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Waste Heat Recovery of Internal Combustion Engine Using Vapour Absorption System

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ABSTRACT

Now a day, Depleting fossil fuels and shortage of energy is major problem worldwide. This leads our attention towards waste heat recovery systems. Internal combustion engine is one of the major sources of waste heat. In an IC engine only 30 to 39% of the total energy of burnt fuel is converted into useful work and almost 55 to 60% of the energy is wasted. This waste heat can be used to run an air conditioning system of automobile using vapour absorption system.

Conventionally, the automobile air conditioner works on VCR cycle which needs high grade mechanical energy. This system will be replaced by a system working on VAR cycle which uses low grade energy like heat. In this system the mechanical compression is replaced by thermal compression. Also the system uses natural refrigerant i.e. water which is environmental friendly whereas the VCR system uses CFCs and HCFCs having high GWP and ODP.

***Keywords*— CFCs, HCFCs, GWP, ODP, VAR, VCR**

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I. Introduction

To reduce use of CFCs Montreal Protocol is being effective since 1987. There are various substitute developed for replacing these ozone depleting refrigerants but still they have environmental impact due to their high GWP values.

Currently almost all car air-conditioning systems are charged with R-134a but still alternatives with lower GWP than R-134a are desirable. Recently new systems are being developed in order to use natural refrigerants. Due to the international attempt to find alternative energies, absorption refrigeration has become a prime system for many cooling applications where thermal energy is available the absorption refrigerator can very well substitute the vapour compression system.

A. Vapour Absorption System

Figure 1 shows a simple vapour absorption refrigeration system. The low temperature and low pressure refrigerant enters the evaporator and vaporizes by producing useful refrigeration. From the evaporator, the low temperature, low pressure refrigerant vapour enters the absorber where it comes in contact with a solution that is weak in refrigerant. The weak solution absorbs the refrigerant and becomes strong in refrigerant. The heat of absorption is rejected to the external heat sink. The solution that is now rich in refrigerant is pumped to high pressure using a solution pump and fed to the generator. In the generator heat at high temperature is supplied, as a result refrigerant vapour is generated at high pressure. This high pressure vapour is then condensed in the condenser by rejecting heat of condensation. The condensed refrigerant liquid is then throttled in the expansion device and is then fed to the evaporator to complete the refrigerant cycle. On the solution side, the hot, high pressure solution that is weak in refrigerant is throttled to the absorber pressure in the solution expansion valve and fed to the absorber where it comes in contact with the refrigerant vapour from evaporator. Thus continuous refrigeration is produced at evaporator, while heat at high temperature is continuously supplied to the generator. Heat rejection to the external heat sink takes place at absorber and condenser. A small amount of mechanical energy is required to run the solution pump. If we neglect pressure drops, then the absorption system operates between the condenser and evaporator pressures. Pressure in absorber is same as the pressure in evaporator and pressure in generator is same as the pressure in condenser.

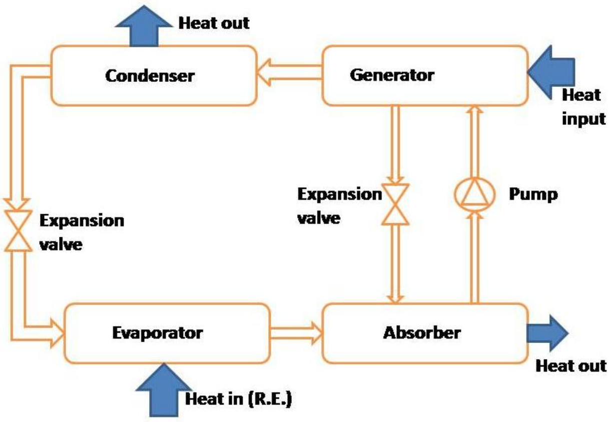

Fig. 1 Simple Vapour Absorption System

II. LITEREATURE REVIEW

There is vast research going on in the field of vapour absorption refrigeration systems recently. The main reason behind that is because of the fast depletion of fossil fuels the cost of thermal utilities are getting higher and higher and vapour absorption systems works on thermal energy as an input, hence they can be integrated with these utilities using waste heat or any source providing thermal energy. There are so many systems using waste heat from sources like waste heat from sugar factory or stationary gensets which are revealed in the literature. But we mainly discuss the VAR systems used in automobiles using waste heat from I.C. engines.

A. Auadha and Y. EI-Gotni have studied the feasibility of using waste heat from marine diesel engines to drive an ammonia-water absorption refrigeration system. The analysis shows the effect of generator, evaporator and absorber temperature on the performance parameters like COP and circulation ratio. A computer program has been prepared in order to calculate the performance of the system [1]. Sohail Bux and A.C. Tiwari presented review of previous and recent developments. Experiment was performed on 4 stroke, 4 cylinder Kirlosker engine and Li-Br water VAR system is being specified. The results are shown for engine performance and its feasibility for using VAR system [2]. In a paper by Khaled S. AlQdah, the authors have done experimental study on 4 cylinder diesel engine setup in lab bringing COP of 0.85 to 1.04 with capacity of 1.37 TR. It shows actual results from the setup like engine speed vs. exhaust heat and temperature [3]. S. Lakshmi Sowjanya investigated exhaust heat availability and use of ammonia- water absorption system with cooling water as preheater before generator for reducing size of generator. A design of condenser and evaporator coil in PRO/E is made and analyzed in ANSYS for aluminium 204 and copper. The results show excellent performance for Al 204 [4]. Shreeshankar K.K. and Vikas P.L. have proposed a system working on VAR system for cold storage. The system is combination of absorption and thermoelectric power generation. The exhaust gases after passing through generator passes to the TEG [5]. A Pathania and D. Mahto have investigated an air conditioning system using engine waste heat in a research paper and a comparative study of VAR and VCR systems has been done. An extensive literature survey on the technologies is done [6]. G Vactos and J Gryzagoridis have done experimental work on Nissan 1400 truck having 15KW of energy available at the exhaust. The suggested refrigerant-absorbent pairs are ammonia-water, Li-Br Water and Tetra-ethylene glycol Dimethyl ether (TEG-DME)-R22. And they suggested MS or SS for piping purpose. The estimated cooling load is 1.13Kw for passenger cabin [7]. G Karthik and K. Usha Rani investigated the VAR system with other refrigerants than ammonia or water. The working model was made and the results are graphically presented [8]. A paper by S.S. Mathapati and Mudit Gupta explains the basic theoretical design for such system for 2KW air conditioning model for Li-Br water system. Modelling was done using EES software and actual program is presented in the article [9]. Satish K. Maurya and Saurabh Awasthi have proposed a model on 3.7 KW single cylinder and theoretically described the simple VAR system using ammonia refrigerant [10]. A paper by C.M. Keinath which gives idea of actual 2 KW cooling capacity air conditioning system and actual results from experiments are presented for cooling and heating loads. The same system is being used for heating in winter and cooling in summer conditions [11]. Shah Alam has proposed a system with three fluid absorption system. The calculated useful exhaust heat is about 4 KJ/Sec and calculated cooling load theoretically 2.22KJ/Sec [12]. Rahul Singh also proposed a system with single effect water-Li-Br system with solution heat exchanger. Thermodynamic study was done using energy and mass balance and shows maximum COP of 0.775 at generator temperature 361 K [13]. Theoretical analysis of modified refrigeration cycle of a single effect Lithium Bromide- water vapour absorption system using exhaust gases of IC engine was done by Raghuvendra Kumar singh using EES software varying generator temperature and obtaining COP of around 0.7 and with another heat exchanger COP improves to 0.9 [14]. Khaled AlQdah, Sameh Alsaqoor have explained the design of most important component generator and designed for standard parameters and the calculated heat transfer area 0.196 m^2 and 2.932 m length of the tubes [15]. A research paper by Vazhappilly C.V. and Tharayil T. explains generator design for VAR system combined with 3.7 KW Kirloskar Diesel engine using plate frame heat exchanger and the author also suggested material for the same [16].

III. SYSTEM DESCRIPTION

The methodology is to use waste heat from internal combustion engine to run air conditioning system particularly in automobiles e.g. cars and trucks etc. The proposed system will be similar to the basic vapour absorption refrigeration cycle containing main parts generator, condenser, evaporator, absorber and expansion device. The system will be modified so as to have better coefficient of performance. The heat input to the generator is provided by using heat of exhaust gases and coolant and then refrigerant evaporate in evaporator coil which gives cooling effect. The condenser is air cooled and small capacity pump is used to maintain circulation of the refrigerant in the system. The proposed model is developed for LiBr-Water as working pair.

In this waste heat recovery system, the strong solution at 35°C is pumped from the absorber to the pre-heater where the temperature of the strong solution is increased to 75°C from the cooling water at 80°C. This solution then enters the generator where the refrigerant, i.e. water gets vaporizes and is passed through the condenser, where the latent heat is removed from the refrigerant. This refrigerant is then passed through the expansion valve to bring the temperature to around 10°C, after which it is passed through the evaporator coil to absorb the latent heat of the refrigerant at 10°C. The vaporized refrigerant then enters the absorber where the weak solution coming from the generator gets mixed liberating heat. This formed solution is again pumped to the preheater using the pump and the cycle is repeated again.

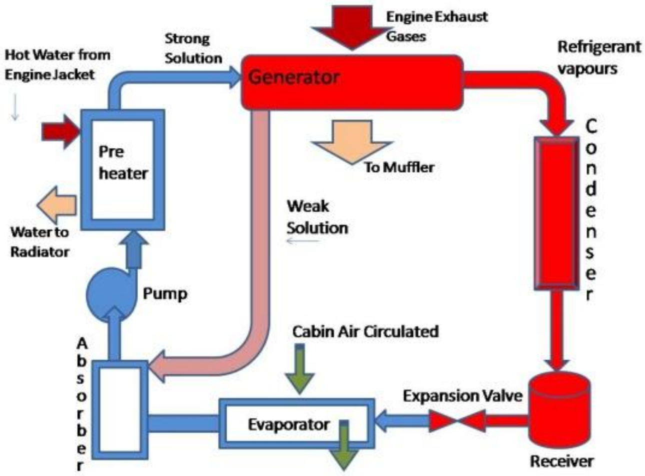

Fig. 2 Proposed system of waste heat recovery

There are basically eight components, let us see the construction of each in detail:

A. *Preheater*

It is a container containing tubes through which the LiBr-water solution passes. It is located in between the generator and the pump of the absorber. Engine cooling water is passed through the container, i.e. it is placed in the path way of hot water flowing from the engine jacket to the radiator. The tubes for the flow of solution are made of copper and the container is made of mild steel and it is placed in engine compartment.

B. *Generator*

It is basically a container where the solution is maintained at constant level. The exhaust pipe is passed through it and its heat is extracted in the generator. There is inlet for solution coming from absorber and two outlets, one for water vapours to condenser and weak solution (weak in refrigerant) back to absorber. The exhaust pipe passing through the generator and the generator tank are made of mild steel.

C. *Condenser*

Usually the condenser of an automobile is of an oval cross-section and finned forced convection type. The same type can be used for VAR system. It is made of aluminium to have easy transfer of heat from the refrigerant coming from generator to the atmosphere. Since the heat supplied in generator varies the condenser heat rejection capacity has to vary and hence it needs to be equipped with cooling fan.

D. *Expansion Valve*

A ball valve is used to drop the pressure of the refrigerant from high pressure to low pressure side. The valve can be used to adjust the pressure in the system and it will control the flow of refrigerant to evaporator.

E. *Evaporator*

The refrigerant from the expansion valve enters the evaporator where the cold refrigerant absorbs heat from the surroundings. To have maximum heat transfer from surroundings to the refrigerant the evaporator is made of copper tubes.

F. *Absorber*

This is the container which has two inlets, one for the refrigerant coming from the evaporator while the other for the weak solution coming from the generator. The one exit is for pumping the solution to the generator. It has a perforated sheet to strain the solution coming from the generator to have a proper mixing of the weak solution with the refrigerant coming from the evaporator. Fins are provided around the container to increase the surface area, to remove the heat developed during the mixing of the refrigerant and the weak solution.

G. *Pump*

A DC pump of 2.9 lpm is used. The selection of the pump depends upon the amount of the solution to be pumped for producing the required effect from absorber to generator.

H. *Control Valve*

It is placed in between the generator and the absorber to bring the solution pressure from high pressure to low pressure. It controls the flow rate of the weak solution back to the absorber.

The most commonly used system in automobiles is VCR. From the comparative study it could be observed that VAR systems are having advantages over VCR systems and can be coupled in IC engines without loss of mechanical work.

TABLE I
Difference between VAR and VCR systems

VAR system	VCR system
Thermal compression	Mechanical compression
Uses low grade energy.	Uses high-grade energy.
Less noise, wear and tear.	More noise, wear and tear.
The system can work on low evaporator pressures without loss of the COP.	The COP decreases with decrease in evaporator pressure.
No effect of reducing the load on performance.	Performance decreases at partial loads.

I. Merits of Using VAR in Automobiles

- Reduction in BSFC (brake specific fuel consumption) hence higher efficiency.
- No refrigerant compressor is required and Moving part is the pump, which is a small element in the system hence operation becomes smooth and also wearing and tearing is reduced.
- Helps engine to cool, as it extracts heat from engine.
- Helps in protecting ozone layer from depletion since it reduces the use of CFCs.
- Reduction in capital cost.
- Reduced maintenance since less moving part and lower pressure.

J. Demerits of Using VAR in Automobiles

- Refrigerating effect will be reduced or will be difficult to produce when the vehicle is at rest or in a very slow moving traffic condition.
- The refrigerating effect produced using a vapour absorption refrigeration system is less compared to a vapour compression refrigeration System.

IV. SYSTEM ANALYSIS

Let us consider an engine of an automobile on which the vapour absorption refrigeration system is to be implemented. The IC engine based on which the calculations are done is

TABLE II
Engine Specifications

Make and model	Maruti Suzuki, Maruti 800
Number of Cylinders	3
Power	37 bHp at 5000 rpm
Capacity	796cc
Number of Strokes	4
Fuel Used	Petrol
Air/Fuel ratio	15:1

A. Waste Heat of the Engine

The main two sources from which the heat is exhausted into the atmosphere from the engine are the cooling water and the exhaust gases. It is necessary to calculate the amount of heat energy carried away by the exhaust gases and the cooling water.

Exhaust gas heat

Volumetric efficiency of the engine, E_{vol} = 70%. Rated speed, N = 2000 rpm Mass flow rate of air into the cylinder,

$m_a = \frac{V.N.E_{vol}}{2}$

$m_a = \frac{0.000796 \times 2000 \times 0.7}{2 \times 60}$ = 0.01m3/s.

Mass flow rate of fuel,

$$m_f = \frac{m_a}{\text{air fuel ratio}}$$

$= \frac{0.02}{15}$

m_f = 0.001335 kg/sec

Total mass flow rate of exhaust gas,

$m_{ex} = m_a + m_f$ = 0.011335 kg/s.

Specific heat at constant volume of exhaust gas

C_{pex}= l kJ/kgk

Temperature available at the engine exhaust, t_{ex}= 300°C

Temperature of the ambient air, t_a = 40°C

Heat available at exhaust pipe

$Q_{ex} = m_{ex} \times C_{pex} \times (t_e - t_a)$

= 0.011335 x (300 - 40)

Q_{ex}=2.94 kW

Cooling water heat

Jacket water inlet temperature, t_{ci}=50°C

Jacket water outlet temperature, t_{co}=80°C

Mass flow rate of water for a 3 cylinder engine,

m_w = 0.1 kg/s

Specific heat of water, C_{pw} = 4.18 kJ/kgK

Heat carried away by cooling water

$Q_w = m_w C_{pw} (t_{co}-t_{ci})$

= 0.1 x 4.18 x (80 -50)

Q_w= 12.54 kW

Now, for COP of the proposed System,

Taking Temperatures of the system as given below,

Generator, t_g = 100°C, Condenser, t_c = 40°C,

Evaporator, t_e = 10°C,Absorber, t_a = 35°C,

Let, m_a = Mass flow rate of the solution back to the absorber,

m_r = Mass flow rate of refrigerant,

m_g = Mass flow rate of the strong solution to the generator,

X_a, X_b = mass fractions,

Latent heat of refrigerant at 10°C, h_{fg} = 2247.7 kJ/kg

Refrigeration effect required,

R.E = 0.5 TR i.e. R.E. = 1.75 kJ/s

But RE = $m_r \times h_{fg}$

m_r = R.E / h_{fg}

$= \frac{1.75}{2247.7}$

m_r = 0.77 gm/sec

Now, $m_g = m_a + m_r$

Divide by m_r

$\frac{m_g}{m_r} = \frac{m_a}{m_r} + 1$

But $\frac{m_a}{m_r} = \frac{X_b}{X_a - X_b}$

$$= \frac{0.57}{0.62 - 0.57}$$

= 11.4 gm/gm of solution

$m_a = m_r$ x 0.77 = 11.4 x 0.77

= 8.778 gm/sec

$\frac{m_g}{m_r}$= 11.4 + 1

= 12.4 gm/gm of solution

$m_g = m_r$ x 0.77

m_g = 12.4 x 0.77 = 9.548 gm/sec

COP of a vapour absorption system,

$$COP = \left(\frac{T_e}{T_c - T_e}\right) x \left(\frac{T_g - T_c}{T_g}\right) = \left(\frac{10}{40-10}\right) x \left(\frac{100-40}{100}\right)$$

COP = 0.2

B. *Design of Components*

Preheater

Outside diameter of the tube = 0.012m

Inside diameter of the tube = 0.01m

Length of the tube = 20.75m

Generator

Outside diameter of exhaust gas tube = 0.04m

Inside diameter = 0.038m

Length of the tube for heat transfer = 1.004m

Condenser

Required surface area for condenser = 0.2096m2

Width of tube = 0.018m and thickness = 0.005m

Length of the tube = 7.93m

Evaporator
Area of flow through tubes = 0.2131m2
Absorber
Outside diameter of absorber = 0.076m
Length of absorber = 0.205m
Outside diameter of fins = 0.109m and no. of fins = 7

C. *Preliminary Observations*

Thermocouples are mounted on various points in car and trials are taken to get actual temperatures at these points. These temperatures will help to design the actual system.
Let, T_1 = Temperature of the exhaust manifold,
T_2 = Temperature of water leaving engine jacket
T_3 = Temperature of cooling water entering engine jacket
T_4 = Temperature of exhaust pipe after muffler
T_5 = Temperature of exhaust pipe before muffler

TABLE IIII
Temperatures at Various Points

	t = 0	t = 5	t = 0	t = 10
T_1	48	125	31	164
T_2	49	85	32	94
T_3	51	69	31	67
T_4	37	40	37	50
T_5	39	115	34	122

D. *Amount of Savings per Year*
Average run of the car per month = 1500 Km
Fuel economy = 18 Km/ litre
Hence, fuel required per month = 1500/ 18 = 83.33 litre
Assume, fuel/month = 84 litre
If air conditioning is used (VCR), then there is drop of economy of around 2km/litre
Hence, reduced fuel economy = 16 Km/litre
Fuel required per month = 1500/16 = 93.75 litre
Assume fuel required = 94 litre
So, the extra fuel required = 94 – 84 = 10 litre/month
Extra fuel required per year = 10 x 12 = 120 litre/year
Extra money required per year = 120 litre /year x 68 Rs/litre = 8160 Rs/year

V. CONCLUSIONS

The feasibility of LiBr Absorption refrigeration system for a car engine is been studied and it shows there is great potential in waste heat from internal combustion engines. The LiBr-water system can be used for air conditioning. The proposed system is designed for small car Maruti 800 and such systems can be adopted in mid range cars as well as in trucks for cabin cooling purpose. The designed system will be fabricated and coupled with actual engine and observed under actual conditions. Though the system is designed for 0.5 TR capacity, there is variation of exhaust gas heat availability with speed and there is need of secondary heating system either by gas burner or by electrical heating coil to boost up generation of refrigerant vapours in generator at start ups and light speeds.

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