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An investigation of a household size trigeneration running with hydrogen

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ABSTRACT

This study examined the performance and emission characteristics of a household size trigeneration based on a diesel engine generator fuelled with hydrogen comparing to that of single generation, cogeneration using ECLIPSE simulation software. In single generation simulation, the engine genset is used to produce electricity only and the heat from the engine is rejected to the atmosphere. In cogeneration and trigeneration, in addition to the electricity generated from the genset, the waste heat rejected from the hot exhaust gases and engine cooling system, is captured for domestic hot water supply using heat exchangers and hot water tank; and a part of the waste heat is used to drive absorption cooling in trigeneration. Comparisons have been made for the simulated results of these three modes of operation for hydrogen and diesel. The results prove that hydrogen is a potential energy vector in the future which is a key to meeting upcoming stringent greenhouse gases emissions. The study show that hydrogen has very good prospects to achieve a better or equal performance to conventional diesel fuel in terms of energetic performance, and a near zero carbon emission, depending on the life cycle analysis of the way the hydrogen is produced. The results also show enormous potential fuel savings and massive reductions in greenhouse gas emissions per unit of useful energy outputs with cogeneration and trigeneration compared with that of single generation.

1. Introduction

The household energy demand includes three forms of energy simultaneously, namely, electricity, heat and refrigeration. According to the statistics, the energy consumption in the domestic sector makes up more than 25% of all energy used in the UK; it can be split into 23% of electricity consumption and 77% of use for heating and hot water [1]. Refrigeration is also a kind of necessities in the households. The conventional way to provide electricity, heat and cooling in the homes is to purchase electricity from the national grid for powering household electrical appliances including refrigerators and a part of heating such as electrical heaters; and/or generate heat separately in a boiler by burning natural gas or oil. In fact, the average efficiency of the thermal power plants for electricity generation is 37% in the UK [2]. That means around 63% of the energy from the burning of fuels (coal, oil and natural gas), was wasted in the form of low-grade waste heat. At the same time, for heating, the conventional boilers in households mostly using gas as the fuel are of only 60–75% efficiency [1]. Not only is this conventional way to use energy now seen as a very wasteful way of utilising primary energy sources, but also one of the main source of environmental pollution. The use of fossil fuels, upon which most conventional generation systems are based, result in a huge amount of emission of greenhouse gases (GHG) that are believed to cause global warming and climate change. The 'peak oil' situation is premised on the belief that, because fossil fuels are finite, global oil supplies will reach a peak at some point in future after which supplies will start to decrease and never rise again. Therefore, it is necessary to optimise the use of the limited fuel resources in the domestic aspect. The utilisation of the low-grade waste heat from the power generation process for heating and/or cooling/refrigeration will be one of the solutions to save the energy usage. The technology to make use of the 'waste heat' is cogeneration and/or trigeneration. Cogeneration is a system, which generates power and heat simultaneously with one fuel input only, also

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called combined heat and power (CHP). Trigeneration, also called combined cooling, heating and power (CCHP), is the production of useful heat and refrigeration/cooling and electricity from the same energy conversion process. In trigeneration, the mechanical energy from the prime mover is changed into electricity. At the same time the absorption refrigerator generates cooling/refrigeration and heat exchangers generates hot water respectively, from the waste heat sources. These technologies can increase primary energy utilisation efficiency up to over 90%. Trigeneration can therefore lead to substantial energy saving and ultimately significant contribution to the reduction of CO_2 emissions [3].

The principles of the basic components of trigeneration; electricity generation, heat exchange and absorption cooling are not new. It is the combination of them to work in one integrated system that is a relatively new concept and that came into use in the mid 1990's [4]. As trigeneration is a recent development, the number of operating systems worldwide is still small with most plants based on gas turbine or internal combustion engine cycle with absorption type chilling for cold production [5]. Cogeneration, the simultaneous production of heat and power, has a much longer history, dating back over 125 years in the 1880s when steam was the primary source of energy in industry and electricity was just surfacing as a product for power and lighting [6]. Research and application of trigeneration [7–13] has been growing fast due to the growing interest in it as a way to increase the efficiency as well as to tackle the climate change.

The majority of existing trigeneration systems is fuelled by natural gas which is also a finite fossil fuel and needs to be substituted by more sustainable alternatives. Alternative fuels that aspire to replace fossil fuels include alcohols, bio-fuels, hydrogen, vegetable oils, biogas and producer gas. Of these, hydrogen has been identified as one of the most prospective and long term renewable and less polluting fuels [14], if the effective way can be found to generate 'renewable hydrogen' to meet our demand. There are many studies on hydrogen as an internal combustion engine fuel [15–17]. Van Vorst [15] reviewed early work on hydrogen as an engine fuel dating back from the first recorded use of hydrogen in an internal combustion engine described in the work of Reverend William Cecil in England in the early 1800s. Some research work in the period before the early 1990s has been reviewed by Das [16]. White et al. (2006) [17] presented a technical review of hydrogen fuelled internal combustion engines. Ruijven et al. [18] presented the potential role of hydrogen in energy systems. Hydrogen emits only a minimum amount of pollutants. These are NO_x from the combustion of nitrogen in the air, particularly at high engine loads; and a very little amount of CO and CO_2 from lubrication oil that may leak into the combustion cylinders. The combustion product of hydrogen is water, which, unlike carbon dioxide and other pollutants from fossil fuels, is not harmful to the environment.

The objective of this study was to investigate the performance, efficiency and emissions of a micro-scale trigeneration based on a diesel engine genset using hydrogen as the fuel in a domestic application, comparing with that of single generation, cogeneration; and compared to that of using original diesel fuel. The study used the ECLIPSE simulation software to model all of the three generations, i.e., single generation, cogeneration and trigeneration.

2. The design of the trigeneration and the computational software

The trigeneration system studied is shown in Fig. 1. The design of the system is based on the energy (including electricity and heat) consumptions in the households in the UK [19–27]. A diesel engine genset (6.5 kW) is selected for the generation of electrical power; a heat recovery system is designed; an absorption refrigerator is selected for the household trigeneration system. The study is also based on the previous research outcomes, which proved that using hydrogen as a fuel for a diesel engine generator and the use of micro-trigeneration system were feasible [28–30,4]. The main components of the micro-trigeneration system are: one Yammar diesel engine genset (YTG6.5S model, rated 6.5 kW electrical power output), a heat driven absorption refrigerator and a heat recovery systems including heat exchangers and heat storage tank to recover heat from engine cooling system and exhaust gases. The whole trigeneration system is being built and available for experimental study in laboratory at Newcastle University on different bio-fuels.

Previous to the experimental testing, a computational simulation is needed to carry out the initial evaluation of the performance and emissions when the generation system fuelled with hydrogen, comparing with that of original diesel fuel. The performance and emission study of the three generations, namely, single generation, cogeneration (CHP) and trigeneration, are all based on the primary mover – the Yammar genset. The engine test cycles used in the

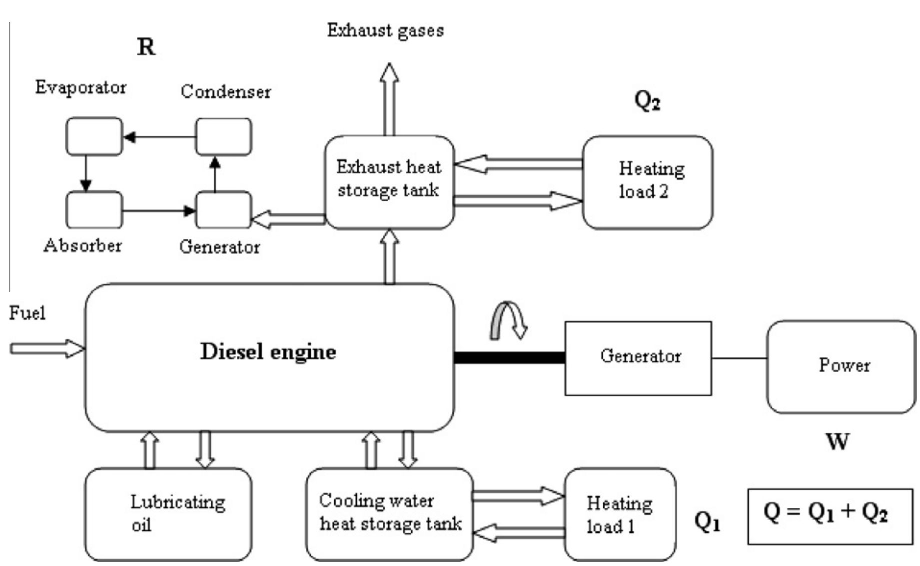

Fig. 1. A schematic diagram of the 6.5 kWe diesel engine trigeneration system.

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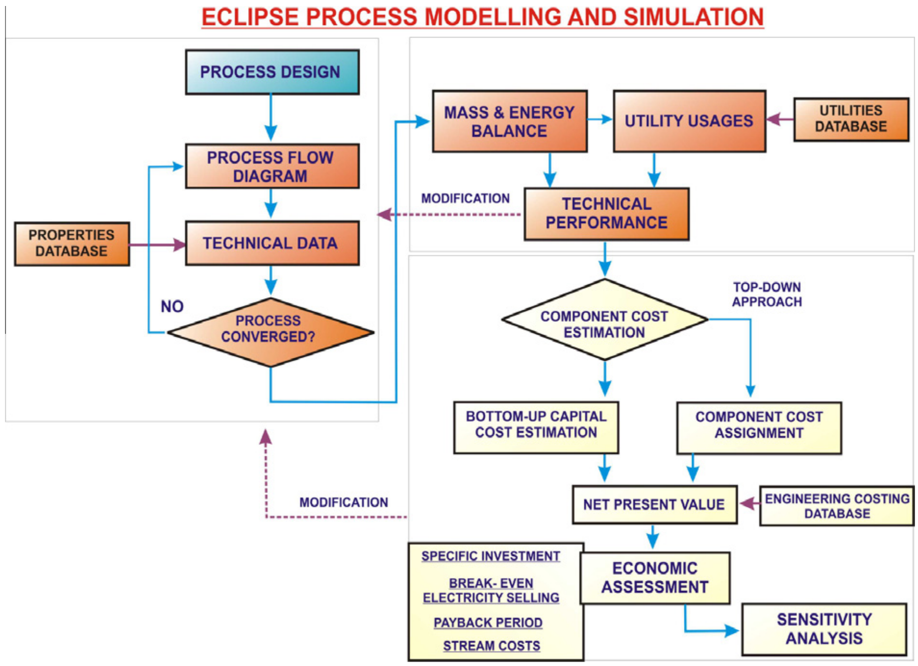


Fig. 2. The simulation process of ECLIPSE modelling.

investigation 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.

A computational software called ECLIPSE, whose simulation process is shown in Fig. 2, is used to simulate the working process of the proposed trigeneration, and the single generation and cogeneration to provide a consistent basis for evaluation and comparison [31,32]. 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 [33]. 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 thermodynamic, chemical and allied processes. It is used to carry out the simulation of the whole trigeneration system, including engine working processes, such as air and fuel(s) intake, compression, combustion and expansion, and finally exhaust processes. The software is also used to carry out the simulation of the waste heat recovery system and the absorption refrigeration system in the trigeneration. ECLIPSE uses generic chemical engineering equations and formulae, which keeps the energy and mass in balance, namely, the energy input equals to the energy output; so is the mass. It 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.

3. Results and discussion

3.1. Simulation programmes

The combustion processes of diesel and hydrogen in the engine cylinder in the form of global single step reaction are shown as the following equations:

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

$$2H_2 + (O_2 + 3.76N_2) \rightarrow 2H_2O + 3.76N_2 \quad (2)$$

The simulations are based on the above equations and the ECLIPSE software is used to carry out the simulation for mass and energy balance in the process. The cases simulated are single generation, cogeneration and trigeneration fuelled with two different fuels – diesel and hydrogen respectively. Fig. 3 shows the simulation diagrams of single generation, cogeneration and trigeneration in ECLIPSE.

3.1.1. Overall efficiencies and useful energy outputs

The simulation results are shown in the following table and figures. Table 1 shows the results of the six cases when the engine genset runs at full load that the electricity output is 6.5 kW. Figs. 4–7 show the results when the engine runs at different loads from 10%, 25%, 50%, 75% and 100%.

Fig. 4 shows the overall efficiency for single, cogeneration and trigeneration using diesel and hydrogen. It can be seen that for diesel fuel, electrical efficiency is low at low loads, 11% only at the engine 10% of load; and increases gradually to its maximum of about 31% at full load. For hydrogen fuelled case, the electrical efficiency increases from 10% at the engine 10% of load, to 30% at the engine 100% of load. The low efficiency at low loads is because of work that has to be done to overcome frictional forces between the moving parts in the engine, such as the crankshaft with its bearings, pistons with cylinders. This work to overcome friction is approximately constant for all load conditions. At low load conditions with low fuel feeds, the proportion of the energy input that goes into overcoming friction is higher than at higher load conditions with

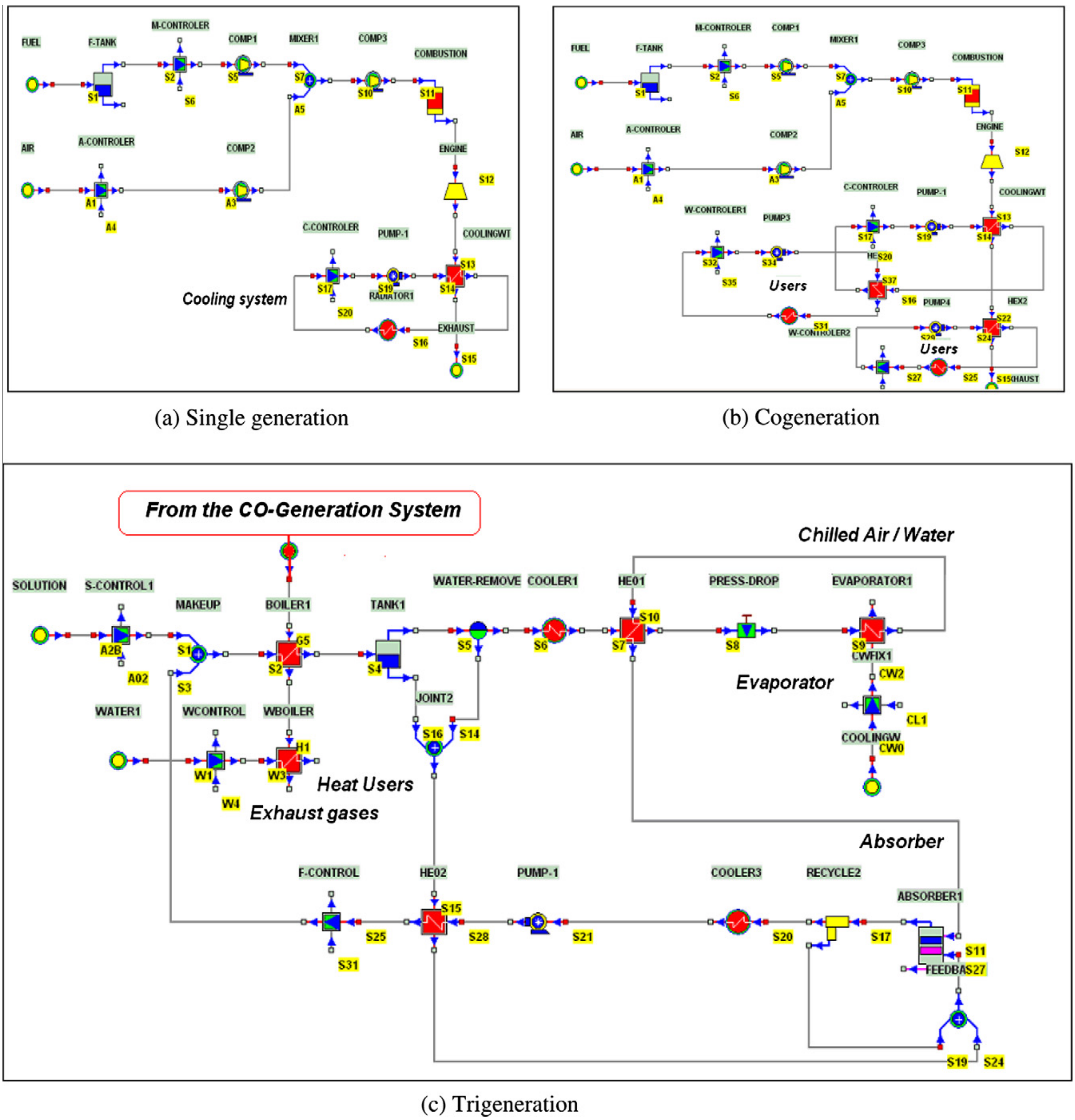


Fig. 3. The flow diagram of the three generation systems in ECLIPSE.

higher fuel feed. These friction losses caused the lower efficiency at the engine low loads.

The cogeneration and trigeneration efficiency start at around 50% at 10% load for diesel; 56% for hydrogen; rising gradually to 80% for diesel and 83% for hydrogen at full load. This represents efficiency increases of about 390% at 10% of engine load to 170% at engine full-load for both cogeneration and trigeneration compared to that of single generation. From the figures and Table 1, it can be seen that trigeneration is similar to cogeneration, in terms of the performances and emissions. This is because the refrigerator used in the study is quite small (0.4 kW only), which only consumes very small amount of heat (0.61 kW) from the engine exhaust. But it can also be seen that trigeneration is slightly less efficient than cogeneration. The differences are between 7.4% and 1.23% for diesel fuelled engine; 5.1–1.2% for hydrogen fuelled engine. This is due to a part of the waste heat from the engine input into the absorption refrigerator. Notice the fact that the COP of absorption refrigerator is less than 1. This means the refrigeration output is less than the heat input into the absorption refrigerator. This causes less efficient of the trigeneration than that of cogeneration.

For the comparison of the generations run on two fuels, in the case of single generation, the efficiencies of engine fuelled with diesel, are all higher than that of fuelled with hydrogen, from 9.1% at engine 10% load, to 3.2% at the engine full load. As for cogeneration and trigeneration, the engine efficiency fuelled with hydrogen are all higher than that fuelled with diesel at different engine loads, from 12.0% at 10% of engine load to 3.75% at the

Table 1
Technical and emission results at engine full load (at 6.5 kW electricity output).

Fuel used	Diesel			Hydrogen		
Generation	Singlegen[a]	Cogen	Trigen	Singlegen	Cogen	Trigen
Fuel input (kg/s) $\times 10^{-3}$	0.498	0.498	0.498	0.18	0.18	0.18
LHV (MJ/kg)	42.893	42.893	42.893	120.1	120.1	120.1
Total thermal input (kW_{th})	21.36	21.36	21.36	21.36	21.36	21.36
Electrical output (kWe)	6.53	6.53	6.53	6.50	6.50	6.50
Electrical efficiency (%)	31%	31%	31%	30%	30%	30%
Engine exhaust temperature (°C)	557	557	557	576	576	576
Carbon dioxide emissions (kg/kW h)	0.855	0.324	0.329	0	0	0
Exhaust gas mass flow (kg/min)	0.7650	0.7650	0.7650	0.7464	0.7464	0.7464
Heat recovered from cooling system and exhaust (kW_{th})		10.7	10.06		11.8	11.15
Total useful energy output (kW) (electricity + heat + refrigeration)	6.53	17.23	16.99	6.50	18.26	18.05
Exhaust temperature at exit of the system (°C)		150	150		150	150
Heat consumption of refrigeration (kW)			0.61			0.61
Refrigeration effect at −10 °C (kW)			0.11			0.11
Refrigeration effect at +5 °C (kW)			0.29			0.29
COP			0.66			0.66
Overall efficiency	31%	81%	80%	30%	84%	83%

[a] Singlegen – Single generation, Cogen – Cogeneration, Trigen – Trigeneration.

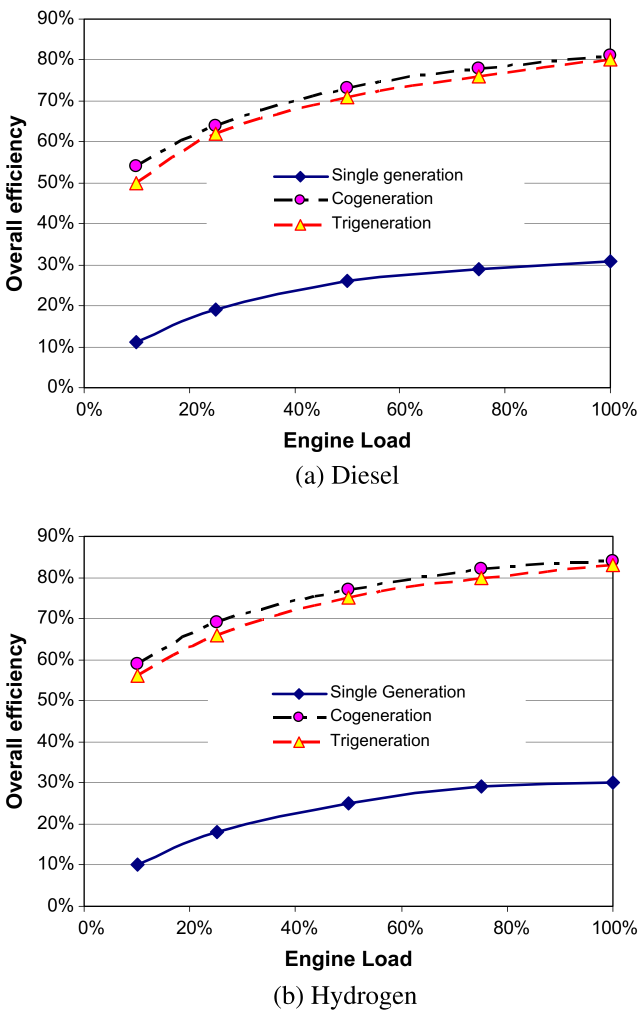


Fig. 4. Overall efficiency for single, cogeneration and trigeneration using diesel & H_2.

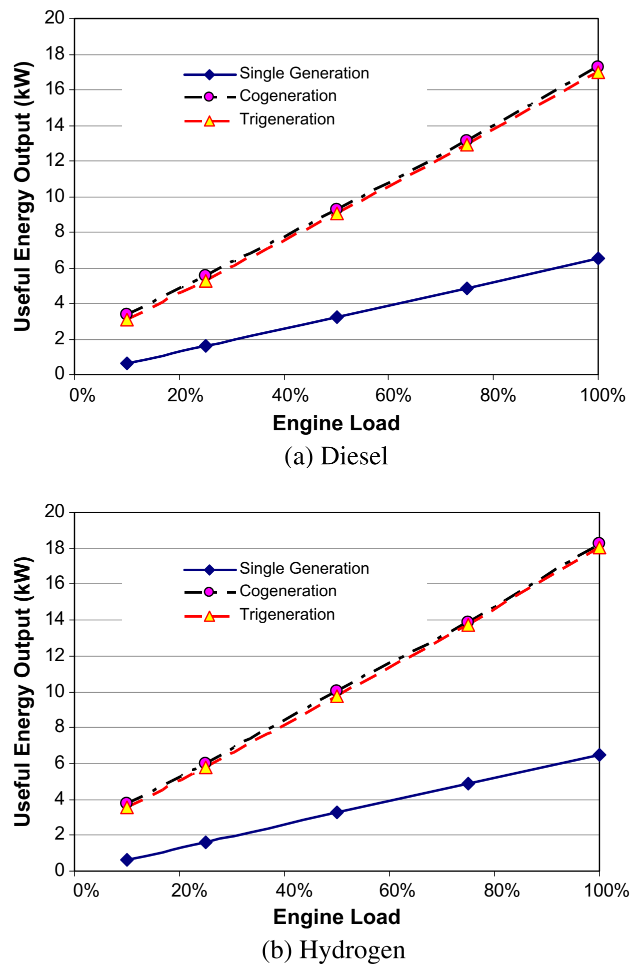
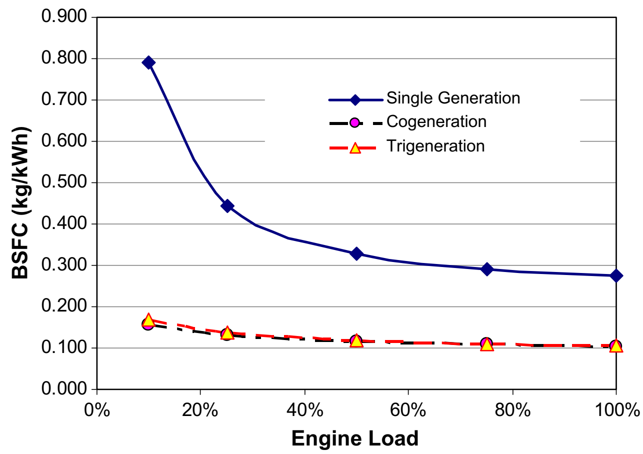


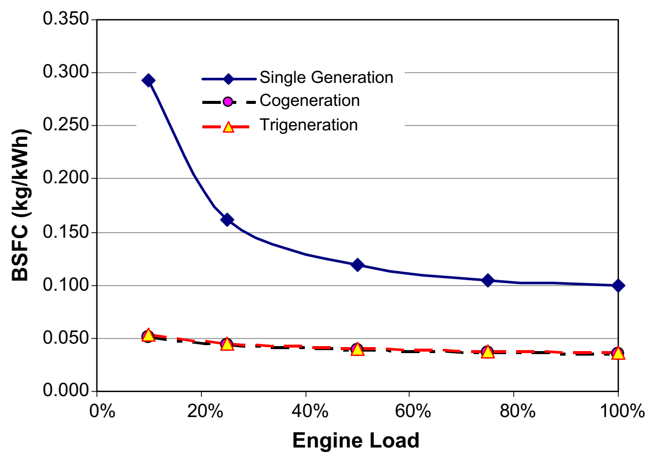
Fig. 5. Useful energy output for single, cogeneration and trigeneration using diesel & H_2.

engine full load for cogeneration; from 9.3% at 10% of engine load to 3.70% at the engine full load for cogeneration. The reason for that is probably the combustion of diesel and hydrogen in engine are different, the energy from the combustion of hydrogen transferred more heat to the cooling system and the exhaust, therefore reduced the energy changed to electricity.

Fig. 5 shows and compares the useful outputs from single generation, cogeneration and trigeneration for each fuel. It can be observed that the useful outputs from trigeneration are less than that of cogenerations fuelled with diesel and hydrogen. As discussed



(a) Diesel



(b) Hydrogen

Fig. 6. Brake specific fuel consumption (BSFC) for single, cogeneration and trigeneration using diesel & H_2.

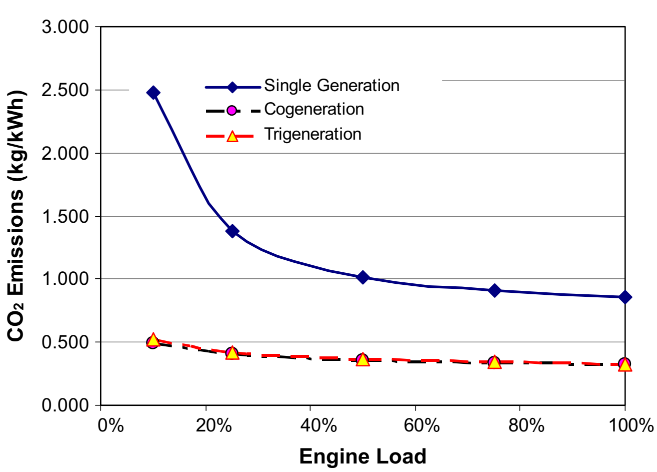


Fig. 7. CO_2 emissions for single, cogeneration and trigeneration using diesel.

above, this is due to the effect of the COP of absorption refrigerator is less than 1, which effectively reduces the useful energy outputs from the trigeneration, due to the absorption unit uses more heat inputs than the resultant cooling effect.

3.1.2. Brake specific fuel consumption (BSFC) and CO_2 emissions

BSFC is defined as the rate of fuel consumption per kW of useful energy output in single generation, cogeneration and trigeneration for each fuel. As can be seen from Table 1 an corresponding Fig. 6, for both fuels, the BSFC curves have the same general trends. That is, higher BSFC at low loads for single generation, e.g. 0.791 kg/kW h at the engine 10% load for diesel, 0.292 kg/kW h at 10% of engine load for hydrogen; and gradually the BSFC declines to about 0.275 kg/kW h for diesel and 0.100 kg/kW h for hydrogen. This difference in mass per kW h for the two fuels reflects the differences in energy density by mass of the two fuels. The BSFCs for cogeneration and trigeneration, when using both fuels, are much lower compared to those of single generations; and they are almost equal to each other, with that of trigeneration slightly higher, reflecting the slightly lower overall energetic efficiency of trigeneration compared to cogeneration.

From the results in Table 1 it can be seen that the resulting in CO_2 emissions from the engine for all load conditions when fuelled with hydrogen is zero; while that from diesel decreases with the load increases, i.e., from 2.48 kg (CO_2)/kW h at the engine 10% load to 0.855 kg (CO_2)/kW h at the engine full load, as can be seen in Fig. 7. From the results, it can be seen that at low load conditions where single generation is much less efficient, the CO_2 emissions per kW h rise sharply. From the figure, it can also be seen that single generation produces more CO_2 per kW h than cogeneration and trigeneration. Compared to cogeneration, single generation emits 80.4% more CO_2 at 10% of the engine load; to 62.1% more CO_2 at the engine full load. Compared to trigeneration, single generation emits 78.9% more CO_2 at 10% of the engine load; to 61.6% more CO_2 at the engine full load.

4. Conclusions

From the above results and discussions, conclusions can be drawn as follows for the study of the household size trigeneration compared to that of single generation and cogeneration:

- It is feasible to use hydrogen as the fuel to run the domestic micro-trigeneration based on a diesel engine genset.
- The efficiencies of the single generation, trigeneration and cogeneration run by hydrogen are comparable to those run by diesel, respectively.
- The micro-trigeneration has much higher overall efficiency and higher useful energy output than that of single generation.
- The trigeneration produces zero CO_2 emissions when fuelled with hydrogen. This means, if the hydrogen used is from renewable resources, the hydrogen fuelled trigeneration will be a net-zero energy system for the application in households. It has also much lower CO_2 emissions than that of single generation when fuelled with diesel.
- Although the trigeneration has a lower overall efficiency and lower useful energy output than that of cogeneration, it has one more useful refrigeration output using a small part of waste heat from the genset.

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