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Experimental investigation of thermal storage integrated micro trigeneration system

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ABSTRACT

In this study a 4.4 kW stationary compression ignition engine is coupled with a double pipe heat exchanger, vapour absorption refrigeration system and thermal energy storage system to achieve Trigeneration i.e. power, heating and cooling. A shell and tube type heat exchanger filled with erythritol is used to store thermal energy of engine exhaust. Various combinations of thermal energy storage system integrated micro-trigeneration were investigated and results related to performance and emissions are reported in this paper. The test results show that micro capacity (4.4 kW) stationary single cylinder diesel engine can be successfully modified to simultaneously produce power, heating and cooling and also store thermal energy.

1. Introduction

Increasing demand of energy has raised the prices of conventional energy sources, and environmental awareness has led to increase in use of renewable energy sources and focus on increased energy efficiency. In context of increased energy efficiency, thermal energy storage and waste heat recovery play an important role as these systems improve overall efficiency of various systems [1,2]. The energy available in the exit stream of many energy conversion devices goes waste; if not utilized properly [3,4]. Among several options available for waste heat recovery, micro-cogeneration and micro-trigeneration are emerging as the fast growing techniques to increase energy efficiency and reduce overall emissions in domestic and small-scale applications [5,6]. Micro-cogeneration (MCHP, Micro Combined Heat and Power Generation), is the combined production of electric power (lower than 50 kW) and thermal power. Micro-trigeneration (MCCHP, Micro Combined Cooling, Heat and Power Generation), is a combined cooling, heating and power generation system that consists basically of a module generating electricity (lower than 50 kW) and heat that, depending on the demand, is used either to satisfy domestic hot water requirement and/or space heating or for cooling purposes, or for both [7]. The major technical constraint that prevents successful implementation of waste heat recovery is its intermittent and time mismatched demand and availability [8,9]. Thermal energy storage (TES) technology plays an important role to overcome this problem by way of rational use of energy as it allows excess thermal energy to be stored for later use [10].

A lot of work has been carried out in the field of thermal energy storage, cogeneration and trigeneration systems. Godefroy et al. [11] presented design and analysis of possible trigeneration systems based on a gas engine mini-CHP unit (5.5 kW) and an ejector cooling cycle and analyzed that an overall efficiency around 50% could be achieved with systems designed for applications with simultaneous requirement for heating and cooling. Huangfu et al. [12] introduced a micro-scale combined cooling, heating and power (MCCHP) system which mainly consisted of a reciprocating internal combustion LPG and natural gas engine/generator, an adsorption chiller and heat recovery devices. With an analysis it was concluded that for high efficiency and good regulation performance, the system had to operate with electricity output greater than 50% of peak load. From the exergy point of view, the electricity efficiency of the gas engine/generator should be enhanced for an improved MCCHP system. Cakir et al. [13] studied the importance of cogeneration systems in sustainable energy. Majid et al. [14] presented a study on operation and performance of thermal energy storage system installed at a cogeneration plant for campus cooling. Iten and Liu [15] presented a review on procedure to design an effective short term thermal energy storage (TES) system using phase change materials. Nomura et al. [16] described heat release performance of a direct contact heat exchanger using erythritol as a PCM. Hatami et al. [17] presented a review of different

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Nomenclature

BSFC	brake specific fuel consumption (kg/kW h)	T_{wvao}	final temperature of water in VA system (°C)
BTE	brake thermal efficiency (%)	$\dot{m}_f$	mass flow rate of fuel (kg/s)
CHP	combined heating and power	$\dot{m}_{ex}$	mass flow rate of exhaust gases (kg/s)
CCHP	combined cooling, heating and power	$\dot{m}_w$	mass flow rate of water (kg/s)
DPHE	double pipe heat exchanger	m_w	mass of water (kg)
LCV	lower calorific value of fuel (kj/kg)	C_{pex}	specific heat of exhaust gases (kJ/kg-K)
PCM	phase changing material	T_{wi}	inlet temperature of water (°C)
TES	thermal energy storage	Tw_o	outlet temperature of water (°C)
TESS	thermal energy storage system	$T_{eng\ ex\ gas}$	engine exhaust gas temperature (°C)
VA	vapour absorption	$T_{ambient}$	ambient temperature (°C)
Cpw	specific heat of water (kJ/kg-K)	$T_{f\ PCM}$	final temperature of PCM (°C)
C_{ppcm}	specific heat of Phase changing material (kJ/kg-K)	$T_{i\ PCM}$	initial temperature of PCM (°C)
$C_{p\ liq\ pcm}$	specific heat of Phase changing material in liquid state (kJ/kg-K)	T_{melt}	melting point temperature of PCM (°C)
$T_{f\ liq\ PCM}$	final temperature of PCM in liquid phase (°C)	$T_{i\ liq\ PCM}$	initial temperature of PCM in liquid phase (°C)

heat exchangers' designs for increasing the diesel exhaust waste heat recovery and concluded that using fins is more applicable and appropriate than foam sand porous materials due to the lower pressure drop and higher heat transfer rate. Khatri et al. [6] experimentally studied a micro-trigeneration system based on a CI engine which was designed and realized in the laboratory. Trigeneration system consisted of stationary single cylinder diesel engine for electric power, fin and plate type heat exchanger for water heating and vapour absorption refrigeration system for cooling. Johar et al. [1] experimentally studied performance of thermal storage integrated micro cogeneration system and concluded that the idea of thermal storage integrated co-generation system is feasible and this type of system was successful and effective to utilize the resources more efficiently. Wang et al. [18] investigated performance and efficiency of a diesel engine based trigeneration system fuelled with pure diesel and with raw jatropha oil using a software tool named ECLIPSE. Marques et al. [19] obtained an expression for the calculation of the thermodynamic performance of a generic trigeneration. Moussawi et al. [20] presented a review on various trigeneration technologies. Sonar et al. [21] presented a brief review of micro trigeneration system as strategic means to achieve energy security and efficiency with positive impact on economy. Zhao et al. [22] investigated design and operation of a trigeneration system for station. Angrisani et al. [23] presented a review of the available indices and methodologies to assess the performance of poly-generation systems. Shelar and Kulkarni [24] presented a thermodynamic and economic analysis of diesel engine based trigeneration systems for Indian hotels.

The novelty of this study is to investigate the feasibility of successfully modifying a micro capacity (4.4 kW) stationary single cylinder diesel engine to thermal storage integrated trigeneration system which simultaneously produces power, heating and cooling; and storing thermal energy storage of engine exhaust. In this work, a double pipe heat exchanger, a shell and tube type heat exchanger and modified vapour absorption refrigeration system was were developed and integrated with the engine. Double pipe heat exchanger was used for water heating purpose, shell and tube type heat exchanger filled with erythritol ($C_4H_{10}O_4$) was used to store energy and VA system was used to achieve cooling.

2. Development of double pipe heat exchanger and thermal energy storage system

In present work, to achieve trigeneration, power was produced by the engine, heating was done in a double pipe heat exchanger and cooling was produced by VA system. A double pipe heat exchanger used for water heating purpose was designed and fabricated (dimensions are given in table 1). The generator of VA system was modified. In modified system the electric heating system in generator was replaced by heat exchanger which was also designed and fabricated. Fig. 1(a) shows the schematic diagram of electrolux type vapour absorption system. To store the energy a finned shell and tube heat exchanger thermal energy storage system was developed (specifications are given in Table 2). For designing thermal energy storage system, initially a phase change heat storage material was selected. Based on the engine exhaust gas temperature it was decided that the selected PCM must possess a melting point temperature between 100^0-130 °C (because at part load condition, the temperature of exhaust gas is low, hence, it was not possible to achieve high melting point). From the available PCMs, Erythritol ($C_4H_{10}O_4$) was selected for experimental investigation.

3. Experimental setup

The experimental setup consisted of a single cylinder, four stroke, air cooled, Kirloskar make diesel engine coupled to an electrical dynamometer (specifications of engine are given in Table 3), integrated with a double pipe heat exchanger (for water heating purpose), a thermal energy storage system (TESS) and 41 L electrolux type vapour absorption refrigeration system (for cooling purpose). Positions of these components are changed as given in methodology section. Fig. 1(b) and (c) show the pictorial view and schematic diagram of the experimental setup with combination III. Burette meter was used to measure the mass flow rate of fuel, air box was used to measure air flow and k-type (Cr/Al) thermocouples were used to measure temperature at various places. 21 thermocouples were placed at three different planes at a height of 100 mm, 200 mm and 300 mm from bottom in TESS. AVL make DITEST (AVL DiGas 4000 light) 5 gas analyzer was used to analyze the exhaust emission from the engine. The exhaust emission

Table 1
Specifications of double pipe heat exchanger.

Parameter	Value
Hot fluid	Engine exhaust (Inner tube)
Cold fluid	Water (Outer tube)
Outside tube diameter	5.08 cm
Inside tube diameter	3.81 cm
No. of passes	Single
Contact area of water with hot fluid	810 cm^2