PERFORMANCE OF A COOLING SYSTEM DRIVEN BY ENGINE EXHAUST HEAT

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ABSTRACT

The use of stationary generators for electricity generation is widespread in areas where access to power distribution networks is limited, including rural areas and in developing countries. Often, a significant portion of the electricity generated by these systems is used to provide refrigeration and cooling of food products, as well as medication and vaccines. However, the cost of providing electricity for refrigeration, by this means can be expensive, and means a significant amount of energy is rejected in the form of heat from the engine exhaust. Therefore, this study examines the feasibility of recovering the heat in the exhaust of a stationary engine and using this "waste" heat to drive a diffusion-absorption refrigeration. In doing so it shows that the exhaust heat can deliver useful cooling by this means, thus allowing the electricity generated to be used for other purposes and hence improving the sustainability of small scale generation systems.

Keywords: Waste Heat, Engine, Diffusion Absorption Refrigeration, Performance

1. INTRODUCTION

In spite of positive developments in the utilization of renewable energy, there has been a growing demand in the use of fossil fuels, especially oil which have resulted both in the depletion of the oil resources and environmental issues. Therefore, in order to address these issues, the design and development of energy utilization techniques where oil is used as a primary energy source needs to be improved. Co-generation and tri-generation are among the most promising methods for the utilization of this energy. In co-generation, the primary source of the energy is utilized to simultaneously generate power and heating/cooling whereas tri-generation is the simultaneous production of power, heating and cooling. A typical co/tri-generation system consists of a prime mover, generator, heat exchanger, thermally activated cooling system and control system. The prime mover used in most of these systems is the conventional reciprocating internal combustion engine which is coupled with an electrical generator. The waste heat energy of the engine, is in the form of exhaust gases and hot coolant water, can be recovered and used to generate hot water and/or drive thermally activated cooling systems.

Realising the need of energy in isolated areas, numerous studies have been conducted on small-scale co/tri-generation systems suitable for households where no central power exists (Deepesh et al 2013)**.** These systems are characterized of delivering electrical power of less than 15 kW (Lin et al, 2007). In general, many of the studies highlight the effectiveness of both the co-generation tri-generation over single generation systems (Miguez et al, 2004; Godefroy et al, 2007). However, the efficiency of such systems is affected by the performance of their cooling system (Huangfu et al, 2007).

In many studies, thermally activated cooling system such as absorption cooling is used for the cooling cycle, driven by the exhaust waste heat of the engine (Khatri et al, 2010; Goyal et al, 2015). However, an absorption cooling system depends not only on the thermal energy to drive it but also requires a work input in order to circulate the working fluid. Therefore, in order to select a cooling system which does not require any work input, another type of cooling system called a Diffusion Absorption Refrigeration (DAR) system. There have been very limited studies on co/tri-generation system using DAR as the cooling system and hence further investigation on such type of systems is required. Therefore, the objective of this to study is to investigate the performance of a DAR system in a co/tri-generation system under different engine load conditions.

2. EXPERIMENTAL METHOD

For this work, a stationary diesel engine was coupled to a small DAR system by means of an exhaust gas heat exchanger, Figure 1 shows the schematic layout of the experimental setup. The system consisted of a test bed on which the diesel engine coupled to a hydraulic brake dynamometer, exhaust heat driven DAR system, heat exchanger for hot water and the control system were placed.

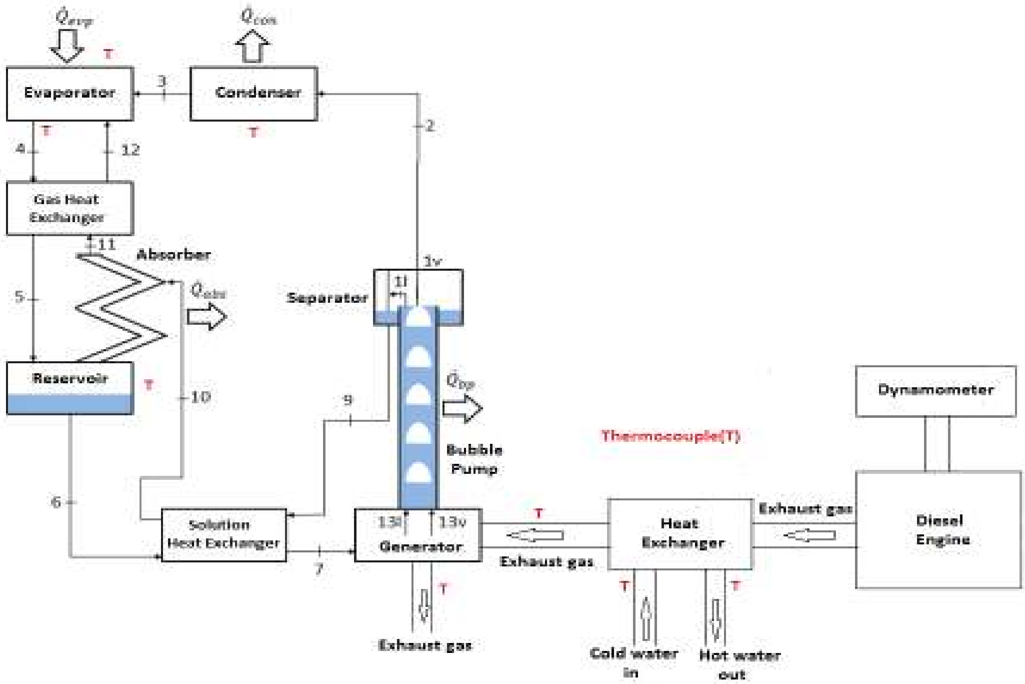

Figure 1. Schematic of the experimental system

The engine selected for this study was a 5.2 kW Robin DY41 4-stroke, overhead valve, air cooled single cylinder stationary diesel engine. Due to its size the selected engine is a possible candidate for any micro so- or tri-generation system. The engine was coupled to the water brake dynamometer that was used to vary the shaft load on the engine, thus acting in the same manner as an electrical generator. As mentioned earlier the cooling system used was a DAR system this comprises a generator and bubble pump, a condenser, an evaporator, an absorber and two heat exchangers. Unlike conventional absorption refrigeration cycles that utilise a solution pump to circulate the fluid, the DAR cycle uses a heat driven bubble pump to circulate the fluid. The working fluid used in DAR system is the binary mixture of ammonia as refrigerant, water as absorbant and hydrogen as an inert gas. The generator and the bubble pump of the DAR system were modified to utilize the waste heat of the exhaust gases.

Additionally a heat exchanger was fabricated in order to utilise the waste heat of the exhaust gases for producing hot water. The other purpose of the heat exchanger was to control the temperature of exhaust gas entering into the generator of the DAR cycle. The heat exchanger built was a tube-in-tube counter flow type and made of stainless steel with baffles to direct the flow. An insulated piping system was used to connect the heat exchanger between the engine and the DAR system.

The experimental plan was executed by running the system in combined cooling and power (CCP) and combined cooling, heating and power (CCHP) modes. In CCP mode the exhaust gas to water heat exchanger was shut off and all the exhaust engine gas was directed towards the DAR without any pre-cooling. As such the exhaust gas enters the generator of the DAR system where it transfers its energy to the working fluid of the cooling cycle by increasing its temperature. The exhaust gas then exits the cooling system and is released into the environment. In the case of the CCHP mode the exhaust gas to water cycle is turned on, thus generating hot water. As such, the hot exhaust gases first enters the heat exchanger where it releases part of its energy to the cold water, resulting in the production of hot water. The amount of heat transferred from the exhaust gas was determined by measuring the volume flow rate of the water and its change in temperature measured by T-type thermocouples at the inlet and outlet of the heat exchanger. After exiting the heat exchanger, the exhaust gas enters the generator and activates the DAR system. In order to assess the performance of the cooling system, the temperature at different points of the DAR system were measured by T type thermocouples mounted at the evaporator inlet and outlet on the condenser, the absorber and the ambient conditions. J-type thermocouples were used to measure the temperature of the exhaust gas entering and leaving the DAR system to allow the rate of heat transferred to the DAR system to be determined in addition to it's coefficient of performance. In undertaking testing in CCP mode, the load on the engine were varied by 0, 25, 50, 75 and 100 percent and in the case of CCHP mode, measurements were taken at 100 percent engine load. Finally, the torque produced by the engine was recorded in order to estimate the brake power produced by the engine.

3. ENERGY ANALYSIS

Now, the refrigerating effect ($\dot{Q}_{evp}$) produced by the DAR system can be calculated using Equation 1:

$$\dot{Q}_{evp} = hA_{evp}\left[\left(\frac{t_{evpi} + t_{evpo}}{2}\right) - t_{amb}\right] \quad (1)$$

Now because an active load could not be provided to the condenser, the condenser was acting to cool the surrounding air hence h is a natural convection heat transfer coefficient (W·m^{-2}·°C^{-1}), A_{evp} is the surface area of the evaporator (m^2), t_{evpi} and t_{evpo} are the inlet and exit temperature at the evaporator (°C), t_{amb} is the ambient temperature (°C). The parameters A_{evp}, t_{evpi}, t_{evpo} and t_{amb} have been calculated and recorded during the time when the experiment was running whereas h was determined using Equation 2:

$$Nu = \frac{hD}{k} \quad (2)$$

where Nu is the Nusselt number, D is the characteristic length (diameter) of the evaporator tube (m) and k is the thermal conductivity of the ambient air (W·m^{-1}·°C^{-1}). Now, to ease of the calculation for the heat transfer coefficient, the serpentine type evaporator tube was considered to be a horizontal tube having the length equal to the serpentine length. In regards to this, the Nusselt number for natural convection can be estimated using Equation 3 as given by (Churchill and Chu, 1975):

$$Nu = \left\{0.6 + \frac{0.387Ra^{1/6}}{[1 + (0.469/Pr)^{9/16}]^{8/27}}\right\}^2 \quad (3)$$

where Ra is the Rayleigh number and Pr is the Prandtl number of the ambient air. Now, the Rayleigh number can be determined using Equation 4:

$$Ra = \frac{g\beta\left(\left(\frac{t_{evpi} + t_{evpo}}{2}\right) - t_{amb}\right)D^3}{v^2}Pr \quad (4)$$

where g is the gravitational acceleration (m·s^{-2}), β is the coefficient of volume expansion (K^{-1}), D is the diameter of the evaporator tube (m) and v is the kinematic viscosity of the air (m^2·s^{-1}). The property database of Engineering Equation Solver (EES) was used to evaluate the parameters k, Pr and v at t_f, which is the film temperature (°C), and is given by Equation 5:

$$t_f = \frac{\left(\frac{t_{evpi} + t_{evpo}}{2}\right) + t_{amb}}{2} \quad (5)$$

The coefficient of volume expansion β for air can be evaluated using Equation 6:

$$\beta = \frac{1}{t_f} \tag{6}$$

Now, the heat transfer rate from the exhaust gas to the DAR system can be evaluated using Equation 7

$$\dot{Q}_{gen} = \dot{m}_{ex}(t_{exi} - t_{exo}) \tag{7}$$

where $\dot{Q}_{gen}$ is the heat input to the DAR system (W), t_{exi} and t_{exo} are the temperatures of the exhaust gas entering and leaving the DAR system (°C) and $\dot{m}_{exh}$ is the mass flow rate of the exhaust gas (kg·s^{-1}). Now, $\dot{m}_{ex}$ is evaluated by applying mass balance across the engine which is given by Equation 8:

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_a \tag{8}$$

where $\dot{m}_f$ and $\dot{m}_a$are the mass flow rate of fuel and air (kg·s^{-1}). The mass flow rate of fuel $\dot{m}_f$ can be calculated using Equation 9:

$$\dot{m}_f = sfcQ_{brake} \tag{9}$$

where Q_{brake} is the engine shaft output power (W) and sfc is the specific fuel consumption (g·kW^{-1}·h^{-1}) which can be evaluated from the engine performance curve.

The mass flow rate of the induced air can be calculated using Equation 10:

$$\dot{m}_a = \rho_a V_a \tag{10}$$

where $\rho_a$is the density of air (kg·m^{-3}) and $V_a$is the volume of the air induced (m^3·s^{-1}) which can be estimated by Equation 11:

$$V_a = V_d \frac{N}{2} \tag{11}$$

where N is the speed of the engine(rev·min^{-1}) and V_d is the displaced volume in the cylinder (m^3) which can be evaluated by Equation 12:

$$V_d = \frac{\pi}{4} B^2 L \tag{12}$$

where B is the bore of the cylinder (m) and L is the length of the cylinder (m). The values of B and L were taken from the available engine data.

Now, the heat transfer rate from the exhaust gas to the cold water in the heat exchanger can be evaluated using Equation 13:

$$\dot{Q}_w = \dot{m}_w c_p (t_{HXo} - t_{HXi}) \tag{13}$$

where $\dot{Q}_w$is the heat input to the water (W), $\dot{m}_w$ is the mass flow rate of water (kg·s^{-1}), c_p is the specific heat of water (J·kg^{-1}·°C^{-1}), t_{HXi} and t_{HXo} is the temperature of water at entering and leaving the heat exchanger (°C).

4. RESULTS AND DISCUSSIONS

In CCP mode when the engine was run at steady state under 0% and 25% load conditions, it was observed that no refrigerating effect was produced by the DAR system. This is due to the fact that for both the load conditions the temperature of the exhaust gas was not high enough to activate the DAR system. At an engine load of 50%, it was observed that as the temperature of the exhaust gas entering the DAR system exceeds 190˚C, the temperature at the evaporator starts dropping as shown in Figure 2. A steady state cooling period was recorded when the temperature of the exhaust gas was maintained between 200-220°C during which time the minimum evaporator temperature recorded was approximately -1°C.

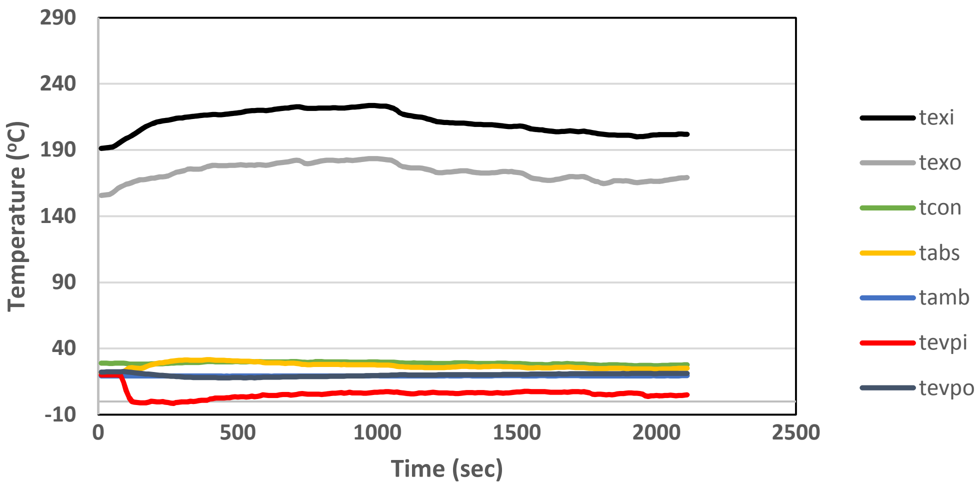

Figure 2. Temperature profile at 50% CCP mode

Now, by increasing the load on the engine to 75%, a steady state period of cooling was again achieved. In doing so the evaporator temperature achieved was lower than the temperatures achieved at 50% load. At this load condition the temperature of the exhaust gas entering the DAR system was between 200-240°C as shown in Figure 3 while the minimum evaporator temperature recorded was approximately 0°C.

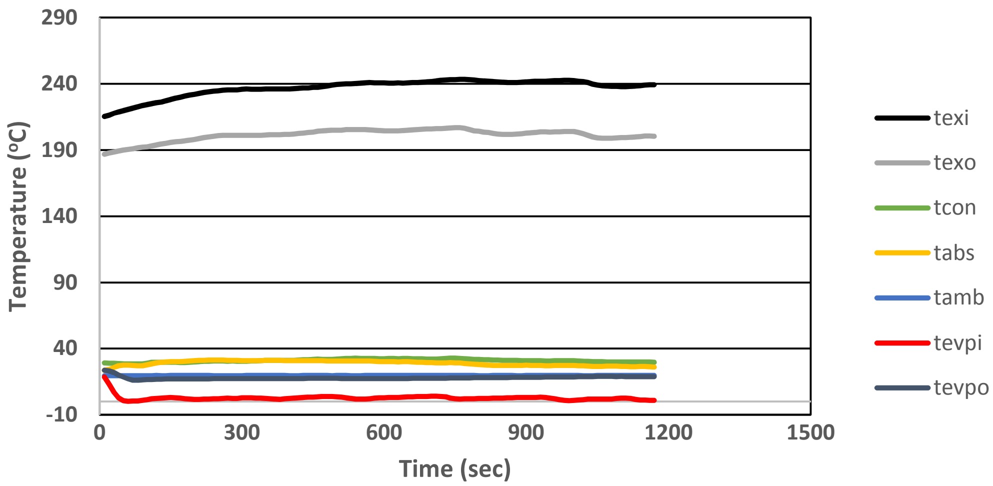

Figure 3. Temperature profile at 75% CCP mode

The performance of the DAR system was also evaluated at high exhaust temperature conditions by running the engine at 100% load conditions as shown in Figure 4. It was observed that between the temperature range of 250-260°C a sudden drop in evaporator temperature occurred. However, no drop in evaporator temperature was observed when the inlet exhaust gas temperature exceeded 290°C which is due to the fact that at high temperature a large quantity of working fluid in the DAR generator is converted into vapour. This in turn reduces the pumping performance of the bubble pump, whereas in order to pump the fluid effectively in the DAR system, a proper balance of working fluid should be present inside the generator in the form of two phase flow i.e. liquid and vapour as shown by Yousuf et al (2014). As such, no steady state cooling period was achieved at this load condition.

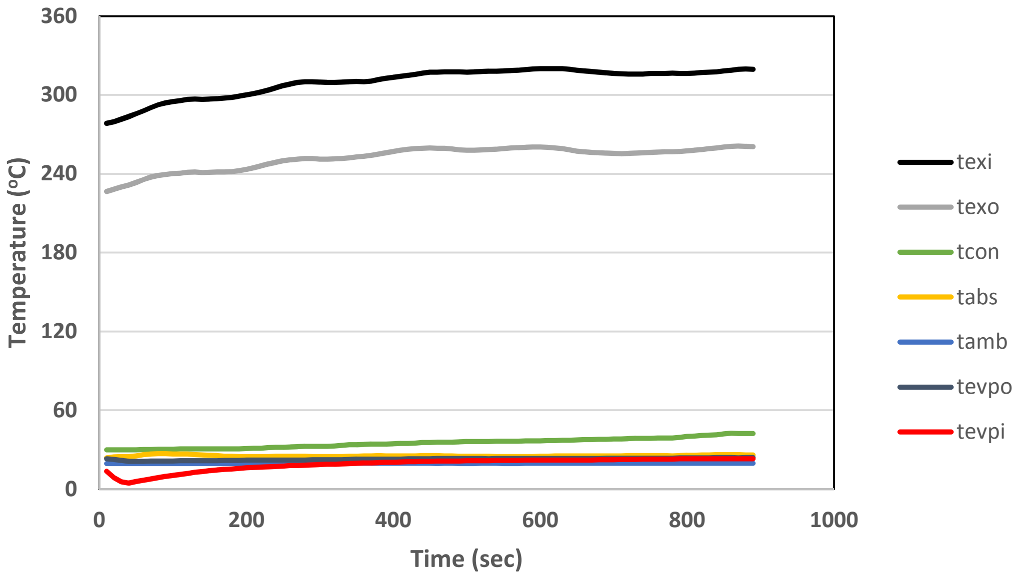

Figure 4. Temperature profile at 100% CCP mode

Since no steady state cooling period was recorded at the high inlet exhaust temperatures achieved at full load it was decided to run the system in CCHP mode by passing the exhaust gas through the exhaust gas heat exchanger where it releases its energy to cold water resulting in an increase in the temperature of the water and a decrease in the temperature of the exhaust gases. As shown in Figure 5, a steady state cooling was observed when the temperature of the exhaust gas leaving the heat exchanger is between 200-205°C. The minimum temperature recorded at this load condition was approximately -5°C.

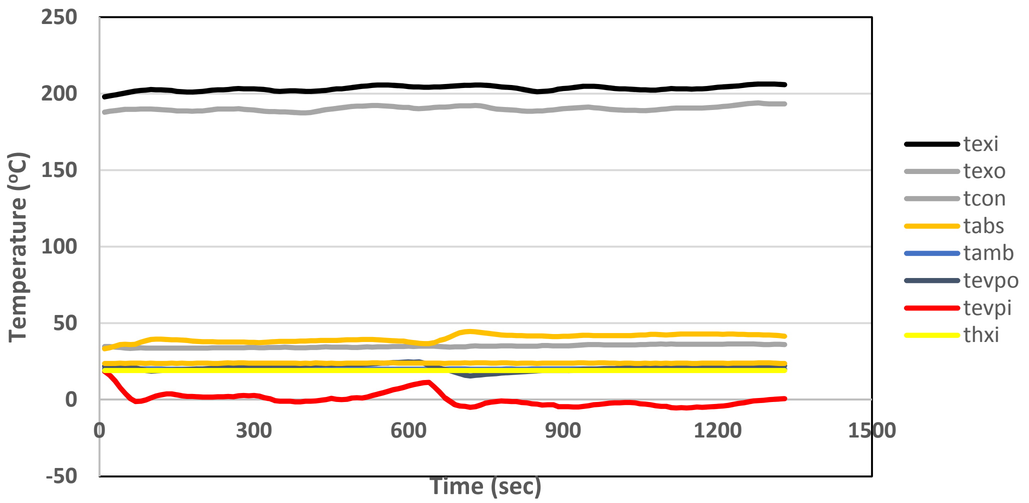

Figure 5. Temperature profile at 100% CCHP mode

In analysing these results further, the amount of heat input into the DAR system is shown in Figure 6. From this it can be seen that an increased amount of heat was required for the system running in CCP mode at 100% load condition, whereas the amount of heat input in CCHP mode for activating the DAR system is less than in the other modes. This is interesting to note, since in CCHP mode a portion of heat of exhaust gases is recovered for hot water cycle before entering the DAR system.

Now, the amount of the cooling effect produced for the steady state conditions is shown in Figure 7, in doing so it should be noted that the low capacity is due to the load being provided as natural convection of air over the evaporator. The minimum amount of cooling was produced when the system was running at CCP mode of 100% load conditions which supports Yousuf et al (2014) modelling that found that at high input (generator) temperatures the performance of the DAR system reduces. More interestingly, in CCHP mode the amount of cooling produced by the DAR system was greater than other modes. This is due to the fact that the temperature of the exhaust gas entering the DAR system was controlled by recovering a portion of its heat for hot water cooling and thus providing a strong case for the use of tri-generation.

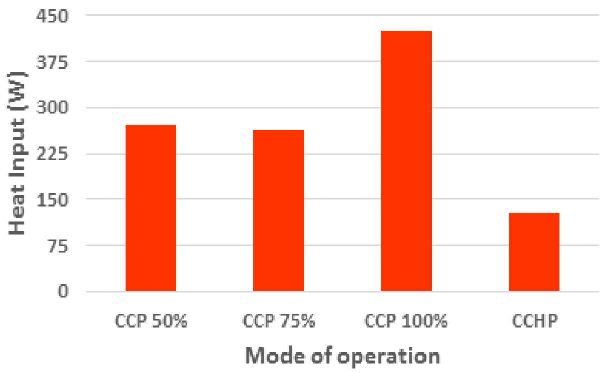

Figure 6. Heat input to the DAR system

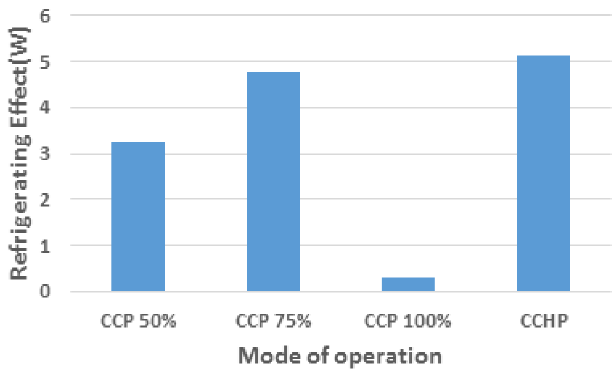

Figure 7. Refrigerating effect for different mode conditions

Exploring this further, the performance of the DAR system is shown in Figure 8, from this it can be seen that the maximum coefficient of performance was approximately 4% for the system operating in the CCHP mode condition. For CCP modes the performance at 50% engine load was better than other load conditions due to the fact that by increasing the load on the engine the temperature of the exhaust gas increased which in turn impairs the activation of the DAR system. It should be noted that the activation of the DAR system depends upon the exhaust temperature not on engine load which is greatly influenced by the type of engine.

Looking at the overall system, the useful output energy which consists of the brake power, cooling and heating for both CCP and CCHP mode is shown in Figure 9. In the case of CCP modes there is not much difference if the system is operated at 75% and 100% load condition, as the power produced by the engine is similar and the cooling capacity is very small. However, in the case of the CCHP mode since there is an additional output in form of hot water is obtained, the output energy is much more than in CCP modes. This demonstrates that even for small systems, tri-generation results in a larger utilisation of the input energy and so offers significant potential for areas in which energy supply and security are constrained.

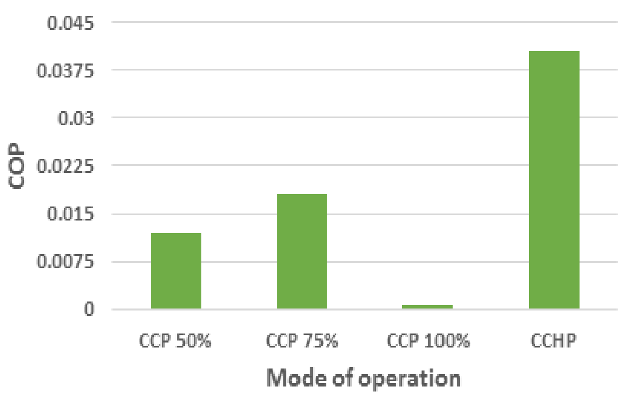

Figure 8. Performance of the DAR system

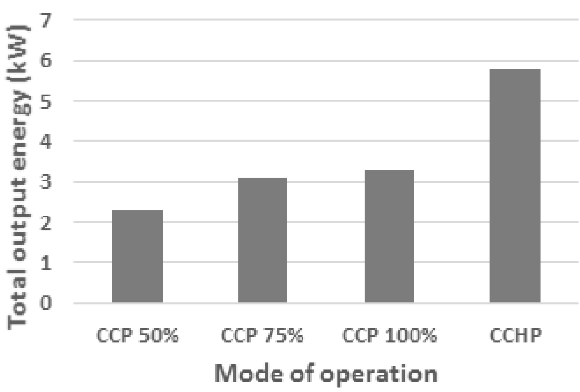

Figure 9. Useful output energy obtained

5. CONCLUSIONS

In this study, the feasibility of the exhaust waste heat of an internal combustion engine for running a cooling system was evaluated. The cooling system used was a Diffusion Absorption Refrigeration system and its performance was evaluated for different operation modes and engine load conditions. It was observed that the DAR system generates steady state cooling when the inlet exhaust temperature is in the range of 200-210°C. The lowest evaporator temperature was achieved when the system was running on CCHP mode. In the case of CCP modes, the DAR system was able to produce a cooling effect, with continuous cooling periods observed when the system was operated at engine load conditions of 50% and 75%. The use of the exhaust gas heat exchanger in CCHP mode enabled better control of the temperature of the exhaust which delivered better cooling and overall utilization than the CCP modes. The experimental results show that the exhaust heat of small stationary engines can be utilized to run a small scale tri-generation system and thus offer significant scope for electricity generation, provision of hot water and refrigeration in areas where access to power distribution networks is limited, including rural areas and in developing countries.

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