Analysis of Yearly Effectiveness of a Diaphragm Ground Heat Exchanger Supported by an Ultraviolet Sterilamp

Sławomir Rabczak * and Paweł Kut

The Faculty of Civil and Environmental Engineering and Architecture, Rzeszow University of Technology, 35-959 Rzeszow, Poland; p.kut@prz.edu.pl
* Correspondence: rabczak@prz.edu.pl

Received: 29 April 2020; Accepted: 30 May 2020; Published: 1 June 2020

Abstract: Ground heat exchangers supplement ventilation systems and provide notable power gains by heating ventilated air during winter and cooling it in summer. Additionally, they prevent recuperator exchangers from freezing. In atmospheric air, there are many types of contaminants and microorganisms that significantly affect the quality of ventilated air. The air that flows through the system of pipes of the heat exchanger may also become contaminated. In order to remove contamination from ventilated air, ultraviolet radiation may be used. This article presents a 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 ground heat exchanger. The UV-C lamp, apart from clearing the air, may also decrease operational costs thanks to eliminating contamination that forms bacterial jelly on heat exchanger elements.

Keywords: ground heat exchanger; UV-C; sterilamp; biopollution

1. Introduction

A ground heat exchanger is an apparatus in which or through which heat is carried from one environment to another [1–5]. It is simply a pipeline or gravel bed placed in the ground through which ventilated air flows. A heat exchange medium is either homogeneous (constant, a liquid or gas) or nonhomogeneous (heterophasic). The installation of a ground heat exchanger allows for supplementing the ventilation and heating system of the building [6,7]. The external air, which is introduced to the exchanger space, is initially heated in winter or cooled in the summer. We know that long-standing research shows that during freezing weather air getting into the building is heated from –22 °C outside the ground heat exchanger to +2 °C at the entry to the ground air intake duct of the building. Such an effect does not heat the building, but it will provide a notable power gain. An additional and also very important benefit of the ground heat exchanger is protection of the ventilation system against freezing, especially for the recuperator exchanger. [8]. During high temperatures in summer, the ground heat exchanger constitutes an effective cooling system of the building, without installation of compressor-based cooling systems whose operation is expensive. An adequately designed exchanger cools air coming into the building in summer through a heating and ventilation system operating with a proper recuperator. A ground heat exchanger is intended for energy-saving buildings whose demand for cooling in summer and for heating energy in winter is low, which results from a good building insulating power and the application of energy recovery systems [9,10]. In the atmospheric air, apart from components which exist in it permanently in unchanged proportions, there are many components that form air contamination. Their presence in the natural environment is undesired but unavoidable, unfortunately. If their emission (quantity/volume, rate) and toxicity are low, then, as a
result of natural processes taking place in the environment, such components become inactivated due to sedimentation, assimilation, and decomposition/degradation. Otherwise, the environmental balance may be disturbed.

One element that has an important influence on environmental air quality is the presence of microorganisms that form bioaerosols. Air is a mixture of gases that may not constitute a proper environment for microorganisms to develop, because it does not contain nutrients and favorable physical and chemical conditions that enable their development. So, theoretically, air should be free from microorganisms; however, such a state does not practically exist in nature [11]. Methods of removing microorganisms from ventilation air are mentioned in previous research [12–16].

Air going through a pipe system or a bed with a stone filling, which is the essence of the ground heat exchanger, comes into contact with the exchanger surface that may be contaminated with microorganisms due to favorable conditions existing inside the exchanger, especially in summer during its operation break due to necessary regeneration. Flowing air carries away a part of such contamination and forms bioaerosols.

2. Bacteriological Contamination

The proposed solution uses UV-C electromagnetic waves, with a wavelength of 200–280 nm; the natural wavelengths are almost nonexistent on the Earth’s surface because they are entirely absorbed by the atmosphere; they destroy, among other things, the genetic structure of vegetative forms of bacteria by disturbing the DNA replication process, and the most effective radiation wavelength is 253.7 nm. The proposed solution consists in the use of a UV-C lamp installed on an air duct in front of an air conditioning unit with a special design and shape that allows the air stream to be directed into the UV-C space in an optimal way. It should be stressed that the UV-C lamp is an integral part of the recuperation center offered by the applicant. Moreover, numerous studies confirm that the application of this type of solution does not cause significant problems in the form of accumulation of colony-forming units. The effectiveness of UV radiation depends on the exposure time. On the basis of studies developed by the Rzeszów University of Technology, gram-negative bacteria were found to be the most sensitive to UV radiation, followed by gram-positive bacteria and then bacterial and fungal spores. The application of the radiator tested in UV-C laboratory conditions limited the growth of bacteria after 2 min of exposure to radiation, while fungi were limited after 5 min, in accordance with the conditions under which the experiment was carried out. Under real conditions, slightly smaller values should be expected. Complete inhibition of bacterial growth was observed after 5 min of exposure, and fungi after 10 min. The prototype device with the UV-C filter used under the specified operating conditions allows for about a 70% reduction of microbiological contamination, which is very important for users with allergies (Table 1). Such a solution could be very widely used in the sector serving people who may suffer from allergies, such as nurseries, kindergartens, schools, hospitals, and individual users of single family buildings.

| Indicator Examined       | Degree of Reduction, % |
|-------------------------|------------------------|
| Total number of bacteria| 77.4                   |
| Number of hemolytic staphylococci | 69.2            |
| Total number of fungi   | 66.4                   |

An additional advantage in the use of UV-C lamps is the reduction of operating costs of the air conditioning system by about 10%–20%. This is due to the fact that the biological membrane is growing and forming on the elements of the heat exchangers—heaters and coolers—in the air handling unit, which results in increased flow of the heating and cooling medium through the exchangers, increased operation of circulation pumps, and increased internal resistance of the air handling unit, which leads to a decrease in the efficiency of the ventilation stream or an increase in the power of
the fans, depending on the control method. Therefore, elimination of contamination in the form of viruses, bacteria, and other similar organisms leads both to improvement of bacteriological quality of the air supplied to the rooms, reduction of health risks for people exposed to such ventilation air stream, and reduction of operating costs of the air conditioning system in which the UV-C lamp works. The energy consumption of the lamp is in the range of 36 to 95 W at 8000 operating hours, which is comparable to the energy consumption of air handling unit fans.

3. Operational Costs of a Ground Exchanger Equipped with a UV-C Lamp

Operating costs of this type of system were calculated for a fruit sorting plant with social and office facilities having an area of 127.5 m² and located in the Sub-Carpathian Region, Poland. The functional specification provided for including all rooms necessary to use technical and auxiliary facilities for the staff. For office spaces, a ventilation and heating system connected with the ground heat exchanger was designed [17]. The ground heat exchanger was supported by the UV-C lamp at the exit from the exchanger but in front of the entry to the ventilation system. The functional block diagram is presented in Figure 1.

It was assumed that the building is ventilated with an air stream $V_w = 3000$ m³/h. The ground heat exchanger with the length of 162 m was put at the depth of 1.5 m. Rehau AWADUKT Thermo DN 630 pipes were selected for the exchanger. The building was assumed to be located in the city of Rzeszów, Poland. The temperatures of ground and air behind the ground heat exchanger were calculated on the basis of [6]. The ground temperature for the analyzed city, external air temperatures, and temperatures behind the ground exchanger are presented in Figure 2. The temperature behind the ground heat exchanger was calculated by assuming that the efficiency of the exchanger is 73%. This value was based on the ecodesign directive of the European Union and is the minimum value that can currently be adopted [18]. Electricity cost for calculations were assumed to be 0.1267 Euro/kWh.

The yearly quantity of energy that may be obtained from the ground heat exchanger (GWC) is calculated from the following formula:

$$Q_{GWC} = \sum_{i=1}^{12} V_w \cdot \rho \cdot C_p \cdot \Delta T_i \cdot \tau_i \cdot 10^{-3} \quad (kWh)$$  

Figure 1. Diagram of an air–ground heat exchanger equipped with a UV-C lamp.
where $V_w$ is the ventilated air stream in m$^3$/h, $\rho$ is the air density (1.2 kg/m$^3$), $C_p$ is the specific heat of air (1005 J/(kg·K)), $\Delta T_i$ is the temperature difference of air behind the external air exchanger, and $\tau_i$ is the ground heat exchanger operation time, calculated from the following formula:

$$\tau_i = T_M \frac{t}{24} \text{ (h)}$$

where $T_M$ is the number of hours in month and $t$ is the ground heat exchanger operation time per day (10 h is assumed).

Operational costs of the ground heat exchanger without costs required to supply the UV-C lamp are calculated using Equation (3):

$$K^d_{GWC} = \sum_{i=1}^{12} \frac{V_w \cdot \Delta P_{GW C} \cdot \tau_i \cdot k_{el}}{\eta_{tot}} \text{ (Euro)}$$

where $\Delta P_{GW C}$ is the resistance to flow at the ground heat exchanger (60 Pa is assumed), $\eta_{tot}$ is the total efficiency of the ventilator–engine system (0.8 is assumed), and $k_{el}$ is the cost of electricity.

The operational costs of the UV-C lamp are calculated from Equation (4):

$$K^d_{UV-C} = \sum_{i=1}^{12} N_{UV-C} \cdot \tau_i \cdot k_{el} \text{ (Euro)}$$

The UV-C lamp power $N_{UV-C}$ is assumed to be 1 kW.

The total operational costs of the system, both the ground exchanger and the UV-C lamp, are a sum of unit costs:

$$K^d_{tot} = K^d_{GWC} + K^d_{UV-C} \text{ (Euro)}$$

To better depict the possibility of the analyzed type of the air–ground heat exchanger, a factor presenting the heat volume (or cool volume in summer) obtained from the ground to the unit cost of 1 Euro is introduced. It is possible for the system $E_{GWC}$ to create thermal energy according to the Equation (6) using the unit cost:

$$E_{GWC} = \sum_{i=1}^{12} \frac{Q_{GW C}}{K^d_{tot}} \text{ (kWh/Euro)}$$

The $E_{GWC}$ factor is calculated both for the option of independent operation of the ground heat exchanger and for the option of UV-C lamp operation, which is presented in Table 2 and Figure 3. The $E_{UV}$ factor refers to the above by analogy, but for the unit consumption of thermal energy by the ventilation system, Equation (7) is used:

$$E_{UV} = \sum_{i=1}^{12} \frac{V_w \cdot C_p \cdot \rho \cdot (T_z - T_{AirOut}) \cdot \eta_{tot} \cdot (1 - \eta_{HR})}{V_w \cdot \Delta P_{UV} \cdot \theta_{el}} \text{ (kWh/euro)}$$

where $T_z$ is the external temperature, $\eta_{HR} = 0.73$ is assumed as the heat recovery efficiency at the ground exchanger, and $T_{AirOut}$ is the air temperature behind the ground heat exchanger.

A ventilation system with recuperation having an efficiency of 0.8 is assumed. Results of the calculations appear in Table 2 and Figure 3. For the selected location, it is possible to draw heat from the ground from October to March and ventilated air may be cooled by the heat exchanger from April to September. Figure 3 presents factors of thermal energy unit production by the heat exchanger $E_{GWC}$ and a factor of the unit demand for thermal energy by the ventilation system with recuperation $E_{UV}$. In winter when ventilated air needs to be heated, it is possible to obtain a greater amount of heat from the ground heat exchanger at a lower cost in the option without using the UV-C lamp (from January to
approximately the end of March (point A, Figure 3) and from September (point D, Figure 3) to the end of the year. However, the difference in the case for using the UV-C lamp is very small and is 39.3 Euro monthly. Taking into account the total operational costs of the ground heat exchanger with the UV-C lamp, which is a maximum of 245 Euro, constitutes a cost increase of 16.0% (Table 2).

![Figure 2. External temperatures, ground temperatures, and air temperatures behind the ground heat exchanger for each month.](image-url)

**Figure 2.** External temperatures, ground temperatures, and air temperatures behind the ground heat exchanger during the year.

It is also possible to determine cooling period limits (Figure 3) between months indicated at points B and C, i.e., from the middle of May to the beginning of August. The remaining months are transitional periods. Recall the main idea for using the UV-C lamp, which fulfills in the system a very significant role of protecting the internal environment against undesired biological contamination. It provides a low cost method for bacteriological protection of the building interiors.

| Month | $K_{GWC}$ (Euro) | $K_{UV-C}$ (Euro) | $Q_{GWC}$ (kWh) | $K_{tot}$ (Euro) | $E_{GWC}$ (kWh/Euro) | $E_{UV}$ (without GHE) (kWh/Euro) | $E_{GWC}$ (without lamp) (kWh/Euro) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | 245.536         | 39.286          | 3783.804        | 284.821         | 13.285          | −0.120          | 0.321           | 15.410          |
| 2     | 221.774         | 35.484          | 1172.655        | 257.258         | 4.558           | −0.034          | 0.257           | 5.288           |
| 3     | 245.536         | 39.286          | 208.979         | 284.821         | 0.734           | 0.003           | 0.248           | 0.851           |
| 4     | 237.615         | 38.018          | −2189.164       | 275.634         | −7.942          | 0.084           | 0.156           | −9.213          |
| 5     | 245.536         | 39.286          | −3474.044       | 284.821         | −12.197         | 0.121           | 0.098           | −14.149         |
| 6     | 237.615         | 38.018          | −3919.196       | 275.634         | −14.219         | 0.135           | 0.042           | −16.494         |
| 7     | 245.536         | 39.286          | −3094.428       | 284.821         | −10.864         | 0.098           | 0.040           | −12.603         |
| 8     | 245.536         | 39.286          | −2146.709       | 284.821         | −7.537          | 0.062           | 0.030           | −8.743          |
| 9     | 237.615         | 38.018          | −2217.724       | 275.634         | −8.084          | −0.003          | 0.074           | −0.933          |
| 10    | 245.536         | 39.286          | 2342.287        | 284.821         | 8.224           | −0.087          | 0.172           | 9.539           |
| 11    | 237.615         | 38.018          | 3494.974        | 275.634         | 12.680          | −0.125          | 0.235           | 14.709          |
| 12    | 245.536         | 39.286          | 3867.925        | 284.821         | 13.650          | −0.129          | 0.276           | 15.834          |

**Table 2.** Most important results of the calculations.
Air heated by the ventilation system with recuperation requires a higher cost due to great resistance to air flow through the air handling unit itself and through the network of distributing ducts. This is because a much smaller amount of thermal energy supplied to rooms is obtained for 1 Euro. It should be noted that the cooperation of the ventilation system with recuperation and the ground heat exchanger results in a significant reduction of operational costs. The operation of the ventilation system with recuperation in winter, when it cooperates with the ground heat exchanger, generates demand for thermal energy of 14.891 kWh. An analogous system operating independently without the ground heat exchanger generates demand for thermal energy of 111.054 kWh. That is 86.6% times higher demand whose cost will be relatively higher during the use. In this comparison, costs of the UV-C lamp cooperating with the ground heat exchanger seem to be very well justified for economic reasons and also due to protecting the health of people using the building.

4. Summary

When analyzing solutions aimed at introducing UV-C lamps that cooperate in the ventilation system with recuperation to systems with a ground heat exchanger, the benefit for eliminating factors that are a serious source of biological contamination should be stressed. It is a new, unprecedented and innovative solution. Its innovativeness is reflected in using the UV-C lamp in close proximity to the source of contamination, which is unprecedented in Poland. In Europe, such solutions are used individually or as system solutions, such as built-in air handling units, mainly roof-top systems, but there are no system solutions for using UV-C lamps in air ducts behind the ground heat exchanger. Roof-top units, obviously, do not cooperate with the ground heat exchanger and the main background contamination comes only from the external air drawn by the unit. In the solution suggested, the use of a UV-C lamp eliminates contamination coming mainly from the ground heat exchanger, and the external air constitutes only background contamination in this solution. Moreover, it should be noted that in the near future, the amount of colony forming units in 1 m³ of air will be limited and a UV-C lamp will be a simple, low cost, effective, and reliable method that will provide for standard values of acceptable bacteriological contamination concentrations.

**Author Contributions:** Conceptualization, S.R. and P.K.; methodology, S.R.; formal analysis, S.R.; resources, S.R. and P.K.; writing—original draft preparation, S.R. and P.K.; writing—review and editing, S.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.
References

1. Javadi, H.; Mousavi Ajarostaghi, S.S.; Rosen, M.A.; Pourfallah, M. Performance of ground heat exchangers: A comprehensive review of recent advances. *Energy* 2019, 178, 207–233. [CrossRef]

2. Selamat, S.; Miyara, A.; Kariya, K. Analysis of short time period of operation of horizontal ground heat exchangers. *Resources* 2015, 4, 507–523. [CrossRef]

3. Larwa, B.; Kupiec, K. Heat transfer in the ground with a horizontal heat exchanger installed—Long-term thermal effects. *Appl. Therm. Eng.* 2020, 164, 114539. [CrossRef]

4. Pisarev, V.; Rabczak, S.; Nowak, K. Ventilation system with ground heat exchanger. *J. Ecol. Eng.* 2016, 17, 163–172. [CrossRef]

5. Kopeć, P. Obliczenia i dobór gruntowego wymiennika ciepła dla pompy ciepła. *J. Civ. Eng. Environ. Archit.* 2015, 62, 167–176. [CrossRef]

6. Gao, J.; Li, A.; Xu, X.; Gang, W.; Yan, T. Ground heat exchangers: Applications, technology integration and potentials for zero energy buildings. *Renew. Energy* 2018, 128, 337–349. [CrossRef]

7. Rabczak, S.; Proszek-Miaśik, D. The impact of selected heat pumps on CO2 emissions. In Proceedings of the VI International Conference of Science and Technology INFRAEKO 2018 Modern Cities. Infrastructure and Environment, Cracow, Poland, 7–8 June 2018; Volume 8, pp. 1–8.

8. Gan, G. Dynamic thermal simulation of horizontal ground heat exchangers for renewable heating and ventilation of buildings. *Renew. Energy* 2017, 103, 361–371. [CrossRef]

9. Nabi, M.; Al-Khoury, R. An efficient finite volume model for shallow geothermal systems—Part i: Model formulation. *Comput. Geosci.* 2012, 49, 290–296. [CrossRef]

10. Eicker, U.; Vorschulze, C. Potential of geothermal heat exchangers for office building climatisation. *Renew. Energy* 2009, 34, 1126–1133. [CrossRef]

11. Florides, G.; Kalogirou, S. Ground heat exchangers—A review of systems, models and applications. *Renew. Energy* 2007, 32, 2461–2478. [CrossRef]

12. Hassan El-abdalall, A.; Abdullah Al-dakheel, S.; Abdulhadi Al-Abkari, H. Impact of Air-Conditioning Filters on Microbial Growth and Indoor Air Pollution. *Energy-Efficient and Sustainable Buildings*. 2019, pp. 1–27. Available online: https://www.intechopen.com/online-first/impact-of-air-conditioning-filters-on-microbial-growth-and-indoor-air-pollution (accessed on 2 May 2020).

13. Farnsworth, J.E.; Goyal, S.M.; Won Kim, S.; Kuehn, T.H.; Raynor, P.C.; Ramakrishnan, M.A.; Anantharaman, S.; Tang, W. Development of a method for bacteria and virus recovery from heating, ventilation, and air conditioning (HVAC) filters. *J. Environ. Monit.* 2006, 8, 1006–1013. [CrossRef] [PubMed]

14. Feigley, C.; Khan, J.; Salzberg, D.; Hussey, J.; Attaway, H.; Steed, L.; Schmidt, M.; Michels, H. Experimental tests of copper components in ventilation systems for microbial control. *HVAC&R Res.* 2013, 19, 53–62.

15. de Robles, D.; Kramer, S.W. Improving indoor air quality through the use of ultraviolet technology in commercial buildings. *Procedia Eng.* 2017, 196, 888–894. [CrossRef]

16. Bolashikov, Z.D.; Melikov, A.K. Methods for air cleaning and protection of building occupants from airborne pathogens. *Build. Environ.* 2009, 44, 1378–1385. [CrossRef] [PubMed]

17. Demir, H.; Koyun, A.; Temir, G. Heat transfer of 27 horizontal parallel pipe ground heat exchanger and experimental verification. *Appl. Therm. Eng.* 2009, 29, 224–233. [CrossRef]

18. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products (Recast) (Text with EEA Relevance). Available online: eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02009L0125-20121204 (accessed on 2 May 2020).

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).