

The Integration of a Vortex Cooling System and Photovoltaics for Space Cooling

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Abstract: A vortex cooling system powered by solar energy is environment-friendly. Air is used as a working fluid for the cooling system. This article presents results of an investigation into space cooling using a vortex tube. Laboratory experiments have been carried out to determine the performance of a vortex tube for space cooling. A small-scale vortex cooling system driven by air compressor was tested under various operating conditions. The potential of integration of photovoltaic into a building to supply electricity to the air compressor for the vortex cooling system was analysed. The analysis was based on the space cooling requirement for an office room in the building.

Keywords: photovoltaic, vortex tube, cooling

NOMENCLATURE

C	Specific heat
COP	Coefficient of Performance
$\dot{m}$	Mass flow rate, kg/s
P	Pressure, Pa
Q'	Volume flow rate, m ³ /s
q	Specific cooling power, kJ/kg
R	Gas constant, kJ/kg · K
T	Temperature, K
w	Specific power, kJ/kg

Subscripts

a	Atmosphere
c	Cold
h	Hot
in	Inlet
p	At constant pressure
r	Room
s	Isentropic
t	Total
v	At constant volume

Greek

η	Efficiency
γ	Specific heat ratio
μ	Cold air fraction
ΔT	Temperature difference, K

1. INTRODUCTION

The Kyoto Summit brought an agreement from countries around the globe to reduce CO₂ emission to the atmosphere. Refrigeration is one process which usually involves the discharge greenhouse gases to

atmosphere and as the global air temperature continues to rise, the demand for air conditioning to provide human comfort is also expected to increase. In addition, some existing air conditioning systems use working fluids involving CFCs which also pollute the environment and damage the ozone layer.

A vortex cooling system contains fewer components than conventional air conditioning system. It includes an air compressor, a vortex tube device, and a duct system and employs air as the refrigerant. The system can be driven by solar energy and so does not give rise to any environmentally harmful emissions. The use of air as a refrigerant also has the advantage that no extra component is required to exchange the heat between the refrigerant medium and the supply air and cold air can be distributed directly into the cooling space via a duct system. This means that the system is compact and environmentally benign.

A vortex tube was first studied by Ranque for the temperature separation effect in the small cylinder tube in 1934^[1]. Hilsch^[2] further investigated the operation of vortex tubes. Later, researchers attempted understand the energy separation in the tube based on thermodynamic and fluid dynamic theory. The limit of temperature separation and chiller performance was found by Ahlborn et.al.^[3-4]. Performance of a vortex refrigerator with different gas refrigerant medium has been examined by Saidi and Valipour^[5].

As yet no research has been carried out on using the vortex tube device for space cooling to serve the building.

This paper presented the performance of the vortex cooling system which determined experimentally under various operating conditions. Potential applications of the cooling system powered by photovoltaic integrated into the roof of building were discussed.

2. SYSTEM DESIGN

2.1 Cooling requirement

The system design is based on the cooling requirement for an office room (3.5x3.5x3 m³, window size 1x1.5 m²) occupied by two people in Nottingham location, the cooling requirement for the room is computed using the heat gain method during the peak summer time and assuming that the room was occupied from 9.00 to 17.00 hours. A calculation method is described in section A5 in CIBSE Guide A [6] and the cooling load is determined using the HEVACOMP [7] design software.

The geometrical data is Nottingham located at latitude 51.15 N, Longitude 1.15 W, Elevation 49 meter. The maximum temperature is 35 °C(DB), 24 °C(WB) and minimum temperature 12.4 °C(DB), 8.3 °C(WB) in the summer.

The mean cooling requirement for the room is found at 600 Watt. The high peak is 672 Watt at 14.00 hours and the low peak is 443 Watt at 9.00 hours as shown in Fig 1.

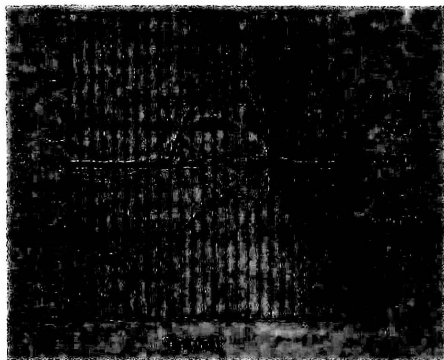


Figure 1: Cooling requirement during the day in summer for an office room

2.2 Vortex space cooling

Compressed air enters through tangential nozzle into the vortex swirl chamber and then goes into the cylindrical tube resulting in a screw-like motion. Eventually air escapes via both ends of tube as low pressure air streams shown in Fig.2.

Energy separation can be simply explained as follows. The vortex at the inlet causes the pressure distribution in the radial direction. The pressure of air near the inner wall is increased while the pressure of air at the axis of rotation is decreased. As a result a free vortex produced the peripheral warm stream and a forces vortex creates the central cold stream. The cold air leaves the tube via a central orifice at one end whilst the hot air exits the tube at the other end. The proportion of cold and hot air can be adjusted by a needle valve adjacent to the hot air outlet at the far end of the tube.

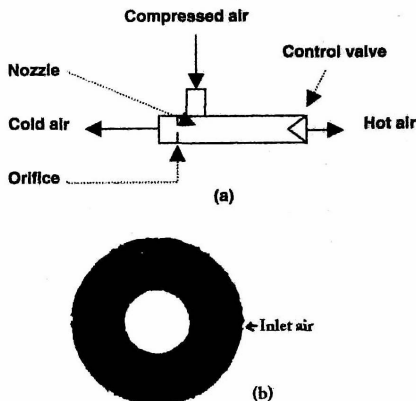


Figure 2: (a) Schematic diagram of a vortex tube
(b) Cross-section of entrance nozzle

A schematic diagram of the vortex cooling system is illustrated in Fig. 3. An air compressor powered by photovoltaic panels provides the high-pressure air for the vortex tube to produce hot and cold air. An inverter is required to convert from direct current electricity produced by PV to alternating current electricity for the compressor. The cold air is supplied to the building via diffusers in the ceiling while the warm air is rejected to outdoors. The compressed air could be stored in an air vessel to provide stable operation and could be used when the air compressor is not operating continuously.

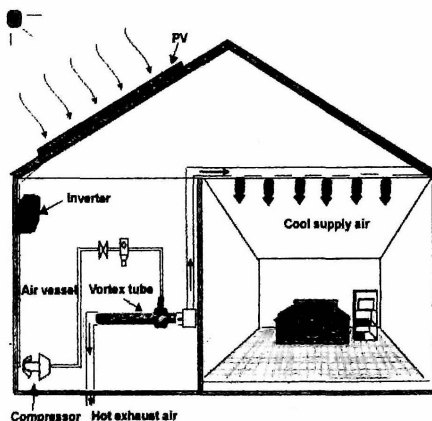


Figure 3: Schematic diagram of vortex cooling system

2.3 Vortex cooling modelling

The conditions of compressed air entering a vortex tube are represented by the temperature T_{in} and pressure P_{in} . The temperature of the cold air stream is T_c and the temperature of the hot air stream

T_h . The outlet pressure of both hot and cold air streams is P_a .

The cooling effect can be represented by

$$\Delta T_c = T_{in} - T_c \quad (1)$$

The heating effect is

$$\Delta T_h = T_h - T_{in} \quad (2)$$

Isentropic efficiency of the vortex cooling is

$$\eta_t = \Delta T_c / \Delta T_s \quad (3)$$

where ΔT_s is the isentropic temperature difference[5]

$$\Delta T_s = (T_{in} - T_s)$$

$$\Delta T_s = T_{in} \left[1 - \left(\frac{P_a}{P_{in}} \right)^{(\gamma-1)/\gamma} \right] \quad (4)$$

where $\gamma = C_p/C_v = 1.4$ (for an air)

The amount of heat that the cold stream receives from air passing through the vortex tube is the specific cooling power of the vortex tube;

$$q_c = \mu C_p (T_{in} - T_c) \quad (5)$$

where μ is cold fraction. This equals the ratio of a cold air mass flow-rate to the total air mass flow-rate,

$$\text{i.e. } \mu = \dot{m}_c / \dot{m}_t$$

Work input required by an air compressor for an isentropic process [8] is represented by

$$w = \frac{\gamma R T_{in}}{\gamma - 1} \left[\left(\frac{P_a}{P_{in}} \right)^{(\gamma-1)/\gamma} - 1 \right] \quad (6)$$

The coefficient of performance for cooling is

$$COP = \frac{q_c}{w} \quad (7)$$

3. LABORATORY TESTING

3.1 Experimental set-up

A small-scale vortex cooling system driven by air compressor has been tested under controlled conditions. A schematic diagram of the experimental set-up to determine the performance of a vortex tube for space cooling is shown in Fig. 4. An air compressor with a maximum pressure and volume flow rate of 0.7 MPa and 0.0196 m³/s respectively was used to produce compressed air. The

compressed air flowed through the inlet valve and an air regulator with filter into the vortex tube. The pressure of the compressed air was measured using a pressure gage. The compressed air expanded in the tube and separated into cold and hot streams, the temperatures of which were measured using thermocouples. The cold air was delivered to the test chamber with a volume of 0.7 m³. The chamber air temperature, the ambient air temperature and the compressed air temperature were also measured using thermocouples. The two outlet air flow rates were determined using a pitot tube and an inclined manometer. The flow measurement was calibrated using a nozzle before the testing.

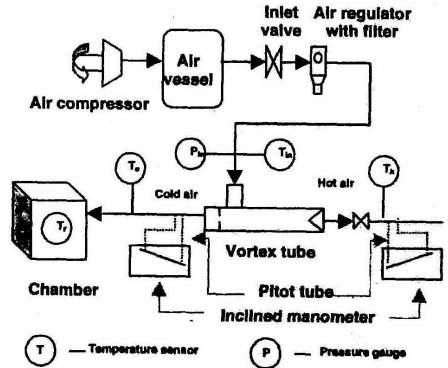


Figure 4: Schematic diagram of the experimental setup

The vortex tube used in the laboratory testing was the counter-current flow type, model 3230, manufactured by Exair corporation^[9]. The dimensions of the vortex tube are as follows; 106 mm long, 38 mm generator diameter, 1/4 (M) NPT diameter of inlet bore and 3/8 NPT (F) diameter of cold exit bore. * (NPT = National pipe thread)

3.2 Results

Operating performance curves of a vortex cooling system at inlet air pressures of 0.4 MPa and 0.5 MPa are shown in Fig.5. The cold-air temperature difference reaches the peak with the operation of the vortex tube at a cold fraction of 0.55. On the other hand, the hot-air temperature difference is highest at a higher cold fraction at about 0.8. In some applications such as cooling the chamber of biological product and food and beverage storage, low temperatures are required. That would require operating a vortex tube at lower value of cold fraction than heating application.

However, space cooling does not need to supply air at a very low air temperature. The cool fresh air is required at a rate of 8-10 litres/second (0.008- 0.01 m³/s) for each occupant^[6]. The suitable operating point for a vortex cooling system to provide a high cooling capacity is at a cold fraction between 0.6 and 0.7.

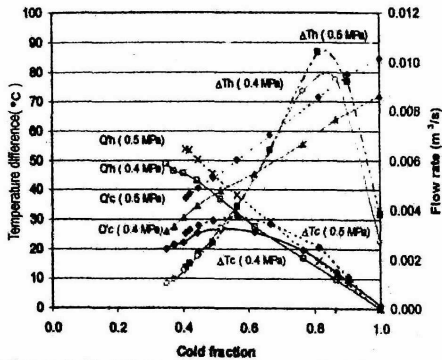


Figure 5: Variations of temperature and air flow rate at inlet pressure 0.4 MPa and 0.5 MPa

Figure 6 shows the vortex cooling power at various inlet air pressures. It does depend on the temperature difference and air flow rate which are influenced by the inlet pressure. It is clear that the system operated at high pressures provides more cooling power than at lower pressures; however, more power supply will be needed to operate at higher pressure.

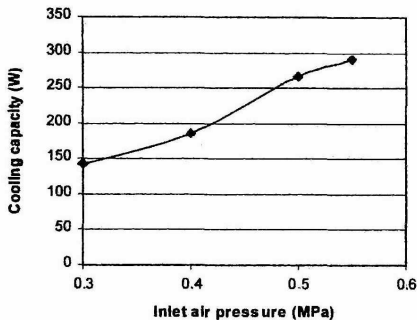


Figure 6: Vortex cooling power at cold fraction 0.6.

Consequently, the coefficient of performance at lower pressure is higher and similar effect on the isentropic efficiency of a vortex cooling system is shown in Fig.7.

To provide enough cooling power for an office room mentioned above with as high performance as possible, the system would require two vortex tubes and be operated at inlet air pressure of 0.5 MPa with cold fraction of 0.6.

Figure 8 shows that the chamber temperature was reduced from initial uniform temperature of 28 °C to 20 °C within 10 minutes when operating the vortex tube at inlet air pressure of 0.4 MPa, cold air flow rate 0.01 kg/s and cold temperature about 9 °C. This shows the potential of vortex space cooling.

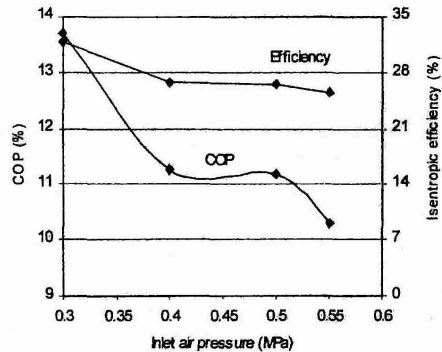


Figure 7: Coefficient of performance and Isentropic efficiency of vortex cooling operating at cold fraction 0.6

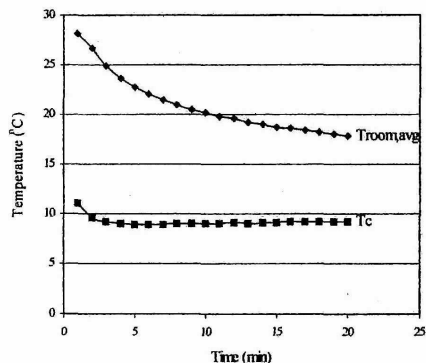


Figure 8: Air temperature inside chamber versus time

4. INTEGRATION OF PHOTOVOLTAIC PANELS INTO THE ROOF STRUCTURE OF THE BUILDING

A grid-connected PV system is more reliable for this type of application. During the sunny days, the power from PV would drive the cooling system. The power from grid will provide the electricity during the time where there is not enough solar radiation. A benefit of this system is that excess electricity from PV generation can be exported back to the grid.

The system components include PV arrays, inverter, air compressor, vortex tubes and kilowatt – hour meter as shown in Fig.9. The size of the main components could be determined as follows:

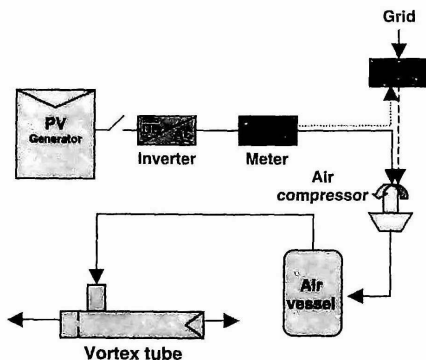


Figure 9: Diagram of vortex cooling system powered by photovoltaic.

4.1 Load requirement

An air compressor provides a pressure up to 0.7 MPa with the air flow rate of 0.016 m³/s. The power needed by an air compressor available in the market that matches the requirement for the vortex tube is 5.6 kW. An air vessel is needed to provide constant compressed air for vortex tubes.

Based on the cooling requirement for an office room and experimental results from a vortex cooling system, the system could be operated for 6 hrs a day, during 9:00 to 17:00 hrs, for energy conservation it could avoid running the air conditioning system at first half an hour, lunch hour and the final half an hour of the working days. The cooling system would be required to operate approximately for 20 working days a month during summer^[10]. Therefore, the need for power within three summer months of a year is about 2016 kWh.

4.2 PV system requirement

The sizing of a photovoltaic system is based on the electricity consumption of the air compressor for cooling in the three summer months. Accordingly, the load demand equals 2016 kWh.

The PVSYSY software is employed for designing the PV system^[11]. Simulations were done using the meteorological data for the Nottingham site. This software provides the combination of PV array and the inverter size for given location, tilt and shading.

Simulation produced the following optimum results; the tilt angle 34 degrees, an inverter of 2.8 kW, operating voltage 210 – 550 V with 20 polycrystalline modules of 150 Wp by connecting 10 modules in series, and 2 series of PV modules in parallel. The arrays operating power is 2.7 kW (at 50 °C). The PV system generates about 2214 kWh/year at performance ratio 0.76. The extra electricity could be sold back to the grid^[6].

The area of a building-integrated PV array required to provide electricity for the compressor

would be about 25 m². The PV modules can be integrated into both roof and façade to provide enough power for running the cooling system.

5. CONCLUSIONS

The cooling power of a vortex tube system increases with the inlet air pressure. The efficiency of vortex cooling is higher with operating at lower inlet air pressure. The optimum operating point can be found based on the requirement of cooling.

Space cooling using a single stage vortex tube powered by solar energy would need a large area for integration of PV into the building.

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