COMSOL
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2023 MUNICH

Geothermal Energy for Efficient Cooling of Intake Air in Harsh Environments: A Combined Experimental-Modelling Approach

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Abstract

In this work we present a novel approach to enhance energy efficiency in cooling intake air for air conditioning (AC) systems in harsh environments using geothermal energy. We developed a 3D finite element model to simulate the heat transfer between underground soils/gravels and cooling pipes, which effectively precools intake air before it enters the AC system. To validate the model, we installed sensors at various depths ranging from 1 meter below ground to 10 meters. These sensors enabled us to accurately measure the underground temperature profiles. Based on the measured temperature data, we constructed a geothermal model that captures the behavior of the underground thermal environment. The model was built using COMSOL Multiphysics software, version 5.3, and utilized the Heat Transfer Module and the Time Dependent solver. A physics-controlled mesh was employed with an average element quality of 0.78.

The model was tested with data of August-2022, a month characterized by extreme temperatures exceeding 50°C in the ambient air. Remarkably, the underground temperature at a depth of 10 meters remained almost constant about 30°C throughout the year. These findings illustrate the significant potential of the underground temperature for precooling applications. By introducing water into the cooling pipes, we could efficiently exchange cooled water with the intake air of the AC system. This approach maintained a stable intake air temperature of 30°C for up to 4 days using the same circulated water. However, to avoid the cumulative effects of cooling and prevent a reverse temperature increase, the circulating water had to be replaced every 5 days. Alternatively, the model revealed that by introducing air into the cooling pipes and directly utilizing it as intake air, we could shave the ambient air temperature up to 10°C but only for a single day which can save up to 50% of AC energy consumption. Consequently, to prevent the reverse temperature increase and cumulative heat, the air needed to be replaced daily. Introducing water as a coolant instead of air was significantly more effective due to its relatively higher sensible heat.

The outcomes of our study demonstrate the feasibility and effectiveness of utilizing geothermal energy as an energy-efficient solution for cooling intake air in AC systems operating in harsh environments. The findings provide valuable insights for optimizing the design and operation of geothermal cooling systems, offering significant potential for energy savings and environmental sustainability.

Keywords: *Geothermal energy, precooling, cooling intake air, energy efficiency, 3D finite element model*

1. Introduction

The importance of environmentally sustainable and energy-efficient cooling and heating solutions has never been more critical. Geothermal energy, which utilizes the consistent thermal reservoirs beneath the Earth's surface, has emerged as a viable alternative to conventional heating and cooling methods. As highlighted by Alsagri et al. (2022)[1], geothermal technologies have made significant strides in the realms of cooling and refrigeration systems, pointing to their increasing relevance in the modern energy landscape. Egg and Howard (2011)[2] emphasized the "green" attributes of geothermal heating and cooling (HVAC) systems, underlining their potential to reduce carbon footprints substantially.

The applications of geothermal energy are not just restricted to traditional heating. Chaibi and Bourouni (2005)[3] provided insights into the effectiveness of geothermal water-cooling systems in regions like Tunisia, suggesting a broader applicability across various global contexts. The importance of a well-designed geothermal system was underscored by Angrisani et al. (2016)[4], who delved into the energy and economic implications of such systems. Moreover, Herez et al. (2017)[5] extended the understanding of geothermal energy by evaluating its efficiency in cooling applications through a parametric study.

Recent reviews by Greco et al. (2022)[6] and Kumar et al. (2022)[7] have reinforced the ecological advantages of geothermal systems, particularly in the air-conditioning sector. Such systems have been associated with both reduced energy consumption and minimal environmental degradation. Kaushal (2017)[8] and Soltani et al. (2019)[9] provided comprehensive insights into the mechanics and efficiencies of geothermal systems, emphasizing the vital role of ground heat exchangers. Furthermore, research by Naicker and Rees (2018)[10] focused on the performance analysis of large-scale geothermal systems, shedding light on their potential for broader applications in both urban and industrial contexts.

Even in unique settings, such as underground mines, geothermal energy has found utility, with Watzlaf and Ackman (2006)[11] highlighting its potential in geothermal heat pump systems. Interestingly, Zhelykh (2019)[12] explored the thermal efficiency of geothermal ventilation, especially in regions with temperate climates, presenting another facet to the adaptability and versatility of this energy source.

With the wealth of research conducted across various contexts, it is evident that geothermal energy holds tremendous promise for the future of sustainable heating and cooling. As this paper unfolds, we aim to provide a modeling insight, to further advance our understanding of geothermal energy's potential for cooling applications in harsh environments.

2. Background/Theoretical Framework

2.1 Basics of Geothermal Energy

Geothermal energy arises from the natural decay of radioactive materials within the Earth and the original heat retained during Earth's formation. As this energy traverses through the crust, it warms the rock and vast reservoirs of water located beneath the Earth's surface (Rosen & Koohi-Fayegh, 2017)[13]. In specific regions, this heat is close enough to the surface to be harnessed directly for heating and cooling applications. By tapping into these steady underground temperatures, we can derive heating during colder months and cooling during warmer periods

2.2 Geothermal Cooling Challenges in Harsh Environments

Harsh environments, which may include deserts, industrial zones, or areas with extreme temperature fluctuations, present unique challenges for cooling systems. The primary concern is the significant heat loads, which require cooling mechanisms to work overtime, leading to higher energy consumption and often less efficient operation (Egg & Howard, 2011)[2]. Moreover, factors like dust, salinity, and humidity can impact the performance and longevity of conventional cooling systems. The quest, therefore, is for a robust solution that remains efficient under such conditions.

2.3 Geothermal Energy in Cooling Systems

Using the Earth's consistent temperature, geothermal cooling systems work by transferring heat from the building or structure into the ground during warm periods, essentially using the ground as a heat sink (Alsagri et al., 2022)[1]. This is typically achieved through a network of pipes (often termed as ground heat exchangers) buried underground. A fluid, usually a mix of water and antifreeze, circulates within these pipes. In the cooling mode, the fluid absorbs heat from the building and transfers it to the ground. Conversely, for heating, the process is reversed.

2.4 Previous Work in the Domain

Over the past few decades, numerous studies and experiments have been conducted to understand and optimize geothermal energy systems for cooling purposes. Angrisani et al. (2016)[4] highlighted the significance of a well-designed geothermal system and its implications on energy savings. Studies like those conducted in Tunisia by Chaibi and Bourouni (2005)[3] provide empirical evidence of the feasibility and efficiency of geothermal cooling in arid regions. Furthermore, a comprehensive review by Greco et al. (2022)[6] touched upon the various advancements and techniques associated with geothermal renewable energy systems, emphasizing their increasing importance in eco-friendly air-conditioning.

2.5 Geothermal System's Environmental Impact

One of the significant advantages of geothermal energy systems, aside from their efficiency, is their minimal environmental footprint. Unlike fossil-fueled systems, geothermal systems release negligible amounts of greenhouse gases. This attribute, combined with the renewable nature of the energy source, positions geothermal cooling as not just a sustainable solution for harsh environments but a model for future global energy systems (Kumar et al., 2022)[7].

In this theoretical framework provides a foundation to appreciate the relevance and potential of geothermal energy in addressing the challenges associated with cooling intake air in extreme environments.

3. Methodology

3.1 Experimental setup

Within the ambit of this study, a comprehensive underground dataset was collected over a 12-month period from a scientifically outfitted site rig located at the Qatar Foundation’s outdoor test facility. The site setup consists of a solar-powered datalogger, (Campbell Scientific ENC12/14), configured to capture underground temperature readings. These temperatures were ascertained using advanced multiparameter smart sensors (CS650), that were embedded at various depths between 1 and 10 meters as illustrated in Figure 1.

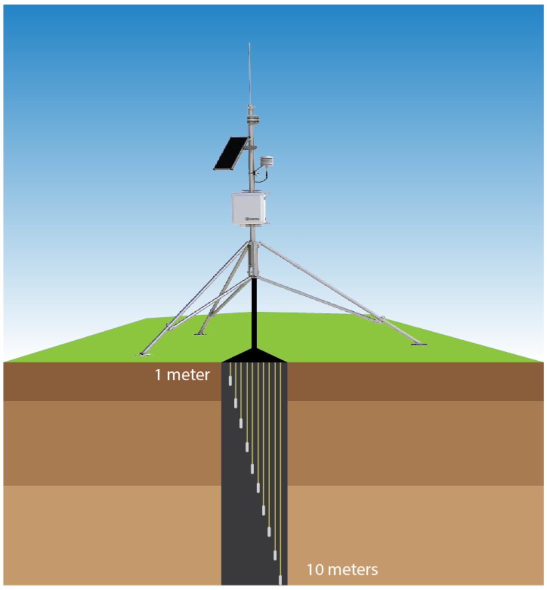

Figure 1. Illustration of the underground temperature monitoring system

Figure 2. Actual underground temperature monitoring setup at the outdoor test facility

Utilizing such a rigorous setup, the study yielded high-fidelity data spanning from June 2022 to May 2023, with observations meticulously recorded at 10-minute intervals. The collected dataset was used to delineate the subterranean temperature profile and carryout the simulation work of our system model via the COMSOL platform.

3.2 Model description and assumptions

To optimize energy efficiency in air conditioning systems operating in extreme climates, we harness geothermal energy as a precooling solution. Our methodology utilizes a 2D finite element model, developed in COMSOL Multiphysics software (version 5.3a), to simulate heat transfer interactions between underground soils and cooling pipes. This model is grounded in actual temperature measurements taken from depths of 1 to 10 meters over a span of one year and captures the nuances of the underground thermal dynamics. The analysis employed a Time Dependent solver accompanied by a physics-based mesh. operates on several pivotal assumptions:

- Materials: Considered homogeneous, suggesting uniform properties, and isotropic, implying consistent properties across all directions.
- Fluid Flow: Fluid flow is taken as laminar, without turbulence.
- Material Properties: Characteristics such as density, specific heat, and thermal conductivity are deemed constant.
- Heat Transfer Direction: Simplifying the model, heat transfer is conceived to be two-dimensional.
- Radiative Transfer: Any form of radiative heat transfer is considered negligible.
- Fluid Consistency: The circulating fluid is viewed as incompressible, maintaining a steady density irrespective of pressure variations.
- Boundary Conditions: Inflow and outflow heat flux system. The insulation boundary conditions are at the sides of the soil.

3.3 System domain

The system geometry is reflected in Figure 3, where a 2D model was built using COMSOL Multiphysics software v 5.3a utilizing the heat transfer in solids as well as the heat transfer in pipes modules. The system mimics the geothermal effect by defining the underground soils as geothermal reservoir with the measured temperature at the respected depths. In addition, a rectangular duct of 5 cm width and 10 cm height has been placed for heat exchange with the underground soils. The heat exchanger has been designed as serpentine for better heat transfer. The inlet water/air was set at 25 °C at closed loop system. The surrounding temperature was set as the measured ambient temperature.

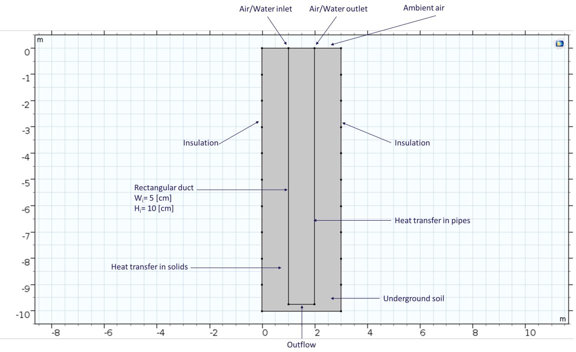

Figure 3. System geometry and boundary conditions

3.4 Governing equations

Heat transfer in solids

$$d_z \rho C_p \frac{\partial T2}{\partial t} + d_z \rho C_p u . \nabla T2 + \nabla . q = d_z Q + q_0 + d_z Q_{ted}$$

$$q = -d_z k \nabla T2$$

Heat transfer in pipes

$$\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p u e_t . \nabla_t T = \nabla_t . (AK \nabla_t T) + \frac{1}{2} f_D \frac{\rho A}{d_h} |u| u^2 + Q + Q_{wall}$$

The AC energy consumption has been calculated as a function of intake air by using the below simplified equation: -

Energy consumption (E)

$$E = aT^3 + bT^2 + cT + d$$

Parameters: a = 0.01; b = -0.3; c = 2; d = 100

3.5 Meshing system

In this study, a mesh of 8066 elements (Figure 4) mostly of triangular shapes was used, resulting in an average element quality of 0.895.

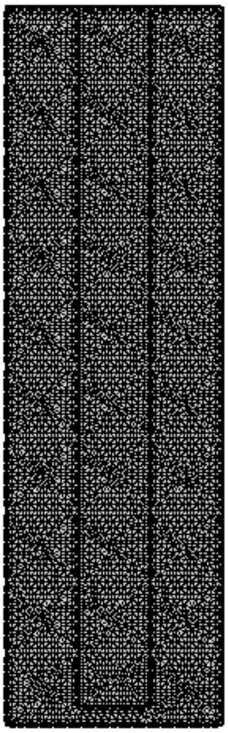

Figure 4. Meshing system

4. Results and Discussion

n our study of using geothermal energy to adjust air temperatures for air conditioning, especially in extreme climates, we found important results. During the peak of summer in August 2022, when outside temperatures reached up to 53°C, the underground temperatures were noticeably cooler. Precision sensors, strategically embedded at variant depths, relayed pivotal temperature metrics. Remarkably, the data showed that at a depth of 10 meters, the winter temperatures dropped to about 30°C. This significant temperature difference highlights the cooling and heating advantages of the underground environment. As illustrated in Figure 5, the median ambient temperature spectrum fluctuates between of 40°C during the summer to 20°C amidst winter months. Figure 6 displays the daily temperature changes during the hottest summer days, showing a range from 30°C at night to a high of 53°C at midday.

it was evident that our measurements were in harmony with initial predictions, emphasizing the model's precision. The potential to significantly reduce AC energy consumption by harnessing subterranean for precooling intake air is evident, suggesting considerable cost and energy savings if adopted more widely. Despite the challenges faced, like calibrating sensors for extreme temperatures, our results consistently held.

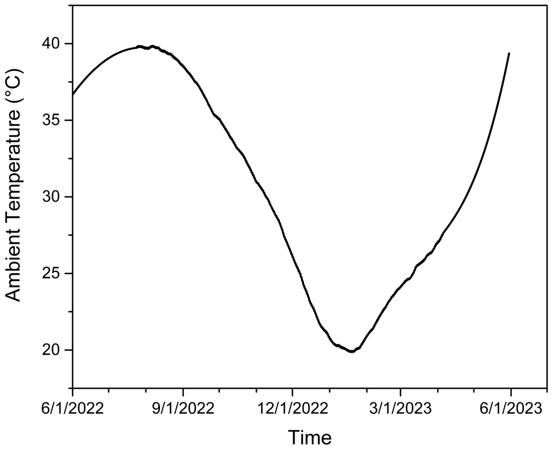

Figure 5. One year of measured ambient temperature from 01-06-2022 to 31-05-2023

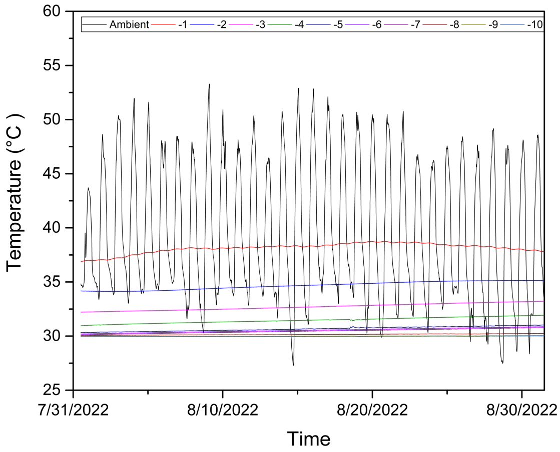

Figure 6. August-2022 measured underground and ambient temperature

It is known that handling high-resolution datasets presents considerable computational challenges. The granularity and intricacy of such data demand substantial computational resources, often leading to prolonged processing times and increased demands on memory storage. Given these challenges, it often becomes imperative to adopt a pragmatic approach. By aggregating data points and using average values, or other statistical summarizations, the computational load can be significantly reduced without compromising the overall integrity and this to a great extent what we had to do with our dense datasets to come up with representable figures and results. In Figure 6, the underground temperature readings for August-2022 at different depths are displayed, where the temperature varies from 35°C at 1 meter below ground, where it almost stabilize at 30 °C at 4 meters below ground, which confirm that the underground temperature in harsh environment can be beneficial due to their relatively constant temperature and it can be considered as an isothermal reservoir that can be utilized for different heat exchange purposes. In addition, the average underground temperature across one year is shown in Figure 7, where it confirms that the underground temperature is almost constant below 4 meters at 30

°C throughout the year, which ensure system reliability and stability.

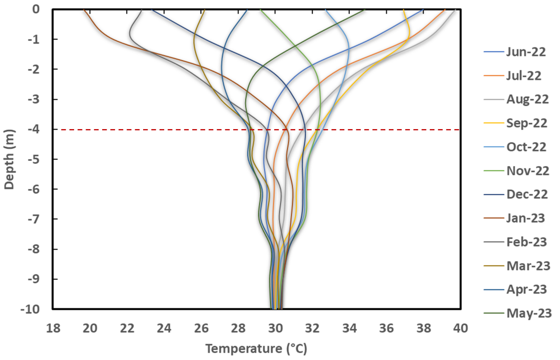

Figure 7. Underground average temperature profiles measured from 01-06-2022 to 31-05-2023

Two cooling methods were evaluated: circulating water in the cooling pipes and directly introducing air. Water, as a coolant, exhibited superior performance (see Figure 8). By introducing water into the cooling pipes and then exchange it with the ambient air before intaking the AC unit, we achieved a consistent intake air temperature of 30°C for a span of 4 days using the same circulated water. In contrast, while using air as a coolant effectively reduced the ambient air temperature by up to 10°C (see Figure 9), this was sustained for only a single day. Beyond these durations, both methods began to experience a reverse temperature increase. This necessitated the replacement of circulating water every 5 days and daily air replacement to circumvent the cumulative heat effects. The distinguishing performance of water, as compared to air, can be attributed to its higher sensible heat. This characteristic of water makes it more adept at exchanging heat with the intake air of the AC system, offering a prolonged cooling effect.

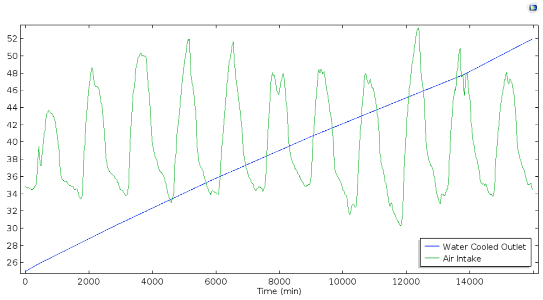

Figure 8. Circulating water as heat exchange fluid with underground soil

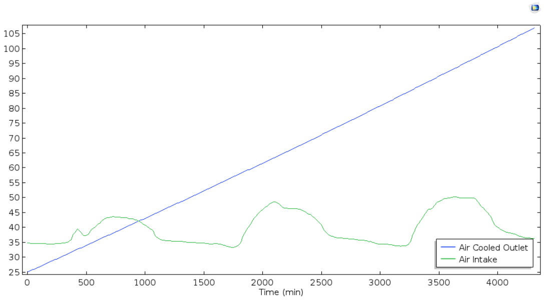

Figure 9. Circulating air as heat exchange fluid with underground soil

It is worth mentioning that the effect of precooling the air intake, on the AC energy consumption is shown in Figure 10, where cooling the intake air from 55 °C to 35 °C due to the heat exchange with underground soil could save up to 50% of the AC energy consumption.

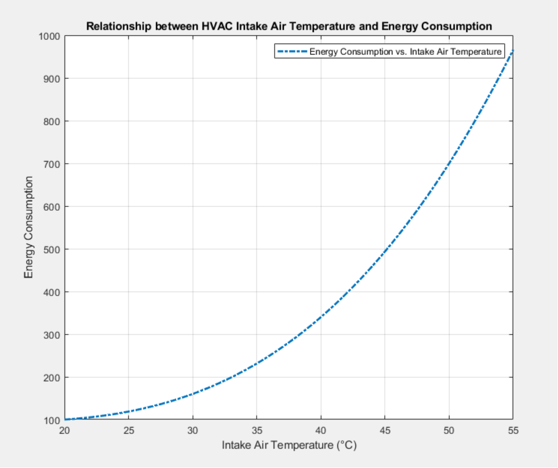

Figure 10. Relationship between HVAC intake air temperature and energy consumption

The observed results not only confirm the feasibility of geothermal energy as a precooling solution but also offers insights into the design and operational optimization of such systems. Using water as a coolant has clear advantages, especially in terms of prolonging the cooling effect, making it an energy-efficient and sustainable choice for AC systems in extreme conditions. The empirical evidence from our study underscores the transformative potential of geothermal energy in providing energy-efficient solutions for AC systems. The differential underground temperatures, when harnessed effectively, can lead to substantial energy savings, and contribute to environmental sustainability. Future endeavors in this field would benefit from these insights, optimizing the design and operational aspects of geothermal cooling systems.

5. Conclusions

In this research, we introduced a groundbreaking method to enhance energy efficiency in air conditioning systems in harsh environments using geothermal energy as a precooling source. By harnessing the consistent temperatures found underground, particularly at depths of 10 meters, we showcased the substantial precooling potential inherent in the subterranean environment. Through both water and air experiments, water proved to be a superior coolant, maintaining a stable intake air temperature for up to four days. Our results underline the potential of geothermal energy as a sustainable solution for AC systems in extreme climates, offering noteworthy energy savings and a path towards environmental sustainability that is evident by the potential for significant carbon emission reductions.

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