Design - Analysis of Generator of Vapour Absorption Refrigeration System for Automotive Air- Conditioning

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Abstract— **Automotive air conditioning is the equipment that commonly uses CFC compounds, and the leakage of CFCs from such air conditioners affect the environment. The absorption cycle in which compressor is replaced by an absorber, a pump, a generator and a pressure reducing valve was found to be an ideal option. In the present work, the generator is designed which is the main unit of vapour absorption refrigeration system. This will be located nearest to the exhaust manifold at tail-end where the heat is available from exhaust gases. The air conditioning for small car can run at 0.8 TR and need about 5 KW for evaporating refrigerant in vapour absorption system. This heat is available in the exhaust gases and has been estimated based on actual I.C-Engine driving cycles.**

Keywords*— *Vapour Absorption system, Ammonia-water, Exhaust gas, Internal combustion engine, Generator, Absorber

I. INTRODUCTION

The internal combustion engines of automobiles have a thermal efficiency of 45 percent. The remaining energy is rejected to the atmosphere in the form of hot exhaust gases or as energy convected from the radiator and the engine. Carbon dioxide coming out of every automobile is a greenhouse gas which has dramatic affect on climate changes and utlimately on everyone of us on the planet due to global warming. For this reason, there are growing efforts to reduce the green house gases. In Automobiles, air conditioning is currently performed by vapour compression refrigeration systems, but the refrigerants in vapour compression refrigeration systems are mainly HCFCs and HFCs, which are not environmentally friendly, and the compressor uses a significant portion of the engine power. According to the statistic information, 60-65% of the combustion energy of the fuel consumed is taken away by the radiators and exhaust gases. If the waste heat can be recovered, it is enough to satisfy the input power need for air-conditioning. The waste heat from exhaust gases constitutes a large percentage of the total waste heat. Much work now in progress is directed to the improvement of the thermal efficiency by achieving better consumption of the fuel. The waste heat can be used for air-conditioning and refrigeration. Trucks used for the transport of perishable foodstuffs such as milk, vegetables, fruits, and meat, which deteriorate rapidly at ambient temperature must be equipped with refrigeration systems. Automobile refrigeration is mainly divided into three major categories. The most widely used system utilizes a vapor compression machine powered by the vehicle engine via pulley and belt or by an APU (Auxiliary Power Unit). Some vehicles use a eutectic solution plate refrigeration storage system. Also some uses expendable liquid nitrogen or carbon dioxide spray systems. All of these systems consume precious fuel or electricity to achieve refrigeration. One alternative to the vapour compression system is the absorption refrigeration system, which employs ammonia as refrigerant and water as absorbent. Ammonia contains no halogen atoms at all, and even its gradual leakage into the atmosphere poses negligible environmental or atmospheric risks. By employing waste heat discharged from a vehicle's internal combustion engine to drive an absorption refrigeration system, the engine shaft can be relieved of the load required by the compressor of a conventional vapour-compression system, and considerable fuel can be saved. Another attractive feature is that an absorption refrigeration system is almost noise-free and virtually maintenance-free.

II. AQUA-AMMONIA VAPOUR ABSORPTION REFRIGERATION SYSTEMS

The technology of absorption refrigeration plants has been used for cooling purposes for over a hundred years now. In a vapour compression cooling machine, the refrigerant evaporates at low temperature and low pressure. The vapour is extracted from the evaporator, than transformed to a higher pressure by compressor and liquefied in the condenser. The main difference between a compression and an absorption cycle is that the former needs mechanical energy as a driving source for the compressor and the latter needs thermal energy for the Absorber and only a small amount (2% of the driving energy) of electricity for the liquid pump. A Vapour Absorption Refrigeration (VAR) System is similar to a Vapour Compression Refrigeration (VCR) System. In both systems the required refrigeration is provided by refrigerants vaporizing in the evaporator. However, in the VAR System, a physico-chemical process replaces the mechanical process of the VCR system and heat rather than a mechanical and electrical energy is used. In the vapour absorption refrigeration system the vapour is drawn from the evaporator by absorption into liquid having high affinity for the refrigerant. The refrigerant is expelled from the solution by application of the heat and its temperature is also increased. This refrigerant in the vapour form passes to the condenser where heat is rejected and refrigerant gets liquefied. This liquid again flows to the evaporator at the reduced pressure and cycle is completed a shown in fig (1). The elimination of the necessary shaft work has been the prime reason for the economic success of vapour absorption system. Aqua ammonia system is employed for applications below 32°F (0°C) in which the refrigerating fluid is ammonia and absorbent or carrier is water. The combination of aqua ammonia has been particularly attractive because of the following advantages: a) Its performance is better than that of Fluoro Carbon refrigerant. b) It is free from the limitation imposed by the high freezing temperature of the refrigerant and low crystallization temperature of the solution, as in lithium bromide water system, or extreme corrosiveness in ammonia sodium Thio-Cyanate system so the controls in Ammonia water machines are simpler. The only disadvantage with ammonia water system is the volatile nature of the water used as the absorbent. However this difficulty can be overcome by incorporating a properly designed rectification column. While operating under ideal conditions the overall COP of the Ammonia water cycle is 0.5-1.0.

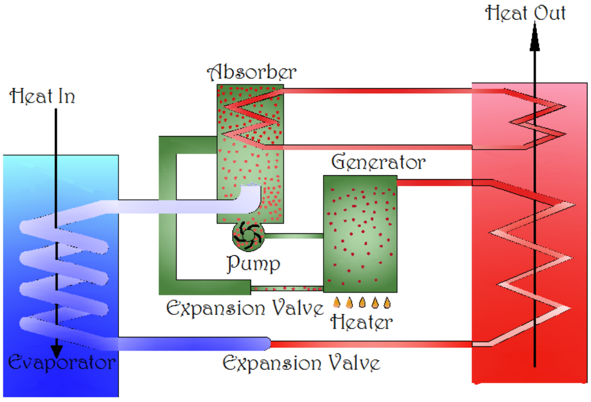

Figure 1. Basic vapour absorption refrigeration system

In Automobile refrigeration system using exhaust gas, the volume flow rate and the gas temperature could be varied continuously in order to simulate the various operating conditions of an actual engine.

III. COOLING LOAD ANALYSIS

It is difficult to determine the actual cooling load in car air conditioning because of the variation of the load in the climatic conditions when the car is exposed during the course of long journey. The cooling load of a typical automobile is also considered at different steady state conditions. The cooling capacity is affected by outdoor infiltration into car and heat gain through panels, roofs, floors etc. The cooling load considered in this analysis is given in Table 1.The table shows that heat load inside the car is approximately 2.35 kW. Therefore, 0.8 ton air conditioning unit is sufficient to fulfill the cooling requirement and capable to run this air conditioning system from exhaust gas heat as further calculation.

Table 1 Heat load considered in small automobile

Heat load	Amount of heat (Kj/hr)
Solar radiation (roof ,walls, glasses)	400
Normal heat gain through glass	1300
Normal heat gain through wall	4400
Air leakage	1100
Passenger including driver	1300
Total	8500 KJ/Hr or 2.35 KW

IV. EXHAUST GAS

In Vapour absorption refrigeration system, generator portion is designed for utilizing exhaust gas from internal combustion engine. Type of engine and also details of engine parameters are given below. Temperature of an exhaust gas in Kirloskar engine is calculated by an heat balance on engine by using electrical loading. Fuel used in engine is high speed diesel. Exhaust gas temperature range is varied depends upon the type and also amount load acting on the engine.

TABLE I. ENGINE SPECIFICATIONS

1	ENGINE MAKE	KIRLOSKAR
2	ENGINE TYPE	SINGLE CYLINDER FOUR STROKE
3	POWER	3.5 KW
4	SPEED	1200 rpm
5	BORE DIAMETER	70 mm
6	STROKE LENGTH	100 mm
7	ROOM TEMPERATURE	30ºC
8	EXHAUST GAS TEMPERATURE RANGE	120ºC to 250ºC

Heat available from engine exhaust can be calculated as
FP=mf X Cv
Where , mf = fuel mass flow rate
Cv = calorific value of the fuel i.e 42000kj/kg
Taking 10 liter per hour fuel consumption for a 100 BHP engine. the available heat rejected can be calculated as:-
Q_{rej}=0.3 X mf X Cv = 31 KW.

V. DESIGN OF GENERATOR IN VAPOUR ABSORPTION SYSTEM

The generator is used to create the same task as of the compressor in the conventional compression refrigeration cycle. It is located where the heat is available from the exhaust gases, and the important limiting factor is the space occupied by generator. The generator used to evaporate the mixture of ammonia that react with water and leaves pure ammonia or mixture with high ammonia concentration.

The generator is design to have a capacity of 5 kW required to evaporate refrigerant with temperature around 95°C and pressure of 20 bar. The maximum space available in the automobile that this component can be installed is 50 cm long, 25 cm wide and 15 cm high.

Figure 2 shows the vapour absorption refrigeration system using heating coil. It is used to generate the vapour refrigerant in generator outlet. ammonium-water refrigerant is used in refrigerant and absorber.

In the generator a mixture of ammonia and water is heated. The boiling point of ammonia is lower than that of water, so it vaporizes, separating the refrigerant from the absorbent. Since the vapour is not a pure ammonia gas, it must be purified as it flows through rectification system. The rectification system consisting of the generator, rectifier and analyser. As shown in the figure, strong solution from absorber enters through the heat exchanger to the analyser. A heat exchanger is located between the absorber and the generator. The strong solution pumped from the absorber to the generator must be heated and the weak solution from the generator to the absorber must be cooled. Therefore the heat exchanger consequently reduces the cost of heating the generator and cooling the absorber. The vapour rich in ammonia leaves at the top of the analyser and weak solution leaves from the bottom of the generator. The heat exchangers of the generator rectification system were designed as compact plate-fin heat exchangers and the column was filled with stainless steel Pall rings. The almost pure ammonia vapor flows from the top of the column to the condenser as a high-temperature, high pressure mixture. As ambient air passes over the condenser, it removes heat from the gas-mixture and the vapor condenses to a liquid. Since the boiling point of water is higher than that of ammonia, the trace water condenses first, resulting in liquid with a considerably higher water concentration at the start of the condensation process.

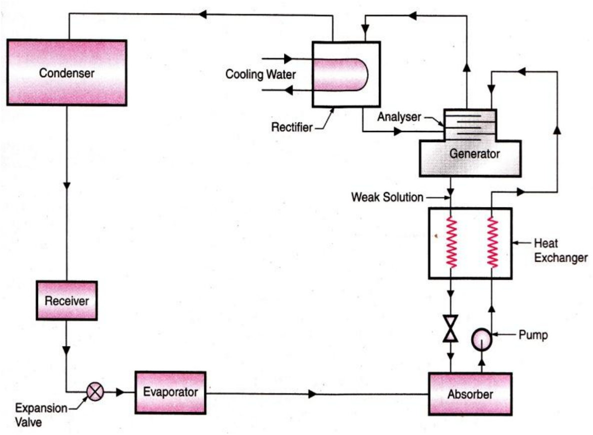

Figure 2 Ammonium-water vapour absorption system.

A heating medium supplies the required heat input to the generator and heat is rejected to the cooling water in the rectifier which is a water cooled heat exchanger where final elimination of water vapour occurs along with some ammonia and sent back to the generator.

It can be seen that compared to heat input to the system at the generator, the work input to the system is almost negligible (less than 0.5 percent) The system COP is reduced as the required heat input to the generator increases due to heat rejection at rectifier. However, this cannot be avoided as rectification of the vapour is required. However, it is possible to analyze the rectification process to minimize the heat rejection at the rectifier.

As stated earlier the air conditioning system for small car can run at 0.8 TR and needs 5 kW heat for evaporating refrigerant. Therefore the generator is designed to have capacity of 5 kW with temperature around 95°C and pressure of 20 bar. The generator of the car has been designed for 1800 rpm at 250°C temperature.

The external heat transfer area of the generator (A_G) required is calculated as:

$$A_G = \frac{Q_g}{U_0 X LMDT} \quad ....(i)$$

Qg = Heat input to the Generator

Uo = Overall Heat transfer coefficient.

LMTD = Logarithmic mean temperature difference

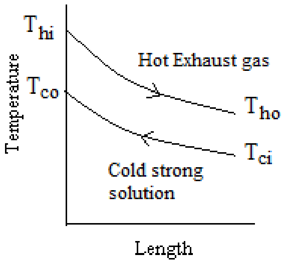

Figure 3 Temperature difference in Generator.

LMTD:

Assume the cross flow type heat exchanger for heating process for generator, therefore the logarithmic mean temperature difference(LMTD) is calculated as,

$$\therefore \ [LMTD\ ]\ \theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1 / \theta_2)} = \frac{40}{0.298} \quad .....(ii)$$

Where,

$\Delta\theta_1 = T_{hi} - T_{co}$

$\Delta\theta_2 = T_{ho} - T_{ci}$

T_{hi} = Inlet temperature of hot exhaust gas = 250 °C

T_{ho} = Outlet temperature of cold exhaust gas.= 200 °C

T_{co} = Outlet temperature of ammonia vapour = 95°C

T_{ci} = Inlet temperature of strong solution = 85 °C

The hot fluid and cold fluid inlet and outlet temperature has been calculated using empirical relation-

Therefore, LMTD = 134.0064 °C

Calculate the inside heat transfer coefficient of generator (hi):

The Inside heat transfer coefficient of generator is calculated from Nusselt number .

$$Nu_{di} == \frac{h_i d_i}{k_l} \quad ....(iii)$$

Assuming Inside and outside diameter of steel tube to be 25 mm and 28 mm.

The flow inside the generator is generally two phase flow and liquid wets the surface. The Nusselt number for the two phases for generator is as under:-

$$Nu_{Di} = 0.06 \times \left(\frac{\rho_l}{\rho_v}\right)^{0.28} \times \left(\frac{diGx}{\mu_l}\right)^{0.87} \times (Pr)^{0.4} \ ...(iv)$$

Mass flux is calculated using formula from data book: -

$$Gx = \frac{mass\ of\ strong\ solution}{Ai} = 93.7\ kg/m^2 s$$

The Thermo-physical properties of water at mean temperature 95°C are taken as under:-

Density of liquid (ρ_l) = 961 kg/m^3,
Dynamic viscosity (μl) = 0.297×10^{-3} N-s/m^2,
Prandtl number (Pr) = 1.85,
Density of vapour (ρv) = 0.505 kg/m^3,
Thermal conductivity (k_l) = 0.677 w/mk.

Nusselt no is calculated using equation (iv),

$$\mathrm{NuDi} = 0.06 \times \left(\frac{961}{0.505}\right)^{0.28} \times \left(\frac{0.025\times 93.7}{0.297\times 10^{-3}}\right)^{0.87} \times (1.85)^{0.4}$$
$$= 1561.6$$

Inside heat transfer co-efficient is calculate using eq (iii),

$$h_i = \frac{1561.6\times 0.677}{0.025} = 42289.5\ w/m^2k$$

Now, Calculate the outside heat transfer coefficient of generator (h_o) using empirical formula:

Outside heat transfer coefficient from Nusselt Number -

$$\mathrm{Nu}_{Do} = \frac{h_0 d_0}{k_g} \qquad \text{........ (v)}$$

The outside Nusselt number for air flowing through the tube in generator is taken as,

$\mathrm{Nu}_{Do} = 1.13C\,(\mathrm{Re}_{Do})^n\,(\mathrm{Pr})^{0.33}$.......... (vi)

Where, C and n are constant.

Re_{Do} = Outside Reynolds no.

n = 0.6, C = 0.37073

Pr = Prandtl no.

T_g= 498 K So we take the properties Pr = 0.69

The Thermo-physical properties of the exhaust gas have been calculated at mean temperature T_g=225 ^{0}C or 498K

From Silva and Costa, Density of exhaust gas:

$$\rho_g = \frac{353}{Tg} = \frac{353}{498} = 0.70kg/m^3, \text{.........(vii)}$$

Viscosity of exhaust gas is calculate using empirical relation,

$(\mu_g) = 1.348\times 10^{-5} + 2.68\times 10^{-8}\times (T_g)$ ....(viii)

$= 1.348\times 10^{-5} + 2.68\times 10^{-8}\times 498$

$= 2.6826\times 10^{-5}$ Ns/m^2

Thermal conductivity of exhaust gas is as under,

$(k_g) = 8.459\times 10^{-3} + 5.7\times 10^{-5}\times (Tg)$ ......(ix)

$= 8.459\times 10^{-3} + 5.7\times 10^{-5}\times (498)$

$= 0.03684$ w/mk,

Specific heat of exhaust gas is calculated as,

$(C_{pg}) = 962.097 + 0.1509\times (Tg)$ ....(x)

$= 962.097 + 0.1509\times 498$

$= 1037.2$ J/kgk

Vertical spacing between tubes of the generator,

$St = 1.5d_0$

$=1.5\times .028$

$= 0.042$ m,

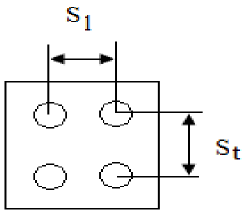

Fig.4 Diagram for in line design of generator tube

Horizontal spacing between tubes,

$S_l = 1.25d_0$

$= 1.25\times 0.028$

$= 0.035$ m,

Velocity of exhaust gas is calculated using empirical relation,

$$U_g = \frac{m_{exh}}{\rho_g\times\frac{\pi}{4}\times d_{eq^2}} \qquad \text{.........(xi)}$$

Where, m_{exh} is the mass of exhaust gas = 0.025 kg/s (assume),

ρ_g is the density of exhaust gas and

d_{eq} is the equivalent diameter.

Equivalent diameter is calculate as under,

$$d_{eq} = \frac{2\times w\times h}{w+h} \qquad \text{............(xii)}$$

Here, w is the width of generator and

h is the height of generator.

Taking w = h = 0.096 m

Therefore, $d_{eq} = 0.096\ m$

Velocity of exhaust gas is calculated using (xi),

As such,

U_g = 4.9 m/s

Maximum velocity of exhaust gas is calculated as,

$$U_{max} = \frac{U_g\times S_t}{S_t - d_0} = 25\ m/s \qquad \text{............(xiii)}$$

Reynolds number,

$$Re_{Do} = \frac{\rho_g\times U_{max}\times d_0}{\mu_g} \qquad \text{.............. (xiv)}$$

Hence, $R_e d_0$ = 18266

And Nu_{Do} = 133.64

Using values in equation (v),

$$\mathrm{Nu}_{Do} = \frac{h_0 d_0}{k_g}$$

Thus, h_o = 175.83 W/m^2k

The overall heat transfer coefficient:

The overall heat transfer coefficient, neglecting the fouling resistance of the tube,

$$\frac{1}{U_0} = \frac{1}{hi}\times\frac{d_0}{di} + \frac{d_0}{2Ks}\times l_n\left(\frac{d_0}{di}\right)\times\frac{1}{h_0} \qquad \text{........... (xv)}$$

Take k_s = 42 w/m^{2}k for steel.

U_0 = 173.86 W/m^2k

The external heat transfer area (A) required is calculated :-

$$A = \frac{Q_g}{U_0\times LMTD} = 0.22\ \mathrm{m}^2$$

$A = \pi d_0 l$, Hence $l = \frac{A}{\pi d_0} = 2.5m$

In order to distribute the available length in the specified space we have a space for tubes of long 8 cm and outside diameter 2.8 cm to leave space for the solution to be collected through the other space. Therefore the number of tubes required is 32

Number of tube

$$N = \frac{Total\ length\ of\ tube}{Length\ of\ each\ tube} = 32$$

The space available in the automobile to install the generator near the exhaust manifold can be taken as 50cm long, 12cm wide and 8cm height.

Number of row

$$= \frac{Height\ of\ generator}{Vertical\ space\ between\ tube} = 1.9 \cong 2$$

Number of tube per row

$$= \frac{Length\ of\ generator}{Horizontal\ space\ between\ tube}$$

= 14.28 ≈ 15

The recommended shape of the proposed generator as shown in fig (5).

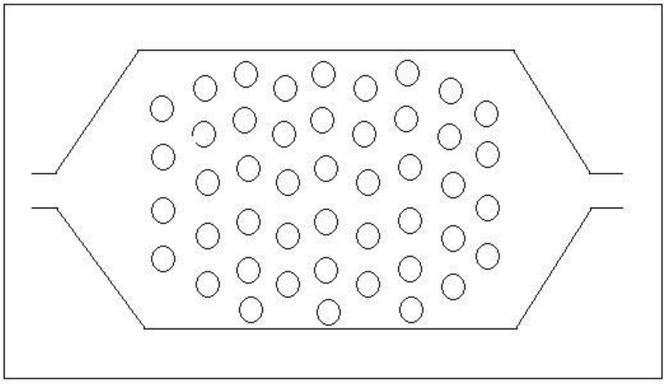

Figure 5. Schematic diagram for the tubes arrangement in the proposed generator from the other side of the generator

VI CONCLUSION

Diesel engines can be considered as a potential energy sources for absorption refrigeration systems, because of the energy wasted through the exhaust gas. The absorption refrigeration system may be able to take advantage of the exhaust gas power availability and provide the cooling capacity required for automotive air conditioning. The waste heat energy available in exhaust gas is directly proportional to the engine speed and exhaust gas flow rates. As calculated the air conditioning system for small car can run at 0.8 TR and needs 5 kW heat for evaporating refrigerant from mathematical modelling calculation. Therefore the generator is designed to have capacity of 5 kW with temperature around 95°C and pressure of 20 bar of area 0.22 m^2 with no. of tubes 32 having approx. weight 2 kg. The coefficient of performance can be found to be between 0.85 and 1.045. Reducing the fresh air intake and sealing the automobile body can result in a saving in cooling requirements such as door sealing and tinting the glass.

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