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Experimental investigation of a reversible heat pump/organic Rankine cycle unit designed to be coupled with a passive house to get a Net Zero Energy Building

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ABSTRACT

This paper presents an innovative reversible Heat Pump/Organic Rankine Cycle (HP/ORC) experimental unit designed to be coupled to a Net Zero Energy Building (connected to a 120 m^2 thermal solar roof and a ground heat exchanger). The system can operate in three different modes: an ORC mode to produce electricity when a large amount of heat is collected by the solar roof, a direct heating mode using exclusively the solar roof, and a HP mode for space heating during cold weather conditions. This paper describes a comprehensive experimental campaign carried out on a prototype unit using a modified HVAC scroll compressor (4 kWe). From the results, the technical feasibility of the system is demonstrated. A cycle efficiency of 4.2% is achieved in ORC mode (with condensation and evaporation temperature respectively of 25 °C and 88 °C) and a COP of 3.1 is obtained in HP mode (with condensation and evaporation temperature respectively of 61 °C and 21 °C).

Etude expérimentale d'une pompe à chaleur réversible/d'un système à cycle organique de Rankine conçu pour une maison passive pour obtenir un bâtiment à consommation énergétique nulle

Mots clés : Pompe à chaleur ; Cycle organique de Rankine ; Réversible ; Expérimentation ; Bâtiment à consummation énergétique nulle

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Nomenclature

Variables

COP	Coefficient of performance [–]
cp	Specific heat [J (K kg)$^{-1}$]
g	Gravity [m s^{-2}]
h	Enthalpy [J (Kg)$^{-1}$]
H	Height [m]
$\dot{m}$	Mass flow [kg s^{-1}]
NPSH	Net Positive Suction Head [m]
P	Pressure [bar]
$\dot{Q}$	Heat transfer [W]
Res	Residual [W]
t	Temperature [°C]
$\dot{V}$	Volumetric flow [m^3 s^{-1}]
$\dot{W}$	Power [W]
X	Oil fraction [–]

Greek symbols

ρ	Density [kg m^{-3}]
ε	Effectiveness [–]
η	Efficiency [–]
ϕ	Filling factor [–]
φ	Kinetic energy factor [m^3 kg s^{-2}]
Δ	Difference [–]

Subscripts

amb	Ambient
cd	Condenser
cp	Compressor
el	Electrical
ev	Evaporator
ex	Exhaust
exp	Expander
Hp	Heat pump
hp	High pressure
is	Isentropic
lp	Low pressure
oil	Oil
ORC	Organic Rankine Cycle
pp	Pump
r	Refrigerant
sat	Saturation
sc	Sub-cooler
su	Supply
vol	Volumetric
th	Theoretical
tot	Total
w	Water

1. Introduction

By 2020, greenhouse gases emissions must be reduced by 20% as compared to the levels of 1990, according to European objectives (20–20–20 objectives) (European Commission, 2012). This goal will be achieved both through an increase in the proportion of renewable energy from 9% to 20%, and an increase in energy system efficiency of 20%. Households account for 27% of the final energy consumption (European Commission, 2011) and therefore have the potential to contribute significantly to the targeted reduction in emissions.

Various technologies and concepts are being investigated, developed and implemented in the building sector. In this particular project, five different concepts are combined: Net Zero Energy Buildings (NZEB), heat pumps (HP), solar energy, micro-combined heat and power generation (μCHP) and the Organic Rankine Cycle (ORC).

Net Zero Energy Buildings (Jagemar et al., 2010; Kurnitski et al., 2014) are expected to gain a significant importance: by 2019, all new buildings should present a total renewable energy production higher than their primary energy consumption (European commission, 2010). This concept has already been successfully implemented using solar thermal and photovoltaic collector technology (Saitoh and Fujino, 2001). An alternative is the integration of a reversible HP/ORC, which constitutes a promising solution for NZEBs.

The use of water-to-water heat pumps is an established technology that allows the production of heat efficiently in various applications (Hepbasli and Yalinci, 2009). It is estimated that in the European Union, a reduction of 54% of CO_2 emissions could be achieved with the introduction of heat pumps into the building sector (Bettgenhäuser et al., 2013). The prototype unit presented in this paper is very similar to a classical water-to-water heat pump in terms of components and costs (see Section 3.3).

There is a necessity to increase the share of renewable resources in the primary energy balance, both for environmental reasons and energy security (European Commission, 2012). The International Energy Agency (IEA) projections involve, among others, a 16% coverage of the needs of low temperature heat by solar heating (International Energy Agency, 2012). However, thermal collectors are characterized by the mismatch between heat supply and demand, i.e., during summer months, the heat demand is at its lowest at a time when heat production through the solar collectors is the highest. This leads to the necessity to either undersize the solar collectors (leading to low solar factors), or to collect a large amount of unused heat. Thus, using any excess heat to produce electricity constitutes an interesting option, given an appropriate conversion technology such as the proposed HP/ORC unit.

The idea of using solar powered Rankine system for domestic applications has been investigated for several years (Wolpert and Riffat, 1995). Although PV panels produce electricity with a higher efficiency (≈12%–20%) than current low temperature (<100 °C) ORC systems (≈12%) (Twomey et al., 2013), some authors have shown that low temperature ORCs could reach a potential efficiency of up to 20% by using an