An Experimental Investigation and Exergy Analysis of Compression Ignition Engine Operated Cooker

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Abstract**—**To achieve an optimal solution for the current energy crisis, the world needs to focus more on (a) renewable sources of energy or (b) look for recycling / appropriate utilization of energy being wasted. An alarming amount of heat is wasted from exhaust systems of various engines – stationary or in automobiles. Our common goal is to achieve this task in the most efficient, cost effective, and least polluting manner. In this paper describes the 4.4 kW stationary compression ignition engine operated cooker to utilize the waste heat of engine exhaust. An experimental investigation has carried out for effectiveness of the cooker, effect on exhaust emissions and performance of engine when the cooker was incorporate with engine. It has found that the effectiveness of waste heat operated cooker was 0.3642 at a load of 3.0 kW (Around 70% of full load). 14.87% of available energy of the waste heat was recovered by using the CI engine waste heat operated cooker. From the exergetic point of view, exergy efficiency of either of the integrated systems was marginally higher compared to the traditional power generation system (single generation). No adverse impacts on any parameter were found while operating with waste heat operated cooker.

Keywords**—**Compression Ignition engine, Exhaust emissions, Waste heat recovery, Waste heat operated Cooker.

I. Introduction

Considering the fast growing energy demand, limited energy resources and increasing CO_2 emissions, for a sustainable future, there is a great need to identify alternative and clean sources of energy as also energy conservation techniques to enhance the efficiency of various systems. The energy available at the exit stream of prime mover goes waste if it is not utilized properly. With effective means, more than half of this waste heat could be recovered so that a considerable amount of primary fuel can be saved. It is established fact that in an internal combustion engine, a great amount (almost two-third) of energy is wasted in the form of heat carried away by exhaust gases and cooling water / air to the environment. If this waste heat is utilized for cooling and/or heating purpose, then this heat is known as recovered heat and the system which is used to recover waste heat is known as waste heat recovery (WHR) system. The exhaust gas temperature of a diesel engine is about 600°C and for gasoline engine, this temperature is around 700°C [1]. Since the temperature of exhaust gas is quite high, there is a great potential for recovery or utilization of heat from these exhaust gases.

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The development of various waste heat recovery systems for IC engines started since the IC engines were in developing stage. Liu Junhong et al., 2003 investigated the feasibility of a WHR that was composed of an oil heater, bitumen tank, oil circulation system and some auxiliary instruments, which utilized the truck exhaust gas to heat the bitumen used in road maintenance by means of heat transfer oil as working fluid [1]. Feng Yang et al., 2003 checked the feasibility of using heat pipe heat exchangers for heating HS663, a large bus from waste heat. A mathematical model developed for designing a heat exchanger for heating purpose. The experimental results showed that it is valuable to use heat pipe heat exchanger to utilize exhaust gas for this purpose [2]. G.Th, Kaldellis et al., 2004 evaluated the techno-economic aspects of a new desalination plant for Crete Island, utilizing a thermal desalination process and taking advantage of the heat content of the exhaust heat [3]. M. Sadeghzadeh, 2007 described a water heating apparatus based on utilization of exhaust energy of domestic gas heater. They mounted device on the roof, connected to the stack and the hot exhaust flows through its inner gear-shaped tube and tested the potential of heat recovery of this parallel-flow heat exchanger for 5.2 and 7.2 kW heater powers and different exhaust temperatures in the range of 100-185°C [4]. Hugues, Beyene et al., 2009 have utilized waste heat of a 2.8 L V6 internal combustion engine to run a modified 10.55 kW (three ton) absorption chiller. To find the feasibility of this project, the mathematical model studied and some experiments have carried out. Test results suggested that the concept is thermodynamically feasible and could significantly enhance system performance depending on part-load of the engine [5]. Andre Aleixo Manzela, 2010 worked on an Ammonia–water absorption refrigeration system using the exhaust of an internal combustion engine as energy source. The author, in this study, evaluated the availability of exhaust gas energy and the impact of the absorption refrigeration system on engine performance, exhaust emissions, and power economy. A production automotive engine tested in a bench test dynamometer, with the absorption refrigeration system adapted to the exhaust pipe and results showed that the cooling capacity could be highly improved for a dedicated system. Exhaust hydrocarbon emissions were higher when the refrigeration system was installed in the engine exhaust, but carbon monoxide emissions were reduced, while carbon dioxide concentration remained practically unaltered [6]. V. Pandiyarajan, 2011, integrated a shell and finned tube heat exchanger with an IC engine setup to extract heat from the exhaust gas and a thermal energy storage tank used to store the

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excess energy available. Authors designed, fabricated and tested a combined sensible and latent heat storage system for thermal energy storage using cylindrical phase change material (PCM) capsules. The performance of the engine with and without heat exchanger evaluated and it found that nearly 10–15% of fuel power was stored as heat in the combined storage system, which was available at reasonably higher temperature for suitable application. The various performance parameters pertaining to the heat exchanger and the storage tank were also evaluate, such as, amount of heat recovered, heat lost, charging rate, charging efficiency and percentage energy saved [7].

So far, the researches carried out in this domain show the feasibility of WHR systems for various purposes. The objective of the current study was to utilize the waste heat of a low capacity engine (4.4 kW) for small-scale cooking purposes and also investigate the feasibility, performance (Energy & Exergy analysis) and exhaust emissions of small capacity agricultural diesel engine (4.4 kW).

II. Design Of Waste Heat Operated Cooker

For designing the waste heat operated cooker, at first, the properties of hot gases (engine exhaust) and cold fluid (water) were observed and calculated as shown in table 1.

TABLE 1: PROPERTIES OF HOT AND COLD FLUID.

Properties	Value
m_h	21.6 kg/hr
m_c	2 kg
T_{hi}	430 ^{0}C
T_{ci}	25^{0}C (Atmospheric)
T_{ho}	285^{0}C (From energy balance)
T_{co}	100^{0}C (Boiling temp.)
c_{ph}	1.2 kJ/kgK
c_{pc}	4.18 kJ/kgK

For calculating heat exchange rate between two fluids, energy balance equation applied and the equation is as following:

$$Q = m_c c_{pc}\left(dT_v / dt \right) = m_h c_{p_h} (T_{hi} - T_{ho}) \quad \text{(i)}$$

From the theory of heat exchanger

$$Q = UA(\Delta T_m) \quad \text{(ii)}$$

The equation for time required for heating the water from T_{ci} to T_{co} is given as:

$$\ln\left(\frac{T_{hi} - T_{ci}}{T_{hi} - T_{co}} \right) = \left(\frac{W_h}{W_c} \right)\left(\frac{\beta - 1}{\beta} \right) \quad \text{(iii)}$$

Where,

$$W_h = m_h c_{ph}$$

$$W_c = m_c c_{pc} \quad \text{and}$$

$$\beta = \exp.\left(UA / W_h \right)$$

Now after calculating the area of heat transfer, the diameter and length of pot can be determined by using following relation

$$n = A / \pi dl \quad \text{(iv)}$$

Based on the above, suitable dimensions of the cooker (pot and shell) were obtained which are shown in figure1.

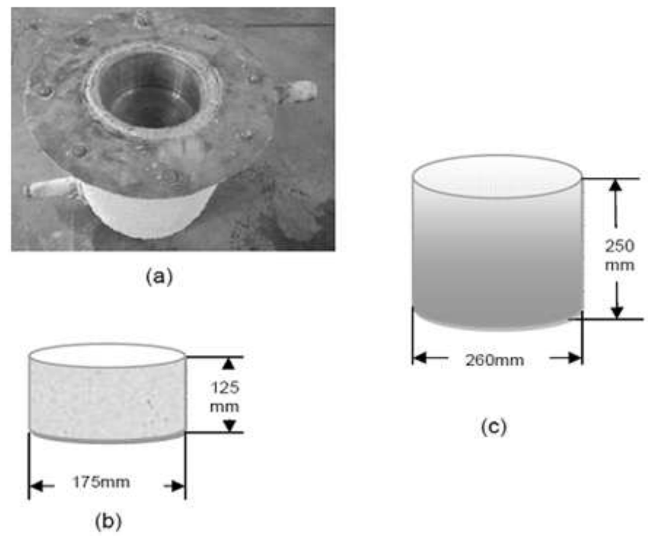

Fig 1: (a) Pictorial view of waste heat operated Cooker, (b) Dimensions of utensil , and (c) Dimensions of shell

III. Experimental Setup

To utilize the waste heat of engine exhaust for cooking purpose an experimental setup was developed. The experimental setup consisted of a diesel engine coupled with electric dynamometer and waste heat operated cooker. To measure the air flow rate, air was introduced in the engine through an air box. Fuel supply system consisted of fuel tank and burette to measure the volumetric fuel flow rate. K-type thermocouples were placed at various places on engine and waste heat operated cooker to measure the temperatures. These thermocouples were attached to a six-channel selector switch and digital panel meter. The range for these thermocouples was -200^{0}C to +1200^{0}C. The experimental setup is shown in figure 2.

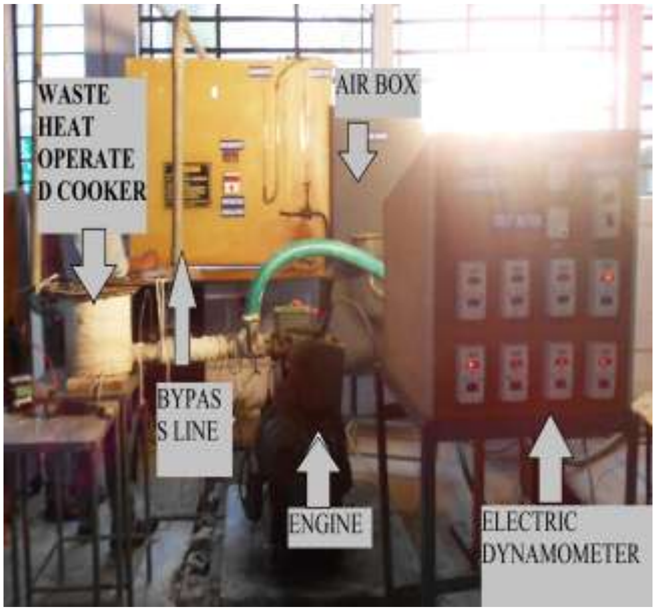

Fig 2: Photographic view of experimental set-up

IV. METHODOLOGY

Experiments were carried out in two stages. In the first stage, the inlet valve to the waste heat operated cooker was closed and bypass valve was opened. Since the inlet valve to the cooker was closed, the waste heat operated cooker was not integrated with the engine. At this stage, the various parameters of the engine (BTE and BSFC) were evaluated. In the second stage, initially the inlet valve to the cooker was closed to obtain the steady state, and on the accomplishment of the same, the bypass valve was closed and inlet valve to the cooker was opened. At this condition, the exhaust was allowed to pass through the waste heat operated cooker and the various parameters (BTE, BSFC and various temperatures) were evaluated.

To estimate the performance of waste heat operated cooker, the engine was operated at different loads, with 2 kg of water in the cooker at each load. Once the steady state condition of the engine was attained, the bypass valve was closed and valve inlet to cooker was opened. At the steady state stage, a record of different 54data is prepared by taking the reading of engine generator power output, fuel consumption and exhaust emission, and different temeratures like temperature of engine exhaust, inlet to waste heat operated cooker, outlet of cooker and water temperature, at every 2 minutes’ interval, until the temperature of water in the cooker reaches 100^{0}C. The engine was stopped as the water started boiling and sufficient time was given to the set-up to cool down or to restore to the primary condition, and the process is repeated at different loads.

V. ENERGY AND EXERGY ANALYSIS

This section elaborates the energy & exergy analysis of CI engine waste heat operated cooker system. The principles of mass or energy conservation and the second law of thermodynamics have been applied. The exergy analysis is carried out for the steady flow steady state condition. For the exergy analysis the atmospheric pressure and temperature is taken as 1 atm & 40^{0}C (313K) respectively as the reference state.

First Law Analysis (Energy Method):

The following equations are used to determine the performance parameter of the diesel engine operated micro trigeneration system based on energy principle.

Thermal energy content in fuel input:

$$E_f = \dot{m}_f LCV \quad kW$$

Thermal energy carried by the Exhaust Gas:

$$E_{ex} = \dot{m}_{ex} C_{p_{ex}} \{T_{eng.ex.gas} - T_{ambient}\} \quad kW$$

Thermal energy recovered by cooker:

$$E_{cw} = \dot{m}_w C_{p_w} \{T_{water\ out} - T_{water\ in}\}$$

Total useful energy for combined heating and power:

$$E_{tCHP} = Electric\ output + E_{cw} \quad kW$$

Thermal energy efficiency for the diesel engine (only power):

$$\eta_p = \frac{Electric\ output}{E_f}$$

Thermal energy efficiency for combined heating & power:

$$\eta_{CHP} = \frac{E_{tCHP}}{E_f}$$

Second Law analysis (Exergy Method):

Kotas [9] examined the ratio of input exergy to input energy (e_f/E_f) for hydrocarbons and found it to be constant and that the proportionality constant between fuel exergy and fuel energy is 1.04.

The input exergy to the diesel engine:

$$e_f = 1.04 E_f \quad kW$$

Exergy lost in exhaust gases:

$$e_{ex} = \dot{m}_{ex}[C_{p_{ex}}\{T_{eng.ex.gas} - T_{ambient}\} - T_0\{S_{eng.ex\ gas} - S_{ambient}\}] \quad kW$$

or

$$e_{ex} = \dot{m}_{ex}[C_{p_{ex}}\{T_{eng.ex.gas} - T_{ambient}\} - T_0(C_{p_{ex}}\int\frac{dT}{T} - R\ln\frac{Pout}{Pin})] \quad kW$$

Exergy recovered in cooker (heating):

$$e_{cw} = \dot{m}_{ex} C_{p_{ex}}[\{T_{inlet\ cooker} - T_{exit\ cooker}\} - T_o \ln(\frac{T_{inlet\ cooker}}{T_{exit\ cooker}})]$$

Total useful exergy for combined heating & power:

$$e_{tCHP} = Electric\ output + e_{cw}$$

Exergy efficiency of diesel engine (only power):

$$\eta_p = \frac{Electric\ output}{e_f}$$

Exergy efficiency for combined heating & power:

$$\eta_{CHP} = \frac{e_{tCHP}}{e_f}$$

VI. Results And Discussions

The various parameters defined in the above section for the energy and exergy analysis are evaluated and the values are given in table 4 & 5 at different engine load. The engine generator system performed satisfactorily on the single generation and waste heat operated cooker. The readings were found to be quite consistent on repetition of tests.

TABLE 4 EXERGY ANALYSIS

S. No.	Parameters	Load 1 kW	Load 2 kW	Load 3 kW	Load 3.6 kW
1	Exergy content in fuel input (kW)	7.136	9.813	12.935	15.166
2	Electrical output (kW)	1	2	3	3.6
3	Exergy recovered in heating (kW)	0.144	0.295	0.583	0.797
4	Total useful exergy (kW)	1.144	2.295	3.583	4.397
5	Exergy efficiency only in diesel engine %	14.01	20.38	23.192	23.737
6	Exergy efficiency of diesel engine with integrated system %	16.03	23.38	27.70	28.99

TABLE 5 ENERGY ANALYSIS

S.No	Parameters	Load 1 kW	Load 2 kW	Load 3 kW	Load 3.6 kW
1	Fuel input (kg/hr)	0.576	0.792	1.044	1.224
2	LHV (kJ/kg)	42893	42893	42893	42893
3	Thermal energy content in fuel input (kW)	6.862	9.436	12.438	14.583
4	Electrical output (kW)	1	2	3	3.6
5	Engine Exhaust Temperature (^{0}C)	244	336	463	535
6	Exhaust gas mass flow (kg/hr)	21.168	21.384	21.636	21.780
7	Energy carried away by exhaust gases in kW	1.411	2.117	3.057	3.591
8	Thermal Energy recovered by cooker in kW	0.493	0.8054	1.305	1.655
9	Total useful energy for combined power and recovered in kW	1.493	2.8054	4.305	5.255
10	Thermal energy efficiency for the diesel engine (%)	14.573	21.195	24.119	24.686
11	Overall thermal energy efficiency for diesel engine integrated system (%)	21.75	29.73	34.61	36.03

A. Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) is one of the important parameters of engine performance because it gives a measure of net power developed by the engine, which is available for use at the engine output shaft, with respect to heat supplied in the form of fuel. Variation in BTE has been plotted against Load when engine was operated without and with integration of waste heat operated cooker as is shown in figure 3.

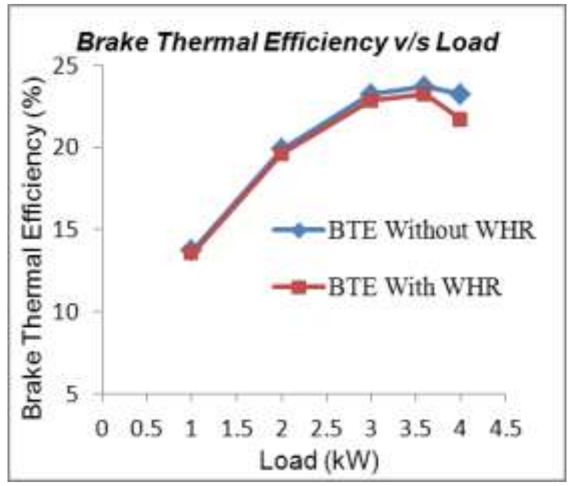

Fig 3: Variation in BTE against Load with and without integration of WHR (Waste Heat Recovery)

It has been observe from this graph that the BTE was slightly lower when engine was integrate with waste heat operated cooker or when waste heat recovery was done. The maximum value of BTE was 23.70% when engine was not integrate with waste heat operated cooker, and was 23.24% when engine was integrate with waste heat operated cooker at a load of 3.6 kW.

B. Brake Specific Fuel Consumption

Specific fuel consumption is an important parameter that shows how efficiently an engine is converting fuel into work. Variation in Brake Specific Fuel Consumption (BSFC) is plot against load when engine was operate without integration and with integration of waste heat operated cooker as is shown in figure 4.

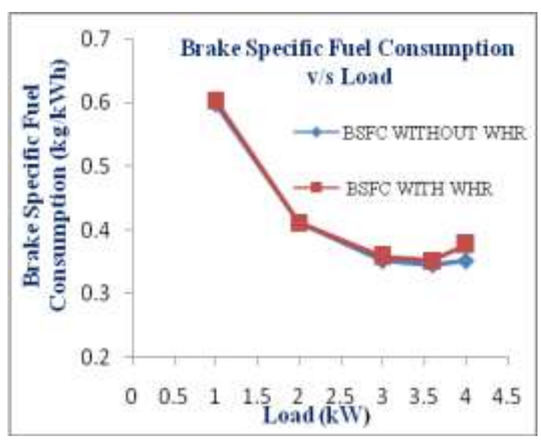

Fig 4: Variation in BSFC with Load with and without integration of WHR

It was observe from this plot that BSFC decreases with increase in load on engine and then starts increasing after a point at around 80% load on engine. The minimum value of BSFC when engine was not integrated with waste heat operated cooker was 0.3450 kg/kWh and 0.3520 kg/kWh when engine was integrated with waste heat operated cooker at 3.6 kW load. It has been observe that BSFC of WHR system gets slightly lower than BSFC of without WHR system.

C. Effectiveness of the system

Effectiveness was calculated and a plot between effectiveness and Load has shown in figure 5. It has observed from the plot that there was a continuous rise in the effectiveness of waste heat operated cooker up to a load of 3.0 kW because of higher rate of heat transfer. On further increasing the load, the effectiveness decreases due to increased radiation losses.

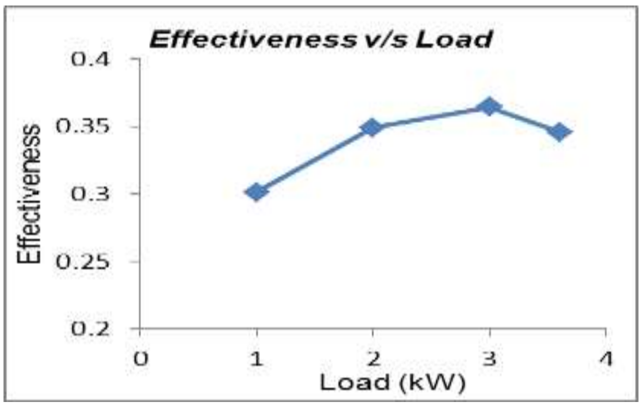

Fig. 5: Variation in effectiveness with Load

Comparison of Energy & Exergy Efficiency:

Figure 6 shows the energy and exergy efficiencies of the diesel engine. The exergy efficiency of diesel engine is slightly lower than energy efficiency because chemical availability of fuel which is considered as the input in exergy analysis is slightly higher than the calorific value of fuel which is considered as the input in energy analysis.

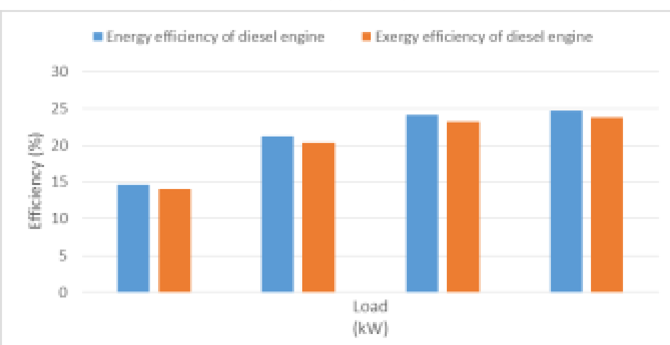

Fig 9 Variation of energy and exergy efficiency of diesel engine with load

Figure 7 shows the energy and exergy efficiency of combined system with load. It observed from the graph that the energy efficiency of combined system is higher than that of exergy efficiency. This is due to the low storage of exergy at lower temperature.

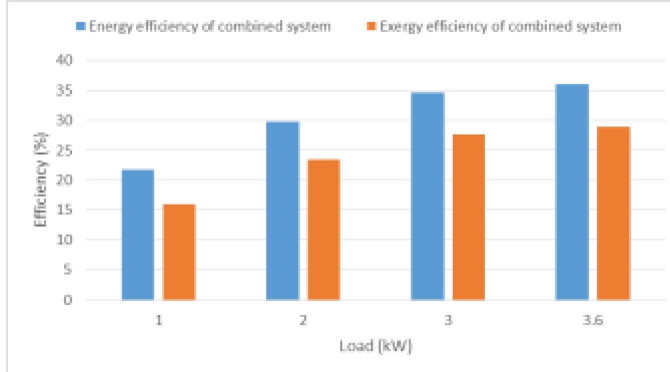

Fig. 9 Variation of energy and exergy efficiency of combined system with load

Figure 8 shows the Energy and Exergy efficiencies of diesel engine and combined system with load. The exergy efficiency in the combined systems are marginally higher than that in single generation (only power). It means the energy is more effectively utilized in combined system than in traditional only power generation system.

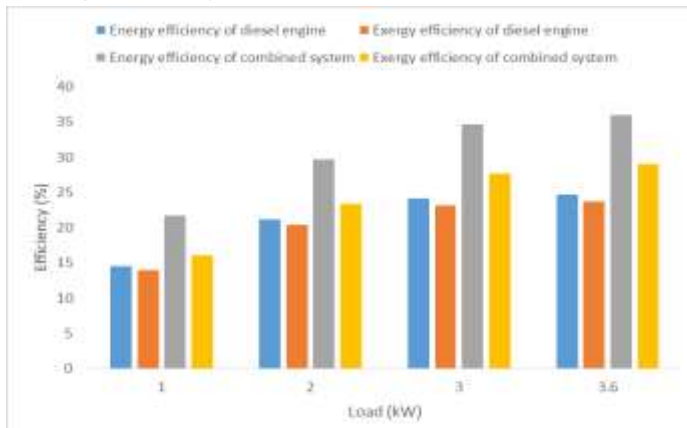

Fig. 9 Variation of energy and exergy efficiency of diesel engine and combined system with load

Figure 9 shows the energy and exergy recovered by cooker at various load. It can be seen from the figure that only 0.144 kW to 0.797 kW of exergy of fuel is available to produce useful work and total energy recovered varies from 0.493 kW to 1.655 kW.

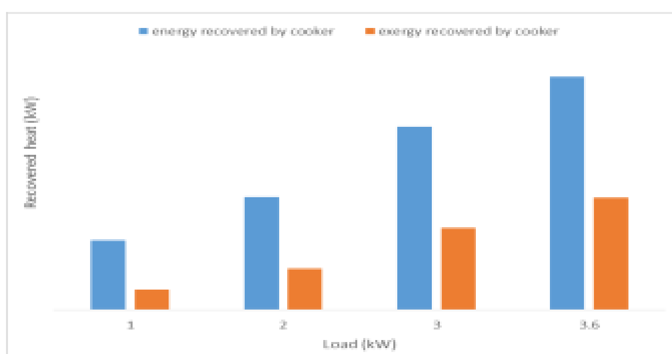

Fig. 9 Variation of energy and exergy recovered heat by cooker with load

VII. CONCLUSIONS

Large amount of energy in the form of heat comes out with diesel engine exhaust gas. Investigation of a cooker developed for utilization of waste heat from diesel engine exhaust was done. Performance and emission parameters of the above system were measured and analyzed. Following conclusions can be drawn from the study:

1. Waste heat cooker developed was feasible.
2. There is no effect on engine performance as Brake thermal efficiency and brake specific fuel consumption for the compression ignition engine were found to be nearly same for both the cases.
3. The effectiveness of waste heat operated cooker was found to be 0.37.
4. 14.87% of available energy of the waste heat was recovered using the waste heat operated cooker.
5. Exergy efficiency of the waste heat operated cooker was slightly higher than the exergy efficiency of single generation (power only) system. It means energy is more effectively utilized in the integrated system compared to that in single generation system.
6. The experimental results show that the design of the co-generation system is successful and effective to utilize the resources more efficiently.

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