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Experimental and Numerical Analysis of Shallow Horizontal Geothermal Ventilation (SGV) in Desert Climates

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Abstract - Space cooling is a major energy demand in the UAE and the Middle East, contributing significantly to carbon emissions. The research of the shallow geothermal energy studies the potential of harnessing the stable ground temperature for heat exchange, as a sustainable cooling energy source to alleviate this energy burden. Historically, records indicate that the Middle East is the first to adopt the shallow horizontal geothermal system as the ancient middle eastern homes used the "Qanat" system, combined with air towers, to achieve natural housing cooling. To revive and modernize this concept, an innovative thermally controlled laboratory facility is constructed, dedicated to evaluating the cooling capabilities of shallow horizontal geothermal systems under various environmental conditions. This facility performs comprehensive tests, examining different UAE soil types, airflow, thermal exchange models, groundwater sources, and ambient air conditions. The research project aims to investigate the potential contribution of the green technology of horizontal shallow geothermal systems in cooling structures in arid and semi-arid regions, with a focus on UAE's climate as a representative example

***Keywords*:** Geothermal energy, Energy geostructures, Hot-dominated climates, Cooling systems, Shallow horizontal, Geothermal ventilation, SGV, Closed Loop, Dubai, Arid

1. Introduction

The construction sector's share of the final energy consumption by different users is typically more than 25%. 60% - 85% of this energy is used for air conditioning and water heating. The gulf region of the middle east is among the top regions in the world in energy consumption per capita, most of which is directed to air conditioning. Saudia Arabia (KSA) and UAE top global ranking for the air conditioning share in household electricity consumption [1]. The energy used for air conditioning mainly relies on fossil energy (natural gas and petroleum) and has limited dependency on renewable energy. With the global transition towards green energy, UAE (and the rest of the Arab gulf countries) put a clear significance on the importance of increasing the reliance on clean energy and zero carbon emission technologies and adopted this direction as a national move (Dubai Clean Energy Strategy aims to cover 75% of energy demands of Dubai from clean energy Dubai by 2050 [2]. Furthermore, there is a need within the industrial and agricultural (greenhouses) sectors in the region for efficient and cheap cooling technologies. The research project aims to investigate the potential contribution of the green technology of horizontal shallow geothermal systems in cooling structures in arid and semi-arid regions, with a focus on UAE's climate as a representative example.

The use of shallow geothermal energy technology in heating and cooling structures has been vastly growing in the past three decades (since the 90s). There are remarkable examples worldwide of structures completely relying on the shallow geothermal energy to cover their heating and cooling energy needs. The system proved to be environmentally friendly (compared to conventional fossil fuel application) with significant financial feasibility in many cases. Shallow geothermal technology is based on the fact that soil temperature with depth is mildly affected by the variation of the outside ambient air temperature, until reaching a specific depth (typically between 6 m – 10 m depending on the soil profile) where the soil temperature becomes stable (Fig. 1). The ground's relatively stable temperature is used to inject to (or extract from) the structure's extra heat. For shallower depths where the ground temperature has not reached stability, there still is a difference in temperature with the ambient air, which still can be utilized for thermal exchange to contribute to heating/cooling structures.

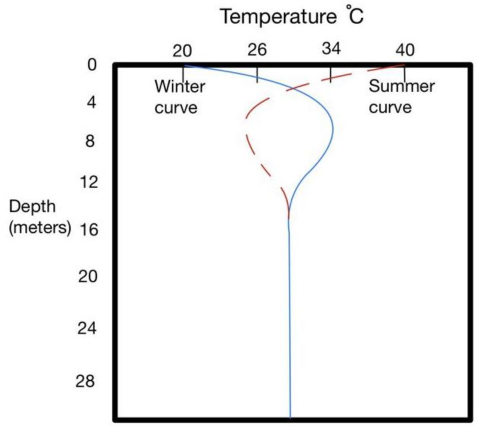

Fig. 1 A typical ground temperature variation profile with depth

The geothermal application however has been limited to temperate zones where the ground temperature is generally moderate (10-15º C), and where the system application is alternating between heating and cooling through the year. The application feasibility is doubtful in arid and semi-arid regions due to the cooling dominating requirement and the relative high ground temperature. However, the technology will have a significant impact on the carbon footprint and fossil energy demand reduction in the region should it be proven feasible.

Historically, some older middle eastern houses used the "Qanat" system in conjunction with an air chimney (air tower) to cool down houses [3] (Fig. 2). A hole is dug in the ground reaching down to the ground water table and connecting to the house basement. The wind tower creates a negative air pressure which triggers air to flow through the borehole, thermally exchanges the heat with the borehole walls and water aquifer, before reaching the house basement (Fig. 3).

Fig. 2 Ancient Qanat system in the Middle East a) ground holes for air entry b) underground conduit for air flow and water stream c) water stream outlet [3]

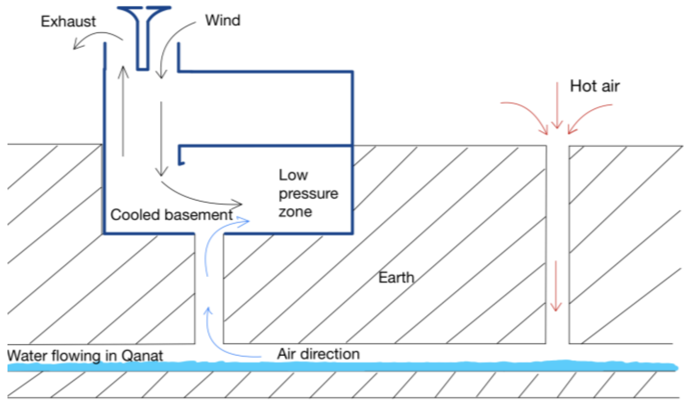

Fig. 3 Mechanism of airflow cooling in the Qanat system

The research project aims to investigate the potential contribution of the green technology of horizontal shallow geothermal systems in cooling structures in arid and semi-arid regions, with a focus on UAE's climate as a representative example.

2. Methodology

A small-scale, closed-loop, horizontal geothermal ventilation system (SGV) is developed to model the Earth-Air Heat Exchange (EAHX) performance under the climate conditions of UAE. The experimental setup is comprised of a rectangular tank 4.8m x 2 m x 1.2 m tank, built with plywood walls, and a metal frame, lined with multiple layers of thermal and hydraulic insulation, including a 2.5 mm HDPE waterproof membrane, and 5 mm thermal insulation foam. The tank is placed in a thermally controlled container (Fig. 4).

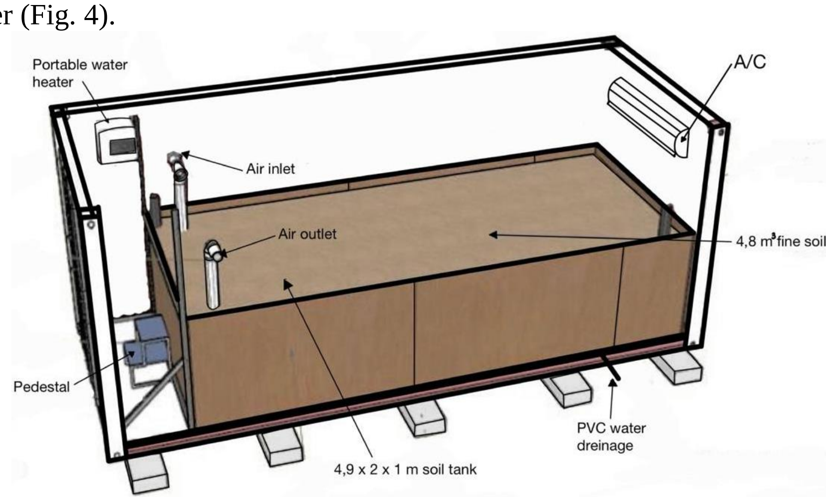

Fig. 4 A schematic representation of the experimental setup

2.1 Materials and Configuration

- 4" PVC pipes, 27m long were laid at mid depth of the sand tank with 0.16 m spacing (Fig. 5a).
- Medium grained, red dune sand was used to simulate Dubai's typical surficial soil, with a thermal conductivity of approximately 0.84 W/m K, and dry density of 1700 kg/m³.
- Two 6W axial fans (model HI-100SD) were installed at the pipe's inlet and outlet to control airflow. Multiple air velocities were tested ranging from 1.52 m/s to 5.83 m/s (Fig. 5b).
- 15 thermocouples sensors were embedded along the pipe at regular intervals (Fig. 6) and nine additional sensors were positioned at different soil depths to capture the thermal and moisture gradients.

Prior to fan installation, air velocity calibration tests were conducted to determine the optimal fan replacement and ensure minimum velocity losses in fittings and junctions. The experiment included both long-term runs (36 hours) at constant airflow rates, and short-term runs (30 min) at peak daytime temperatures. Inlet/outlet temperatures, soil temperatures, and airflow velocities are recorded hourly.

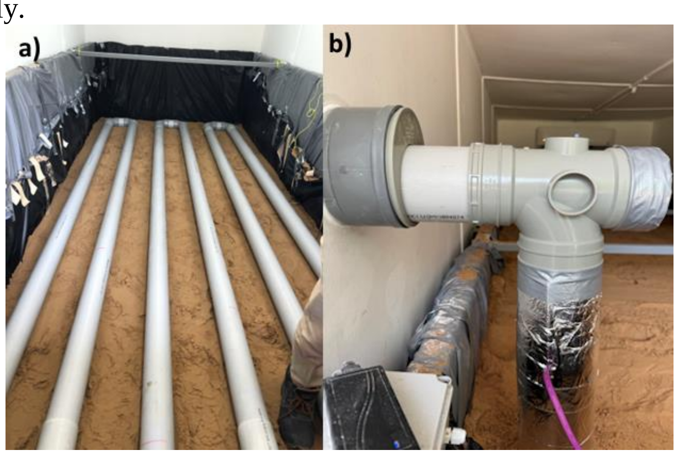

Fig. 5 Experimental setup a) pipes' alignment mid depth of the sand tank b)pipes' inlet and embedded fan

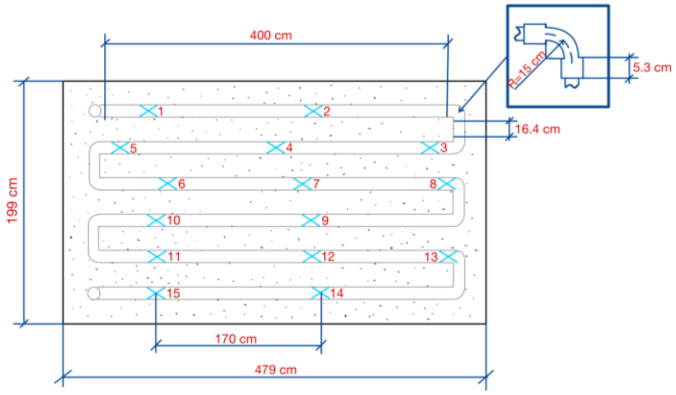

Fig. 6 Embedded sensors locations

2.2 Validation

To ensure the reliability of the experimental findings, the results are validated against i) mathematical model based on fundamental heat transfer principals, and ii) Computational Fluid Dynamics (CFD) simulations performed using ANSYS CFX software[4]. Both methods aim to replicate the experimental conditions and evaluate the accuracy of observed thermal behaviour.

i. Mathematical Model Validation

The mathematical model was developed to quantify the heat transfer between the air flowing inside the pipe and the surrounding soil. The model incorporated the convective heat transfer (air to pipe wall), conductive resistances through the PVC pipe material, and conductive resistance through surrounding soil.

ii. CFD Simulation Validation

To further validate the results and visualize the internal fluid and thermal behaviour, a steady-state CFD model is developed using ANSYS CFX software. The geometry and meshing replicated the physical experimental setup, with temperature and air velocity boundary conditions assigned along the pipe's surface, inlet and outlet (Fig.7).

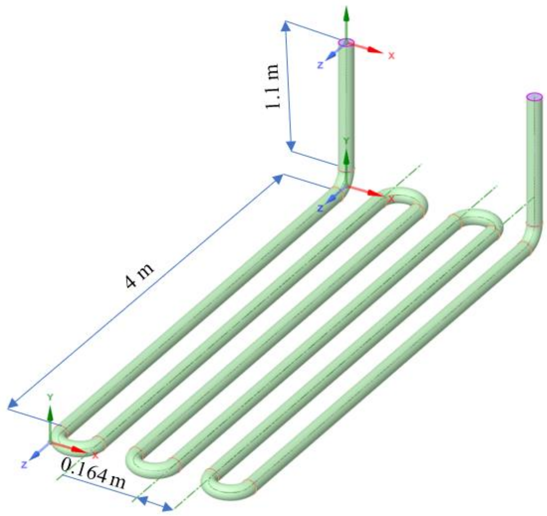

Fig. 7 Geometry of the CFD model

4. Conclusion

This study presents a comprehensive experimental framework to evaluate the thermal performance of a shallow horizontal closed-loop geothermal ventilation (SGV) system under UAE climate conditions. The experimental setup includes a 27 m buried PVC pipe network with controlled airflow rates and real-time thermal and humidity monitoring. The results are validated through mathematical modelling and ANSYS CFX simulations. The results derived from this setup provide a critical foundation for validating numerical models and establishing design guidelines for scalable SGV systems in hot arid climate.

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