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Earth-Air Heat Exchanger thermal performance in Egyptian conditions: Experimental results, mathematical model, and Computational Fluid Dynamics simulation

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ABSTRACT

In this paper, the thermal performance of an Earth-Air Heat Exchanger (EAHE) used for heating and cooling purposes is investigated under Egyptian weather conditions. The soil temperature profile and the temperature distribution of flowing air through horizontal Earth-Air Heat Exchanger (EAHE) is experimentally studied. Also, a mathematical model based on unsteady, one-dimensional and quasi-state is developed for energy conservation equation. Moreover, an explicit finite difference numerical method is used to solve the developed mathematical model with the help of MATLAB code. Finally, three-dimensional, steady and double precision Computational Fluid Dynamics (CFD) ANSYS Fluent simulation model is established to predict the air and soil temperature. Whereas, the standard $\kappa - \in$ model is applied to simulate the turbulence kinetic energy of the flowing fluid. The mathematically developed model and CFD simulation result validated against experimental results. Good agreement is achieved with an average error and correlation coefficient of 2.09, 97% and 3.3 and 95.5% for CFD simulation and mathematical model respectively. The CFD model is used in a parametric investigation. A parametric study carried out to explore the impact of different parameters such as pipe diameter, pipe material, pipe space, pipe length and flowing fluid velocity. The results show that some of these parameters have noticeable results in air temperature. Whereas, the pipe diameter increases the air temperature decreases. The outlet air temperature declines from 20.4 °C to 18.7 °C as the pipe diameter expands from 2 to 3 in. Furthermore, as pipe length increases, outlet air temperature enhances. The temperature changes from 19.7 to 19.9 °C as the pipe length elongates from 5.45 m to 7 m. A bit change occurs in outlet air temperature from 19.7 °C to 19.8 °C when pipe space changes from 0.2 to 0.5 m. Moreover, three different pipe materials such as PVC, steel and copper are implied. The outlet air temperature was 19.7 °C in PVC pipe and 19.8, 19.8 °C for steel and copper respectively. So the conclusion is that the change in outlet air temperature for various pipe material is neglected compared with their prices. Finally, the effect of fluid velocity was investigated. Therefore, the outlet air temperature declines from 20.4 °C to 19.2 °C as air accelerates from 1 to 3 m/s.

1. Introduction

In the last decays, with the shadow of energy crises which strikes all over the world especially the developing countries like Egypt. Moreover, the energy use per capita increased to reach with annually population growth rate of 2.2 in 2014 according to world data bank [1]. The residential energy consumes about 26% of total energy use in Egypt [2]. Air conditioning used basically for cooling; it represents significant energy consumption in the residential building due to relatively high indoor air temperature in summer. It is vital to looking for alternative passive cooling and heating technique. The Earth-Air Heat Exchanger (EAHE) is one of passive technology used for heating and cooling purposes. Whereas, it has both economic and environmental benefits. It utilizes the thermal potential of the underground soil. The soil at a reliable depth has a constant temperature, which used as energy storage/sink in winter and summer seasons. Thermal performance assessment is authentic essential to optimize the design of EAHE. The design includes pipe diameter, pipe length, pipe material, heat exchanger

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Nomenclature

$A1, \ldots, A7$ constants
A_∞ the cross section of a hollow cylinder of soil around the pipe
A_{inter} the cross section area of soil from pipe outer radius to the soil penetration depth r_{soil}
A_p pipe cross section area in (m^2)
CFD Computational Fluid Dynamics
COP coefficient of performance
Cp fluid specific heat in (kJ/kg K)
D air thermal diffusivity in (m^2/s)
e error
EAHE Earth-Air Heat Exchanger
E-JUST Egypt-Japan University of Science and Technology
ERE Energy Resources Engineering Department
$G_{1\varepsilon}$, $G_{2\varepsilon}$ and $G_{3\varepsilon}$ constants
G_k and G_b generation of turbulence kinetic energy due to mean velocity gradients and buoyancy
GSHP ground source heat pump
HP heat pump
K the turbulence kinetic energy
N and E north and east
N_t no. of time steps
N_x no. of domain elements
p the pressure or normal stress in (Pa)
PVC polyvinyl chloride
Q_{air}^{Soil} the heat flux from/to the subsurface in (J/s m)
R the effective thermal resistance
RPM revolution per minute
r correlation coefficient
r_o and r_i outer and inner pipe radius
R_{pipe} the pipe conduction thermal resistance
r_{soil} the soil domain radius
R_{soil} the soil conduction thermal resistance
SC solar chimney
S_k and S_e user-defined source terms
T flowing air temperature in (K)
T_{amb} ambient dry bulb temperature in (k)
T_{soil} pipe surrounding soil temperature in (K)
$T_{undisturbed}$ the undisturbed soil temperature
WAHE Water Air Heat Exchanger
Y_M the contribution of the fluctuating dilatation incompressible turbulence to the overall dissipation rate
TRNSYS transient system simulation tool

Subscripts
b buoyancy
daily daily
i inner
inter intermediate
k kinetic
o outer
p pipe
P pressure or normal stress in (Pa)
pipe pipe
soil soil
t time
undisturbed undisturbed
x x direction

Greek symbols
β_1, β_2 and β_3 constants
ω daily cyclic in (s^{-1})
δ daily penetration depth or disturbed layer thickness in (m)
ρ fluid density in (kg/m^3)
υ fluid velocity in (m/s)
μ the dynamic viscosity in (Pa s)
Δx the element size in (m)
$\in$ the rate of dissipation
σ_κ and σ_e the turbulent Prandtl numbers for κ and $\in$
Δt time step in (s)
∞ refer to ground surface
$\vec{u}$, $\vec{v}$, $\vec{w}$ velocity component in x, y and z direction respectively

configuration, buried depth and air flowing speed through buried pipes. Enormous numbers of researches done in this objective with different methodology. In this literature, the author presents some of them. Experimental methods carried out to study the visibility of coupled EAHE with the building. Carvalho et al. [3] showed that ground source heat pumps (GSHP) have high efficiency and high potential for building space conditioning. Moreover, it is suitable for electrical load management because of its load flexibility especially when it is combined with thermal energy storage capacity. Emmi et al. [4] integrated between solar thermal collector and GSHP to balance ground loads over a yearly cycle. They used this system to heat environments in a cold climate. They concluded that such system could assist in maintaining more efficient heat pumps (HP). Also, it reduces the total borehole length and the initial cost of installation. Li et al. [5] proposed a new system consist of the coupling between EAHE, solar collector and solar chimney (SC) used in totally passive air conditioning. Their experimental results show that the SC drove up to 0.28 m^3/s (1000 m^3/h) outdoor air into space. Furthermore, The EAHE provided a maximum 3308 W total cooling capacity. Finally, the coupled system almost covered the building design cooling load. Flaga-Maryanczyk et al. [6] coupled EAHE with the residential house for heating purposes in the cold climate in Australia. Their results indicate F that such coupling could conceal outside air temperature fluctuation. Also, it carried about 24% of the heating demand in February, and 15% of it during the period from December to April. Vaz et al. [7] investigated soil properties and characteristics, weather conditions in Brazil. They deducted that such system conveyed about 48% of heating and cooling demands. Demir et al. [8] examine the coefficient of performance (COP) of the GSHP in residential heating scope. Moreover, they analysis the relation between soil thermophysical properties and outlet air temperature from GSHP. Their results prove that soil thermal conductivity has a significant effect on fluid outlet temperature. Vaz et al. [9] explore the annual cyclic variation of flowing air temperature. Their results demonstrate that there are +8 and −4 °C temperature difference between outlet and inlet air temperature in heating and cooling respectively. Abbaspour-Fard et al. [10] claimed that COP of EAHE is 5.5 in cooling mode and 3.5 in heating mode at Iran climate conditions. Hatraf et al. [11] introduced a parametric study to evaluate the profile of air temperature inside tubes in the conditions of Algeria. They confirmed that pipe material has no effect on the thermal performance of the heat exchanger. Chel et al. [12] used transient system simulation tool (TRNSYS) to evaluate the dynamic thermal performance of residential building coupled with EAHE and Water Air Heat Exchanger (WAHE). They concluded that EAHE and WAHE had a reduction of the annual heating consumption of 66% and 7% respectively. Gao et al. [13] studied experimentally the benefits of combination between a rain garden and GCHE. They found that the increment in the soil moisture content led to enhancement in the