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Fuzzy Control of Thermally Isolated Greenhouse Building by Utilizing Underground Heat Exchanger and Outside Weather Conditions

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Abstract**—**A traditional greenhouse is a metal frame agricultural building used for cultivation plants in a controlled environment isolated from external climatic changes. Using greenhouses in agriculture is an efficient way to reduce the water consumption, where agriculture field is considered the biggest water consumer world widely. Controlling greenhouse environment yields better productivity of plants but demands an increase of electric power. Although various control approaches have been used towards greenhouse automation, most of them are applied to traditional greenhouses with ventilation fans and/or evaporation cooling system. Such approaches are still demanding high energy and water consumption. The aim of this research is to develop a fuzzy control system that minimizes water and energy consumption by utilizing outside weather conditions and underground heat exchanger to maintain the optimum climate of the greenhouse. The proposed control system is implemented on an experimental model of thermally isolated greenhouse structure with dimensions of 6x5x2.8 meters. It uses fans for extracting heat from the ground heat exchanger system, motors for automatic open/close of the greenhouse windows and LED as lighting system. The controller is integrated also with environmental condition sensors. It was found that using the air-to-air horizontal ground heat exchanger with 90 mm diameter and 2 mm thickness placed 2.5 m below the ground surface results in decreasing the greenhouse temperature of 3.28 ˚C which saves around 3 kW of consumed energy. It also eliminated the water consumption needed in evaporation cooling systems which are traditionally used for cooling the greenhouse environment.

Keywords**—**Automation, earth-to-air heat exchangers, fuzzy control, greenhouse, sustainable buildings.

I. Introduction

A. Ground Heat Exchanger (GHE)

As depth of ground increases, the temperature fluctuations at the surface of the ground decreases because of the soil high thermal inertia and the time lag in temperature fluctuation between the surface and the ground. The ground temperature distribution has three separate zones which are, sequentially listed from surface to inner: the surface zone, the shallow zone, and the deep zone [1]. In the surface zone, the ground temperature is sensitive to short-time weather changes and has a depth of 1 m from the surface. However, the temperature in the shallow zone is nearly constant, and its distribution depends on the seasonal cycle weather conditions. The temperature in this zone is close to the average annual air temperature, and the zone depth depends on the soil type extending from 1 m to 8 m for dry light soils and can reach up to 20 m in moist heavy sandy soil. In the deep zone, which is below the shallow zone, the temperature is practically constant and rises slowly with depth, with an average gradient of around 30 ˚C/km [2]. Since the temperature is almost constant in the shallow and deep zones, the ground temperature is always higher than that of the outside air temperature in winter and is lower in summer. This difference in heat makes the ground heat exchanger an attractive, sustainable, energy-efficient and environmentally-friendly way for cooling/heating systems especially that most of the energy demands in buildings is consumed by these systems [3]. Basically, the ground heat exchanger consists of circulating medium (water, air or antifreeze solution) that passes through pipes buried in the ground to extract heat from the environment in summer and dumps it to the ground and vice versa in winter. The yield of thermal energy at higher temperature is based on a reverse Carnot thermodynamic cycle [2]. Usually a heat pump is coupled to a heat exchanger system to increase the thermal transfer efficiency. In fact, the efficiency of a ground heat exchanger depends mainly on its type, design, pipe configuration and length, type of backfill materials and ground thermal conductivity. Fig. 1 shows the main types of the ground heat exchanger where the Earth-to-Air type was used in this research for its simplicity and low cost.

B. Greenhouse Climate Control

The greenhouse climate control problem is to create a favorable environment to improve the development of the plantations and to minimize the production cost in terms of raw materials, water and energy consumptions [4]. Controlling the greenhouse environment is mainly focused on controlling the water and fertilizers that feed the plants in one side, controlling the sunlight, temperature, relative humidity and other environmental conditions that surround the plants on the other side. By controlling the greenhouse environment, better productivity of plants is gained; electricity and water consumption is reduced as well as human intervention in the system [5]. Recently, greenhouses were fully automated and monitored using different methodologies and algorithms. Two main approaches are followed in literature for controlling the greenhouse system. The first one is a mathematical or physical

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modeling approach which uses the state space model and a set of differential equations obtained from the greenhouse system mass and energy balance equations. The second approach is a black box model approach that tries to approximate the behavior of the greenhouse system based on the input-output data of the process. The second approach is not based on mathematical or physical equations but considered to be easier than the first approach and uses algorithms such as neural network, polynomial fitting and fuzzy logic. It is considered a better control solution especially in non-linear complex systems like greenhouses.

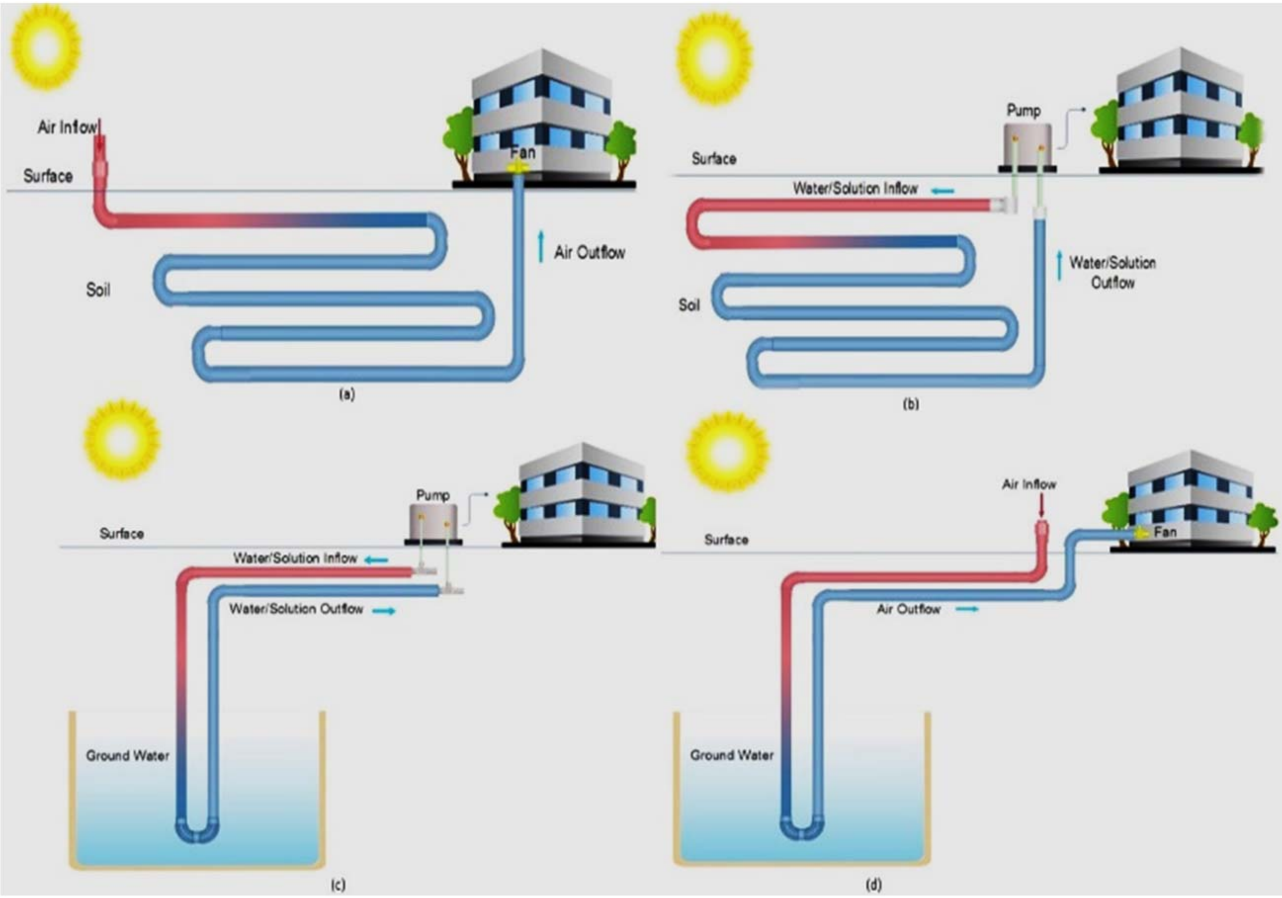

Fig. 1 (a) Earth-to-Air Heat Exchangers (b) Earth-to-Water Heat Exchangers (c) Ground-Water-to-Water Heat Exchanger (d) Ground-Water-to-Air Heat Exchanger

II. Objectives

The main objective of this research is to design a controller that utilizes the ground temperature and the weather conditions to maintain the optimum climate of the thermally isolated greenhouse building.

III. Methodology

A. Fuzzy Controller

A Mamdani fuzzy controller was designed using MATLAB R2017b fuzzy logic toolbox consisting of five inputs and two outputs as shown in Fig. 2. The inputs to the fuzzy controller are the greenhouse temperature, humidity and the outside weather conditions (i.e. outside temperature, humidity, and wind speed). The outputs are the percentage of GHE utilization and the opening percentage of the linear actuators which controls the windows opening of the greenhouse for thermal exchange and light passage. In addition, in the cases where opening the windows is not convenient due to undesired weather conditions, the fans are used to extract the heat from the installed underground PVC pipes to cool down/ heat up the system. The LED is controlled by a separate "if" condition that switches it "ON" whenever the weather is cloudy, or the windows are closed during the day time. Table I shows the fuzzy rules of the temperature control, and Table II shows the humidity fuzzy control which is only considered when the temperature is tolerable as advised by agricultural experts proposed controller. For real implementation, a wired sensor network was installed at different places inside and outside greenhouse to monitor the climate changes and updates are sent to the fuzzy controller every five minutes. Also, the membership functions of the fuzzy controller were developed with the guidance from agricultural experts. The sensors distribution in the greenhouse was also designed based on agricultural requirements using wired sensors network to provide more reliable sensory communication with the controller hardware. The sensors and actuators were connected to Atmega2560 micro-controllers for sensing, sampling and sending control signals. The micro-controllers are connected to the developed fuzzy controller using local area network for system monitoring and decision making.

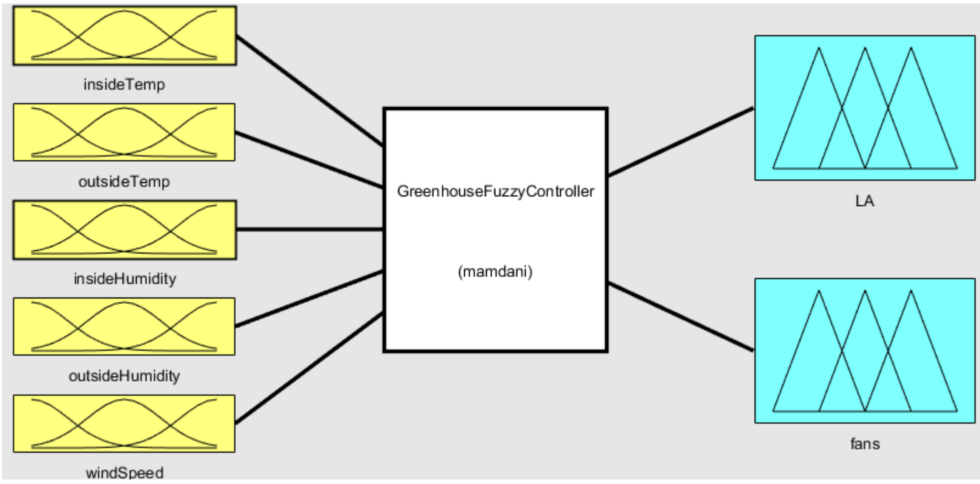

Fig. 2 Mamdani Fuzzy Controller Structure

TABLE I
FUZZY RULES FOR TEMPERATURE CONTROL (LA = LINEAR ACTUATOR, F=FANS)

T_in / T_out	Wind Speed	Extremely Hot (EH) LA	Extremely Hot (EH) F	Hot (H) LA	Hot (H) F	Normal (N) LA	Normal (N) F	Cold (C) LA	Cold (C) F
Extremely Hot (EH)	Acceptable	0	100	0	0	0	0	25	0
	Strong	0	100	0	0	0	0	0	50
Hot (H)	Acceptable	25	100	0	0	0	0	25	0
	Strong	0	100	0	0	0	0	0	50
Normal (N)	Acceptable	100	0	100	0	100	0	100	0
	Strong	0	100	0	0	0	0	0	50
Cold (C)	Acceptable	75	0	50	0	0	0	0	100
	Strong	0	100	0	100	0	0	0	100

TABLE II
FUZZY RULES FOR HUMIDITY CONTROL (LA = LINEAR ACTUATOR, F=FANS)

Inside Hum. / Outside Hum.	Dry LA	Dry F	Normal LA	Normal F	Wet LA	Wet F
Dry	X	X	0	X	75	0
Normal	100	0	100	0	100	0
Wet	75	0	0	X	X	X

X indicates that the outside weather conditions cannot be utilized for maintaining the greenhouse humidity. Hence, the decision of opening the windows or running the fans depends on the temperature (i.e. if the outside weather conditions cannot be utilized for maintaining the humidity but can be utilized for ventilation purpose then the windows should be opened). Also, if the humidity cannot be maintained and the inside temperature is cold, the fans should be running to heat up the system.

B. Earth-to-Air Ground Heat Exchanger

The soil temperature was modeled at 2.5 m depth as in [6]. Also, the greenhouse temperature was modeled as a first order differential equation that considers the ground thermal diffusivity, the thermal capacitance and resistance of the insulated greenhouse building. It takes as an input the ambient temperature which was collected by the meteorological center at Al Ain airport station and used for testing the controller in simulation mode for a complete one year. In addition, the greenhouse temperature takes the fans velocity, which is affected by the number of fans running that is determined by the fuzzy controller, and the soil temperature as inputs.

For experimental implementation, an Air-to-Air ground heat exchanger system was designed and tested in UAEU Al Foah farm, UAE. The system consists of six PVC pipes with 90 mm diameter and 2 mm thickness) placed 2.5 m below the ground surface. The inlet and outlet temperature and humidity were measured using Illuminance UV recorder (Model TR-74Ui) to find the cooling capacity of the system. The data were logged for 14 days, and the measurements were taken every five minutes.

IV. RESULTS

Fig. 3 shows the greenhouse variables when running the fuzzy controller for one complete year. Results showed that the proposed fuzzy controller can maintain the greenhouse temperature most of the year's day and works in pre-cooling mode in summer season which reduces the greenhouse temperature by 6 ˚C. Also, Fig. 4 shows the experimental greenhouse temperature when the heat exchanger is not utilized (i.e. no fan is running) and when it is fully utilized. The greenhouse temperature follows the outside temperature with attenuation in amplitude and some delay when ground heat exchanger is not utilized as shown in Fig. 4 (a). However, Fig. 4 (b) shows that the greenhouse temperature remains almost constant at 26 ˚C when the heat exchanger is fully utilized.

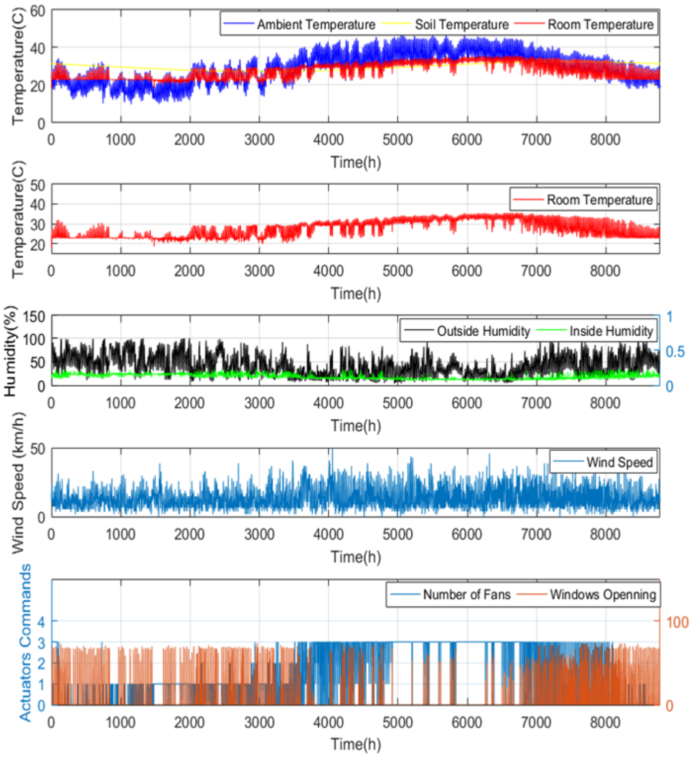

Fig. 3 Greenhouse temperature control over one year

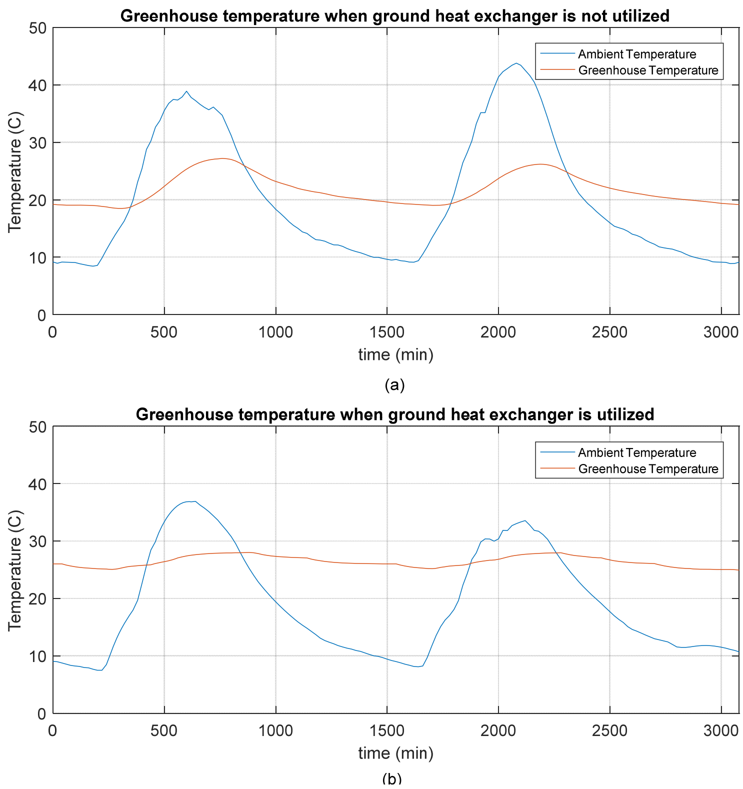

Fig. 4 (a) Greenhouse Temperature when ground heat exchanger is not utilized. (b) Greenhouse Temperature when ground heat exchanger is utilized

Moreover, the soil utilization was examined in simulation for one complete year with different capacities, and the results are shown in Fig. 5. It was found that, the difference between greenhouse room temperature when four fans are running (full capacity) compared to when one fan is running is about 1.5 ˚C. Moreover, running one fan makes the greenhouse system sensitive to the ambient temperature. However, when two, three or four fans are running the system is less affected by the ambient temperature. Moreover, the difference in temperature when running two, three or four fans is very small, and hence the decision of the running number of fans depends on the required heating/cooling speed in the control system.

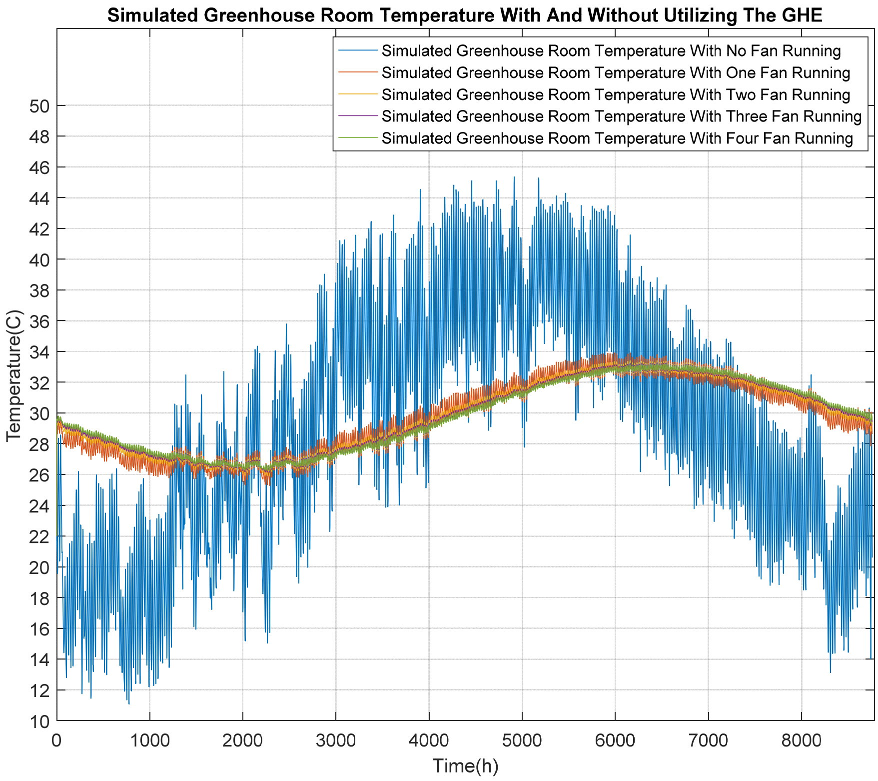

Fig. 5 Simulated room temperature when utilizing the ground heat exchanger at various capacities for one complete year

For the ground heat exchanger, it was found that the underground temperature is hotter than the outside temperature during night hours while it is cooler during daytime. Therefore, with proper use of fans the ground heat exchanger was used to cool down the greenhouse during daytime and to heat it up during night to maintain the desired temperature for the lettuce crop which is between 18-22 ˚C. The proposed controller was able to process the data from the sensors and generate the desired outputs for the system actuators and hence maintain the greenhouse climate.

V. Conclusion and Recommendations

In this work, a fuzzy controller was designed and implemented in a thermally isolated greenhouse structure. The controller utilized the ground temperature and the weather conditions to maintain the optimum climate of the greenhouse with less energy and water consumptions. The proposed controller was able to keep the greenhouse temperature within the acceptable range (between 18 ˚C and 22 ˚C) by utilizing the outside weather conditions in winter. However, it was only able to pre-cool the greenhouse temperature for about 30 ˚C. Results showed the heat exchanger can keep the greenhouse temperature at a constant level of about 26 ˚C. It hence can be used for pre-cooling in summer and heating in winter.

Despite the big variation in design and optimization techniques of the ground heat exchangers, all the conducted experiments at different places of the world proved the efficiency of using the geothermal energy in cooling/heating processes. However, more researches must be conducted on the performance of ground heat exchangers for a long-term period considering the thermal load imbalance issue and the ground thermal recovery cycle. Future work should focus on providing comprehensive economic analysis together with Coefficient of Performance (CoP) for different designs of ground heat exchangers. Also, conventional ON/OFF controller should be developed and tested against the proposed fuzzy controller to evaluate the system stability and performance.

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