*energies*

*Case Report*

# The Direct-Contact Gravel, Ground, Air Heat Exchanger—Application in Single-Family Residential Passive Buildings †

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**Abstract:** This paper presents proposals for using the direct-contact gravel, ground, air heat exchanger in single-family residential buildings with a passive house standard, according to the Passive House Institute (PHI). The methodology of their application consists of using heat and cold from the ground at an insignificant depth (about 1.5–4.0 m below the ground level for the central European climate) through an aggregate that is buried in the ground. This solution of simple installations is used for preheating and cooling fresh air drawn into the building through a mechanical ventilation system with heat recovery. In more complex applications it can be integrated with the source of heat and cold in passive buildings to create complete heating, cooling, and ventilation systems. In both cases, the air flowing through the exchanger is cooled and dried in summer, heated and humidified in winter, and filtered from pollen and bacteria all year. Direct contact of the deposit with the surrounding native soil facilitates rapid regeneration of the bed temperature. This article presents several proposals for integration with systems ensuring climatic comfort in a passive building, as exemplary applications. The paper presents preliminary estimates of energy (savings of up to 70% of electrical energy consumed), economic (SPBT = 3.65 years), and environmental (69.5% reduction in $CO_2$ emissions) benefits related to implementing this solution in various configurations of technological systems for buildings in Poland. The calculations were carried out for the city of Poznań, taking into account the hourly intervals and using the author's code written in MS Excel. The analysis of the operation of the direct-contact gravel, ground, air heat exchanger (GGAHE) system is based on a theoretical heat and mass exchange model. The integrated solutions of technical systems presented in this article provide an interesting alternative to traditional heating, cooling, and ventilation systems.

**Keywords:** air direct-contact; gravel; ground heat exchanger; heating and cooling support; passive buildings

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## 1. Introduction

The presented article is an extension of the conference referat [1]. Research on heat acquisition from the ground and heat dissipation to the ground at a small depth below ground level (about 1.5–4.0 m below the ground level for the central European climate) has been carried out since the 1980s. For the central European climate, the ground temperature at a depth of about 4 m is essentially stabilized throughout the year at about +10 (±1.5) °C [2]. The natural temperature of the ground has been the subject of many studies [3–6]. This property of the soil is used in the gravel, ground, air heat exchanger (GGAHE) [7]. For other climates not considered in this publication, the temperature of the ground in the subsurface layer can vary significantly up to a depth of 20–30 m below the ground level. The temperature may be influenced by meteoric waters, solar radiation, etc. This soil property is used in the gravel, ground, air heat exchanger (GGAHE). The most important element of this type of heat exchanger is a gravel deposit acting as a heat accumulator, in which external air flows through an off-road inlet into the building. The gravel deposit is used for preliminary preparation of the air supply to the building (thermal and humidity control), relying on the heating period, in the initial heating and humidifying of the extracted air, and the cooling period, in its initial cooling and drying. Subsequently, air flows to the air-handling unit or air-conditioning unit. In Polish climatic conditions, the GGAHE exchanger is usually designed in such a way that, in winter, for external design temperature e.g., −20 °C, the air drawn in is heated to a positive temperature close to 0 °C, which protects the cross-flow recuperator (in case of application) against potential frost. As reported in [8], in order to improve the thermal energy storage properties of the stone deposits, it was proposed that they can be additionally sprayed with water. Water sprinkling increases the efficiency of heat and mass transfer processes in the accumulation filling. A desirable phenomenon for the winter period is the increase in relative humidity of the air that leaves the GGAHE. The sprinkler system enables periodic disinfection and washing of the deposit. It was concluded that the number of particles from air pollution following the exchanger got reduced to half of the value contained in atmospheric air. Thus, the exchanger is additionally, a specific kind of filter. The disadvantage of such a solution is its sensitivity to the groundwater and, in the case of the stone deposit being too small, the necessity of its regeneration. When designing a ground heat exchanger, it is necessary to analyse the physical properties of the ground, its temperature profiles at various times of the year, and the impact of heat extraction or supply on changes in its temperature. It is crucial to apply mathematical modelling for this purpose, as it allows for specification of the time needed for thermal regeneration of the ground after the heating season, among other functions. Despite the existence of natural thermal regeneration in the summer season, too much intensive exploitation of a heat exchanger during the heating season can cause excessive cooling of the ground [9,10]. In [2], it was found that during the winter season, the gravel heat exchangers can be used to provide about 50% of the heat for ventilation, and during the summer season to meet up to 100% of demand for building cooling. The ratio of electrical energy required to force airflow through the gravel deposit to heating or cooling obtained from the deposit is 1:40 in peak periods, and 1:25 on average. Figure 1 presents the results of calculations for the percentage coverage of heat demand to heat the extracted ventilation air through the ground exchanger, which is subject to regeneration [2]. It is noted that, for the winter period, the exchanger covers more than 60% of the heat demand. This allows for a significant reduction in heating costs.

The simulations carried out in [9–11] show that the ground thermal conductivity significantly affected the value of the minimum temperature occurring at a given depth of the heat exchanger's installation. Therefore, the ground heat exchanger will be best protected against the occurrence of excessively low temperatures if it is installed in- ground with high thermal conductivity. As can be seen from the calculations, the lower relative humidity of the ambient air and evaporation rate coefficient raised the minimum annual ground temperature very slightly, improving the operation of the ground heat exchanger to a small extent. In [11] it was demonstrated that the amount of latent heat that was captured and dissipated by a GGAHE significantly affected the building's overall energy balance. This observation should be taken into account in the design and engineering methods for calculating a building's energy load.

In [12], the authors presented the results of the analysis of particles retained on filters located at the inlet and outlet of the ground heat exchanger and the results of the analysis of collected sediments on the gravel deposit, which have been used without external intervention by the operators for the last 13 years. In that study, small amounts of microorganisms were found in the air coming out of the GGAHE and subsequently, blown into the building. It was shown that the number of living bacteria and fungi, as well as chemical markers of microorganisms detected using the analytical method, were much lower behind the gravel deposit than in front of it. The content of fungi and their spores in the sediment on the gravel deposit decreased from 10.8 pg/mg to 0.3 pg/mg, and the content of Gram-negative bacteria and endotoxin markers decreased from 0.147 nmol/mg to 0.01 nmol/mg. No increased growth of bacteria or fungi was observed on the surface of the deposit, which means that the gravel exchanger has very good air conditioning properties. To intensify the air purification, [13] presents the concept of using a UV-C (ultraviolet with a wavelength of 200–280 nm) lamp in the air duct in front of the air-handling unit connected to the GGAHE. The UV-C lamp is used to purify the air and can lower the cost of exploitation by eliminating the pollutants that form bacterial jelly on heat exchanger elements.

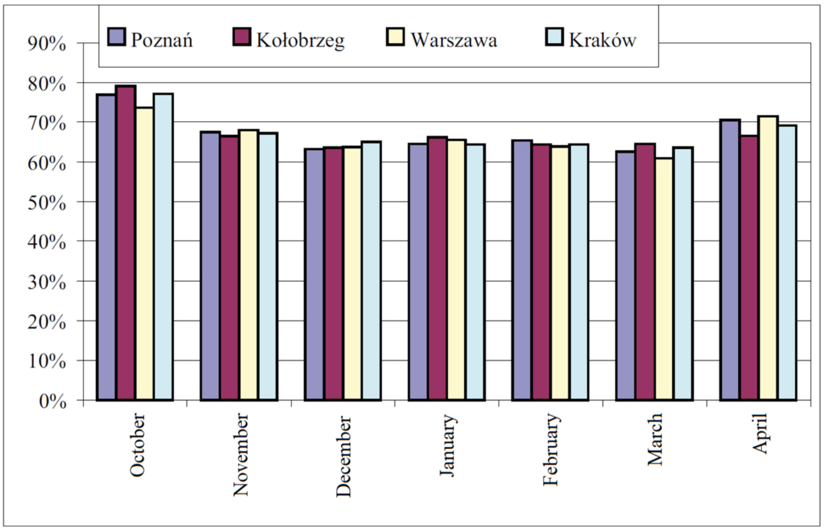



**Figure 1.** The percentage coverage of heat demand for ventilation through a ground heat exchanger (Poznań, Kołobrzeg, Warszawa, Kraków) [1].

In [14], measurements of dust concentration before and after the installation of the GGAHE were carried out. After three measurement tests of concentrations of PM1, PM2.5, PMresp, PM10, and PMTOTAL before and after the exchanger, the efficiency of stopping the particulate matter by the exchanger was determined to be 75–76%, which showed that the GGAHE also has very good filtration properties. These features of the GGAHE are definitely an added value of this type of heat exchanger.

The purpose of this article is to perform simulation calculations of GGAHE operation throughout the year for applications in a passive house built in the Polish climate. The next step will be to validate the calculations on a real test stand. It is expected that the use of GGAHE will reduce final energy consumption, reduce CO2 emissions to the environment, and enable the use of heating and cooling devices with lower power.

## 2. Types of Gravel, Ground, Airborne Heat Exchangers

The membraneless ground, air-grade gravel heat exchangers can be divided into two types. The first type is a single ground heat exchanger with a high storage capacity of deposit, which guarantees the desired preparation of the extracted ventilation air all year round without the need to regenerate the deposit (Figure 2). The second type consists of two ground heat exchangers arranged parallel to each other (Figure 3). The extracted air flows through exchanger I, and then is directed through the air-handling unit to the building. The used air is extracted from the rooms and directed to exchanger II, which is regenerated. After a given time, the settings in the dampers are changed, exchanger I is regenerated, and exchanger II gives off the accumulated heat/cold. This allows for higher efficiency than in the case of the first solution. The condition for using the second type of heat exchanger with the regeneration of the deposit is the absence of volatile toxic substances in the air ejected from the building.

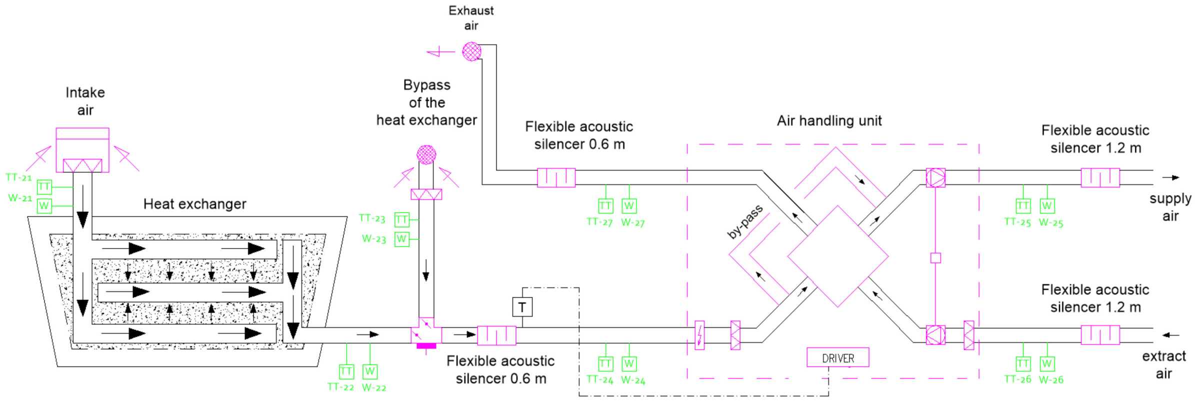



**Figure 2.** GGAHE diagram.

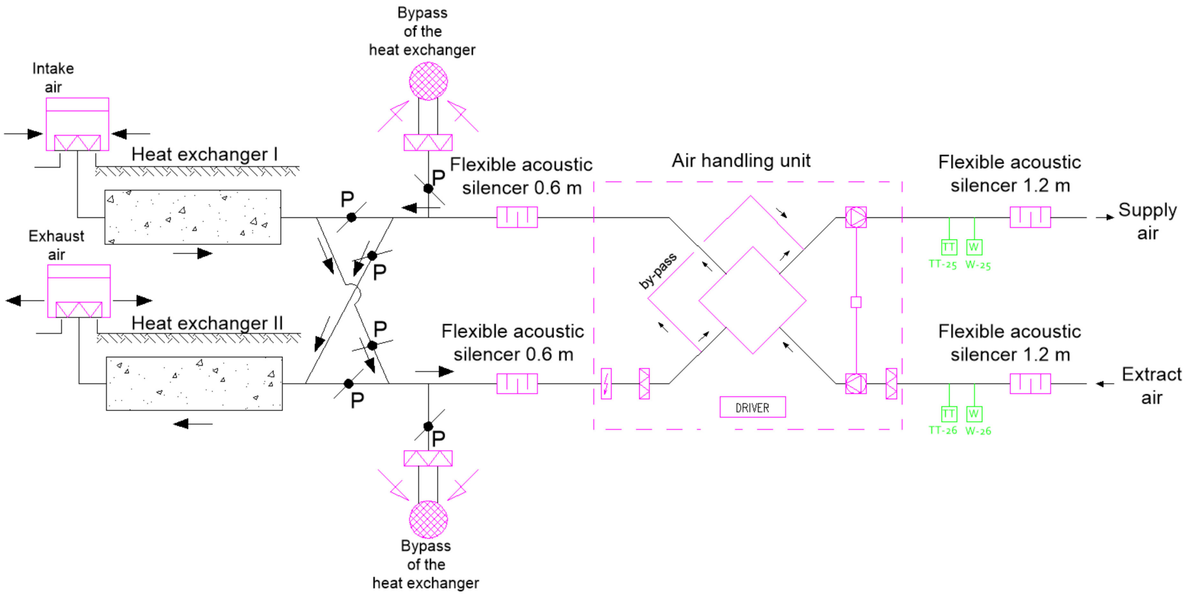
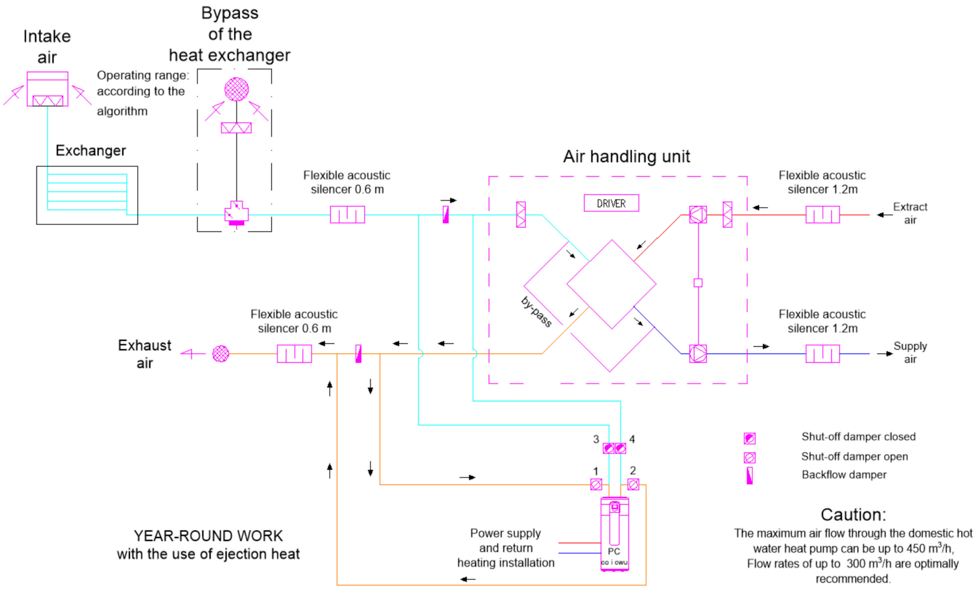



**Figure 3.** GGAHE diagram (based on [1]).

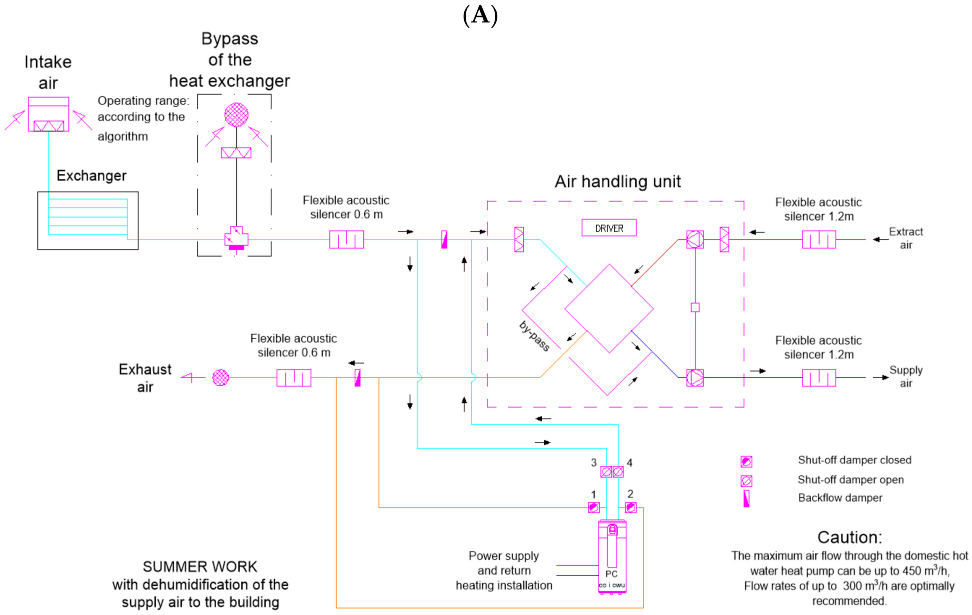
## 3. The Use of Direct-Contact, Gravel, Ground, Air Heat Exchangers

The possibilities for using direct-contact, gravel, ground, air heat exchangers are numerous. They can be used wherever it is desirable to reduce primary energy consumption. The most common solution is to use GGAHE for the preparation of preliminary air (thermal and humidity control) in single or multi-family buildings, but also in industry [15,16]. Figure 2 shows the diagram of the application of direct-contact gravel, ground, air heat exchangers for a single-family building in the passive standard [17–19], located in Sierosław (near Poznań). Figure 2 shows the applied technological system with an indication of the measuring equipment. Currently, measurement data of temperature and relative air humidity in seven measurement points are collected. During the winter, the air collected by the field probe flows through the ground gravel heat exchanger, and then is directed to the air-handling unit equipped with highly efficient heat recovery (>90%), and is subsequently blown into the rooms. In summer, the air bypasses the heat recovery exchanger located in the air-handling unit through the by-pass, because in this period the ground heat exchanger ensures 100% supply of cold air within the building. In the transitional periods, it is possible to draw fresh air using an additional wall intake, built on the external wall of the building, the so-called bypass system of the ground heat exchanger. During this time, the gravel deposit is regenerated. In addition, during the winter season, if the gravel heat exchanger is over-exploited, an electric inlet air heater is used to avoid cross-freezing of the heat recovery heat exchanger located in the air-handling unit. The presented system is effective; during the winter it provides heating of the extracted ventilation air to positive temperature parameters (TC > 0 °C) and regulation of the relative humidity of indoor air in the building at the level of φWEW > 30%, while during the summer season it is responsible for total dissipation of heat from the building, maintaining a comfortable temperature inside the building at the level of TWEW < 24 °C, at the same time as regulating relative humidity, which does not exceed φWEW < 70%. As a result of air contact with the ground in GGAHE, the soil gets drained during hot summer periods, moisturized in winter, and cleansed.

In more complex applications, the GGAHE can be integrated from the heating and cooling source for passive buildings while creating complete heating, cooling, and ventilation systems. A proposal for this is shown in Figure 4A,B.




(**A**)




(**B**)

**Figure 4.** (**A**) Diagram of GGAHE integration with the heat pump—year-round mode. (**B**) Diagram of GGAHE integration with the heat pump—summer mode.

## 4. Energy, Economic, and Environmental Efficiency of the GGAHE

The simplest way to determine the energy efficiency of a ground heat exchanger is to calculate the heat flow exchanged in the system. It can be calculated using the formula [20]:

$$\dot{Q} = \dot{m} \cdot \Delta h \ [\mathrm{kW}] \quad (1)$$

where

$\dot{Q}$ is instantaneous power output from the GGAHE [kW]
$\dot{m}$ is the air mass flow rate flowing through GGAHE [kg/s]
$\Delta h$ is the difference in the specific enthalpy of the moist air between the inlet and outlet of the GGAHE [kJ/kg]

The air mass flow rate can be determined by knowing its flow rate through the exchanger according to the formula [20]:

$$\dot{m} = \frac{\dot{V} \cdot \rho}{3600} [\mathrm{kg/s}] \quad (2)$$

where

$\dot{V}$ is the volumetric flow rate of the air flowing through the GGAHE [$\mathrm{m^3/s}$]
$\rho$ is the density of the air flowing through the GGAHE [$\mathrm{kg/m^3}$]

The specific enthalpy of humid air can be determined from the formula [20]:

$$h_1 = 1.005 \cdot t_1 + x_1 \cdot (1.86 \cdot t_1 + 2500.8) [\mathrm{kg/s}] \quad (3)$$

where

$t_1$ is humid air temperature [°C]
$x_1$ is moisture content of the moist air [kg/kg]

The amount of energy derived from the GGAHE can be determined from the formula [20]:

$$Q = \dot{Q} * \Delta t \ [\mathrm{Wh}] \quad (4)$$

where

$\Delta t$—time [h]

Using the above relationships and knowing the quantitative (flow) and qualitative (temperature and relative humidity) parameters of the air flowing through the GGAHE, in points in front of and behind the exchanger, it is possible to determine the amount of energy taken from the ground during the winter and the amount of energy given back to the ground during the summer using the gravel, ground, air heat exchanger. Knowing the amount of guiding electrical energy inserted additionally to force the air through the GGAHE, it is possible to determine the energy efficiency of the GGAHE application for the whole year.

For this work, we decided to assume quality parameters (temperature and relative humidity) of the air flowing out of the GGAHE by the data presented in [2,3,15,16,21], which were indicated and statistically calculated based on many years of measurements. In Figure 5, average values for air temperature after passing through the GGAHE and average values of outdoor air temperature and soil for Poznań were presented. These data can be used in designing and providing the basis for the performance of any analyses connected with the full-year operation of the device. Knowing the unit prices of electricity and fossil fuels for an alternative way of supplying heating and cooling to the extracted outside air and its humidifying and dehumidifying capabilities, it is possible to calculate the operating cost savings and thus the economic efficiency and payback time of the GGAHE. Similarly, environmental performance can be determined using the GGAHE.

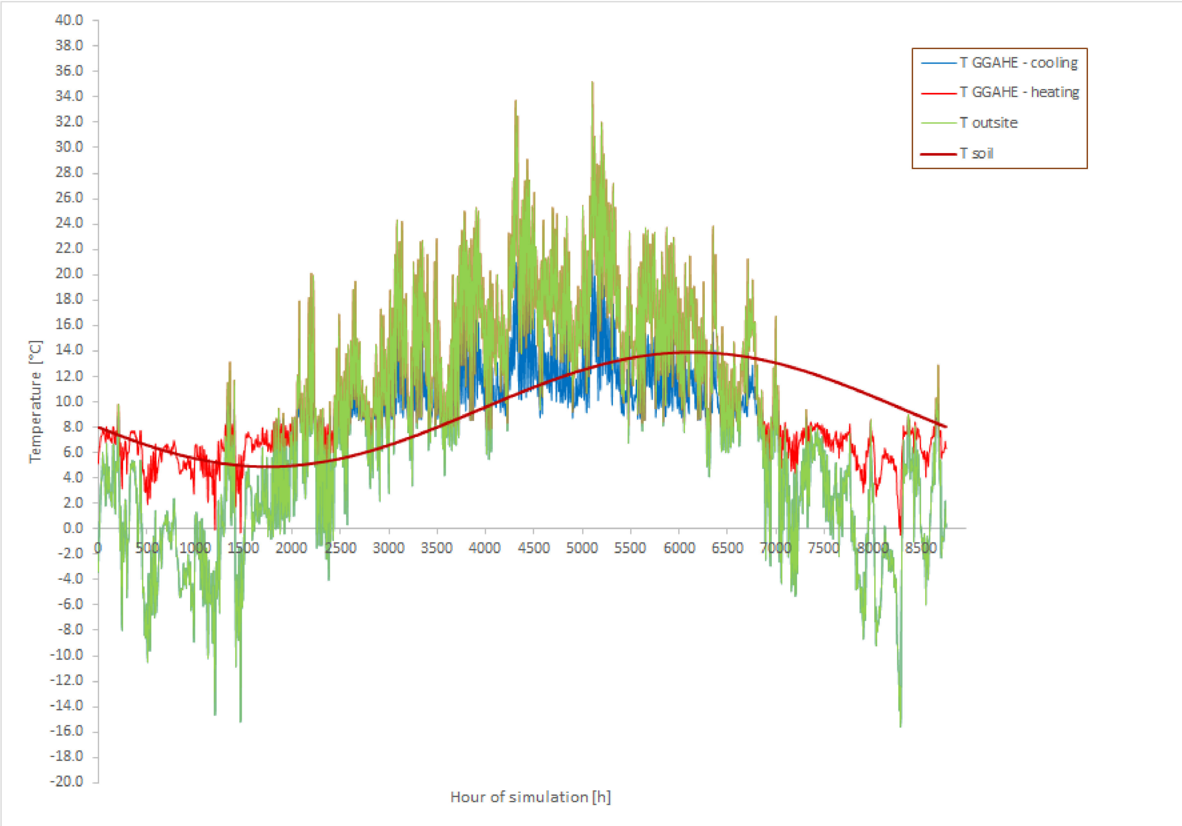



**Figure 5.** Average ground and outside air temperatures after passing through the GGAHE.

## 5. Calculation

### 5.1. Passive Building

This analysis considers a single-family residential building in the passive building standard. There are four users in the building. It is located in the 2nd climate zone according to Polish Standard PN-76/B-03420. The heating consumption coefficient does not exceed 15 kWh/(m$^2$·a) and is fully covered using renewable energy sources, including heat pump and GGAHE. Building description:

Total useful floor area with adjustable temperature: $A_G$ = 154.0 m$^2$
Total usable volume: $V_G$ = 475.5 m$^3$
Energy demand for heating and ventilation: 2237.2 kWh/a
Specific energy demand for heating and ventilation: $EU_{H+W}$ = 14.53 kWh/(m$^2$·a)
Calculation thermal power for heating and ventilation: $Q_{CO}$ = 2.2 kW
Calculation thermal power for DHW production: $Q_{DHW}$ = 2.6 kW
Airtightness of the building: n50 = 0.6 h-1
Heat transfer coefficient of the external walls: $U_W$ = 0.1 W/(m$^2$·K)
Heat transfer coefficient of the roof: $U_{R\,=}$ 0.09 W/(m$^2$·K)
Highly insulated windows with external blinds, to protect from overheating in the cooling season: U = 0.8 W/(m$^2$K): $U_{G\,=}$ 0.5 W/(m$^2$K), $g_{WIND\,=}$ 0.7, $g_{SUM\,=}$ 0.35.

### 5.2. Heating and Cooling System

The heat source is a heat pump with a vertical ground heat exchanger. The heating capacity Qg = 5.9 kW (B0/W35) and the COP = 4.7 (B0/W35). The average annual efficiency of the heat pump is SCOP = 5.0. The average overall seasonal efficiency of the heating system is equal to 3.85. The top heat source is the floor heating system with heating water temperatures of $t_{sup}/t_{ret}$ = 30/25 °C. The heat pump supplies the DHW storage tank with a volume of 300 $dm^3$. The electric heater is the peak heat source for heating domestic hot water. The heat pump is equipped with a passive cooling module.

### 5.3. Mechanical Ventilation System with Heat Recovery

The building under consideration is equipped with a supply and exhaust ventilation system (AHU) with a nominal airflow designed as $\dot{V}_{IN}/\dot{V}_{OUT}$ = 200/200 $m^3/h$ in winter. The recuperator efficiency is 88%. During the summer, the airflow is $\dot{V}_{IN}/\dot{V}_{OUT}$ = 400/400 $m^3/h$. In summer mode, the air bypasses the recuperator or uses heat recovery in the mode of dehumidifying the intake air. The multi-step electric heater (with electric power of 1.5 kW) is the peak heat source for the air-handling unit. The electric heater is used to pre-heat the fresh air to the temperature of −1 °C, at subzero outside temperatures.

Characteristics of the ventilation system and assumptions:
AHU performance within the cooling season (from 1 May to 30 September): 400 $m^3/h$
AHU performance within the heating season (from 1 October to 30 April): 200 $m^3/h$
Pressure drop through a mechanical ventilation system: 100 Pa
Efficiency electric heater: 95%
Airflow is constant during the day/night period
Electricity consumption by the air-handling unit (Pin/Pout): 58/58 W

### 5.4. The Direct-Contact Gravel, Ground, Air Heat Exchanger (GGAHE)

As part of this article, it was decided to calculate the energy, economic, and environmental benefits of GGAHE in accordance with option no. 1 (Figure 2). GGAHE description:

- Width × length × height: 4.0 × 5.0 × 1.2 m
- Gravel: 63 mm pure fraction, granite, washed gravel, no sand, hygienically clean and odourless
- Collection pipe DN: 315 mm
- Constant flow rate through the bed: 0.1 m/s
- The level of the free table of groundwater: 2.5 m
- Additional air-flow resistance through the gravel bed: 100 Pa
- Additional electricity consumption by the air-handling unit (Pin add): 18 W

Assumptions:

Airflow through the GGAHE over the year
The GGAHE works in heating mode when the external air temperature is lower than 10 °C; the GGHE heats the airflow; during this period the outside air is also moisturized
The electric heater supports its work
In cooling mode, the GGAHE cools the airflow to the resulting temperature only when the outdoor temperature exceeds 16 °C; during this period the outside air is also dried

### 5.5. Simulations

The calculations were carried out for the city of Poznań and are presented in Table 1. The calculations were made in MS Excel with the use of proprietary code. The hourly interval was taken into account in the calculations. The analysis of the operation of the GGAHE system was based on a theoretical heat and mass exchange model [22]. It describes a system that consists of the heat and mass transfer to or from the ground and from or to conditioning air. The thermodynamic properties of water and air were approximated using appropriate equations [23]. The heating, cooling, drying, and moisturizing operations of fresh, ventilated air in the GGAHE rely on Equation (1). The simulation model was created based on heat and mass exchange equations shown in [24]. Because the calculations were carried out in an MS Excel application some simplifying assumptions were made, according to [22]—Section 3.2. "Simulations". The reference temperature of the ground at a depth of 2 m is calculated according to the methodology shown in [23].

**Table 1.** Amount of heat and energy taken/given from the ground through a GGAHE.

| Results Concerning Ground, Air–Ground, Gravel Heat Exchanger | | |
|---|---|---|
| Amount of heat taken from the ground during the heating period ($T_{out}$ < 10 °C) | 1609.4 | kWh/a |
| Amount of heat transferred to the ground during the heating period ($T_{out}$ < 10 °C) | −20.9 | kWh/a |
| Amount of energy taken from the ground during the heating period ($T_{out}$ < 10 °C) | 1956.1 | kWh/a |
| Amount of energy transferred to the ground during the heating period ($T_{out}$ < 10 °C) | −23.7 | kWh/a |
| Amount of heat taken from the ground during the transitional periods (10 °C < $T_{out}$ < 16 °C) | 0.0 | kWh/a |
| Amount of heat transferred to the ground during the transitional periods (10 °C < $T_{out}$ < 16 °C) | −686.5 | kWh/a |
| Amount of energy input from the ground during the transitional periods (10 °C < $T_{out}$ < 16 °C) | 0.2 | kWh/a |
| Amount of energy transferred to the ground during the transitional periods (10 °C < $T_{out}$ < 16 °C) | −720.4 | kWh/a |
| Amount of heat taken from the ground during the cooling period (10 °C < $T_{out}$ < 16 °C) | 0.0 | kWh/a |
| Amount of heat transferred to the ground during the cooling period ($T_{out}$ > 16 °C) | −1677.5 | kWh/a |
| Amount of energy taken from the ground during the cooling period ($T_{out}$ > 16 °C) | 0.0 | kWh/a |
| Amount of energy transferred to the ground during the cooling season ($T_{out}$ > 16 °C) | −2177.8 | kWh/a |

Simulations were prepared using meteorological data of the Poznań City (EN-ISO 15927:4). The climatic data take into account the dry- and wet-bulb temperature variations, relative humidity, and moisture content for every hour of the year. The main point of the simulation is to examine changes in temperature and relative humidity of the external air flowing through the GGAHE into the building throughout the year.

*5.6. Results and Discussion*

The results of the calculations are shown in Tables 1–3. The tables show the results of a GGAHE. The simulation results indicate that the application of the GGAHE contributed to the extraction of a significant amount of heat and water from the ground during the heating period and, during the cooling period, it contributed to the transfer of a significant amount of heat and water to the ground. During the transitional periods, heat was transferred from the outside air to the ground. During winter, the GGAHE preheated the airflow. An electric heater was not needed. The savings were 346.6 kWh/a of heating produced from electricity. During summer, the GGAHE precooled the airflow and obviated the need to use the active cooling system. The savings were 1677.5 kWh/a of cooling produced from electricity.

**Table 2.** The amount of heat supplied/exhausted into the supply air of the building.

| Results of the Heat Input/Output to the Supply Air | | | |
|---|---|---|---|
| | **GGAHE** | **Without GGAHE** | |
| Amount of heat obtained in the heating period ($T_{out}$ < 10 °C) mechanical ventilation system with heat recovery | 5788.0 | 5634.9 | kWh/a |
| Heat output during the cooling period ($T_{out}$ > 16 °C) mechanical ventilation system with heat recovery | −1677.5 | 0.0 | kWh/a |
| Heat quantities needed to heat the supply air to a building in the heating season ($T_{out}$ < 10 °C) | 572.7 | 725.8 | kWh/a |
| Heat quantities needed for the electric heater to pre-heat the intake air | 0.0 | 312.66 | kWh/a |
| Amount of electricity used by the electric heater to pre-heat the intake air | 0.0 | 329.12 | kWh/a |

**Table 3.** Conditioning (humidifying and dehumidifying) the supply air to the building.

| Results of Intake Air Humidification | | | |
|---|---|---|---|
| | **GGAHE** | **Without GGAHE** | |
| Amount of water abstracted from the ground during the heating period ($T_{out}$ < 10 °C) | 488.5 | 0.0 | kg/a |

**Table 3.** *Cont.*

| Results of Intake Air Humidification | | | |
|---|---|---|---|
| | **GGAHE** | **Without GGAHE** | |
| Amount of energy taken from the ground to be humidified during the heating period ($T_{out}$ < 10 °C) | 346.6 | 0.0 | kWh/a |
| Amount of electricity for humidifier purposes in the heating period ($T_{out}$ < 10 °C) | 0.0 | 358.5 | kWh/a |
| Maximum amount of water abstracted from the ground during the heating period ($T_{out}$ < 10 °C) | 0.65 | 0.0 | kg/h |
| Maximum electric power of the humidifier | 0.0 | 0.48 | kW |
| **Results of the Dehumidification of Intake Air** | | | |
| | **GGAHE** | **Without GGAHE** | |
| Amount of water released to the ground during the cooling season ($T_{out}$ > 16 °C) | −723.5 | 0.0 | kg/a |
| Amount of energy released to the ground during the cooling season ($T_{out}$ > 16 °C) | −500.2 | 0.0 | kWh/a |
| Amount of electricity for the dehumidifier in the refrigeration period ($T_{out}$ > 16 °C) | 0.0 | 1067.7 | kWh/a |
| Maximum amount of water released to the ground during the cooling season (Tout > 16 °C) | −2.40 | 0.0 | kg/h |
| Maximum electrical power of the dehumidifier | 0.0 | 3.55 | kW |

*5.7. Energy, Economy, and Environmental Analysis*

To determine the total energy, economic, and environmental benefits of using the designed GGAHE system instead of the traditional mechanical ventilation system with electrical air heating, the additional cooling and dehumidification of intake air in summer and the additional humidification of intake air in winter must be investigated. The results of the analysis are shown in Table 4. Assumptions for energy, economic, and environmental analysis:

Average seasonal efficiency of chill production (for the non-integrated system), SEER = 3.0
Electricity unit price, $P_{EL\,=}$ 0.120 euro/kWh
Total investment cost of GGAHE installation and integration, $I_0$ = 1520 euro
Additional total investment cost for humidifying and dehumidifying installation, $I_{0HDH}$ = 540 euro
$CO^2$ emission factor (National Centre for Emissions Management), $e_{CO2}$ = 798 kg/MWh

**Table 4.** Energy economy and environmental analysis.

| Results Concerning the Amount of Electricity | | | |
|---|---|---|---|
| | **GGAHE** | **Without GGAHE** | |
| Electricity consumption of the air-handling unit | 833.1 | 721.2 | kWh/a |
| Electrical energy consumption for heating the air during the heating period ($T_{out}$ < 10 °C) | 148.7 | 188.5 | kWh/a |
| Electrical energy consumption for electric pre-heater air during the heating period ($T_{out}$ < 10 °C) | 0.0 | 329.12 | kWh/a |
| Electrical energy consumption for humidifying air during the heating period ($T_{out}$ < 10 °C) | 0.0 | 358.5 | kWh/a |
| Electrical energy consumption for cooling the air during the cooling period ($T_{out}$ > 16 °C) | 0.0 | 559.2 | kWh/a |

**Table 4.** *Cont.*

| Results Concerning the Amount of Electricity | | | |
|---|---|---|---|
| | **GGAHE** | **Without GGAHE** | |
| Electrical energy consumption for air dehumidification during the cooling period ($T_{out}$ > 16 °C) | 0.0 | 1067.7 | kWh/a |
| Total electricity consumption | 981.82 | 3224.18 | kWh/a |
| **Economic analysis** | | | |
| | **GGAHE** | **Without GGAHE** | |
| Variable system operating costs | 117.39 | 385.50 | euro/a |
| Additional investment costs | 1520.00 | 540.00 | euro |
| Simple payback time | 3.66 | | a |
| **Ecological analysis** | | | |
| | **GGAHE** | **Without GGAHE** | |
| $CO_2$ emissions to the environment | 783.49 | 2572.89 | kg $CO_2$/a |
| Reduction of $CO_2$ emissions to the environment | 1789.40 | | kg $CO_2$/a |

## 6. Conclusions

The use of a GGAHE to pre-prepare the air in the process of air conditioning passive buildings should be preceded each time by an in-depth analysis. The analysis should include the full-year operation of the system. Savings of up to 70% per year of electrical energy consumed can be expected compared to a GGAHE-free system. The use of GGAHE reduces the required power and size of air treatment devices (heating systems, cooling systems, humidifiers, dryers, etc.). Simple payback time for investments is less than four years. The presented solution contributes to sustainable development goals because it minimizes energy consumption and reduces $CO_2$ emissions, which is important. It also decreases running costs, while the investment itself is modest.

We are planning to validate the calculations based on collected measurement data in the near future. Figure 2 shows the applied technological system with an indication of the measuring equipment. Incomplete data have been collected since 1 November 2018.

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## Nomenclature

$\dot{V}$ The volumetric flow rate of the air flowing, $m^3/h$
$\rho$ The density of air, $m^3/h$
$t_1$ Humid air temperature, °C
$\dot{Q}$ Instantaneous power output, kW
$\dot{m}$ The air mass flow rate, kg/s

| | |
|---|---|
| $\Delta h$ | Difference in the specific enthalpy, kJ/kg |
| $x_1$ | Moisture content of the moist air kg/kg |
| $\Delta t$ | the difference between two time-scales, h |
| $T_{\mathrm{soil}}$ | soil temperature, °C |
| $T_{\mathrm{out}}$ | outside temperature, °C |
| $T_{\mathrm{GGAHE}}$ | air, gravel, ground heat exchanger temperature, °C |
| $A_g$ | total useful floor area, m$^2$ |
| $Q_{CO}$ | demands for heat generation power for heating and ventilation, kW |
| $Q_{CWU}$ | demands for heat generation power for hot water production |
| $n_{50}$ | air tightness of the building, h$^{-1}$ |
| $U_W$ | heat transfer coefficient of the external walls/roof, W/(m$^2$·K) |
| $U_g$ | heat transfer coefficient of the windows, W/(m$^2$·K) |
| $t_{\mathrm{sup}}$ | supply temperature, °C |
| $t_{\mathrm{ret}}$ | return temperature, °C |
| COP | coefficient of performance, [-] |
| SCOP | seasonal coefficient of performance, [-] |
| $\dot{V}_{\mathrm{IN}}$ | inlet air airflow, m$^3$/h |
| $\dot{V}_{\mathrm{OUT}}$ | outlet air airflow, m$^3$/h |
| $P_{\mathrm{EL}}$ | electricity unit price, zł/kWh |
| SEER | average seasonal efficiency of chill production, [-] |
| $I_0$ | total investment cost of GGAHE installation and integration, zł |
| $I_{0HDH}$ | additional total investment cost for humidifying and dehumidifying installation, zł |
| $e_{\mathrm{CO2}}$ | $CO_2$ emission factor, kg/MWh |
| $P_{\mathrm{in}}$ | electricity consumption by the supply air-handling unit, W |
| $P_{\mathrm{out}}$ | electricity consumption by the return air-handling unit, W |
| $P_{\mathrm{in\ add}}$ | additional electricity consumption by the air-handling unit, W |

## References


1. Radomski, B.; Kowalski, F. 3rd International Conference on the Sustainable Energy and Environmental Development. 2019. Available online: http://www.ize.org.pl/wydawnictwo/materialykonferencyjne/2019/seed2019-book-of-abstracts.pdf (accessed on 1 August 2022).
2. Besler, M.; Schwitalla, A.; Besler, G.J. *Intensification of Heat and Mass Transfer in Gravel Exchangers*; Ciepłownictwo, Ogrzewnictwo, Wentylacja: Warszawa, Poland, 2011; pp. 132–134. Available online: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BAR9-0009-0043 (accessed on 1 August 2022).
3. Krarti, M.; Lopez-Alonzo, C.; Claridge, D.E.; Kreider, J.F. Analytical model to predict annual soil surface temperature variation. *J. Sol. Energy Eng.* **1995**, *117*, 91–99. [CrossRef]
4. Khatry, A.K.; Sodha, M.S.; Malik, M.A.S. Periodic variation of ground temperature with depth. *Sol. Energy* **1978**, *20*, 425–427. [CrossRef]
5. Givoni, B.; Katz, L. Earth temperatures and underground buildings. *Energy Build.* **1985**, *8*, 15–25. [CrossRef]
6. Mihalakakou, G. On estimating soil surface temperature profiles. *Energy Build.* **2002**, *34*, 251–259. [CrossRef]
7. Besler, M.; Cepiński, W.; Kęskiewicz, P. Direct-Contact Air, Gravel, Ground Heat Exchanger in Air Treatment Systems for Cowshed Air Conditioning. *Energies* **2022**, *15*, 234. [CrossRef]
8. Topolańska, J.; Krawczyk, D.A. Gruntowy powietrzny wymiennik ciepła typu żwirowego jako przykład wykorzystania OZE przy budynkach jednorodzinnych efekty energetyczne i ekonomiczne. *Civ. Environ. Eng.* **2017**, *8*, 141–147.
9. Leski, K.; Luty, P.; Gwadera, M.; Larwa, B. Numerical Analysis of Minimum Ground Temperature for Heat Extraction in Horizontal Ground Heat Exchangers. *Energies* **2021**, *14*, 5487. [CrossRef]
10. Chung, W.J.; Park, S.H. Utilization of Thermally Activated Building System with Horizontal Ground Heat Exchanger Considering the Weather Conditions. *Energies* **2021**, *14*, 7927. [CrossRef]
11. Skotnicka-Siepsiak, A. An Evaluation of the Performance of a Ground-to-Air Heat Exchanger in Different Ventilation Scenarios in a Single-Family Home in a Climate Characterized by Cold Winters and Hot Summers. *Energies* **2022**, *15*, 105. [CrossRef]
12. Szponar, B.; Iwanicka, M. Gnjntowy wymiennik ciepła. Mikrobiologiczna czystość. Magazyn Instalatora nr 2. 2006, pp. 18–19. Available online: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-79eb7f0c-e7c9-4e03-ae52-cae5d855b4f8 (accessed on 1 August 2022).
13. Rabczak, S.; Kut, P. Analysis of Yearly Effectiveness of a Diaphragm Ground Heat Exchanger Supported by an Ultraviolet Sterilamp. *Energies* **2020**, *13*, 2804. [CrossRef]

14. Komosiński, B.; Konieczny, T. Sprawozdanie z badań C2-810/2018/NP.-E (etap 1). Available online: https://taniaklima.pl/files/18luty06.pdf (accessed on 1 August 2022).
15. Cepiński, W.; Besler, M. Industrial applications of the air direct-contact, gravel, ground heat exchanger. *E3S Web Conf.* **2017**, *22*, 00027. [CrossRef]
16. Besler, M.; Skrzycki, M.; Cepiński, W. Energy saving by using natural energy from the shallow ground depths—many years operating results. *E3S Web Conf.* **2017**, *22*, 00016. [CrossRef]
17. Wąs, K.; Radoń, J.; Sadłowska-Sałęga, A. Maintenance of Passive House Standard in the Light of Long-Term Study on Energy Use in a Prefabricated Lightweight Passive House in Central Europe. *Energies* **2020**, *13*, 2801. [CrossRef]
18. PASSIPEDIA. What Is a Passive House? Available online: https://passipedia.org/basics/what_is_a_passive_house (accessed on 18 April 2022).
19. Lang, A. Defining the Nearly Zero Energy Building, Passive House Institute. Available online: https://passreg.eu/upload/PassREg_International_EN/Flipbook.pdf (accessed on 18 April 2022).
20. Recnagel, Sprenger, Schramek Taschenbuch für Heizung + Klima Technik, 80. Ausgabe 2021/2022. Available online: https://www.bookcity.pl/recknagel-taschenbuch-fur-heizung-und-klimatechnik-80-ausgabe-2021-2022-premiumversion/pid/A40378540 (accessed on 1 August 2022).
21. Michalak, P. Hourly Simulation of an Earth-to-Air Heat Exchanger in a Low-Energy Residential Building. *Energies* **2022**, *15*, 1898. [CrossRef]
22. Radomski, B.; Drojetzki, L.; Mróz, T. Integration of a heat exchanger on the supply air with the ground-source heat pump in a passive house—Case study. In Proceedings of the IOP Conference Series: Earth and Environmental Science 214, Krakow, Poland, 14–17 November 2017; Available online: https://iopscience.iop.org/article/10.1088/1755-1315/214/1/012087 (accessed on 1 August 2022).
23. Popiel, C.O.; Wojtkowiak, J.; Biernacka, B. Temperature distributions of ground in the urban region of Poznan City. *Exp. Therm. Fluid Sci.* **2001**, *25*, 301–309. [CrossRef]
24. Bergman, T.L.; Lavine, A.S.; Incropera, F.P.; Dewitt, C.P. *Fundamentals of Heat and Mass Transfer*, 7th ed.; John Wiley & Sons: New York, NY, USA, 2011.