Chapter

Innovations in Heat Pump Design Using Computational Fluid Dynamics with Control Volume Method

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Abstract

Mathematical modeling of the heat pump as a result of continuity, momentum, and energy equations is obtained. To solve these equations numerically, the problem is divided by a finite number of control volumes. Then the differential equations in these control volumes integrated and converted into algebraic equations. The importance of computational fluid dynamics in Industry 4.0 applications is to make current applications more efficient in heat pump applications. In this study, the book section is composed of the application of computational fluid dynamics by the control volume method using Ansys fluent program, which will benefit readers from industry 4.0 perspective, especially in energy efficiency issues according to the volume method of controlling correct heat pump designs.

Keywords: heat pump design, industry 4.0, computational fluid dynamics, energy equations, control volume method

1. Introduction

The ever increasing demand for energy and the depletion of energy resources accelerate the search for new energy resources. The effects of global warming based on excessive fossil fuel consumption and problems in meeting the energy demand enabled the energy to become the main agenda item of the world as a current problem. In developed countries where energy is the main agenda item, frequent sessions are held on the balance of energy supply and demand. In particular, the search for cheap electricity, which the increasing population and industry needed, has increased the requirement for renewable energy resources. Hydraulic, solar, wind, and geothermal energy are important renewable energy sources because of their importance, easy-to-find, and cheap production [1–3].

At the same time, geothermal energy, which is used in the technology of soil air source heat exchanger and which is mentioned in renewable energy sources, is extensively used in topics such as cooling as well as heating homes, electricity generation, tourism, and heating greenhouses [4].

2. Soil air heat exchangers in general

In general, soil air heat exchangers passively cool or heat their environment according to the seasons in which they are used. Thermal performances of soil air heat exchangers generally vary according to pipe lengths, pipe diameters used, air inlet speeds, and number of deflectors [5].

3. Passive cooling systems

The increase in energy costs caused by the economic crises also reveals the need to reduce environmental damage by the method of recovering the heat generated. Therefore, energy-saving measures that can be taken in the main residences can be taken. The system capacities of buildings could be reduced by mechanical cooling packages.

Passive cooling is an alternative way to mechanical cooling. Heat wells, natural cooling sources as well as COP include mechanical cooling systems greater than 4. Buildings can be cooled in low energy and passive systems provided by several natural heat wells such as soil under the soil surface, utilizing ambient air.

Passive cooling systems

- Radiant cooling at night, providing a direct cooling tank for daytime use
- Night ventilation that provides direct human comfort during the day
- Comfort ventilation that directly provides human comfort daytime use
- Night ventilation aimed at cooling the building body at night
- Radiant cooling at night that supplies the cold during the day
- Direct evaporative cooling that cools the ventilation air non-mechanically
- Pool on the roof, etc. indirect evaporative cooling that provides cooling by doing can be classified as [6–8].

3.1 Soil sourced passive cooling system

It acts as a heat well especially for cooling the circulation air due to the temperature differences for a soil building. This type of energy can be used in shapes if the soil temperature is low enough. Passive cooling is possible if the building can be surrounded by soil as much as possible, provided that the wall's thermal conductivity is high, that is, uninsulated. This application is very suitable in mild winter and hot summer climates. In climates with cold winters, the method is not preferred as that will raise the heat losses. Next to the building, the soil mass beneath and sometimes above it can be considered like a natural cooling source for the building in many climatic zones. In most places with a depth of 2–3 m, soil cooler can be a source. This may not be the case for very hot regions. If the soil surface is germinated or during the daytime, dilution of the soil can be effective in using the soil as a heat source in hot regions [9, 10].

There are two known methods for ground-source passive heat source. The two methods common feature is that the soil design is provided so that evaporation is not prevented by the shading method [9, 10].

In the first method, at least 10 cm thick in summer, on the soil surface, it is covered with materials such as pebble, tree, and watered [9, 10].

In the second method, water evaporation is provided from the soil surface with irrigation and summer rains. Thus, the soil temperature below is lowered and the surface temperature decreases [9, 10].

Ground-based cooling takes place in two methods, indirect and direct. Indirect contact, the thermal mass of the soil provides a decrease in indoor temperature with the soil. The precooling aspect is indirect. The circulated air temperature or water decreases thanks to the cool soil layer, so that the coolness inside the building can be used in the pipes installed underground [9, 10].

PVC pipes can be placed in the ground if the building is insulated very well as a heat exchanger. The building circulation air could be circulated to cool these pipes. Air circulation, which could be considered as a closed circuit, can also be the outside air intake. The internal air through the pipes, by circulating, buried in the ground, the air temperature could reach 10 K lower than the outside air temperature. Efficiency increases even further in lands with very high outdoor temperatures [9, 10].

4. Computational methods

4.1 Navier Stokes equations and continuity

Continuity equation and Navier-Stokes equations that can be applied to all flows are important flow equations. A conservation equation expresses the mass conservation law of fluid passing through a control volume of differential dimensions. If we apply Newton's second law to a control volume, we encounter momentum and motion conservation equations and Navier-Stokes equations. In Cartesian coordinates with isothermal constant physical properties, motion and continuity equations for a newton type and incompressible flow can be written as follows [11–17].

Navier Stokes Equations

x-dimension

$$\rho\left(\frac{\delta u}{\delta t}+u\frac{\delta u}{\delta x}+v\frac{\delta u}{\delta y}+w\frac{\delta u}{\delta z}\right)=-\frac{\delta P}{\delta x}+\rho g_x+u\left(\frac{\delta^2 u}{\delta x^2}+\frac{\delta^2 u}{\delta y^2}+\frac{\delta^2 u}{\delta z^2}\right) \quad (1)$$

y-dimension

$$\rho\left(\frac{\delta v}{\delta t}+u\frac{\delta v}{\delta x}+v\frac{\delta v}{\delta y}+w\frac{\delta v}{\delta z}\right)=-\frac{\delta P}{\delta x}+\rho g_y+u\left(\frac{\delta^2 v}{\delta x^2}+\frac{\delta^2 v}{\delta y^2}+\frac{\delta^2 v}{\delta z^2}\right) \quad (2)$$

z-dimension [11–17]

$$\rho\left(\frac{\delta w}{\delta t}+u\frac{\delta w}{\delta x}+v\frac{\delta w}{\delta y}+w\frac{\delta w}{\delta z}\right)=-\frac{\delta P}{\delta x}+\rho g_x+u\left(\frac{\delta^2 w}{\delta x^2}+\frac{\delta^2 w}{\delta y^2}+\frac{\delta^2 w}{\delta z^2}\right) \quad (3)$$

Here, all of the equations determined with the notations u, v, and w appear as the executive equation. Here, u gives the flow components x, y gives the flow components y, and z gives the flow components z. Fluid mechanics and dynamics problems are managed with this equation. For the soil air heat exchanger, this problem can be solved with various simulation software packages. Three-dimensional and two-dimensional solutions are possible. u, v, and w velocity components are variable. From other notations, P (pressure), ρ (density), and μ (dynamic viscosity) are taken constantly [11–17].

Continuity equation [11–17]

$$\frac{\delta u}{\delta t}+\frac{\delta v}{\delta t}+\frac{\delta w}{\delta t}=0 \tag{4}$$

4.2 Energy equations

The energy equation to be used for incompressible flow in Cartesian coordinates is given below in turbulent flow [11–17].

$$\left[u\frac{\delta T}{\delta x}+v\frac{\delta T}{\delta y}+u\frac{\delta T}{\delta z}\right]=\alpha\left[\frac{\delta^2 w}{\delta x^2}+\frac{\delta^2 w}{\delta y^2}+\frac{\delta^2 w}{\delta z^2}\right]+u\phi \tag{5}$$

$$\phi=2\left[\left(\frac{\delta T}{\delta x}\right)^2+\left(\frac{\delta T}{\delta y}\right)^2+\left(\frac{\delta T}{\delta z}\right)^2\right]+\left(\frac{\delta v}{\delta x}+\frac{\delta u}{\delta y}\right)2+\left(\frac{\delta w}{\delta y}+\frac{\delta v}{\delta z}\right)2+\left(\frac{\delta u}{\delta z}+\frac{\delta w}{\delta x}\right)2 \tag{6}$$

4.3 Models of turbulence

Turbulence is the irregularity of a liquid or gas in motion. Non-turbulent flow is called laminar flow. The Reynolds number determines if flow conditions are turbulent or laminar. Turbulence is one of the problems that have been handled by many scientists but no analytical solutions have been found. The molecules of a fluid with a uniform flow tend to stay as close to each other as possible and behave similarly. At the beginning of the nineteenth century, basic problems of fluids with regular fluids were solved and the foundations of fluid dynamics were laid. However, science refused to work on turbulence for a long time, seeing turbulence as an engineering problem. Turbulence modeling has an important place in computational fluid dynamics, and different numerical approaches have been developed to analyze turbulent flow [11–17].

In the DNS method called direct numerical simulation, the digital network and time resolution are at a level that can resolve the vortexes of all scales, and simulations are carried out using basic moving equations without any modeling. The fact that this method requires a lot of computational cells and time steps makes the use of DNS in academic studies limited and practically impossible [11–17].

In high Reynolds numbers, in turbulent flow, the inertial forces of the flow become more dominant than viscous forces. As a result, fluid motion becomes unstable. Velocity and all other flow properties begin to change randomly and chaotically, and the flow becomes three-dimensional. The solution of a turbulent problem is as complex as its nature, and therefore various turbulence models have been developed for use in solving turbulent problems. The developed turbulence models cannot fully define the flow. There is no single turbulence model for each flow simulation. Different turbulence models can be used for flow models with different properties. Different turbulence models have been developed for turbulent flow analysis. Some of these developed models are given below [11–17].

- Turbulence models;
- Zero equation model
- k–ε (epsilon) model
- RNG k–ε model (Reynolds normalized group turbulence model)
- k–ω (omega) model
- SST (shear stress transport) model
- The Reynolds stress model
- Omega-based Reynolds stress model
- Ansys Cfx transition model
- The large eddy simulation (LES) model
- The detached eddy simulation (DES) model
- The scale adaptive simulation model (SAS) [11–17]
- Buoyancy turbulence model

For accuracy and computational convergence accuracy, k-ε models are a good choice. Generally, this model is suitable for industrial applications with and without heat transfer for complex flows. In the k-ε models, similar to the k-ω model, two transport equations are solved, but there is a difference in the selection of the second turbulence transport variable and is frequently applied in the CFD simulations of the k-ε and k-ω models. In terms of convergence and accuracy, the calculation cost is a good choice for the k-ε model [11–17].

4.4 k-ε standard model

In the numerical solutions of the most commonly used turbulent fluids, the k-ε model is used. Diffusion ratio (ε) and turbulent kinetic energy (k) equations are given [11–17].

$$\frac{\delta}{\delta t}(\rho k)+\frac{\delta}{\delta x_i}(\rho k u_i)=\frac{\delta}{\delta x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\delta k}{\delta x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \qquad (7)$$

and due to the distributions of ε,

$$\frac{\delta}{\delta t}(\rho\varepsilon)+\frac{\delta}{\delta x_i}(\rho\varepsilon u_i)=\frac{\delta}{\delta x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\delta\varepsilon}{\delta x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+G_{3\varepsilon}G_b\right)-C_{2\varepsilon}\frac{\varepsilon^2}{k}+S_\varepsilon \qquad (8)$$

The turbulence viscosity and turbulence conductivity of the k-ε standard model can be expressed as follows [11–17].

$$k_t = \frac{\mu t C_p}{\sigma_t} \tag{9}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{10}$$

Model constants for turbulence models are

$$C_{1\varepsilon} = 1.44\ ,\ C_{2\varepsilon} = 1.92,\ C_\mu = 0.09,\ \sigma_\varepsilon = 1.3, \sigma_k = 1.0.$$

4.5 Dimensionless parameters and heat transfer coefficients

The dimensionless parameters and heat transfer coefficients are given below are defined for the heat transfer occurring in the soil air heat exchanger (**Figures 1** and **2**) [11–17].

4.6 Heat transfer coefficients for convection

The equation below is for heat transfer from air to pipe.

$$h_a = \frac{Nu\, k_a}{D} \tag{11}$$

$$\mathrm{D} = \text{pipe diameter}\,(\mathrm{m})$$

k_a = heat coefficient for air (W/mK)

Nu = Nusselt number [11–17]

The following equation is expressed for heat transfer from pipe to ground.

$$h_s = \frac{k_s}{r_2 \ln\left(1 + \frac{\delta}{r_2}\right)} \tag{12}$$

r_2 = pipe outer diameter (m)

δ = soil thickness (m)

k_s = soils heat conduction constant $\left(\frac{W}{mK}\right)$ [11–17]

4.7 Reynolds number

Laminar to turbulent flow transition, among other parameters, relys on surface roughness, geometry of surface, free flow speed, temperature of surface, and fluid type. In the 1880s, Osborne Reynolds showed that the flow regime was based on the ratio of inertial forces to viscous forces as a result of experimental studies. The

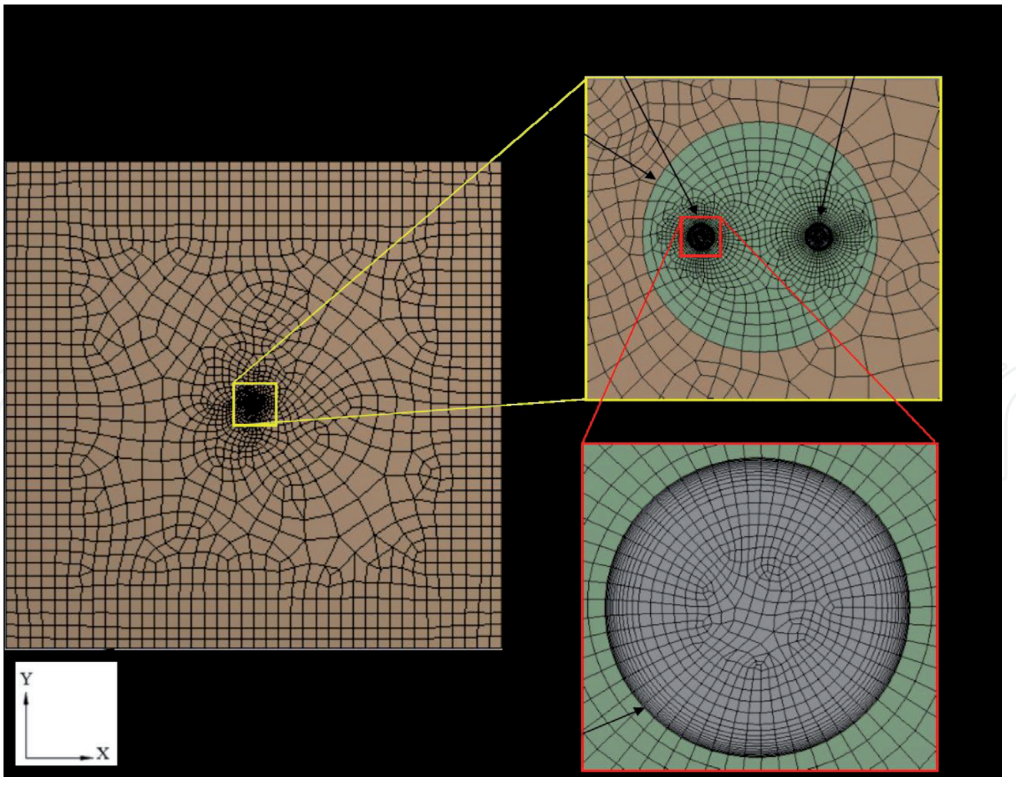

Figure 1.
Cross-sectional view of a sample domain with soil thickness [18].

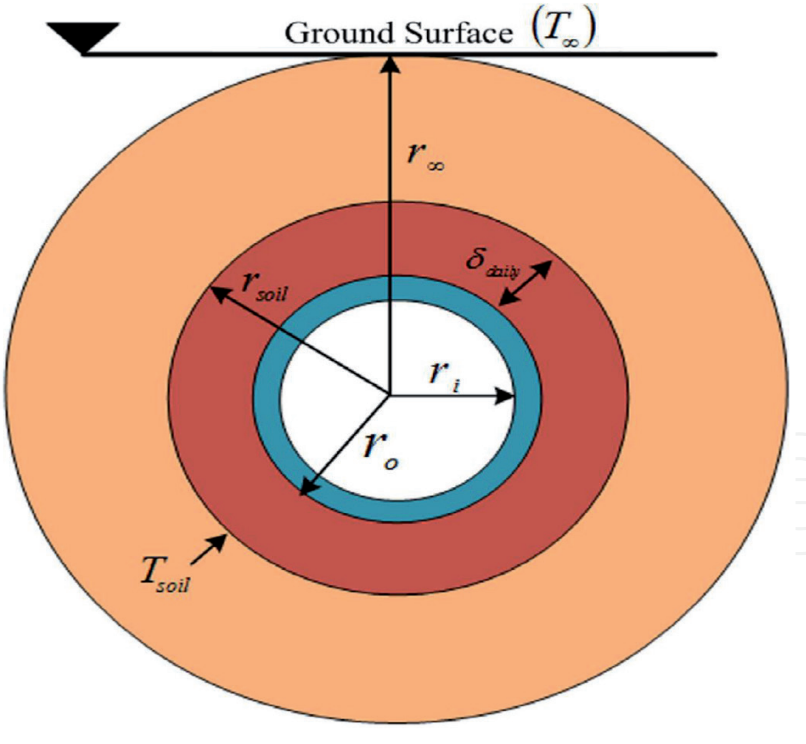

Figure 2.
A sample ground earth-air source geometry domain [19].

Reynolds number is a dimensionless group. The Reynolds number for the flow in the circular tube is expressed as follows [11–17].

$$\mathrm{Re} = \frac{\rho V_{ort} D}{\mu} = \frac{V_{ort} D}{\upsilon} \tag{13}$$

4.8 Friction factor

The friction factor in turbulent flow is expressed as follows for smooth pipes.

$$f = (0.790 \ln \mathrm{Re} - 1.64)^{-2} \quad 3000 < \mathrm{Re} < 5 \times 10^{6} \tag{14}$$

can be found from the first Petukhov explicit equation [11–17].

4.9 Nusselt number

The Nusselt number on a fluid is the result of the heat transfer recovery in that fluid layer to the ratio of transport to conduction. How effective the transport depends on the large number of Nusselt. The Nusselt number is associated with the friction factor in turbulent flow, and the sensitivity of this correlation at lower Reynolds numbers is expressed as follows:

$$\mathrm{Nu}= \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)}s \quad (0.5 \le \mathrm{Pr} \le 200) \quad (3 \times 10^{3} < \mathrm{Re} < 5 \times 10^{6}) \tag{15}$$

is given with [11–17].

4.10 Prandtl number

Expression of thicknesses of thermal layers and velocity;

$$\mathrm{Pr} = \frac{v}{\alpha} = \frac{\mu C_p}{k} \tag{16}$$

If given as a dimensionless parameter defined by Prandtl number [11–17]

5. Computational fluid dynamics

A numerical method based on the principle of solving basic momentum, mass, and energy equations by computer is called computational fluid dynamics (CFD) (**Figure 3**). CFD partial differential equations that can be solved in computers are converted into several algebraic equations and provide a practical and fast study on fluid dynamics. Partial differential equations can easily access many sub-data depending on the parameters of speed, pressure, and temperature distributions in the flow and these parameters by numerically solving the model expressing the flow. A model of the relevant physical problem is defined by this model, which creates basic chemical and physical principles related to flow by using CFD method, by defining this model by using fluid dynamics with various computer software, the physical and chemical principles related to fluid are defined in this model. Information about the real behavior of the problem can be obtained. This method allows the geometry of the problem to be easily created and analyzed. The emphasis on CFD is that it provides benefit from experimental studies relatively economically and from time. Computational fluid dynamics is widely used in product design and research and development today [11–17].

Many parameters related to temperature distribution of an underground reservoir, air velocity around a moving car, pressures on an airplane wing, and airflow distribution in an environment can be found using CFD. Developments

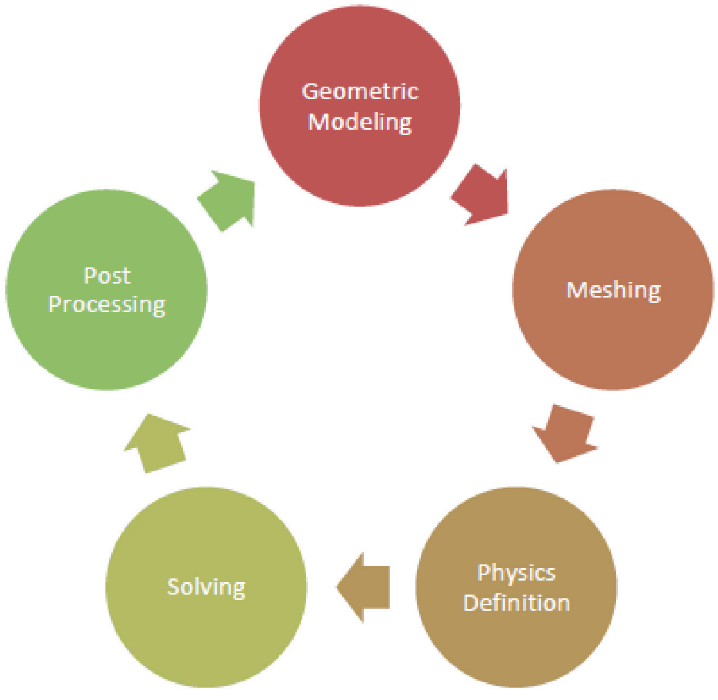

Figure 3.
Basic steps for CFD [20].

in dynamical systems and computer software have been created in the virtual environment by analyzing high turbulent flows numerically with computational fluid dynamics theory in recent years. In addition, single-phase flows, as well as multi-phase flows, have been resolved with maximum similarity. For example, the structure of harmful factors such as cavitation in pumps is examined and precautions are taken according to the results. CFD software developed to solve flux, heat, and chemical reaction problems takes place in three basic stages as solution, pretreatment, and post-treatment [11–17].

If heat transfer is discussed with numerical method, for example, in a 3-dimensional geometry, the issues such as soil properties should be well understood due to the complexity of heat transfer. Many factors such as working fluid flow rate, soil air boundary conditions can affect the verification of the numerical method result. The following assumptions can be proposed for numerical modeling of an exemplary 3D soil air heat pump.

1. Since the model is designed in three dimensions, the average thermal properties of the ground are assumed to be constant throughout the geometry.

2. The first soil temperature defined in the model is a function of depth.

3. The effect of groundwater flow in the solid zone, which is considered as pure heat conduction, is neglected.

4. The velocity profiles of the U-shaped pipe of the ground air heat pump are equal.

Since the numerical method established is completely exposed to the external environment, the temperature is directly affected by solar radiation. When the ground surface is covered with a building, its protection from both other structures and direct sun radiation results in a low temperature fluctuation near the ground surface. For the reasons described above, the ambient temperature only represents

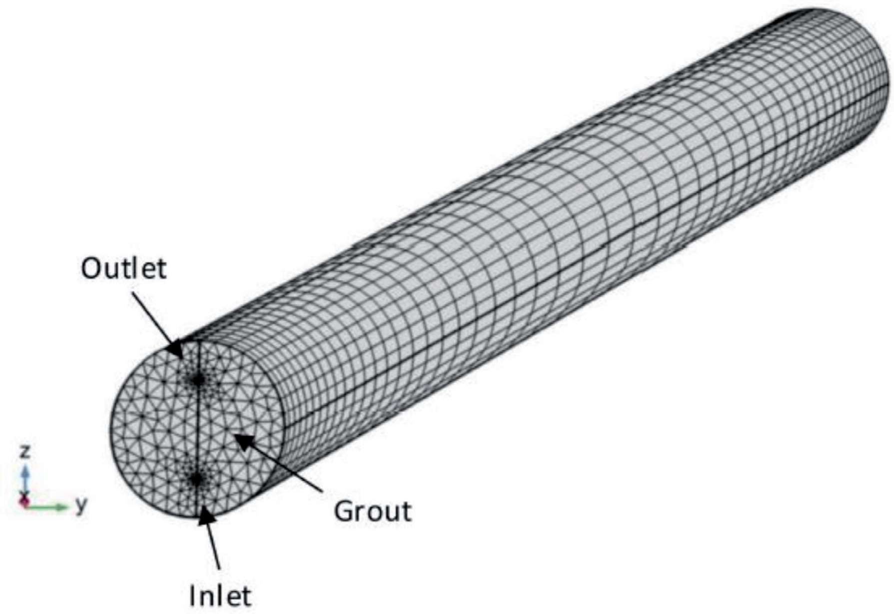

Figure 4.
A sample mesh geometry for the earth-air heat pump [21].

the floor temperature. The energy equations of the outlet and inlet pipes are derived from parameters such as the inlet and outlet angle of the working fluid of the fluid regions according to the finite volume method [11–17].

5.1 Numerical model for solution

The finite volume method, which is a numerical method used in the solution of partial differential equations, is used to solve the integral states of fluid motion equations by separating them in physical space [11–17].

For the solution to be examined, the solution must be splitted into a finite number of control volumes that do not overlap. All finite number elements are called digital networks or solution networks. Variables are generally calculated at the center of control volumes. With the finite volume method applied to very flexible solution networks, calculations are not made at the node points unlike other methods. It gives successful results in non-structural solution networks as well as structural solution networks. To be more flexible and applicable to complex geometries, mostly non-structural solution networks are preferred (**Figure 4**) [11–17].

6. Recent studies for earth-air heat pump

6.1 Earth-air heat pump study-1

In this study, the residential buildings in the Mediterranean climate describe the three parameters simulation effect on the thermal performance of the soil air source heat pump system. These three parameters are diameter of pipe, flowing air velocity, and gaps between pipes. ANSYS-CFX is used. In the simulation results confirmed by experimental data and analytical results, it was concluded that the increase of air velocity and the distance between adjacent pipes for a given pipe diameter is inversely proportional to the heat transfer for cooling. It is concluded that the soil air heat efficiency will continue even when the distance between the pipes falls from 1 to 0.5 m, with the result that it should be in the presence of 50% more soil area (**Figure 5**) [18].

Figure 5.
Experimental scheme for the study [22].

6.2 Earth-air heat pump study-2

The need for prefabricated housing can be considered especially to compare the short-term housing needs of people who are victims of migration. In this work, a design proposal was made for a refugee house that fits the Swedish climate of the three main passive cooling and heating solutions, including the Trombe wall, the Ground air heat exchanger, and the green wall. The main purpose of combining these systems is to reduce the heating as well as cooling loads and thus reducing emissions, reducing the negative impact of the house on energy use in the environment. The prefabricated refugee house is designed to consume 180 kWh/m^2/year of energy annually. ANSYS (simulation) and TRNSYS (dynamic system modeling) software are used. According to the simulation results, 2.8 kWh/m^2/year cooling load and 7.9 kWh/m^2/year heating load were obtained. Also it is seen that the total energy consumption reached 18.4 kWh/m^2/year. 7.4 years repayment period is the pre-feasibility cost during its 25-year construction life. Main energy request is 0.032 GJ/m^2/year and CO_2 emission amount is 231.1 kg CO_2e/year. In Lund, which has an urban living laboratory in Sweden, a proof of concept has been applied to validate the simulation results through a 12-month post couple assessment and monitoring study (**Figure 6**) [19].

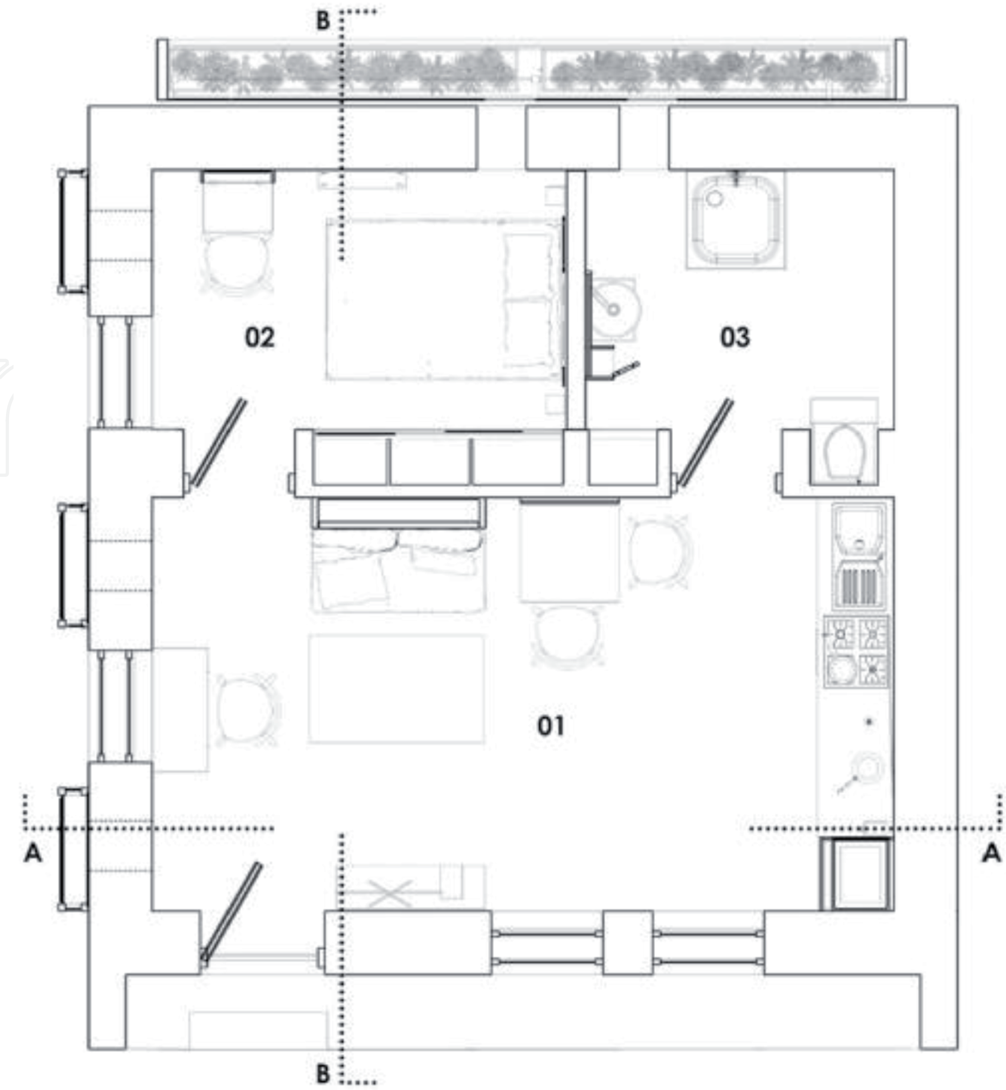

Figure 6.
A refugee building for CFD study [23].

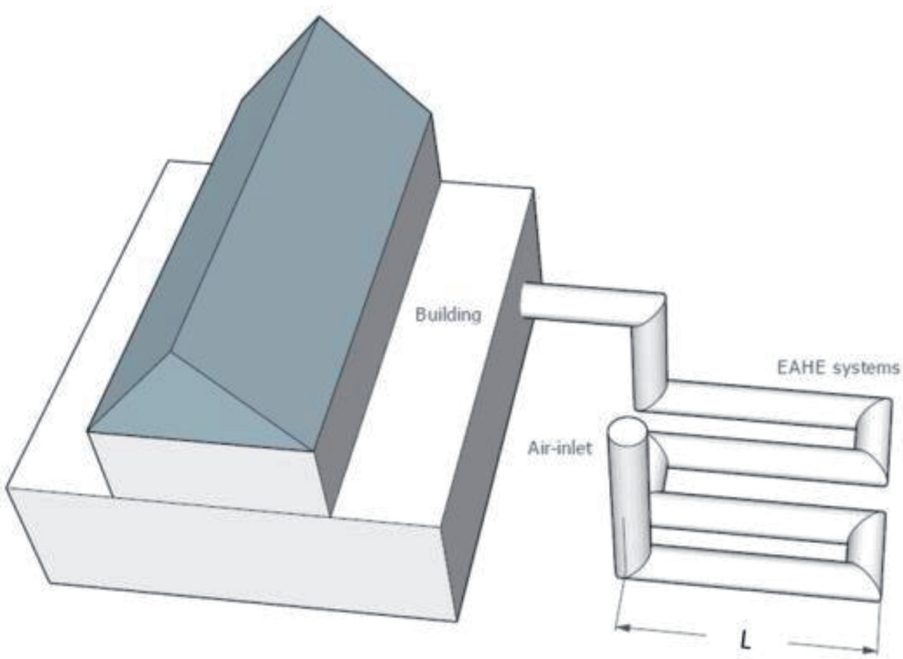

Figure 7.
An experimental domain for the study [24].

6.3 Earth-air heat pump study-3

The relationship between the cooling technology of the ground-air heat pump heat exchanger of an office building in Jinan city and the indoor heat exchange was investigated. The thermal distribution of the interior was analyzed with CFD. With the Airpak software, the distribution of the speed field, the internal temperature field, and the PMV index were obtained. In this study, energy use efficiency was also analyzed. Important conditions in the airflow design of office rooms have been determined in small temperature differences of the soil air heat exchanger. This study provides a basic reference for the soil-air heat exchanger cooling system design (**Figure 7**) [20].

6.4 Earth-air heat pump study-4

Natural and thermal ventilation behavior is evaluated as in an underground construction and determines the behavior of building components such as chimneys, tunnels, and caves in different parts of the year. With the advanced CFD model, the temperature distribution when a more realistic simulation of underground constructions is exposed to natural ventilation is provided. In every period, the role of the building components mentioned above in the arrangement of the interior changes significantly. According to the results obtained from the study, thermal stability has been provided in the cave despite the extreme energy temperatures and zero energy consumption. Floor temperature plays an important role in the regulation of natural ventilation. This is the key element in the ventilation of the building construction. Due to the lower air velocities, the ventilation shaft has no significant effect on the above situation. Adjustments and boundary conditions of advanced CFD models can play an important role in deciding the design of the energy management system and ventilation and may even be a reference model in other underground projects [25].

7. Conclusions

Computational fluid dynamics is of vital importance, particularly in determining soil air heat pumps, which are difficult to build and implement in residential buildings, especially in building energy efficiency. CFD technique is important especially in the widespread application of soil air heat pumps, which will provide less energy usage and thus increase the environmental impact.

As emphasized in the studies, for example, the three-dimensional solution of the thermal properties of a three-dimensional structure is possible only with a temporary heat transfer model. By determining a circular cross section region, it can be estimated with a rectangular geometry close to the same area. Energy balances can be established separately in the fluid and solid regions. Experimental data about the section where the liquid comes out, soil temperatures, numerical model are verified. Thermal short circuit effects between the heat transfer rate between two U pipes and the outlet thermostat temperature can be investigated. The effects of flow rate are also important. As a result of the analyzes, it can be said that the distance between the two pipes per unit soil depth gradually increases or decreases the rate of heat transfer. Numerical approaches can create effective estimates, although the soil temperature and liquid output are not stable. These studies actually reveal the value of the numerical method in evaluating the energy performance of a building or industrial facility for 1 year of energy from ground or air source heat pumps.

Conflict of interest

The author declares no conflict of interest.

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