Process Analyzing of the Vortex Tube and The Teaching and Learning of Energy Efficiency and Sustainability

Don Van[1], Joel Ingram[2], Kenneth Mayo[3] and Kian Jost[4]

Abstract – Vortex Tubes (also known as "Ranque Vortex Tube", "Hilsch Tube", "Ranque-Hilsch Tube" and "Maxwell's Demon") produce hot air and cold air from a high pressure air source using no moving parts. It is possible to get a two-hundred and ten degree Fahrenheit difference between the hot and cold exits [4]. Vortex Tubes have been used in industry for spot cooling machines [2] as well as for mine cooling [Jianggang, 3]. Previous research has shown that Vortex tubes are not efficient at all when compared to standard air-conditioning units, a standard air-conditioning system will have a coefficient of performance up to thirty-four times greater than the coefficient of performance of a Vortex tube [Newton, 4]. Although the efficiency is not stellar compared to standard air-conditioners, they do have the advantage of being simpler and using air directly, instead of a refrigerant. Since Vortex Tubes are simpler designs than standard air-conditioners, there is less maintenance required [Swing, 5]. How does this fit in the realm of energy sustainability and environmental responsibility? This paper will show an analysis of the operation of the vortex tube with regard to the relevant conversion of energy. Experimental data will be used to quantify the efficiency of the device as a function of compressed air inlet. Teaching and learning of energy efficiency and sustainability will be shown using the analyses conducted using this device. A feasibility study will be presented with regard to a potential use of a vortex-tube based air-conditioning system.

Keywords: Efficiency, Vortex Tube, Coefficient of Performance, COP, Sustainability

1. INTRODUCTION

Businesses and industries are under intense pressure to embrace policy of sustainability or face economic reprisal by the investment community [6]. At the core, sustainability makes a lot of sense. Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations [7].

Sustainability has everything to do with a harmonious co-existence of the economy, society and the environment [Wilkening et al., 8] [Noorman et al., 9]. The economic engine requires energy to run. The society depends on economic growth and a healthy and sustainable environment to thrive and the environment requires responsible energy harvesting and utilization to be inhabitable. In light of this interdependence, it is proposed that we view energy as the common thread that holds these three sectors together in an optimized fashion.

[1] Union University, 1050 Union University Dr., Jackson TN 38305 dvan@uu.edu

[2, 3, 4] Union University. joel.ingram@my.uu.edu, kian.jost@my.uu.edu, Kenneth.mayo@my.uu.edu

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Since sustainability means different things to different groups [Johnston, 10] [Smerdon, 11] [Frosch, 12] [Peet, 13] [King, 14] [15], in the context of this paper, energy sustainability is defined as the ability to fuel the world's economic engine in support of its economic growth by minimizing the use of fossil fuels to the extent that there is no associated environmental impact.

If energy sustainability means engineering ability to design to the compliance of corporate sustainability policy, then future engineers (engineering students) must be trained and equipped with the know-how and creativity of engineering to explore new venues, to develop new methods and to enhance the existing efficiency. But all those could not be accomplished if the engineers being educated today are not aware of the immense responsibility expected of them concerning future generations.

Energy sustainability is not about energy curtailment. It is rather about efficient use of energy. This paper investigates the potential use of the vortex tube (or similar processes) to provide cooling from compressed air. Although the efficiency is not stellar compared to standard air-conditioners, they do have the advantage of being simpler and using air, instead of a refrigerant. Since vortex tubes are simpler designs than standard air-conditioners, there is less maintenance required [Frank, 5]. How does this fit in the realm of energy sustainability and environmental responsibility? This paper shows a case study in which the concept of sustainability was taught in an engineering course (Energy Conversion). A group of students was given an energy conversion device through which they were challenged with the following learning outcomes: (1) understanding (a) how it functions technically and (b) how it impacts environmentally, and (2) providing recommendations regarding the use of the device based on its efficiency study.

2. ANALYSIS OF THE VORTEX TUBE

2-1 Background

The vortex tube was invented by a French physicist named Georges J. Ranque in 1931. It is a device (see Figure 1) that uses compressed air to make both a heated and a cooled stream without moving parts. The tube performs this phenomenon through a simple design. Basically, a vortex tube is a cylinder with a tangential inlet nozzle. The compressed air is injected through the nozzle in the tube in a swirling motion. Some of the air is allowed to escape through a control valve on one end, and the rest is pushed back through the tube in the opposite direction through the center of the original stream. On one end, the exiting air is hot, and the other end contains cold exiting air.

Figure 1-Vortex Tube [15]

When the compressed air is directed into the inlet of the tube, the tangential design of the nozzle causes the air to be forced into the cylinder in a centrifugal motion. The centrifugal motion causes the air to increase in pressure along the outer edge of the tube, and decrease in pressure in the middle of the tube along the axis. As shown on the right end of Figure 1, the control valve only allows some of the high-pressure air near the outer edge of the stream to escape. The rest of the air is forced back through the center of the shaft of air. The centrifugal field causes the air near the center of the tube to expand, and decrease in temperature. Also, Hilsch [Hilsch, 16] explains that internal friction tries to establish a constant angular velocity throughout the cross section of the tube. Therefore, a considerable amount of kinetic energy from the air stream in the center is given to the outer stream in the form of heat, causing it to increase in temperature.

There are many different explanations for the thermal separation phenomenon of the vortex tube as it is not yet fully understood. However, Hilsch's explanation described earlier regarding constant velocity and both streams moving as

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a solid body is widely accepted [Chengming, 17]. Since the angular velocity is directly related to the radius, the inner air stream would naturally have a higher angular velocity than the outer stream. However, since friction is causing them to move at the same angular velocity, the inner stream loses energy and cools down. Hilsch [Hilsch, 16] states, “Compressed air of a few atmospheres pressure and 20°C will easily produce a temperature of +200°C in the [hot end] and -50°C in the [cold end].”

There are many advantages of the vortex tube, which include: no moving parts, easily controllable output, low cost, and compactness. Vortex tubes are most commonly used for spot cooling, but can it be (more importantly, should it be) used for cooling on a large scale? Why or why not? These questions will be explored based on measuring data.

2-2 Establishing the device’s operating data

To first explore how the vortex tube works, we ran a preliminary experiment in which we measured the temperature of the air at each end of the tube with varying starting pressures in the air compressor. We gathered the following data:

Pressure (PSIG)	Cool End Temp. (F)	Hot End Temp. (F)	Temp. Difference (F)
30	27.9	96.8	68.9
60	7.2	89.8	82.6
90	-14.8	124.3	139.1
120	-36.5	128.5	165

Table 1- Temperature Difference with Varying Starting Pressure

In our actual experiment that will later be discussed, we used a constant pressure of 48 psig. We used this number because that is a pressure at which the air compressor could hold constant over time while the air was flowing out through the vortex tube.

To determine the coefficient of Performance (COP) for cooling of the vortex tube, we compared the heat output of the cold side of the Vortex tube to the energy consumed by the air compressor. See the schematic diagram of the experiment (below in Figure 2).

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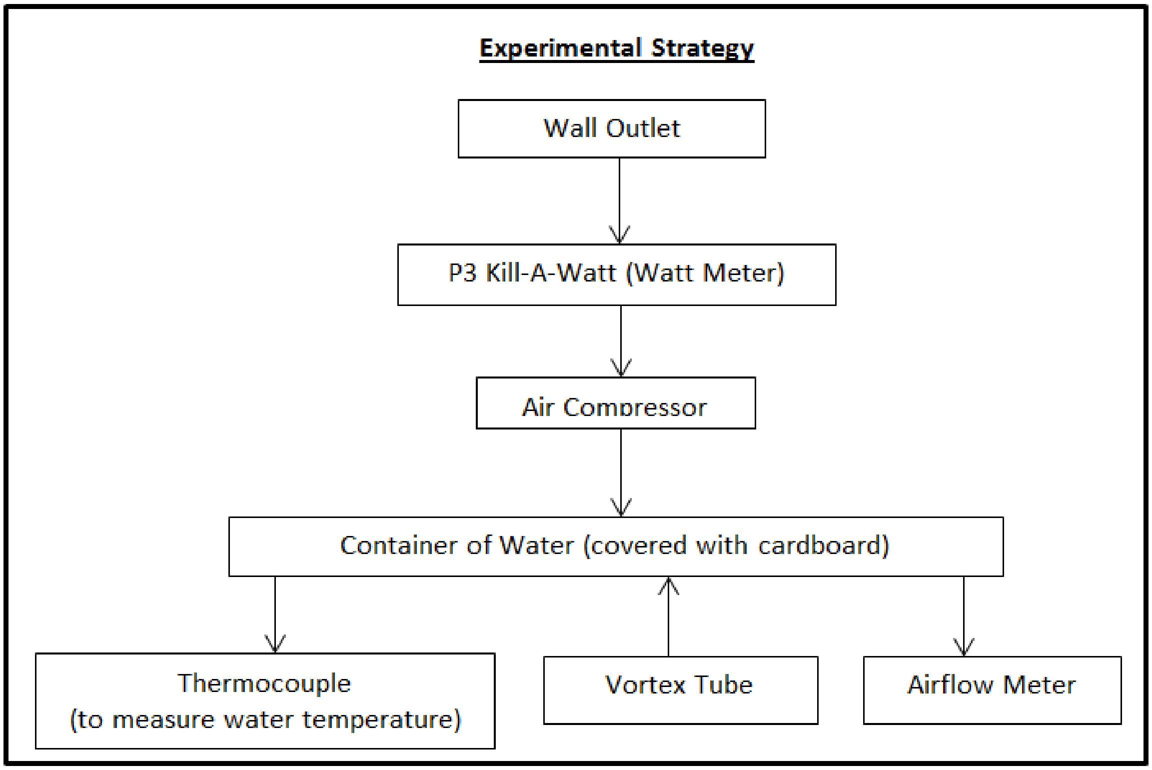

Figure 2- Experimental Strategy flowchart

2-3 Calculating the device's C.O.P

We were not able to measure pressure of the cold side of the vortex tube because the flow rate of the air was not large enough to overcome the static pressure of the pressure gauge we had attached to it. In order to get around this issue, we cooled a known mass of water by the vortex tube. We measured the weight of an empty plastic container and then filled it with water and re-measured the weight. The mass of the water was the difference between the two. We used this mass in the equation for heat energy of the water $\boldsymbol{Q = mC_p\Delta T}$ where m is the mass of the water, C_p is the specific heat for constant pressure and $\boldsymbol{\Delta}$T is the difference in the temperature of water from before the cooling started to after the cooling. The water is the medium that we are cooling with the vortex tube; therefore, the initial water temperature is acting as our ambient temperature. We cooled the water by running air through the vortex tube for five minutes with the air compressor releasing air at 48 psig. The result of cooling for five minutes is shown below in Figure 2. We used a Watt-meter to measure the wattage being consumed by the air compressor; average reading of 1540 watts was obtained. For an elapsed time of 300 seconds, the energy input of the system was calculated to be 462,000 joules. The energy gained by the water was determined to be the energy leaving the system, 32,154 joules. There was additional energy leaving the system through air out of the water container; however, we determined this energy to be negligible compared to the heat released by the water. The energy released by the water was 32,154 joules and the energy lost by the air leaving was 0.0564 joules. The COP of cooling of the vortex tube was found by dividing the energy out of the system by the energy into the systems. We found the COP value to be 0.07. James Newton said in "Hilsch Vortex Tube Cooling/Heating" [Newton, 4] that he found Vortex tubes to have a COP value of 0.04, this shows we are slightly off (which might be caused by slight losses during testing) but within the same range as expected. A high COP value is much larger than 1 for an air-conditioner. A 0.07 COP value is really low. This shows that more than ninety percent of the energy that is put into the system is lost in inefficiencies leading to just below ten percent of the energy being used to actually cool.

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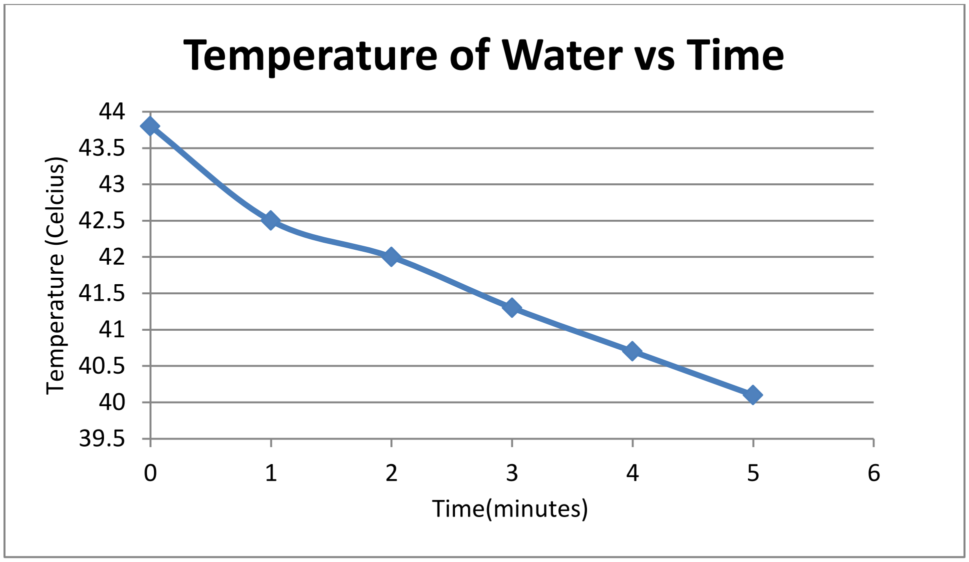

Figure 3- Cooling Energy from the Vortex Tube

2-4 INVESTIGATING THE ENVIRONMENTAL IMPACT FROM USING SUCH DEVICE

Due to the small COP value that vortex tubes have, the ramifications that they impose are quit large on an environmental scale. Because the COP value is so small, there is a larger amount of fuel that is needed to produce the same amount of cooling, in this case, than for a similar machine, for example a refrigerator. In the combustion reaction below, the production of the byproduct greenhouse gas (CO_2) from the burning of coal and natural gases are respectively shown below:

$$6.72\ C + 2.23\ H_2 + 0.06\ S + 0.075\ O_2 + 0.04\ N_2 + 0.19\ H_2O + 7.82\ O_2 + 29.39\ N_2 \rightarrow 6.72\ CO_2 + 2.42\ H_2O + 0.06\ SO_2 + 29.43\ N_2$$

$$CH_4 + 2(O_2 + N_2) \rightarrow CO_2 + 2H_2O + 2N_2$$

The issue of environmental sustainability can be seen from the above reactions through the production of Carbon Dioxide (CO_2) by-products of the burning of fossil fuels. While the amount is not very much on a per-tube scale, if used in mass, the environmental impact could be quite substantial. According to a study done at Carnegie Mellon University, for every 23g of Carbon (the primary element in coal) burned, there is 44g of Carbon Dioxide created, assuming a complete reaction [Hilsch, 16]. Since such a large amount of pollutant is created for such a small amount of usefulness, the practicality of burning fuel for the only purpose of using the vortex tube is not very high. If a vortex tube is being used for its cooling effects, there would be a need to have pre-compressed air, or an excess of compressed air to justify the usage of the tube. If the scale of the cooling project is a larger project then either the time needed to produce the cooling effect would increase or the number of tubes needed for a shorter time period would increase, both of which create the need for more energy and, thereby, more carbon dioxide produced.

The main problem with the vortex tube is the inherent waste of energy. The calculated 0.07 COP implies that 93% of the energy used to compress the air is being wasted into the environment and not used for the actual cooling. To put this in perspective, if only 1 vortex tube was used for 8 hours every day for a year, about 4180 kWh per year would be wasted. The environmental impact of this includes the 1.363 lbs. of CO_2 emitted per kWh produced. This one vortex tube would therefore cause about 5700 lbs. of extra CO_2 every year. Now, say 100,000 vortex tubes were used for cooling 8 hours every day. This leads to about 420 million kWh of wasted energy and an extra 570 million lbs. of CO_2 produced.

Not only is there a negative environmental impact of using vortex tubes for cooling, but a financial one as well. Previous research has shown that vortex tubes are not efficient at all when compared to standard air-conditioning

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units; a standard air-conditioning system can have a coefficient of performance up to thirty-four times greater than the coefficient of performance of a vortex tube [Newton, 4]. As seen in Table 2 below, the energy necessary to create an identical cooling effect was significantly less for the air conditioning unit than for the vortex tube. This was calculated by equating the coefficient of performance value of the air-conditioning unit, which as calculated by multiplying thirty-four and 0.07, to the cooling energy divided by the necessary input energy. In order to compare the two cooling methods, the cooling effect must be the same, so using the cooling energy that was calculated from the vortex tube experiment the amount of Joules needed by the air conditioning unit was calculated. Once the required energy was calculated, in Joules, values were then converted to kWh for the calculations of total energy cost and energy cost savings based on 100,000 operational units at an average cost of energy $0.0945/kWh as shown in Table 2 below.

	COP Value	Required Energy (J)	(kWh)	Cost ($)
Vortex Tube	0.07	*462,000	449,590,706	42,486,322
AC Unit	2.38	*13,510	13,147,122	1,242,403
Difference		*448,490	436,443,584	41,243,919

All values were calculated assuming 100,000 units were used for 8 hours a day for a full year

*values with the asterisk are calculated for 1 unit over a 300-second interval

Table 2**- Comparison of Vortex Tube and Air Conditioning Unit**

Because the coefficient of performance is so small and the fact that compressed air is necessary, the applications of vortex tubes are fairly few. In order to have a smaller environmental impact, excess compressed air should be used to run the tube. With this in mind, practical applications for the vortex tube would be in a mechanical or electrical workshop, to cool down gases in a control chamber for scientific experimentation, cooling tools after use, etc. All of the mentioned possible applications have readily accessible compressed air due to the fact that the compressed air is needed for other tools or equipment that is needed. Because the tube is small, durable, and easy to use, it should easily be able to quickly cool any small equipment that is necessary in these locations.

3. CONCLUSION

This paper represents an excellent case study for integrating technical nature of energy system or component analysis and the pedagogy of sustainability concept in engineering curriculum. This group of students was presented with a course project to study the feasibility and efficiency of a seemingly versatile energy device. The project provided an opportunity to teach experimental strategy, design of a test procedure for data collection, computing of power demand, energy consumption and greenhouse gases emission. The following sums up the learning outcomes of the project from the students' point of view:

The Ranque-Hilsch Tube is quite a unique device in that it is able to generate an extraordinary temperature difference with no moving parts, and with only compressed air as a necessary addition. While the thermodynamic effects can be seemingly great, the negative effects can be equally astounding. With a poor coefficient of performance the environmental impact that the Ranque-Hilsch tube can, when used in mass quantities, be ruinous. Vortex Tubes would be a great option for cooling if for some reason a company had waste compressed air. However, since there are not many industrial applications that result in wasted compress air vortex tubes simply have too high of a cost. The environmental cost is high in that they use more energy than standard air-conditioners so they release more carbon dioxide, sulfur oxide and nitrogen oxide into the air having negative effects on global warming and acid rain. Also it is our responsibility to ensure that we are wisely using the natural resources we have now so that generations to come will not be left without. The fact that vortex tubes are up to thirty-four times less efficient than air-conditioners eliminates them for practical use from an environmental standpoint, a financial standpoint and a sustainability standpoint.

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Don Van, PhD., PE., CEM is professor of Engineering and Director of Accreditation at Union University.
Joel Ingram is graduating senior from Union University with ME Concentration (May 2013)
Kian Jost is Junior engineering student from Union University with ME Concentration.
Kenneth Mayo is Junior engineering student from Union University with ME Concentration.

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