Organic Rankine Cycle System for Waste Heat Recovery from Twin Cylinder Diesel Engine Exhaust

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ABSTRACT

This paper aims to prove the possibility of making a waste heat recovery system for an IC engine. About 20% - 30% of the thermal energy available to an I.C engine is transformed to useful work. The rest is lost through exhaust gases and engine cooling. This paper studies the workableness of using an Organic Rankine Cycle (ORC) to harness the waste thermal energy. The working fluid of the Organic Rankine Cycle acts as the coolant for exhaust gases. The energy absorbed by the working fluid is then fed to rotate a micro-turbine (expander). The work output of the turbine can be coupled to an electric generator to recharge the battery or to power an accessory. This can reduce the temperature of exhaust gases and increase the fuel efficiency.

Keywords: *Exhaust Heat, Heat Recovery, I.C Engine, Organic Rankine Cycle, Refrigerant.*

1. INTRODUCTION

In recent years there has been lot of improvements in fuel economy. But the focus has been on optimisation of air-fuel mixture, higher compression ratio, higher injection pressure etc. to raise the fuel economy. But the biggest and untapped source of energy in I.C engines; waste heat energy lost through exhaust gas and cooling water[10]. As the thermal efficiency is around 30% the rest of the heat energy can be made use of to produce useful work in one way or the other. The waste heat can be utilised using a suitable working fluid and thermodynamic cycle. This work can be extracted using some sort of expander to produce shaft work. This work can be used to rotate a generator to produce electric energy that can be used to recharge the battery or to work some accessory. In high capacity engines enough power may be extracted by the expander to supplement the crank work.

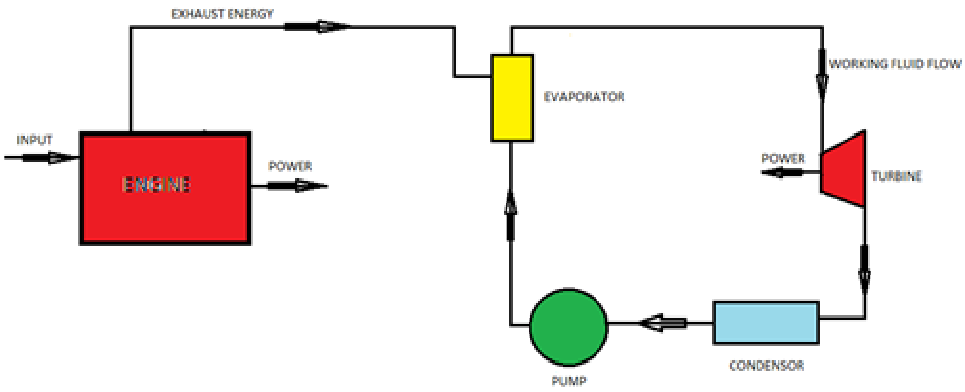

Fig.1 General Layout of the System

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There are mainly two sources of waste heat energy; the radiator (cooling water) and the exhaust gas. In this paper we are proposing a heat recovery system for a four stroke twin cylinder water cooled diesel engine producing a rated power of9.5 HP at 1500rpm that utilises the heat energy available with the exhaust gas only. The energy in the radiator is not considered even though large amount of heat is available in it because the lower temperature of radiator compared to exhaust temperature i.e., the energy for the cooling water is lower than the exhaust gas. Hence only a small part of that energy can be extracted using a heat exchanger.

2. APPROACH

- A heat balance test is conducted on an engine. Then we estimate the amount of work available at 50% of rated load. From this we gain a clear understanding about how much chemical energy of the fuel is utilised or rather wasted in an engine.
- Next step is the selection of working fluid. It is found that for Rankine cycle either water or a
- refrigerant can be used. If a refrigerant is used, then the Rankine cycle is called as Organic Rankine Cycle. The selection of the working fluid will be mentioned in later sections.
- Next a suitable turbine which can utilise the waste heat from the exhaust gas is to be selected from a range of commercially available micro-turbines.
- Then a suitable pump is to be selected to achieve the required mass flow rate and the inlet pressure required by the turbine.
- Then the heat exchangers are to be designed so that maximum amount of heat is transferred from the exhaust gas to the working fluid.

In this paper we are not discussed about the selection of micro turbine, pump and heat exchangers. These can be selected according to the requirements.

3. SYSTEM DESCRIPTION

3.1. Heat Exchangers

Two heat exchangers have been used, one as evaporator and the other as condenser. Evaporator is working in high temperature which helps to transfer heat effectively from exhaust gas to working fluid. Also the condenser is used in the system where the heat is rejected from the working fluid to the cooling water. The heat exchangers are to be designed using the standard designing methods in such a way that maximum heat transfer should take place and also the size of the heat exchangers should not add bulk to the system.

3.2. Turbine

A standard micro turbine can be used as expander. A Scroll type expander turbine can work in very low pressure difference. So this will be suitable for such low heat recovery system. The output of the shaft can be directly utilized or can be coupled to an alternator to produce electricity. As the size and weight of the turbine is very less, it will not make the system bulky and heavy so that it can be also used in vehicles with better efficiency.

3.3. Pump

The pump is selected in such a way that the outlet of condenser is in liquid form so that a simple positive displacement pump can be used to pressurize the fluid. As we all know the pump work is

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lower than the compressor work, added this advantage for the system, the net work output can be increased as it is depending on pump work also.

3.4. Pipe selection

The system is working in two different phases; two type of copper pipe must be selected to optimize cost and durability of the system.

1. Vapour line - Standard cold rolled copper pipe can be used for vapour region for improving durability.
2. Liquid line - Standard 3/8 copper pipe can be used for liquid line to achieve cost reduction.

4. RANKINE CYCLE SYSTEM FOR INTERNAL COMBUSTION ENGINES

Rankine cycles have been widely used in both prime movers and bottoming cycles. Reciprocating Rankine cycle has been used in locomotives, ships and stationary engines. Rotary expanders, primarily, steam turbines are used principally in power generation [1]. In order to be technically feasible for vehicle applications, the Rankine system should be kept as simple as possible. A simple structure of Rankine cycle and its ideal T-S diagram are shown in Fig.2

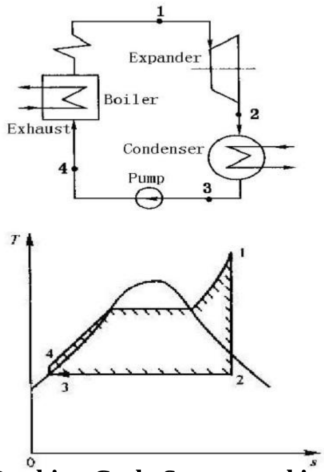

Fig.2 Structure of Rankine Cycle System and its Ideal T-S Diagram

The ideal Rankine cycle consists of the four following processes:

1 – 2: Isentropic expansion in an expander.
2 – 3: Heat rejection in a condenser with constant pressure
3 – 4: Compression in a pump
4 – 1: Heat delivery in a boiler with constant pressure.

The thermal efficiency of Rankine cycle can be expressed as follows

$$\eta_T = 1 - \frac{h_2 - h_1}{h_1 - h_4} \quad (1)$$

The thermal efficiency represents the Rankine cycle itself neglecting the thermal behavior of heat sources and sinks, however, as illustrated in Fig.3, variation of the heat sources temperature may result in the change of the working fluid temperature in an evaporator for a typical heat recovery system[2, 3, 4]. Taken this influence into consideration total heat recovery efficiency - a more meaningful parameter-is used to measure the performance of heat recovery system. It is givenby the thermal efficiency of Rankine cycle η_R and theefficiency of the boiler η_E , as pointed out by the following equations.

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$$\eta_T = \eta_E \cdot \eta_R \quad (2)$$

$$P_T = Q_{in} \cdot \eta_R = Q_{av} \cdot \eta_E \cdot \eta_R \quad (3)$$

The efficiency of the boiler, which transfers the heat from the heat source to the working fluid, is defined by Eq. (4):

$$\eta_E = \frac{Q_{in}}{Q_{av}} = \frac{T_{in} - T_{out}}{T_{in} - T_4} \quad (4)$$

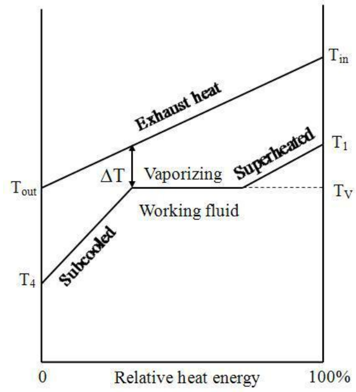

Fig.3 Variation of Waste Heat Temperature and Working Fluid Temperature in an Evaporator for a Typical Heat Recovery System

5. HEAT BALANCE TEST

The source of energy for the Rankine cycle has to determined first. As it is the energy available in the exhaust gas, the amount available must be calculated. And also to show the significance of this paper, heat balance test has to be done on the selected engine. Heat balance test [9] gives the exact distribution of energy. Thus the energy available in the exhaust gas is obtained.

5.1 Obtained Data

Heat Input (H.I) = 18.86 kW (100%)
Brake Power (B.P) = 1.587 kW (8.41%)
Coolant Loss (C.L) = 8.36 kW (44.32%)
Exhaust Loss (E.L) = 2.89 kW (15.28%)
Unaccounted Loss (U.L) = 6.035 kW (31.99%)

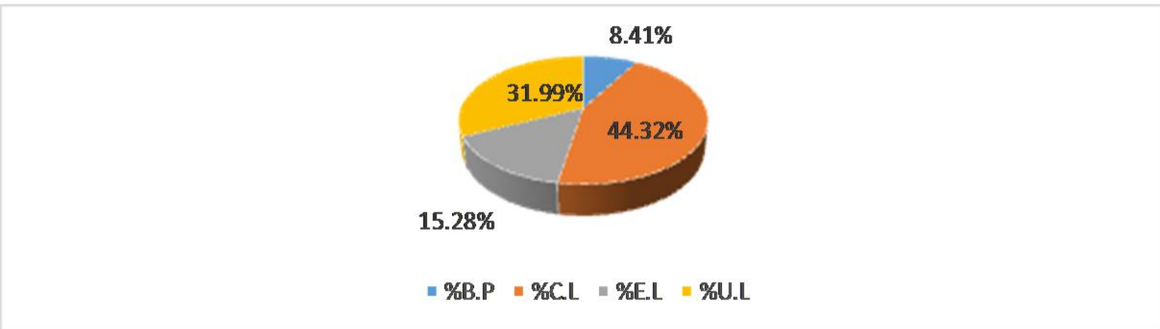

Fig.4 Pie Chart for the Heat Energy Balance

6. WORKING FLUID

The efficiency of a Rankine cycle system varies with the characteristics of the working fluid. Many working fluids have been tested for Rankine cycle applications. These working fluids may

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(P) 2347-8772

be wet, dry, and isentropic fluids. Corresponding Rankine cycles for the three types of working fluids are illustrated in Fig.5, where CP, L and V indicate the critical point, liquid phase and vapor phase respectively. Typical wet fluids are water and ammonia with simpler molecules, which have a negative slope in the saturated vapor line. Thus, if the superheat is insufficient, the expansion process will end in the two phase (wet) region. Typical dry fluids are R245ca and R245fa with more complex molecules, which have a positive slope in the saturated vapor line when the state is not very close to CP. For the dry fluids, the expansion process ends in the superheated vapor (dry) region. R123 are examples of isentropic fluids. The saturated vapor line for isentropic fluids are nearly perpendicular to the X-axis in most of the temperature range and thus, in an isentropic expansion process, the working fluid remains as the saturated vapor[5, 6].

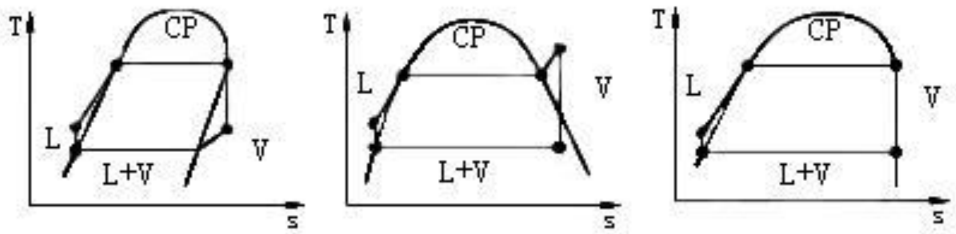

Fig.5 T-S Diagram Dry, Wet and Isentropic Fluid

6.1 Working fluid Selection Methods

Selection of the working fluid is one of the important processes in heat recovery system. The selection of working fluid includes some methods. Basic parameters that governed the selection process are as follows.

- Working fluid must have got high latent heat of absorption.
- Working fluid must be highly volatile ie, it can easily evaporate.
- It must be of low cost and reliable.
- It must satisfy the environmental norms.
- CFCs can't be selected due to the environmental degradation such as ozone depletion.
- It must not be flammable.
- It must not cause any harm to passengers in case of automobiles.
- It must be non-poisonous.

Selected working fluid must satisfy these conditions. Also working conditions of the particular cycle is an important factor.

If water is used as working fluid, the efficiency of Rankine cycle increases with the increase of the expander inlet temperature T_1[1], therefor T_1 is supposed to close to T_{in}. If R123, R245ca, R245fa or butane used as working fluid, the efficiency of Rankine cycle decreases with the increase of the expander inlet temperature. So the expander inlet temperature is assumed to a little higher than evaporating temperature T_V.

Fig.6 presents the total heat recovery efficiency for different working fluids with the exhaust temperature of 450 °C. In Fig.6, water shows the highest efficiency. Fig.7 presents the total heat recovery efficiency with the exhaust temperature of 400 °C and Fig.8 shows the total heat recovery efficiency with the exhaust temperature of 350 °C. In Fig.7 R123 shows the highest total heat efficiency. In Fig.8 water shows the lowest total heat efficiency. Fig.6 ~Fig.8 show that the total heat recovery efficiency for organic working fluids almost keep constant with different exhaust temperature while the total heat recovery efficiency for water decreases with the decrease of exhaust temperature. In comparison to water, refrigerant are preferable when the exhaust temperature is low and/or variable.

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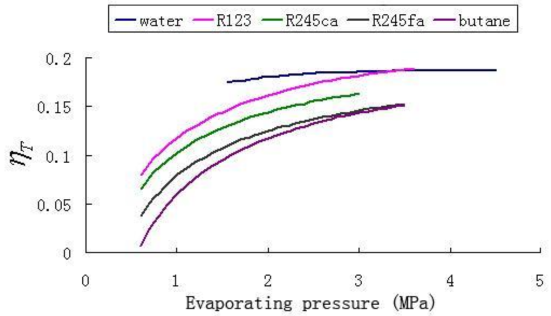

Fig.6 Total Hear Recovery Efficiency with Respect to Evaporating Pressure (T_{in}=450^{0}C)

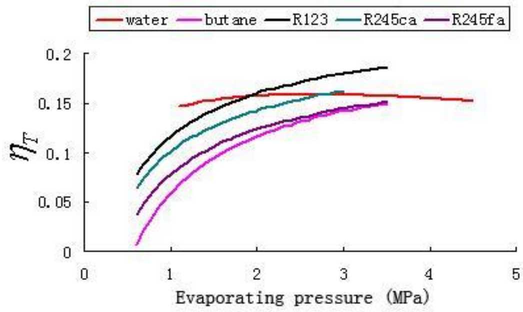

Fig.7 Total Hear Recovery Efficiency with Respect to Evaporating Pressure (T_{in}=400^{0}C)

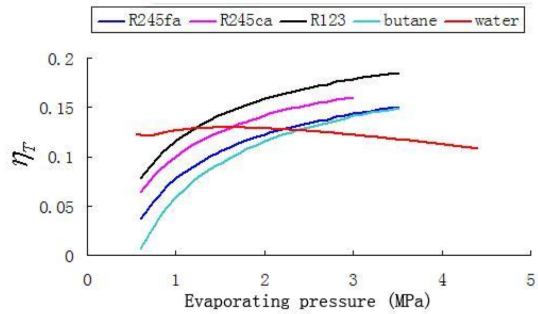

Fig.8 Total Hear Recovery Efficiency with Respect to Evaporating Presseure (T_{in}=350^{0}C)

Where η_T, is the total heat recovery efficiency.

Rody Ei Chammas[1] et al. proposed a system to recover the exhaust heat based on Rankine cycle using turbine expander. A large number of theoretical works were carried out in this research. HoTeng[5] et al. discussed the possibility of using Supercritical dry-type ORC (Organic Rankine Cycle) for waste heat recovery in heavy duty diesel engines. Diego A. Arias[7] et al. also conducted some deep research in engine waste heat recovery strategy.

From the above inference, it is clear that for the specified engine, the working fluid should be a refrigerant. Also butane can’t be used because of its low condensation temperature. If it is used extra work should be given for condensing it and thus reduces the efficiency.

For the heavy duty CI engines such as truck engines produces exhaust gas at comparatively high temperature ie , above 350℃. While for ordinary passenger vehicles it ranges from 200 to 350℃. Refrigerant is selected according to the working temperature which be below the critical temperature. Basically after heat addition, the exit temperature of refrigerant will be of the range 80 to 150℃.

The possible refrigerants that can be used for the engine specified here are

Refrigerant	Boiling temperature at 1 atm (^{0}C)	Critical temperature at 1 atm (^{0}C)	Critical Pressure (bar)
R123	27.85	183.8	36.74
R245ca	26	178.5	38.6
R245fa	15.1	154.05	36.512

7. WORKING PRINCIPLE OF THE SYSTEM

Basic working principle of the waste recovery system is based on Organic Rankine cycle. Basically the system works on 4different thermodynamic cycles which describe heat absorption process, expansion process, heat rejection process and the pump work.

The system consists of an evaporator or a heat generator, a turbine basically scroll or screw type, condenser and a pump. The waste heat obtained from the exhaust gas is supplied into the shell and tube heat exchanger ie, the evaporator at a temperature around 200^0C – 250^0C at 5 bar pressure . In the evaporator the working fluid is heated to super heat condition at temperature around 100℃ inside the tube of the shell and tube heat exchanger. Now through the vapour line super heated refrigerant vapour flows into a turbine having single stage. By the expansion of super heated vapour in turbine, turbine starts rotating thus required output power is produced. Now the expanded vapour is in the form of super heated state or saturated vapour state or in liquid vapour form at exit condition i.e., about 50℃ at 1 bar. This vapour is now fed into a water cooled condenser, where the vapour is condensed into the liquid form. Now this liquid refrigerant is fed through liquid line and is pumped to the working pressure i.e. at 5bar by means of a positive displacement pump basically a diaphragm pump. The cycle is repeated for 'n' number of cycles. Now the micro turbine is coupled to an alternator to produce electrical energy and stored in a battery.

8. CONCLUSION

- For an IC engine about 30% of total energy is wasted in the form of exhaust heat. This lost heat from the exhaust can be efficiently recovered using a Rankine cycle.
- Fluid selection for Rankine cycle is an important criteria depending on the target application and the working conditions. From our observation it is found that refrigerants can be effectively used as working fluid for heat recovery since the exhaust temperature of our test engine is relatively low.
- The selection of working fluid based on the thermoeconomic optimization leads to the utilization of Organic Rankine cylce for effective heat recovery.
- Heat recovery system using Organic Rankine cycle by utilizing components of suitable packaging dimensions can considerably increase the engine output power without increasing the fuel consumption.
- Further research using various advanced refrigerants can lead to the selection and utilization of a more optimized working fluid in terms of economic profitability.

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