Experimental Investigation of unused heat recovery using ORC cycle in a passenger car

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Abstract: The internal combustion engines of automobiles generally operate around 25-40 percent conversion efficiency. The productivity of the engine can be improved by using the dissipated waste heat by the automobile cooling jacket. An ORC (Organic Rankine Cycle) unit can be installed to recover the waste heat in engine cooling jacket of a passenger car. The installation of this unit shall reduce part load from the engine by reducing the load acting directly on the alternator. The System shall increase the overall efficiency and also improves the fuel economy by using the waste thermal energy. A Thermodynamic cycle analysis and prototype fabrication of model has been considered for the experimental evaluation of the efficiency and effectiveness of ORC system. The cycle is considered using an Automotive Air-conditioning Scroll compressor as the turbine expander and also as an feed pump. Low temperature heat source from a heater is considered for the heat source in the boiler setup. The ORC turbine shall be coupled with an Electric Generator and then to the battery for recharging. The whole Setup is considered for mass production of ORC Units for cheaper price and light weight. Owing to the fact that this setup is a prototype the efficiency of the cycle can be improved further in order to careful adjustment of the critical parameters such as pressure, temperature, flow rate of the refrigerant of the thermodynamic cycle and the flow rate of the coolant according to the actual performance of the vehicle.

Keywords: IC Engines, ORC, Alternator, Compressor, Turbine, Refrigerant

1. Introduction

Considering the environmental change and the deficiency of non-sustainable power source assets, the interests in squander heat recuperation has been developing strikingly, particularly during the previous decade. Squander heat recuperation from vehicle interior burning motors (ICE) is one of the open doors for conserving of vitality utilization. In an ICE, a lot of fuel vitality is squandered in type of warmth because of warm confinements. Approximately 33% of fuel vitality is changed over to mechanical force and the rest is discharged to the encompassing in type of warmth. For instance, the consumer light weight vehicle in production in the current scenario has the heat loss from radiator ranging from 2-128.39 kW from Table 1.1 and Table 1.2.

Table 1. Total heat loss by radiator with cooled fan.

| RPM | NISSAN | FORD | MITSUBISHI | HONDA | WIRA |
|-----|--------|------|------------|-------|------|
| 1000 | 24.34  | 15.4 | 29.74      | 13.51 | 4.015|
| 1500 | 41.32  | 20.73| 27.72      | 27.6  | 13.23|
| 2000 | 64.59  | 29.6 | 55.73      | 50.232| 23.18|
| 2500 | 73.35  | 39.45| 78.69      | 61.03 | 74.83|
| 3000 | 86.16  | 41.59| 128.39     | 121.02| 96.19|
Conklin and Szybist [1] researched that the level of fuel vitality changed over to valuable work just 10.4% and furthermore found the warm vitality lost through fumes gas about 27.7%. As indicated by the fuel vitality dispersion graph (Fig 1.1) 61.9% of the fuel vitality is squandered as warmth in coolant, grinding and others. The appropriation diagram obviously demonstrates that enhancement for usage of waste warmth from motor coolant will expand the eco-friendly of the vehicle.

There are a considerable measure of waste warmth through fumes gas and coolant of an inward burning motor. Natural Rankine cycle is one of the open doors in inside ignition motors squander heat recuperation. Various techniques have been suggested for squander heat recuperation from ICE, for example, thermo electric, ingestion refrigeration framework, and natural Rankine cycle (ORC). For instance the examined thermo electric technique in fumes gas squanders heat recuperation of a three chamber flash start motor through a test. Squander heat recuperation utilizing ORC is a productive strategy contrasted and different strategies. Car makers utilize this technique to upgrade the proficiency of their items. Also the examined proficiency of a substantial diesel motor utilizing the techniques for heat recuperation from fumes gas. These strategies incorporate mechanical turbo exacerbating, electrical turbo aggravating and steam Rankine cycle. Another examined heat recuperation from a 1.7 liter flammable gas fueled inward burning by CO2 transcritical power cycle.

Numerous scientists have been performed about utilizing diverse working liquids, various designs of Rankine cycle, and improving the framework parts during the ongoing years. The contemplated the impact of utilizing various liquids on the warmth recuperation Rankine cycle and streamlined the thermodynamic boundaries like energy effectiveness for the considered working liquids [2-8]. The considered the impact of different working liquids on the proficiency of Rankine cycle utilized for squander heat recuperation. One more examined the impact of utilizing Rotary - Vane Type expander on the effectiveness of Rankine cycle utilized for squander heat recuperation. The inspected the fumes squander heat recuperation capability of a high-efficiency, low-outflows double fuel low temperature ignition motor utilizing an ORC. Organic Rankine Cycle (ORC) was planned, adjusted from information accessible in writing and advanced to fit the model vehicle Ohio State University EcoCAR (model module half and half electric vehicle). Recreations were then done to assess the measure of vitality recuperated by the ORC framework, considering both urban and parkway driving conditions. The aftereffects of the reenactments show that a straightforward ORC framework can recoup up to 10% of the motor waste warmth on parkway driving conditions, comparing to an expected 7% improvement in fuel utilization, with low punishment of the additional load to the vehicle electric range [9-18].

In this experimental investigation the waste heat recovery using automobile engine cooling jacket is considered. The prototype setup is assembled using the automobile scrap available in the market. The thermodynamic cycle analysis is considered for both the experimental setup and the actual model if considered on the passenger car.

Table 2. Total heat loss by radiator without cooled fan.

| RPM   | NISSAN | FORD  | MITSUBISHI | HONDA | WIRA |
|-------|--------|-------|------------|-------|------|
| 1000  | 9.465  | 7.702 | 26.02      | 5.63  | 2.007|
| 1500  | 13.77  | 7.974 | 23.94      | 13.14 | 4.106|
| 2000  | 43.07  | 3.7   | 33.17      | 28.46 | 7.095|
| 2500  | 57.05  | 10.38 | 36.2       | 52.56 | 36.73|
| 3000  | 58.37  | 9.042 | 47.02      | 98.54 | 38.77|
2. Experimental setup

Initially the components required for the experiment (scroll compressor, condenser, boiler setup and the generator) were measured for proper dimension to make an stand on which the experiment is performed. The stand and the experimental setup is as shown in fig.3.1 & fig.3.2.

The system is connected to the vacuum pump and evacuated for 30 minutes. Then the refrigerant R134a is charged to the system by standard procedures. Initially the system took a little time to run in a cycle as pre-determined then little adjustments on the pressure valve made the system run smoothly.

The experimental setup will help determine the ORC cycle efficiency for the standard considered temperature limit and the flow rate due to limited practical power available in the form of heat. The genuine ORC Unit will have the accompanying properties as appeared in table.3.1.

![Turbine and Generator Coupled to the Pump Fixed in the Stand](image1.png)

**Figure 1.** The turbine and generator coupled to the pump fixed in the stand.

![Isometric View of the Whole Setup](image2.png)

**Figure 2.** Isometric view of the whole setup.

| Conditions                        | Variables       |
|-----------------------------------|-----------------|
| Evaporator pressure (in bar)      | 16 – 26         |
| Evaporator temperature (in deg C) | 80 – 120        |
| Heat available from the Radiator (kW) | 2 - 128.39 |
| Condenser pressure (in bar)       | 6 - 7.5         |
| Condenser temperature (in deg C)  | 25 – 30         |

**Table 1.** Actual ORC Unit Specification
The experimental cycle considered for the investigation has the design specifications as shown in table 3.2

| Conditions                  | Values |
|-----------------------------|--------|
| Evaporator pressure (in bar)| 16.82  |
| Evaporator temperature (in deg C)| 90     |
| Degree of superheat (in deg C)| 30     |
| Heat available from the Radiator (kW)| 4.5    |
| Condenser pressure (in bar)| 7.27   |
| Condenser temperature (in deg C)| 28     |
| Volume of refrigerant flow (in LPM)| 1.167  |

2.1. Assumptions in the Experiment
Before performing the experiment some of the variables in the experiments were assumed based upon the previous investigations carried out on the components.

2.1.1. Expander
The expander used in this experiment used is the Automotive scroll compressor [Sanden TRSA05]. The isentropic efficiency of the scroll compressor acting as an expander is assumed to be 50% according to the performance study conducted by Manolakos D, Kosmadakis G, Kyritsis S, Pa G [7]. Generally, lightweight materials are used in automobile and structural applications [8-18].

2.1.2. Feed Pump
The boiler feed pump used in this experiment is Automotive scroll compressor [Sanden TRSA05]. In a perfect world, specialists of thermodynamic frameworks use siphon bends relating stream, speed, force and head to settle on plan decisions for explicit framework. By and by, in any case, it is hard to get this data. This is expected to some degree to the divided connections between automobile makers, OEM providers, and the different firms that really sub-gotten the plan work and the mass producer of the siphons. Following this data through the automobile makers is troublesome in light of the fact that the data is viewed as restrictive, or on the grounds that there is an unwillingness to talk about specialized perspectives o car gear for use in applications outside the car business.

Regardless of the hindrance insinuated over, this venture expects to check the pertinence of car scroll blower for use as evaporator feed siphons in an ORC framework. The isentropic productivity of parchment blower utilized as heater feed siphon is thought to be half.

2.2. Testing & Evaluation
Experimental Measurements from the setup were taken to make sure that the inlet test conditions are satisfied. The pressure gauge reading from the experiment is taken from the service valve in the setup. The test value taken from the experiment is taken for the calculation of overall cycle efficiency of the cycle. The software used for the purpose of evaluating the results and plotting the graph is SOLKANE 8.0.0.

3. Results and Discussions
3.1. Results
The experimental setup with the proposed configuration of ORC model is assumed with input parameters as shown in table 4.1.
Table 1. Input Parameters for Experimental Configuration

| Parameter                | Value  
|--------------------------|--------
| Generator temperature   | 60 C   
| Superheating             | 30K    
| Heating Capacity         | 4.5 kW 
| Condenser Temperature    | 28 C   
| Condenser Subcooling     | 0 K    
| Turbine efficiency       | 0.5    
| Generator efficiency     | 0.65   
| Feed pump efficiency     | 0.5    

Table 2. Output results for the experimental Conditions

| Parameter                | Value     
|--------------------------|-----------
| Condenser                | 4.33 kW   
| Turbine                  | 0.20 kW   
| Generator                | 0.13 kW   
| Feed pump                | 0.03 kW   
| Mass flow                | 20.20 g/s 
| Feed Pump Volume flow    | 0.06 m³/h 
| Efficiency ratio, complete| 0.02     

Table 3. State point Parameters

| bar  | deg C | dm³/kg | KJ/kg | KJ/kgK | -       |
|------|-------|--------|-------|--------|---------|
| 7.27 | 28    | 0.84   | 238.96| 1.1336 | 0       |
| 16.82| 29.11 | 0.84   | 240.55| 1.1389 | 0       |
| 16.82| 60    | 0.95   | 287.33| 1.2845 | 0       |
| 16.82| 60    | 6.2    | 356.98| 1.4935 | 0.5     |
| 16.82| 60    | 11.46  | 426.63| 1.7024 | 1       |
| 16.82| 90    | 14.29  | 463.34| 1.808  | 1       |
| 7.27 | 57.14 | 32.99  | 443.11| 1.808  | 1       |
| 7.27 | 67.26 | 34.49  | 453.22| 1.8381 | 1       |
| 7.27 | 28    | 28.27  | 413.71| 1.7148 | 1       |
| 7.27 | 28    | 14.55  | 326.33| 1.4224 | 0.5     |
| 7.27 | 28    | 0.84   | 238.96| 1.1336 | 0       |

The scaled model for the actual model of ORC the parameters are expected to be as shown in the table.4.4 & table.4.5

Table 4. Input Parameters for Actual Configuration

| Parameter                | Value     |
|--------------------------|-----------|
| Generator temperature    | 60 C      |
| Superheating             | 30K       |
| Heating Capacity         | 80 kW     |
| Condenser Temperature    | 28 C      |
Condenser Subcooling | 0 K
---|---
Turbine | 0.5
Generator | 0.65
Feed pump mech | 0.5
Feed pump motor | 1

### Table 5. Output results for the experimental Conditions

| Component        | Output [kW] |
|------------------|-------------|
| Steam generator  | 80          |
| Condenser        | 79.94       |
| Turbine          | 3.63        |
| Generator        | 2.36        |
| Feed pump        | 0.57        |
| Pressure ratio   | 2.31        |
| Pressure difference | 9.55 bar   |
| Mass flow        | 359.1 g/s   |
| Feed Pump Volume flow | 1.08 m3/h |
| Efficiency ratio, complete | 0.02 |

### 3.2. Application in Passenger car

A WHR using the proposed Organic Rankin Cycle is estimated for the values obtained for the HONDA CIVIC model. The technical specification for the HONDA CIVIC is obtained from the WWW (from official website of HONDA). The Car alternator used for the purpose of comparison is (Delco 22SI type12V-100A). The Car alternator is assumed to be coupled to the engine at the speed ratio of 2:1. The technical data for the Delco 22SI type12V-100A as experimented values are taken from the Fig.4.3. for an Delco 22SI type12V-100A at a battery voltage of 14V, ambient temperature of 25° C and maximum excitation current.

![Figure 4.3. Characteristics of Delco 22SI type12V-100A.](image)

The Output simulated for the DELCO Alternator and an actual ORC in a passenger car may be represented in Table 4.6 & Table 4.7.
### Table 6. Output for Delco 22SI type 12V-100A

| Engine RPM | Alternator RPM | Electrical Power (W) | Efficiency | Mechanical Power (W) | Torque (Nm) |
|------------|----------------|----------------------|------------|-----------------------|-------------|
| 1500       | 3000           | 1104                 | 0.46       | 2400.000000           | 7.643312102 |
| 1750       | 3500           | 1140                 | 0.44       | 2590.909091           | 7.072545289 |
| 2000       | 4000           | 1200                 | 0.43       | 2790.697674           | 6.665679159 |
| 2500       | 5000           | 1260                 | 0.43       | 2930.232558           | 5.599170493 |
| 3000       | 6000           | 1320                 | 0.42       | 3142.857143           | 5.004549591 |

### Table 7. Output for ORC in HONDA CIVIC

| Engine RPM | Waste Heat Flow Rate (W) | Electrical Power (W) | Torque (Nm) |
|------------|--------------------------|----------------------|-------------|
| 1500       | 27.6                     | 810                  | 0           |
| 1750       | 38.916                   | 1150                 | 0           |
| 2000       | 50.232                   | 1480                 | 0           |
| 2500       | 61.03                    | 1800                 | 0           |
| 3000       | 121.02                   | 3570                 | 0           |

The percentage in increase of Brake thermal efficiency and the percentage in reduction of Specific Fuel Consumption for the HONDA CIVIC Model may be tabulated as given in Table 4.7.

### Table 8. Performance Improvement using ORC

|                        | Using Alternator | Using ORC          |
|------------------------|------------------|--------------------|
| Engine Speed (RPM)     | 1750             | 1750               |
| Torque (Nm)            | 200              | 207.0725453        |
| Brake Power (kW)       | 36.633333333     | 39.224242422       |
| Mass flow of fuel (kg/s)| 0.000544872       | 0.000446626        |
| Specific Fuel Consumption (kg/kWh) | 1.48737E-05 | 1.21918E-05       |
| Mileage (km/L)         | 26               | 31.71930579        |

It is found that there is and 6.6% increase in brake thermal power and the SFC is reduced by 0.18%. Due to the decrease in SFC of the vehicle there is 22% increase in the mileage of the Car.

**4. Conclusion**

Implementation of ORC waste recovery in passenger car shall result in downsizing of engine cooling radiator, decrease of part of the load acting on the engine due to the alternator and it shall also account for reduce fuel consumption of the vehicle. The systems to increases the heat utilization from every drop of fuel and hence it yields better mileage. The prototype modeling just indicates how the waste heat can be tapped into useful work however proper installation of waste heat recovery unit shall need careful attention of sizing of the condenser, pump and generator. Though the system only yields an
overall efficiency of 2%, the ORC Unit is a comparatively feasible solution to the unwanted heat recovery systems in the current market.

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