



LOCALIZED COOLING BY VORTEX TUBE POWERED BY SOLAR PV

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Abstract. *The search for new refrigeration cycles has become the subject of study of several researchers. Ranque-Hilsch tubes are generally used for localized cooling, where there is availability of compressed air. No refrigerants, inexpensive and no moving parts, they are used for localized refrigeration with compressed air. In this work, a vortex tube was constructed in PVC, nylon and solid VC (polymer manufactured from rapid prototyping). A PV array and a compressor were sized to replace the conventional drive used in industry. The tests results show achieved values at temperatures below the freezing point of water, that is, temperatures from -13°C to a gauge pressure in the inlet pipe 4 bar. With the improvement of cooling system, new applications and installation in remote locations can contribute to the solution of energy and environmental issue in society. This project involves the dimensioning and construction of a vortex tube operating at low pressure and with new configurations of vorticity chamber. This device is instrumented so that they can measure their thermo physical properties and it is operated by renewable energy supply from a PV array previously selected to drive the compressor. In this context, photovoltaic solar energy is used with extreme simplicity due to its modular feature where you can assemble systems from mW to MW without any moving mechanical part and anywhere there is sunlight. The motivation for this work was due to high levels of solar radiation in the northeast of Brazil, which promotes the use of photovoltaic systems, and the need to use electricity in places of difficult access. The vortex tube may be used for localized cooling at low temperatures to cool the material from photovoltaic electrical supply.*

Keywords: *Vortex Tube; Localized Refrigeration; Photovoltaic Solar Energy*

1. INTRODUCTION

Refrigeration and air conditioning have traditionally used the concept of operation of the thermodynamic cycle vapor compression, either for cooling chambers chilled or frozen, either to ambient air conditioning, or even other applications. And this requires basic components such as refrigerant, heat exchangers and compressors.

However, this technology presents problems regarding to environmental damage caused by refrigerants and the increasing global consumption of electrical energy. The usual CFCs (chlorofluorocarbons), proven toxic to the ozone layer, have been replaced by modern gases HFCs (hydrofluorocarbon) in countries signatory to the Montreal Protocol in 1987. However, this change was not, in fact, the solution to environmental problems since these gases may be about a hundred times more powerful than carbon dioxide in terms of potential for trapping heat, exacerbating the greenhouse effect. An alternative to the currently used HFCs would be the blends (mixtures) which have less Ozone Depletion Potential (ODP) and lower value of Global Warming Potential (GWP), but show a reduction in energy efficiency around 15%, and consequently, a higher consumption of electricity. According to the International Institute of Refrigeration, cooling systems demand about 15% of the world's electricity (IRR Guides, 2003).

The development of technological alternatives to conventional cooling can reduce the impacts caused by the use of these systems. It is known that from the apex of the Brazilian energy crisis in 1973 and later in 2001, the air-conditionings have been described as "villains" when it comes to electricity conservation. And to supply most of the consumption in common residences or industries, for example, (something like 20% or even 25%), these devices are usually linked during the day when the demand is higher, as well as the cost.

A promising alternative to conventional refrigeration for cooling applications is the introduction of vortex tubes. The vortex tube or pipe Ranque - Hilsch is a device which enables the production of hot and cold air when compressed air flows tangentially into a chamber through a narrow entrance. Its main component is the development of a type vorticity in the flow, where the fluid is divided into two streams, one high temperature air and the other with low temperature air. This device has been applied in different sectors in the fields of engineering, e.g., cooling parts of machinery and electronic control cabinets to cool food, dehumidifying gas samples and other applications. To better understand how this process works, it is very important to analyze some elements relevant to the nature of the flow inside the fluid. Nowadays, the vortex tube has a wide variety of applications in industries that operate with refrigeration machines. It has been widely used in the fields of industrial cooling because it provides advantages in several aspects, such as low

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power consumption, lightweight, pollution-free and no-need of refrigerants, in other words, it does not denote huge environmental damage. Moreover, it is inexpensive, easy to clean and it does not work with chemicals.

The vortex tube typically has the following parts: one or more inlet nozzles, one vortex chamber, a tube for hot air conduction, a tube for cold air conduction, a diaphragm and a control valve at the hot end of the tube, as shown in Fig. 1, from Eiamsa, et al (2007).

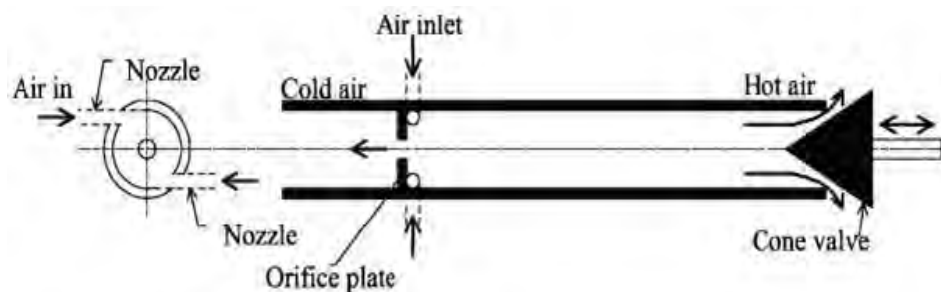


Figure 1. Schematic vortex tube

Since its discovery, the mechanism of separation that occurs in the power section of a vortex tube has intrigued many researchers. Even today, there is no clear theory that can completely explain the phenomenon. The laws of thermodynamics are applied to the system in order to determine a relationship between the mass flows in and out and the differences between the inlet temperature and outlet temperature at the hot and cold ends. Hypotheses are considered as the operation of the system is in a steady state, there is no transfer of heat between the atmosphere and the walls of the tube and the air behaves as a perfect gas.

In this work, the design and construction of a new vortex tube which operates at low pressures with cooling purposes and with new configurations of the camera vorticity were proposed. This device will be instrumented so that they can measure their thermo physical properties and can operate by renewable energy supplying from a PV array previously selected to drive the compressor. In this context, solar PV is used and it has extreme simplicity due to its modular feature where you can assemble systems from mW to megawatts without any mechanical mobile parts and anywhere there is sunlight. The motivation for this work was due to high levels of solar radiation in some regions of Brazil, which enables the use of photovoltaic systems, and the need to use electricity in remote places where there is no electricity supplying from local companies. The vortex tube may be applied in "ice storage" at low temperatures to cool the water as well, using electricity from PV supplying in industrial processes such as pasteurization equipment, dairies, cooling machines, conservation of vaccines, etc.

In general, since this project allows that refrigeration systems, without usual electricity companies, become able to supply the demand of local cooling in the countryside cities, the main goal is the utilization of solar panels, the vortex tube devices and compressors altogether.

2. THEORY

This chapter comprises a summary of the history and theory behind the vortex tubes and solar PV technologies. Aspects of the project design of the device, which will be powered indirectly by a renewable energy resource, are included as well.

2.1 History

The vortex tube was discovered unconsciously by George Rankine in 1928, a physicist and metallurgist Frenchman who was doing an experiment with a vortex pump when he noticed warm air exhausting from one side and cold air on the other. Rankine forgot his pump and started a small business to explore the commercial potential of this strange device produced by hot and cold air and no moving parts. However, his small company failed and although Rankine had presented a paper to the scientific society of France, in 1933, the examiners disbelieved in his work and did not give much importance to his project, and then the vortex tube slipped into obscurity.

In 1945, Rudolph Hilsch, a German engineer, published a scientific paper about this device. It was widely researched by Hilsch a way of increasing the thermodynamic efficiency of the vortex tube. His work states the effect of the compressed air inlet pressure and geometric parameters in the performance of the vortex tube and provided a possible explanation for the separation energy (Hilsch R, 1947).

Thus, Vortex tube or Ranque-Hilsch Vortex Tube (*RHV*T) is a simple device, which can separate an incoming compressed gas stream of uniform temperature into two streams, one warmer than the inlet stream and the other colder than the inlet stream. Physically, this device consists of a cylindrical tube with a fluid inlet positioned so that the flow

goes into the device and it tangents the inner surface of the tube radially. The secondary fluid flow leaves the vortex tube with opposite directions or with coincidentally at the axial direction, depending on the type of construction used.

2.2 Operating Principle

The vortex tube is a mechanical device that operates as a refrigerating machine without mobile parts. It separates a stream of compressed gas in a stream of low temperature and another with higher temperature. This phenomenon is called thermal separation (or energy separation).

2.2.1 Device Types

There are two kinds of instruments concerning the direction flow and geometry at the ends of the tube: Counter Flow and Parallel Flow Vortex Tube.

(a) The Counter Flow Vortex Tube

Figure 2.1 shows a counter flow vortex tube, which is named so due to the secondary fluxes leaving the tube in opposite directions.

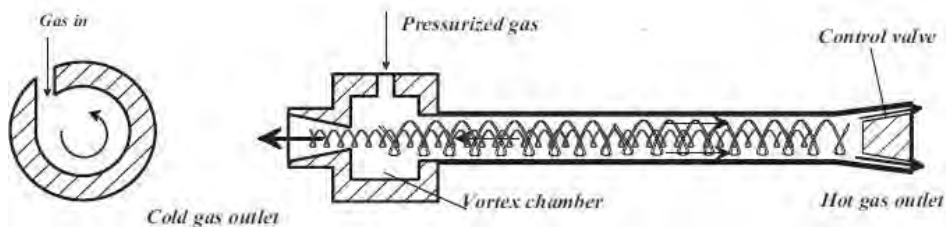


Figure 2.1, Schematic drawing of the counter flow RHVT system (Gao, 2005)

Cockerill (1998) indicates that the flow of cold gas is expelled from the vortex tube through one end of the tube, which is restricted by a lid with a circular hole positioned at the center of the tube. The flow of hot gas is expelled from the device in the opposite direction of the out flow of cold gas. This device end also has a valve in the shape of a cone which performs the adjustment of the relation between low-temperature fluid and fluid heating. When the air, at a certain pressure, is injected tangentially into the vortex chamber at inlet nozzles, a flow-shaped swirl is created within the chamber. This compressed air is expanded and travels through the hot tube at an elevated temperature until the end. There is a valve there that controls the air outlet and the part that returns to the cold pipe at a lower temperature.

(b) The Parallel Flow Vortex Tube

Instead of using opposite directions, the secondary flows leave the tube in the same way in this configuration. The hot end valve includes centered holes that provide an exit for each kind of air stream, as shown in Fig. 2.2.

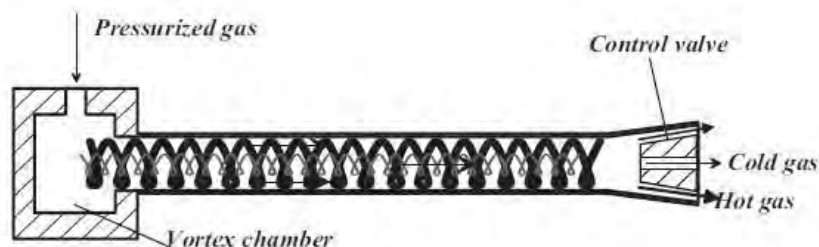


Figure 2.2, Schematic drawing of the parallel flow RHVT system (Gao, 2005)

2.2.2 Separation Temperature Principle Theory

There are many theories and hypotheses that attempt to explain the principle of energy separation. However, there is no studies that, in fact, proves scientifically the phenomenon.

Ranque and Hilsch suggested that the expansion of the air from a high pressure close to the wall of the tube to a low pressure in the center of the tube generates a velocity gradient in the radial direction, which results in transfer of kinetic energy by the viscous forces, from the inner layers to the outer layers of the tube (Dutta, et al, 2010).

One of the most accepted theories about the occurrence of separation energy states that the internal and external vortices rotate in the same direction and angular velocity. That is, a particle in the internal flow completes one rotation in the same amount of time that a particle in the external flow. However, due to the principle of conservation of angular momentum, the angular velocity of the vortex should be greater smaller. This does not occur because the speed of the internal vortices remains the same as the external. This can be explained by the principle stated above, inasmuch as angular momentum was lost from the inner vortex. The energy loss becomes the heat received in the external vortices. Thus, the external vortices are heated and the internal vortices are cooled (Gao, 2005).

2.3 Thermodynamical Analysis of the RHVT System

Figure 2.3 shows the control volume considered in the thermo dynamical analysis, which is taken as a black box. Only the gas properties at the walls, the inlet and the exhaust are of interest, i.e. the analysis details of the internal process do not need to be considered. There are three open boundaries namely A_{in} , A_h and A_c . The gas properties on these open boundaries are listed as follows: p_{in} , T_{in} , ρ_{in} , V_{in} , \dot{H}_{in} , on A_{in} with subscript "in", "h" and "c" for inlet, hot and cold, respectively. p is the pressure, T the temperature, ρ the density, V the velocity and the enthalpy flux.

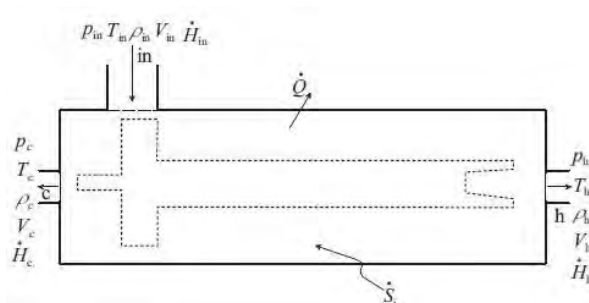


Figure 2.3, Control volume as a black box for the thermodynamical analysis

2.3.1 Mass Conservation

In the steady flow, mass conservation among the inlet flow \dot{m}_{in} , the cold \dot{m}_c and the hot \dot{m}_h outlet flows can be related as in Eq. (1):

$$\dot{m}_{in} = \dot{m}_h + \dot{m}_c \quad (1)$$

The cold flow mass ratio is the most important parameter that indicates the vortex tube performance and the temperature/energy separation inside the RHVT. The performance of the RHVT's is evaluated based on the cold fraction. The cold mass fraction is the percentage of input compressed air that is released through the cold end of the tube and it is resulted from the mass flow rate of cold gas divided by mass flow rate of the inlet gas, as in Eq. (2) below.

$$\varepsilon = \dot{m}_c / \dot{m}_{in} \quad (2)$$

2.3.2 The first law of thermodynamics

In the analysis of the First Law of Thermodynamics it is considered as assumptions negligible variations of kinetic and potential energy. In the steady state, the time rate of change of energy in the control volume is zero. The heat exchange is negligible, assuming there is no heat transfer from the borders of the tube to the environment and the work on the system is also negligible. With these conditions, Gao (2005) reaches a theoretical equation, Eq. (3), for the mass fraction of cold gas, which depends on the variation of temperature between the hot and cold ends, ΔT_h and ΔT_c , respectively.

$$\varepsilon = \frac{\Delta T_h}{\Delta T_{hc}} \quad (3)$$

Where $\Delta T_h = T_h - T_{in}$, $\Delta T_c = T_c - T_{in}$ and $\Delta T_{hc} = T_h - T_c$.

3. METHODS AND MATERIALS

The project can be divided in many components, such as measurements devices projection, data analyses and how to supply energy to that system.

A compressor, feed and cleaning system, vortex tube and the components of a solar panel are the principal devices used in this refrigeration. In the solar projection, the panel, batteries, load controllers and inverters have to be well selected to provide enough energy supplying, and in the data acquisition, registers, thermocouples and computers are used to maintain the refrigeration process controlled.

The compressed air feeder used at the first measurements is a Chiaperini CJ 30 APV/250 – 7,5HP compressor, which can provide a highest pressure of 12 bars and a volume of 250 liters. A 12 mm length Mantova PVC hose is coupled to the compressor and a valve controls the flux.

In the vortex chamber, also used to contain the vortex generator and the end and feeding tubes, the rapid prototyping techniques were used together with a SD300 Pro 3D printer, resulting in materials based on PVC and with high stiffness. The chamber consists of two parts which fit together to minimize leakage, as in Fig. 3.1.

Compressible fluid, which is tangentially introduced into the vortex tube from nozzles, starts to make a circular movement in the vortex tube at high speeds because of the cylindrical structure of the tube depending on its inlet pressure and speed (Dincer et al, 2007). Due to the importance of vortex nozzles, four nozzle types were designed as well as different cold ends, as in Fig. 3.2.



Figure 3.1, Vortex Chamber



Figure 3.2, Vortex Generators with nozzles and cold end

The design of such generators must provide tangential air entry to maintain the tube ends temperature difference as desired. With this principle, the vortex generators have some important geometrical parameters, as shown in Fig. 3.3.

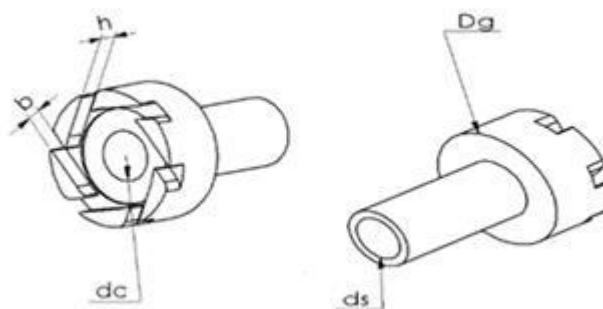


Figure 3.3, Geometrical Parameters of a Vortex Generator

To conclude the vortex tube construction, a traditionally fabricated nylon valve was added at the hot end to set the mass flux ratio in the tube.

After the tube design, the development of a workbench started. This workbench includes a *Contemp* data register (model A202 with 8 multifunctional channels) with a 2 MB data LOG, 16 configurable alarms and a digital entry. This data LOG received thermocouples of K-type (Nickel-Chrome), with an operation boundary of $-270\text{ }^{\circ}\text{C}$ e $1372\text{ }^{\circ}\text{C}$ for the temperature. To measure the temperatures, the thermocouples were installed inside of the cold and hot end tube.

Table 1 presents the main physical and geometrical parameters. Each one has been chosen based on pre-studies and articles and some adaptations were used as well.

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Table 1. Physical and geometrical parameters of Vortex Tube Refrigeration System.

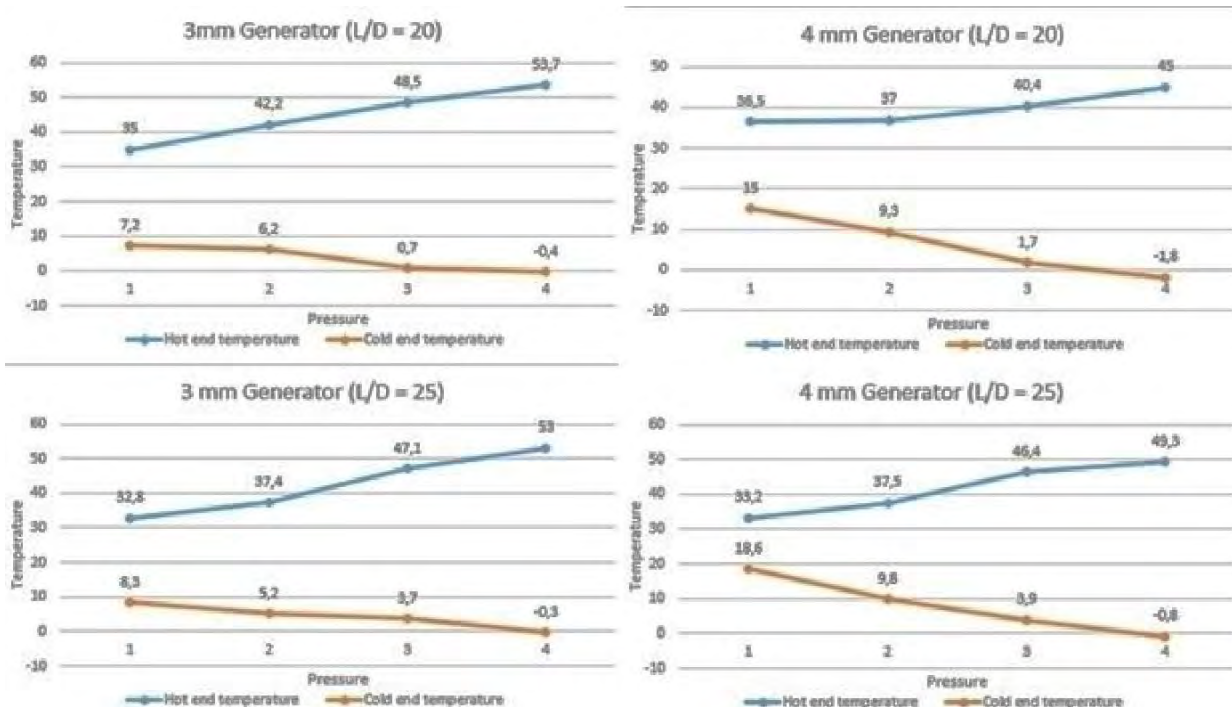
Parameter	Symbology	Value
Length/Diameter Ratio	L/D	20, 25, 30
Vortex Tube Diameter	D	11 mm
Nozzles quantity	n	6
Nozzles height	h	1 a 4 mm
Nozzles base dimension	b	3 mm
Fluid used	-	Comprsed Air
Tube material	-	PVC
Chamber material	-	SolidVC
Cold orifice diameter	d_c	8,9,10,11 mm ²
Cold end diameter	D_s	11 mm
Generator diameter	D_g	30 mm
Entry nozzle diameter	$S_b = bh$	3,6,9,12 mm ²

4. PRELIMINARY RESULTS AND DISCUSSION

Up to now, the study of refrigeration by vortex tube devices with air compressors, powered by the energy of local electricity company COELCE, has shown the four types of vortex generators and the three distinctive size tubes performances. These performances will soon be compared to the vortex tube devices supplied by solar energy.

For each experiment, the environmental temperature was 26,5 °C and the relative humidity was 55%. In total, there were 12 measurements of the temperature at the tube end in function of the air pressure.

According to these results, as Marynovskii and Alekseev (1957) had already discussed, if the pressure at the input is increased, so does the difference between the temperatures at the hot and cold ends. Good results were achieved even with low pressures for each nozzle height (from 1 up to 4mm), as shown in the Fig. 4.1 and 4.2 below.



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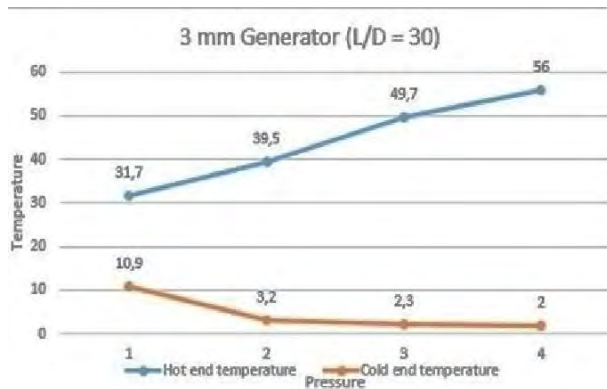


Figure 4.1, 3 mm Generator performances with L/D = 20, 25, 30

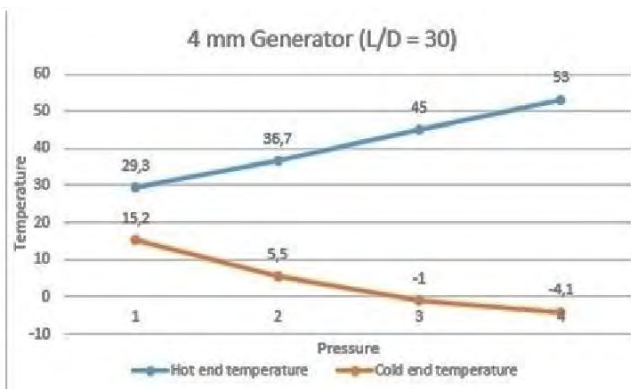


Figure 4.2, 4 mm Generator performances with L/D = 20, 25, 30

The vortex generator with the nozzle height of 4 mm and fed by a 4 bar air flux achieved the best result. The difference between the tube ends was 57,1 °C, with -4,1 °C at the cold end. It is important to state that even with a pressure of 3 bar, negative temperatures were possible to measure with this vortex generator.

Beyond the vortex tube, the compressor, the feed hose and filters are important components in this system. Their work must be carefully controlled, and since even though good results were achieved in the first part of this project, head loses may had appeared, and they could have influenced the results with low pressures.

5. CONCLUSION

With regard to the compressor, one of the most important devices in this refrigeration system, its capacity to supply enough mass flow and power will give an idea of the temperature gradient and how many solar panels will be installed.

Using 3 different types of compressor, 20, 100 and 250 L of storage, and increasing the pressure at the vortex tube entrance, it will be possible to know how much time the compressors runs out of new charge at the automatic mode. It is desirable that this refrigeration system become able to handle 8h of work using the energy of the solar system as less as possible. In a 100L compressor, it is proven the availability of the supplying of mass flow to the vortex tube, with a power of 2hp. Thus, since this compressor uses a huge volume and a motor with approximately the same power of the 20L compressor, this project will be an adaptation, i.e. an usual compressor with tanks coupled to that system.

Also, to improve the efficiency of the refrigeration, new vortex generators are been designed and printed by the SD3000 Printer, and all of them having the 4 mm nozzles height, the nozzle height of the generator that provided the highest efficiency in the first experiment, as in Fig. 4.2. At this time, new cold orifice diameters are been used, due to there are lots of articles stating that the cold orifice diameter should have approximately a ratio of 0.5 related to the vortex tube diameter (11 mm).

Ultimately, this localized cooling system, using vortex tubes and solar PV, will be tested in the university campus for different demands of energy and after the checking it will be installed in an area with a high necessity of refrigeration that nowadays the usual electricity companies do not offer.

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