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Air conditioning and power generation for residential applications using liquid nitrogen

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HIGHLIGHTS

- Using liquid nitrogen to provide power and air conditioning for domestic applications.
- The proposed system leads to save energy and reduce the peak electricity demands.
- Compared with conventional AC saving up to 36% was achieved at the current LN2 price.
- The widespread of this technology leads to lower LN2 price and saving up to 81%.
- The last configuration was the efficient system with overall thermal efficiency 74%.

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ABSTRACT

Current air conditioning (AC) systems consume a significant amount of energy, particularly during peak times where most electricity suppliers face difficulties to meet the users' demands, and the global demands for AC systems have increased rapidly over the last few decades leading to significant power consumption and carbon dioxide emissions. This paper presents a new technique that uses liquid nitrogen (LN2) produced from renewable energy sources, or surplus electricity at off peak times, to provide cooling and power for domestic houses. Thermodynamic analyses of various cryogenic cycles have been carried out to achieve the most effective configuration that produces the maximum power output with minimum LN2 flow rate, to meet the required cooling of a 170 m^2 dwelling in Libya. A comparison with a conventional AC system was also made. Results showed that at the current LN2 prices, using LN2 to provide cooling and power demands of residential buildings is feasible and saves up to 36% compared to conventional air conditioning systems with an overall thermal efficiency of 74%. However, as the LN2 price decreases to around 1.3 pence per kg, the proposed technology will have significant advantages compared to conventional AC systems with savings of up to 81%.

1. Introduction

The global demands for air conditioning have increased rapidly over the last few decades, particularly in developing countries and these demands form a major part of residential power consumption [1–3]. This power consumption has a potential impact on national electricity grids, particularly during peak times where most electricity suppliers face difficulties to meet the users' demands; and furthermore it contributes to global warming as a result of fossil fuel combustion [4]. Energy storage technologies offer advantages of storing the surplus electricity at off peak times to be used during peak hours to meet various demands. Liquid nitrogen has recently been acknowledged as the most attractive energy storage medium due to its high energy density (770 kJ/kg), availability, safety and environmentally friendly characteristics [5–9]. Liquid nitrogen has a very low boiling temperature (−196 °C) which can be used to provide cooling and power for domestic buildings during peak times to save energy and to reduce the electricity demands on national grids during the peak times.

Using cryogenic fluids to generate cooling and to generate power has been studied by many researchers and most of their reports were focussed on liquid natural gas (LNG). The coolness produced during the regasification process of LNG is used to provide cooling for the liquefaction plant integrated into the regasification plant and to generate power using an open Rankine power cycle [10–14]. Other researchers investigated other cryogenic fluids, mainly liquid nitrogen/air to provide cooling and/or power for various applications. These applications include refrigerators, air conditioners and heating engines. The refrigerator system uses

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Nomenclature

h	enthalpy kJ/kg
CC	specific cooling capacity kW/kg-LN2
COP	coefficient of performance
$\dot{m}$	mass flow rate kg/s
s	entropy kJ/kg K
W	specific power kW/kg-LN2
m_r	the closed Brayton or Rankine cycles mass flow rates to LN2 mass flow rate
m_{r1}	the first closed Rankine cycle mass flow rate to LN2 mass flow rate
m_{r2}	the second closed Rankine cycle mass flow rate to LN2 mass flow rate
η_{th}	thermal efficiency
Subscripts	
B	Brayton cycle
AD	adiabatic expansion
ISO	isothermal expansion
N	liquid nitrogen cycle
R	closed Rankine cycle/first closed Rankine cycle
R'	second closed Rankine cycle
$tank$	cooling tank

either direct evaporating of LN2 by spraying it in a cooling space or indirect evaporating through a heat exchanger to generate cooling [15–17]. The air conditioner system uses the same approach (direct evaporation) and mixes LN2 with liquid oxygen [18,19]. The studying, testing and prototyping of LN2 engines has also been reported where LN2 evaporates using the ambient temperature or low heat source and then expands it in an expander to generate power as an open Rankine cycle [20–24]. Using LN2 to provide cooling or power only is not an efficient way to extract its stored energy; the maximum power output can be achieved by using the open Rankine cycle, for example, 400 kJ/kg which is around half of the energy density of LN2 and 29% of the energy consumed to produce it [10]. More recent published work has focused on combined cycles such as integrating LN2 power cycle with a closed Brayton cycle or with a Stirling engine [25–27]. Ameel et al. proposed another combined system where a LN2 power cycle is integrated with a liquefaction plant to reduce its power requirement [28]. Dearman developed a LN2 system to generate cooling and power for refrigerated vehicles. The engine power output is used to run a traditional refrigerator system and the cold exit vapour is used to improve the refrigerator performance by cooling the system's condenser [29,30].

The reported literature has indicated that utilizing liquid nitrogen/air to provide either cooling or power consumes a large amount of LN2 and recovers only around 30% of the energy consumed to produce it. However, a combined system that provides cooling and power can be a promising technique to extract most of energy stored in the form of liquid air/nitrogen. This indicates that there is a need to investigate various cryogenic cooling and power cycles to extract more stored energy from LN2, and to see the feasibility of using these cycles to meet the residential cooling demands during peak hours. This study investigates the use of LN2 to provide cooling for air conditioning and power, where several thermodynamic cycle configurations were assessed in terms of the cooling and power output, using MATLAB integrated with REFPROP. The cooling load of a typical dwelling in Libya that is shown in Fig. 1 with a total area of 170 m^2 was selected as the case study [31].

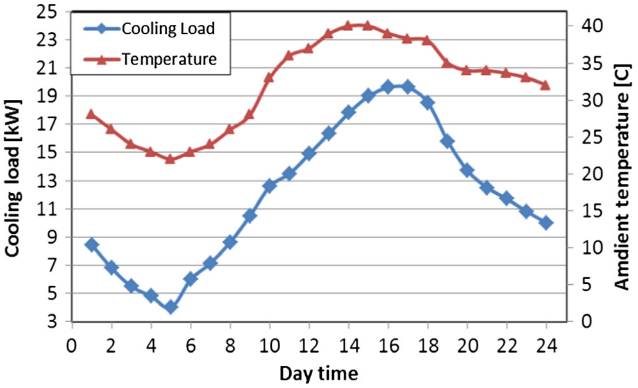

Fig. 1. Variation of cooling load and ambient temperature for the selected dwelling on 21st of June.

2. Thermal modelling and analysis of proposed systems

The proposed technology aims to use the stored energy in liquid N_2 to provide for cooling and power generation in buildings. The system consists of two main circuits: the first utilizes a secondary refrigerant to recover the LN2 to provide for the building's cooling requirements and the second circuit is a LN2 cycle for power generation through the expansion process. Five different configurations were modelled using MATLAB integrated with REFPROP to investigate the effects of various LN2 input pressures (P_{2N}) on the system's LN2 mass flow rate, cooling capacity and power output, compared to a conventional AC system. The model was developed for each configuration to calculate the properties of the working fluids at each point in the cycle; solve the energy and mass balance equations for LN2 and other working fluids, calculating the cooling capacity and the power output. This information will lead to the discovery of the best cycle configuration that achieves the use of the minimum amount of LN2 with the maximum power output and cooling capacity for the selected application.'

2.1. First configuration – cooling only

Fig. 2a shows the baseline configuration (Cycle 1) where liquid nitrogen is evaporating in the cooling tank to cool a secondary fluid used for providing the building's cooling load with no power generation. The cycle T-S diagram is shown in Fig. 2b where the LN2 is evaporated and superheated in the process 1N–3N at atmospheric pressure. By applying the energy balance equation between the cooling load and the specific LN2 enthalpy difference at the inlet and the outlet of the cooling tank, the mass flow rate of LN2 can be calculated using Eq. (1).

$$\dot{m}_N = \frac{Cooling\ Load}{(h_{3N} - h_{2N})} \qquad (1)$$

$$CC = \frac{Cooling\ Load}{\dot{m}_N} \qquad (2)$$

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