Energy Conversion and Management 114 (2016) 324–337

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Parametric study on thermal performance of horizontal earth pipe cooling system in summer

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ARTICLE INFO

Article history:
Received 22 October 2015
Accepted 24 January 2016

Keywords:
Parametric study
Earth pipe cooling
Thermal performance
Hot humid climate

ABSTRACT

Rational use of energy and its associated greenhouse gas emissions has become a key issue for a sustainable environment and economy. A substantial amount of energy is consumed by today's buildings which are accountable for about 40% of the global energy consumption. There are on-going researches in order to overcome these and find new techniques through energy efficient measures. Passive air cooling of earth pipe cooling technique is one of those which can save energy in buildings with no greenhouse gas emissions. The performance of the earth pipe cooling system is mainly affected by the parameters, namely air velocity, pipe length, pipe diameter, pipe material, and pipe depth. This paper investigates the impact of these parameters on thermal performance of the horizontal earth pipe cooling system in a hot humid subtropical climate at Rockhampton, Australia. For the parametric investigation, a thermal model was developed for the horizontal earth pipe cooling system using the simulation program, FLUENT 15.0. Results showed a significant effect for air velocity, pipe length, and pipe diameter on the earth pipe cooling performance, where the pipe length dominated the other parameters.

1. Introduction

The global energy consumption has increased in different forms during the last decades. In 2009, it was about 480 quadrillion Btu that increased to 524 quadrillion Btu in 2012. This signifies an annual average increase rate of 3.06% from 2009 throughout 2012 [1]. Population growth and higher income leads to this high energy demand. The world population is projected to reach 8.3 billion from its current 7 billion by 2030 [2]. Therefore, more energy will be needed for an additional 1.3 billion people.

The residential sector is a substantial energy consumer all over the world. Nationally, the energy consumption of this sector accounts for 16-50% and averages roughly 30% worldwide [3]. This use of energy is mainly due to the space cooling and heating the buildings. It is therefore important to apply energy efficient techniques in these buildings through new and novel building designs, which can be developed by employing several passive air cooling strategies. Earth pipe cooling system is one of the passive air cooling systems, which can reduce the cooling loads of the buildings.

The earth pipe cooling system operates with long buried pipes in which intake air comes through one end and passes through the buried pipes, and thus gets cooled by the soil. The cooled air is then blown out of the other end into a space. Since the system uses the underground spaces, it offers several additional advantages, for example, noise, protection from dust, partial air infiltration, storms and radiation, etc. It also offers a great potential for energy saving for any hot humid climate, like Queensland, since it can supplement the air conditioning load of many homes [4].

As a reasonable and economical option to ordinary cooling, the earth pipe cooling system is a type of choice, since no customary mechanical units are needed. In this system, the earth's near constant underground temperature is used for cooling air in industrial, residential and agricultural buildings [5–7]. The infinite thermal capacity of earth has made it a very useful heat sink for building cooling. The rationale behind this is that the daily and regular temperature variation is significantly diminished in the ground below a certain depth where the soil temperature remains constant. The soil temperature decreases in summer with increasing depth, which allows the utilisation of earth as a heat sink [8]. Meanwhile, the soil temperature increases in winter with increasing depth to a certain point, hence the use of earth as a heat source [9].

Thermal performance assessment is very important in order to measure the cooling capacity of the earth pipe cooling system. To assess the thermal performance of this system, several researches

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http://dx.doi.org/10.1016/j.enconman.2016.01.061
0196-8904/

Nomenclature

k	kinetic energy for turbulent flow ($m^2\ s^{-2}$)
ε	turbulent energy dissipation rate ($m^2\ s^{-3}$)
ρ	air density (kg/m^3)
$q\upsilon$	air flow rate (m^3/s)
υ	air velocity (m/s)
A	area of a region (m^2)
J_j	component of diffusion flux ($m^{-2}\ s^{-1}$)
x_i	component of length (m)
$C_{3\varepsilon} = \tanh\left\|\frac{u_1}{u_2}\right\|$	constant, u_1 and u_2 are the velocity components parallel and perpendicular to the gravitational vector respectively
$C_{1\varepsilon}$, $C_{2\varepsilon}$	constants
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate ($kg\ m^{-1}\ s^{-2}$)
D	diameter of the pipe (m)
ΔT	difference in temperature (K)
i, j, k (=1, 2, 3)	direction vector index
Δx	distance of heat transfer between two surfaces (m)
k_{eff}	effective conductivity ($W\ m^{-1}\ K^{-1}$)
P_{ef}	effective fan power (W)
W_{in}	energy input rate into the earth pipe cooling system (J)
h	enthalpy ($J\ kg^{-1}$)
u_i, u_j	fluid velocity components ($m\ s^{-1}$)
μ	fluid viscosity ($kg\ m^{-1}\ s^{-1}$)
G_b	generation of turbulence kinetic energy due to buoyancy ($kg\ m^{-1}\ s^{-2}$)
G_k	generation of turbulence kinetic energy due to the mean velocity gradients ($kg\ m^{-1}\ s^{-2}$)
Q	heat flow rate (J/s)
$\nabla \cdot (k_{eff} \nabla T)$	heat transfer due to convection
$\nabla \cdot (\bar{\bar{\tau}}_{eff} \cdot \vec{\upsilon})$	heat transfer due to viscous diffusion
l	length of the pipe (m)
m	mass of a substance (kg)
$\upsilon = \mu/\rho$	molecular kinetic viscosity of the fluid ($m^2\ s^{-1}$)
p	pressure (Pa)
ΔP_t	pressure loss (Pa)
$\nabla \cdot \left(\sum_j h_j \vec{J}_j\right)$	species diffusion
c_p	specific heat capacity (J/kg K)
T	temperature (K)
t	time (s)
S_h	total entropy ($J\ K^{-1}$)
ε	turbulent energy dissipation rate ($m^2\ s^{-3}$)
σ_k	turbulent Prandtl numbers for k
σ_ε	turbulent Prandtl numbers for ε
S_K, S_ε	user-defined source terms

were conducted in different hot humid climatic conditions. It's thermal performance was evaluated in a subtropical climate in Queensland, Australia by the authors [10–13]. A 1–2 °C reduction in temperature was attained in those studies for a 27.23 m^3 room. The cooling performance of the horizontal earth pipe cooling system was investigated in an agriculture greenhouse in Thailand by Mongkon et al. [14]. The study shows that this system has the potential to cool the greenhouse during daytime.

In most of the cases, the earth pipe cooling system is supported by a heat pump as a heat exchanger positioned within the buried pipe [15]. This is also identified as an earth pipe air heat exchanger, which can be used for cooling the buildings during summer and for heating in winter [16–19]. Bansal et al. [20] evaluated the cooling capacity of the earth pipe air heat exchanger by a numerical model. The model was developed to assess the impact of different pipe materials and air velocities on the thermal performance of the heat exchanger using FLUENT. The results showed that the pipe materials have no noticeable impact whereas the air velocity has greater influence. Another numerical model was also developed for the earth pipe air heat exchanger [21]. It was found that the model is computationally fast and simple to be implemented into building thermal insulation programs.

As mentioned earlier, the cooling performance of the earth pipe cooling system is mainly influenced by pipe length, pipe radius, buried underground pipe depth and air flow rate used in the earth pipe cooling system. The impact of these parameters on the performance of the earth pipe cooling system was assessed by an implicit and transient model using PHOENICS in Southern China [22]. The results revealed that a daily cooling capacity up to 74.6 kW h can be achieved using the system. Many researchers found that the resulting outlet temperature at the buried pipe decreases with decreasing pipe radius, decreasing mass flow rate in the pipe, increasing pipe length and increasing depths up to 4 m [23].

Various pipe diameters produce different cooling rates in an earth pipe cooling system. A study was carried out to investigate the earth pipe cooling performance using three different buried pipe radius of 0.125 m, 0.180 m and 0.250 m [24]. The outlet temperature of the buried pipe got higher with increased pipe radius. A buried pipe of small radius allows air to transfer excess heat to the soil quickly, since the centre point of the pipe gets closer to the outside soil [25,26]. Ghosal and Tiwari [23] agreed with these and reported that the pipe outlet temperature can be decreased with reducing the pipe radius.

Length of the buried pipes is one of the major factors that influence the earth pipe cooling performance. A longer buried pipe produces lower air temperature at the buried pipe outlet, which has been proved by several researches [23–25]. But, in some cases the longer pipes are not acceptable from the economic point of view. Moreover, the pipes need to be cost effective in case of an efficient cooling system. Their cost efficiency was evaluated for a hot, arid climate in Kuwait [27]. It was measured by calculating the payback time of the system. The payback time for the optimum configuration was obtained as 7.24 years, where the pipe diameter, the pipe length, and the pipe depth were 0.35 m, 56.97 m and 5.47 m respectively.

Material of the pipe is another factor that also affects the performance of the earth pipe cooling system. Each material has different thermal conductivity. The materials of higher thermal conductivity have higher heat transfer rate, and therefore can reduce the buried pipe outlet temperature. The impact of different pipe materials were analysed through a number of studies [28]. It was observed that the pipe material has no noticeable impact on the cooling performance.

Mihalakakou et al. investigated the impact of different pipe depths of 1.2 m, 2 m and 3 m on the earth pipe cooling performance [24]. The deeper pipe depth of 3 m provided the lowest temperature at the pipe outlet. They also conducted a similar study with different pipe depths of 2.5 m, 4 m and lower than 4 m [29]. The outcomes of this study also gave similar result. Air velocity is another key factor that influences the earth pipe cooling performance. To analyse the impact of different air velocities, 2 m/s and 5 m/s were considered for a study conducted in summer [20].