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Experimental investigation of a biomass-fuelled micro-scale tri-generation system with an organic Rankine cycle and liquid desiccant cooling unit

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ABSTRACT

The drastic rise in the conventional fossil fuel prices along with the global warming and climate change have urged the need to switch towards renewable energy resources and use alternative means for more efficient energy resources utilization. Tri-generation technology has attracted considerable interest as a potential alternative to separate conventional energy production with a wide range of applications especially for small-scale systems providing various technical, economic and environmental benefits. In this study, an innovative micro-scale tri-generation system was experimentally investigated, consisting of an organic Rankine-based combined heat and power unit and a combined dehumidification and cooling unit. A compact and low-cost modified scroll expander was employed in the Rankine unit for heat and power generation. In addition, a liquid-desiccant unit coupled with a dew point evaporative cooler was used to provide the cooling capacity through air dehumidification and cooling. An experimental setup was built and the micro-scale tri-generation system was tested under different operational conditions employing a wood pellet biomass boiler as a heating source. It is shown that the proposed system is capable of providing about 9.6 kW heating power, 6.5 kW cooling power and 500 W electric power. The overall efficiency of the tri-generation system is about 85%.

1. Introduction

Although CHP (combined heat and power) is a proven technology with technical, economic and environmental benefits, the efficiency of CHP systems tends to decrease dramatically in the hot and temperate climates with long summer season where the need for cooling is superior to the heating demand. Therefore, tri-generation technology is introduced recently allowing simultaneous production of heat, cooling/refrigeration and electric power through coupling a CHP unit with a thermally-activated cooling technology. Tri-generation technology makes use of the wasted excess heat from the power generation unit to provide heating and cooling demands employing different waste-heat recovery and thermally activated units [1]. Compared to the conventional separate energy production systems, tri-generation systems allow more efficient utilization of the energy resources with an overall efficiency reaching 70–90% [2]. This is based on the decentralized nature of the system with on-site energy generation offsetting the need for transmission lines and power distribution units and allowing less operational and maintenance costs compared to centralized power stations. Tri-generation systems increase primary energy savings with less fuel consumption and therefore less greenhouse gas emissions and hazardous materials and pollutants to the environment. In addition, such on-site and near-user multi-generation systems improve the energy supply network reliability insuring a secure and steady energy supply with substantial energetic and economic savings especially for countries depending on energy resources imports to fulfil the energy demands [3,4]. For residential and building applications, micro-tri-generation systems of 1–10 kWe size range can provide heating, cooling and electrical demands with high efficiency, low operational and maintenance costs and less greenhouse gas emissions.

A number of experimental investigations have been presented in the literature for tri-generation systems. Huangfu et al. [5] conducted an experimental study of a tri-generation system for building applications with a 12 kWe ICE (internal combustion

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Nomenclature

CHP	combined heat and power
COP	coefficient of performance
cp	specific heat capacity at constant pressure (J/kg.K)
DC	direct current
EES	engineering equation solver
h	enthalpy (J/kg)
IEC	indirect evaporative cooling
$\dot{m}$	mass flow rate (kg/s)
ORC	organic Rankine cycle
P	pressure (bar)
PEC	psychrometric energy core
Q	heat (W)
RH	relative humidity (%)
T	temperature (°C)
w	humidity ratio (kg_{H_2O}/kg_{air})
$\dot{W}$	power (W)

Greek

Δ	difference
ε	effectiveness
η	efficiency

Subscripts

a	air
Bio	biomass
cond	condenser
Cool	cooling
db	dry bulb
Deh	dehumidifier
dp	dew point
ele	electrical
eq	equilibrium
Ex	expander
hf	heating fluid
in	input
is	isentropic
mech	mechanical
out	output
P	pump
Reg	regenerator
su	supply
Th	thermal
Tri	tri-generation
v	vapour
wb	wet bulb

engine) and a 9 kW adsorption chiller. Angrisani et al. [6] investigated a micro-tri-generation system using natural gas-fuelled ICE and a thermal-chemical absorption cooling unit, and they reported 5.4 kWe electricity production and a reduction of 30% on the operating cost and 26% on CO_2 emissions. Another experimental study was presented by Godefroy et al. [7] employing a 5.5 kWe gas engine with an ejector cooling unit and an overall efficiency of 50% was attained. A micro-scale residential tri-generation system using a diesel engine was tested by Lin et al. [8]. They reported an increase in the thermal efficiency by 2.2–4 times and a reduction in CO_2 emissions between 67.2 and 81.4% compared to power generation plants. A similar experimental study of a micro-scale tri-generation system employing a compression ignition diesel engine was conducted by Khatri et al. [9]. Preter et al. [10] presented an experimental study of a tri-generation system employing a 30 kWe micro-turbine and a direct-fired absorption chiller, and an overall primary energy utilization factor of 70% for the tri-generation mode was reported. Rocha et al. [11] compared the performance of two small-scale natural gas-fuelled tri-generation systems with 26 kW ICE and 30 kW micro-turbine as prime movers and a 17.6 kW water-ammonia absorption chiller. The ICE-based system attained 44.2% primary energy savings compared to only 15.1% for the micro-turbine unit.

In addition, very few studies have investigated the use of liquid desiccant cooling to provide the additional cooling effect in tri-generation systems. Fu et al. [12] presented an experimental study of a tri-generation system with a 70-kW natural gas-fuelled ICE with a liquid desiccant dehumidification system and a double-effect absorption heat pump. They reported 90% overall system efficiency at peak operating conditions in winter. Badami and Portoraro [13] studied experimentally an ICE-based tri-generation system with LiCl-water desiccant cooling unit, and a payback period between 6.8 and 7.6 was reported. In another study [14], the authors compared the performance of two natural gas-driven small-scale tri-generation systems. The first system comprises a micro-turbine coupled with LiBr–water absorption chiller where the second system employs an ICE and a liquid LiCl–water desiccant cooling unit. It was shown that the ICE-based tri-generation system with the liquid desiccant unit provides higher overall efficiency. Moreover, organic Rankine cycle-based units employing an organic working fluid have received an increasing attention recently due to their simplicity, lower operation temperature and pressure, high levels of safety and cost effectiveness [15,16]. Few researches have studied the use of ORC units in tri-generation systems [17–21], indicating that ORC units have a large potential as tri-generation prime movers but additional research and development is still needed to demonstrate their potential.

Maraver et al. investigated the technical and environmental feasibility of using biomass-fuelled tri-generation systems employing three different life cycle assessment methods. They reported that the biomass-driven tri-generation systems using stirling engines and organic Rankine cycle units provide substantial environmental benefits compared to stand-alone conventional systems [22]. Combining an ORC-based heat and power generation unit and a liquid desiccant cooling system in a micro-scale tri-generation system can provide heating and power demands for residential and building applications in addition to thermal comfort and good indoor air quality. Such combination has yet to be investigated in the literature to meet cooling, heating and power needs in micro-scale applications. In this study, a biomass-driven micro-scale cooling, heating and power system is experimentally investigated. The innovative tri-generation system comprises an ORC-based combined heat and power unit employing a compact and low cost expander modified from an air conditioning scroll compressor and utilizing an environmentally friendly HFE7100 working fluid. In addition, a desiccant cooling system consisting of a liquid desiccant-based dehumidification unit and a dew point cooling unit is employed to dehumidify and cool the supply air. An experimental setup was built and the system units were investigated under different conditions to assess the feasibility of using such small-scale tri-generation systems with this new combination to provide heating, cooling and power demands in buildings. The tri-generation system configuration is described and the experimental investigation data are reported. In addition, the effect of different operational parameters on the tri-generation system units performance was studied and discussed.