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Trigeneration running with raw jatropha oil

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ABSTRACT

The performance and the efficiency of a trigeneration system fueling with pure diesel and with raw jatropha oil are investigated using the ECLIPSE software. The study is based on a diesel engine generating set. The genset is used for electrical power generation only, acting as a single generation. The trigeneration system consists of the genset, a waste heat recovery system and an absorption refrigerator. The genset is used to generate electricity; the waste heat system is used to collect the waste heat from the cooling system and the exhaust from the engine, to supply heating/hot water; and the absorption refrigerator is used to supply cooling/refrigeration, which is driven by the waste heat from the engine instead of electricity. A comparison of the thermal efficiencies and the CO_2 emissions of trigeneration with single generation and cogeneration (combined heat and power — CHP) is carried out. The results from the study show that the thermal efficiency of trigeneration is higher than that of single generation; the CO_2 emissions of trigeneration are lower than that of single generation. The results also show the performance differences between the trigeneration and single generation; and the differences between trigeneration and cogeneration.

1. Introduction

Global warming and climate change have increased concerns on the ways we consume/use fossil energy in the world. As a result, applications of renewable energies have become more important. Renewable biofuels are one of these application areas. As a matter of fact, the idea of using vegetable oil as the fuel for diesel engine is not new. The original diesel engine that Rudolph Diesel designed ran with vegetable oil. He used peanut oil to fuel one of his engines at the Paris Exposition in 1900 [1]. But soon afterwards, the application of vegetable oils as fuel was dropped due to the cheap supply of petroleum based fossil fuels available in the world during the last century.

Since the petroleum crises in the 1970s, the rapidly increasing prices and uncertainties concerning petroleum availability, and a growing concern on the environment and the effect of greenhouse gases during the last decades, have revived more and more interest in the use of bio-oils from plants as a substitute of fossil fuel. Bio-oils have their own advantages: firstly, they are available everywhere in the world. Secondly, they are renewable as the plants which produce oil seeds can be planted year after year. Thirdly, they are "greener" to the environment, as they are considered as 'carbon neutral' due to the very short carbon cycle and they seldom contain sulphur element in them. This makes bio-fuel studies become popular topics.

Previous studies on different kinds of biofuels such as raw vegetable oil, waste cooking oil, and biodiesel, have shown that they are potential fuels for diesel engines [1–8]. But these fuels are derived from eatable oils, which mean that the fuels may have a problem of competition with food supply to human beings.

Jartropha is a kind of plant native to Central America [9] and has become naturalized in many tropical and subtropical areas, including India, Southeast Asia, South of China, Africa and North America. Jatropha contains compounds that are highly toxic, so the oil is not eatable. Jatropha is resistant to drought and pests and can be planted in the deserted areas, and produces seeds containing up to 40% oil. When the seeds are crushed and processed, the resulting oil has similar properties as vegetable oils, e.g. heating value and viscosity. This makes it possible to be used as a fuel in diesel engines.

Trigeneration is an energy system based on the engine genset or thermal power plant, using waste heat to supply heating and to drive absorption or adsorption cooling/refrigeration machine to supply cooling/refrigeration. Previous studies have shown that the system is able to generate three useful energy forms with only one energy/fuel input [10–17]. If a trigeneration system, based on a diesel genset, is fuelled with raw jatropha oil, that would make it a 'net zero carbon emission system' or nearly a 'net zero carbon emission system'.

The objective of the study is to investigate the effect and the performance of the application of raw jatropha oil to a diesel genset based trigeneration system, comparing with the system that is fuelled with diesel, using a computational simulation model in the ECLIPSE software.

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2. The trigeneration system and the simulation software

2.1. The proposed trigeneration system

The trigeneration system contains three main units: the diesel engine genset (Volvo, 240 kW electrical power output), which is the basic primary mover of the system; a heat recovery and storage system; and an absorption refrigeration/cooling system, as seen in Fig. 1. The system is operated in the way of following: the engine genset is run with diesel/raw jatropha oil; a heating system, with the heat recovered from the engine cooling system and the exhaust gases, is used to recover and store the waste heat and supply hot water/central heating for the building; an ammonia absorption system, which is run by a part of the waste heat from the engine exhaust, is used to supply the cooling for the building when necessary.

2.2. The properties of the fuels

The fuels tested are diesel and raw jatropha oil. The properties of the fuels are listed in the following table (Table 1) [18]. They are from the analysis report of oil samples at Lloyds Register FOBAS, which are from the fuels used in our engine experiments. Diesel fuel has the chemical component of $C_{12}H_{26}$ and jatropha oil can be approximated as a single component $C_{18}H_{34}O_2$ [19].

2.3. The software — a brief introduction of ECLIPSE

A computational simulation software called ECLIPSE is used to simulate the working process of the proposed trigeneration system to provide a consistent basis for evaluation and comparison [20,21]. ECLIPSE was developed for the European Commission and has been used by the Northern Ireland Centre for Energy Research and Technology at the University of Ulster since 1986 [22]. ECLIPSE was successfully used for many European and international projects to implement techno-economic analysis of power systems.

ECLIPSE is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes. ECLIPSE uses generic chemical engineering equations and formulae and includes a high-accuracy steam–water thermodynamics package for steam cycle analysis. It has its own chemical industry capital costing program covering over 100 equipment types. The chemical compound properties database and the plant cost database can both be modified to allow new or conceptual processes to be evaluated. A techno-economic assessment study is carried out in stages; initially a process flow diagram is prepared, technical design data can then be added and a mass and energy balance completed. Consequently, the system's environmental impact is assessed, capital and operating costs are estimated and an economic analysis performed. The proposed trigeneration system is simulated using the function of the energy and mass balance of ECLIPSE.

Table 1
Jatropha oil and diesel properties [18].

	Diesel	Jatropha oil
Viscosity at 40 °C (cSt)	3.238	34.67
Density at 15 °C (kg/m^3)	871.7	917.7
Flash point (°C)	86	240
Cetane number	>40	51–58.4
C %(m/m)	85.40	77.01
H %(m/m)	11.68	12.01
O %(m/m)	0.25	10.98
N %(m/m)	0.15	0.00
S %(m/m)	0.025	<0.0044
Chemical component	$C_{12}H_{26}$	$C_{18}H_{34}O_2$
Gross heating value (MJ/kg)	42.893	38.960

The combustion processes of diesel and jatropha oil in the engine cylinder in the form of global single step reaction are shown as the following equations [19]:

$$C_{12}H_{26} + 18.5(O_2 + 3.76N_2) \rightarrow 12CO_2 + 13H_2O + 69.56N_2 \quad (1)$$

$$C_{18}H_{34}O_2 + 25.5(O_2 + 3.76N_2) \rightarrow 18CO_2 + 17H_2O + 95.88N_2 \quad (2)$$

3. Simulation results and discussion

3.1. The design conditions of the system

The simulations are based on the experimental results of a diesel engine genset (Volvo TAD1240GE, 240 kW electrical power output) in

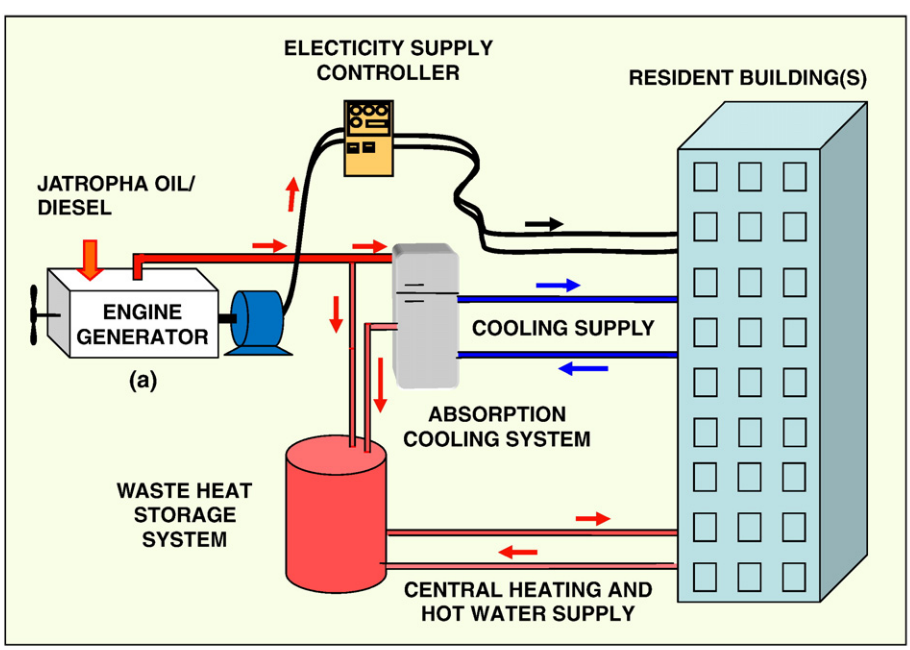

Fig. 1. The schematic diagram of the proposed trigeneration system.

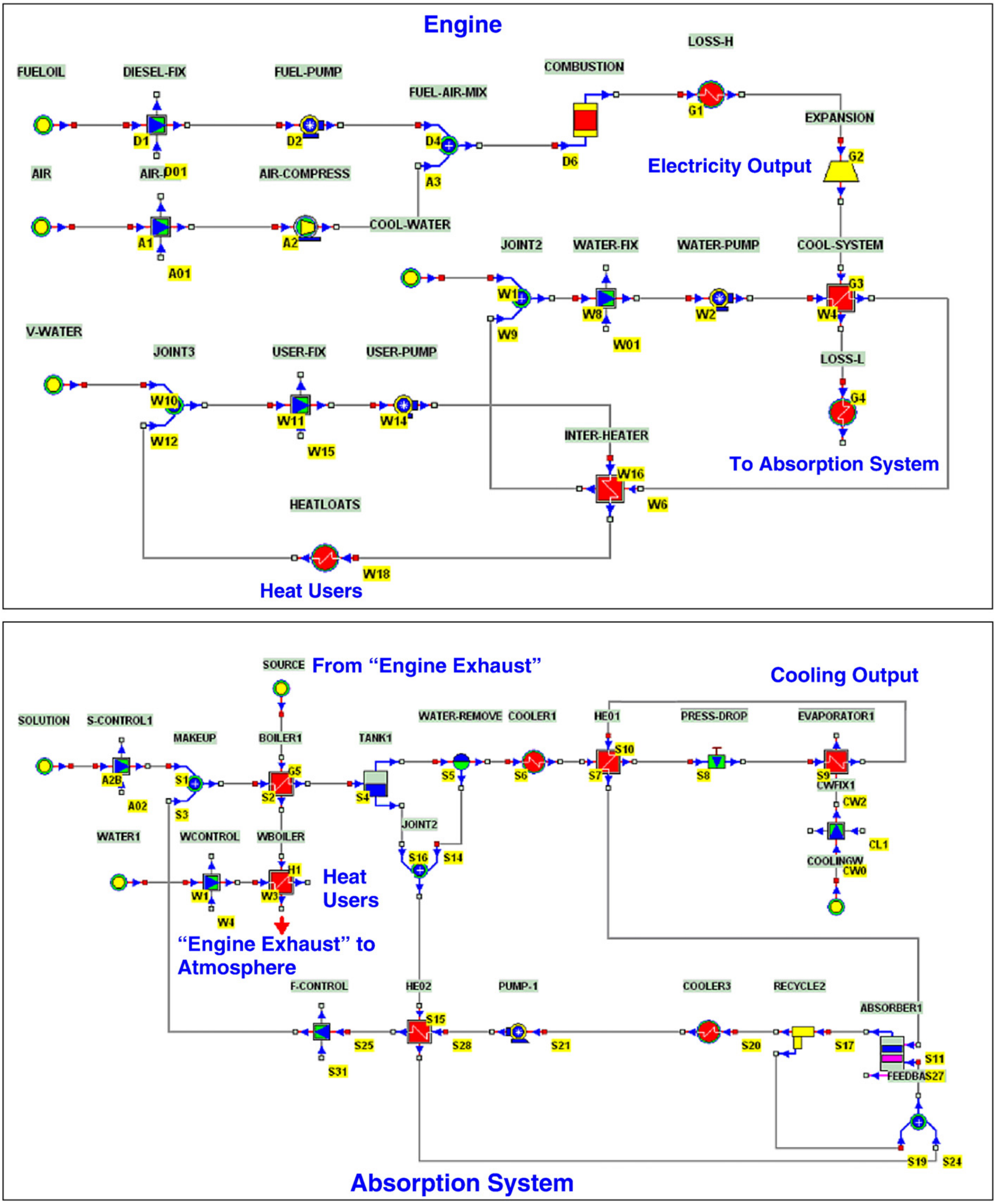

Fig. 2. The flow diagram of the trigeneration system in ECLIPSE.

a laboratory, run by diesel and raw vegetable oil. The engine test cycles are selected according to the British Standard (EN ISO 8178 4, Reciprocating internal combustion engines, Test cycles for different engine applications), i.e., 10%, 25%, 50%, 75% and 100% of the engine load. The specifications of the Volvo engine give an exhaust gas temperature of 494 °C, and energy rejected to the environment from

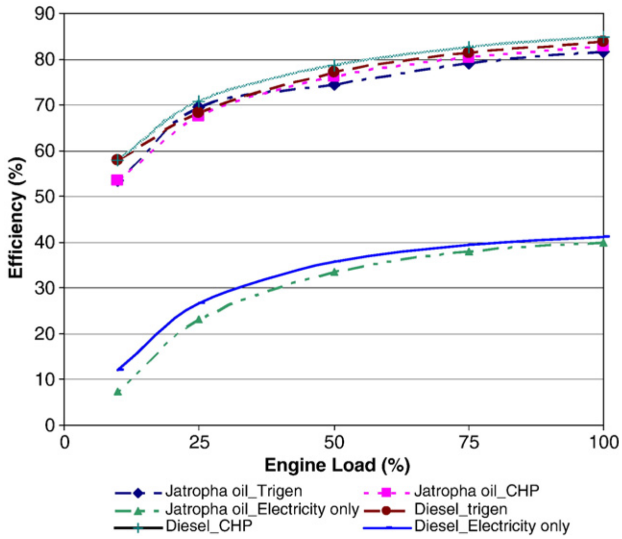

Fig. 3. Comparison of efficiencies using diesel/jatropha oil.

the engine's cooling system 130 kW (at full load). It was also known from an experimental test of the engine that the diesel fuel consumption (fuel flow rate) of the genset at full engine load (240 kW electricity output) was 0.0136 kg/s. The cooling capacity of the Absorption–Refrigeration system was known as well and it's been designed to be 13 kW with the refrigeration temperature — 5 °C. The flow diagram of the proposed trigeneration system in ECLIPSE is shown in Fig. 2.

3.2. Results and discussion

The simulation results are shown in the following tables and figures. Fig. 3 and Table 2 show the results of the efficiencies of single electricity generation (SG), CHP and Trigeneration (TG) run with diesel and jatropha oil. It can be seen that with the same fuel inputs (by mass), the efficiencies of the three systems run by jatropha oil are all lower than those run by diesel. This is because of the lower calorific value of jatropha oil. The efficiencies of the CHP and TG are all higher than that of SG, regardless of the kind of fuels being used. The increases are greater than doubled, as can be seen in the table and the figure.

Fig. 4 and Table 3 show the comparisons of the specific fuel consumption (SFC) of the systems of SG, CHP and TG run with diesel and jatropha oil. The SFCs of SG are all higher than those of CHP and TG, and this trend is related to the lower thermal efficiencies of SG. The SFCs of the systems fuelled with jatropha oil were all higher than those fuelled by diesel fuels for the three systems studied, respectively. The reason is also the lower calorific value of jatropha oil.

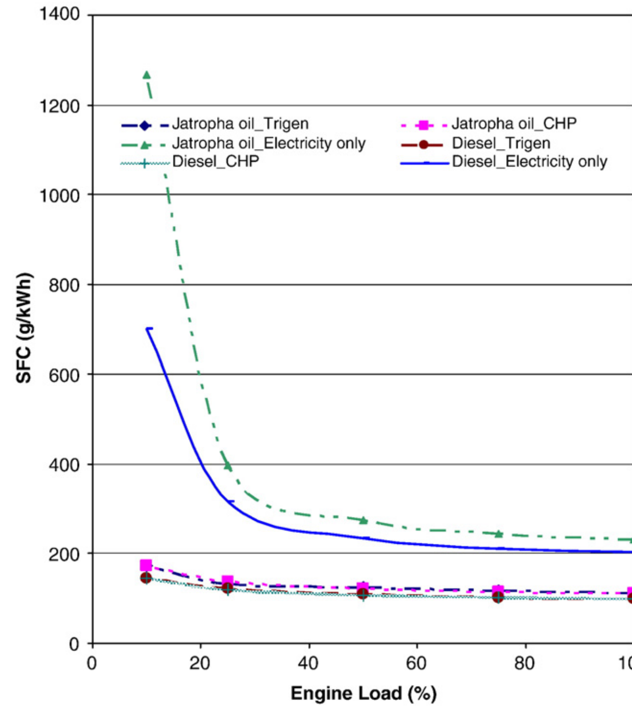

Fig. 4. Comparisons of SFC for different generations using jatropha oil and diesel.

Fig. 5 and Table 4 show the comparisons of the CO_2 emissions of the systems of SG, CHP and TG run with diesel and jatropha oil. From the figure and the table, it can be seen that the CO_2 emissions (in kg/kWh useful energy output) from SG are more than doubled compared to those from CHP and TG. For example, the CO_2 emissions at the full load (100% load) are 107.3% higher than those of CHP system; 104.5% higher than those of TG. For the comparisons of the same systems, respectively, the CO_2 emissions fuelled with jatropha oil are higher than those fuelled with diesel, due to the higher fuel consumptions. Considering that jatropha oil is from renewable resources, the CO_2 emissions from burning it can be treated as 'net zero carbon emission'; the systems using jatropha oil will be more environmentally friendly.

Fig. 6 and Table 5 show the comparisons of the heat recovered from the systems of CHP and TG run with diesel and jatropha oil. From the figure and table, it can be seen that the waste heat recovered from the CHP/TG when fuelled with jatropha oil is lower than that fuelled with diesel, which is around 10% less. For the TG system compared with CHP system, the waste heat collected from TG is less than that

Table 2
Comparison of efficiencies using diesel/jatropha oil.

Engine load (%)	10	25	50	75	100
Jatropha oil					
The efficiency differences between CHP and SG (%)	633.8	190.0	126.8	112.6	107.3
The efficiency differences between TG and SG (%)	633.8	198.9	122.0	109.2	104.5
Diesel					
The efficiency differences between CHP and SG (%)	382.6	165.8	120.0	109.1	105.5
The efficiency differences between TG and SG (%)	382.6	156.3	115.8	106.1	103.0

Table 3
Comparison of specific fuel consumptions (SFC) using diesel/jatropha oil.

Engine load (%)	10	25	50	75	100
Jatropha oil					
The SFC differences of CHP compared to that of SG (%)	633.8	190.0	126.8	112.6	107.3
The SFC differences of TG compared to that of SG (%)	633.8	198.9	122.0	109.2	104.5
Diesel					
The SFC differences of CHP compared to that of SG (%)	382.6	165.8	120.0	109.1	105.5
The SFC differences of TG compared to that of SG (%)	382.6	156.3	115.8	106.1	103.0

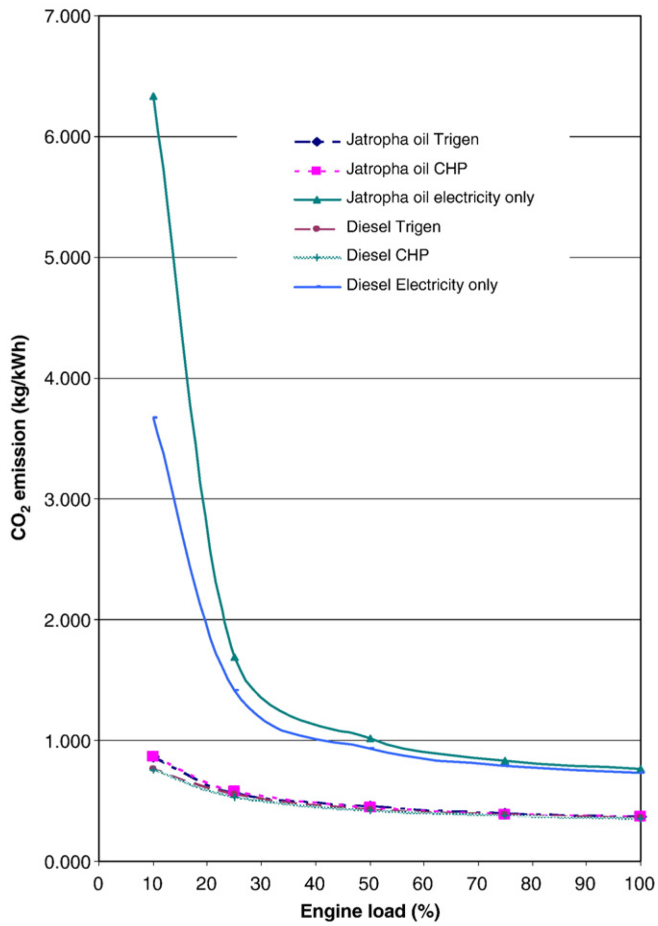

Fig. 5. Comparisons of CO_2 emissions for different generations using jatropha oil and diesel.

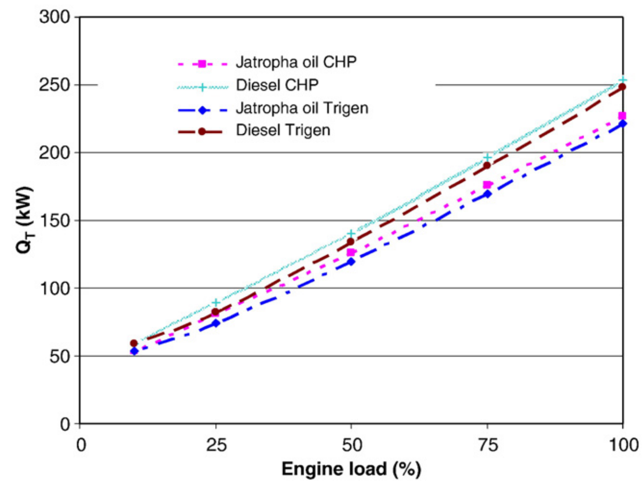

Fig. 6. Comparison of total heat recovery from CHP/trigeneration fuelled with diesel and jatropha oil.

from CHP, when fuelled with both diesel and jatropha oil. The reason for this trend is due to some part of the waste heat from the engine in the TG system being used for driving the absorption refrigeration unit, which results in less heat being recovered.

4. Conclusions

From the results and discussions, it can be concluded that:

- It is feasible to use jatropha oil as the fuel to run a diesel engine genset based TG and CHP.
- The efficiencies of the SG, TG and CHP run by jatropha oil are a little lower but comparable to those run by diesel, respectively.
- The efficiencies of TG and CHP are all higher than those of SG.
- The SFCs of TG and CHP are all lower than those of SG.
- The SFCs of the three systems fuelled with jatropha oil were all higher than those fuelled by diesel fuels for the three systems studied, respectively, due to the lower heating value of the jatropha oil.
- The CO_2 emissions (in kg/kWh useful energy output) from TG and CHP are less than half of those from SG.
- The CO_2 emissions fuelled with jatropha oil are a little higher than those fuelled with diesel, due to the higher fuel consumptions. As jatropha oil is a kind of renewable fuel, the CO_2 emissions from burning it can be treated as 'net zero carbon emission'. Then the systems using jatropha oil will be treated as zero carbon emission.
- The waste heat recovered from TG and CHP fuelled with jatropha oil is lower than that fuelled with diesel, which is around 10% less.
- For the TG system compared with the CHP system, the waste heat collected from TG is less than that from CHP, when fuelled with both diesel and jatropha oil. This is because some part of the waste heat from the engine in trigeneration is used for driving the absorption refrigeration unit, which results in less heat being recovered.

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Table 4
Comparison of CO_2 emissions (kg/kWh useful energy output) using diesel/jatropha oil.

Engine load (%)	10	25	50	75	100
Jatropha oil					
The CO_2 savings of CHP compared to that of SG (%)	633.8	190.0	126.8	112.6	107.3
The CO_2 savings of TG compared to that of SG (%)	631.9	198.9	122.0	109.2	104.5
Diesel					
The CO_2 savings of CHP compared to that of SG (%)	382.9	166.0	119.8	109.2	105.3
The CO_2 savings of TG compared to that of SG (%)	379.7	156.3	115.7	106.0	103.0

Table 5
A comparison of total waste heat recovered from engine's cooling system and exhaust (kW).

Engine load (%)		10	25	50	75	100
Jatropha oil	CHP	54	81	126	176	227
Diesel	CHP	59	89	140	196	254
Differences between different fuels (%)		8.47	8.99	10.00	10.20	10.63
Jatropha oil	TG	54	74	120	170	221
Diesel	TG	59	82	134	190	248
Differences between different fuels (%)		8.47	9.76	10.45	10.53	10.89

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