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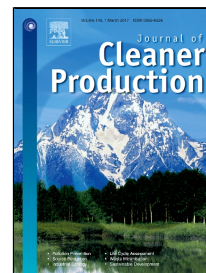
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Liquid Air utilization in air conditioning and power generating in a commercial building

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Abstract

Current air conditioning (AC) systems use a vapour compression system that consume a great amount of energy particularly during the peak times where most electricity suppliers facing difficulties to meet the users demands. Shifting the peak cooling demands to off-peak times using cold energy storage systems is a promising technique leads to save energy and to reduce the CO_2 emissions. This study presents new technology that uses the cold energy storage in form of liquid Air (LAir) or liquid nitrogen (LN2) to provide air conditioning and power to commercial buildings. Four different cryogenic cycles were modelled and analysis from a thermodynamic point view, and compared in terms of their, output power, cooling capacity, recovery efficiency, COP and how much energy could save when compared with the traditional AC system. The results showed that system performance when LAir is used is 21-25% higher than that of when LN2 is used, and the 4th configuration is the most effective cycle and it recovered up to 94% of the energy stored in LAir and 78% of the energy stored LN2. Compared to the conventional system at the current LAir and LN2 prices, the 1st, 2nd, 3rd and 4th cycles showed saving up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used and -3.5%, 5%, 16% and 24%, consecutively, when LN2 is used.

Key words; liquid air/nitrogen; cryogenic system; air conditioning; peak demand; cold storage

1-   Introduction

Conventional air conditioning (AC) systems use a vapour compression system that consumes a great amount of energy particularly during the peak times, and the demands of these systems have increased rapidly over the last few decades. Forecasts have shown that space cooling demands in Europe will increase rapidly over the next 15 years by 72% and will reach 30 times its current value by 2100 (Ahmad et al., 2016; Cox, 2012; Davis and Gertler 2015). Shifting the peak cooling demands to off-peak times using cold energy storage systems is a promising technique leads to save energy, to reduce the CO_2 emissions and to reduce the system size (Navidbakhsh et at., 2013). However, the performance of this technique affects significantly by the chosen storage medium, storage temperature and the operating strategy (Zhai et at., 2013).

There is a new cooling systems use cold storage medium in form of liquefied gases such as liquefied natural gas, air, nitrogen and CO_2 was also reported, and liquid air / nitrogen were considered as the most attractive storage

33 medium due their high energy density, availability and environmental friendly (Knowlen et at., 1998). Place, 1909

34 developed LAir cooling system to cool railway carriages to preserve food by evaporating it in channels fitted around

35 the cooling space. An air conditioning uses liquid air was developed by Harold in 1960 where the liquid air is

36 evaporated in a heat exchanger then vented to the cooling space. A liquefied nitrogen and natural gas uses to cool a

37 food transport lorry where the liquefied gases evaporated and superheated in heat exchanger fitted in the cooling

38 space roof to generate cooling and then the mixture uses to run the lorry engine (Newman et al., 2014). Saia et al.,

39 1994 modified the conventional refrigerator of a food transport lorry which uses to transfer a frozen food, using a

40 liquefied carbon dioxide. The system evaporates liquid CO_2 in a heat exchanger fitted around the cooling space and

41 provides cool at a wide range of sub-zero temperatures. Cooling the cutting tools using LN2 with a compressed air

42 and lubricating fluids was also reported and tested by many researchers. This technique leads to reduce the tip

43 temperature, cutting force, the consumption of the cutting fluid and increase the cutting speed and the feed rate

44 (Tazehkandi et al., 2015; Giasin et at., 2016; Pereira et al., 2016). An air conditioning system and refrigerator that

45 use a direct spray of LAir into the cooling space were reported by (Garlov et at., 2002). Skobel et al. 2012 developed

46 a beverage dispenser that uses liquid nitrogen (LN2) cooling system and it was effective in producing cooling, quite,

47 suitable for remote areas and environmental friendly. A LAir engine that provides cooling and power for food

48 transport vehicles was presented by (Strahan et al., 2013; Dearman, 2015) and the engine is used to run a traditional

49 AC system and other auxiliary devices. Exhaust cool from the engine is used to enhance the performance of the AC

50 system by reducing its condenser temperature. A comprehensive study of various cryogenic cycles that use LN2 to

51 provide cooling and power for domestic applications was carried out by Ahmad et al. 2016, and the results showed

52 that, at the current LN2 prices savings up 36% was achieved and 74% of the LN2 stored energy was recovered

53 (Ahmad et at. 2016)

54   The above mentioned work shows using cold storage systems in form of liquid Air/nitrogen to provide cooling

55 and power is feasible and leads to save energy, reduce the CO_2 emissions and reduce the peak electricity demands.

56 The last mentioned work was used LN2 to provide cooling and power for domestic applications, however, mere than

57 25% of the energy consumed to produce LN2 does not recovered. The current study aims to investigate using LAir,

58 which consumes 20% less energy than LN2, to provide cooling and power to a commercial building located in

59 Ahwaz, Iran (Navidbakhsh, et al., 2013). A thermodynamic analysis of four different cryogenic cooling and power

60 cycles were carried out modeled using MATLAB integrated with REFPROP software. These cycles were compared

61 in terms of their cooling capacities and output powers, recovery efficiencies and COPs, and also were compared

62 with the conventional AC system (MATLAB, 2008; REFPROP, 2010).

63

2- Proposed cryogenic cooling and power cycles

The proposed systems use the cold stored energy in form of liquid air to generate air conditioning and power for commercial buildings at the peak times to save energy, to increase the national electricity grid stabilities by reducing the peak electricity demands. The proposed systems consist of two circuits; the first one circulates a secondary coolant to meet the building cooling demands. This cooling load is used as heat source to the second circuit (LAir cycle) which provides cooling and power by evaporating pressurized LAir and expanded it in an expander. Four different cryogenic cycles were modelled using MATLAB combined with REFPROP software to find out the most efficient cycle that recovers most of the energy stored in LAir. The model investigates wide range of LAir inlet pressure (represented by P_{2A} in the following figures) to find out how it will affect the system performance, and a cost analysis to compare the conventional AC system with the proposed systems was also carried out.

The first cycle is shown in Fig. 1(a, b) where the liquefied air is pumped to a coil immersed inside the cooling tank to be evaporated and superheated by the secondary coolant load before it passes through an expander to generate power. The expansion process can be either adiabatic or isothermal expansions as shown in Fig. 3b. In the adiabatic expansion scenario, the expansion process reduces the air outlet temperature so it returns to the cooling tank in order to increase the system cooling capacity. However, for the isothermal expansion scenario (that represented by dash line in Fig. 1b) where the expanded air leaves at the secondary coolant temperature, so it vents directly to the atmosphere. This later scenario has advantages by absorbing more heat in the expansion process which increases the system cooling capacity and output power. Also the inlet pressure (P_{2A}) can be increased to more than 500 bar whereas this value cannot exceeds 100 bar in the first scenario duo to lowering the exit temperature below saturated line as shown in the expansion process (a-b) in Fig.1b. More than 80% of the isothermal expansion can be practically achieved by gaining heat from the surroundings using secondary fluid or by having a high value of surface to volume ratio expander or by three stage expander with reheat after the first and the second stage (Ahmad et al., 2016; North, 2008; Knowlen, et al., 1997; Vitt and Peter, 1997; Ordonez, 2000).

The second cycle is presented in Fig. 2(a, b) where the previous LAir cooling and power cycle is used to drive a closed Brayton cycle by cooling down its working fluid (in the process 4B-1B) while the LAir evaporates and superheats in the process (2A-3A). The cooling process followed by compression (1B-2B), heating (2B-3B) and expansion (3B-4B) processes as shown in the Fig.2. The closed Brayton cycle output power affects by its mass flow rate, which depends on the selected evaporator outlet temperature (T_{3A}), and its pressure ratio, which restricts by the compressor outlet temperature (T_{2B}) which has to be less than the secondary coolant temperature. These values and the closed cycle working fluid should be carefully selected to achieve the maximum output power and to avoid any

condensation in the evaporator. The closed Brayton working fluid should has boiling point lower than that of LAir and many gases can be used such as Neon, Helium or Hydrogen, and the later one was selected for the current work.

The third cycle is similar to the second cycle; however, in this case LAir power cycle drives a closed Rankine cycle which more efficient the Brayton cycle. The cycle is shown in Fig.3(a, b) where closed Rankine cycle (1R, 2R, 3R and 4R) uses LAir to condense it working fluid in HE1 while it evaporates and superheats. The condensed fluid is pumped to a separate heat exchanger immersed in the cooling tank (1R-2R) to evaporate and superheat in the process (2R-3R) then expanded in a separate expander (3R-4R). The closed cycle working fluid should be carefully selected to achieve the maximum output power. Xenon with boiling temperature of -108 °C at atmospheric pressure was selected as working fluid of the closed Rankine cycle in this study.

Fig.4(a, b) shows the fourth cycle where the LAir cycle drives two cascades closed Rankine cycles which are named as the first and the second closed Rankine cycles. The first closed Rankine cycle represents by (1R, 2R, 3R, 4R and 5R) and the second closed Rankine cycle represents by (1R', 2R', 3R' and 4R'). The LAir evaporates and superheats (2A-3A) in HE1 while it condenses the first closed Rankine cycle working fluid (5R-1R). Then the superheated air passes through HE2 and the cooling tank (3A-4A and 4A-5A) for further heating before it expands in an expander (5A-6A). The condensed fluid of the first closed cycle is pumped to HE2 (1R-2R) where it evaporates (2R-3R) and condenses the second closed cycle working fluid (4R'-1R'). Then the vapour passes through a separate expander (4R-5R) after been superheated in the cooling tank (3R-4R). The second closed cycle working fluid pumps to the cooling tank (1R'-2R') where it evaporates and superheats (2R'-3R') then passes through another separate expander. The working fluids of the two closed Rankine cycles should be carefully selected to meet the cycle and the application requirements. For the current study R14, which boils at -127 °C at the atmospheric pressure, was chosen as working fluid for the first closed cycle and R13, which boils at -81 °C at the atmospheric pressure, was chosen as working fluid for the second closed cycle.

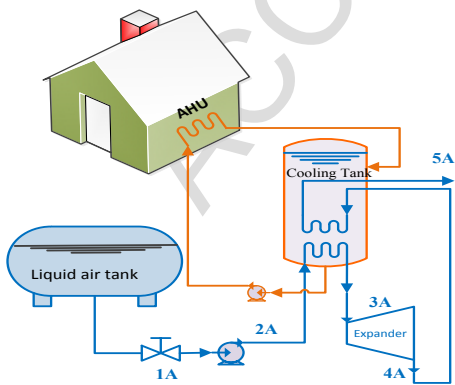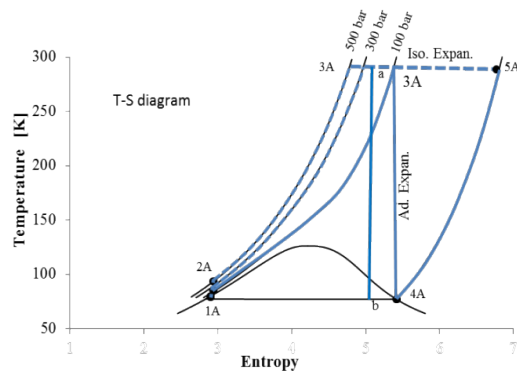Fig.1a First cycle, LAir cooling and power cycle

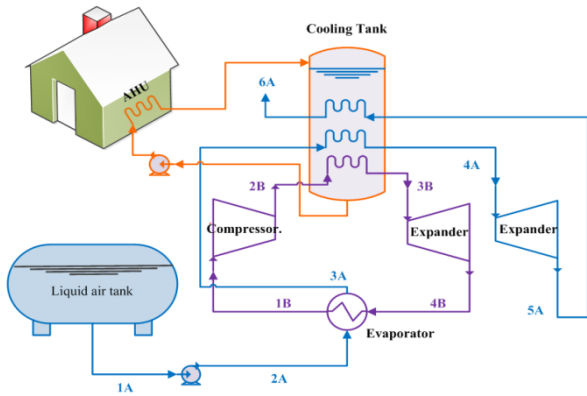Fig.1b First cycle's T-S diagram.

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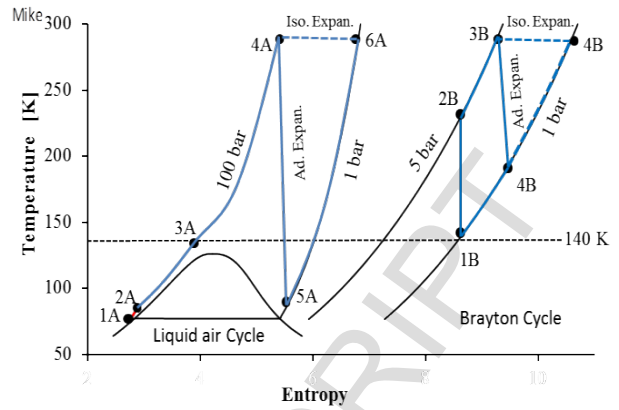Fig.2a Second cycle, LAir drives closed Brayton cycle

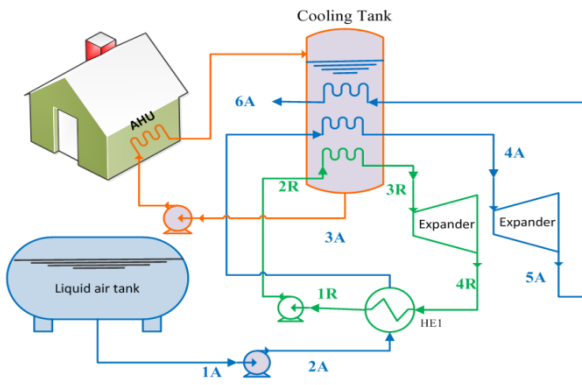

Fig.2b Second cycle 's T-S diagram.

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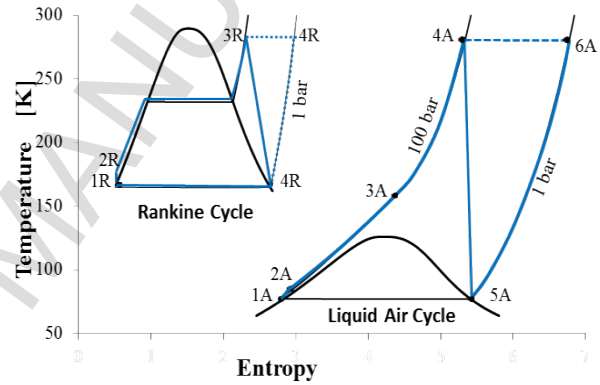Fig.3a Third cycle, LAir drives closed Rankine cycle

Fig.3b Third cycle's T-S diagram
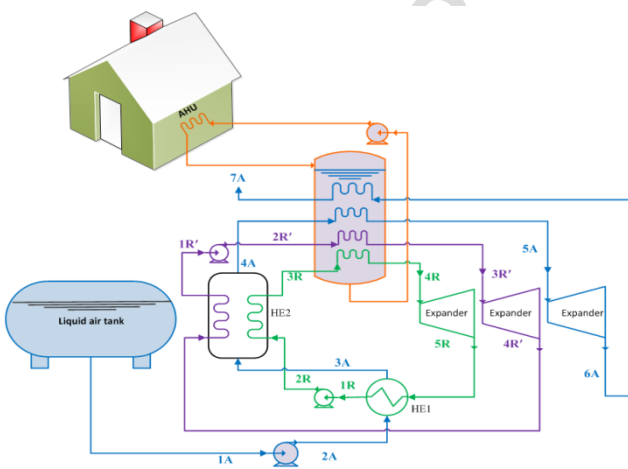
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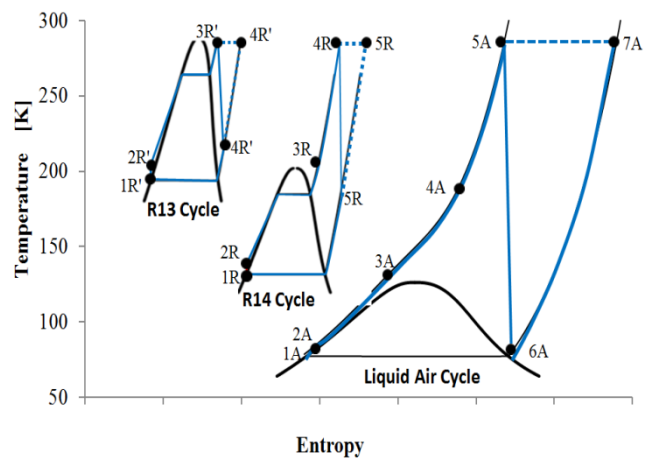
Fig.4a Fourth cycle, LAir drives two closed Rankine cycles

Fig.4b Fourth cycle's T-S diagram.

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121 **3- Thermodynamic modelling**

122   The proposed cycles were analysed from thermodynamic point view to find out the most effective system

123   which recovers most the energy storage in LAie/LN2, and provide higher output power and cooling capacity to

124   for the selected application. A mathematical model was developed for each of the above cycles using MATLAB

125   combined with REFPROP software to (a) calculate the properties of all working fluids at each state in the cycle,

126   (b) optimizer the operating conditions, (c) solve the energy and mass balance equations, (d) calculate LAir/LN2

127   mass flow rate, power output, cooling capacity, efficiency and the cycle COP. Both expansion processes were

128   considered in the current study and a wide range of the inlet pressure (P_{2A}) was discovered. The model was

129   simplified by the following:

130   • Liquid enters to the system at 78 K at near atmospheric pressure, and leaves as gas at 283 K.

131   • Heat absorbs or loss from/into the surroundings is negligible.

132   • The inlet pressure of all pumps and compressors is atmospheric pressure.

133   • The isentropic efficiency of pumps, expanders and compressors are 90%, 90% and 85% respectively.

134   • The pressure drop in all cycle's components is negligible.

135   For the first cycle shown in Fig.1 (a, b), the specific work output was calculated using Eqs.1 when adiabatic

136   expansion process is considered and Eq.2 when isothermal expansion process is considered.

137    $W_{Ad} = [(h_{3A} - h_{4A}) - (h_{2A} - h_{1A})]$ (1)

138    $W_{Iso} = [T_{tank}(s_{4A} - s_{3A}) - (h_{2A} - h_{1A})]$ (2)

139   Where; W is specific work in kJ/kg, h is the specific enthalpy in kJ/kg T is temperature in K and s is specific

140   entropy in kJ/kg-K. Whereas the subscripts *Ad, Iso, A* and *tank* refer to adiabatic expansion, isothermal

141   expansion, LAir cycle and cooling tank, respectively. While the specific cooling capacity was calculated using

142   Eqs.3 for the adiabatic expansion and Eqs.4 for the isothermal expansion process.

143    $CC_{Ad} = [(h_{3A} - h_{4A}) + (h_{5A} - h_{4A})]$ (3)

144    $CC_{Iso} = [T_{tank}(s_{4A} - s_{3A})]$ (4)

145   Where; *CC* is specific cooling capacity in kJ/kg.

146   Regarding the second cycle shown in Fig.2 the ratio of the closed Brayton cycle mass flow rate to the LAir

147   mass flow rate was calculated first by applying energy balance equation to the fluids enter and leave the

148   evaporator using Eq.5.

149 $\quad m_r = \dfrac{\dot{m}_B}{\dot{m}_A} = \dfrac{(h_{3A} - h_{2A})}{(h_{1B} - h_{4B})}$ (5)

150 Where; $\dot{m}_B$ is the mass flow rate in kg/s for the closed Brayton cycle, and $\dot{m}_A$ is the mass flow rate of the LAir

151 cycle in kg/s. The specific output works were calculated using Eqs. 6-8 for the adiabatic expansion and Eqs. 9-

152 11 for the isothermal expansion processes.

153 $\quad (W_A)_{Ad} = [(h_{4A} - h_{5A}) - (h_{2A} - h_{1A})]$ (6)

154 $\quad (W_B)_{Ad} = m_r[(h_{3B} - h_{4B}) - (h_{2B} - h_{1B})]$ (7)

155 $\quad W_{Ad} = (W_A)_{Ad} + (W_B)_{Ad}$ (8)

156 $\quad (W_A)_{Iso} = [T_{tank}(s_{5A} - s_{4A}) - (h_{2A} - h_{1A})]$ (9)

157 $\quad (W_B)_{Iso} = m_r[T_{tank}(s_{4B} - s_{3B}) - (h_{2B} - h_{1B})]$ (10)

158 $\quad W_{Iso} = (W_A)_{Iso} + (W_B)_{Iso}$ (11)

159 Where; the subscript A refers to the LAir cycle, and the subscript B refers to the closed Brayton cycle. The

160 specific cooling capacity was calculated using Eq.12 when adiabatic expansion process is considered and Eq.13

161 when the isothermal expansion process is considered.

162 $\quad CC_{Ad} = [(h_{4A} - h_{3A}) + (h_{6A} - h_{5A})] + m_r(h_{3B} - h_{2B})$ (12)

163 $\quad CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_r[T_{tank}(s_{4B} - s_{3B})]$ (13)

164 In the same previous manner, the ratio of the closed Rankine cycle mass flow rate to the LAir mass flow rate

165 for the third cycle shown in Fig.3 was calculated first by applying energy balance equation to the fluids enter

166 and leave HE1 as in the following Eq14.

167 $\quad m_r = \dfrac{\dot{m}_R}{\dot{m}_A} = \dfrac{(h_{3A} - h_{2A})}{(h_{1R} - h_{4R})}$ (14)

168 Where; $\dot{m}_R$ is the mass flow rate of the closed Rankine in kg/s and subscript R referred to the closed Rankine

169 cycle, the specific output works were calculated using Eqs. 15-17 for the adiabatic expansion and Eqs. 18-20 for

170 the isothermal expansion processes.

171 $\quad (W_A)_{Ad} = [(h_{4A} - h_{5A}) - (h_{2A} - h_{1A})]$ (15)

172 $\quad (W_R)_{Ad} = m_r[(h_{3R} - h_{4R}) - (h_{2R} - h_{1R})]$ (16)

173 $\quad W_{Ad} = (W_A)_{Ad} + (W_R)_{Ad}$ (17)

174 $\quad (W_A)_{Iso} = [T_{tank}(s_{5A} - s_{4A}) - (h_{2A} - h_{1A})]$ (18)

175 $\quad (W_R)_{Iso} = m_r[T_{tank}(s_{4R} - s_{3R}) - (h_{2R} - h_{1R})]$ (19)

176 $\quad W_{Iso} = (W_A)_{Iso} + (W_R)_{Iso}$ (20)

7

177 The specific cooling capacity was calculated using Eq.21 when the adiabatic expansion process is considered

178 and Eq.22 when the isothermal expansion process is considered.

179 $$CC_{Ad} = [(h_{4A} - h_{3A}) + (h_{6A} - h_{5A})] + m_r[(h_{3R} - h_{2R})] \quad (21)$$

180 $$CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_r[T_{tank}(s_{4R} - s_{3R})] \quad (22)$$

181 Regarding the fourth cycle shown in Fig.4 where the LAir cycle derives two cascades Rankine cycles, the

182 ratio of mass flow rate of the first closed Rankine cycle working fluid to the LAir mass flow rate (m_{r1}) was

183 calculated using the energy balance in HE1 as in Eq.23, and ratio of mass flow rate of the second closed

184 Rankine cycles working fluid to the LAir mass flow rate (m_{r2}) was calculated using the energy balance in HE2

185 as in Eq.24

186 $$m_{r1} = \frac{\dot{m}_R}{\dot{m}_A} = \frac{(h_{3A} - h_{2A})}{(h_{5R} - h_{1R})} \quad (23)$$

187 $$m_{r2} = \frac{\dot{m}_{R'}}{\dot{m}_A} = \frac{m_{r1}(h_{3R} - h_{2R}) + (h_{4A} - h_{A3})}{(h_{4R'} - h_{1R'})} \quad (24)$$

188 Where; $\dot{m}_R$ is the mass flow rate in kg/s for the first closed Rankine cycle and $\dot{m}_{R'}$ is the mass flow rate in kg/s

189 for the second closed Rankine cycle. The subscripts *R* is referring to the first second closed Rankine cycle, while

190 the subscript *R'* is referring to the second closed Rankine cycle.

191 The specific work output was calculated using Eqs.(25-28) when the adiabatic expansion process is considered

192 and Eqs. (29-32) when the isothermal expansion process is considered.

193 $$(W_A)_{Ad} = [(h_{5A} - h_{6A}) - (h_{2A} - h_{1A})] \quad (25)$$

194 $$(W_R)_{Ad} = m_{r1}[(h_{4R} - h_{5R}) - (h_{2R} - h_{1R})] \quad (26)$$

195 $$(W_{R'})_{Ad} = m_{r2}[(h_{3R'} - h_{4R'}) - (h_{2R'} - h_{1R'})] \quad (27)$$

196 $$W_{Ad} = (W_A)_{Ad} + (W_R)_{Ad} + (W_{R'})_{Ad} \quad (28)$$

197 $$(W_A)_{Iso} = T_{tank}(s_{6A} - s_{5A}) - (h_{2A} - h_{1A}) \quad (29)$$

198 $$(W_R)_{Iso} = m_{r1}[T_{tank}(s_{5R} - s_{4R}) - (h_{2R} - h_{1R})] \quad (30)$$

199 $$(W_{R'})_{Iso} = m_{r2}[T_{tank}(s_{4R'} - s_{3R'}) - (h_{2R'} - h_{1R'})] \quad (31)$$

200 $$W_{Iso} = (W_A)_{Iso} + (W_R)_{Iso} + (W_{R'})_{Iso}$$

201 (32)

202 The specific cooling capacity was calculated using Eq.33 when the adiabatic expansion process is considered

203 and Eq.34 when the isothermal expansion process is considered.

204     $CC_{Ad} = [(h_{5A} - h_{4A}) + (h_{7A} - h_{6A})] + m_{r1}[(h_{3R} - h_{2R}) + m_{r2}[(h_{3R'} - h_{2R'})$ (29)

205     $CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_{r1}[T_{tank}(s_{4R} - s_{3R})] + m_{r2}[T_{tank}(s_{4R'} - s_{3R'})$ (34)

206   The above cycles provide cooling and power which makes the system neither heat engine nor heat pump, so

207   assessing the system performance seems different than normal systems. The study defined two different factors

208   to evaluate the system performance; The first one is *COP* by considering the whole system as heat pump, in this

209   case, the output power converted to an equivalent cooling capacity (which is a cooling produced using this

210   output power to run a conventional AC system that has a COP of 3.5). Then the system COP was calculated

211   based on the total cooling capacity and the energy consumed to produce LAir or LN2 as in using Eq.35 (which

212   is 1080 kWh/kg for LAir and 1350 kWh/kg for LN2 (Ameel, 2013)) as in Eq35.

213     $COP = \left[\dfrac{Total\ cooling\ capacity}{1080}\right]_{LAir}$ or $COP = \left[\dfrac{Total\ cooling\ capacity}{1350}\right]_{LN2}$ (35)

214   The second factor is *Recovery Efficiency* (η_{RE}) where the whole system considered as heat engine. In this

215   case, the output cooling capacities were converted to an equivalent power (which is the input power needs to run

216   a conventional AC system that has a COP of 3.5 to provide the same cooling capacity). Then the system

217   *Recovery Efficiency* was calculated based on the total output power and the energy consumed to produce LAir or

218   LN2 as in using Eq. 54.

219     $\eta_{RE} = \left[\dfrac{Total\ output\ power}{1080}\right]_{LAir}$ or $\eta_{RE} = \left[\dfrac{Total\ output\ power}{1350}\right]_{LN2}$ (36)

220   **4- Results and discussion**

221   The proposed cycles use to provide cooling and power to commercial buildings at the peak times leading to save

222   energy and to reduce the electricity peak demands with more environment friendly solution. The above cycles

223   were investigated using two different clod storage mediums LAir and LN2, which are having almost similar

224   physical and thermodynamic properties, and the different requirements to produce each of them. LAir consumes

225   20% less energy and less required components than that of LN2 needs and this will enhance the system

226   performance significantly when LAir is used as the following results are showing;

227   Figs. 5-12 present specific output works, specific cooling capacities, the system COP and the system *Recovery*

228   *Efficiency* for the adiabatic and the isothermal expansion processes for all proposed cycles either using LAir or

229   LN2. For the adiabatic expansion scenario, the specific work vs the inlet pressure (P_{2A}) for all proposed cycles

230 presents in Fig.5 (a, b) where Fig.5a relates to LAir and Fig.5b relates to LN2. The figure shows the specific

231 output works have the same trend whether for the both working fluid (LAir or LN2) and there is no significant

232 change after a value of inlet pressure of 30 bar. The maximum power output for the 2nd, 3rd and 4th cycles

233 increases by 10.6%, 56.9% and 133.1% respectively compared with the first cycle when LAir is used and by

234 10.8% 54.8% and 129.5% consecutively when LN2 is used. The specific cooling capacities followed the same

235 output power trend as shown in Fig.6 (a, b) and compared to the first cycle, the maximum values of the cooling

236 capacities for 2nd, 3rd and 4th cycles show improvement by 3.0%, 15.2% and 36.8% when LAir is used and by

237 2.8%, 7.8% and 15.3% respectively when LN2 is used.

238 Regarding the isothermal expansion scenario, the specific output works and specific cooling capacities are

239 higher than that of adiabatic one as Fig.7 (a, b) and Fig.8 (a, b) shown. This expansion process allows the system

240 to increase the inlet pressure up to 500 bar or even more but after 300 bar there is no significant change

241 indicating no reason to increase the inlet pressure further. Compared with the adiabatic expansion, the output

242 works are increased by 3.1, 3.2, 2.6 and 2.0 times for the 1st, 2nd, 3rd and 4th cycles consecutively, when the

243 system uses LAir and almost the same values when LN2 is used. Also, compared with 1st cycle the specific

244 output works increased by 16.2%, 31.5%, 47.7% and for 2nd, 3rd and 4th respectively when LAir is used and by

245 13.7%, 32.5% and 48.4%, consecutively, when LN2 is used. The specific cooling capacities have almost the

246 same output work trend as shown in Fig.8 and their maximum values are 1.5, 1.5, 1.4 and 1.3 times that of the

247 adiabatic expansion for 1st, 2nd, 3rd and 4th cycles, consecutively,. Compared to the first cycle, the maximum

248 cooling capacities of the 2nd, 3rd and 4th cycles show improvement by 2.8%, 7.8% and 15% when, respectively,

249 LAir is used and 0%, 7.6% and 15%, consecutively, when LN2 is used.

250 The systems performance were assessed based on its *Recovery Efficiency* and COP as mentioned in section 3,

251 and for the adiabatic scenario, the *Recovery Efficiencies* and COPs of all proposed cycles are presented in Figs.

252 (9, 10) and their trends look similar to that of the output works. The figures indicate that the 4th cycle has highest

253 *Recovery Efficiency* and COP, and they reach 55% and 2, respectively, when LAir is used and 45% and 1.6,

254 consecutively, when LN2 is used. However, for the isothermal expansion scenario, the *Recovery Efficiencies*

255 and COPs of all proposed cycles are followed the output powers as shown in Figs. (11, 12). The figures show

256 that, the *Recovery Efficiency* and COP of the lowest system performance (1st cycle) reach 70% and 2.4,

257 respectively, when LAir is used and 55% and 1.9, respectively, when LN2 is used. However, in 4th cycle these

258 values reach 94% and 3.3, consecutively, when LAir is used and 78% and 2.7, consecutively, when LN2 is used.

259   The figures show clearly that, the systems *Recovery Efficiencies* and COPs when LAir is used are more than

260   20% higher than that of when LN2 is used. The fourth shows the highest system performance while the 1st cycle

261   shows the lowest.

262

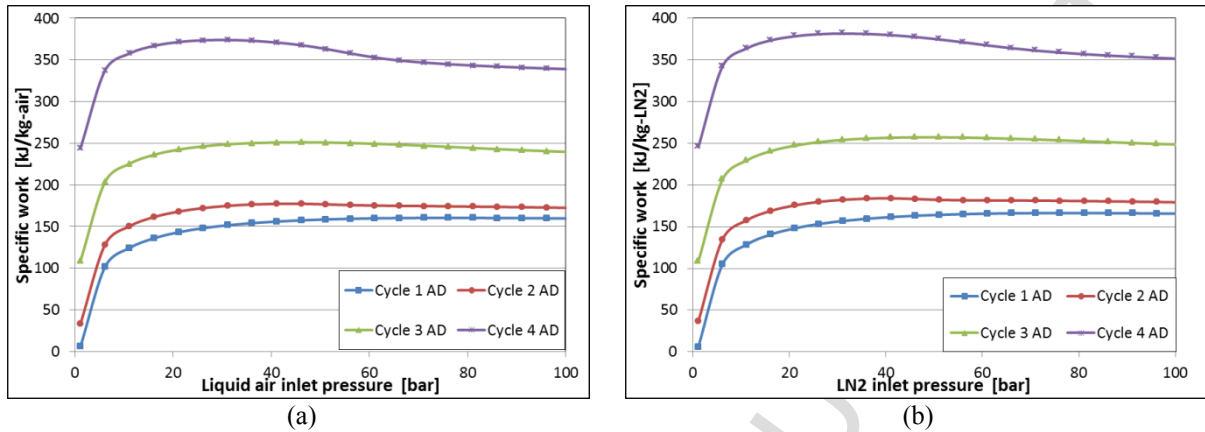(a)   (b)

Fig.5 specific output work at various inlet pressure for the adiabatic expansion

263

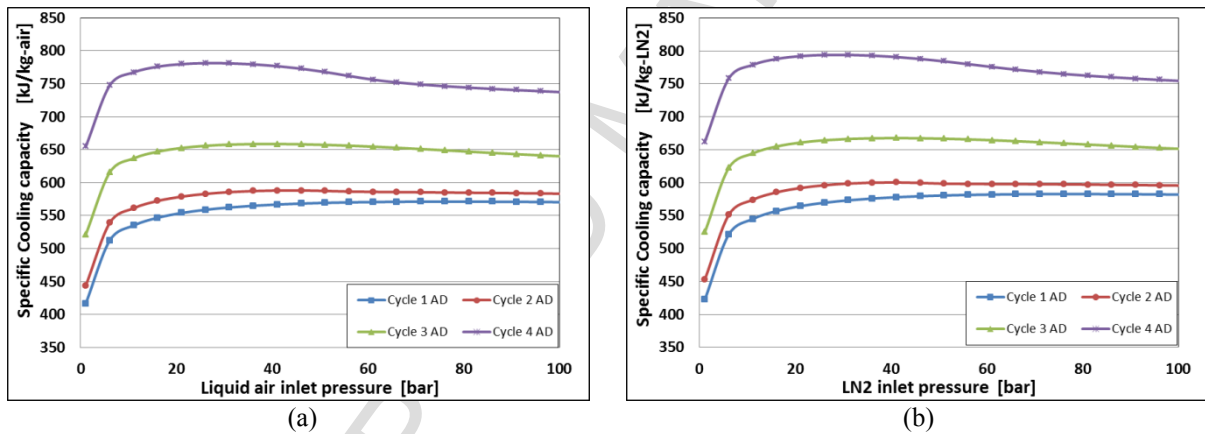(a)   (b)

Fig.6 Specific cooling capacity at various inlet pressure for the adiabatic expansion

264

(a)   (b)
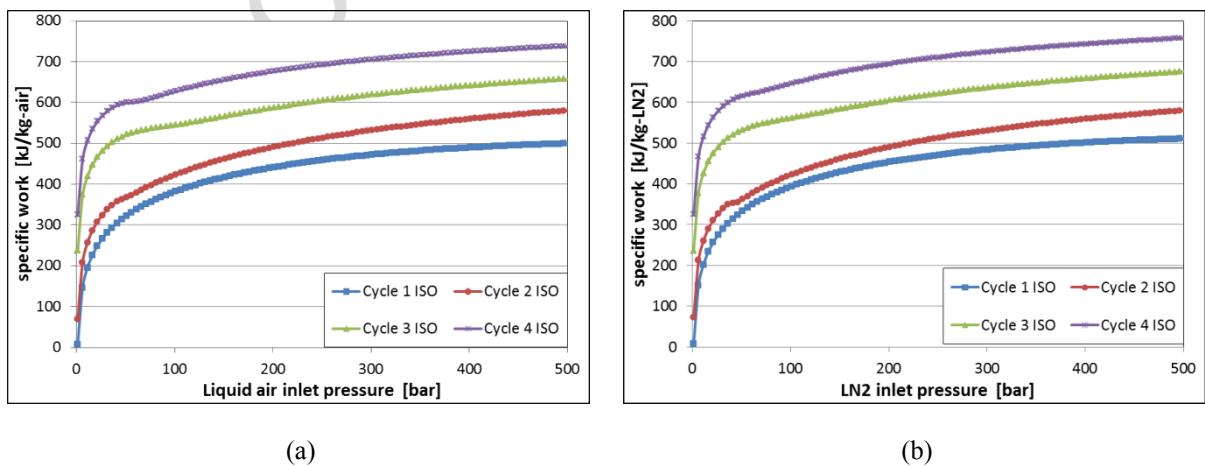
Fig.7 specific output work at various inlet pressure for the isothermal expansion

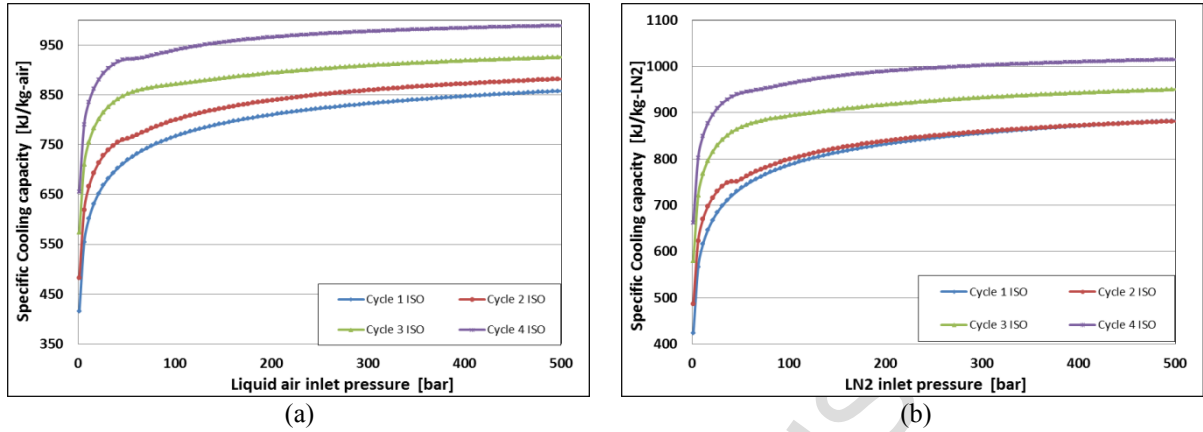265

266

(a)   (b)

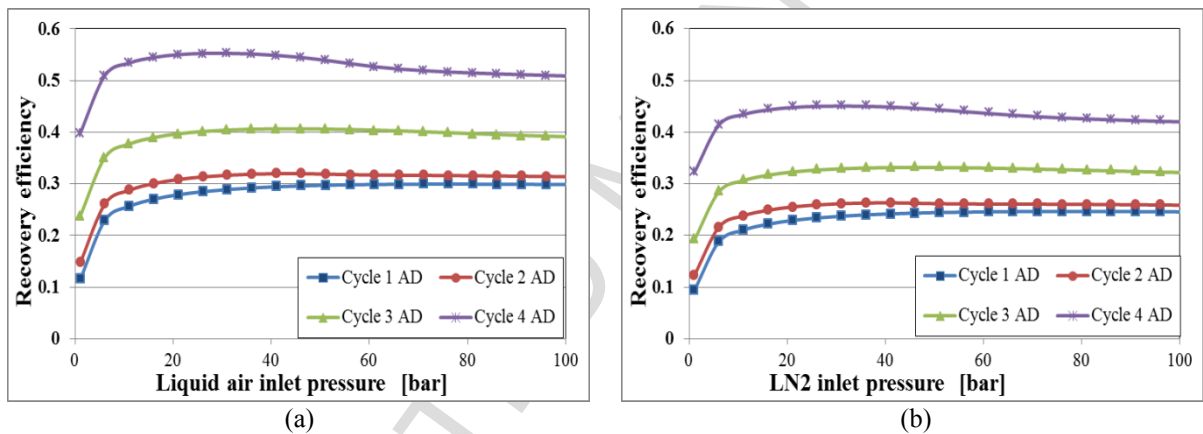Fig.8 Specific cooling capacity at various inlet pressure for the adiabatic expansion

267

(a)   (b)

Fig.9 *Recovery Efficiency* at various inlet pressure for the adiabatic expansion
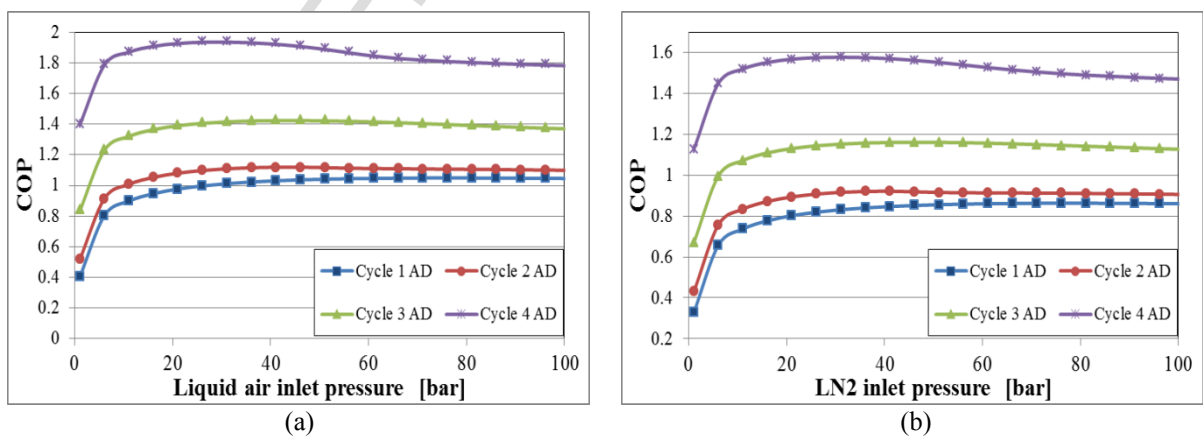
268

(a)   (b)

Fig.10 COP at various inlet pressure for the adiabatic expansion
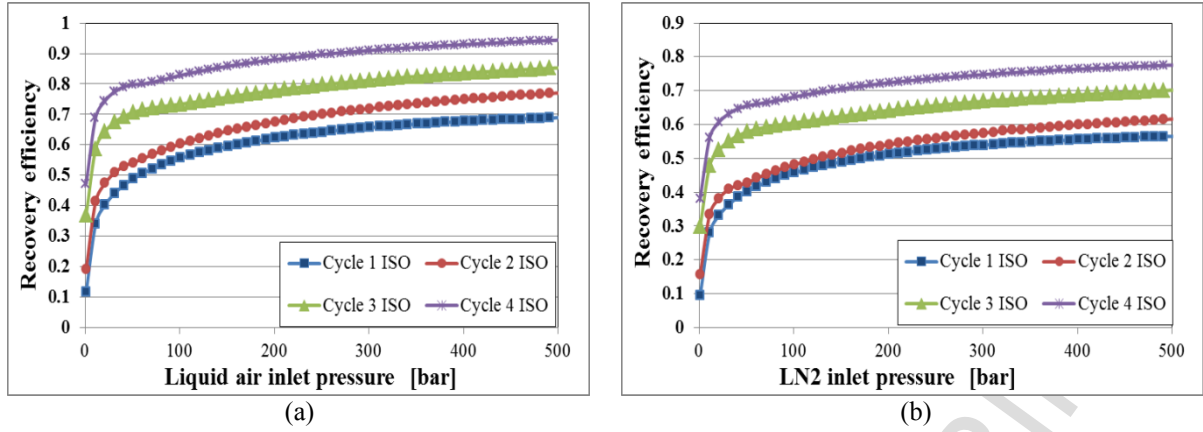
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(a)　　　　　　　　　　　　　　　　(b)

Fig.11 *Recovery Efficiency* at various inlet pressure for the isothermal expansion

270
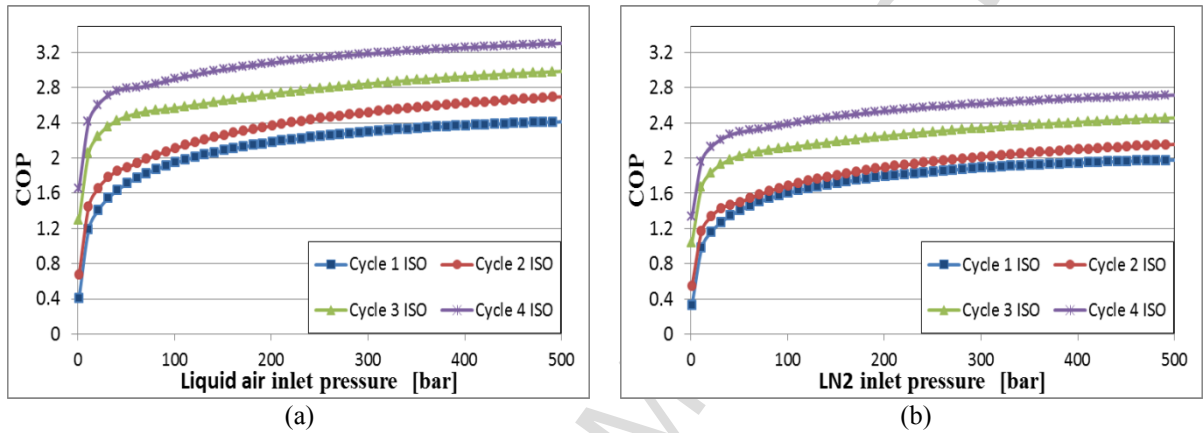

(a)　　　　　　　　　　　　　　　　(b)

Fig.12 COP at various inlet pressure for the adiabatic expansion

271　　Table 1 presents a comparison between LAir and LN2 when they use to fuel the proposed systems in terms of

272　　output work, cooling capacity, *Recovery Efficiency* and COP. The table shows in all cycles the output works and

273　　the cooling capacities are slightly higher when LN2 is used with difference less than 4%, however, the *Recovery*

274　　*Efficiencies* and the COPs are higher by 21-25% when Lair is used indicating using LAir is more efficient than

275　　LN2.

276　　Table 1 comparison between of the proposed systems in terms of maximum work output, cooling capacity,
277　　Recovery Efficiency and COP when they the two different fluids (LAir and LN2).

		Adiabatic Expansion				Isothermal Expansion			
Cycle No		1	2	3	4	1	2	3	4
Max. specific power output	Air	160	177	251	373	499	580	656	737
	Nitrogen	166	184	257	381	510	580	676	757
Difference [%]		3.6	3.8	2.3	2.1	2.2	0.0	3.0	2.6
Max. specific cooling	Air	571	588	658	781	858	882	925	989
	Nitrogen	582	600	667	793	883	881	950	1015
Difference [%]		1.9	2.0	1.3	1.5	2.8	-0.1	2.6	2.6
Max. recovery efficiency [%]	Air	29.96	31.98	40.66	55.29	68.95	77.09	85.33	94.43
	Nitrogen	24.66	26.34	33.18	45.07	56.53	61.64	70.19	77.61
Difference [%]		21.5	21.4	22.5	22.7	22.0	25.1	21.6	21.7
Max. system COP	Air	1.05	1.12	1.42	1.93	2.41	2.69	2.98	3.3
	Nitrogen	0.86	0.92	1.16	1.57	1.97	2.15	2.45	2.71
Difference [%]		22.1	21.7	22.4	22.9	22.3	25.1	21.6	21.8

278

279   A commercial building located in Ahwaz, Iran was selected as case study to find out how much energy the

280   proposed systems can save compared with the conventional AC systems, and the building cooling load is shown

281   in Fig.13. The comparison was made based on the cost of the required LAir or LN2 or the conventional AC

282   system power consumption to meet the building cooling load. The results are very sensitive to the LAir and LN2

283   prices and at the current prices of LAir , LN2 and kWh electricity (Ahmad et ta., 2016) all above cycles in the

284   isothermal expansion scenario consume less energy than the conventional system when LAir is used and only

285   the 1st cycle consumes higher when LN2 is used as shown in Fig.14 (a, b). At this level of price the 1st, 2nd, 3rd

286   and 4th cycles show savings up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used, and -3.5%, 5%,

287   16% and 24%, consecutively, when LN2 is used. Where the negative sign indicates there is no saving achieved

288   in this cycle.

289   It has been reported that the widespread of this technology and using the co-located systems leads to further

290   reduction in LAir and LN2 prices leading to further energy savings and further reduction in CO_2 emissions

291   (Akhurst et at., 2013). Fig.15 present the energy cost saving of each the above cycles at three different LAir and

292   LN2 prices (3.5, 2.5 and 1.5 pence per kg). The negative values mean the conventional AC system has less cost

293   of energy consumption, and all of these values except one refer to the adiabatic expansion process which is

294   practically difficult due to the heat gaining from the surround where the temperature is much higher than inside

295   the system. At the lowest LAir and LN2 prices the 1st, 2nd, 3rd and 4th cycles show savings up to 63%, 67%, 70%

296   and 72%, respectively, when LAir is used, and 55%, 59%, 63% and 67% , consecutively, when LN2 is used.

297   And at this level of price, the 4th cycle, which is the more complex one among the investigated cycles, shows

298   savings only14%, 8% and 3% higher than the 1st, the 2nd and the 3rd cycles, respectively, indicating these is no
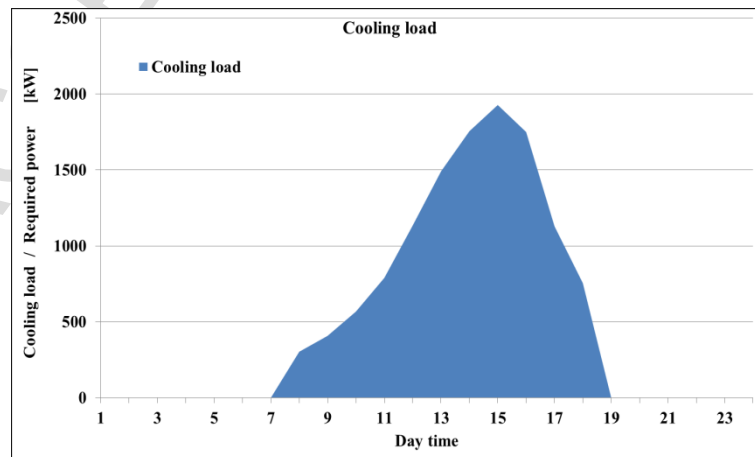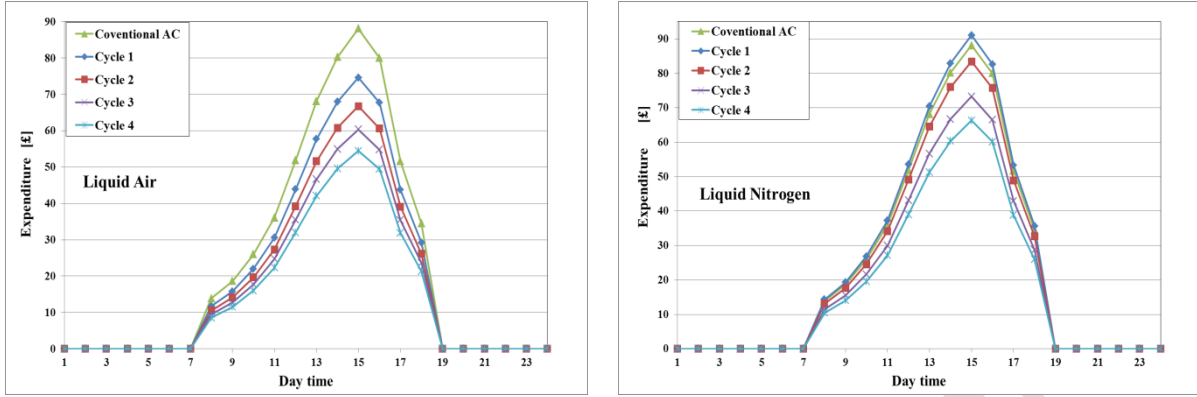
299   point to use such complex system.

300
301   Fig.13. cooling load and the required power of the selected building (Navidbakhsh, et al., 2013)
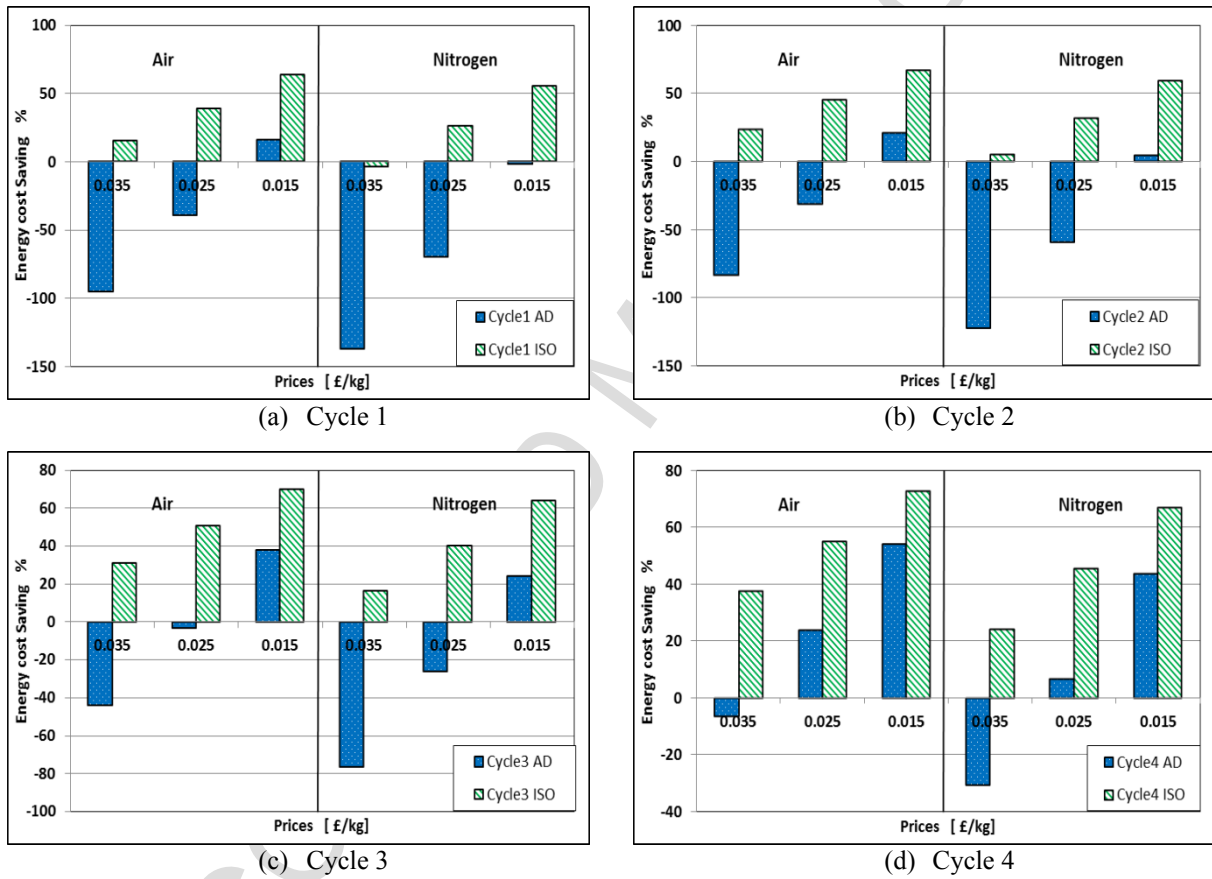
302

(a) Liquid Air

(b) Liquid Nitrogen

Fig.14. Daily energy cost for the proposed cycles and conventional AC system

303

(a) Cycle 1

(b) Cycle 2

(c) Cycle 3

(d) Cycle 4

Fig.15. Saving of each proposed cycle against the conventional AC system

305 **5- Conclusions**

306 The conventional AC systems consume great amount of energy particularly during the peak times where the

307 national electricity grid facing difficulties to meet the user's electricity demands. Consequently there is a need to

308 modify the traditional AC systems or to produce new technology that leads to save energy, reduce the peak

309 demands and reduce the CO_2 emissions. Cold energy storage in form of Liquid Air/N_2 is an attractive storage

310 system and can be used to provide air conditioning and power. Four different cryogenic cycles use either LAir

311 or LN2 to provide cooling and power to a commercial building were investigated and compared with the

312 conventional AC system and results showed that:

313 1- The 4th cycle showed the highest system performance, and it recovered up to 94% of the energy stored in

314 LAir and up to 78% of the energy stored in LN2, also it showed cost saving of the energy consumption up

315 73% when LAir is used and 67% when LN2 is used. However, the decisions about the selection of the

316 most economical solution must take into consideration the complete design of the system including

317 equipment sizing and investment costs.

318 2- LN2 system showed slightly higher (less than 4%) output works and the cooling capacities than LAir,

319 however, LAir system showed 21-25% higher *Recovery Efficiency* and COP than LN2 due to its lower

320 required energy to produce it.

321 3- Compared to the conventional system at the current LAir and LN2 prices the 1st, 2nd, 3rd and 4th cycles

322 showed cost energy saving up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used, and -

323 3%, 5%, 16% and 24%, consecutively, when LN2 is used.

324 4- Extensive of using this technology leads to further reduction in the LAir and LN2 prices, and results

325 showed that, at price level of 1.5 pence kg-LAir/LN2 the 1st, 2nd, 3rd and 4th cycles saved up to 63%,

326 67%, 70% and 72%, respectively when LAir is used, and 55%, 59%, 63% and 67%, consecutively

327 when LN2 is used, leading to use the simplest cycle.

328

Nomenclature		**Subscripts**	
h	enthalpy kJ/kg	A	Liquid air cycle
CC	specific cooling capacity kW/kg-LAir	B	Brayton cycle
$\dot{m}$	mass flow rate kg/s	Ad	Adiabatic expansion
s	entropy kJ/kg.K	Iso	Isothermal expansion
W	specific power kW/kg-LAir	R	Closed Rankin cycle/first closed Rankin cycle
m_r	the closed Brayton or Rankin cycles mass flow rates to LAir mass flow rate	R'	Second closed Rankin cycle
m_{r1}	the first closed Rankin cycle mass flow rate to LAir mass flow rate	$tank$	Cooling tank
m_{r2}	the second closed Rankin cycle mass flow rate to LAir mass flow rate		

329 **Acknowledgment**

332

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