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Experimental Evaluation for Air Cooling of LCV by Vortex Tube Refrigeration

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ABSTRACT

The vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device that separates a compressed gas into hot and cold streams. The main objective is to create a Refrigeration system in Low Commercial Vehicles without using air conditioner. The refrigerants used in VCRS have ozone depleting potential (ODP) and global warming potential (GWP) and are toxic. Leakage of the refrigerant during accidents is also a problem causing deaths due to its inhalation. The high pressure created in the air compressor, which is run through engine shaft, is used as inlet to a vortex tube which is placed inside the vehicle cabin. The cold air from the vortex tube is used to cool the vehicle cabin and the hot air is exhausted to atmosphere. The result is a drop of 13 degrees at the vortex tube cold outlet. The cooling load & heating load comes out to be 8874.58 Watts & 7086 Watts. It's a cooling system which doesn't use the Freon utilizing system. The societal impact of the project is the absence of a Freon consuming cooling system. Thus, it will help in reducing the ozone depletion and global warming.

Key words: - *Vortex Tube, VCRS, LCV, ODP & GWP*

I. INTRODUCTION

The vortex tube was discovered in 1930 by French physicist Georges Ranque. Vortex was the first company to develop this phenomenon into practical, effective cooling solutions for industrial applications. Fluid that rotates about an axis - like a tornado - is called a vortex. A vortex tube creates a vortex from compressed air and separates it into two air streams - one hot and one cold. Compressed air enters a cylindrical generator which is proportionately larger than the hot (long) tube where it causes the air to rotate. Then, the rotating air is forced down the inner walls of the hot tube at speeds reaching 1,000,000 rpm. At the end of the hot tube, a small portion of this air exits through a needle valve as hot air exhaust. The remaining air is forced back through the center of the incoming air stream at a slower speed. The heat in the slower moving air is transferred to the faster moving incoming air. This super-cooled air flows through the center of the generator and exits through the cold

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air exhaust port. Vortex tube products have been solving industrial cooling problems for years. Using only filtered, factory compressed air as a power source, they convert ordinary compressed air into two air streams - one hot and one cold. At 100 PSIG (6.9 Bar) and 70° F (21°C) inlet temperature, a vortex tube can produce refrigeration up to 6000 BTUH (1512 kcal/H) or temperatures to -40° F (-40° C).

II. METHODOLOGY

To run the system some power from the vehicle engine shaft is diverted by a pulley arrangement to run an air compressor. The high pressure created in the air compressor is used as inlet to a vortex tube which is placed inside the vehicle cabin. The cold air from the vortex tube is used to cool the vehicle cabin and the hot air is exhausted to atmosphere.

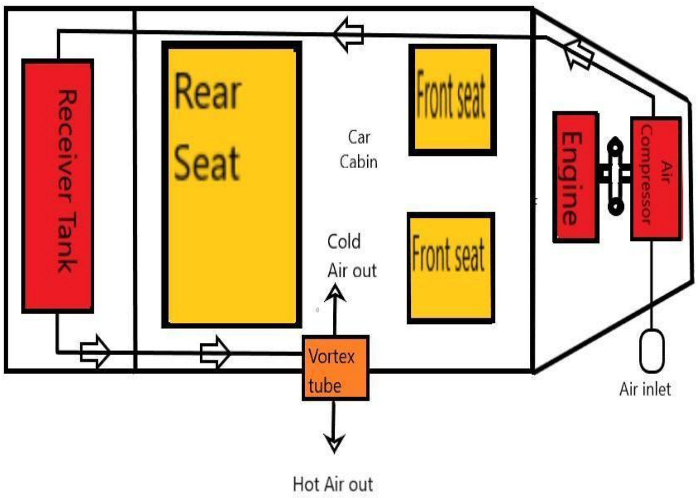

Fig1. Experimental setup

The experimental set up is having

1. Air inlet pipe with air filter
2. Vehicle Engine
3. Single cylinder, Single h.p. Reciprocating Air-Compressor (5 bar).
4. Vortex Tube, 8 SCFM (227 SLPM), for max. refrigeration, 550 Btu/hr. (139 Kcal/hr.), Small Size
5. Pressure reducing valve with two side connectors along with pressure gauge and air filter.
6. Belt
7. Air receiver tank (40 lts) with safety valve and pressure gauge
8. Air delivery pipe

The atmospheric air is compressed in a reciprocating air compressor run by the vehicle engine shaft. The compressed air is stored in storage tank which is set up in back side of the vehicle. Air is supplied in to vortex tube at various pressures to get the required comfort air temperatures.

III. THERMODYNAMIC ANALYSIS OF COUNTER FLOW VORTEX TUBE

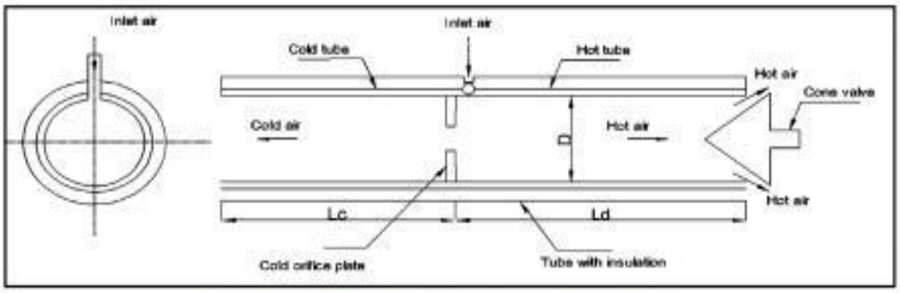

Fig. 1 : Schematic sketch of counter-flow vortex tube

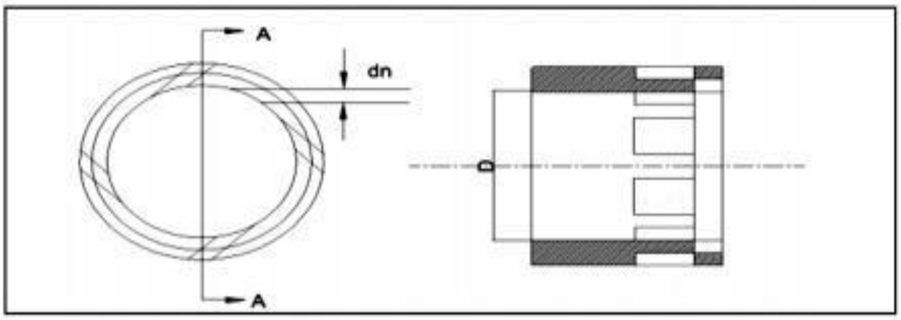

Fig. 2 : Nozzle configuration or swirl generator

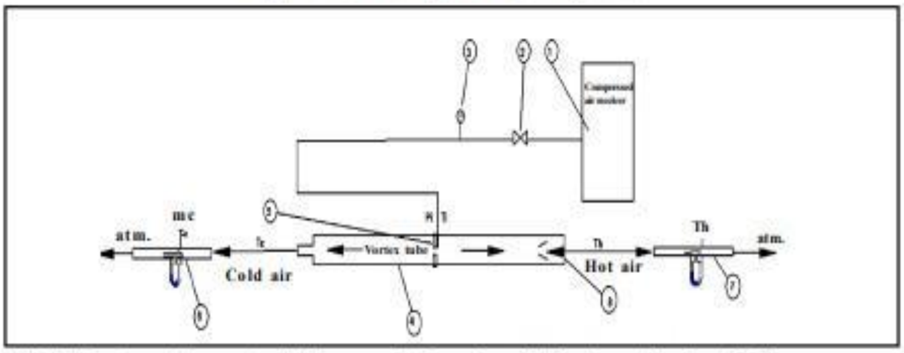

Fig. 3 : Experimental apparatus, (1) Compressed air receiver , (2) Hand operated valve , (3) Pressure gauge , (4) Counter flow vortex tube , (5) Aset of orifice flow meters, (6-7) Orifice flow meter, (8) Cone-shape valve

Vortex tube gets high pressure air from an air compressor through a tangential nozzle. Assume suffixes i, h, c stands for inlet to the nozzle, hot end and cold end, respectively then the mass and energy conservation of control volume given by

Mass balance $m_i = m_c + m_h$ 1

Steady flow energy balance

$m_i*hi = m_c*h_h + m*.h_h$ 2

Assuming the kinetic energies are negligible.

The cold gas temperature difference or the temperature drop of the cold air tube is defined as

$$\Delta T_c = T_i - T_c. \quad .....3$$

The hot gas temperature difference or the temperature raise of the hot air tube is defined as

$$\Delta T_h = T_h - T_i \quad ...4$$

If the system is isentropic then the heat lost by the cold stream is equal to heat gained by hot stream,

$$m_c (T_i - T_c) = m_h (T_h - T_i) = (m_i - m_c)*(T_h - T_i)$$

$$T_i - T_c = [(m_i/m_c)-1].(T_h - T_i) = (\mu-1)^{-1}.(T_h - T_i) \quad .....5$$

where μ is the ratio of cold air to the air supplied, called as cold mass fraction.

From equation 2.3 we get.

$$\mu (T_i - T_c) = (1 - \mu)*(T_h - T_i)$$

$$\mu [(T_i - T_c) + (T_h - T_i)] = (T_h - T_i)$$

$$\mu = (T_h - T_i)/[(T_i - T_c) + (T_h - T_i)]$$

$$\mu = \Delta T_h/(\Delta T_h + \Delta T_c)$$

$$\mu = m_c/m_i \quad ....6$$

If the process had undergone an isentropic expansion from inlet pressure Pi to atmospheric pressure Pa at the cold end then the static temperature drop due to expansion is given by

$$\Delta T'_c = T_i - T'_c = T_i [1-(P_a/P_i)(\gamma-1)/\gamma] \quad ....7$$

The temperature drop occurred in vortex tube is $\Delta T'_c$. The ratio of ΔT_c to $\Delta T'_c$ is called Relative Temperature drop

$$\Delta T_{rel} = \Delta T_c/\Delta T'_c \quad .....8$$

The product of μ and ΔTrel represents the adiabatic efficiency of the vortex tube because it is defined As,

$$\eta ab = \frac{\text{actual cooling gained in vortex tube}}{\text{cooling possible with adiabetic expansion}}$$

$$\eta_{ab} = (m_c\Delta T_c C_p)/(m_i\Delta T'_c C_p) = \mu\Delta T_{rel}$$

$$\eta_{ab} = [\Delta T_h/(\Delta T_h + \Delta T_c)]*(\Delta T_c/\Delta T'_c) \quad ...9$$

The C.O.P of the vortex tube is defined as the ratio of the cooling effect to the work input to the air compressor.

$$\text{Cooling effect} = m_c\Delta T_c C_p$$

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Work input to air compressor = $(C_p m_i T_i)[(P_i/P_a)(\gamma-1)/\gamma-1]/\eta_{ac}$

where η_{ac} is the adiabatic efficiency of the compressor.

$$COP = \frac{\text{Cooling Effect}}{\text{Work input}}$$

$$C.O.P = [(m_c \Delta T_c C_p).\eta_{ac}]/(C_p m_i T_i)[(P_i/P_a)(\gamma-1)/\gamma-1]$$

$$C.O.P = \mu(\Delta T_c.\eta_{ac})/\{T_i[(P_i/P_a)(\gamma-1)/\gamma-1]\} \quad \text{....10}$$

Substituting the value of Ti from equation 2.5 in equation 2.8

$$COP = \frac{\{\mu(\Delta Tc.\eta ac)\}}{\{(\Delta T'c/[1-(Pa/Pi)(\gamma-1)/\gamma])[(Pi/Pa)(\gamma-1)/\gamma-1]\}}$$

$$C.O.P = \mu.(\Delta T_c/\Delta T'_c)\eta_{ac}.[(P_a/P_i)(\gamma-1)/\gamma] \quad \text{....11}$$

Substituting the value of μ $(\Delta T_c/\Delta T'_c)$, from equation 2.7

$$C.O.P = \eta_{ab}.\ \eta_{ac}.\left(\frac{P_a}{P_i}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{....12}$$

3.1 Cooling load calculations

The following assumptions were made in quantifying the amount of heating load on a car.

- Heat conducted from the outside through the glass is considered.
- Heat conducted through the firewall into the passenger compartment has been neglected. It is assumed that enough insulation is provided to minimize this heat transfer.

Also, the data is directly taken from different references.

The following calculations estimate the heat gain loss via glass, from occupants, and infiltration.

$Q_{load} = Q_{glass} + Q_{inf} + Q_{occ}$ …..1

3.2 Heat gain via glass (Q_{glass}) :

The heat gain through an automobile glass can be expressed as the sum of solar heat gain, due to transmitted and absorbed solar radiation and the heat conducted, due to the difference between outdoor and indoor air temperature.

$Q_{glass} = Q_{solar} + Q_{cond}$ …..2

Solar radiation varies temporally and spatially. The heat conducted through the glass depends on the solar heat gain, as the amount of absorbed radiation affects the temperature distribution of the glass. Heat loss from the car is taken as negative and heat gain is taken as negative.

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3.3 Solar Heat Gain ,(Q_{solar})

Solar heat gain is obtained by summing direct normal, diffuse horizontal and solar radiation due to ground reflection.

Q_{solar} = 1960 Watts.

Q_{solar_dffuse} = 43.69 Watts.

Q_{solar_ground} = 447 Watts.

$\therefore Q_{solar} = Q_{solar\_direct} + Q_{solar\_dffuse} + Q_{solar\_ground}$

= 1960+44+447

= 2450 Watts. (approx)

4 Conduction Load (Q_{cond}):-

The following assumptions have been made for calculating conduction load.

- Glass is in steady state (thermally).
- Clear glass with reflectance r_{glass}= 0.07; transmittance τ_{glass} =0.8 and absorptance β= 0.13 (for normal incidence).
- Most of the absorption takes place on the outer surface of the glass.

Solar heat gain is obtained by summing direct normal, diffuse horizontal and solar radiation due to ground reflection.

Q_{cond} = 513 Watts.

$\therefore Q_{glass} = Q_{solar} + Q_{cond}$ 3

= 2450 + 513

= 2963 Watts. (approx)

4.1 Cooling load due to Infiltration:-

The heat gain due to infiltration has both sensible and latent components.

$Q_{inf} = Q_{inf\_sense} + Q_{inf\_lat}$ 4

1. Sensible load = 2000 Watts. (approx)
2. Latent load (Q_{inf_lat})= 426 Watts. (approx)

Hence, the total load due to infiltration is

$Q_{inf} = Q_{inf\_sense} + Q_{inf\_lat}$

= 2000 + 426

= 3099 Watts.

4.2 Cooling Load due to Occupants:-

Similar to the cooling load due to infiltration, the occupant load also has both sensible and latent components given by

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Q_{OCC} = 65 *4 persons
= 260 Watts

Q_{lat_occ} = Q_{lat_person}* Nocc
= 30 * 4 persons
= 120 Watts.
∴ Q_{OCC} = 260 + 120 = 380 Watts.

5 Total Generated Heat Load (Q_{load}):

$Q_{load} = Q_{glass} + Q_{occ} + Q_{inf}$

$Q_{load} = Q_{solar} + Q_{cond} + Q_{occ} + Q_{inf}$

$Q_{load} = Q_{solar\_direct} + Q_{solar\_diffuse} + Q_{solar\_ground} + Q_{cond} + Q_{occ} + Q_{inf}$

Q_{load} = 6442 Watts.

Let us consider 10% of total heat leaks into the cabin,

Q_{load} = 6442 + 644

Q_{load} = 7086 Watts.

The cold outlet temperature of the vortex tube inside vehicle cabin is, $T_c = 17^oC$
Average ambient air temperature at 01:00 pm, $T_i = 30^o$ C
Temperature difference = 13^oC
Air pressure after compression, P = 5 bar
Mass flow rate of air inside the pipe = 0.638 kg/s

Specific heat at constant pressure of air = 1.07 kJ/kg K

$Q_{cool} = m_a c_{pa}(T_i - T_o)$

Q_{cool} = 8874.58 Watts

IV. RESULTS & DISCUSSION

The experiment was conducted to cool the car cabinet by the effect of the cold mass fraction on the cold air temperature. Analysis was carried out to evaluate the performance of the vortex tube keeping inlet air pressure to the vortex tube constant at 5 bar.

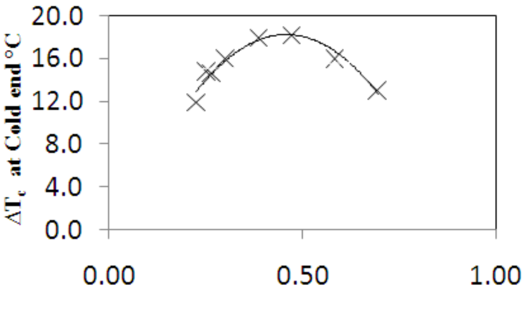

Fig. 4 : Temperature drop at cold end as a function of cold air mass fraction

Fig.4 shows the plot of temperature reduction in cold air to the cold mass fraction for input pressure of 5 bar. It was observed that the temperature reduction ⊗Tc of the cold air increase with increase in cold mass fraction up to 0.4 and then the temperature reduction decreases. The maximum temperature drop recorded was 13°C.

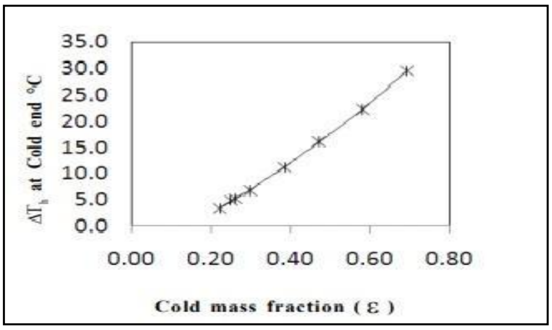

Fig.5: Temperature rise at the hot end as a function of cold air mass fraction

Fig.5 shows the increase in hot air temperature as a function of cold mass fraction, it is observed that the rise in temperature increases almost linearly with increasing in the cold mass fraction up to 0.8. and maximum rise in temperature recorded is 29.8°C.

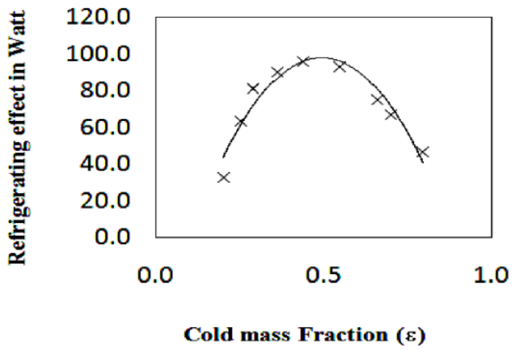

Fig. 6 : Refrigerating effect as a function of cold air at inlet pressure 5 bar mass fraction

Fig. 6 shows the effect of the refrigerating effect as a function of cold mass fraction. It is observed that the refrigerating effect increase initially and then decrease after 0.5. The range in which the refrigerating effect is found to be effective lies between the cold mass fraction of 0.35-0.65.

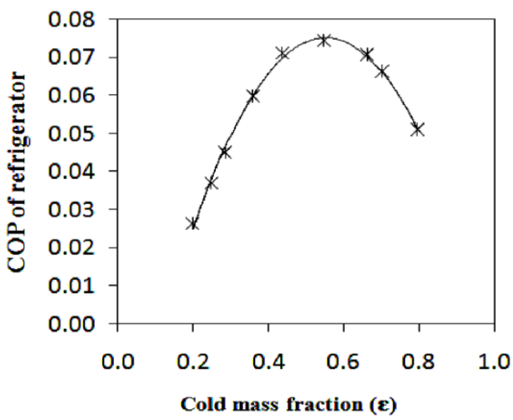

Fig 7 COP as function of cold air mass fraction at inlet pressure 5 bar

Fig. 7 shows the plot of COP of refrigerator as a function of cold mass fraction. It is observed that the maximum COP is found to be 0.08. Here it is assumed that the work of compression required to increase the pressure from the exit (atmosphere) condition to the inlet pressure follows reversal isothermal process.

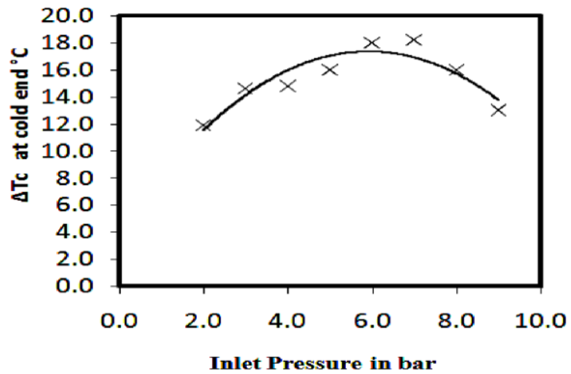

Fig. 8 Temperature drop at cold end (°C) as a function of inlet pressure (bar)

Fig. 8 shows the plot of drop in temperature of cold air as a function of increase in the inlet pressure keeping the valve opening fix, orifice diameter and tube diameter constant. It is observe the drop in the cold air temperature enhances linearly with the increase in the inlet pressure. It may be due to stronger vortex that is created on the inner periphery of the tube due to increase in the inlet pressure and the temperature separation is a function of the inlet pressure and the exit pressure.

The heat load that has to be removed from inside cabin is 7086 Watts

The cooling load that is generated by the vortex tube is 8874.58 Watts

Also the temperature difference between the ambient air & cold outlet air is 13^{o}C

V. CONCLUSIONS

By installing the Vortex Tube Refrigeration System in LCV to get the required cooling conditions, the air temperature at the outlet of vortex tube is 17^{o}C. Use of refrigerant isn't there. The working fluid is atmospheric air. The temperature inside the car cabin is reduced by the vortex tube refrigeration system. Global warming and Ozone depletion can be reduced. The passengers feel comfortable inside the vehicle.

The vortex tube is the low cost solution for cooling parts, chambers, heat seals and various processes. They're easy to use, can be adjusted to produce cold air down to -50°F (-46°C) and have no moving parts to wear out.

VI. FUTURE SCOPE

Vortex Tube Refrigeration System is giving cooling conditions but not humidity conditions inside the vehicle cabin. For getting comfort conditions in the vehicle both cooling as well as humidity conditions are to be maintained. By installing humidifier along with the Vortex Tube Refrigeration System, the required comfort

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conditions i.e. temperature & humidity will be maintained in the vehicle cabin. Vortex tube comes in a range of varieties. Installing a higher SCFM vortex tube can cause reduction in the outlet air temperature. If we connect vortex tubes in series we can get a higher temperature drop. Also, by increasing the mass flow rate of air, same can be achieved.

Thus the vortex tube refrigeration system can be a feasible refrigeration system.

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