Waste Heat Recovery of IC Engine Using VAR System

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Abstract: Depleting fossil fuels is a future challenge. Internal combustion engines are major consumer of fossil fuels. Large amount of energy from internal combustion engine is wasted into the environment. This low grade energy can actually be recovered for useful purpose. In this paper we focus on recovery of this heat for running air conditioning system using NH_3-H_2O vapour absorption refrigeration system. The major use of internal combustion engines is in automobiles. Conventionally, automobile AC works on VCR cycle which consumes mechanical energy and reduces economy. This VCR system is replaced by VAR system by utilizing coolant and exhaust waste heat. In this work, feasibility of the waste heat recovery system is studied and the system components are designed using basic thermodynamic laws and heat transfer correlations. A working model is fabricated and tested. The performance of the system is also analyzed in EES (Engineering Equation Solver) for various working conditions.

Keywords: **Vapour Absorption Refrigeration, Waste Heat Recovery, Internal Combustion Engine.**

I. INTRODUCTION

Till date great efforts are taken in the development of internal combustion engines. But an engine can convert only 35 to 49 % of fuel's energy into useful work (Ouadha, Y. EI-Gotni, 2013). The following fig.1 shows typical IC engine heat balance.

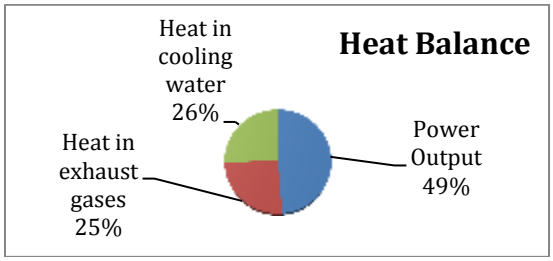

Fig.1 Heat Balance of typical IC engine

It can be observed that a large amount of energy in the form of heat from exhaust gases and cooling water is lost into the environment. Vapour absorption system works on heat as an input energy. The systems are bulky and hence not used for mobile applications. But the VCR systems in automobiles are noisy and need maintenance. They are charged with CFC's like R134a which is having GWP of 400(Bux and Tiwari, 2014). To reduce this power consumption by refrigerant compressor as well as to utilize the waste heat the vapour absorption system is introduced to air condition the passenger compartment.

II. VAPOUR ABSORPTION SYSTEM

In vapour absorption refrigeration cycle, heat is provided at generator which generates the refrigerant vapours. These vapours are then condensed in condenser by loosing heat. The high pressure liquid refrigerant is then throttled through expansion valve to lower pressure at evaporator. The refrigerant at such lower pressure and temperature evaporates and produces cooling effect. The refrigerant vapours then pass to absorber. The weak solution in absorber absorbs the refrigerant vapours and the solution is pumped to higher pressure to generator by a pump. The weak solution from generator is fed back to absorber where it absorbs the refrigerant vapours coming from evaporator (K. AlQdah, 2011). Fig.2 shows a single effect vapour absorption system.

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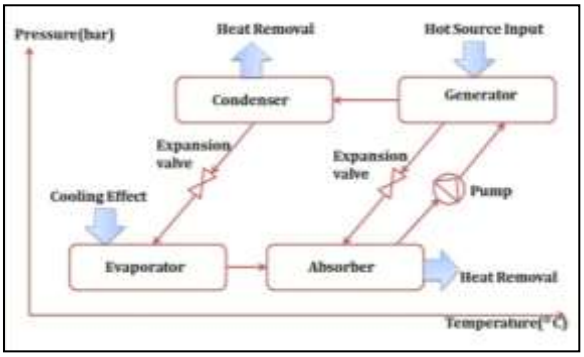

Fig.2 Simple vapour absorption system

2.1 Refrigerant

The desirable properties of refrigerant in VAR cycle are listed below:

1) It should have high latent heat of vaporization
2) It should be more volatile than absorbent
3) It should have high solubility in absorbent
4) It should be chemically stable in working temperature range, non toxic, non explosive, non corrosive.
5) It should be economical and environment friendly.

The most commonly used refrigerant absorbent pairs are H_2O-LiBr and NH_3-H_2O. For the WHR system ammonia-water pair is selected.

Some of the properties of ammonia as refrigerant are listed below (Bux and Tiwari, 2014):

1) Latent heat of vaporization = 1226 kJ/kg
2) Boiling point at 1bar = -33.3^0C
3) Freezing point at 1 bar = -77^0C
4) 800m^3 of ammonia can be absorbed by 1m^3 of water
5) Critical Temperature = 132.6^0C
6) It is available easily and economical
7) It is corrosive to copper
8) It is toxic (Group 2 refrigerant)
9) Global warming potential and Ozone depletion potential is zero.

Without considering certain drawbacks, NH_3-H_2O pair is selected as refrigerant-absorbent since the WHR system works at varying temperature conditions and LiBr salt is having crystallization issue(S. Manojprabhakar, *et al*, 2014).

III. LITERATURE REVIEW

Ahmed Ouadha and Youcef EI-Gotni have examined the feasibility of waste heat recovery (WHR) from marine diesel engine to run NH3-H2O VAR system. A simple mathematical model is used for calculation and analysis of the system using fundamental thermodynamic relations. S. Bux and A. Tiwari have proposed vapour absorption based automobile AC working on waste heat of 25kW Kirloskar make, 4 cylinder diesel engine. A plate heat exchanger is used to utilize heat of exhaust gases for working of LiBr-H2O VAR system. K. AlQdah has studied experimentally, the feasibility of using waste exhaust energy to design generator and absorber. It has been reported that the experiment on four cylinder diesel engine gives COP of 0.85 to 1.04 with capacity of 1.37 TR. S. Prabhakar *et al* used NH_3-H_2O VA system for 0.48 TR capacity with actual COP of 0.22 and reached steady state condition of 13^0C after 3hrs. S. Lakshmi Sowjanya studied the use of energy from the exhaust gas of IC engine to power a VAR system to air condition an ordinary passenger car. A preheater is employed to utilize the cooling water heat for preheating the NH_3 solution flowing from absorber to generator. Thermal analysis of condenser and evaporator is done in ANSYS for Al alloy 204 and copper. An exploration has been done by A. Pathania and D. Mahto to research the possibility of WHR to run AC system of vehicle. A three fluid VAR system is proposed. Air finned forced convection condenser and evaporator and shell and tube type generator are suggested. G. Vicatos *et al* have done experimental study on VAR cycle of capacity 2.18kW using waste heat of Nissan 1400 truck achieving COP of 0.09. The model is verified by both lab and road tests. S. Mathapati *et al* have theoretically evaluated LiBr-H_2O based VAR system using exhaust heat of engine. It is found that the exhaust useful energy is around 5kW and estimated cooling load is 1.9kW. The performance is analyzed in EES software by preparing mathematical model. S. Maurya *et al* have studied the possibility of WHR from a single cylinder 3.7kW Kirloskar engine. A NH_3-H_2O VAR system is proposed. C. Keinath *et al* investigated a NH_3-H_2O single effect VAR sytem driven by heat rejected by a diesel engine. A thermodynamic model is prepared for 2kW capacity for cooling and heating mode. The COP of 0.695 is achieved. R. Singh *et al* examined through thermodynamic analysis the feasibility of LiBr-H_2O VAR system using waste heat of diesel engine and COP of 0.775 is achieved. K. AlQdah *et al* designed the generator of 4.6kW capacity utilizing engine exhaust heat and the proposed COP is 1.04 for the system at generator pressure of 19 bar and temperature of 90^0C. V. Krishnadasan and N. Mohammed Sajid have investigated experimentally the integration of

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10Hp single cylinder engine exhaust with 170cc triple fluid VAR system. It is concluded that the system performance increases for higher engine loads and better condenser cooling. A. Bangotra and A. Mahajan have designed a 3 TR aqua ammonia VA system for standard conditions and detailed thermal design of heat exchangers is done. It is useful for basic design calculations.

IV. EXPERIMENTAL SETUP

The block diagram of the system is shown in fig. 3 below.

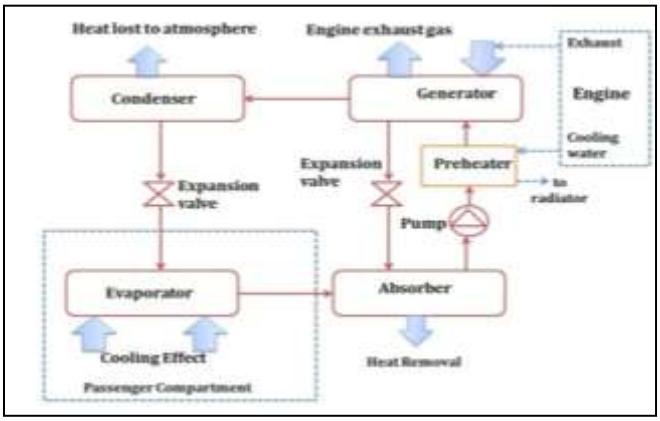

Fig.3 Waste heat recovery using VAR cycle

The hot exhaust gases from the engine are passed through generator which is a shell and tube heat exchanger filled with ammonia solution in shell. The heat is absorbed by NH_3 solution in generator and at 100^0C ammonia evaporates from the solution. The ammonia vapours are passed to condenser which is a copper tube air cooled finned heat exchanger placed in front of car as shown in fig. 4. The vapours are condensed at high pressure in condenser by loosing heat to surrounding. The refrigerant is then throttled through expansion valve to lower pressure in evaporator which is copper tube finned heat exchanger placed in passenger compartment. At such lower pressure ammonia evaporates by absorbing latent at 10^0C. The vapours then enter in absorber and get absorbed by weak solution which is at 40^0C. The solution becomes strong and is passed to preheater by a DC pump. The solution is preheated to 75^0C in preheater by hot engine jacket cooling water. Preheater is another shell and tube type heat exchanger placed in engine compartment. The cooling water from preheater then passed to radiator and then circulated into engine jacket. The solution then enters in generator and weak solution from generator is passed to absorber through an expansion valve. The Engine of the car under experiment has following specifications:

Table 1 Car engine specifications

Engine	Maruti 800
Number of Cylinders	3
Power	27.5 kW @ 5000 rpm
Capacity	796cc
Number of Strokes	4
Fuel	Petrol

The experimental setup has number of components which are installed on the car. The components are made from the materials available in market and as per design specifications.

Fig.4 Experimental setup

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As shown in fig.4 the parts of the complete system are indicated and listed in table below.

Table 2 Components of the system for fig.4

1	Condenser	2	Generato r	3	Expansion valve
4	Solution Pump	5	Preheater	6	Evaporator
7	Exhaust manifold	8	Front view	9	Absorber

V. THERMODYNAMIC ANALYSIS

From the basic thermodynamic calculations it is found that at normal running at 2000rpm,

1) The waste heat in exhaust gases = 3.12 kW
2) The waste heat in cooling water = 10.45 kW

For design following assumptions are made:

1) Temperature at generator = 100^0C
2) Temperature at Condenser = 40^0C
3) Temperature at evaporator = 10^0C
4) Temperature at absorber = 40^0C
5) Temp of solution leaving preheater = 75^0C
6) Temperature of exhaust pipe = 200^0C
7) Temperature of outside air = 30^0C
8) Steady state operation
9) No pressure drop due to friction
10) Ammonia condensed in condenser (liquid) and leaving evaporator (vapour) is saturated
11) Expansion is adiabatic.

5.1 Mass flow rate of refrigerant

For a baseline capacity of 0.5 TR i.e. 1.75kW
Latent heat of ammonia at 10^0C = 1226 kJ/kg

$$Mass\,flow\,rate = \frac{refrigeration\,effect}{Latent\,heat\,of\,vapourization}$$

$$Mass\,flow\,rate = \frac{1.75\,kW}{1.226\,kJ/Kg} = 1.42\,g/s$$

5.2 Theoretical COP

$$COP = \frac{T_e}{T_c - T_e} \times \frac{T_g - T_c}{T_g}$$

$$COP = \frac{283}{313-283} \times \frac{373-313}{373} = 1.517$$

The components are designed using basic thermodynamic equation and heat transfer correlations and details are tabulated below:

Table 3 Component Characteristics

Component	kW	Dimensions
Preheater	2.49	Outer Diameter D_o= 0.012m Inner Diameter D_i= 0.01m Length of tube L= 2.83m
Generator	1.26	D_o= 0.04m, L= 0.8m
Condenser	1.84	D_o= 0.01m, D_i= 0.008m, L= 5.72m
Evaporator	1.75	D_o= 0.01m, D_i= 0.008m, L= 4.75m
Absorber	3.0	D_o= 0.225m, L= 0.3m

Trials are taken for half hour ride and temperatures at certain locations are recorded using K type thermocouples. The variations of temperatures over time in minutes are plotted below. Where,
T1 = Temperature of the exhaust manifold

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T2 = Temperature of hot water from engine jacket
T3 = Temperature of water entering engine jacket

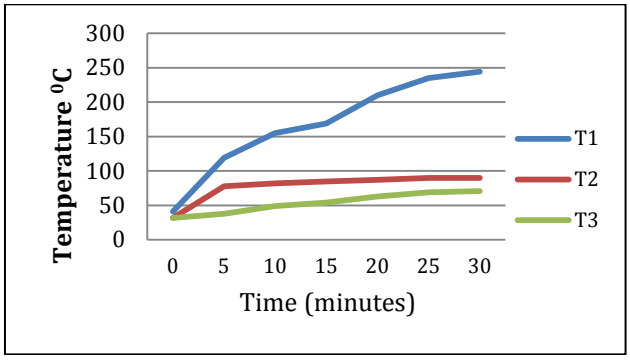

Fig.5 Temperature variation at engine locations

Using property correlations for ammonia solution a computer program is prepared in EES (Engineering Equation Solver). The EES window is shown in fig.6 below.

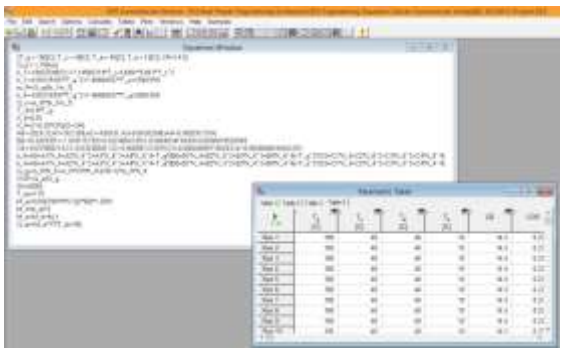

Fig.6 EES window with parametric table

The performance of the system is affected by temperatures at generator, evaporator, condenser, absorber and the circulation ratio.

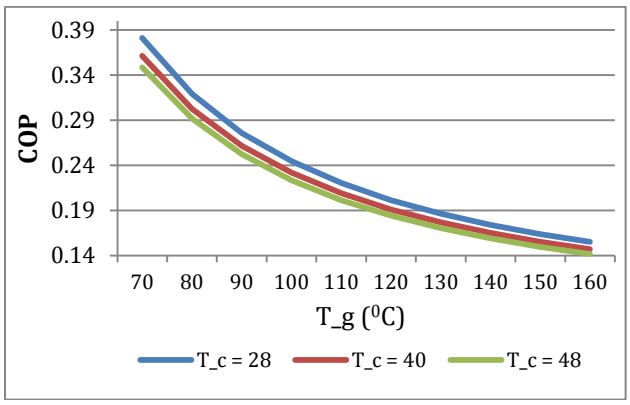

Fig.7 Variation of COP with generator temperature

Fig.7 shows that the COP of the system decreases as the generator temperature increases. This is because of the increased heat duty for condenser. It should be noted that there is a minimum temperature of generator below which there is no refrigeration effect from the system.

VI. RESULTS

The exhaust heat available is plotted against the engine rpm in fig. 8 and it shows the exhaust heat increases with increase in engine rpm.

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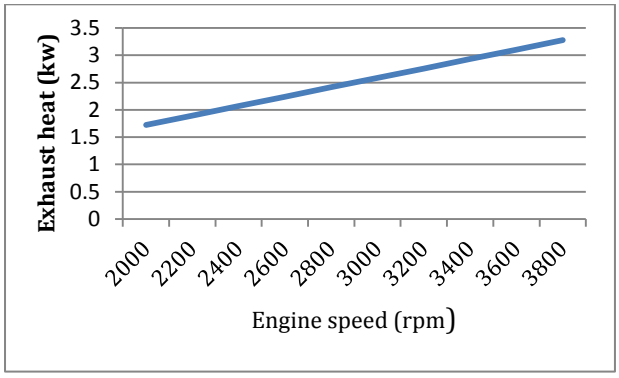

Fig.8 Variation of exhaust heat with engine speed

The trials are taken for two hour in idling condition after fitting of all the components and charging of the system by 25% ammonia solution and the temperatures were observed and plotted in fig. 9 below. The results are,

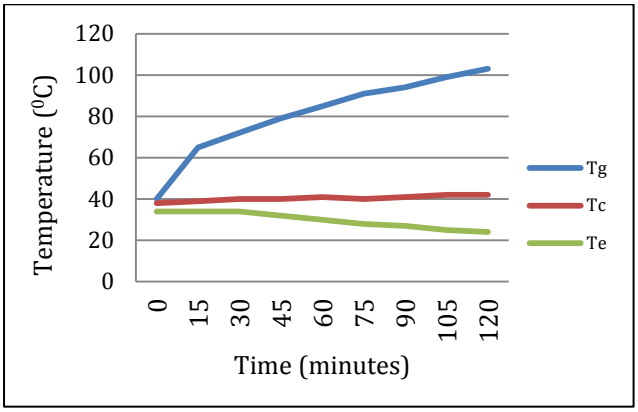

Fig.9 Temperature variation in actual trial

Where,
T_g = Generator Temperature (^{0}C)
T_c = Condenser Temperature (^{0}C)
T_e = Evaporator Temperature (^{0}C)
The trial took two hours and observations are as follows:
1) The generator temperature reaches to 103^{0}C
2) Condenser temperature increases to 42^{0}C
3) Evaporator temperature decreases with time from 34^{0}C to 24^{0}C.

VII. CONCLUSION

The work can be concluded as follows:

1) It is observed that, large amount of low grade heat is available. i.e. up to 3.275kw which can be recovered from the exhaust.
2) It is visibly shown that, COP of the system decreases with increase in generator temperature and increase in condenser temperature.
3) Theoretically it is estimated to have COP of about 1.517 can be achieved.
4) There is 10^{0}C temperature reduction observed at the evaporator and it is the refrigeration effect produced using the waste heat.
5) It can be concluded that the waste heat recovery system can produce refrigeration effect successfully and can be implemented on cars by using compact design.

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