Energy Conversion and Management 128 (2016) 34–43

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Liquid nitrogen energy storage for air conditioning and power generation in domestic applications

Abdalqader Ahmad *, Raya Al-Dadah, Saad Mahmoud

The University of Birmingham, School of Mechanical Engineering, Edgbaston, Birmingham B15-2TT, UK

ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 10 September 2016
Accepted 20 September 2016

Keywords:
Air conditioning
Liquid nitrogen/air
Cryogenic
Peak times

ABSTRACT

The global demands for air conditioning have increased rapidly over the last few decades leading to significant power consumption and CO_2 emissions. Current air conditioning systems use mechanical vapour compression systems which consume significant amount of energy particularly during peak times and use refrigerants that have global warming potential higher than that of carbon dioxide. This paper presents a new approach for providing air conditioning and power using liquid nitrogen produced from surplus electricity at off peak times or renewable energy sources. Thermodynamic analyses of different cryogenic cycles was carried out to achieve the most effective configuration that provides the required cooling and power for a 170 m^2 dwelling in Libya with minimum LN_2 consumption. Results showed that at today LN_2 prices, it is feasible to use LN_2 to provide for cooling and power demands of residential buildings with saving of up to 28% compared to conventional AC systems. However, as the LN_2 price decreases to around 1.3 pence per litre, the proposed technology will have significant advantages compared to AC systems with savings of up to 79% with almost 85% of the energy stored in LN_2 is recovered.

1. Introduction

The global demands for air conditioning have increased rapidly over the last few decades where about 87% of US households have air conditioning and 50 million units were sold in China in 2010 [1]. In summer time, approximately 40% of the residential power consumption in India and Australia is consumed by AC units [2]. In china and UK, AC systems consume about 20% and 17% of the total power consumption respectively. In Saudi Arabia, more than 50% of the power consumption at summer peak times is used to power AC systems [1,3]. In Europe, forecasts have shown that demands for space cooling will rapidly increase over the next 15 years by 72% and will reach 30 times its current value by 2100 [4,5]. This huge energy consumption has a major impact on national electricity grids particularly during peak times. Also, it contributes to global warming as a result of fossil fuel combustion and leakage of the CFC/HCFC refrigerants used in conventional AC systems. According to the National Institute for Public Health and the Environment in Netherlands, leakage from 32 refrigeration systems will contribute 25% of the total emissions by mid of this century [1].

Energy storage technologies offer advantages of balancing the demand and supply of the electricity grid throughout the day where surplus electricity at night can be stored and used during peak hours to meet various demands. Liquid air/Nitrogen have recently been identified as energy vector with high energy storage density defined as the maximum possible work that can be gained by bringing the liquid from the stored condition to the environment conditions [6–9]. The energy density of liquid nitrogen (LN_2) compared to other cryogenic fluids is presented in Table 1, and it is clearly seen that, the energy density of LN_2 per kg is higher than that of other cryogenic fluids, except methane where it is around 40% higher than that of LN_2. However, the energy density of LN_2 per litter is around 25% higher than that of Methane making LN_2 more attractive energy vector to use [10,11].

The cryogenic storage medium can be used to provide cooling for various applications and generate power through expansion process. Many researchers have used the cold stored energy in liquid natural gas (LNG), for example, during regasification process to provide cooling for liquefaction plant, and to generate power using an open Rankine power cycle [12–17]. These studies reported that, it is possible to recover the energy stored in LNG, however, most proposed systems integrated with regasification plant which makes it difficult to use for domestic applications. Other researchers have investigated other cryogenic fluids mainly liquid air/nitrogen due to their energy density, availability, safety and

* Corresponding author.
E-mail address: aya325@bham.ac.uk (A. Ahmad).

http://dx.doi.org/10.1016/j.enconman.2016.09.063
0196-8904/

Nomenclature

h	enthalpy (kJ/kg)
CC	cooling capacity (kW/kg)
$\dot{m}$	mass flow rate (kg/s)
S	entropy (kJ/kg K)
W	output power (kW)
m_r	ratio of the closed Brayton or Rankine cycles mass flow rates to LN_2 mass flow rate
m_{r1}	ratio of the first closed Rankine cycle mass flow rate to LN_2 mass flow rate
m_{r2}	ratio of the second closed Rankine cycle mass flow rate to LN_2 mass flow rate

Subscripts

B	Brayton cycle
AD	adiabatic expansion
ISO	isothermal expansion
n	nitrogen/LN_2
N	liquid nitrogen cycle
R	Rankine cycle/first closed Rankine cycle
R'	second closed Rankine cycle
tan$k$	cooling tan$k$

environmental aspects to use for domestic applications to provide cooling [18–24] or power only [25–29] or to provide both cooling and power [30–36].

Regarding cooling applications of liquid air/nitrogen, Place, developed a cooling system using liquid air to cool railway carriages to preserve food by passing liquid air in channels around the cooling space leading to reduction in the weight compared to using ice [18]. Harold has used a mixture of liquid air and oxygen for air conditioning of airplanes and spaceships. The mixture is evaporated in a heat exchanger then the cold gas is passed through the cooling space [19]. Saia et al. have replaced the traditional refrigerator system of a lorry used to transfer frozen food, using a new refrigerator system that uses liquefied carbon dioxide. In this system the liquid CO_2 evaporates in a heat exchanger fitted in the cooling space roof to provide cooling at a wide range of sub-zero temperatures [20]. Dakhil has used LN_2 to run air conditioning system by directly releasing LN_2 from a pressurized vessel to a closed space where it flashes and evaporates, then passes to room space using fan [21]. Garlov et al. used LN_2 for cooling food transport vehicles where LN_2 is sprayed directly in the food [22]. Skobel et al. invented an open refrigerator system for a beverage dispenser by using LN_2 where the LN_2 flow rate is controlled by temperature activated valve. The machine was effective in producing cooling, quiet and environmental friendly [23]. Watanabe et al. have reported on new project in Japan to cool the high-temperature superconductor (HTS) cables using liquid nitrogen to keep them at superconducting state [24].

Regarding power production, Manning and Schneider have patented LN_2 engine that works near isothermal expansion process by using three stages expander with reheating after the first and the second stage in order to increase its output power [25]. Ordonez et al. have analysed and tested a cryogenic heat engine using different cryogenic fluids and they reported that, liquid nitrogen is the most attractive fluid to run such engine [26,27]. Knowlen et al. have studied the heat transfer in a reciprocating engine that used LN_2 as working fluid, reported achieving 85% of the isothermal expansion process by having a high surface-to-volume ratio [28]. Chen et al. carried out a comparative study to compare liquid air with compressed air as energy storage vectors for fuelling a zero emission vehicles in terms of the power output, energy density and efficiency. They found that, for a given pressure (300 bars) and temperature (300 K), compressed air engine has slightly higher efficiency than liquid air engine, however, its volumetric energy density is 2.45 times less than that of liquid air. [29]. Ordonez et al. improved the open LN_2 power engine by combining it with a closed Brayton cycle where the evaporating LN_2 is used to cool the working fluid of the closed Brayton cycle before the compression process [30].

Dearman developed LN_2 system to generate cooling and power for refrigerated vehicles. The engine generated power is used to run a conventional AC system and other auxiliary devices while the LN_2 exhaust from the engine is uses to improve the performance of the AC system by cooling the system condenser [31,32]. Ameel et al. proposed a new system that increases the recovered energy from liquid air/nitrogen by integrating the liquid air/nitrogen power cycle with liquefaction plant to reduce its power requirement [33]. Newman and McCormick replaced the conventional refrigeration system in lorry with LN_2 and LNG refrigerator, where both liquids evaporates in a finned heat exchanger to refrigerate products to temperatures below 0 °C then the mixture is used to run the lorry engine [34]. Another combined system reported by Wang et al. where the open LN_2 power cycle is used to cool the cold side of Stirling engine to recover more stored energy [35,36].

The reported literature have indicated that, utilizing Liquid air/Nitrogen to provide cooling or power only consumes large amount of LN_2 and not fully recovering the stored energy. However, combined system that provides cooling and power can be a promising technique to extract the energy stored in Liquid air/Nitrogen. This indicates that there is a need for investigating various cryogenic cooling and power cycles to extract more stored energy in LN_2. This study investigates the use of LN_2 to provide cooling for air conditioning and power where a number of thermodynamic cycle configurations were assessed in terms of the cooling and power output using Matlab integrated with Refprop. This study was carried out for a typical dwelling in Sabha, Libya with a total area of

Table 1
Energy density of various cryogenic fluids.

Fluid	Storage temperature at atm (K)	Density (kg/m^3)	Availability (kJ/kg)	Availability (W h/kg)	Availability (W h/L)
Liquid nitrogen	77.4	809	768	213	173
Liquid air	78.9	886	737	205	181
Liquid oxygen	90.2	1140	635	176	201
Methane (without burning)	111.6	423	1093	304	128
Ethane (without burning)	184.6	545	352	97.7	53.2
Compressed air at 200 (bar)	300	233	258	715	16.7