Advances in Materials Physics and Chemistry, 2026, 16(2), 48-68
https://www.scirp.org/journal/ampc
ISSN Online: 2162-5328
ISSN Print: 2162-531X

Critical Analysis and Perspectives of Earth-to-Air Energy Exchangers: Limitations of Classical Models and the Need for New Continuous Analytical Approaches

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How to cite this paper: Elombo Motoula, S.M., Oko Ganongo, A., Mimiesse, M.G., Ndzessou, W.B., Mombeki Pea, H.J. and Gomat, L.J.P. (2026) Critical Analysis and Perspectives of Earth-to-Air Energy Exchangers: Limitations of Classical Models and the Need for New Continuous Analytical Approaches. *Advances in Materials Physics and Chemistry*, **16**, 48-68.
https://doi.org/10.4236/ampc.2026.162003

Received: November 4, 2025
Accepted: January 30, 2026
Published: February 2, 2026

Abstract

Earth-to-Air Energy Exchangers (EAEEs) represent a promising passive solution for air preconditioning in buildings, exploiting the ground's thermal inertia. However, conventional analytical models rely on simplifying assumptions: dry air, homogeneous soil, neglected vertical section, and ignored internal condensation. Although these assumptions are necessary for an analytical formulation, they limit the models' ability to faithfully represent real system behavior, particularly in tropical and semi-arid climates. Numerical approaches (CFD, finite element methods) offer increased physical realism but remain computationally expensive and difficult to apply in parametric studies or practical sizing. In this context, this article provides a critical analysis of existing models and discusses the need for alternative analytical approaches that reconcile physical realism with engineering practicality. The Initial Basis Analysis Method (IBAM) is introduced as a continuous analytical framework capable of solving the coupled energy and mass transport equations analytically, while incorporating thin-film condensation, the vertical section, atmospheric fluctuations, and thermal and hygrometric soil variability. Rather than presenting a new experimental validation campaign, the manuscript relies on comparisons with experimental results and prior work to discuss the validity domain and practical applicability of the proposed approach. This contribution aims to clarify the assumptions, contributions, and limitations of the IBAM method, and to provide a useful analytical framework for the modeling and design of earth-to-air energy exchange systems.

Keywords

Critical Analysis, Continuous Analytical Approach, Earth to Air Energy Exchanger, Humidity Ratio, IBAM

1. Introduction

Energy efficiency in the building sector is today one of the major pillars of global strategies for ecological transition and greenhouse gas emission reduction [1] [2]. The sustained growth in air conditioning, ventilation, and heating needs exerts increasing pressure on electrical grids, particularly in rapidly expanding urban areas. In this context, interest in passive or semi-passive air conditioning systems based on the exploitation of local environmental resources continues to grow [3]. Among these solutions, earth-to-air energy exchangers (EAEEs) occupy an important place due to their ability to precondition outdoor air through the natural thermal inertia of the soil [4]-[6]. The operation of EAHEs relies on the thermal stability of the soil beyond a certain depth, generally between 1 and 3 m, where daily and seasonal fluctuations become strongly damped. This behavior is linked to the thermophysical properties of the soil, particularly its thermal diffusivity, and can be described by the classical theory of harmonic heat diffusion [7]. Nevertheless, the literature still presents several important limitations. Despite abundant literature, several limitations persist in the analytical modeling of EAEEs. Classical analytical models often rely on oversimplifying assumptions: dry air, homogeneous and isotropic soil, absence of condensation, or neglect of mass transfer [8] [9].

Numerical approaches based on computational fluid dynamics (CFD) or finite element methods constitute a robust alternative to relax some assumptions, but their high computational cost and implementation complexity limit their use in extensive parametric analyses or in pre-design phases [10] [11]. Furthermore, research published in recent years highlights a long-underestimated phenomenon: the importance of air humidity and internal condensation processes. These phenomena can significantly influence outlet temperature and exchanged thermal power, particularly in humid tropical, semi-arid climates or those subject to strong hygrometric variations. In this context, the Initial Base Analysis Method (IBAM), recently developed by [12], stands as an analytical approach aiming to improve the representation of thermo-hygrometric phenomena in EAEEs, without claiming to provide an exhaustive three-dimensional local description. Thus, this article aims to propose a critical analysis of existing models, clarify their assumptions and limitations, and present the methodological framework of IBAM as an analytical contribution intended for the modeling and design of EAEEs in various climatic contexts.

2. Description of Earth to Air Energy Exchangers (EAEEs)

Earth to air energy exchangers (EAEEs), also known as Canadian wells, are now widely studied shallow geothermal technologies used for the passive preconditioning of air in buildings (**Figure 1**). Their operating principle is based on exploiting the thermal stability of the ground, whose daily and seasonal temperature variations rapidly attenuate with depth, thereby providing a natural source of heating or cooling for air conditioning purposes [13] [14]. In a context where HVAC systems account for approximately 30% - 40% of the total energy consumption of buildings [15] [16], EAEEs are attracting increasing interest due to their potential to reduce energy demand and associated emissions. This technology is fully aligned with bioclimatic design strategies aimed at limiting the use of energy-intensive mechanical systems and enhancing the thermal resilience of buildings [3].

The operation of an EAEE relies on heat exchanges between the air flowing inside a buried duct and the surrounding soil. As air passes through the buried pipe, it exchanges heat by internal convection with the pipe wall and by conduction within the soil, resulting in a temperature decrease in summer and an increase in winter [4] [17]. The thermal variability of the ground follows a harmonic dissipation process governed by soil thermal diffusivity and the frequency of atmospheric excitation, leading to the concept of thermal penetration depth, as defined in the classical works of Harlan (1973) and subsequent studies [18]. The thermal damping capacity of the soil strongly depends on its physicochemical properties, particularly volumetric moisture content, compaction, and thermal conductivity [19] [20].

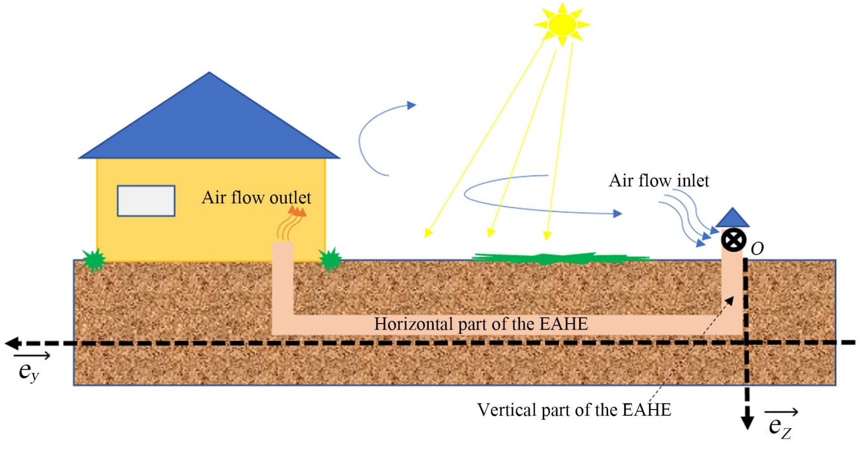

Figure 1. Operating schematic of an EAEE.

Atmospheric air always contains a significant amount of water vapor, which plays a crucial role in the actual performance of EAEE systems. When the temperature of the inner pipe wall falls below the dew point, condensation may occur

(**Figure 2**), releasing latent heat and profoundly modifying heat transfer conditions [21] [22]. This phenomenon, long underestimated in analytical models, has been highlighted in several recent experimental studies conducted in tropical and semi-arid climates [23] [24]. These studies show that thin-film condensation can enhance internal heat transfer and lead to significant changes in convective heat transfer coefficients, thereby requiring a more rigorous thermodynamic approach than that adopted in traditional models.

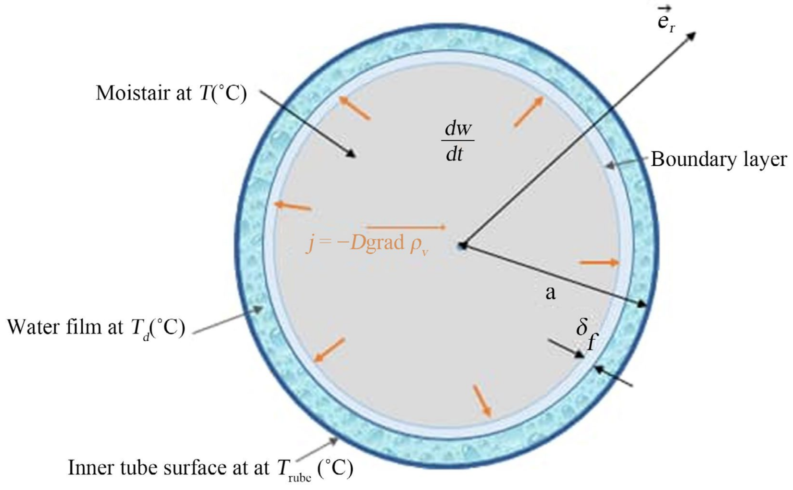

Figure 2. Mass transfer during the condensation phase inside the pipe [22].

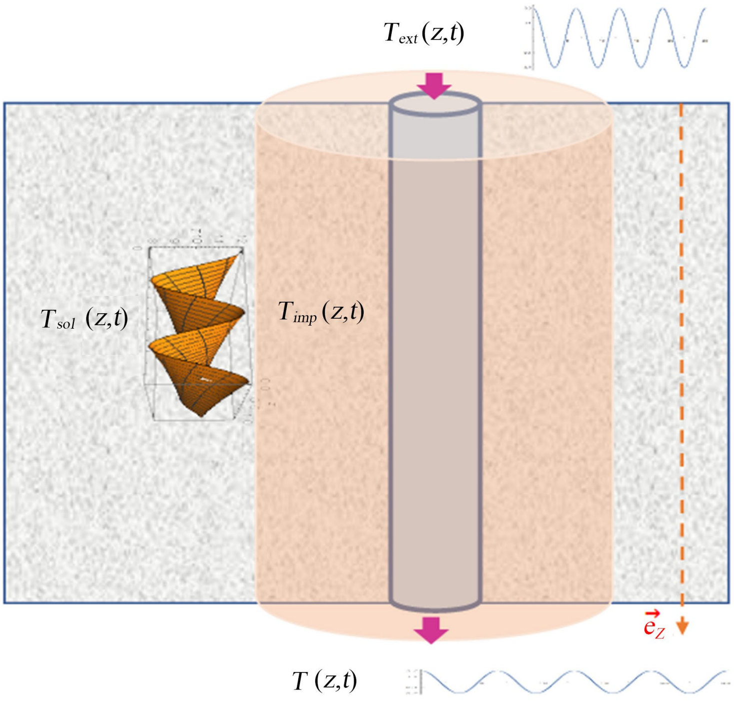

Figure 3. Cross-sectional view of the vertical section of an EAEE [25].

The geometry of an EAEE has a significant influence on thermal transfer processes. Classical configurations consist of a buried horizontal section, an open air intake, and a vertical section connecting the outdoor environment to the buried zone (**Figure 1**). For a long time, the vertical section was considered negligible due to its relatively short length [25] [26]. However, recent studies have demonstrated that it plays a crucial role in establishing the initial conditions of the air entering the horizontal section, particularly by influencing the inlet temperature and humidity applied in transport models [22] [27]. The exposure of this section to atmospheric fluctuations, along with the internal convective mechanisms that develop within it (**Figure 3**), implies that neglecting this portion leads to systematic errors in theoretical models, thereby explaining some of the persistent discrepancies observed between numerical simulations and experimental measurements.

The spatial and temporal variability of soil properties constitutes another major challenge for modeling. Contrary to the commonly adopted assumption of homogeneity, soil may exhibit pronounced thermal and moisture gradients, which directly affect thermal conductivity and heat capacity [28]. Studies published between 2022 and 2024 emphasize the importance of incorporating the effects of water content, internal phase changes within the soil, and variable thermo-hydraulic properties in order to better reproduce observations under real operating conditions [29] [30]. Similarly, recent research shows that classical analytical models are often insufficient to account for hygrometric coupling, condensation phenomena, and transient soil behavior, thus highlighting the need for more robust continuous analytical approaches.

Historically employed analytical models are often based on steady-state or quasi-steady-state assumptions, whereas numerical approaches relying on CFD or finite element methods involve high computational costs and a strong dependence on input data quality [18] [31]. Recent studies advocate the development of new analytical techniques capable of simultaneously representing energy and mass transport phenomena, while incorporating realistic boundary conditions and accounting for atmospheric fluctuations [23] [24]. In this context, methodological advances based on continuous analytical approaches, such as the Initial Base Analysis Method (IBAM) developed in the works of Gomat *et al.* [12], represent a significant contribution to both the fundamental understanding and practical modeling of EAEE systems.

3. Analysis of Existing Methods

3.1. Analytical, Numerical, and Advanced Models of EAEEs

The modeling of Earth to Air Energy Exchangers (EAEEs) has seen significant progress in recent decades, driven by the need to better understand the complex interactions between air flowing in buried ducts, the surrounding soil, and atmospheric variations. Early work primarily relied on simplified analytical models aimed at solving the heat equation in a semi-infinite soil subjected to periodic thermal excitation, typically sinusoidal in nature [13] [14]. These models consider the soil as a homogeneous and isotropic medium and assume that atmospheric temperature follows a harmonic signal, which allows the dissipation of heat in the geological medium to be described using damped exponential solutions. Although these approaches provide an initial understanding of heat transfer, they neglect several essential phenomena, such as soil moisture, irregular atmospheric temperature fluctuations, duct roughness, and internal condensation related to water vapor in the air.

Subsequently, more sophisticated analytical models were proposed to refine the description of thermal exchanges. The work of [5] and [32] introduced formulations that better represent radial conduction in the soil around the tube, while [26] proposed a semi-empirical approach describing the exponential decay of air temperature along the tube as a first-order system. However, these models remain limited by the assumption of a constant internal convective heat transfer coefficient, which in reality depends on the flow regime, air velocity, humidity level, and the potential presence of condensation. Indeed, several experimental investigations have revealed that the evolution of the internal convection coefficient varies significantly between laminar, turbulent, or mixed flow regimes, and that thin-film condensation can strongly increase local heat exchanges [17] [21].

Semi-analytical models later attempted to combine the physical realism of numerical approaches with the simplicity of deployment of analytical formulations. The work of [33], for example, incorporated Dittus–Boelter or Gnielinski-type correlations to better represent the evolution of the Nusselt number in buried ducts. [4] enriched this approach by introducing variations in the Reynolds number and the effect of internal roughness, allowing for a better estimation of heat fluxes in real-world configurations. However, these models remain unable to accurately represent fast transient regimes induced by atmospheric fluctuations or to capture the thermodynamic behavior of humid air in the presence of internal condensation. Several studies demonstrate that semi-analytical models can lead to deviations exceeding 2˚C - 4˚C between predicted and measured temperatures, particularly in tropical or semi-arid climates where thermo-hydraulic gradients are more pronounced [18] [22].

The emergence of Computational Fluid Dynamics (CFD) marked an important step in EAEE modeling. Three-dimensional simulations based on the Navier–Stokes equations coupled with heat transfer enable a detailed description of velocity fields, temperature distributions, turbulence effects, and radial and longitudinal thermal gradients [28] [31]. CFD models also offer the possibility of integrating internal roughness, pressure losses, complex geometries, multiphysics interactions, and transient flow regimes. Nevertheless, these approaches remain heavily dependent on the chosen boundary conditions and the accuracy of experimental data used for validation. Moreover, they require significant computation times, making them poorly suited for parametric studies or simulations covering complete annual cycles [18] [34]. Consequently, using CFD models as design tools in common practice remains challenging.

Concurrently, finite element and finite volume approaches have been developed to describe the thermal couplings between soil and ducts, taking into account temperature variations with depth and the thermophysical properties of the soil. These models provide an accurate representation of three-dimensional thermal diffusion in the soil but suffer from the same limitations as CFD approaches when it comes to integrating humid air dynamics, condensation effects, or spatial variability of soil characteristics [11] [35]. Recent work has shown that even sophisticated numerical models fail to correctly represent the air-vapor two-phase behavior in ducts, particularly during rapid diurnal cycles where the internal wall periodically reaches the dew point [24].

Since 2022, several researchers have proposed coupled thermo-hydraulic models that more faithfully represent condensation, evaporation, and vapor transport phenomena. These models, introduced notably by [29] and [30], explicitly integrate the variation of the mixing ratio, specific enthalpy of humid air, and vapor diffusion in the internal flow, offering a complete description of the transition between dry and humid regimes. They constitute a notable advancement as they account for phenomena entirely absent from historical models, such as condensate film formation, latent heat release, and local modifications of heat transfer coefficients.

Furthermore, recent research has focused on the thermal and hydraulic variability of soil, a determining but long-neglected aspect. The work of [36], enriched by more recent contributions [29], shows that soil thermal conductivity and diffusivity are strongly dependent on water content, which influences the thermal penetration depth and the dynamic response of the system. Lateral and vertical soil heterogeneity can generate significant local fluctuations in heat transfers, explaining some discrepancies between models and experimental observations.

3.2. Experimental Studies, Hygrometry, Condensation, and Actual Performance

The experimental evaluation of Earth to Air Energy Exchangers (EAEEs) holds a central place in the literature, as it provides indispensable validation for analytical and numerical models. Early experimental studies demonstrated that the actual performance of EAEEs is closely dependent on geometric configuration, soil type, air humidity, airflow rates, and local climate [18] [32]. Unlike analytical models, which often rely on simplifying assumptions, experimental measurements reveal complex dynamic behaviors dominated by nonlinear interactions between the air, the duct wall, and the surrounding soil. Numerous experimental campaigns conducted in temperate, Mediterranean, continental, or tropical climates have shown that theoretical performance predicted by linear models is often higher than the actual performance observed [17] [26].

One of the most significant aspects highlighted by experimentation is the role of air humidity, which strongly influences internal heat exchange. Atmospheric air typically contains between 5 and 20 g/kg of water vapor, depending on the climate and season. As this air flows through the buried duct, its temperature gradually decreases upon contact with the wall, increasing its relative humidity until, in some cases, reaching the dew point. Several studies have shown that internal condensation is a frequent phenomenon, particularly in tropical and subtropical regions where relative humidity can exceed 90% [21] [24]. Experiments conducted by [4] and extended in recent work by [23] have demonstrated that this condensation manifests as a thin film along the inner wall, profoundly altering the thermal regime through the release of latent heat. This phenomenon leads to a local increase in the convective heat transfer coefficient, thereby intensifying heat exchange, particularly in the first section of the duct where the difference between air temperature and soil temperature is greatest.

Despite its crucial role, internal condensation was long underestimated or omitted in analytical models. However, experimental measurements consistently show that the presence of condensation leads to a faster reduction in air temperature in the first few meters, followed by more stable thermal damping. [22] showed that, under the climatic conditions of the Congo, this phenomenon can result in a difference of 1˚C to 3˚C compared to models that neglect condensation. The results of [29] confirm these observations in a humid subtropical climate, emphasizing that more than 30% of heat exchange can be attributed to latent heat in certain configurations. These findings demonstrate the necessity of integrating hygrometric processes into models to obtain reliable predictions.

Concurrently, experiments have highlighted the importance of spatial and temporal variability in soil properties. Soil is a heterogeneous medium whose thermal conductivity and heat capacity depend strongly on its composition, water content, compaction, and history of drying or wetting [19] [36]. Long-term experimental studies show that the thermal behavior of soil is not strictly periodic due to irregular climatic variations and precipitation phenomena. Thus, experimental models conducted by [28], followed by more recent work at instrumented European sites [30], have shown that the soil thermal gradient can fluctuate significantly within the same day, especially during substantial moisture variations. These fluctuations affect the wall temperature and, consequently, the overall system performance, particularly during abrupt transient cycles.

The analysis of experimental EAEE performance also reveals a systematic discrepancy between theoretical predictions and field measurements. Several studies report that analytical models based on homogeneous soil predict performance 15% to 25% higher than actual measurements [18] [31]. These discrepancies are generally attributed to three main factors: soil variability, unaccounted thermal losses in the air intake and vertical section, and internal condensation which is often ignored. Experiments conducted in various countries (Greece, France, India, Turkey, Argentina, and recently in China and Brazil) show that accounting for the vertical section significantly improves the prediction of outlet temperature [27]. This section, long neglected in models, directly influences the initial temperature and humidity conditions of the air entering the buried portion, explaining some of the observed discrepancies.

Recent experimental studies have also focused on the effect of airflow rate on system performance. Several researchers have shown that lower flow rates increase air residence time and improve heat exchange but also promote internal condensation [21] [23]. Conversely, high flow rates reduce condensation but decrease overall efficiency due to reduced exchange effectiveness. These results indicate that a dynamic compromise must be found to simultaneously optimize outlet temperature, air quality, and energy efficiency.

Furthermore, the integration of advanced measurement instruments such as multi-point probes, capacitive humidity sensors, high-frequency data acquisition systems, and infrared thermal cameras has significantly improved the quality and accuracy of observations. This has led to a finer understanding of the longitudinal distribution of condensation, the radial thermal profile in the soil, and humid air dynamics. Nevertheless, many studies still emphasize the difficulty of obtaining reliable measurements at depth, particularly due to local disturbances caused by sensor installation [29].

Experiments conducted in hot and humid climates have revealed particularly contrasting performance depending on the season. In tropical climates, EAEEs show high efficiency during the day but reduced performance at night, when soil temperature sometimes exceeds air temperature [22]. This leads to asymmetric behavior between daytime cooling and nighttime warming, requiring a detailed analysis of hourly temperature profiles. On an annual scale, systems show positive performance most of the time, but transitional periods around seasonal changes reveal complex behaviors not captured by standard models.

Overall, experimental studies converge on a clear conclusion: EAEEs are a promising technology, but their performance depends on a complex combination of thermal, hydraulic, geological, and atmospheric phenomena, difficult to capture in a single model. These studies highlight the need to develop models capable of simultaneously integrating humidity, condensation, soil variability, the vertical section of the duct, and rapid climatic fluctuations. They also underscore that hybrid approaches combining improved analytical models, targeted numerical simulations, and detailed experimental measurements represent the most promising path toward a comprehensive and reliable understanding of EAEEs.

4. Methodology and Mathematical Model

4.1. General Framework and Modeling Assumptions

The modeling of Earth-to-Air Energy Exchangers (EAEEs) is based on the description of the coupled heat and mass transfers between a flowing fluid (humid air), the conduit wall, and the surrounding soil. These phenomena are, by nature, three-dimensional, transient, and strongly coupled. However, to propose an analytically tractable formulation for engineering purposes, a number of modeling assumptions are introduced.

The system studied consists of a buried cylindrical conduit connected to the outside atmosphere by a vertical section. Air circulates at a prescribed average velocity, assumed to be uniform across the conduit section. The flow regime is considered locally quasi-steady, while the external thermal and hygrometric conditions vary over time.

The main assumptions adopted are as follows:

- the variation of thermal and hygrometric quantities is primarily longitudinal, allowing for a dimensional reduction of the problem along the conduit axis;
- the radial exchanges (soil conduction, internal convection, potential condensation) are integrated in an averaged manner through effective coefficients;
- the soil is characterized by equivalent thermal properties, representative of an average behavior over the considered depth;
- the air is treated as a humid mixture, described by its temperature, mixing ratio, and specific enthalpy;
- the internal condensation is accounted for in the form of a thin film when the wall temperature falls below the dew point of the air.

These assumptions do not aim to provide an exhaustive local description of the physical fields, but to establish a coherent analytical framework that enables the analysis of the dominant mechanisms of EAEE operation.

4.2. General Energy and Mass Balances

Based on the principles of conservation (mass, energy, and momentum), the general equations governing the thermo-hygrometric behavior of the fluid within the conduit can be expressed in the form of energy and mass balances.

A one-dimensional approach is adopted to study the problem. The energy conservation equation used to track air particles as they flow through the tube is:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_D \rho e \,\mathrm{d}v = \frac{\mathrm{d}}{\mathrm{d}t}\int_D \varrho \,\mathrm{d}v + \int_D div\,\boldsymbol{q}\,\mathrm{d}v + \Phi_v \tag{1}$$

The energy flux entering D through convective heat transfer $\boldsymbol{q}$ is given by Fourier's Law:

$$\boldsymbol{q} = -k\,\boldsymbol{grad}\,T(a,\eta,t) \tag{2}$$

It is assumed that no chemical reaction, material source, or energy source is present in domain D ($\varrho = 0$); and that the heating of air by friction (pressure losses) is neglected ($\Phi_v = 0$).

The energy balance of an air particle followed during its movement in an EAEE tube (Equation (1)) can be represented by the air temperature equation:

$$U_0\frac{\partial T(\eta,t)}{\partial \eta} + \frac{\partial T(\eta,t)}{\partial t} + H_c T(\eta,t) = H_c T_{sol}(\eta,t) + H_c Q\frac{\partial T_{\text{soil}}(\eta,t)}{\partial t} \tag{3}$$

with,

$$H_c = \frac{2h_c}{a\rho c_v\left[1 + a h_c\left(\frac{1}{k_{\text{tube}}}\ln\frac{a+e_{\text{tube}}}{a} + \frac{1}{k_{\text{soil}}}\ln\frac{a+e_{\text{tube}}+e_{\text{imp}}}{a+e_{\text{tube}}}\right)\right]} \tag{4}$$

and,

$$
\begin{aligned}
Q = & -\frac{e_{\text{tube}}\left(2a+e_{\text{tube}}\right)}{4\chi_{\text{tube}}}-\frac{e_{\text{imp}}\left(2a+2e_{\text{tube}}+e_{\text{imp}}\right)}{4\chi_{\text{soil}}}+\frac{a^2}{2\chi_{\text{tube}}}\ln\frac{a+e_{\text{tube}}}{a} \\
& +\frac{\left(a+e_{\text{tube}}\right)^2}{2\chi_{\text{soil}}}\ln\frac{a+e_{\text{tube}}+e_{\text{imp}}}{a+e_{\text{tube}}}-\frac{k_{\text{tube}}}{k_{\text{soil}}}\frac{e_{\text{tube}}\left(a+e_{\text{tube}}\right)}{2\chi_{\text{tube}}}\ln\frac{a+e_{\text{tube}}+e_{\text{imp}}}{a+e_{\text{tube}}}
\end{aligned}
\tag{5}
$$

When the thickness of the tube material and that of the impacted surrounding soil are neglected ($e_{\text{tube}}=0$, $e_{\text{imp}}=0$) and $Q=0$, the equations presented in the literature are recovered [37]-[39].

The resulting air temperature equation for the vertical portion of an EAEE (Equation (3)) constitutes a major analytical contribution, distinguishing this work from those found in the literature. This result offers a more comprehensive view of the interaction between the soil and the air flowing in EAEE tubes. Indeed, besides the soil temperature, its local variation also influences the air temperature inside the tube. The temperature equations found in the literature are, in fact, approximations of Equation (3), valid only under conditions where the influence of air temperature in the impacted soil zone is neglected ($e_{\text{imp}}=0$), the tube thickness is assumed to be zero ($e_{\text{tube}}=0$), and $Q=0$.

To determine the mass transport equation in an EAEE, the following mass conservation equation is used to track the water vapor particles in the air during their phase change movement:

$$
m_{as}\frac{\mathrm{d}\varpi\left(\eta,t\right)}{\mathrm{d}t}=\int_D div\boldsymbol{J}\mathrm{d}v \tag{6}
$$

where $\varpi\left(\eta,t\right)$ is the mixing ratio of humid air, and $\boldsymbol{J}$ represents the mass flux leaving the air to deposit on the inner wall of the tube. According to Fick's law:

$$
\boldsymbol{J}=-h_f\left(\varpi_s-\varpi\right)\boldsymbol{e}_r \tag{7}
$$

where h_f represents the mass transfer coefficient in the boundary layer δ_f , facilitating the passage of water vapor particles from the air to the condensed water on the inner wall of the tube.

The equation for the evolution of the mixing ratio of humid air moving in the vertical and horizontal tubes of an EAEE [22], established from the mass conservation equation, can be expressed in the following form:

$$
U_0\frac{\partial\varpi\left(\eta,t\right)}{\partial z}+\frac{\partial\varpi\left(\eta,t\right)}{\partial t}+\Omega_f\varpi\left(\eta,t\right)=\Omega_f\varpi\left(T_{\text{tube}}\left(\eta,t\right)\right) \tag{8}
$$

with,

$$
\varpi\left(T_{\text{tube}}\left(\eta,t\right)\right)=605242\mathrm{e}^{-\frac{5144}{T_{\text{tube}}\left(\eta,t\right)+273.15}} \tag{9}
$$

and,

$$
\Omega_f=\frac{2h_f}{a\rho_{as}} \tag{10}
$$

To make the problem analytically tractable, a dimensional reduction is performed by assuming that longitudinal gradients dominate transverse gradients. The three-dimensional effects related to radial conduction in the soil, internal convection, and mass transfer are integrated in the form of effective coefficients derived from a homogenization process.

Under these assumptions, the conservation equations (Equation (3) and Equation (8)) can be reduced to a generalized one-dimensional transport equation expressed along the conduit axis:

$$\alpha \frac{\partial f(x,t)}{\partial x} + \frac{\partial f(x,t)}{\partial t} + \beta f(x,t) = \beta\left[m + g(x,t)\right] \tag{11}$$

With the following boundary and initial conditions:

$$\begin{cases} f(x=0,t) = f_b(0,t) \\ \lim\limits_{x \to \infty} f(x,t) = m \\ \dfrac{\partial f(x,0)}{\partial t} = 0,\ x \in [0,L] \end{cases} \tag{12}$$

where x represents the 1D spatial variable, t the time.

The coefficients α, β, m and the parameters associated with the source term $g(x,t)$ are not arbitrary constants but result from the grouping of the dominant physical mechanisms.

The coefficient α is directly related to the average flow velocity and represents the longitudinal convective transport. The coefficient β combines all the equivalent thermal and hygrometric resistances, including internal convection, conduction through the conduit wall, and radial conduction in the soil. The function $f(x,t)$ represents the transported quantity (temperature or mixing ratio), m is a positive constant, and the term $g(x,t)$ integrates the influence of variable boundary conditions, notably the soil temperature and humidity as well as the atmospheric fluctuations applied to the vertical section [12].

This approach allows for a clear physical interpretation of the parameters while simplifying the mathematical resolution. This formulation constitutes the core of the selected analytical model.

Contrary to many classical analytical models, the vertical section of the conduit is explicitly integrated into the methodology. It is treated as a segment directly subjected to variable atmospheric conditions, whose output constitutes the initial condition for the buried horizontal segment.

The air temperature and humidity at the inlet of the horizontal part are thus determined consistently from solving the transport equation on the vertical section, ensuring the physical and mathematical continuity of the model.

4.3. Principle of the Initial Basis Analysis Method (IBAM)

The solution to the one-dimensional transport equation is carried out using the Initial Basis Analysis Method (IBAM). This method is based on decomposing the solution into an analytical basis associated with the initial condition, allowing for the effective treatment of non-stationary boundary conditions (**Figure 4**).

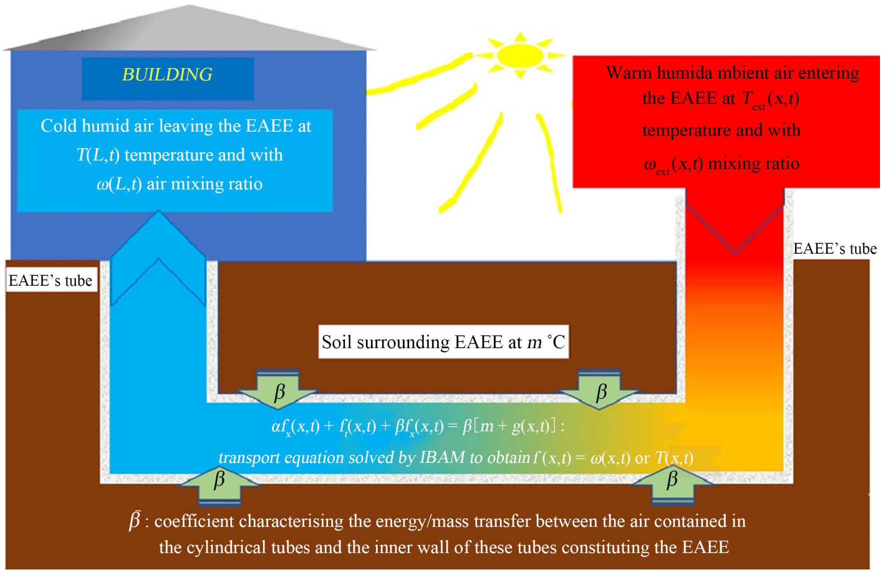

Figure 4. Presentation of the IBAM method [12].

The main advantage of IBAM lies in its ability to provide a continuous analytical solution, avoiding classical discretization schemes and their numerical stability constraints. It thus enables rapid resolution of the problem, making it particularly suitable for parametric studies and sensitivity analyses.

By writing the entire Equation (11) in its initial condition, we have:

$$\alpha \frac{\partial f(x,0)}{\partial x} + \frac{\partial f(x,0)}{\partial t} + \beta f(x,0) = \beta\left[m + g(x,0)\right] \tag{13}$$

With the same boundary conditions for this problem, we have:

$$\begin{cases} f(0,0) = f_b(0) \\ \lim_{x\to\infty} f(x,t) = m \\ \lim_{x\to\infty} g(x,0) = 0 \end{cases} \tag{14}$$

After solving Equation (13), the initial condition of the problem is found as follows:

$$f(x,0) = m + \left[f_b(0) - m + A(x) - A(0)\right]\mathrm{e}^{-\frac{\beta}{\alpha}x} \tag{15}$$

with

$$A(x) = \frac{\beta}{\alpha}\int g(x,0)\mathrm{e}^{-\frac{\beta}{\alpha}x}\mathrm{d}x \tag{16}$$

The analytical solution of the problem takes the form:

$$f(x,t) = \alpha_1(t) + \alpha_2(t) f(x,0) \tag{17}$$

The solution satisfies the boundary conditions such that:

$$\begin{cases} \alpha_1(t) + \alpha_2(t) f_b(0) = f_b(t) \\ \alpha_1(t) + \alpha_2(t) m = m \end{cases} \tag{18}$$

where the function $f_b(t)$ is a known function with an explicit analytical expression.

After solving this system (Equation (11)) using the IBAM method [12], the analytical solution of the problem is found in the form:

$$f(x,t) = m\frac{f_b(t) - f_b(0)}{m - f_b(0)} + f(x,0)\frac{m - f_b(t)}{m - f_b(0)} \tag{19}$$

where the function $f_b(t)$ is a known function with an explicit analytical expression.

Specifically, the aim here is to promote a continuous approach for solving the energy and mass transport equations of an EAEE in all its parts, first considering the absence of air humidity and subsequently its presence. It is pertinent to note that many studies in the literature have omitted consideration of the vertical portions of EAEEs, assuming they have only a negligible impact on the overall system.

5. Solution of Transport Equations by IBAM

This section presents the analytical results derived from solving the energy transport equation (Equation (3)) and the mass transport equation (Equation (8)), applied to the vertical section of the EAEE as well as to the entire EAEE system. The analysis is conducted successively under the assumptions of dry air and then humid air, based on the continuous IBAM approach described in Section 4.3.

5.1. Energy Transport Equation

- Case of dry air

The equation giving the initial condition for dry air temperature in the inlet vertical section is [25]:

$$T(z,0) = T_m + X_0 \mathrm{e}^{-\frac{H_c}{U_0}z} + X_1 \mathrm{e}^{-\frac{z}{\delta_a}} \sin\left(\varphi_3 - \frac{z}{\delta_a}\right) + X_2 \mathrm{e}^{-\frac{z}{\delta_J}} \sin\left(\varphi_4 - \frac{z}{\delta_j}\right) \tag{20}$$

where X_0, X_1, X_2, φ_3 and φ_4 are known expressions [25].

The equation giving the analytical solution for dry air temperature in the inlet vertical section is [25]:

$$T(z,t) = T_m + \left[T_{ext}(0,t) - T_m\right]\mathrm{e}^{-\frac{H_c}{U_0}z} + \Gamma_v(z) \tag{21}$$

where $\Gamma_v(z)$ is a known function [25].

The equation giving the initial condition for dry air temperature in the horizontal section of the EAEE is [25]:

$$T(y,t_\delta) = T_m + \left[T(z=\delta,t_\delta) - T_m\right]\mathrm{e}^{-\frac{H_c}{U_0}y} \tag{22}$$

where $T(z=\delta,t_\delta)$ is a known function [25].

The equation giving the analytical solution for dry air temperature in the horizontal section of the EAEE is [25]:

$$T(y,t) = T_m + \left[T(z=\delta,t_\delta) - T_m\right]\mathrm{e}^{-\frac{H_c}{U_0}y} \tag{23}$$

- Case of humid air

The equation giving the initial condition for humid air temperature in the inlet vertical section is [22]:

$$T(z,0) = T_m + \left[T_{ext}(0) - T_m + A_{Tv}(z) - A_{Tv}(0)\right] \mathrm{e}^{-\frac{H_c}{U_0}z} \quad (24)$$

where $A_{Tv}(z)$ is a known function [22].

The equation giving the analytical solution for humid air temperature in the inlet vertical section is [22]:

$$T(z,t) = T_m + \left[T_{ext}(0,t) - T_m\right] \mathrm{e}^{-\frac{H_c}{U_0}z} + \Gamma_{Tv}(z) \quad (25)$$

where $\Gamma_{Tv}(z)$ is a known function [22].

The equation giving the initial condition for humid air temperature in the horizontal section of the EAEE is [22]:

$$T(y,t_\delta) = T_{m_{sol}} + \left[T(z=\delta,t_\delta) - T_{m_{sol}}\right] \mathrm{e}^{-\frac{H_c}{U_0}y} \quad (26)$$

where $T(z=\delta,t_\delta)$ is a known function [22].

The equation giving the analytical solution for humid air temperature in the horizontal section of the EAEE is [22]:

$$T(y,t) = T_{m_{sol}} + \left[T(z=\delta,t_\delta) - T_{m_{sol}}\right] \mathrm{e}^{-\frac{H_c}{U_0}y} \quad (27)$$

5.2. Mass Transport Equation: Case of Humid Air

The equation giving the initial condition for the mixing ratio in the inlet vertical section is [22]:

$$\varpi(z,0) = \varpi_s(T_m) + \left[\varpi_{ext}(0) - \varpi_s(T_m) + A_{\varpi v}(z) - A_{\varpi v}(0)\right] \mathrm{e}^{-\frac{H_c}{U_0}z} \quad (28)$$

where $A_{\varpi v}(z)$ is a known function [22].

The equation giving the analytical solution for the mixing ratio in the inlet vertical section is [22]:

$$\varpi(z,t) = \varpi_s(T_m) + \left[\varpi_{ext}(0,t) - \varpi_s(T_m)\right] \mathrm{e}^{-\frac{\Omega_f}{U_0}z} + \Gamma_{\varpi v}(z) \quad (29)$$

where $\Gamma_{\varpi v}(z)$ is a known function [22].

The equation giving the initial condition for the mixing ratio in the horizontal section is [22]:

$$\varpi_s\left(T_{m_{sol}}\right) + \left[\varpi(z=\delta,t_\delta) - \varpi_s\left(T_{m_{sol}}\right) + A_{\varpi h}(y) - A_{\varpi h}(0)\right] \mathrm{e}^{-\frac{\Omega_f}{U_0}y} \quad (30)$$

where $A_{\varpi h}(y)$ is a known function [22].

The equation giving the analytical solution for the mixing ratio in the horizontal section is [22]:

$$\varpi(y,t) = \varpi_s\left(T_{m_{sol}}\right) + \left[\varpi(z=\delta,t_\delta) - \varpi_s\left(T_{m_{sol}}\right)\right] \mathrm{e}^{-\frac{\Omega_f}{U_0}y} + \Gamma_{\varpi h}(y) \quad (31)$$

where $\Gamma_{\varpi h}(y)$ is a known function [22].

6. Discussion

Although the literature on Earth-to-Air Energy Exchangers (EAEEs) has expanded considerably over the past three decades, several methodological and structural limitations persist, hindering the ability of current models to satisfactorily represent the real behavior of these systems. Classical analytical approaches, long favored for their ease of use and low computational cost, rely on a set of simplifying assumptions; linearity, thermal homogeneity of the soil, stationary conditions, absence of mass transfer, that restrict their validity domain and frequently lead to an overestimation of performance [13] [18] [32]. A recurring shortcoming remains the poor consideration of air humidity in theoretical models. Modeling atmospheric air as a dry fluid constitutes a significant source of error, particularly in tropical climates or those with high hygrometric variability. Although internal condensation can contribute significantly to the overall thermal balance, few analytical models explicitly integrate the thermodynamics of humid air and the release of latent heat. Another important limitation lies in the representation of the soil, generally treated as a homogeneous and isotropic medium, despite widely documented spatio-temporal variability [28] [36]. A further weakness concerns the vertical portion of the conduit, long neglected but now recognized as decisive in establishing the initial conditions of the incoming air [22] [27].

Numerical approaches, although extremely powerful, remain limited by their high computational cost and the availability of necessary input data, particularly for parametric studies. These observations highlight the absence of an intermediate analytical framework, both physically relevant and practical for engineering.

In this context, the work of [22], based on the IBAM method [12], stands as an analytical contribution, without claiming to provide an exhaustive three-dimensional description. Comparisons with experimental data from previous works show satisfactory agreement, strengthening the credibility of the approach within its validity domain. However, the IBAM method presents structural limitations that should be emphasized, notably its dependence on the parameters α, β and m, and its one-dimensional nature. These limitations justify the need for future developments, including the improvement of parametric identification, extension to more complex geometries, and hybridization with numerical methods.

7. Conclusions

Earth-to-Air Energy Exchangers represent a relevant passive solution for air preconditioning in buildings, particularly in the context of energy transition and management of electricity demand. However, modeling these systems remains a challenge, due to the complexity of the coupled heat and mass transfers, the variability of atmospheric conditions, and the heterogeneity of the soil. This work proposed a critical analysis of existing analytical and numerical approaches, highlighting the limitations of classical models and the operational constraints of highfidelity numerical methods. This analysis sheds light on the absence of an intermediate analytical framework reconciling physical realism and engineering practicality. In this context, the Initial Basis Analysis Method (IBAM) is presented as a continuous analytical approach, based on a generalized one-dimensional transport equation, enabling the integration of the vertical portion of the conduit, atmospheric variations, and thermo-hygrometric phenomena. The dimensional reduction performed relies on an averaging of three-dimensional effects, integrated through effective coefficients whose physical meaning has been discussed. Comparisons with experimental results from previous works show satisfactory agreement, within the model's validity domain, while highlighting the sensitivity of the approach to the correct identification of transfer parameters.

The IBAM method does not aim to replace three-dimensional numerical models, but to serve as a complementary analytical tool adapted to parametric studies and preliminary design. Finally, several development perspectives have been identified, including the improvement of parametric identification, the integration of more realistic soil properties, extension to complex geometries, and the development of hybrid approaches.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

U_0	Air velocity inside the pipes (m/s)
$T(\eta,t)$	Air temperature (˚C)
$\eta = z$	Spatial variable along the vertical pipe
$\eta = y$	Spatial variable along the horizontal pipe
t	Time (h)
t_δ	Time at depth δ (h)
Φ_v	Pressure Loss
φ_3,φ_4	phase shifts (rad)
H_c	Global convective energy transfer frequency (Hz)
$T(z,t)$	Air temperature in the tube (˚C)
T_m	Mean annual outdoor air temperature (˚C)
T_{msol}	Mean daily soil temperature (˚C)
$T_{\text{soil}}(\eta,t)$	Temperature of the soil surrounding the EAEE pipe (˚C)
$T_{\text{tube}}(\eta,t)$	Temperature of the EAEE pipe wall (˚C)
h_c	Convective heat transfer coefficient (W/(m^{-2}·˚C))
δ	Burial depth of the EAEE tubes (m)
δ_a	Annual characteristic depth of the soil (m)
δ_j	Daily characteristic depth of the soil (m)
e_{tube}	Thickness of the pipe material (m)
e_{imp}	Thickness of the thermally affected soil region (m)
e	Specific internal energy (J)
a	Inner radius of the pipe (m)
$\vec{q}$	Total heat flux vector (W/m^2)
χ_{soil}	Thermal diffusivity of the soil (m^2/s)
χ_{tube}	Thermal diffusivity of the pipe material (m^2/s)
ρ	Air density (kg/m^3)
ϱ	Material source or energy source
c_v	Specific heat capacity of air (J/(kg·˚C))
k	Tube thermal conductivity (W/(m·˚C))
k_{tube}	Thermal conductivity of the pipe material (W/(m·˚C))
k_{soil}	Thermal conductivity of the soil (W/(m·˚C))
Ω_f	Global mass transfer frequency (Hz)
$\varpi(\eta,t)$	Air humidity ratio (g/g)
$\varpi_{ex}(t)$	Mixing ratio of air saturated at T_m (g/g)
$\varpi_s(T_{\text{tube}}(\eta,t))$	Saturated air humidity ratio at $T_{\text{tube}}(\eta,t)$ (g/g)
$\varpi_s(T_m)$	Mixing ratio of air saturated at T_m (g/g)
$\varpi_s(T_{msol})$	Mixing ratio of saturated air at T_{msol} (g/g)

Continued

h_f	Mass transfer coefficient (W/(m^2·˚C))
ρ_{as}	Dry air density (kg/m^3)
α	Convection coefficient
β	Global transfer frequency coefficient
m	Positive constant