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PERFORMANCE EVALUATION OF A RESPIRATOR VORTEX COOLING DEVICE

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ABSTRACT

The United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina, is dedicated to promoting site-level risk-based inspection (RBI) practices in order to maintain a safe and productive work environment. Protective suits are worn by personnel working in contaminated environments. These suits require that cooling be applied to keep the interior temperature within safe and comfortable limits. A vortex tube, also known as the Ranque-Hilsch vortex tube, could provide the necessary cooling. As mechanical devices void of moving components, vortex tubes separate a compressed gas into hot and cold streams; the air emerging from the "hot" end reaching temperatures of 320 degrees F, and the air emerging from the "cold" end reaching 32 degrees F [4]. Therefore, routing the cold stream of the vortex tube to the user's protective suit facilitates the required cooling.

Vortex tubes currently in use at SRS are pre-set, through sole modification by and within the Respiratory Equipment Facility (REF), to provide a temperature reduction between 40 and 45 deg F. Current model vortex tubes lack the capability of user adjustment during use within the field. However, a new type of vortex tube capable of user adjustment in the field recently became available and was tested to determine an achievable temperature drop. The statistical test plan, data analysis, thermodynamic calculations, and conclusions were reviewed. Significant cost savings from implementation will result from the use of the new model of vortex tube because the product could be shipped directly to the end user, circumventing modification by the REF.

NOTATIONS

ASME	American Society of Mechanical Engineers
SRS	Savannah River Site
SCFM	Standard Cubic Feet per Minute
COP	Coefficient of Performance
DIFF00	Initial temperature drop(deg C) relative to ambient room temperature
DIFF10	Temperature drop(deg C) after 10 minutes relative to ambient room temperature
DIFF20	Temperature drop(deg C) after 20 minutes relative to ambient room temperature
Del 00 10	Temperature drop(deg C) from the initial temperature to 10 minutes
Del 10 20	Temperature drop(deg C) from 10 to 20 minutes
Del 00 20	Temperature drop(deg C) from the initial temperature to 20 minutes

INTRODUCTION

The vortex tube, also known as the Ranque-Hilsch vortex tube (RHVT) is a mechanical device operating void of mobile components which separates a compressed gas of homogeneous temperature into hot and cold fluid streams. The resultant separation of streams allows for the vortex tube to function as a refrigeration or heating device - respectively reducing or increasing the temperature of an enclosure. Within prior studies, it has been demonstrated that the air emerging from the "hot" or "cold" end of the device varying plus or minus 40-50 degrees from ambient [4].

The physical separation of streams by the vortex tube is achieved through the tangential injection of a pressurized gas into a partially enclosed *swirl chamber* where which the fluid stream is accelerated at a high rate of rotation. Due to the conical nozzle located at one end of the tube, only the outer shell of the compressed gas (the hot fluid stream) is allowed to escape there. The remainder of the gas (the cold fluid stream) is forced to return in an inner vortex of a reduced diameter within the outer vortex, exhausting opposite the direction of the hot fluid stream, see Figure 1.

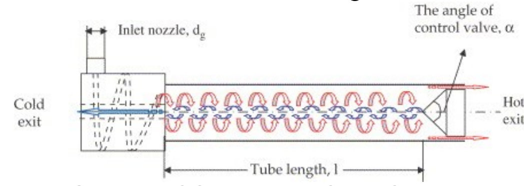

FIGURE 1: COUNTERFLOW VORTEX TUBE

One theory behind the operation of a vortex tube, the "Viscous-Shear Theory," identifies that as both fluid vortices rotate at the same angular velocity and direction, the inner vortex loses angular momentum. The decrease of angular momentum is transferred as kinetic energy to the outer vortex subsequently increasing the temperature of the outer vortex while reducing the temperature of the inner vortex [7]. This is somewhat analogous to a Peltier effect device, which uses electrical pressure (voltage) to move heat to one side of a dissimilar metal junction, causing the other side to grow cold.

The primary purpose of the vortex tube in this study is to evaluate its performance as a refrigeration device in reducing the temperature within a site designed plastic radiation suit. Remaining content within this article contain sections pertaining to the background and purpose of vortex tube testing as a cooling device, the experimental setup, thermodynamic analysis, statistical analysis, and test integrity verification. Then, the article then concludes with a brief summary of findings.

BACKGROUND

Connecting the cold exhaust flow of a vortex tube to an Industrial Hygiene (IH) Plastic Radiation Protection Suit allows a user to significantly reduce his/her ambient temperature in the field.

Though vortex tubes are currently available for use at SRS, a new vortex tube model became available which offers numerous potential advantages over the current models. One such new advantage includes the incorporation of a preset temperature drop of 20 degrees Fahrenheit with a user adjustable Ranque-Hilsch Vortex Tube control capable of reducing the cold air stream temperature approximately 10 additional degrees Fahrenheit, for a total temperature reduction around 30 degrees Fahrenheit.

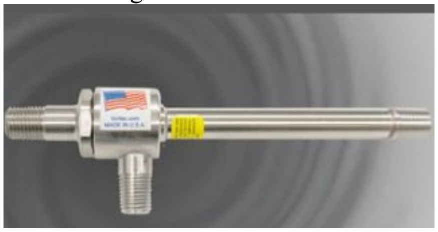

FIGURE 2: RHVT, COURTESY OF ITW VORTEC

Additional advantages of the new vortex tube model over current models also include eliminating the need for adjustment at the SRNS Respiratory Equipment Facility (REF), providing additional suitability with the availability of 3/8" x 50', 100', and 150' breathing air hoses, obviating the use of heat shields or leather sleeves due to tube encasement, and increasing convenience with the addition of a belt loop on the vortex tube with an adjustable waist belt and a plastic buckle. Testing of a prototype similar to the current adjustable model was completed by Savannah River National Laboratory during the year 2014, indicating high potential for use of this device and warranting further study.

EXPERIMENTAL SETUP

For observations of the volumetric air flow, an inline rotameter was mounted to a modified scaffold structure (Figure 3, below) and connected to a plastic suit silencer distributor (PSSD), servicing the helmet plenum and two leg air hoses. The PSSD received the cold air flow exhausted directly from the vortex tube and routed it to different locations within the plastic suit, as indicated in Figure 4.

Testing of each of the 25 vortex tubes began by labeling each tube, numbered 1 through 25. Then, a single vortex tube was attached to the in-line rotameter and the airflow released through manipulation of the ball valve lever. The airflow regulator was then adjusted, or verified, to produce a pressure of 100 psig. A structured testing procedure was developed during testing and included adjusting the RHVT to the fully closed position, ensuring that the rotameter float remained unaffected by excessive friction between the float and the guide rod, and allowing adequate time for the system to recover from the effects of hysteresis prior to collecting data. Incorporating this structured testing procedure, the initial volumetric air flow data point collected for the RHVT in the closed position then occurred after the RHVT was opened slowly and exactly to the point where the vortex tube ceased producing undesirable whistling noise. Next, the RHVT was opened completely and the volumetric air flow measurement for the muffler in the open position was recorded. Following the collection of the volumetric airflow measurements, the RHVT was returned to the closed position. Then, the quick release fitting on the rotameter was disconnected, and the vortex tube was attached to a Cejn test apparatus.

This test apparatus consisted of a 3/8" diameter Cejn 342 Series quick release fitting with a two inch segment of 3/8" breathing air hose attached to the ribbed end of the fitting, as seen within Figure 5. With the inlet air stream adjusted to 100 psig, the temperature of the cold stream was then measured at a specified point on the two inch segment of breathing air hose (delineated by a black line on the outer surface of the Cejn test apparatus) utilizing a Fluke thermometer, seen below in Figure 6. Then, after adjusting the muffler to the fully open position, a stopwatch began tracking the test trial time, and the initial cold airflow temperature measurement was recorded. After 10 and 20 minutes of continuous airflow through the vortex tube, the second and final airflow temperature measurements were recorded. The procedure was then repeated in entirety with the five randomly selected vortex tubes, chosen in accordance with ANSI/ASQ Z1.4 Lot Quality Assurance Sampling for a lot size of 25 samples, were evaluated for the volumetric airflow and air temperature of the exhausted cold stream, with the RHVT in the previously described closed and open positions. Then, with the inlet air pressure set to 100 psig, the temperature of the exhausted cold stream was recorded once while the RHVT was adjusted to the closed position and then three additional times (initial, after 10 minutes, after 20 minutes) while the RHVT was adjusted to the open position.

FIGURE 2: VORTEX TUBE TESTING STATION

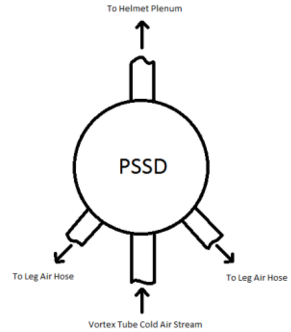

FIGURE 3: THE PSSD RECEIVES THE COLD AIR STREAM FROM THE VORTEX TUBE AND DISTRIBUTES FRACTIONS OF THE COLD STREAM TO THE HELMET PLENUM AND LEG AIR HOSES

FIGURE 4: A FLUKE 51 II THERMOMETER WAS UTILIZED TO COLLECT AIR TEMPERATURE MEASUREMENTS DURING TESTING

FIGURE 5: THE CEJN TEST APPARATUS CONSISTED OF A 3/8" CEJN QUICK DISCONNECT FITTING ATTACHED TO A SMALL LENGTH OF BREATHING AIR HOSE

Note that, for all cases in which cold air stream temperatures were measured, the ambient temperature was recorded prior to commencing testing. Post-collection of all data with inlet air pressure corresponding to 100 psig, the pressure was increased to 120 psig. The initial testing procedure was then replicated for each of the five randomly selected vortex tubes and recorded. Subsequent to the completion of all time trials analyzing the vortex tube cold air stream temperatures, all 25 vortex tubes were placed, individually, into a lab designed Plexiglas box airflow chamber, as seen within Figure 7. The entire perimeter of the cover was sealed using weather stripping material, allowing air to only flow out of the box at a single orifice. An in-line mass flow transmitter, connected to the box orifice, then measured the total volumetric airflow (the combined exhausted hot stream and cold stream) that was exhausted through the vortex tube. For each of these collected total volumetric flow measurements, the inlet airflow corresponded to a test pressure of 100 psig. A final collection of data evaluated the noise level present within the plastic suit helmet during the use of a vortex tube. This testing utilized five plastic suits, excluding the pants for all cases, and 15 different, randomly selected, vortex tubes. (Reference Figure 8 below for the experimental setup utilized during sound testing.) Testing included the analysis of each vortex tube for three different suit sizes; two Extra-large, two Tween, and one Large. Data samples collected with a sound level meter during this test procedure were respective to inlet air pressures of both 100 psig and 120 psig.

FIGURE 6: A PLEXIGLAS AIRFLOW CHAMBER UTILIZED TO MEASURE THE TOTAL VOLUMETRIC AIRFLOW

FIGURE 7: NOISE LEVEL EVALUATION OF A PLASTIC RADIATION SUIT JACKET AND HELMET

THERMODYNAMIC ANALYSIS

With the primary purpose of the vortex tube intended to reduce the temperature within a site designed plastic radiation suit, product performance as a refrigeration device was evaluated. Analysis of the performance of the vortex tube as a refrigeration device was completed utilizing the relationship defined within Equation 1, treating the enclosure as an open system control volume,

$$\beta = \frac{\dot{Q}}{\dot{W}} \qquad (1)$$

for which β is the coefficient of performance, $\dot{Q}$ is the refrigeration effect of the vortex tube, and $\dot{W}$ is the work done to compress the air from atmospheric pressure and temperature to the vortex tube inlet conditions. The refrigeration effect of the vortex tube is defined by the relationships present within Equation 2,

$$\dot{Q} = \Delta\dot{H}_c = \dot{m}_c C_p (T_i - T_c) \qquad (2)$$

Here, the refrigeration effect of the vortex tube is identified to be the change in enthalpy in the exhausted cold stream; calculated as the product of the mass flow rate of the cold stream, the specific heat of air at constant pressure, and the difference in the inlet stream and cold stream temperatures, respectively $\dot{m}_c,\ C_p,\ T_i,\ and\ T_c$.

The work done by the compressor is defined within Equation 3,

$$\dot{W} = \frac{\dot{m}_i R (T_2 - T_1) n}{n-1} \qquad (3)$$

where T_1 and T_2 are the respective compressor inlet and exit temperatures, and while assuming a reversible and polytropic process, n is the polytropic exponent equivalent to the specific heat ratio of air. For an ideal gas where $n \neq 1$, the inlet and exit temperatures relate to inlet and exit pressures according to the relationship defined within Equation 4,

$$\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \frac{T_2}{T_1} \qquad (4)$$

Furthermore, considering that the specific heat of air at constant pressure with respect to temperature is equivalent to the ratio of the product of the specific heat ratio of air and the Gas Constant of dry air to the difference of the specific heat ratio of air and one (1), as shown within Equation 5,

$$C_p(T) = \frac{nR}{n-1} \qquad (5)$$

the equation of the work done by the compressor simplifies to the relationship shown within Equation 6,

$$\dot{W} = \dot{m}_i C_p (T_2 - T_i) \qquad (6)$$

Here, the product of the rate of change of the mass flowing into the system, the specific heat of air at constant pressure, and the difference of the temperature of air following compression and the temperature at atmospheric conditions calculate the ideal work needed to drive the compressor.

The time rate of flow of mass in the cold exhaust stream of rotameters was calculated, in each case, as the product of the measured volumetric flow rate of the cold air stream and the the density of the air at the corresponding temperature value and relative air humidity, as seen within Equation 7,

$$\dot{m}_c = \dot{V}_c * \rho(T_c) \qquad (7)$$

where $\dot{V}_c$ refers to the volumetric flow rate of the cold air stream $\rho(T_c)$ is the density of air at the corresponding cold air temperature.

Calculated coefficients of performance identified results similar to actual COP values contained within published literature [6]. Numerical data indicated that the devices are highly irreversible, with corresponding COPs around 0.075. Average values of the refrigeration effect and work done by the compressor were equivalent to 650 BTU/hr and 8800 BTU/hr, respectively.

STATISTICAL ANALYSIS

Following calculations of the changes in enthalpy for each case, utilizing collected temperature measurements, the tested vortex tubes were found to perform in accordance to the manufacturer's published product specifications, identifying a cooling capacity averaging approximately 650 BTU. Additionally, the average temperature reduction from ambient conditions was determined to be approximately 30 degrees Fahrenheit;20 degrees Fahrenheit preset by device design and an additional, though approximate, 10 degrees Fahrenheit adjustable by the user. Also demonstrated through this product testing was that the radiation suits are capable of maintaining a noise level below 80 dBA while using the new model of vortex tube.

Internal SRNS Procedures require air flow ranging between 15 SCFM to 25 SCFM for a radiation protection suit to maintain an assigned protection factor of 10,000 (as approved through NIOSH, National Institute for Occupational Safety and Health). Testing identified that the sample set's total cold volumetric air flow measurements averaged 19.42 SCFM. Additionally, all collected cold volumetric airflow measurements ranged between 18 SCFM to 20 SCFM; meeting SRS manual specifications for plastic radiation suits. In addition to the air flow required to service the suit, the attached helmets require an air flow between 6 SCFM and 10 SCFM be supplied to the helmet plenum in order to provide a safety factor of 1000 (as approved through NIOSH). With the collected air flow measurements for the helmets ranged between 10.4 and 11.4, the air flow supplied to the helmets through the current sample set exceeded the internal SRNS specification.

At the conclusion of 20 minutes of testing with uninterrupted airflow through each vortex tube at 100 psig, the temperature drop (Diff20) between ambient room conditions and the average cold air stream of the vortex tube was 30.24 degrees Fahrenheit (Table 1). Individual measurements ranged between 27.5 and 33.1 between degrees Fahrenheit. The temperature measurement from suit #16 (lowest point in Figure 9) was determined to be an outlier possibly due to design and assembly issues that are being remediated. Therefore, it was not included in further statistical analysis.

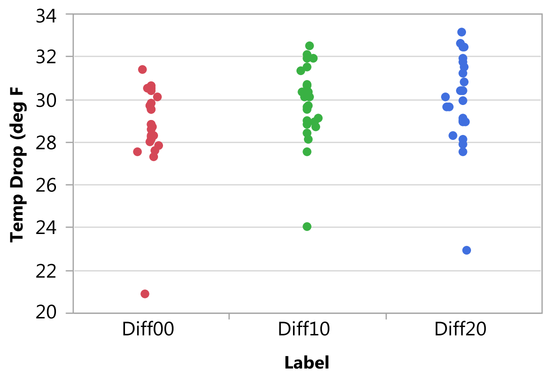

FIGURE 9: THE TEMPERATURE DROP RELATIVE TO AMBIENT ROOM TEMPERATURE INITIALLY, AFTER 10 AND AFTER 20 MINUTES

The data contained in Table 1, summarized the statistical results for the temperature drop relative to ambient room temperature initially (Diff00) and after 10 (Diff10) and 20 minutes (Diff20). The statistics include the mean, standard deviation, and 95% error limits for the mean.

TABLE 1: THE STATISTICAL VALUES FOR THE 24 VORTEX TUBE SAMPLE SET WERE COLLECTED FOR ANALYSIS.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Diff00	24	29.07	1.15	28.59	29.56
Diff10	24	30.04	1.35	29.47	30.61
Diff20	24	30.24	1.61	29.56	30.92

Considering that the largest drop in temperature from ambient conditions occurred for the data set collected after 20 minutes of continuous airflow, it remains the data of current focus. At 20 test minutes, a mean of 30.24 deg F and a standard deviation of 1.61 deg F produces a the 95% confidence interval with bounds respective to lower and upper limits of 29.56 deg F and 30.92 deg F for the n=24 test units; meaning that wholly repeating the testing procedure for the entire sample set would result in a newly calculated mean values between these lower and upper bounds with 95% confidence. The difference in temperature drop from the initial measurement to 10 minutes (Del 00 10) was 0.97 degrees F on average and is significant (Table 2) as determined by the 95% confidence interval (0.57, 1.37). However, the difference in the average temperature drop between 10 and 20 minutes (Del 10 20) was insignificant.

TABLE 2: STATISTICS VALUES FOR THE VORTEX TEST DATA

Statistic	Del 00 10 (deg F)	Del 10 20 (deg F)	Del 00 20 (deg F)
Mean	0.97	0.20	1.17
Std Dev	0.94	0.73	1.08
Std Err Mean	0.19	0.15	0.22
Lower 95% Mean	0.57	-0.11	0.71
Upper 95% Mean	1.37	0.51	1.62

A statistical process control chart for Diff20 (Figure 10) plotted according to the test sequence shows no visible trends or patterns over the experimental campaign indicating that the data are essentially random.

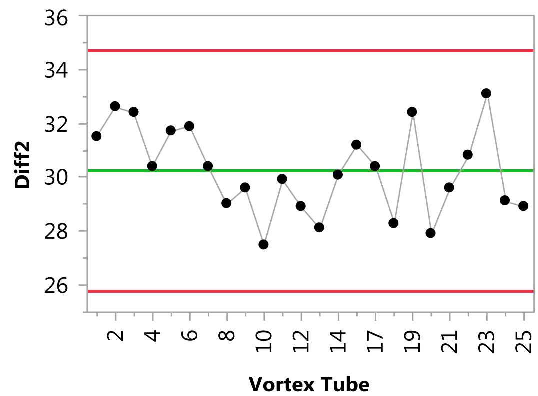

FIGURE 10: SPC CHART OF TEMPERATURE DROP RELATIVE TO AMBIENT ROOM TEMPERATURE (DEG F) AT 20 MIN (DIFF20)

A Normal Quantile Plot (NQP) in Figure 11 was used to visualize the extent to which Diff20 is normally distributed. The NQP is also called a quantile-quantile plot, or Q-Q plot. The normal quantile plot also shows Lilliefors confidence bounds (Conover 1980) and probability and normal quantile scales. This NQP shows that Diff20 can be modeled by a normal distribution, because the points of the NQP can be approximated by a straight line. Typical good of fit statistics p-values are 0.76, 0.61, and 0.30 for the Anderson-Darling, Shapiro-Wilk, and the Skewness-Kurtosis test, respectively. The Skewness-Kurtosis All test for normality is one of three general normality tests designed to detect all departures from normality. It is comparable in power to the other two tests. It is the default test because it is not affected by ties like both the Anderson-Darling and Shapiro-Wilks tests. The normal distribution has a skewness of zero and kurtosis of three. The test is based on the difference between the data's skewness and zero and the data's kurtosis and three. It is the default test because it is not affected by ties like both the Anderson-Darling and Shapiro-Wilks tests. The normal quantile plot also shows Lilliefors confidence bounds (Conover 1980) and probability and normal quantile scales. Even so, a number of other probability distributions were identified through use of a Skewness-Kurtosis Plot (Figure 4) and found to give reasonable representations of the data.

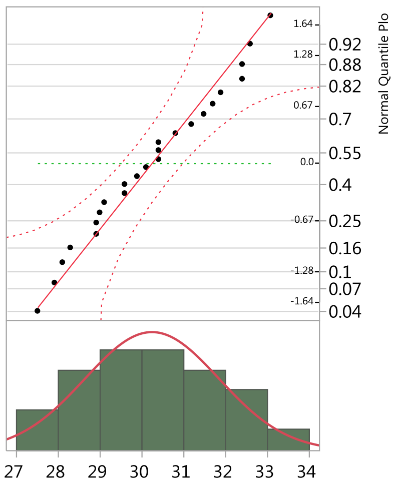

FIGURE 11: NORMAL QUANTILE PLOT, HISTOGRAM, AND FITTED NORMAL DISTRIBUTION FOR DIFF20 (DEG F)

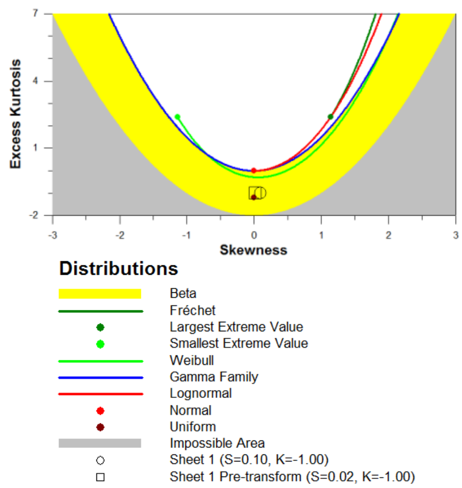

FIGURE 12: SKEWNESS-KURTOSIS PLOT FOR DIFF20 DATA

Two-parameter distributions like the normal distribution are represented by a single point on a Skewness-Kurtosis Plot (Figure 12). Three parameters distributions like the lognormal distribution are represented by a curve. Four parameter distributions like the beta distribution are represented by a shaded region. At the bottom of the plot is a gray shaded region called the impossible region where no distributions can fall.

The skewness is measure of the symmetry of the distribution. A skewness of zero means the distribution is symmetrical like the normal distribution. A positive skewness means the upper tail is longer than the lower tail like the Largest Extreme Value distribution. A negative skewness means the lower tail is longer than the upper tail like the Smallest Extreme Value distribution. A skewness value of 1 and above or -1 and below represents a sizable departure from normality. The formula used for estimating the skewness from a set of data is:

$$\text{Skewness} = \frac{n}{(n-1)(n-2)} \frac{\sum_{i=1}^{n}(x_i - \overline{X})^3}{S^3} \quad (8)$$

where n is the sample size, x_i represents the data points, is the average and S is the standard deviation.

The excess kurtosis = kurtosis - 3. This results in the normal distribution having an excess kurtosis of zero. An excess kurtosis above 0 indicates the tails are heavier than the normal distribution. An excess kurtosis below 0 indicates the tails are lighter than the normal distribution. An excess kurtosis value of 1 and above or -1 and below represents a sizable departure from normality. The formula used for estimating the excess kurtosis from a set of data is:

$$\text{Kurtosis} = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \frac{\sum_{i=1}^{n}(x_i - \overline{X})^4}{S^4} - \frac{3(n-1)^2}{(n-2)(n-3)} \quad (9)$$

where n is the sample size, x_i represents the data points, is the average and S is the standard deviation.

The test rejects the hypothesis of normality when the p-value is less than or equal to 0.05. Failing the normality test allows you to state with 95% confidence the data does not fit the normal distribution. Passing the normality test only allows you to state no significant departure from normality was found. Similar statements apply to any other assumed probability distribution. With the idea of robustness, a number of probability distributions can be used to represent the data (Table 3). None of the probability distributions in Table 3 can be rejected according to their p-values (in comparison with the threshold value p=0.05). Over the seven probability distributions the lower tolerance limit for 99% coverage (with 95% confidence) is 24.63 deg F, and the upper limit is 37.13 deg F.

TABLE 3: TOLERANCE INTERVALS FOR DIFF 20 (DEG F) 99% COVERAGE WITH 95% CONFIDENCE

Distribution	Lower TI	Upper TI	p
Normal	24.63	35.84	0.30
Beta	27.45	33.16	0.59
Largest Extreme Value	25.11	34.72	0.38
Smallest Extreme Value	26.31	35.83	0.43
Gamma	25.74	37.13	0.37
logNormal	25.34	36.69	0.33
Uniform	27.45	33.15	0.54

Note: Ho = The data is from the Normal distribution.
Small p-values ($p \leq 0.05$) reject Ho.

TEST INTEGRITY VERIFICATION

Experimental proceedings spanned over a two day duration. Lower ambient room temperatures were observed in the morning hours of testing and higher, plateauing, temperatures observed in the afternoon (Figure 13); ranging between 68.4 and 73.6 degrees F. A plot of the temperature reduction (Diff20) vs. ambient room temperature (Figure 14) demonstrated independence between the two variables.

Though, in theory, the temperature reduction should not be grossly affected by the ambient room temperature. The temperature reduction should be calculated utilizing the temperature of the inlet air stream for which, because the air reservoir was located outside the testing facility, the compressed air would normalize to, and correspond with, the atmospheric temperature prior to use within the testing facility. However, the site approved experimental test setup did not allow for obtaining temperature measurements of the air prior to entering the RHVT. So, results were calculated assuming that the ambient room temperature varied in accordance with the atmospheric temperature as time progressed throughout the day. In order to perform the calculations, local atmospheric conditions corresponding to the time experimental proceedings took place were obtained from on-line resources [1].

The calculated results in temperature reduction displayed no correlation to ambient temperature primarily due to unavoidable inconsistencies within the testing procedure. The vortex tube manufacturer's design omitted the incorporation of a finite location for which the RHVT was considered to be within the fully open position. Minor variance in the machining of each vortex tube RHVT's screw threads would allow for alternate fully open RHVT locations to be utilized, subsequently affecting the fraction of hot air flow. Each test was dependent upon the test administrator's feel for where the screw threads reached maximum resistance; heavily dependent on the quality or cleanliness of the machined screw threads of each RHVT. The manufacturer's design and assembly, currently under investigation for remediation, further limited the fraction of hot air flow in accordance with the installed configuration of a steel mesh filter; reduced volumetric flow rates of the hot air caused by an overly compact filter.

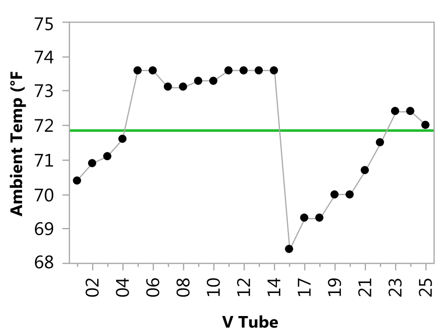

FIGURE 13: AMBIENT ROOM TEMP (°F)

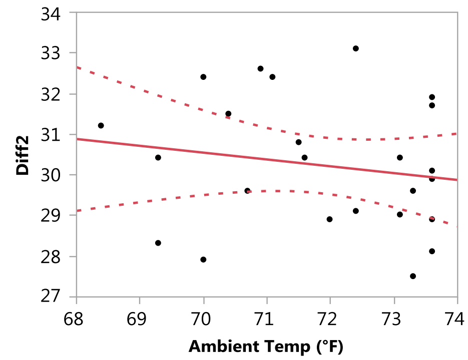

FIGURE 14: DIFF20 VS. AMBIENT TEMP (°F)

A test was conducted to determine the impact of air flow pressure at 100 psig versus 120 psig. Five vortex tubes were randomly selected from the sample set and temperature data were collected for analysis. As above, the temperature reduction after 20 minutes was determined. The Diff20 at 100 psig and Diff20 at 120 psig were treated as matched pair differences (Figure 15). The Matched Pairs platform compares the means between the two correlated variables and assesses the differences. The *paired t-test* takes the correlated responses into account. Figure 15 displays a graph of the paired differences by the paired means, and the paired *t*-test results.

Relevant statistics for the impact of pressure differences are presented in Table 4. The average temperature reduction after 20 minutes at 120 psig is 30.22 deg F and at 100 psig is 30.82 psig. There is no statistical difference in temperature reduction between the two pressures. The Tukey mean-difference (Cleveland 1994, p. 130) plot, which plots the difference of the two responses on the *y*-axis against the mean of the two responses on the *x*-axis, was used. One can conclude that an increase in air flow pressure held no discernable correlation to the temperature of the cold air stream.

TABLE 4: STATISTICS FOR IMPACT OF PRESSURE DIFFERENCES

Diff20 120 (deg F)	30.22	N	5
Diff20 100 (deg F)	30.82	Correlation	0.168
Mean Diff (deg F)	-0.60	t-Ratio	-0.629
Std Error (deg F)	0.954	DF	4
Upper 95% (deg F)	2.05	Prob > |t|	0.56
Lower 95% (deg F)	-3.25		

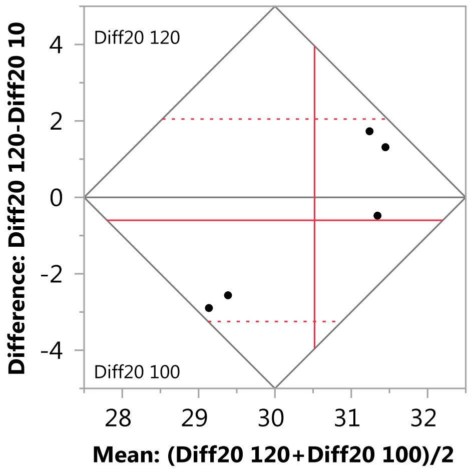

FIGURE 15: MATCHED PAIRS: DIFF20 120-DIFF20 100

CONCLUSIONS

Analysis of the test data indicated that the average temperature drop from ambient room temperature after 20 minutes of continuous airflow through the vortex tube was 30.1 degrees Fahrenheit. Also, the test data identified no discernable correlation between air flow pressure and the temperature of the cold air stream. A more complete and diverse set of data is currently being run at SRS to determining whether enhanced cooling can be obtained through device design changes and manufacturing improvements. Additional experimentation with increased testing times, incorporation of alternate breathing air hose sizes, and evaluation at elevated inlet air temperatures will provide a more complete analysis of the product performance.

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