Application of ground-to-air heat exchanger for preheating of supply air

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Abstract. This study focuses on assessing the contribution of the passive ground-coupled air heat exchanger system to decreasing the energy consumption of air conditioning and ventilation systems for office buildings in the Latvian climate conditions. The theoretical part of the thesis deals with methods of office building ventilation, supply air preheating and heat recovery as well as particularities of using ground-coupled air heat exchangers, their design parameters and their joint impact on the thermal performance. The engineering project part includes a ventilation system for an office building with an integrated ground-coupled air heat exchanger. By simulating energy consumption of the ventilation system for a duration of one year, the thesis analyzes the contribution of the heat exchanger to the overall energy consumption, which totals 9.53 MWh and 4.02 MWh a year, according to the desired parameters of the indoor climate. The possible alternative heat recovery solutions are investigated to reach by European Regional Development Fund projectNr.1.1.1.1/16/A/048 “NEARLY ZERO ENERGY SOLUTIONS FOR UNCLASSIFIED BUILDINGS”.

1. Introduction

Building ventilation and air conditioning systems consume a big part of total energy consumed by building mainly for heating ambient air in winter and cooling it in summer. Therefore integration of different passive systems can make a significant contribution in reducing building energy consumption.

Most of the passive systems use solar energy in direct or indirect way. Directly it is used in the production of electricity and heat energy. Other types of passive systems are based on the heat recovery and preheating of incoming air. Interesting and promising technology is the use of ground-air heat exchanger. It is based on the heat exchange between the air and the pipes buried in the ground, which has a high heat capacity. At certain depth the ground temperature is lower than outside air temperature in summer, and higher than in winter. In such ground-to-air heat exchanger indirectly uses solar energy to preheat the incoming air in winter and cool it in the summer.

In order to make precise evaluation of such heat exchangers the non-stationary heat transfer should be taken into account [1-7].

The aim of this paper is to evaluate an investment of using ground-to-air heat exchanger in reduction of energy consumption for office building heating and air conditioning systems in Latvian climatic conditions. The efficiency and calculation methodology of ground-to-air heat was already proved in late 90ies by [1,8]. However there are several studies on updated calculation models [4,5]. For example study [3] shows heat exchanger of 200mm in diameter with length of 40 m insure supply air temperature close to soil temperature.
2. Materials and methods

While choosing an appropriate design of the ground-to-air heat exchanger, it is necessary to define the desired requirements. First of all it is necessary to determine building air change rate. Secondly, it is important to determine the required temperature of outgoing air from heat exchanger. For example, in cold weather, the air temperature should be higher than the freezing point to prevent icing of the ventilation heat recovery unit. And at last, depending on the intended primary task, the exhaust air from heat exchanger should partially or fully cover the required cooling capacity of the building.

The above mentioned results in the following design parameters: V - building the necessary amount of air, Tg, outdoor - outdoor temperature, nTg, outgoing - desired outgoing air temperature, Tsoil - soil temperature.

Ground-to-air heat exchanger geometric parameters are defined primarily depending on the space available. It depends on the location of the building, building design and dimensions as well as economic factors affecting the choice of the length and amount of the tubes. It is therefore very important to have possibility to estimate effect of these parameters on the overall performance of the heat exchanger. Ground-to-air heat exchanger geometric parameters are: D - diameter of the pipe inserted into the ground; L - length of pipe placed in the ground; n - number of tubes placed in parallel.

The interaction of ground-to-air heat exchanger with the surrounding soil is shown in Figure 1.

![Figure 1. The interaction of ground-to-air heat exchanger with the surrounding soil](image)

A long tube with a small diameter is more effective from point of view of heat transfer, which in turn creates bigger pressure losses, leading to bigger fan power to overcome this loss.

The pressure loss is reduced by selecting a larger pipe diameter and smaller air flow in each pipe. From this point of view, a bigger number of pipes with larger diameter is a more effective solution. However, this is contrary to efficient heat transfer, which is provided using bigger number of small diameter pipes. In both cases, a bigger number of parallel tubes has a positive impact on both, the hydraulic and thermal performance. The most efficient solution is an optimization problem for finding optimal combination between pipe length and diameter.

Although there are various software programs available on the ground-to-air heat exchanger calculations, many systems do not provide the expected performance as the result of improper construction or design choice. To select the most efficient design parameters of the ground-to-air heat exchanger design at an early stage, it is convenient to use thermo-hydraulic ground-to-air heat exchanger design development method developed by M. De Paepe [2]. It is based on an analytical one-dimensional model that allows to estimate the influence of ground-to-air heat exchanger design parameters on overall thermal and hydraulic performance. A relation is derived for the specific pressure drop J, linking thermal effectiveness with pressure drop inside the pipes. The resulting ratio is used to define a design method,
which can be used for determining the characteristic dimensions of ground-to-air heat exchanger in such way, that optimal thermal effectiveness with acceptable pressure loss is achieved.

The relationship between the specific pressure drop $J$ and volume $V$ of air flowing through the tube is expressed in the equation:

$$J = 0.258 \frac{c_{p,\text{air}} \rho_{\text{air}}^2 \xi}{\lambda_{\text{air}} N_u D^5} V^3$$  \hspace{1cm} (1)

$c_{p,\text{air}}$ - air heat capacity J/(kg*K); $\rho_{\text{air}}$ - air density, kg/m$^3$; $\xi$ - coefficient of friction, which depends on the duct inner surface roughness and air movement mode, f (Re); $V$ - air flow, m$^3$/s; $\lambda_{\text{air}}$ - air heat transfer coefficient, W/(m*K); $N_u$ - Nusselt number; $D$ - diameter of the pipe, m.

This ratio for different tube diameters is shown Figure 1 (on the right), where the two axes are log (base 10).

The relationship between pipe length $L$ and $J$ - specific head loss equation is expressed in the following equation [2]:

$$L = -\ln(1 - \varepsilon) \left[ \frac{c_{p,\text{air}} \rho_{\text{air}} D^5}{8 \lambda_{\text{air}} \xi N_u^2} \right]^{1/3} \left[ \frac{J}{J} \right]^{1/3}$$  \hspace{1cm} (2)

$c_{p,\text{air}}$ - air heat capacity J/(kg*K); $\rho_{\text{air}}$ - air density, kg/m$^3$; $D$ - diameter of the pipe, m; $J$ - specific pressure drop, Pa; $\lambda_{\text{air}}$ - air heat transfer coefficient, W/m*K; $\xi$ - coefficient of friction, which depends on the duct inner surface roughness and air movement mode, f (Re); $N_u$ - Nusselt number

This ratio for different tube diameters is shown in Figure 2 (on the left), where the x-axis is log (base 10).

**Figure 2.** Chart for dimensioning and choosing ground-to-air heat exchanger design (with an efficiency of 80%)

Ventilation is an air exchange process by which the premises are supplied with fresh air and excess secretions are removed.

If the air circulation and exchange of air in the system is the driven by difference in internal and external air temperature (density) or occurs as a result of wind pressure, it is called a natural ventilation. Air pressure in natural ventilation system channels is small and working range is limited.

Therefore, especially in larger objects, mechanical ventilation systems, in which air is propelled through a duct fan, are widely used. The system output can be controlled. Hybrid ventilation systems combine properties of mechanical and natural ventilation systems. The main idea is to combine these systems in such way that it allows to use the best qualities of these two systems and to overcome the problems associated with the use of natural ventilation itself. A way of combining these systems is determined by the required quantity of air supply as well as the outside air and climate parameters. Reducing energy consumption for heating and cooling air can best be achieved by using heat recovery, which is very important in Latvian climatic conditions. Mechanical ventilation system enables to regulate the flow as a function of consumption and maintain the required flow of air at a variable pressure.
drop, which is important in the heat recovery. Recuperation system efficiency can be increased by combining it with a variety of passive preheating and/or precooling systems. Therefore a low-pressure mechanical ventilation system using hybrid ventilation components was chosen to be the most suitable for integrating ground-to-air heat exchanger. Different categories of indoor air quality can be applied to non-residential buildings, thus affecting the amount of ventilation required. The amount is derived from the design documentation, according to the national standards, or by using any of the methods recommended in standard LVS/EN 15251 B.1. A constant internal air quality in ventilation systems is maintained regardless of the outdoor temperature. Therefore, it is important to know the meteorological parameters of outside air. Ventilation calculations are based on estimation of the external air parameters according to local building rules and regulations.

3. Results

Using a graphical design tool described, necessary design parameters for three different tube diameters were defined. The maximum pressure loss in pipes was set at 25 Pa. Air speed in tubes was defined as an additional design parameter and thus number of parallel tubes was adjusted so the maximum air speed is below 3 m/s. The necessary amount of air change for the building was estimated to be 9950 m³/h for a typical three storey office building according to LVS/EN 15251 indoor environment class B. Three design variations with similar performance were selected and summarized in Table 1.

| D, mm | Number of tubes | Air flow in one tube, m³/h | Length of one tube L, m | Pressure loss Δp, Pa | Inner pipe surface area, m² |
|---|---|---|---|---|---|
| 315 | 14 | 711 | 48 | 18 | 615.7 |
| 400 | 9 | 1106 | 64 | 17 | 671.0 |
| 500 | 6 | 1658 | 83 | 15 | 727.2 |

Ground-to-air heat exchanger is placed next to the building under the parking area. Increasing the number of parallel pipes reduces the spacing between them. This in turn negatively affects soil temperature near the pipe and the interaction between them increases, which reduces the heat exchange between the air and the ground.

The larger tube diameter provides greater flow rate in each tube, keeping the air speed in 3 m/s range. A smaller number of parallel tubes increase the distance between pipes and reduce their interaction. In third variation tube length is too large for the available area. Therefore two more modifications were offered: keep the chosen length of the tubes by adding a turn (modification 1) or to reduce the length of parallel tubes to the available space (modification 2).

Theoretical maximum amount of energy exchanged between the air and the ground was obtained using ground-to-air heat exchanger simulation program GAEA [1]. Results for each of variations are shown in Table 2.

| Variation | Energy gain for pre-heating air MWh a year | Energy gain for cooling MWh a year |
|---|---|---|
| Variation 2 | 22.00 | 1.03 |
| Variation 3 | 24.47 | 1.14 |
| 3. variation with 1. modification | 23.88 | 1.07 |
| 3. variation with 2. modification | 24.00 | 1.10 |

Since the placement of the heat exchanger area is limited, and the modifications of third variation does not provide the desired results, it was chosen to use the second design variation.
Feeding cool air from the ground-to-air heat exchanger when the building needs air conditioning, can give an additional energy savings for the building air conditioning system. To evaluate cooling gain, the calculation were made for the hours in which all the following conditions are met:

1) The air temperature coming from the ground-to-air heat exchanger is higher than 17 °C;
2) The air temperature coming from the ground-to-air heat exchanger is lower than outside air temperature;
3) The facilities require operation of conditioning system.

Total energy savings are shown in Table 3. It shows theoretical maximum net energy gain during the year. However, ventilation system is designed not to operate at full power when office space is not used (during non-working hours ventilation system allows air exchange of 0.1 h\(^{-1}\)). Thus energy gain evaluation is made using required air volumes for office building in accordance with the load schedule.

| Parameters | Process                                      | Heating | Cooling (outside air precooling + additional reduction of conditioning system operation) |
|------------|----------------------------------------------|---------|----------------------------------------------------------------------------------|
| Total energy consumption in MWh/year             | 85.85  | 35.8                               |
| Gain from ground-to-air heat exchanger, MWh/year | 9.53   | 4.02                               |
| Gain from ground-to-air heat exchanger, % from total | 11.1  | 11.2                               |
| Additional electrical power consumption of using ground-to-air heat exchanger, MWh/year | 1.41  | 0.12                               |

4. Discussion
Due to the rising energy prices, it is important to ensure that sustaining indoor climate consumes less energy. Ventilation system power consumption consists of two main elements - moving air in the air ducts and air heating / cooling to the desired indoor climate temperature. Reduction in energy consumption for heating and cooling air can best be achieved by using heat recovery, which is very important in Latvian climatic conditions. Mechanical ventilation system enables to regulate the flow as a function of consumption and maintain the required flow of air at a variable pressure drop, which is important for the heat recovery. Recuperation system efficiency can be increased by combining it with a variety of passive preheating and / or cooling systems.

Heat exchanger simple structure and operating principle has potentially positive impact on its use. Although the ground-to-air heat exchanger design is simple, its geometric parameters interact strongly affecting the thermal performance. It is therefore very important to have possibility to estimate effect of this parameter interaction on the overall performance of the heat exchanger. The use of graphical ground-to-air heat exchanger design tool makes designing process understandable and simple. It provides great opportunities for designers and architects for use in the early building design stage. Such simple techniques can positively influence the use of passive systems for future projects.

However, the method has some disadvantages. For example, it does not allow to assess the effect on heat transfer between parallel tubes located near to each other as well as the impact of deployment depth due to the pipe construction inclination for condensate removal. While choosing the most effective design parameter variations, it is important to assess the impacts and take into account the possibilities to take the necessary measures (slope providing condensate removal, air intake location, etc.) for ensuring high air quality in order to achieve the best energy gain estimation.

Ground-to-air heat exchanger performance calculation uses office building air consumption schedule that enables to evaluate the theoretical maximum useful energy gain from using this system. Such calculations are the closest to the actual situation, and if necessary, allow an accurate assessment of the economic aspects of using ground-to-air heat exchanger.
5. Conclusions
There are different types of passive systems, but the possible gain from some systems can be very difficult to calculate, and not all systems are suitable for Latvian climate characteristics. Ground temperature has a low fluctuations under varying weather, which is important for ensuring the necessary level of comfort in times when external conditions do not allow the operation of other passive systems.

By simulating energy consumption of the ventilation system for a duration of one year, the contribution of ground-to-air heat exchanger to the overall energy consumption totals 9.53 MWh (11.1% of total energy consumption for the heating of supply air) and 4.02 MWh (11.2% of total energy consumption for the cooling of supply air) a year, according to the desired parameters of the indoor climate. Also it was calculated that the hours with incoming air temperature ≤ -4 °C into the air handling unit (AHU) reduced from 1131 to 630 hours a year. Therefore recuperation efficiency is increased as there is lower risk of freezing and less hours for defrosting of AHU heat exchanger are needed.

For practical application of earth air heat exchanger, it is important to estimate the additional power consumption and the construction costs compared to the potential energy gain. It is also important to consider integration possibilities into the overall building ventilation system.

However, continuously rising energy costs, a variety of passive energy-saving systems become more demanded. This makes the ground-to-air heat exchanger technology more attractive. Also it should be mentioned that such heat exchanger could be more efficient in combination with passive house or low energy building concept [6].

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