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Original article

Gravity refrigeration cycle: An efficient approach for refrigeration in mountainous regions

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ABSTRACT

Traditional refrigeration methods often rely on energy-intensive, high operational costs and result in considerable negative environmental impacts. This paper introduces a novel and revolutionary approach to refrigeration technology through the implementation of the Gravity Refrigeration Cycle (GRC). GRC utilizes vertical pipelines in high elevation mountains instead of compressors to increase the pressure of refrigeration gases. Gas added to the top of the vertical pipeline is pulled down by gravity, increasing the pressure and density of the gas along the vertical pipeline and liquefying it at the bottom of the pipeline. The liquid is then transported back to the top of the mountain, where cooling services are provided, and the cycle starts again. The estimated coefficient of performance for a GRC system with 28 and −7 °C hot and cold sinks is 4.19, which is 1.84 times higher than conventional, mechanical refrigeration systems and a cost of 274 USD/kWt, 2.2 times higher than conventional systems. Gravity Refrigeration Cycle represents a paradigm shift in refrigeration technology in mountainous regions, particularly for processes with high demand for cooling, such as hydrogen liquefaction. As the world seeks greener and more economical alternatives, GRC could be a promising advancement in refrigeration.

Introduction

The urgency to combat climate change necessitates a fundamental shift in refrigeration technologies [1]. New sustainable alternatives are crucial to reduce greenhouse gas emissions, conserve energy, and ensure reliable cooling solutions across industries [2]. The pressing need for new sustainable refrigeration technologies has never been more evident as the world grapples with the challenges of climate change and population increase in developing countries [3]. Emerging technologies, such as magnetic refrigeration [4], thermoelectric cooling [5] and seawater air-conditioning [6] promise of improved energy efficiency by employing novel mechanisms for heat exchange. These innovations not only reduce operational costs but also decrease the reliance on non-renewable energy sources, fostering a more sustainable energy landscape.

The main contribution of this paper is to present a completely new refrigeration cycle that uses gravity in vertical pipelines to compress the refrigeration gas instead of using compressors or pumps. The technology was named gravity refrigeration cycle (GRC). This is the first paper to mention this technology in the literature and industry. The most similar refrigeration cycle compared with the GRC proposed in this paper found in the literature was created by Von Platen and Muter in 1928 and involves bubble pumps, gravity and absorber [7]. However, GRC does not require an absorber. Gravity is also applied in conventional refrigeration systems to enhance the performance of evaporators and heat pump systems [8], however, the compression is not performed by gravity. Wiencke 2011, describes a cooling system design where gravity is used to separate refrigeration liquids [9]. Lee and Kim 2004 studied how gravity in multi-pass condensers affects refrigerant flow rate distribution in U-bend tubes [10]. Aprea et al. 2003 described the influence of gravity in condensation heat transfer coefficients for $CHClF_2$ [11]. Li et al. 2023 investigated the low boiling heat transfer and pressure drop of $CF_3CH_2CHF_2$ inside horizontal tubes under hypergravity [12]. Killion and Garimella 2003 studied the gravity-driven flow of liquid films and droplets in horizontal tube banks [13].

In contrast to traditional methods, the proposed GRC harnesses the power of gravity with high-density, high-pressure gases to create energy-efficient refrigeration cycles without the need for compressors. In this paper, we provide a comprehensive analysis of the theoretical framework behind the GRC, including thermodynamic models and

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Nomenclature

COP	Coefficient of Performance
CRC	Conventional Refrigeration Cycle
GRC	Gravity Refrigeration Cycle
GWP	Global Warming Potential
LEST	Lift Energy storage technology
M−TES	Mobilized thermal energy storage
SF_6	Sulfur Hexafluoride
USD	United States Dollar

simulations. We also present results that validate the effectiveness of the proposed approach. Additionally, a comparative case study is conducted, benchmarking the GRC against traditional refrigeration cycles in terms of energy efficiency and cost-effectiveness. This paper is divided into five sections. Section 2 describes the GRC technology and the equations applied. Section 3 presents and discusses the results of the paper. Section 4 concludes the paper.

Methodology

The gravity refrigeration cycle provides cooling services on the top of a mountain with the evaporation of refrigeration gas. After the cooling potential is extracted from the gas, it is added to a vertical pipeline at 10 bar. This is the same pressure as in the evaporator. Thus, there is no need for compressors. A compressor could be added if a lower temperature is required. However, this could lower the efficiency of the system. The gas pressure, temperature, and density will increase along the pipeline. Heat exchangers are embedded along the vertical pipeline to reduce the gas temperature. The heat exchanger could be built within the pipeline to lower costs and reduce friction in the refrigerant gas. It is assumed that the refrigerant gas temperature is 5 °C higher than the ambient temperature, which allows a cool heat transfer between the refrigerant gas and the environment. The gas turns into liquid in the condenser, which uses outside ambient air for cooling. The liquid refrigerant is stored in a lower liquid storage tank. If the refrigeration plant has a small cooling capacity, the liquid is loaded onto an electric truck (Fig. 1a), which transports the liquid refrigerant up the mountain and releases it in the upper liquid storage tank. If the refrigeration plant has a high cooling capacity, the refrigeration liquid is pumped from the lower liquid storage tank to the upper liquid storage tank (Fig. 1b).

The energy efficiency of GRC is compared with the conventional refrigeration cycle by calculating the system's coefficient of performance (COP). This is estimated with Equation (1), where C is the cooling service produced by the GRC system (in W). E is the electricity consumed by the GRC system in (in W). The cooling service is further detailed in Equation (2), m is the flowrate of liquid SF_6 (in kg/s), L is the latent heat of evaporation at the evaporator (in J/kg), T_E is the temperature of the refrigeration gas evaporating on the top of the vertical pipeline (in ^oC), T_A is the ambient temperature (in ^oC), and minus 5 is the required temperature difference for the cooler on the top of the mountain. c_G is the average specific heat of the gas (in J/kg^{o}C). c_L is the average specific heat of the liquid (in J/kg^{o}C). The electricity consumed is further detailed in Equation (3), where H is the altitude difference between the lower liquid storage tank and the upper liquid storage tank (in meters), g is the gravity acceleration, equal to 9.81 m/s^2, and e is the efficiency of the electric truck, assumed to be 60 % [14], or pump assumed to be, 90 % [15]. Equation (4) is used to estimate the pressure variation along the gas and liquid pipelines, where P is the pressure of the section of the column being analyzed (in Pa), P_i is the pressure directly above the section of the column being analyzed (in Pa), ρ is the density of the gas and liquid [16] (kg/m^3), h is the altitude of the sections in the analysis, which in this case is 100 m. The pressure loss in the gas pipeline is negligible as the gas velocity is very low (3 m/s). The velocity must be low as the gas gains must dissipate heat to the environment while it moves down the pipeline. The coefficient of performance (COP), assuming Carnot efficiency, is estimated with Equation (5) [17]. Where COP is the coefficient of performance of the refrigeration system, T_C is the temperature of the cold heat sink (i.e., the temperature in the evaporator in ^oC), T_H is the temperature of the hot heat sink (i.e., the temperature in the condenser in ^oC) and e is the refrigeration system's efficiency.

$$COP = \frac{C}{E} \tag{1}$$

$$C = m \times \mathrm{L} + (T_E - T_A - 5) \times c_G - (T_A + 3 - T_E) \times c_L \tag{2}$$

$$E = H \times m \times g \times e \tag{3}$$

$$P = P_i + \rho \times g \times h \tag{4}$$

$$\mathrm{COP} = \frac{T_C}{(T_H - T_C)} \times e \tag{5}$$

The selection of high-density gases further enhances the efficiency of the GRC. Table 1 presents a comparison of different gases for GRC. The higher the density and molar mass of the gas, the smaller the pipeline altitude to liquefy the gas. The critical temperature must be higher than the ambient temperature. If not, the gas will not liquefy in the bottom of the pipeline. But also, the critical temperature should not be much higher than the temperature at the bottom of the mountain because the density of the gas significantly increases when it is near the critical temperature. We have tested the gases in Table 1 for applying GRC to Saudi Arabia and found that SF_6 is the most suitable gas. The case study intends to produce ice on the top of mountains in Saudi Arabia, where the average ambient temperature can reach 40 °C. The gas selected is

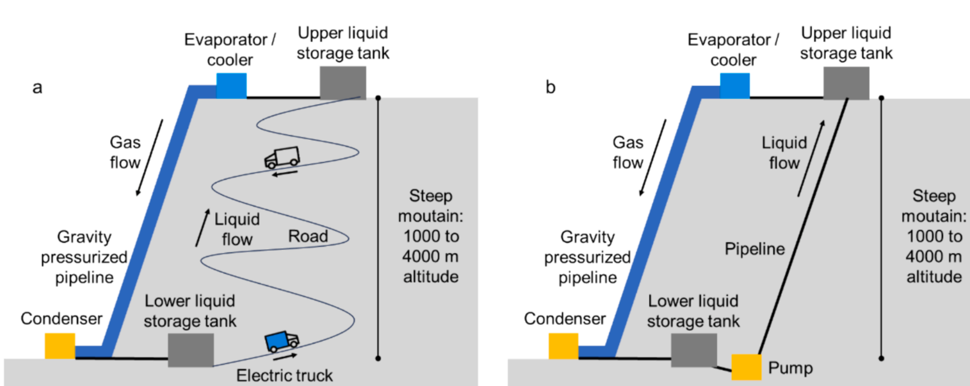

Fig. 1. Gravity refrigeration cycle description using (a) electric trucks and roads or (b) pumps and pipelines.

Table 1
Comparison of different gases for GRC.

Gas	Gas name	Density at STP (kg/m^3)	Molar mass (g/mol)	Critical temp. (^oC)	Critical pressure (bar)	Critical density (kg/m^3)	General comments for GRC application
CO_2	Carbon dioxide	1.98	44	30.98	73.77	467.6	Widely available, but low gas density, low critical temperature and high critical pressure.
Xe	Xenon	5.98	124 to 136	16.7	58.4	1103	High gas density, but low critical temperature, rare and unstable.
SF_6	Sulfur hexafluoride	6.43	146	45.57	37.55	724.3	High gas density, right critical temperature, low critical pressure. Ideal for GRC
C_3F_8	Octafluoropropane	8.17	188	71.87	26.4	628.0	High gas density, but the high critical temperature and does not cool at negative temperatures.
C_4F_8	Octafluorocyclobutane	8.69	200	115.44	27.8	620.0	High gas density, but the high critical temperature and does not cool at negative temperatures.
Rn	Radon	9.73	210 to 224	104	62.8	1630	High gas density, but high critical temperature, rare and unstable.
C_4F_{10}	Perfluorobutane	10.34	238	113.2	23.2	630.0	High gas density, but high critical temperature and does not cool at negative temperatures.

sulfur hexafluoride (SF_6). SF_6 is a colorless, odorless, and non-flammable gas with a 146 M mass. It is suitable for GRC because of its high molar mass and lower boiling point. Other advantages of using SF6 are described in Table 2. The main disadvantage is the high global warming potential (GWP), 23,900 times higher GWP than CO_2 [7]. However, this can be mitigated by minimizing leaks in the system.

Fig. 2 presents the physical characteristics of SF_6 relevant to the paper. Fig. 2a presents the pressure vs temperature phase change diagram for SF_6. The critical temperature and pressure of SF_6 are 45.57 °C and 37.55 bar, and the triple point is −49.60 °C and 2.31 bar [18]. Fig. 2b presents the density vs. pressure phase change diagram, and Fig. 2c presents the density vs.temperature phase change diagram for SF_6 [18], where the critical density is 733.3 kg/m^3. Fig. 2d presents the SF_6 gas pressure along the vertical pipeline. Further details on the physical characteristics of SF_6 gas were taken from [19].

Table 2
Advantage for using sulfur hexafluoride as a GRC refrigerant.

Advantages	
Non-toxic and non-flammable under normal conditions	Safe for various applications. However, it's important to note that if SF_6 leaks into the environment, it can form potentially harmful byproducts when exposed to electrical discharges.
Chemical Inert	It does not react easily with other substances, which increases its lifetime.
Dense gas	Six times denser than air at 1 atm due to a high molar mass of 146.
Low critical temperature	Even though SF_6 has a high molar mass, it still has a low critical temperature. Also, the critical temperature is similar to the ambient temperature of warm desert regions (45.57 °C). This is convenient because the temperature of the pipeline will be similar to the ambient temperature along the pipeline. If the critical temperature is too low, the refrigerant will not liquefy, if the critical temperature is too high, then it will not provide cooling at low temperatures. SF_6 has the ideal critical temperature for this application.
Superior compression characteristics	Enhances cooling effects.
Thermally stable	It can maintain its properties even at high temperatures, which increases its lifetime.
Other applications of SF_6	Insulating gas in electrical equipment, tracer gas for leak detection, cover gas in magnesium production, medical imaging contrast agent, and is applied in various research and industrial processes.
Disadvantage	
Low latent heat of vaporization	The latent heat of vaporization of SF_6 in GRC small 94.14 kJ/kg. This is not convenient for GRC because it takes a lot of energy to pump the liquid SF_6 up the mountain and a little cold can be extracted from evaporating the liquid. The bigger the latent heat, the best it is for GRC.

Results and discussion

Fig. 3 presents the case study in Abha, Saudi Arabia (Fig. 3a). The altitude difference of the proposed vertical pipeline is 1750 m (Fig. 3b). The horizontal distance between the condenser and the evaporator with the pipeline is 6.4 km (an average angle of 15.3°), and with the existing roads is 16.4 km (an average angle of 6.1°). The pipeline cannot be constructed in a tunnel because it dissipates heat from the compressed gas inside it. Thus, it is installed over a clean surface with supports to hold the pipeline above the ground. Fig. 3c shows the proposed GRC project with a topographical background from [21]. This project assumes that the cold will be consumed beside the evaporator. Examples of processes that require a lot of cooling energy are hydrogen, oxygen and nitrogen liquefaction. Options to transport the cold from the GRC plant to Abha are described in the discussion section (Section 4).

Fig. 4a presents the coefficient of performance of conventional refrigeration cycles, using Equation (4) and assuming a hot sink temperature of 28 °C, the temperature on the top of the mountain close to Abha. The cold sink temperature assumed is −7°C, which results in a temperature difference of 35 °C and a COP of 7.6, assuming 100 % Carnot efficiency, 3.8 with 50 % Carnot efficiency, 2.28 with 30 % Carnot efficiency and 0.76 with 10 % Carnot efficiency.

The refrigerated liquid reaches the top of the mountain through the pipeline or electric truck, where it is cooled to 25 °C, then the refringent gas evaporates and cools to −7°C, providing cooling services. After the gas evaporates, it is heated to 18 °C to extract all the cold from the gas. Fig. 4b presents the vertical pipeline temperature of the gas and liquid pipelines, and the ambient temperature. The ambient temperature varies from 23 to 40 °C and the temperature inside the pipelines is assumed to be 5 °C higher. To achieve these temperatures, the heat resulting from the gas compression must be dissipated into the environment. The resulting gas pressure and density along the pipeline are estimated using Equation (4). The heat is extracted along the gas pipeline, as the refrigerant gas should be as cold as possible to increase its density and effectiveness as a gravity refrigerant. Fig. 4c and d show the pressure and density of the refrigerant gas in the pipeline in red, respectively. The pressure of the gas at the top of the vertical pipeline is 10.26 bar, and it increases to 37.55 bar. The density of the gas at the top of the vertical pipeline is 68.2 kg/m^3, and it increases to 724.3 kg/m^3. The closer the gas pressure is to the phase change pressure, the faster the density of the gas increases with pipeline depth. When the gas reaches the condenser, it liquefies, and is added to the lower storage tank and then pumped to the top of the mountain. Fig. 4e and f show the pressure and density of

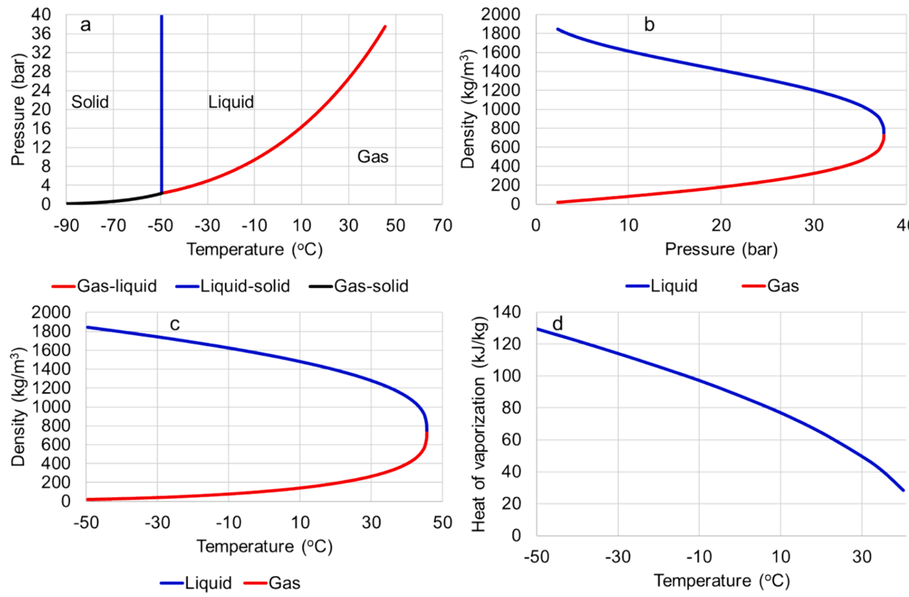

Fig. 2. (a) Pressure vs. temperature phase change diagram for SF_6 [18], (b) density vs. pressure phase change diagram for SF_6 [18], (c) density vs. temperature phase change diagram for SF_6 [18], and (d) heat of vaporization vs. temperature [20].

the refrigerant liquid in the pipeline in red, respectively. The pressure of the liquid at the top of the vertical pipeline is 26 bar and it increases to 282.6 bar. The density of the liquid at the top of the vertical pipeline is 1305 kg/m^3, and it increases to 1609 kg/m^3.

Table 3 compares the coefficient of performance of the conventional refrigeration cycle and the gravity refrigeration cycle. Conventional mechanical refrigerators usually have efficiencies 30 % of the Carnot efficiency, and its COP for cooling from 28 to −7°C is around 2.28. The estimated COP for the GRC plants with pump and truck are 4.19 and 2.80, respectively, 84 and 23 % higher than CRC plants with 30 % Carnot efficiency. Fig. 5 compares the coefficient of performance for CRC and GRC in a diagram. This shows that the COP for GRC is better than that of CRC. As the GRC COP using trucks is comparable to the COP of CRC but higher investment cost, it is not a viable refrigeration solution. To validate these results, it would be interesting to run experimental tests. However, for the experiment to be executed, a vertical pipeline with a 1750 m drop is required. This involves environmental licensing and high implementation costs, which were not available during the implementation of the research.

To estimate the costs of GRC, we used the plant described in Fig. 3b, with 1 GW cooling capacity, using pumps to transport the liquid refrigerant back to the top of the mountain. This plant was designed with pumps and pipelines because of the gains in scale. For instance, producing 1 GW of cooling requires a mass flowrate of 12.5 tons of liquid SF_6 per second. Transporting this with trucks would require two trucks per second with 6.25 tons capacity, which is not practical. Table 4 presents the volume of gas, cross-section area, and number of tunnels in the vertical pipeline. The pipeline diameter is assumed to be 3.5 m and the gas velocity varies from 2.5 to 3.5 m/s. This results in a gas residence time of 12 to 8 min along the pipeline, which is assumed to be enough to lower the temperature of the gas in the pipeline, according to Fig. 4b. The gas pipeline costs assume steel pipes with 100 to 300 m hydraulic head (Fig. M.6.A at [22]) and equals 81 million USD. These are initial cost estimates. With optimized design and substantial investment in the technology, these costs can be lowered. For instance, having 6 pipelines on the top of the mountain is more expensive than having one pipeline with a large diameter, however, the greater the number of pipes, the higher the heat exchange between the gas and the ambient. We assume a low gas velocity in the pipes to allow the heat to exchange with the ambient (3 m/s). A larger gas velocity would result in substantially lower costs. Future work is required to optimize the design and costs of GRC. Table 5 presents a cost estimate for the GRC plant. It turns out that GRC is 2.2 times more expensive than CRC.

If the right conditions for the construction of a GRC plant exist, the decision to invest in GRC instead of CRC will depend on whether, (i) there is a constant demand for cooling throughout the year and the plant operates at a capacity factor of 80 % or higher. This is because the investment cost and operation efficiency of GRC are high, (ii) the interest rate of the project is low (capital is cheap), and (iii) energy prices are high, which increases the operation cost of CRC solutions. A significant disadvantage of GRC is that its potential depends on the topography and that the cooling demand must be close to high mountains. Also, GRC is a centralized cooling technology, and the cooling service should be consumed close to the plant. Industrial processes that require high cooling demand are air, natural gas, and hydrogen liquefaction. There is also the possibility of transporting the cold services with Mobilized thermal energy storage (M−TES) [25] or an ammonia district cooling system [26], however, this would reduce the COP and increase the costs of the system. M−TES consists of using a phase change material to store cold [27], for example, freezing water, and then transporting the ice with electric trucks to the cooling demand [28]. Apart from providing cooling services on the top of the mountain, GRC plants can also be used to provide heating services on the bottom of the mountain.

We have tested the GRC concept with other gases. The main conclusion for the gas selection is that the critical temperature should be higher than the ambient temperature so that the liquid can be liquefied in the pipeline. However, the critical temperature should not be a lot higher than the ambient temperature, as it reduces the gas density and its effectiveness as a gravity refrigerant. The density of the refrigerant gas should be high at ambient temperature. These factors make SF_6 an ideal gas for GRC. CO_2 could be an interesting option as it has a latent heat of 247 kJ/kg, evaporating at −5°C and 30 bar. However, it would require a pipeline with an altitude of 4500 m and a 73 bar pressure on the bottom of the pipeline to achieve a 35 °C cooling effect. This is not practical and viable.

As the energy required in the system is to transport the liquid refrigerant from the bottom to the top of the mountain, the system can be adapted to operate as an energy storage alternative. For example, during the day when there is excess solar power generation, the liquid refrigerant will be pumped from the lower tank to the upper tank, and

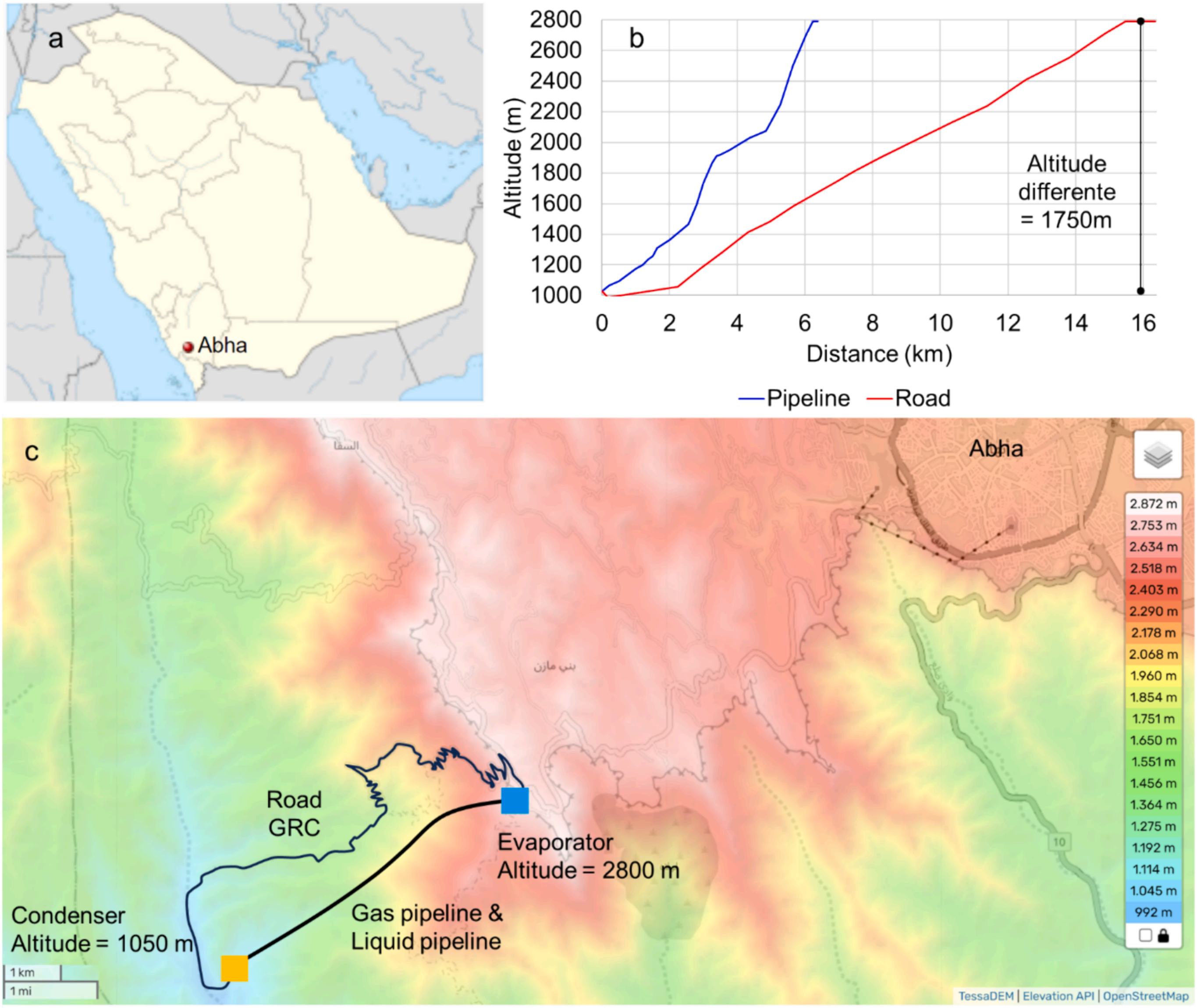

Fig. 3. (a) Case study location in Abha, Saudi Arabia, (b) the altitude difference between the condenser and evaporator with gas and liquid pipeline, and road, and (c) schematic map of the proposed GRC.

some of the liquid refrigerant will be stored in the upper tank. During the night, when there is no solar generation, the pump will not function and the level in the upper tank will lower while the lower tank will rise. However, the energy storage cost might be excessively high, as it would require a liquid pipeline with larger diameter, pumps with higher capacity and larger pressurized tanks to store the refrigerant liquids.

Future work will investigate the use of gravity refrigeration cycle in (i) high rise buildings and in (ii) the deep ocean. In high rise buildings, the refrigerant gas can be transported to the top of the building using existing lifts and autonomous trailers, similar to the Lift Energy storage technology (LEST) [29]. Another alternative for GRC is to build it in the deep ocean. The main benefits are: (i) the temperature in the deep ocean reduces with depth, reaching 1 to 5 °C below 1000 m. (i) the pipeline could be suspended by a ship on the surface and supported by the ground, i.e. vertical, reducing the length of the pipeline, (ii) the potential for GRC would increase significantly, (iii) the pressure of the liquid refrigerate would be similar to the pressure outside the vertical pipeline, (iv) the heat exchange in water is better than in air. The main challenges are: (i) the vertical pipeline pressure would vary between 2 bar to 70 bar, however, the outside pressure would vary from 1 bar to 400 bar (assuming a 4000 m depth), (ii) finding appropriate refrigeration gas that is cheap, inert and with a critical temperature close to 0 °C (temperature of the deep ocean), (iii) the pipeline and heat exchanger should be resistant to seawater corrosion, which would increase costs. Other refrigeration gases and operation parameters will be required for these different applications.

Conclusion

This paper has investigated the possibility of using gravity as the main driving force for refrigeration, i.e., gravity refrigeration cycle. Sulfur hexafluoride (SF_6), a high-density refrigeration gas, was found to be a good candidate for providing cooling services during the summer in Saudi Arabia. Results show that this cooling approach system has 4.19 COP, which is 1.84 times higher than conventional, mechanical refrigeration cycles. However, the gravity refrigeration cycle costs 2.2 times higher than conventional refrigeration cycle. GRC is also restricted to mountainous regions, and the costs of distributing the cold to locations surrounding the plant might be prohibitively high. Even though the proposed case study shows that GRC is more expensive than CRC, there

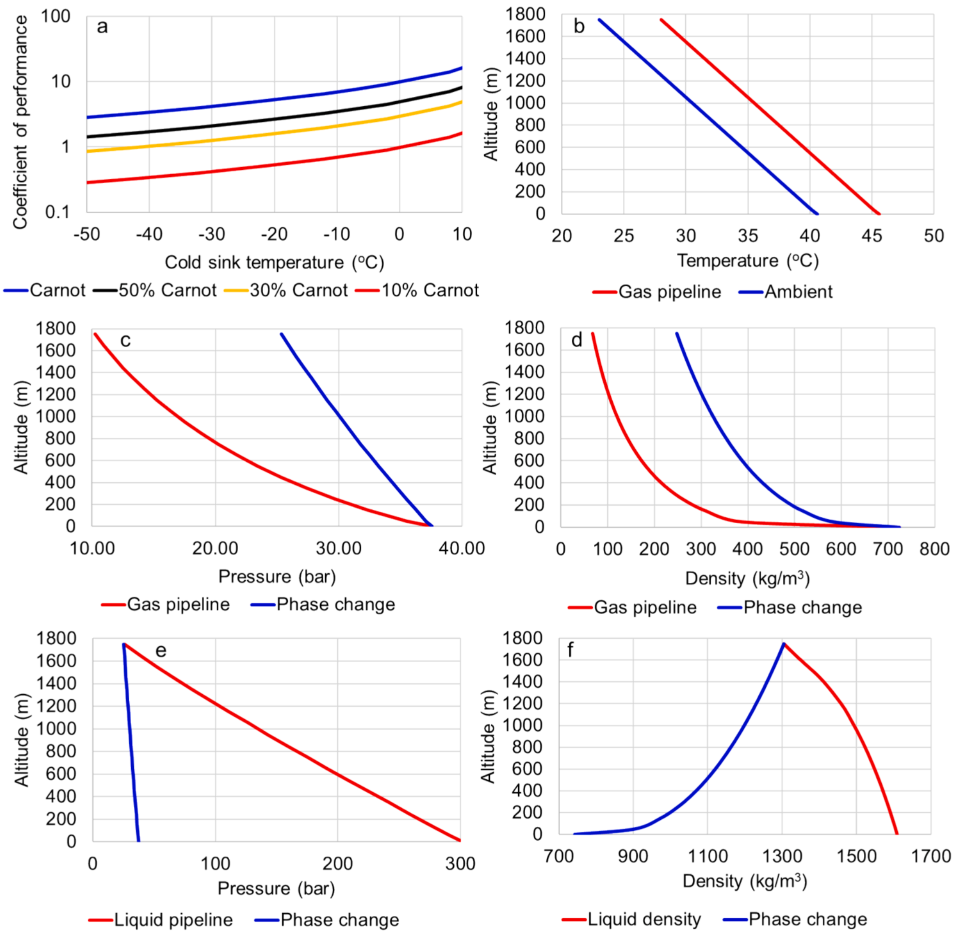

Fig. 4. (a) Coefficient of performance of conventional refrigeration cycles, (b) vertical pipeline temperature of the gas and liquid pipeline, and ambient temperature, (c) gas pressure, (d) gas density, € liquid pressure, and (f) liquid density at different altitudes [16].

Table 3
Comparison between the conventional refrigeration cycle and the gravity refrigeration cycle COP.

System characteristics	Values	
Conventional refrigeration cycle (CRC)		
Hot sink (°C)	28	
Cold sink (°C)	−7	
Temperature difference (°C)	35	
COP (100 % Carnot)	7.60	
COP (50 % Carnot)	3.80	
COP (30 % Carnot)	2.28	
COP (10 % Carnot)	0.76	
Gravitational refrigeration cycle (GRC)		
Altitude difference (m)	1750	
Latent heat (kJ/kg)	94.14	
Gas specific heat coefficient 25 to −7°C (kJ/kg.C)	0.866	
Liquid specific heat coefficient −7 to 18 °C (kJ/kg.C)	1.119	
Cooling potential (kJ/kg)	79.98	
	Pump	**Truck**
Gas column pressure difference (bar)	11.6	–
Average density of the liquid column (kg/m^3)	1496	–
Efficiency (%)	90	60
Electricity consumption (kJ/kg)	19.1	28.6
GRC COP	4.19	2.80
Comparison between GRC and CRC (100 % Carnot)	0.55	0.37
Comparison between GRC and CRC (50 % Carnot)	1.10	0.74
Comparison between GRC and CRC (30 % Carnot)	1.84	1.23
Comparison between GRC and CRC (10 % Carnot)	5.52	3.68

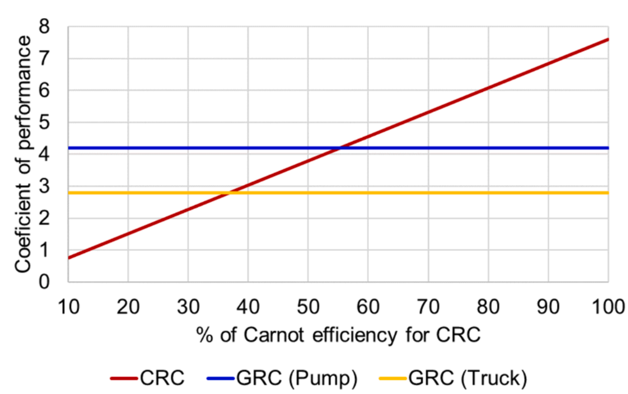

Fig. 5. Coefficient of performance comparison for CRC and GRC.

might be some applications where GRC is cheaper. Future work will investigate the use of GRC with vertical pipelines in the deep ocean to achieve negative temperatures with the intent of increasing the efficiency of methane, oxygen, nitrogen and H_2 liquefaction processes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 4
Gas pipeline dimensioning.

Distance from the top (km)	Volume (m^3/s)	Cross-section area (m^2)	Number of tunnels
0.34	183.39	61.13	6.00
0.67	170.74	56.91	6.00
1.01	158.86	52.95	5.00
1.35	147.64	49.21	5.00
1.68	137.00	45.67	5.00
2.02	126.90	42.30	4.00
2.36	117.32	39.11	4.00
2.69	108.23	36.08	4.00
3.03	99.57	33.19	4.00
3.37	91.32	30.44	3.00
3.71	83.43	27.81	3.00
4.04	75.86	25.29	3.00
4.38	68.56	22.85	3.00
4.72	61.47	20.49	2.00
5.05	54.51	18.17	2.00
5.39	47.57	15.86	2.00
5.73	40.40	13.47	2.00
6.06	32.36	10.79	2.00
6.40	17.26	5.75	1.00

Table 5
GRC cost estimates.

System component	Cost (million USD)
Gravity refrigeration cycle cost	
SF_6 gas required is around 10.000 tons, which costs 3 USD/kg [23].	30
Gas pipeline (Table 4).	81
The liquid pipeline costs assume steel pipes with 200 to 700 m head, 2 m diameter, 3 m/s velocity and Fig. M.6.A at [22]).	33
The pump and motor of the liquid pipeline assume the costs described in Figure M.1.B, Figure M.4.A, Figure E.8.2.A, Fig. E.1.1A and Figure E.8.1.B in [22]. Since pressure along the entire pipeline would be very high with one pump (300 bar), four pumps and motors in series are proposed.	80
Heat exchanges for the evaporator and condenser.	20
Construction cost (20 % of equipment costs)	49
Contingency (20 % of total cost)	10
GRC investment cost (273 USD/kWt)	273
Conventional refrigeration cycle cost	
The capital cost of mechanical refrigeration with 1 GW capacity, assuming 123 USD/kWt [24].	123
Comparison between GRC and CRC	
Comparing GRC and CRC capital costs, GRC is 2.2 more expensive than CRC.	2.2

Data availability

Data will be made available on request.

References

[1] Ismail M, Yebiyo M, Chaer I. A Review of Recent Advances in Emerging Alternative Heating and Cooling Technologies. Energies 2021:14. https://doi.org/10.3390/en14020502.

[2] Hara Chakravarty K, Sadi M, Chakravarty H, Sulaiman Alsagri A, James Howard T, Arabkoohsar A. A review on integration of renewable energy processes in vapor absorption chiller for sustainable cooling. Sustain Energy Technol Assessments 2022;50:101822. https://doi.org/10.1016/j.seta.2021.101822.

[3] Khosla R, Miranda ND, Trotter PA, Mazzone A, Renaldi R, McElroy C, et al. Cooling for sustainable development. Nat Sustain 2021;4:201–8. https://doi.org/10.1038/s41893-020-00627-w.

[4] Alahmer A, Al-Amayreh M, Mostafa AO, Al-Dabbas M, Rezk H. Magnetic Refrigeration Design Technologies: State of the Art and General Perspectives. Energies 2021:14. https://doi.org/10.3390/en14154662.

[5] Pourkiaei SM, Ahmadi MH, Sadeghzadeh M, Moosavi S, Pourfayaz F, Chen L, et al. Thermoelectric cooler and thermoelectric generator devices: A review of present and potential applications, modeling and materials. Energy 2019;186:115849. https://doi.org/10.1016/j.energy.2019.07.179.

[6] Hunt JD, Byers E, Sánchez AS. Technical potential and cost estimates for seawater air conditioning. Energy 2019;166:979–88. https://doi.org/10.1016/j.energy.2018.10.146.

[7] Kim G, Choi HW, Lee G, Lee JS, Kang YT. Experimental study on diffusion absorption refrigeration systems with low GWP refrigerants. Energy 2020;201:117626. https://doi.org/10.1016/j.energy.2020.117626.

[8] Paliwoda A. Calculation of basic parameters for gravity-fed evaporators for refrigeration and heat pump systems. Int J Refrig 1992;15:41–7. https://doi.org/10.1016/0140-7007(92)90066-4.

[9] Wiencke B. Fundamental principles for sizing and design of gravity separators for industrial refrigeration. Int J Refrig 2011;34:2092–108. https://doi.org/10.1016/j.ijrefrig.2011.06.011.

[10] Lee J, Kim MH. Experimental study of the gravity effect on the distribution of refrigerant flow in a multi-pass condenser. Int J Refrig 2004;27:993–1002. https://doi.org/10.1016/j.ijrefrig.2004.07.001.

[11] Aprea C, Greco A, Vanoli GP. Condensation heat transfer coefficients for R22 and R407C in gravity driven flow regime within a smooth horizontal tube. Int J Refrig 2003;26:393–401. https://doi.org/10.1016/S0140-7007(02)00151-2.

[12] Li C, Fang X, Luo Z, Dai Q. Flow boiling heat transfer and pressure drop of R245fa inside horizontal 1.62 mm and 2.43 mm tubes under hypergravity. Int J Refrig 2023;148:96–107. https://doi.org/10.1016/j.ijrefrig.2023.01.004.

[13] Killion JD, Garimella S. Gravity-driven flow of liquid films and droplets in horizontal tube banks. Int J Refrig 2003;26:516–26. https://doi.org/10.1016/S0140-7007(03)00009-4.

[14] Hunt JD, Jurasz J, Zakeri B, Nascimento A, Cross S, Caten C, et al. Electric Truck Hydropower, a flexible solution to hydropower in mountainous regions. Energy 2022;248:123495. https://doi.org/10.1016/j.energy.2022.123495.

[15] Hunt JD, Byers E, Wada Y, Parkinson S, Gernaat D, Langan S, et al. Global resource potential of seasonal pumped-storage for energy and water storage. Nat Commun 2020;11. Article number: 947.

[16] eThermo. Thermodynamics & Transport Properties 2023. http://www.ethermo.us/.

[17] Aziz M. Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety. Energies 2021:14. https://doi.org/10.3390/en14185917.

[18] Liquide A. Sulfur hexafluoride. Gas Encycl 2023. https://encyclopedia.airliquide.com/sulfur-hexafluoride.

[19] Solvay Special Chemical. Sulphur Hexafluoride. 2018.

[20] Baker & Adamson. Sulfur hexafluoride for gaseous insulation. Morristown: 1957.

[21] topographic-map. Saudi Arabia topographic map 2023. https://en-gb.topographic-map.com/map-qw65k/Saudi-Arabia/?center=25.64153%2C42.34131.

[22] Slapgard J. Cost base for hydropower plants. Oslo: Norwegian University of Science and Technology; 2012.

[23] Jiangsu Kaimei Electronic Materials. Low Price Guaranteed Quality Cas No. 2551-62-4 SF6 Gas Sulfur Hexafluoride For Sale. Alibaba 2023. https://www.alibaba.com/product-detail/Low-Price-Guaranteed-Quality-Cas-No_1600440916124.html?spm=a2700.galleryofferlist.normal_offer.d_title.14006172hR68I8.

[24] Shenzhen Hero-Tech Refrigeration Equipment Co. L. 300ton Air cooled industrial cooling screw compressor dual-unit Central control water chiller. Alibaba 2023. https://www.alibaba.com/product-detail/300ton-Air-Cooled-Industrial-Cooling-Screw_1600490412528.html?spm=a2700.galleryofferlist.p_offer.d_image.8ee568ddobz4cL&s=p.

[25] Kuta M. Mobilized thermal energy storage for waste heat recovery and utilization-discussion on crucial technology aspects. Energies 2022:15. https://doi.org/10.3390/en15228713.

[26] Hunt JD, Nascimento A, Zakeri B, Barbosa PSF, Costalonga L. Seawater air-conditioning and ammonia district cooling: A solution for warm coastal regions. Energy 2022;254:124359. https://doi.org/10.1016/j.energy.2022.124359.

[27] Anandan SS, Sundarababu J. A comprehensive review on mobilized thermal energy storage. Energy Sources, Part A Recover Util Environ Eff 2021:1–24. https://doi.org/10.1080/15567036.2021.1942331.

[28] Al-Ghobari H, Dewidar AZ. A comparative study of standard center pivot and growers-based modified center pivot for evaluating uniformity coefficient and water distribution. Agronomy 2021:11. https://doi.org/10.3390/agronomy11081675.

[29] Hunt JD, Nascimento A, Zakeri B, Jurasz J, Dąbek PB, Barbosa PSF, et al. Lift Energy Storage Technology: A solution for decentralized urban energy storage. Energy 2022;254:124102. https://doi.org/10.1016/j.energy.2022.124102.