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Experimental and Analytical studies on Heat Transmission inside EAHE in Tropical zone

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Abstract

An Earth-Air Heat Exchanger (EAHE) is a device installed in buildings so that to exploit the earth's heat. Generally, at an average depth of 2.5 m, the soil maintains a stable temperature between 5 and 15°C depending on the season and the region. Injecting ambient air through ducts buried in the soil can reduce its temperature by 5 to 8 °C. The present paper aims to study the sensitivity of heat transfer coefficient in an EAHE operating in tropical conditions. To achieve that goal, experiments were carried out in a designed EAHE model using cooled sand as a soil sample. Variations at different values of the air velocity and soil temperature allowed performing experimental measurements. Analysis of the obtained results allowed discussing on the influence of low velocity on temperature of the air exiting the EAHE. Results revealed after modeling that the global heat transfer coefficient increases by 2.997 $W.m^{-2}.K^{-1}$ per unit velocity. Comparative study revealed that not only the proposed model is agreed with the existing correlation for Reynolds numbers comprised between 1500 and 3200; but also gives better estimation of the output temperature for Reynolds numbers less than 1500.

1. Introduction

Geothermal energy is one of the renewable energy sources that can be easily accessed for space heating and cooling purposes. Using bioclimatic comfort in the field of green buildings remains a challenge to modern cities. Research in that area has focused on air conditioning and heating using climate sinks. Many studies have been performed on Earth–Air Heat Exchangers (EAHEs) [1, 2]. One of the best-known applications of that natural air conditioning is the provincial well [3, 4]. Depending on the direction of heat transfer, the technics of that well consists of cooling or heating the ambient air to create comfort conditions in a room. Indeed, the Canadian well exploits the geothermal energy of the soil surface [5]. Generally, at a depth within 2 and 3 m, the soil maintains an almost constant temperature which varies between 5 and 15°C depending on the season (winter and summer, respectively) [6]. The principle consists of the circulation of airflow through dust buried in the soil, where temperature variations are less significant than in ambient temperature. Through these stable conditions, it is possible to preheat or pre-cool the air crossing the buried dust before introducing it into the building [7]. This is done by drawing or rejecting heat in the soil. Works on EAHEs started only after 1979 and nowadays, owing to high energy efficiency compared to conventional air conditioning systems, geothermal heat exchangers are increasingly spreading all over the world as an ideal solution for the safe use of energy and precisely for the control of thermal comfort in buildings.

Many experimental and theoretical studies of authors have been conducted on the design and the use of earth–air heat exchangers [8, 9, 10, 11, 12 and 13]. Several of these works focused in particular on the issues of their performances, thermal behavior, and their integration into the building as an air pre-conditioning system [14]. The main conclusion of these researches is that the energy performance of earth–air heat exchangers depends firstly on climatic conditions and secondly on the quality of the soil [15, 16]. However, these performances are much more affected by the nature and conditions of the soil than by the material of the buried dust [17, 18]. Some other authors carried out many studies because of improving the performances of bioclimatic heat exchangers [19]. They all concluded that water, instead of air, could considerably improve the efficiency of a climate sink. However, comparative studies showed that air-soil exchangers are more used in bioclimatic captors because of the simplicity and advantages in it using [20, 21, 22 and 23].

According to these previous works of authors, thermal performances of an earth-air heat exchanger are strongly dependent on the nature of the soil, the climate, and the dust material. Besides these above parameters influencing the thermal performances of an earth-air heat exchanger, heat transfer between the air and the soil is also depending on the nature of the flow in the pipe. So, heat transfer under laminar flow will not be the same as the one under turbulent flow. Focused only on laminar field, the present paper aims owing to experiments, and compared to the theoretical approach, to investigate on the sensitivity of the global heat transfer coefficient while varying the velocity of the air in the pipe and the temperature of the soil.

2. Methodology

2.1 Theoretical approach

An Earth-air heat exchanger implies two modes of heat transfers. There is convection between the air and the wall of the duct, and conduction in the duct material. As illustrated in Figure 1, ambient air enters the duct with temperature T_{in} and comes out with temperature T_{out}. During its crossing through the soil initially at temperature T_{soil}, it transfers a part of its energy to the soil and the heat transferred per unit time can be calculated [24, 25]. So, considering an earth-air heat exchanger operating with a mass airflow $\dot{m}_a$ and of which temperatures at the inlet and outlet of the duct are T_{in} and T_{out}, respectively, the real heat rate transferred to the soil could be calculated by using Equation 1 [26]. Term C_p represents the specific heat of air.

$$q_r = \dot{m}_a C_p [T_{in} - T_{out}] \qquad (1)$$

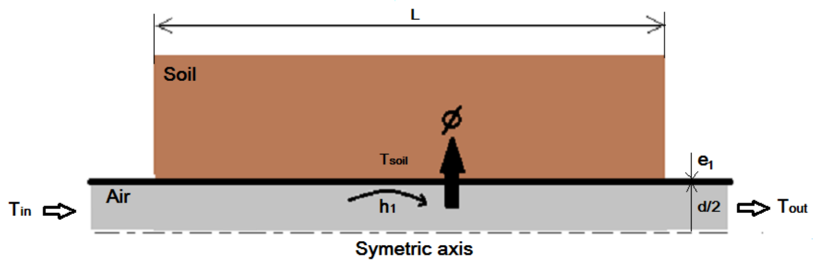

Figure 1: Illustration of heat transfer in an Earth-Air Heat Exchanger

Likewise, assuming that the air circulates in the pipe of length L and diameter d, theoretical heat flux transferred by air during its crossing through the soil, which is supposed to be an isotropic medium, is given by Equation 2. By assuming negligible conduction in the duct's material, the temperature of the inner surface of the duct T_w is supposed equal to the soil's temperature T_{soil}. Term k_1 represents the global heat transfer coefficient of the exchanger and ΔT_{ln} is the logarithmic average temperature difference.

$$q_{th} = \pi\, k_1 d\, L\, \Delta T_{ln} \qquad (2)$$

With:

$$\Delta T_{ln} = \frac{T_{in} - T_{out}}{ln\left(\frac{T_{in}-T_w}{T_{out}-T_w}\right)}$$

Global heat transfer coefficient k_1 is a characteristic coefficient that takes into account the forced convection in the air and the conduction in the duct. Depending on the velocity of air, the diameter of the pipe, and its thermal properties, that coefficient can be estimated from the relation given by Equation 3 established owing to empirical correlations based on dimensionless numbers like the Reynolds (*Re*), Prandtl (*Pr*), and the Nusselt number (*Nu*) [27, 28]. Term μ represents the dynamic viscosity of air. Properties of ambient air in tropical zones are given in Table 1. In laminar flow, the Nusselt number can be determined using Equation 4. Putting together Equation 1 and Equation 2, an expression given the global heat transfer coefficient can be given (Equation 5). So, from some experimental results, the corresponding global heat transfer coefficient could be deduced.

$$k_1 = Nu\,\frac{\lambda}{d} \qquad (3)$$

$$Nu = 1.86\,(Re \cdot Pr)^{1/3}\,(d/L)^{1/3} \qquad (4)$$

$$k_1' = \frac{\rho\, d\, V\, C_p}{4L}\, LN\left(\frac{T_{in} - T_w}{T_{out} - T_w}\right) \qquad (5)$$

Table 1: Mean properties of ambient air in tropical zone (during experiments)

Properties	Values
Temperature (T_{in})	28°C
Relative humidity (RH)	40%
Density (ρ)	$1.204\ \mathrm{kg.m^{-3}}$
Thermal conductivity (λ)	$0.0257\ \mathrm{W.m^{-1}.K^{-1}}$
Dynamic viscosity (μ)	$1.81 \times 10^{-5}\ \mathrm{kg.m^{-1}.s^{-1}}$
Specific heat (C_p)	$1006\ \mathrm{J.kg^{-1}.K^{-1}}$

2.2 Experiments

The experimental device in which tests were carried out is a box of dimensions $1.04\,m \times 0.30\,m \times 0.30\,m$ designed with wood panels of thickness $0.01\,m$ (Figure 2a) and includes an interior box of dimensions $1.02\,m \times 0.20\,m \times 0.20\,m$. That interior box is filled with a sample of soil first cooled in a fridge (Figure 2b). Vacuum space between both boxes is left to limit heat transfer between the cooled soil and the exterior medium. As illustrated in Figure 3, a pipe of length $L = 1.06\ m$ and diameter $d = 7.0\ mm$, passes by the center of both boxes so that to bury exactly a length of 1.0 m in the soil. All this set constitutes the model of Earth-Air Heat Exchanger used to experiment heat transfer between circulating air and cooled soil. Circulation of air in the exchanger is ensured by an electric fan which sucks ambient air and delivers it inside the pipe. Three temperature captors were used among which two type-N thermocouples (with a precision of 0.001°C) set at the inlet (TC1) and outlet (TC2) of the pipe. The third one is a thermometer (TH) of which the probe is immersed in the cooled soil (Figure 4). These sensors are connected to a data acquisition switch (Figure 5) piloted by a computer. For several given temperatures of the soil, tests consisted on varying the air velocity in the pipe and then measuring the inlet and outlet air temperatures. In view of minimizing the influence of ambient parameters such as temperature and humidity, experiments were carried out during the same period and practically between 11 AM and 2 PM so that to have during tests almost constant ambient temperature (~28 °C) and relative humidity (40%).

Figure 2a: Front view of the experimental device designed with wood panels

Figure 2b: Interior view of the experimental device filled with cooled soil

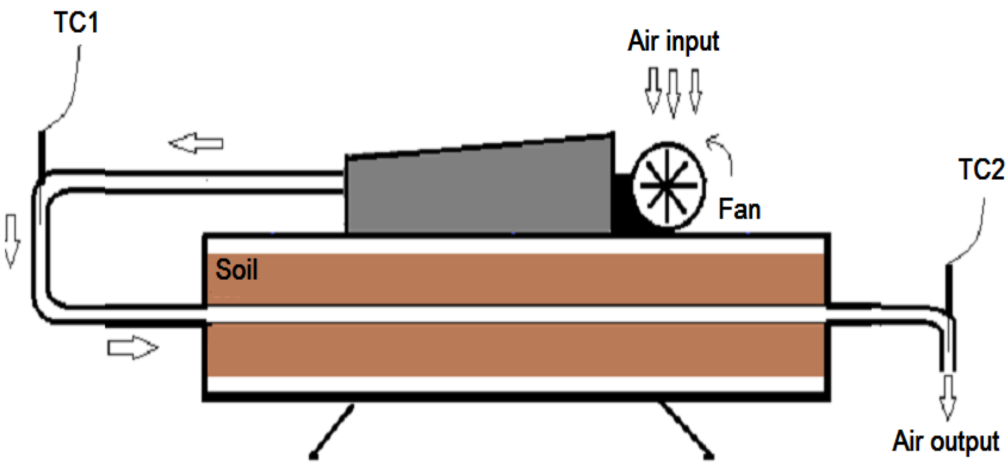

Figure 3: Outlines of the experimental model implementing the air-soil heat transfer

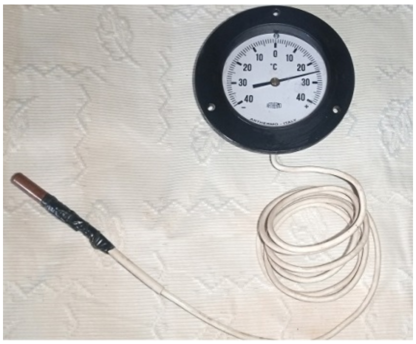

Figure 4: Thermometer used to measure and control the soil temperature (accuracy: 0.5°C)

Figure 5: N-Type thermocouples connected to the Sensor-PC module (accuracy: 0.001°C)

3. Results and Discussion

3.1 Analysis of experiments

Experiments consisted in injecting the ambient air inside a pipe with respective velocities values 1.2 and 2.9 m/s. For each one of these velocities, the temperature of the soil sample has been changed to investigate the behavior of the exchanger. Using these both velocities and varying the soil temperature, many heat transfer tests have been performed and data were collected. Once average values of experimental data were calculated, have been deduced the gap in temperature between the inlet and the outlet of the exchanger ΔT_a as well as the gap in temperature between the inlet air and the soil ΔT_b. Literature allowed calculating the corresponding global heat transfer coefficient k_1. Owing to that coefficient, the supposed or theoretical heat rate q_{th} transferred to the soil was determined and compared with the real transferred heat rate q_r (Table 2).

Table 2: Summary of results obtained during variation of the air velocity and the soil temperature.

V (m/s)	T_{soil} (°C)	T_{out} (°C)	ΔT_b (°C)	ΔT_a (°C)	k_1 $(W.m^{-2}.K^{-1})$	q_{th} (W)	q_r (W)	k'_1 $(W.m^{-2}.K^{-1})$
	0.5	3.495	25.394	22.399		2.209	1.252	5.437
	2.0	6.910	23.406	18.496		2.497	1.034	3.972
1.2	3.0	8.178	22.233	17.055	9.592	2.468	0.954	3.706
	4.0	9.668	21.106	15.438		2.476	0.863	3.344
	5.0	10.993	20.059	14.066		2.455	0.786	3.073
	6.0	9.500	21.821	18.321		2.831	2.473	11.238
	7.0	11.000	20.377	16.377		2.845	2.211	9.998
2.9	8.0	12.800	19.172	14.372	12.868	2.935	1.940	8.504
	9.0	13.980	17.826	12.846		2.849	1.734	7.831
	10.0	15.000	16.723	11.723		2.746	1.582	7.414

Concerning the confrontation between the real heat rate q_r and the theoretical heat rate q_{th}, their variation curves over soil temperature, have been plotted. Using 1.2 m/s (Figure 6) and 2.9 m/s (Figure 7) as air velocities, it can be observed that the theoretical heat rate evolves similarly with both velocities and each one turning around a constant value. With the air velocity of 1.2 m/s, the average heat flux is approximately equal to 2.5 W while it is word 2.8 W with an air velocity of 2.8 m/s. Following these results, it can be noted that while using k_1, the heat rate transferred to the soil does not significantly change with the variation of the soil temperature. However, changing the velocity of air from 1.2 to 2.9 m/s involves a light increase in transferred heat rate by 0.3 W.

Nevertheless, curves of real transferred heat rates deduced from experiments with both velocities decrease while the soil temperature increases. Confrontation of the theoretical and real curves shows an important gap between both heat rates. This means that the use of global heat transfer coefficient k_1 does not allow a better approximation of the heat flux transferred from the air to the soil. In order of proposing a solution to that issue, global heat transfer coefficients k'_1 were determined owing to real heat rates (Table 2).

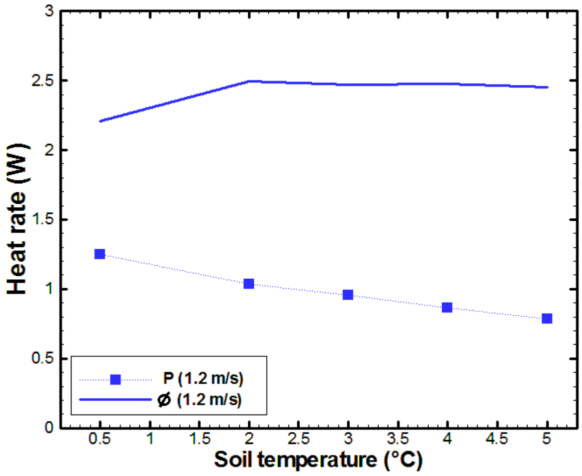

Figure 6: Variation under *V*= 1.2 m/s of the theoretical and real heat rate over the soil temperature

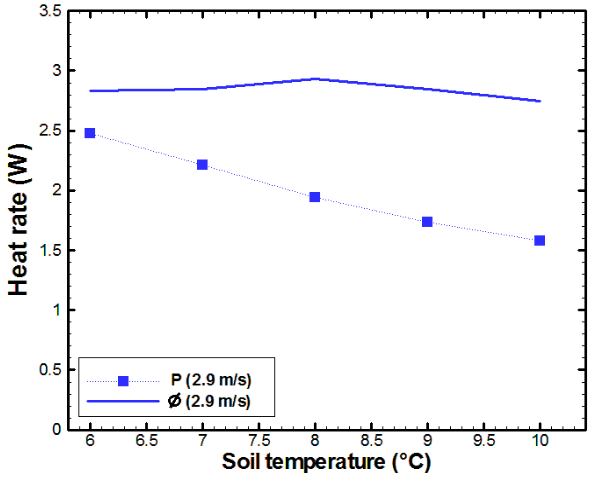

Figure 7: Variation under *V*= 2.9m/s of the theoretical and real heat rate over the soil temperature

Analysis of the above results highlights the effects of velocity on the heat transfer between fluid and soil. In reality, the air velocity mainly influences heat exchange through the global heat transfer coefficient. Figure 8 shows the variation of experimental coefficients over the soil temperature and the air velocity. It can be noted that the global heat transfer coefficient increases slightly with the soil temperature, but strongly with the air velocity. It is observed that curves of both velocities evolve similarly with the soil temperature. The more the soil rises in temperature the fewer decreases the heat transfer coefficient. However, it could be remarked that the transition of the air velocity from value 1.2 to 2.9 m/s involves an increase of the heat transfer coefficient by 4.4 $W.m^{-2}.K^{-1}$.

3.2 Modelling of the heat transfer coefficient

To better estimate the outlet temperature of the air in an Air-Soil heat exchanger, experiments allow investigating the variation of the heat transfer coefficient over the following two parameters. These parameters were the soil temperature which depends on the geographical location of implementation, and the airflow rate in the exchanger, more precisely its velocity. The analysis made in the above section has shown in a global way that the air velocity in the duct has a positive effect on the heat transfer between ambient air and soil in the exchanger. In summary, it was found that in a laminar flow, the global heat transfer coefficient increases by 2.997 $W.m^{-2}.K^{-1}$ per unit of velocity. By integrating that ratio owing to experimental conditions, was proposed a mathematical model estimating the global heat transfer coefficient as a function of the flow rate (Equation 6). Varying the Reynolds number notably the airflow rate in the duct, the corresponding heat transfer coefficients were calculated using Equation 3 and Equation 5 for k_1 and k'_1, respectively.

$$\int dk_1' = \int 2.997\, dV + C \qquad (6)$$

Graphical representation in the field of laminar flows (*Re<4000*) allows observing that the proposed model k_1' increases linearly with the Reynolds number while the literature model k_1 increases following a logarithmic manner. However, for Reynolds numbers less than 2300, curve of the literature model is above the proposed model following a mean gap of 5 $W.m^{-2}.K^{-1}$ (Figure 9). For Reynolds numbers more than 2300, the proposed model passes above the literature model. Intersection between both models is at Reynolds number 2300, corresponding to a mean velocity of 5.0 m/s. Fixing the input temperature of air at 26°C and the soil temperature at 5°C, these both models allowed simulating temperature of the air exiting the exchanger (T_{out} and T'_{out}, respectively).

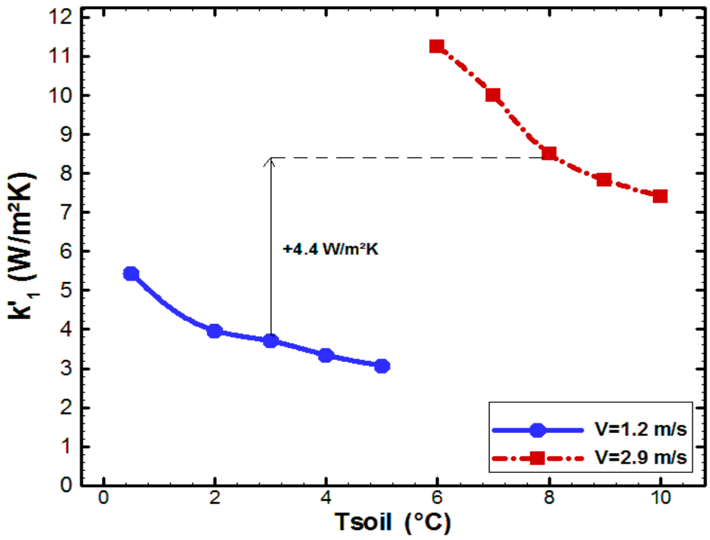

Figure 8: Variation under velocities *V*=1.2 and 2.9 m/s of the heat transfer coefficient over the soil temperature

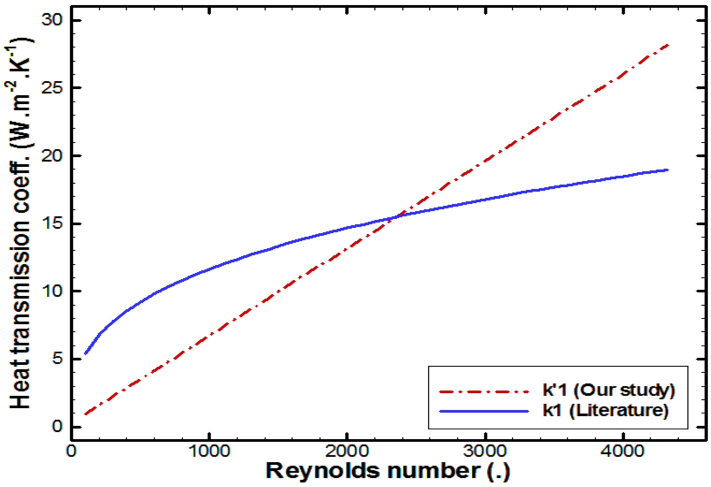

Figure 9: Variation of the heat transfer coefficients over Reynolds number

Figure 10 presents a comparison between variation curves of T_{out} and T'_{out} over Reynolds number. It can be observed that for Reynolds numbers between 1500 and 3200, the output temperature deduced from the present study, is following the output temperature deduced from the literature model. So, for Reynolds number less than 1500, it could be remarked that the model of k_1' described in the present paper better reflects the reality. This is due to the fact that T'_{out} decreases while Re increases. It then appears that the k_1' model is not only significant to describe physics in an air-soil exchanger but also admits accurate results for velocities less than 2.0 m/s.

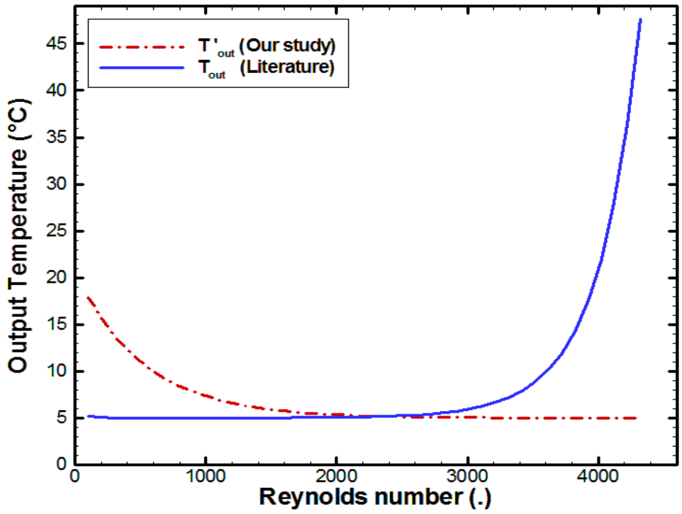

Figure 10: Output temperatures of air over Reynolds number while input and soil temperatures are 26°C and 5°C, respectively

The representation of both models with different soil temperatures notably for T_{soil}=10°C (Figure 11) and T_{soil}=15°C (Figure 12), allowed making identical observations. So as a major remark, whatever the soil temperature, the air-soil heat transfer is maximized when the Reynolds number is comprised between 2000 and 3000. This corresponds to values of air velocities between 2.0 m/s and 6.4 m/s.

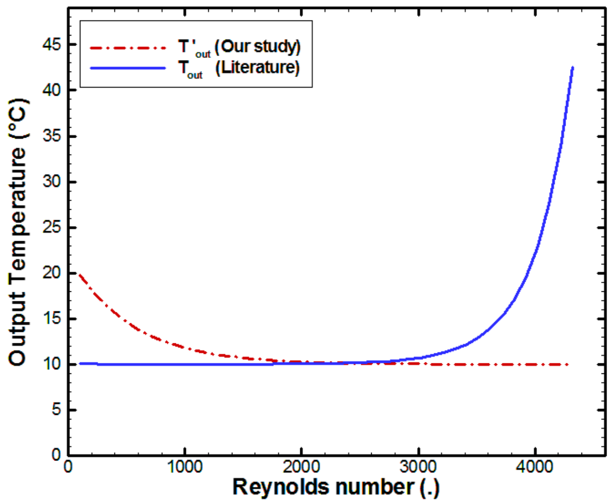

Figure 11: Output temperatures of air over Reynolds number while input and soil temperatures are 26°C and 10°C, respectively

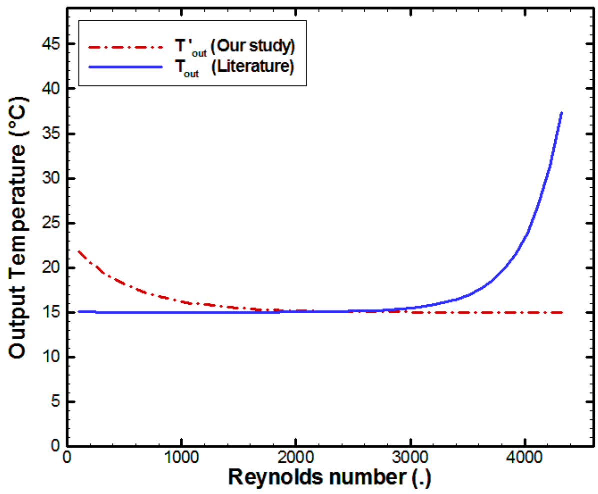

Figure 12: Output temperatures of air over Reynolds number while input and soil temperatures are 26°C and 15°C, respectively

4. Conclusion

This paper was an experimental study of heat transfer in a laboratory bioclimatic air-soil heat exchanger designed in view to experiment the cooling process of ambient air before its injection in a building for comfort needs. In order to study the sensitivity of the exchanger with the air velocity and the soil temperature, few tests were conducted on an experimental device. From the obtained results, a model expressing the global heat transfer coefficient in the field of laminar flows was proposed. Comparative study revealed that the established model is agreed with empirical correlation existing in the literature for Reynolds numbers within 1500 and 3200. Besides, it was also demonstrated that the proposed model gives more precisions for heat transfers with Reynolds numbers less than 1500.

Nomenclature

T_p :	*Temperature of the internal face of duct, °C*
μ :	*Dynamic viscosity of air, kg.m^{-1}.s^{-1}*
ρ :	*Density of air, kg.m^{-3}*
T_{in}:	*Temperature of entering air, °C*
T_{out} :	*Temperature of out coming air, °C*
T_{soil} :	*Temperature of soil, °C*
$\dot{m}_a$:	*Mass flow of air, kg.s^{-1}*
L :	*length of duct (fixed to 1.0 m)*
e_1 :	*Thickness of pipe, m*
d :	*Diameter of duct, m*
q_{th} :	*Theoretical heat flux, W*
q_r :	*Real heat flux, W*
C_p :	*Specific heat of air, J.kg^{-1}.K^{-1}*
V :	*Velocity of air, m.s^{-1}*
Re :	*Reynolds number*
Pr :	*Prandtl number*
Nu :	*Nusselt number*

Conflict of Interest: Authors declare that there are no conflicts of interest.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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