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# NUMERICAL MODELING BASED ON CFD OF THE THERMAL POTENTIAL OF A GROUND-AIR HEAT EXCHANGER FOR 2 CLIMATES OF THE MEXICAN REPUBLIC

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*Alfredo Aranda-Arizmendi*
Facultad de Ciencias Químicas e Ingeniería,
Universidad Autónoma del Estado de
Morelos, Morelos, Mexico.

*Moisés Montiel-González*
Facultad de Ciencias Químicas e Ingeniería,
Universidad Autónoma del Estado de
Morelos, Morelos, Mexico.

*Martín Rodríguez-Vázquez*
Facultad de Ingeniería, Universidad
Veracruzana, Coatzacoalcos, Veracruz
México.

*Carlos Miguel Jiménez-Xamán*
Corporación Mexicana de Investigación en
Materiales S.A. de C.V. (COMIMSA), Ciencia
y Tecnología 790, Coahuila, Mexico

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**Abstract:** This paper presents a numerical study based on Computational Fluid Dynamics (CFD) to evaluate the thermal potential of a Ground-Air Heat Exchanger (GAHE) as a sustainable ecotechnology, to contribute to the thermal comfort of buildings. The numerical modeling was carried out considering two geographical locations in Mexico, the rural community "Jicarero" in Jojutla Morelos and "La Rosilla" Durango, for the meteorological conditions corresponding to the warmest and coldest day of the year 2020. The results show the potential of the GAHE as heating and cooling passive system of buildings, respectively, because for the coldest day in "La Rosilla" Durango there was an average temperature increase of 4.76 °C at the GAHE outlet and for the warmest day in Jojutla Morelos there was an average temperature decrease of 5.83 °C.

**Keywords:** Ground-Air Heat Exchanger (GAHE), Computational Fluid Dynamics (CFD), Thermal comfort, Heating or cooling system.

## INTRODUCTION

In general, a building can be defined as energy efficient, when eco-technologies are implemented to reduce the total energy consumption of the building to cover its needs for heating, ventilation, air conditioning (HVAC systems), lighting, hot water, cooking, and food refrigeration, as well as the use of entertainment systems. Of which it is known that cooling and ventilation cause most of the energy consumption in conventional buildings (Comisión Reguladora de Energía. 2016, Comisión Federal de Electricidad 2020 & Shady Attia et al., 2013), in addition, the direction and speed of the wind are the main responsible for the efficiency of natural ventilation systems, Since buoyancy forces are responsible for 76% more airflow than buoyancy forces (Gauthier C. et al 1997 & B.R. Hughes and M. Cheuk-Ming, 2011), some studies conclude that turbulent winds are difficult to predict, causing either a lack or an increase of ventilation intermittently, while laminar winds create constant ventilation (P. St Clair and R. Hyde, 2009).

## ENERGY POVERTY IN MEXICO

Energy poverty is the situation in which a household is unable to pay for the use of a sufficient amount of energy to satisfy its domestic needs. In 2016 García-Ochoa and Graizbord determined that 36.7% of households in Mexico are in a situation of energy poverty, which implies the deprivation of goods and services, mainly: thermal comfort, efficient refrigerator, lighting, entertainment and gas or electric stove, of which the economic good with the highest rate of deprivation in homes in Mexico is thermal comfort with 33% (García Ochoa and Graizbord, 2016).

To improve the energy efficiency of buildings it is important to analyze and implement modern principles of sustainable development and bioclimatic design (Edgars Bondars, 2013), as well as to focus on all possible passive energy saving actions before adopting active measures (Li, X. et al., 2017). For this, it is necessary to quantify the energy performance of the possible technologies that help to reduce the energy consumption of the building, in order to have a predictive estimate of the contribution or reduction potential in the energy consumption of a building, it has been shown that the use of mathematical modeling software can help to estimate the energy performance resulting from the possible implementation of ecotechnologies to improve the energy efficiency of buildings (Zhiyong Tian, et al., 2015).

It should be noted that the way to measure energy poverty varies according to the geographical location of interest, since the entities where the predominant climate is very hot, humid or cold, will present different needs to enjoy thermal comfort, for this reason, the use of technologies such as GAHE that have the ability to function for space heating or cooling purposes as needed, are highly recommended due to their versatility, low installation and maintenance cost, as well as being friendly to the environment since they do not alter the natural composition of air or soil (Angel Sanchez, 2016) .

## GENERALITIES OF THE GAHE

The Ground-Air Heat Exchangers (GAHEs) have the necessary characteristics to be considered as a sustainable ecotechnology (Ortiz Moreno Jorge A. et al., 2014, Michiko Amemiya R. 2012, Ortiz Moreno Jorge A. et al 2015), due to because its operating principle is based on the use of low enthalpy geothermal energy (Cárcel Carrasco and FJ. Martínez Márquez 2015) to promote thermal comfort conditions, either to heat or cool the interior space of a building, through a thermal exchange between the outside air and contact with the ground at approximately 3 m depth (figure 1), this thanks to the phenomenon of thermal inertia of the soil, since the temperature distribution in the soil is much more stable than the air temperature in the troposphere (Su, H. et al., 2012), because the temperature of the soil at depths ranging from 2 to 5 m tends to be equal to the annual average temperature recorded in the geographical location under study (Badescu V., 2007).

In various theoretical and theoretical-experimental studies, it has been shown that the variables that most influence the performance of the GAHE are the length, diameter, depth of the pipe, wind speed, type of soil and relative humidity of the air (Ascione, F. et al., 2011, Ramírez Dávila, L. et al., 2014 & Xamán J. et al., 2014), it has also been determined that the thermal energy storage capacity of the soil increases with the increase in its moisture percentage and its absorptivity coefficient (Cichota R. et al., 2004).

Most studies have analyzed the thermal performance of the GAHE by means of the difference in air temperature at the inlet and outlet (Xamán, J. et al., 2015). In addition, a large part of the scientific community usually carries out their research applying global energy balances, due to the simplicity of the mathematical models, the use of software based on energy balances and the shorter computation time to obtain results, compared to the time required by CFD-based modeling (Kevin K. et al., 2009). However, the use of more robust tools such as CFD modeling generates more detailed and accurate information on the behavior, conditions, and operating parameters of the GAHE (M. Rodríguez-Vázquez et al., 2020 & H.P. Díaz-Hernández et al., 2019). The nomenclature used in this work is shown in Table 1.

## PHYSICAL MODEL

There are three ways to study fluid dynamics combined with heat and mass transfer: analytical, numerical, and experimental, each one has its respective advantages and disadvantages (Xamán, J., 2016). In this work, the Finite Volume Numerical Method (Hector Manuel M., 2004) with structured programming is used to model the GAHE.

The physical model for a GAHE, with their respective interactions and boundary conditions is shown in Figure 2. In the physical model you can see the different sections considered for CFD modeling, the ground is represented in brown, the blue arrows indicate the air inlet and outlet into the buried duct, and the lilac color shows the thickness of a thermal insulation around the air outlet duct, with the purpose of conserving the thermal energy obtained by the fluid during its journey inside the GAHE. Table 2 shows

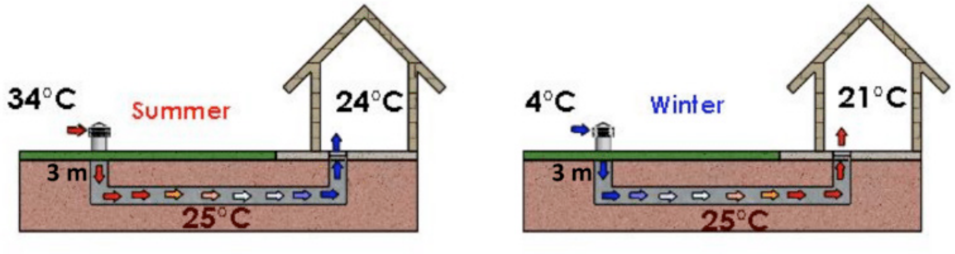

Figure 1: Principle of operation of a Ground-Air Heat Exchanger (GAHE).

| Variable | Symbol (Unit) | Variable | Symbol (Unit) |
|---|---|---|---|
| Thermal conductivity constant | λ (W/m°C) | Density | ρ (kg/m$^3$) |
| Specific heat at constant pressure | ρ (J/kg°C) | Conductive heat flux | $Q_{cond}$ (W/m$^2$) |
| Temperature | T (°C) | Convective heat flux | $Q_{conv}$ (W/m$^2$) |
| Overall horizontal length | Hx (m) | Evaporative heat flux | $Q_{evap}$ (W/m$^2$) |
| Overall vertical length | Hy (m) | Solar irradiance | $G_b$ (W/m$^2$) |
| Number of horizontal nodes | Nx | Vertical velocity component | ν (m/s) |
| Number of vertical nodes | Ny | Horizontal velocity component | υ (m/s) |
| Horizontal element size | Δx (m) | Pressure | P (Pa) |
| Vertical element size | Δy (m) | Soil-to-air convection coefficient | $h_{sup}$ (W/m$^2$°C) |
| Horizontal nodal distance | δx (m) | Emissivity coefficient | ε |
| Vertical nodal distance | δx (m) | Absorptivity coefficient | α |
| Source term | g (W) | Dynamic viscosity | μ (m$^2$/s$^2$) |

Table 1: Nomenclature and symbols

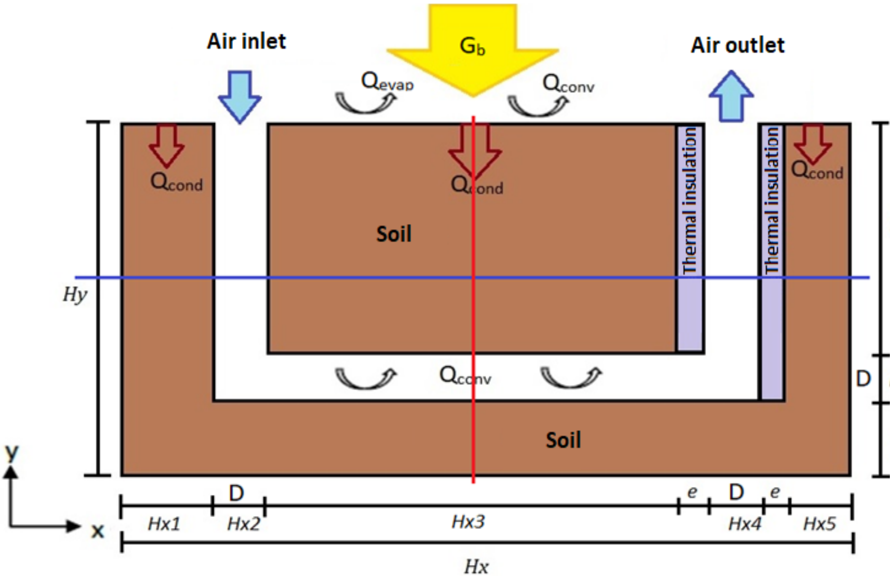

**Figure 2.** Physical model of the GAHE.

| **Dimensions** | **Value** |
|---|---|
| Total depth (Hy) | 3.15 m. |
| Total length (Hx) | 6.3 m. |
| Hy1 | 2 m. |
| Hx3 | 5 m. |
| Hy3 | 1 m. |
| Hx1 = Hx5 | 0.5 m. |
| Insulation thickness (e) | 0.05 m. |
| Diameter = Hy2 = Hx2 = Hx4 = D | 0.15 m. |

Table 2. Dimensions of the GAHE.

| **Number of nodes diameter** | **Average outlet temperature (°C)** | **Computing time (hours)** |
|---|---|---|
| 57 | 21.53 | 1.47 |
| 71 | 21.94 | 1.34 |
| 87 | 22.31 | 1.27 |
| 101 | 22.63 | 1.48 |
| 117 | 22.73 | 2.08 |

Table 3: Number of nodes and computing time

| **Number of nodes H x V** | **Average outlet temperature (°C)** | **Computation time (Hr)** |
|---|---|---|
| 57 x 57 | 22.69 | 1.20 |
| 71 x 71 | 22.65 | 1.37 |
| 87 x 87 | 22.60 | 1.42 |
| 101 x 101 | 22.63 | 1.49 |
| 117 x 117 | 22.59 | 1.67 |

Table 4: Average outlet temperature and computation time for each modeling

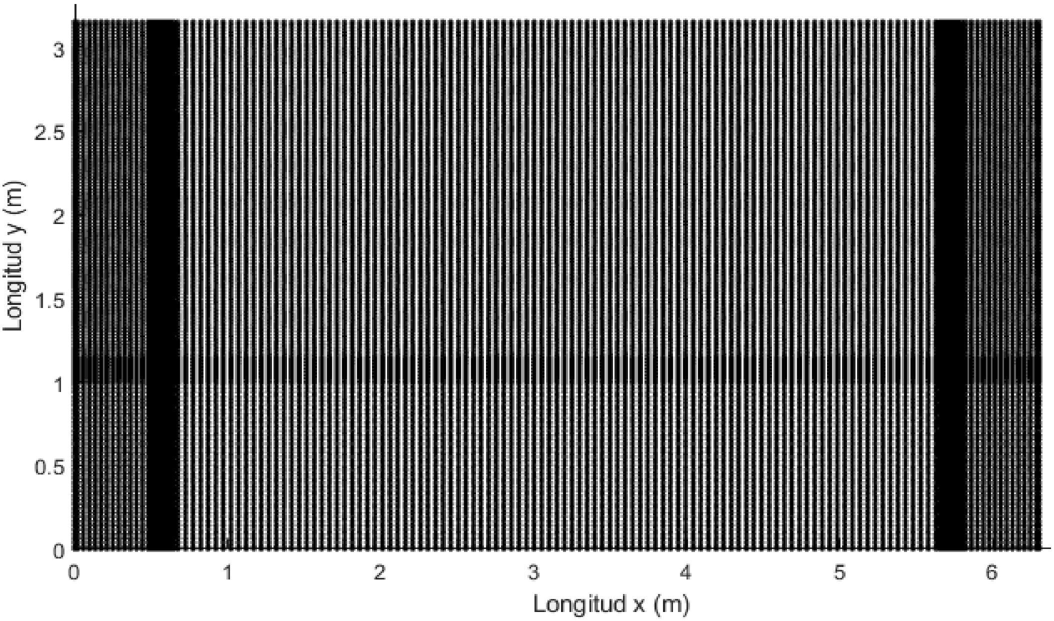

Figure 3: Distribution of nodes in the domain (meshed)

the dimensions of the geometric parameters of the GAHE modeled with CFD.

## MATHEMATICAL MODEL

Before defining the mathematical model, it is necessary to establish the considerations used for the definition of the physical domain, which are:

- Incompressible flow in laminar regime.
- Soil is considered a solid and isotropic medium.
- Boussinesq approximation: density is assumed constant except in the gravity term in the momentum equations where it is varied linearly (Mayeli and Sheard, 2021).
- Radiatively non-participating fluid.
- For the entire non-fluid domain (soil and insulating material), the blocking technique is applied, which involves permanently defining all the flow variables at all nodes of the solid domain with a value of 0 (u = v = P = 0) of such that for the solid domain only conduction heat transfer is evaluated.

The steady state governing equations inside the physical model of the GAHE are the mass, momentum, and energy equations for natural convection described as follows:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial(\rho u\, u)}{\partial x} + \frac{\partial(\rho v\, v)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) - \frac{\partial P}{\partial x} \tag{2}$$

$$\frac{\partial(\rho u\, u)}{\partial x} + \frac{\partial(\rho v\, v)}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) - \frac{\partial P}{\partial y} \tag{3}$$

$$\frac{\partial(\rho u\, T)}{\partial x} + \frac{\partial(\rho v\, T)}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\lambda}{Cp} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda}{Cp} \frac{\partial T}{\partial y}\right) \tag{4}$$

## BOUNDARY CONDITIONS

The boundary conditions are known information, either as constants or functions that represent the physical phenomena present between the computational solution space (domain) and the exterior of the system, this information is located at the border nodes of the entire domain and is the responsible information for each modeling solution.

For the temperature, the East, West, and South boundaries are considered adiabatic:

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0 \qquad \text{for } \ 0 \le y \le Hy \tag{5}$$

$$\left.\frac{\partial T}{\partial x}\right|_{x=Hx} = 0 \qquad \text{for } \ 0 \le y \le Hy \tag{6}$$

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0 \qquad \text{for } \ 0 \le x \le Hx \tag{7}$$

On the other hand, the energy balance proposed by G. Mihalakakou et al. [29] was implemented for the Northern boundary:

$$-\lambda \frac{\partial T}{\partial y}|_{y=Hy} = CE + -(LR) + (SR) - LE \ \text{for } \ 0 \le x \le Hx \tag{8}$$

*CE* represents the convective energy exchanged by the air with the soil surface, calculated as:

$$CE = h_S(T_{amb}) \tag{9}$$

*SR* represents the solar radiation absorbed from the surface of the ground.

*LR* represents the solar radiation emitted by the soil.

According to Badescu et al. (2007), the convective heat transfer coefficient ($h_S$) at the ground surface is a function of wind speed (Badescu V. 2007):

$$h_S = 5.678\left[0.775 + 0.35\left(\frac{V_{wind}}{0.304}\right)\right] \quad \text{for } V_{wind} < 4.88 \tag{10}$$

$$h_S = 5.678\left[0.775 + 0.35\left(\frac{V_{viento}}{0.304}\right)^{0.78}\right] \ \text{for } \ V_{wind} \ge 4.88 \tag{11}$$

$$-(LR) + (SR) = -\varepsilon\Delta R + \alpha G_b \tag{12}$$

In Equation (12), ΔR represents the term that depends on the relative humidity of the soil surface, the effective atmospheric temperature, and the radiative properties of the soil.

LE represents the latent heat flux from the ground surface due to evaporation:

$$LE = 0.0168\, f\, h_{Sup} \left((a\, T_{sup} + b) - HR\, (a\, T_{amb} + b)\right) \qquad (13)$$

In Equation (13), HR represents the relative humidity of the air and f is a fraction which depends mainly on the soil surface.

The factors a, b, and f have a constant value for a mean soil moisture of [29]:

$$a = 103\ (Pa/K) \qquad b = 609\ (Pa) \qquad f = 0.7$$

The boundary condition for the air inlet flow velocity (y = Hy) is calculated as a function of the Reynolds number:

$$v = f(Re)\ ,\ u = 0 \qquad \text{for } Hx1 \leq x \leq Hx3 \qquad (14)$$

The boundary condition for the outlet air flow (y = Hy) and the pressure are:

$$\left.\frac{\partial u}{\partial y}\right|_{y=Hy} = 0, \left.\frac{\partial v}{\partial y}\right|_{y=Hy} = 0, \left.\frac{\partial P}{\partial y}\right|_{y=Hy} = 0 \text{ for } \ Hx3 \leq x \leq Hx5 \ (15)$$

## METHODOLOGY

The methodology used to solve the mathematical model for the proposed physical domain is the finite volume technique, which requires the discretization process of the partial differential equations that make up the mathematical model in a domain that is also discretized or subdivided into small control volumes, known as computational mesh.

The discretization process consists of transforming the partial differential equations into a system of algebraic equations, known as a grouped terms equation, by means of 2 levels of approximation. The first level of approximation performs a defined integration with respect to the size of the element for all volumes. of internal control of the domain, obtained during the mesh generation process. For the second level of approximation, an interpolation scheme is applied for all terms that still preserve partial derivatives (Xamán, J., 2016).

Once the mathematical model has been discretized, the SIMPLEC method or algorithm is applied for the solution of the proposed model and for the iterative solution of the respective system of algebraic equations obtained for the calculated variables (“u”, “v”, “P” and “T”), the LGS-ADI (Line Gauss Seidel-Alternating Direction Implicit) technique was used, which is highly efficient for solving this type of system (Xamán, J., 2016).

## MESH INDEPENDENCE ANALYSIS

The analysis is divided into 2 stages, the first consists of determining the number of nodes necessary for the cross section through which the air flows (pipe diameter) and the second consists of determining the number of nodes for the depth and horizontal length. of the GAHE buried duct, the number of nodes for the solid soil section (Hy3, Hx1, Hx5) remains fixed with a finer mesh than the other sections. Table 3 shows the average temperature values at the outlet of the GAHE and its respective computation time.

It was determined that the number of nodes for the diameter of the pipe will be 101 nodes, since it is the solution that presents the least difference with respect to the result with 117 nodes, in addition to the additional computing time necessary for the solution with 117 nodes. considerably higher. The number of nodes distributed for the vertical and horizontal route of the pipe, as well as the soil occupied by this space, was evaluated at the same time. Table 4 shows the variation present between the outlet temperature and the respective computation time for the modeling. numerical according to the number of nodes used for the vertical and horizontal route of the pipe.

Once the study of mesh independence has been carried out, it is decided to use a structured mesh of 101 x 101 nodes, the variability in the average outlet temperature is negligible with an average value of 0.04 °C, in such a way that the mesh used has a total of 83,835 computational nodes (Figure 3).

## RESULTS

The main objective of evaluating the behavior of the GAHE in different municipalities, has the purpose of assessing the thermal potential of these systems for contribute to the thermal comfort of buildings by numerical modeling based on CFD, considering the respective climatic conditions that exist in the studied locality. Accordingly, numerical modelling is carried out for the two most extreme scenarios that may occur in a typical year in each location chosen as a case study, thus making it possible to determine whether this ecotechnology is feasible as heating or cooling system with based on the gain or loss of thermal potential obtained in the modelling results, or if, on the contrary, its use is not feasible for some periods of time throughout the year.

The numerical modeling of the GAHE was carried out, for 24 hours a day, with 1-hour intervals according to the weather conditions and soil characteristics corresponding to the geographical locations: "Jicarero" community in Jojutla Morelos, and "La Rosilla" Durango, Mexico, with the purpose of analyzing the thermal potential of the GAHE as heating or cooling passive system of buildings, according to the prevailing climate of the region where the application of this ecotechnology is intended. The modeling is carried out with the data reported by NASA (https://power.larc.nasa.gov/data-access-viewer/), for the warmest and coldest days of the year 2020, respectively. Figures 4 and 5 show the comparison between the inlet temperature (ambient temperature) with respect to the temperature obtained at the outlet of the GAHE in the town of Jicarero in Jojutla Morelos for the days 06/04/2020 and 10/02 /2020, respectively.

The results obtained for the Jicarero locality in Jojutla Morelos (figures 4 and 5) are especially satisfactory according to the cooling potential achieved for the warmest day of the year 2020, except for the time period from 6:00 to 11:00 hrs., there is an average reduction of the thermal level for the first 6 hours of the day of 6.01 °C and for the period from 12:00 to 23:00 hrs., there is an average reduction of 10.18 °C, and with an average of 5.8 °C for 24 hours a day, for a Reynolds number of 1000, in such a way that the application of an GAHE as cooling system for the warm season in the town of Jojutla Morelos is highly recommended. While the results obtained for the coldest day of the year, the system behaves as a heater during the first 14 hours of the day, having an average increase in the thermal level of 3.4 °C, during the period from 15:00 to 18:00 hrs., the GAHE works as a cooling system, reducing the average thermal level for that period by 2.37 °C according to the results obtained for a Reynolds of 2000, generating a global average for 24 hours a day as a heating system of 2 ° C.

Figures 6 and 7 show the results obtained for the days 06/05/2020 and 12/31/2020 respectively, in the town "La Rosilla" Durango. In this case, the results showed that the performance of a GAHE is satisfactory as heating system in the coldest season of the year, where an average gain of 4.76 °C was obtained for 12/31/2020, as shown in Figure 7. Furthermore, functions as a heating system 24 hours a day, avoiding subzero temperatures in some periods of the morning considering a Reynolds number of 2000. However, for the warmer season, the use of a GAHE is not convenient for the time periods between 0:00 hrs. and 7:00 hrs. and from 16:00 hrs. to 23:00 hrs., because the system tends to move away from thermal comfort temperature during

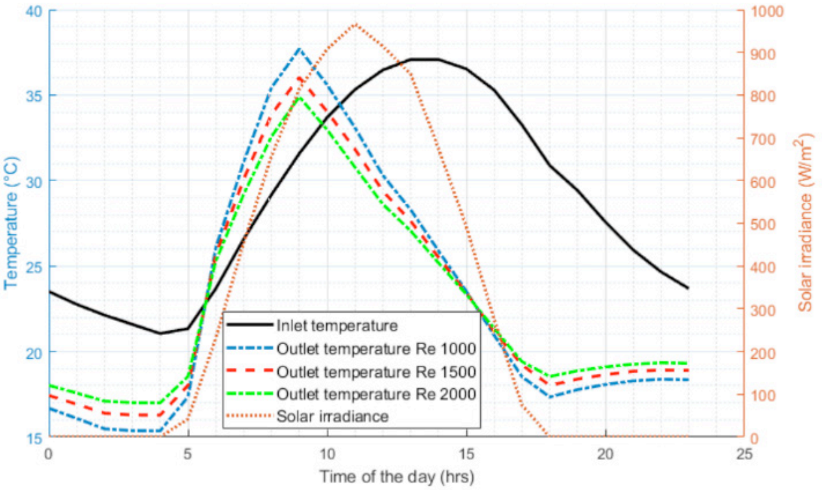

Figure 4: Comparison of the GAHE inlet and outlet temperatures in the Jicarero locality in Jojutla Morelos for the warmest day of the year 06/04/2020.

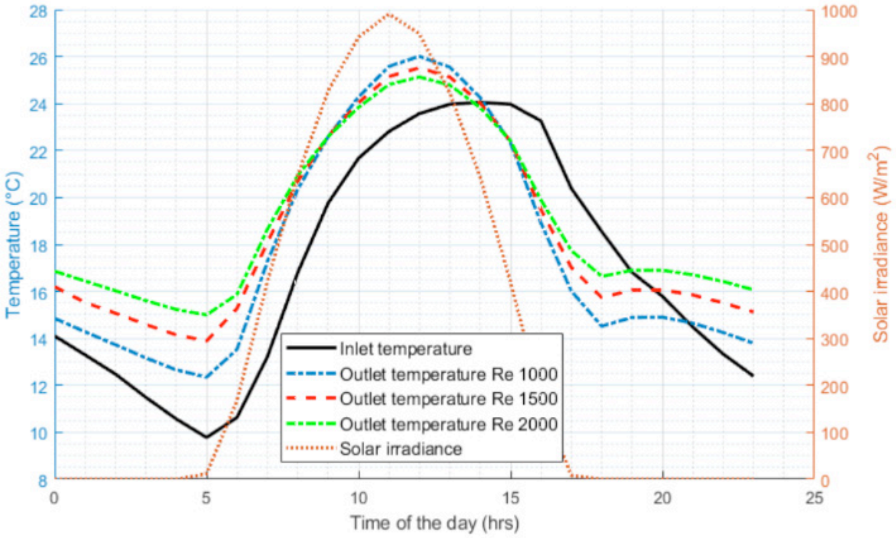

Figure 5: Comparison of the inlet and outlet temperatures of the GAHE in the "Jicarero" locality in Jojutla Morelos for the coldest day of the year 10/02/2020.

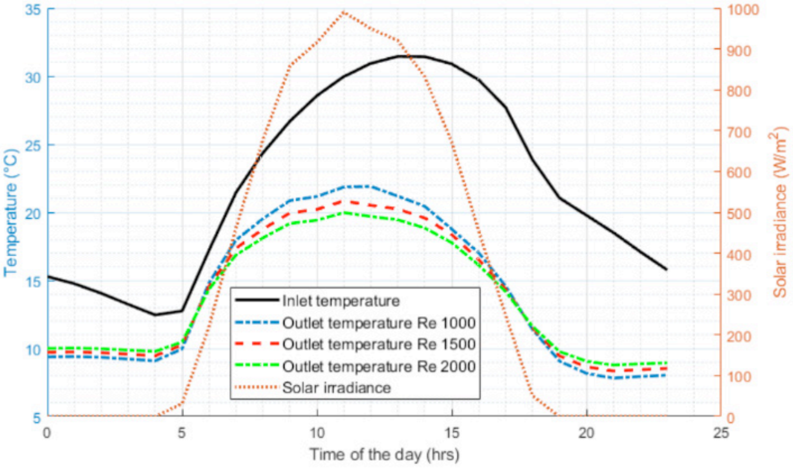

Figure 6: Comparison of the inlet and outlet temperatures of the GAHE in the locality "La Rosilla" Durango for the warmest day of the year 06/05/2020.

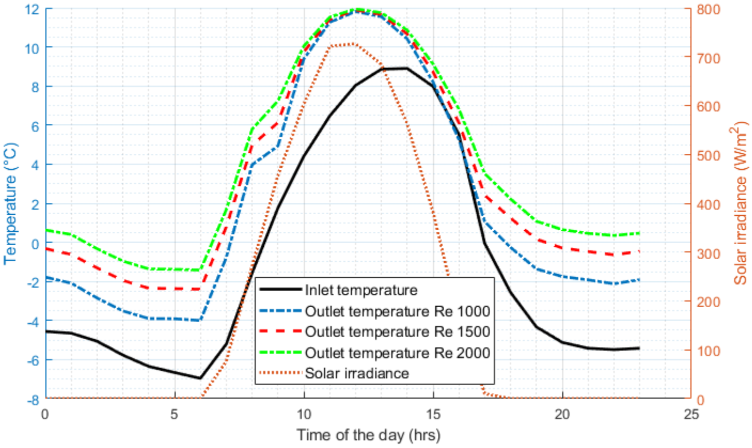

Figure 7: Comparison of the inlet and outlet temperatures of the GAHE in the locality "La Rosilla" Durango for the coldest day of the year 12/31/2020.

that period, but during period from 8:00 hrs. to 15:00 hrs, the system shows an excellent performance by reducing the thermal level of ambient air by an average of 8.57 °C, maintaining an average temperature of 20.71 °C for a Reynolds number of 1000.

## CONCLUSION

The numerical modeling of a GAHE in the town of Jojutla Morelos was satisfactory and feasible as heating and cooling system of buildings because the outlet temperature is equal or closer to the limits of thermal comfort (Figures 4 and 5), especially for the warmest day of the year (06/04/2020) since a reduction in the average temperature of 5.82°C was reported during the 24 hours of the day, for a Reynolds number of 2000, having peaks in the reduction of the thermal level of more than 13 °C for the period from 15:00 hrs. to 17:00 hrs., the results obtained for the modeling according to the conditions of the coldest day of the year generate an increase in the average thermal level of 2 °C, demonstrating that the system it is effective as a heating or cooling system depending on the season of the year, being more effective for cooling purposes in the warm season of the town of Jicarero in Jojutla Morelos.

In the town of "La Rosilla" Durango, the GAHE is effective as a heating system during 24 hours on 12/31/2020 with an average elevation of the thermal level of 4.76 °C for a Reynolds of 2000, while for the hot day 06/05/2020, the thermal performance of the GAHE was satisfactory in the period of 8:00 hrs. to 15:00 hrs., reducing the thermal level of the inlet air (ambient temperature) by an average of 8.57 °C. However, in the hourly from 0:00 to 7:00 hrs. and from 4:00 p.m. to 11:00 p.m., its use is not recommended because the temperatures recorded are already low and the GAHE reduces them even more.

The results confirm what has been reported in the literature, the GAHE have a better performance in extreme climates, since the system was more effective in the warm period of a locality with a climate considered warm (Jojutla Morelos) and for the period of more low temperature of a locality with a climate considered extremely cold ("La Rosilla" Durango).

The modeling of the GAHE in 2 geographical locations, with a predominantly cold and warm climate, shows that the possible implementation of the GAHE is feasible and sustainable as heating system or for purposes of cooling buildings depending on the real operating conditions, at some localities the GAHE fulfills both purposes, as the results obtained for the Jicarero in Jojutla Morelos. These results are valid for any locality and/or town in the world where climatological conditions like those modelled in this study exist.

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