mods. This is why we adopt the simple omenclature 2-H, 4-l 8-H, etc.

emperature Separation Effects n a Vortex Tube

We have already covered the movement of air in the ortex Tube. Now we shall attempt to explain why the hot air ets hot and the cold air gets cold.

You'll recall that the air in the hot tube has a complex rovement. An outer ring of air is moving toward the hot end nd an inner core of air is moving toward the cold end. Both treams of air are rotating in the same direction. More nportantly. both streams of air are rotating at the same ngular velocity. This is because intense turbulence at the oundaty between the two streams and throughout both treams lochs them into a single mass so far as rotational novement is concerned.

Now the proper term for the inner stream would be a forced vortex." This is distinguished from a "free vortex" in hat its rotational movement is controlled by some outside nfluence other than the conservation of angular momentum. this case, the outer hot stream forces the inner (cold) stream rotate at a constant angular velocity.

In the bathtub whirlpool situation (which most people ssociate with the word "vortex"), a free vortex is formed. As e water moves inward, its rotational speed increases to onserve angular momentum. Linear velocity of any particle in he vortex is inversely proportional to its radius. Thus, in noving from a radius of one unit to a drain at a radius of 1/2 nit, a particle doubles its linear (tangential) speed in a free ortex. In a forced vortex with constant angular velocity, the near speed decreases by half as a particle moves from a adius of 1 unit to a drain at a radius of 1/2 Unit.

So, for the situation above, particles enter the drain with 4 imes the linear velocity in a free vortex compared with a forced ortex. Kinetic energy is proportional to the square of linear velocity, so the particles leaving the drain of the forced vortex have 1/16th the kinetic energy of those leaving the drain of the free vortex in this example.

Where does this energy (15/16 of the total available kinetic energy) go? Therein lies the secret of the Vortex Tube. The energy baves the inner core as heat and is transmkted to the outer core.

Now you might say 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 • twoya larger than that of the inner stream, since part Of the outer stream is being discharged at the hot valve. If the BTU's baving the inner stream equal the BTU's 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 rate of fbw is smaller.

If this precept is clear in your mind. a little refbction will albw you to understand why hot end temperatures increase as cold fraction increases, and cold end temperatures decrease as cold fractions decrease.

Effects of Inlet Temperature

k is very easy to predict the temperature drops and rises in a Vortex Tube for various inlet temperatures. The basic rule to remember is that temperature drops or gains are proportional to • baolote inlet temperature. Any temperature expressed in degrees Fahrenheit can be converted to absolute (degrees Rankine) by adding 460. That is. 0°F = 460°R or 70°F = 530°R.

Thus, the entire table is based on an inlet temperature of 530°R. If absolute inlet temperature doubles, so does the temperature drop or gain. As an example, suppose you want to find the temperature drop associated with a Vortex Tube operating at 30% cold fraction and with a 100 PSIG, 200°F inlet.

1. Table gives 118° drop for 100 PSIG, 70°F inbt and 30% CF.
2. Patio of absolute inlet temperature

$$\frac{200 + 460}{70 + 460} = \frac{660}{530} = 1.245$$

3. Drop given in tabb times ratio is 118 x 1.245 = 147°
4. Cold end temperature is 200° - 147" = 63°F

This ratio can be used just as well when the inlet temperature is bwer than the 70°F on which the table is based. For example, if inlet temperature were 0°F, ratio would be

$$\frac{0 + 460}{70 + 460} = \frac{460}{530} = .87$$

In this case the temperature drop is reduced.

Exactly the same approach can be used to convert the temperature rises given in the table. They are greater for inlet temperatures higher than 70°F and smaller for inlets below 70°F.

One additional comment on this method should be made. k applies to the pressure range shown on the tabb only. Whenever pressures considerably higher than the table

PSIG/14.5 = BAR
SCFM x 28.3 = SLPM

are involved, the Joule Thompson effect alters the results somewhat. This effect is small at pressures of 140 PSIG and below, and can be ignored as it is in the method given above. Joule Thompson cooling is the very slight cooling that takes place as gases are throttled.

Using the Performance Table

Two rather important limitations of the performance table in the catabg should be recognized.

First, the table would seem to imply that temperature drops and rises are related to inlet pressure. This is not quite true. They are rotated in a complex way to the absolute pressure ratio between inlet and cob outlet. The table is based upon the assumption that the cold outlet is at atmospheric pressure. For any other cold end pressures, the table cannot be used.

You can appreciate the variation in temperature drops and rises if you consider how quickly the absolute pressure ratio changes with changes in cold end pressure. A 90 PSIG inlet (105 PSIA) provides a 7 to 1 ratio when the tube exhausts to atmospheric pressure (0 PSIG or 15 PSIA). If inlet pressure remains the same and cob outlet pressure rises to only 15 PSIG, the ratb drops to 3.5 to 1.

Calculations of temperature rises and drops for *pressures* other than those shown on the table can be made, but they are beyond the scope of this Short Course. Refer any such problems to Vortec.

The Heat Balance Formula

A very handy formula results from the fact that the *energy* extracted from the cold air by the Vortex Tube appears in the not air.

The formula is:

$$CF \times (t_i - t_c - JT) = (100 - CF) \times (t_h - t_i + JT)$$

where CF = cob fraction, %

t_i = inlet air temperature, °F

t_c = cold air temperature, °F

t_h = hot air temperature, °F

JT = Joule-Thompson temperature correction

°F = 4°F at an inlet pressure of 100 PSIG

By using this formula, cold fraction can he computed from the readings of the three thermometers alone without having to measure any air fbw. As an example, suppose $t_i = 100°F$, $t_c = 50°F$, $t_h = 300°F$. Substituting in the formula,

$$CF \times (100 - 50 - 4) = (100 - CF) \times (300 - 100 + 4)$$

Solving for CF, CF = 81.5%

Vortex Tubes obey this formula very closely, regardless of their efficiency, provided only that the hot pipe be insulated.

The formula can be rearranged as follows:

$$CF = \frac{t_h - t_i + 4}{t_h - t_c} \times 100$$

This is the handiest form for computing cold fraction.

Humidity Effects

The Vortex Tube does not separate humidity between the hot and cold air. The absolute humidity of both cob and hot air, in grains/pound, is the same as that of the entering compressed air.

Moisture will condense and/or freeze in the cold air if its dew point is higher than its temperature. The following table shows the amount of moisture that air can hold in the saturated vapor state as a function of air temperature, at standard atmospheric pressure of 14.7 PSIA:

Temperature, °F	110	loo	90	80	70	60	60	
Saturation*	375	295	217	154	111	77	54	
Temperature, °F	40	30	20	10	0	-10	-20	-30
Saturation*	37	24	15	9	6.5	3.2	1.8	1.0

*Saturation Moisture Content Grains/lb. Air

For example, the above table shows that if the moisture content is 14 gr./lb., condensation will begin when the temperature of the cob air falls below 19°F. At 5 gr./lb., condensation will begin at -1°F.

The satuntbn moisture content of compressed air at 100 PSIG is given in the folbwing tab&:

Temperature, °F	110	100	90	80	70	60	50	40	30	20
Saturation Moisture Content Grains/lb. Air	48	38	26	20	14	9.9	6.9	4.7	3.1	1.9

By comparing the two tables, it is possible to predict the amount of moisture in the compressed air, and the temperature at which moisture will begin to precipitate or freeze in the cob air. As an example, suppose the compressed air is aftercooled to 80°F folbwing *compression.* and the precipitated water drained off. Then the second table shows that it will carry 20 grains/b. of water vapor. When this expands in the Vortex Tube, the upper table shows that precipitation will begin in the cold air when its temperature falls below 26°F if its pressure is 14.7 PSIA.

If the compressed air is cooled under pressure by a chiller to 40°F, the second table shows that it will then carry 4.7 grains/lb. of water vapor. When expanded in the Vortex Tube, precipitation will begin when the temperature of the cold air falls below -3°F at 14.7 PSIA.

If, under unusual conditions, some moisture precipitates in the cold air, the temperature of the cold air will thereby be caused to rise approximately 3/4°F for each grain of moisture that precipitates. This is because some of the sensible refrigeration of the cold air is consumed in producing latent refrigeration of the moisture. This refrigeration is not bst but reappears in the cob air as it warms up in performing its air conditioning duty after leaving the Vortex Tube. when the precipitated moisture *re-evaporates.*

The tables show that condensation will not normally occur at moderate cold end temperatures. When temperatures are bw enough to cause condensation, it appears as snow. The snow has a sticky quality due to oil vapor and will gradually collect and block cold air passages. Continuous operation at bw temperatures can he assured by means of an air dryer or injection of an antifreeze mist into the compressed air feeding a Vortex Tube.

When selecting dryers give consideration to refrigerative and deliquescent types. While their drying abilities are limited (and need to be considered) they are quite compatible with the Vortex Tube. Chemical dessicant dryers such as silicagel and molecular sieve types are exothermic, and tend to heat the compressed air *causing* refrigeration losses.

Application Notes

The Air Supply

Pressure

Standard Vortex Tubes made by Vortec Corporation are designed to utilize a normal shop air supply of 80 to 110 PSIG pressure, Unless pressures run considerably higher than 110