Waste Heat Recovery on IC Engines Using Organic Rankine Cycle

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Abstract— Organic Rankine Cycle is now-a-days rising as a new solution to the heat recovery system. By using this technology to recover the heat from the diesel engine will also help in reducing the fuel consumption. Dry or isentropic fluids can be used in the organic rankine cycles because of their operating ranges and critical temperature. In our research, R134a and R22 will be used as the working fluids. By comparing the results at different pressure and temperatures, the fluid to be used in the experimentation is decided. Available diesel engine from the college laboratory setup is subjected to the heat recovery. Analytically, R134a shows better performance when compared with R22 in same operation conditions. This efficiency indicates the amount of heat recovered out of the total available exhaust heat.

Index Terms— Organic Rankine Cycle, Diesel Engine, Heat Recovery, R134a, R22, dry fluids, isentropic fluids

1 Introduction

1.1 Organic Rankine cycle

Rankine Cycle in which a dry or isentropic fluid with a high molecular mass, liquid-vapour phase change, or boiling point, occurring at a lower temperature than the water-steam phase change is used is termed as Organic Rankine cycle (ORC). The fluid used in the cycle has a boiling and critical point lower than that of the water. Hence it is used for the heat recovery at the temperature lower temperatures.

1.2 How ORC is different than Steam Rankine Cycle?

Steam Rankine Cycle and Organic Rankine cycles have two basic differences. The fluids being used and the temperature range.

1.2.1. Fluids being used

Typically there are three different types of fuels being used in any Rankine Cycle.

A. Wet Fluids which have negative slope and lower Molecular number, such as water.
B. Dry Fluids which have positive slope and higher Molecular number, such as Benzene.
C. Isentropic Fluids which have nearly vertical saturated vapour curves, such as R11 and R12.

1.2.2. Temperature Range

This depends upon the fluid used. Generally fluids like water become saturated after passing through the turbine and can cause damage to turbine. This is completely undesirable. Hence we can use Dry or isentropic fluids. The temperature range depends upon the properties of fluids being used.

1.3 Components used in Organic Rankine Cycle

Components used in the organic rankine cycle are the same as that of steam rankine cycle. But the expander, compressor and the heat exchanger used make a huge difference in the results. We will discuss these three components separately and their effects on the performance of the overall cycle.

1.3.1 Expander

Expanders have a major effect on the performance of the ORC system. According to the operating conditions and the size of the system, the type of expander is selected. Two main types of the expanders are turbo-machines and positive displacement expanders.

Positive displacement expanders are more appropriate for use in small-scale ORC units. They have lower flow rates, higher pressure ratios and much lower rotational speed than the turbo-machines. Scroll expander is used for the fluids R134a and R22[1].

1.3.2 Heat exchanger

Selection of heat exchanger depends on its place of installation in the system. Heat exchangers play an important role in the cost of the system. Hence the optimum condition needs to be achieved.

Heat can be recovered by means of two different setups

1. Direct heat exchange between heat source and working fluid
2. An intermediate heat transfer fluid loop that is integrated to transfer heat from the waste heat site to the evaporator.

In most of the commercial ORC systems, intermediate heat transfer loop is used. In our experimental setup also, we will be using the same type of setup.

1.3.3 Compressor

Compressor selection should be done on the basis of the requirements of work done or the compressions. Care should be taken while installing and using a compressor in the system.

Back Work Ratio (BWR) is the major parameter considered in the compressor selection. BWR is known as the ratio of the compressor consumption to the expander output.

$$BWR = (W_C/W_T)$$

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where,
W_C : compresor consumption
W_T : expander work output

1.3.4 Advantages and Disadvantages

Table 1: Comparison of Steam Rankine Cycle with ORC

Advantages of ORC over Steam Rankine cycle	**Advantages of Steam Rankine Cycle over ORC**
No superheating	Higher efficiency
Lower turbine inlet temperature	Low-cost working fluid
Lower evaporating pressure	Non-flammable, non-toxic working fluid
Higher condensing pressure	Low compressor consumption
Low temperature heat recovery	High chemical-stability working fluid

2 SELECTION OF FLUID

2.1 TYPES OF FLUIDS

As discussed earlier the type of the fluid is decided on the basis of its molecular weight and the slope of its saturated vapour curve. Water which is a wet fluid is used in steam rankine cycle, whereas dry or isentropic fluids are used in the organic rankine cycle because of their operating temperature range.

Fluids are selected according to their working temperature range. Below is the given data for the fluid and its critical temperature.

Table 2 : Critical temperature of different fluids

Fluid	Critical Temperature	Fluid	Critical Temperature
R22	96.2°C	R123	183.68°C
R134a	101.08°C	R11	197.78°C
Iso-butane	134°C	Benzene	288.5°C

Temperature is one of the major deciding parameters. Hence by considering the critical temperature and our requirements, we select the fluid. Initially, we select the fluids having lower critical temperature range so as to recover the heat at lower possible range.

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According to the required and available conditions, and literature survey, one of the fluids amongst R245fa, R123, R22 and R134a is selected. In spite of being the most effective fluid in ORC, R123 and R245fa are mostly avoided for environmental conditions. Hence only R134a and R22 will be studied for the further investigation. Analytical study of R134a and R22 is done. The results are compared to study the effect or fluid, its temperature range, variation in exhaust temperature of the organic cycle

2.2 T-S PLOT OF DIFFERENT FLUIDS VS WATER

Water has the critical temperature of 374°C. Also, as discussed heat below 370°C is difficult to recover. Hence we have studied the fluids which have critical temperature below water. These are found to be either dry or isentropic fluids. The graph is given below.

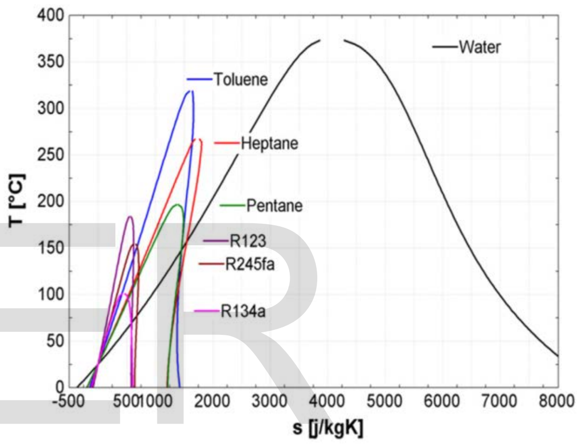

Fig 1: T-s plot of different fluids Vs Water

In this graph, a comparison between dry and isentropic fluids with water is shown according to their Temperature-Entropy variations. This graph is taken from the available literature.

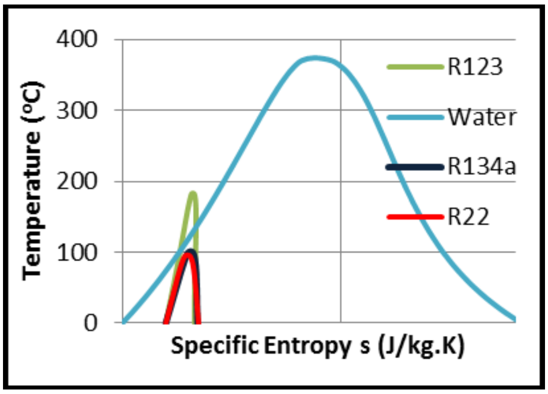

Fig 2: T-s Plot of isentropic fluids Vs Water

In this graph, a comparison between isentropic fluids which are to be studied in the experiment with water is shown according to their Tmperature-Entropy variations. This graph is taken was made by using the thermal properties of these fluids.

R22 is the initial selection of the fluid for having the least critical temperature. To compare the results, analysis of R134a is also done. The analytical results are shown in the further discussion.

3 EXPERIMENTAL SETUP

Referring to the previous ORC setups used for the heat recovery from different system, a setup was designed to perform the experiment on the I.C.Engine available in the college for the heat recovery.

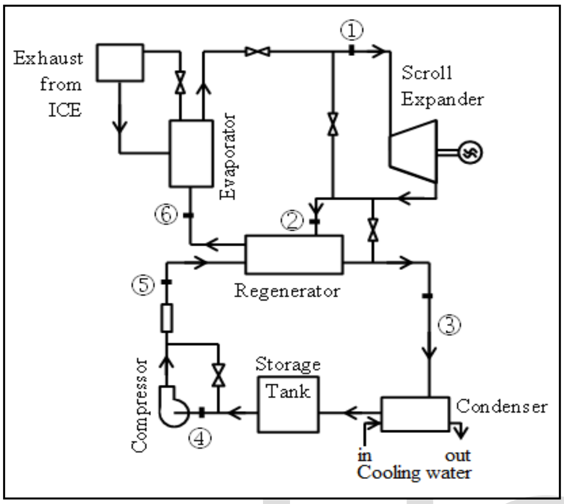

Fig3: Schematic of ORC Setup

3.1 Construction

1 R22 gas is stored in a storage tank as shown in the fig below. It is then allowed to flow from its storage tank.
2 Compressor is connected to the storage tank
3 Plate heat exchanger is used as a regenerator next to the compressor.
4 Next to the regenerator, evaporator is connected where the exhaust heat from the engine is used as the input to the system.
5 R22 gas after flowing through the evaporator is allowed to flow from the turbine. In our case, a prototype is used, which means the work outcome cannot be utilized thereafter. Although the work done by the turbine cannot be used, we can measure it from the electric inputs given to it.
6 After the turbine a flow line from the same previous regenerator is being carried away.
7 Next to the regenerator, the condenser is attached from which the gas R22 again comes back into the storage tank. To make it more effective, a fan is also provided in case of excess heating.
8 Water tank is provided below the condenser to allow the cooling water to flow.
9 Thermocouples are attached at every point where the temperature readings are to be measures, as shown in the setup diagram.
10 These temperature reading are shown on a temperature indicator
11 Pressure indicators are attached at the same points where the thermocouples are connected to check the pressure at these various points.

Fig 4: Experimental Setup

3.2 Working:

1 R22 gas is allowed to flow from its storage tank to start the cycle.
2 From the storage tank it is compressed to the desired pressure by using the compressor. From where it is passed into the regenerator
3 To make the liquid saturated it is first allowed to flow from the regenerator, where it reaches saturation state.
4 It then flows from the evaporator where it takes the heat from the exhaust of the diesel engine and its temperature is raised up to the exhaust temperature or nearby. Heat exhausted from the diesel engine is initially passed from the evaporator of the system to supply the heat input to the ORC system.
5 It then flows through a turbine where its heat is being utilized and converted into work output, which can be actually used to do mechanical, electrical or any work possible.
6 From the turbine it again goes into the regenerator where it cools down to the saturation temperature. It also cools down the gas supplied but to make sure that in the condenser the saturated vapour is being supplied
7 In the condenser the vapour is being cooled up to its saturated liquid state.
8 It again goes into the storage tank and makes a complete cycle.
9 Temperatures and pressures are measured by using the thermocouples and pressure indicators connected at the desired locations.

4 OBSERVATION

By varying the load on the engine, the readings of temperature and pressures are taken. The load was varied from 7kg to 10kg. Also, the time was varied from 5mins to 20 mins to find the effect on the system performance. By using p-h graph for measuring the enthalpy values, we could find the enthalpies at all the 6 locations. And hence can find efficiency and BWR for the system.

The observations made are as tabulated below:

Table3 Temperature and Pressure Values at various load and time

Sr. No	Load	Time	Temperature (°C)						Pressure (MPa)					
	kg	Min	T1	T2	T3	T4	T5	T6	P1	P2	P3	P4	P5	P6
1	7	05	92	39	33	28	33	48	1.95	1.16	1.10	1.14	2.13	2.09
2	7	10	105	46	41	28	37	52	2.18	1.23	1.15	1.16	1.95	1.90
3	7	15	108	49	38	28	40	55	2.00	1.18	1.15	1.14	2.15	1.90
4	8	05	100	41	36	28	34	49	1.89	1.21	1.16	1.19	2.03	1.99
5	8	10	106	45	39	28	36	53	1.92	1.23	1.13	1.17	2.06	1.97
6	8	15	113	55	47	29	35	54	1.99	1.19	1.08	1.10	2.06	1.95
7	8	20	118	56	51	27	41	56	1.92	1.21	1.08	1.10	2.04	1.97
8	9	05	106	43	37	27	33	49	2.02	1.21	1.12	1.17	2.05	2.00
9	9	10	110	49	41	27	36	53	1.83	1.25	1.17	1.21	1.98	1.95
10	9	15	119	56	51	29	39	58	1.98	1.21	1.13	1.19	2.08	2.01
11	9	20	121	59	53	28	40	59	1.97	1.24	1.11	1.16	2.07	2.02
12	10	05	111	46	41	29	35	56	1.90	1.21	1.13	1.19	2.08	1.97
13	10	10	118	53	46	30	37	57	1.98	1.23	1.08	1.13	2.09	1.99
14	10	15	125	57	49	29	41	56	1.97	1.19	1.08	1.14	2.06	2.00
15	10	20	137	62	55	29	42	55	2.02	1.25	1.19	1.22	2.11	2.02

Total 35 sets were taken at the time of the experimentation. Out of them total 15 sets, including various loads and time, are considered. For 7kg load, there are 3sets of 5, 10 and 15mins respectively. For 8kg load, there are 4sets of 5, 10, 15 and 20mins respectively. For 9kg load, there are 4sets of 5, 10, 15 and 20mins respectively. For 10kg load, there are 4sets of 5, 10, 15 and 20mins respectively.

5 RESULTS AND DISCUSSION

From the observed data, and using the standard available formulae, each values of enthalpy were found.

The efficiency and BWR for each of the set is calculated and tabulated as given below.

Table4: Work, efficiency and BWR values

Sr. No.	Load	Time	W	Q_R	Q_2	W_C	Q_{IT}	Q_{IS}	W_S	Efficiency	BWR
	(kg)	(min)	(kJ / kg. K)							(%)	
1	7	05	30.44	3.56	191.22	8.70	216.52	212.96	21.74	10.21	0.29
2	7	10	34.65	2.51	196.44	13.10	220.49	217.99	21.55	9.89	0.38
3	7	15	36.12	7.94	194.14	16.40	221.81	213.86	19.72	9.22	0.45
4	8	05	37.28	2.97	192.49	9.80	222.93	219.96	27.48	12.49	0.26
5	8	10	39.28	2.89	195.28	12.00	225.45	222.56	27.28	12.26	0.31
6	8	15	35.95	4.24	201.14	9.70	231.63	227.39	26.25	11.54	0.27
7	8	20	40.65	1.64	206.46	18.70	230.05	228.41	21.95	9.61	0.46
8	9	05	39.40	2.99	195.08	9.90	227.57	224.58	29.50	13.13	0.25
9	9	10	41.01	4.72	197.27	13.20	229.80	225.08	27.81	12.36	0.32
10	9	15	40.87	2.46	203.24	14.10	232.46	230.01	26.77	11.64	0.35
11	9	20	40.76	2.46	206.31	16.40	233.13	230.67	24.36	10.56	0.40
12	10	05	43.40	2.36	194.08	9.70	244.50	265.40	33.70	12.70	0.22
13	10	10	42.68	2.77	197.86	13.90	251.10	268.70	28.78	10.71	0.33
14	10	15	43.95	3.62	203.30	19.60	254.40	263.20	24.35	9.25	0.45
15	10	20	51.70	4.40	202.98	21.60	256.60	266.50	30.10	11.29	0.42

5.1 Effect of Load

If the load is varie, then all the parameters change. Further is given the graphical representation to check the the effect of load.

5.1.1. Effect of Load on Efficiency

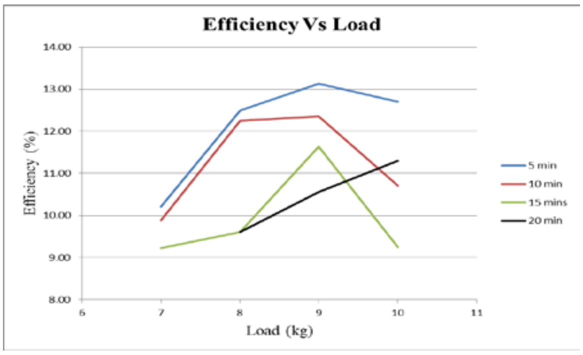

Fig 5: Effect of Load on Efficiency

5.1.2. Effect of Load on Turbine Work

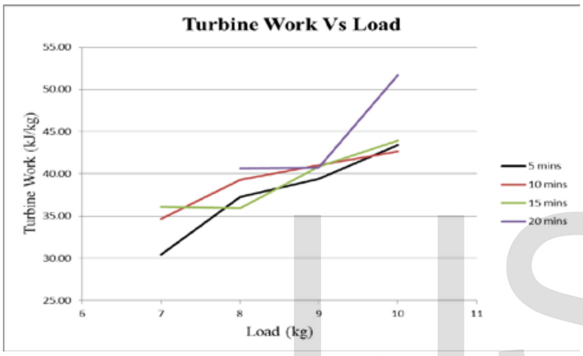

Fig 6: Effect of Load on Turbine Work

5.1.3. Effect of Load on BWR

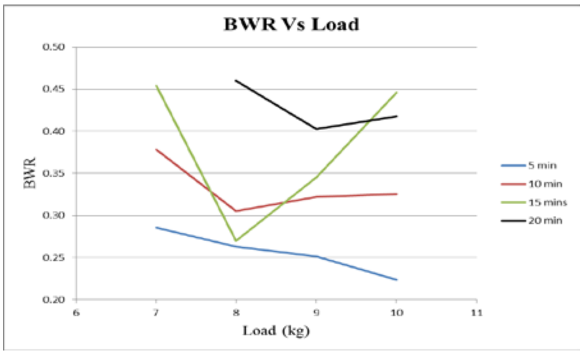

Fig 7: Effect of Load on BWR

5.1.4. Effect of Load on Compressor Work

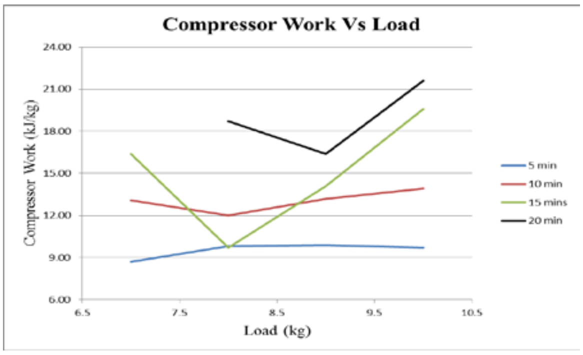

Fig 8: Effect of Load on Compressor Work

5.2 Effect of Time

In the same duration of time, different parameters behave differently. Further is given the graphical representation to show the efft of time on such parameters.

5.2.1 Effect of Time on Efficiency

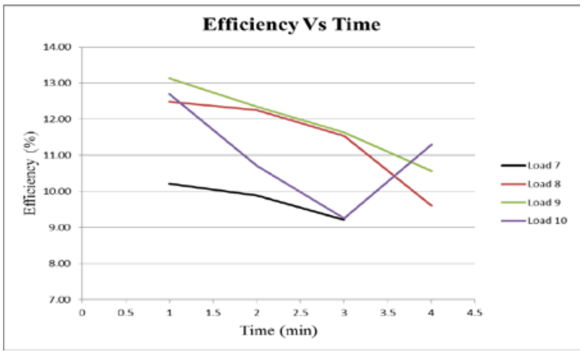

Fig 9: Effect of Time on Efficiency

5.2.2 Effect of Time on Turbine Work

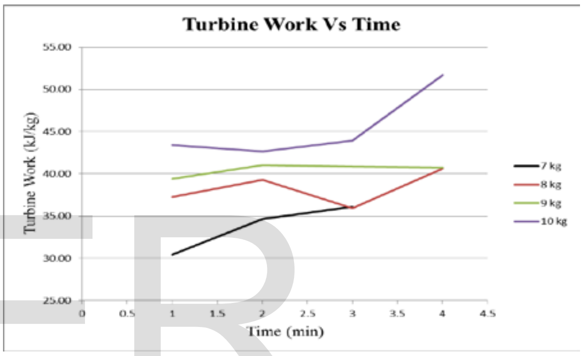

Fig 10: Effect of Time on Turbine Work

5.2.3 on BWR

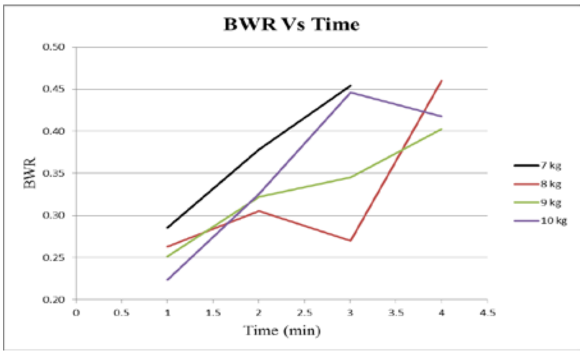

Fig 11: Effect of time on BWR

5.2.4 on Compressor Work

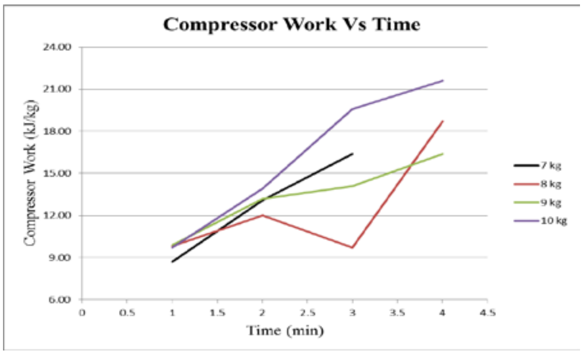

Fig 12: Effect of Time on Compressor Work

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5.3 Verification on p-h Graph

Ideally the plots on the grapth should be like shown in the fig below. But due the heat losses, friction, or any other irreversibility, these plots may vary.

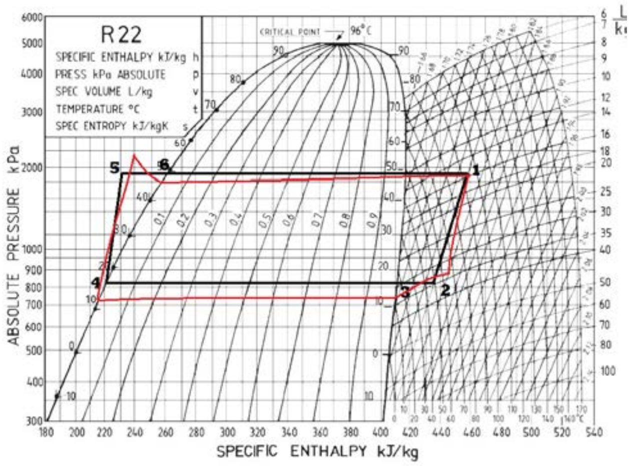

Fig 13: Ideal and actual Rankine Cycle for R22

In this graph the black line shows the ideal process whereas the red line shows the actual process.

For every load p-h values are plotted on the graphs to validate the process. Out of all the 15 readings, 4 processes are shown further.

5.3.1 For Reading 1, 7kg and 5mins

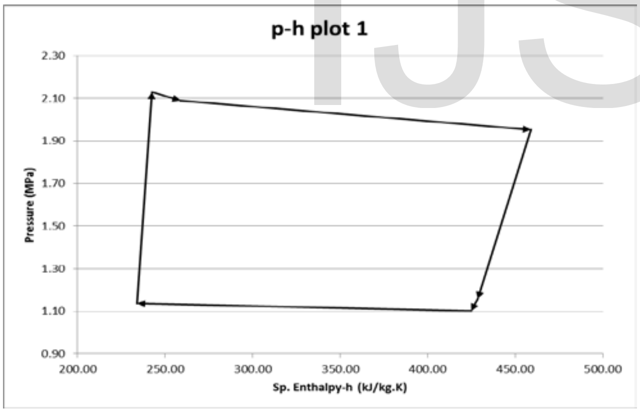

Fig 14: p-h plot for 1st Reading

5.3.2 For Reading 5, 8kg and 10 mins

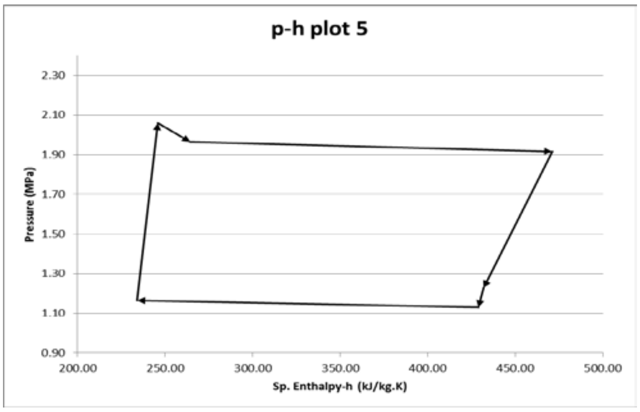

Fig 15: p-h plot for 5th Reading

5.3.3 For Reading 10, 9kg and 15 mins

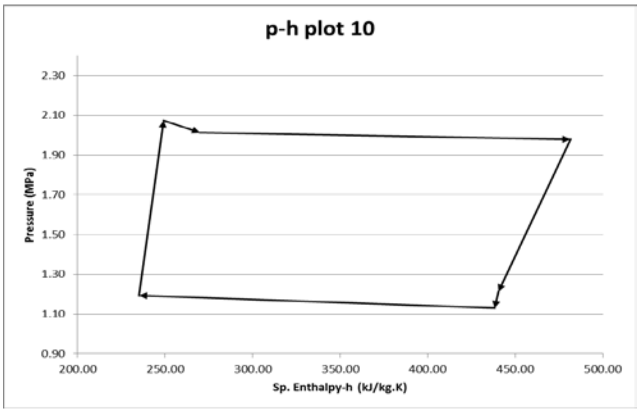

Fig 16: p-h plot for 10th Reading

5.3.4 For Reading 15, 10kg and 20mins

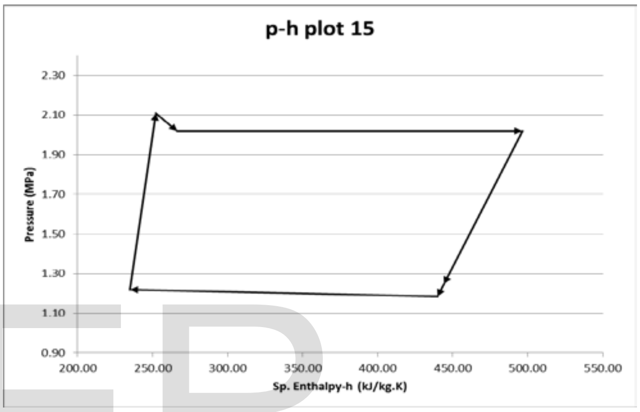

Fig 17: p-h plot for 15th Reading

6. Conclusions

1. When the load is 7kg, efficiency is 10.21% after 5 mins, 9.89% after 10 mins and 9.22% after 15 mins. When the load is 8kg, efficiency is 12.49% after 5 mins, 12.26% after 10 mins and 11.54% after 15 mins and 9.61% after 20mins. When the load is 9kg, efficiency is 13.13% after 5 mins, 12.36% after 10 mins and 11.64% after 15 mins and 10.56% after 20mins. When the load is 10kg, efficiency is 12.70% after 5 mins, 10.71% after 10 mins and 9.25% after 15 mins and 11.29% after 20mins which is higher than the previous value which shows a wrong interpretation of the value. For same Load, as time increases, the efficiency goes on decreasing.
2. After 15 mins, 7kg load gives 9.22%efficiency, 8kg load gives 11.54% efficiency, 9kg load gives 11.64% efficiency and 10kg load gives 9.25% efficiency, which gives a different behavier in efficiency than the previous. These reults indicate that as the load increases, for the same amount of time efficiency increases upto a point and then decreases.
3. When the load is 7kg, workdone by turbine is 30.44kJ/kg after 5 mins, 34.65kJ/kg after 10 mins and 36.12kJ/kg after 15 mins. When the load is 8kg, work-done is 37.28kJ/kg after 5 mins, 39.28kJ/kg after 10 mins,

35.95kJ/kg after 15 mins and 40.65kJ/kg after 20 mins. When the load is 9kg, workdone is 39.40kJ/kg after 5 mins, 41.01kJ/kg after 10 mins, 40.87kJ/kg after 15 mins and 40.76kJ/kg after 20 mins. When the load is 10kg, workdone is 43.40kJ/kg after 5 mins, 42.68kJ/kg after 10 mins, 43.95kJ/kg after 15 mins and 51.70kJ/kg after 20 mins. For same Load, as time increases, the turbine workdone by the system generally goes on increasing.

4. After 10 mins, 7kg load gives 34.65kJ/kg workdone, 8kg load gives 39.28kJ/kg workdone, 9kg load gives 41.01kJ/kg workdone and 10kg load gives 42.68kJ/kg workload. As the load increases, workdone by turbine increases for the same amount of time.

5. Compressor work changes according to time but in very unclear manner. This shows that the compressor work is not affected by the time duration.

6. Similarly, load has no clear effect on compressor work.

7. BWR is a function of Compressor work and turbine work. Although, turbine work is a function of time and load, Compressor work does not have any clear effect of load and time on it. Also from the graphical representations, it can be concluded that load and time have no clear effect on BWR.

8. From the p-h plots we can conclude, that our system gives not ideal but nearly actucal results as we have discussed previously.

9. From the readings at point 3, 4 and 6we can conclude that, the regenerator and the condenser does not actucally give the saturated state of the gas or liquid. This is a variation achieved in the actual process.

10. Similarly, entropy at point 1 and 2 i.e turbine inlet and outlet is defferent. This occurs because of the different readings of pressures and temperatures

11. We can see a pressure drop or rise in the evaporator or the condenser which again is a heat loss occurred due to the non-ideal process.

12. The results indicate that, out of total waste or exhaust heat, some amount of heat is being recovered. From this, we can conclude that by using ORC, overall efficiency of the Diesel engine and the ORC setup combined is increased and due to this, fuel consumption can be reduced.

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