Residential Ground Source Heat Pump Systems Utilizing Foundation Heat Exchangers

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SUMMARY

Foundation heat exchangers (FHX) are an alternative to more costly ground heat exchangers utilized in ground-source heat pump (GSHP) systems serving detached or semi-detached houses. Although the GSHP system is a commonly used sustainable heating-only or heating and cooling system, the initial cost is often a barrier to implementation. Full-scale testing by Oak Ridge National Laboratory [1] demonstrated that an FHX-based GSHP system is feasible for a specific house in one climate. However, additional work is needed to establish combinations of building configuration and construction, climate, soil properties, etc. that allow the FHX to replace a conventional ground heat exchanger. This paper covers a parametric study of FHX-based GSHP systems for several house configurations in a range of European locations, with an emphasis on determining feasible combinations.

INTRODUCTION

Ground-source heat pump (GSHP) systems are perhaps the most widely used “sustainable” heating and cooling systems, with an estimated 1.7 million installed units with total installed heating capacity on the order of 18 GW. They are widely used in residential, commercial, and institutional buildings. While highly efficient, the main disadvantage of these systems is the higher first cost associated with drilling boreholes for vertical ground heat exchangers or excavation required to install horizontal ground heat exchangers.

In general, the length of the ground heat exchanger tubing and the first cost depend on both the total annual heating and cooling loads and the distribution of loads over the year, as well as other factors such as the thermal properties of the ground, the undisturbed ground temperature and the ground heat exchanger design.

In the case of net zero energy homes or homes approaching net zero energy, the greatly reduced heating and cooling loads, compared to conventional construction, give the possibility of using a ground heat exchanger that is significantly reduced in size. Specifically, in this paper, we describe foundation heat exchangers (FHX) that are placed within the excavation made for the basement and foundation along with other excavations used for utility trenching. Figure 1 shows an installation in the basement excavation and the extension into a utility trench. Figure 2 shows an idealized representation that is the basis for the numerical model. By eliminating the need for separate excavation or drilling, the installation cost can be significantly reduced. For houses that do not have basements, such an approach might be possible if trenching for drainage around the house were used, as suggested [2] recently.

a)   b)

Figure 1. FHX. a) in basement excavation, b) extended into utility trench.

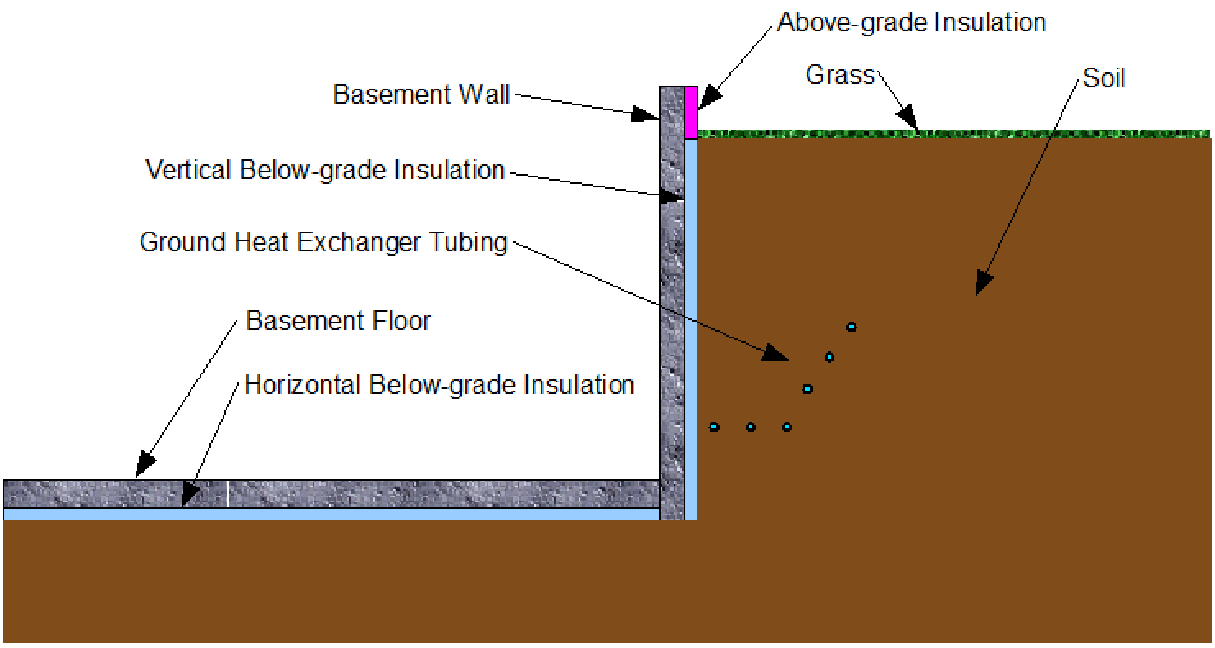

Figure 2. Cross-section of foundation, foundation insulation and foundation heat exchanger.

METHODS

In order to investigate the range of FHX applicability, a small-scale parametric study was performed. This study involved the following aspects which are described below:

1. Development of heating and (in some locations) cooling loads for single-story and two-story houses for ten different locations in Europe. Two different insulation levels were considered.
2. Simulation of foundation heat exchangers for the above cases.
3. Where the entering fluid temperature from the foundation heat exchanger exceeds design limits, simulations of auxiliary horizontal ground heat exchangers that could be placed in utility trenches are performed to determine the required length of auxiliary horizontal ground heat exchangers.
4. One concern about foundation heat exchangers is the possibility of short-circuiting – that is increasing the building heating load by decreasing the earth temperature surrounding the basement. So, the effect of the FHX on the basement is examined.

Heating and Cooling Loads for Prototypical Houses

Ten locations were chosen to give a geographically-diverse set. A recent update of the Köppen-Geiger climate classification scheme [3] was consulted. The ten locations are summarized in Table 1. For two of the climate zones (Cfb and Csa) two locations were chosen to increase the geographical diversity.

Table 1. Selected Locations and Corresponding Climates

Climate Zone	Location	Climate Zone	Location
BSk (Mid-latitude steppe)	Madrid, Spain	Csa (Interior Mediterranean)	Marseille, France
Cfa (Humid subtropical)	Milan, Italy		Athens, Greece
Cfb (Marine/warm summer)	London, UK	Csb (Coastal Mediterranean)	Porto, Portugal
	Frankfurt, Germany	Dfb (Humid continental)	Stockholm, Sweden
Cfc (Marine/cool summer)	Reykjavik, Iceland	Dfc (Subarctic)	Tampere, Finland

Several versions of a prototypical house were used to generate hourly heating and cooling loads for the above locations using the EnergyPlus [4] program. Two configurations – single story and two-story – and two insulation levels – "Very high insulation" (VHI) and "high insulation" (HI) are used. All versions of the house have 148 m^2 floor area and are constructed from structural insulated panels. All versions of the house have windows with a U-factor of 1.8 W/m^2K and SHGC of 0.36 covering 29% of the north and south facades and 3% of the east and west facades. All versions of the house have combined lighting and casual gains of 8.2 W/m^2 and constant infiltration rates of 0.5 ACH. The single story house has a length-to-width ratio of 1.56; the two-story house has a square footprint. The VHI house has U_{wall}=0.20 and U_{roof}=0.13 W/m^2K. The HI house has U_{wall}=0.25 and U_{roof}=0.16 W/m^2K. For purposes of this study, the basements are assumed to be conditioned and have negligible interaction with the above-ground portion of the building.

Simulation of Foundation Heat Exchangers and Horizontal Ground Heat Exchangers

The foundation heat exchanger is modeled using an explicit two-dimensional finite difference model implemented in the HVACSIM+ simulation environment. The model takes entering fluid temperature as an input and determines the average and exiting fluid temperatures. The non-uniform grid with ~7000 cells shown in Figure 3 is used to model the domain, which is 5 m in depth and which extends 4 m to the right of the basement wall and to the center of the building. Initial conditions and the lower boundary condition is set with the Kusuda and Achenbach [5] model. The vertical boundaries in the soil portion of the domain are assumed adiabatic – on the left hand side, this is due to symmetry; on the right hand side, the size of the domain was set so as to have negligible influence by the right hand boundary.

The model treats heat conduction throughout the soil, foundation insulation and the foundation. Moisture transport is not explicitly modeled, but the top surface shown as "grass" in Figure 2 utilizes a full energy balance, including evapotranspiration, solar radiation, convection, thermal radiation and conduction. The evapotranspiration sub-model [6] assumes standard surface vegetation – grass of uniform 12 cm height with a "moderately dry" soil surface.

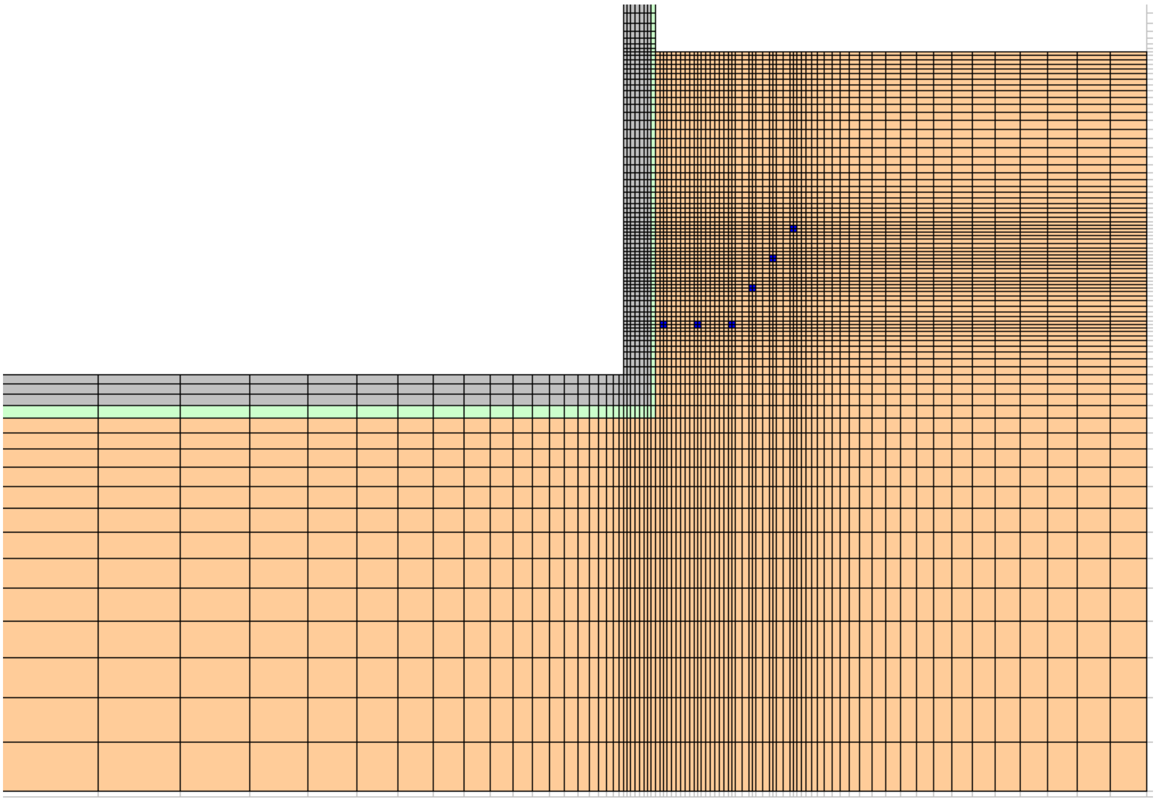
Figure 3. Non-uniform grid.

The inside basement wall and basement floor boundaries are convective, exchanging heat with the basement, which is assumed to be held at a constant temperature. An unconditioned basement can be readily modeled, but for purposes of quantifying short-circuiting type heat transfer, it is convenient to hold the basement air temperature constant so that heat transfer rates can be compared rather than basement air temperatures.

Experimental validation of the model is an ongoing activity. To date, the short-term response of the model to heat input and extraction to/from the tubing has been validated against an analytical solution. The one-dimensional undisturbed temperature response has been validated against sub-surface measurements made at weather stations in Oklahoma. The grid size and the extent of the soil domain have both been chosen to give both grid-independence and domain-size-independence.

Known limitations of the model are associated with un-modeled phenomena: saturated and unsaturated moisture transport, snow accumulation and melting, and freezing of soil.

A very similar model for horizontal ground heat exchangers (HGHX) that may be placed in utility trenches has also been developed. The model is essentially identical, except that there is no basement wall present and, for this study, the HGHX is assumed to consist of six tubes, with pairs of tubes spaced 0.3 m apart at depths of 1.4 m, 1.75 m, and 2.0 m.

For this study, a single set of typical ground thermal properties are assumed – a thermal conductivity of 1.3 W/mK, density of 962 kg/m^3, and specific heat of 2.1 kJ/kgK. The basement walls and floor are covered with insulation that has thermal resistance value of 2.26 m^{2}K/W.

Simulation-based Design of Auxiliary Horizontal Ground Heat Exchangers

The component models of the FHX and HGHX are combined with a heat pump model that takes hourly heating and cooling loads and entering fluid temperature as inputs and which returns exiting fluid temperature and heat pump power consumption. The heat pump model is based on equation fits of manufacturer's data – a commercially available water-to-water heat pump is used for the heating-only locations (Tampere, Stockholm, Reykjavik, London, Frankfurt) and a commercially available water-to-air heat pump is used for the other locations, where cooling may be utilized.

The first question to be answered is whether or not an FHX that surrounds the building perimeter is capable of operating for multiple years without exceeding the design limits for the heat pump entering fluid temperature. This is done by simulating the system without the auxiliary HGHX. If the design temperature limits are exceeded, a system with the full FHX and an auxiliary HGHX is simulated multiple times, iteratively adjusting the length of the auxiliary HGHX.

Analysis of Basement Short-Circuiting Heat Transfer

One concern with the foundation heat exchanger is the possibility of what might be called short-circuiting heat transfer, e.g. where the FHX is extracting heat from the basement, driving up the heating load. In order to try to understand this phenomenon, the basement air temperature is held constant in these simulations so that the heating load with and without an FHX can be compared. The difference between the two results is a first-order estimate of the short-circuiting heat transfer.

RESULTS

For the initial phase of the study, all four variations of the building were simulated with a foundation heat exchanger completely encircling the building but with no auxiliary horizontal ground heat exchanger. Table 2 summarizes the results "1S" and "2S" refer to the single-story and two-story variations, respectively. "VHI" and "HI" refer to the very-high and high insulation levels, respectively. The water-to-water heat pump has a manufacturer-recommended minimum entering fluid temperature (EFT) of -6ºC; the water-to-air heat pump has a recommended minimum EFT of -1ºC and a maximum EFT of 45ºC. EFT that exceed these limits are printed in bold. In no case is the maximum EFT exceeded. Minimum EFTs are exceeded for some building variations in Tampere, Stockholm and Reykjavik.

In all locations and insulation levels, the two-story building has a higher annual variation than the single-story building, due to its smaller perimeter with similar loads leading to higher heat extraction/rejection rates per unit length of the FHX. Likewise, the higher loads of the high insulation level buildings compared to the very-high insulation level buildings lead to higher heat extraction/rejection rates and higher annual variations in EFT.

Looking then at the cases where design EFT limits are exceeded, the required length of the horizontal ground heat exchanger may be determined by iteratively adjusting length of the HGHX until the design minimum EFT limit is reached but not exceeded. (To be clear here – the HGHX length is that of the trench, not the length of the tubing. Six meters of tubing would be needed for every meter of trench.)

Table 2. Summary of results without auxiliary horizontal ground heat exchangers

Location	Minimum Entering Fluid Temperature (°C)				Maximum Entering Fluid Temperature (°C)			
	1S, VHI	2S, VHI	1S, HI	2S, HI	1S, VHI	2S, VHI	1S, HI	2S, HI
Madrid, Spain	6.8	4.7	6.2	4.3	23.6	26.2	23.9	36.0
Milan, Italy	7.6	3.7	6.6	1.7	27.3	28.7	27.5	35.2
London, UK	4.0	1.0	3.2	-0.5	17.6	17.6	17.6	17.6
Frankfurt, Germany	2.1	-1.3	1.3	-2.5	18.2	18.2	18.2	18.2
Reykjavik, Iceland	-2.2	-5.4	-3.0	**-7.5**	12.2	12.1	12.1	11.8
Marseille, France	7.8	5.8	7.1	4.7	24.1	32.5	24.4	33.1
Athens, Greece	11.5	9.5	11.0	9.6	28.0	30.6	28.4	39.3
Porto, Portugal	11.7	9.9	11.2	9.8	23.0	23.9	23.0	29.8
Stockholm, Sweden	-3.1	**-6.5**	-3.9	**-8.6**	15.7	15.6	15.6	15.6
Tampere, Finland	-5.3	**-9.9**	**-6.4**	**-11.1**	15.7	15.7	15.7	15.7

Table 3 Required auxiliary HGHX length (m)

Location	Required Auxiliary HGHX Length (m)			
	1S, VHI	2S,VHI	1S, HI	2S,HI
Reykjavik, Iceland	0	0	0	6.4
Stockholm, Sweden	0	2.1	0	12.0
Tampere, Finland	0	25.8	3.2	34.9

The required auxiliary HGHX length will depend on several factors, including the evolution over time of the required heat extraction and rejection rates per unit length, ground thermal properties, configuration of the HGHX, etc. However, as with other ground heat exchanger types, a critical parameter is the difference between the design heat pump entering fluid temperatures and the time-varying undisturbed ground temperatures. Furthermore, the heat pump manufacturer's recommended minimum EFT may not be a suitable choice of design condition. Possible reasons for choosing a higher EFT include the desire to avoid ice formation around the tubing and possible frost-heaving, provide adequate capacity, improved efficiency, and avoiding the use of antifreeze solutions.

Figure 4 illustrates the sensitivity of the required auxiliary HGHX length to the design minimum heat pump EFT for the two-story, high insulation level house at four different locations. All cases asymptotically approach a point of diminishing returns where increasing the length gives little improvement in increasing the minimum heat pump EFT. For Frankfurt, it might be possible to avoid the use of antifreeze with a long enough HGHX, although leaving a margin of safety in the design might require at least a weak antifreeze solution. We attempted to look at required auxiliary HGHX lengths to meet a design minimum heat pump EFT of -1ºC, but for Tampere, even lengths in excess of 300 m will not allow that condition to be met.

One other concern about foundation heat exchangers is the possibility of short-circuiting. In order to obtain a first-order estimate of the problem, the basement air temperature was fixed at 20ºC and the annual heating load was computed for the very-high insulation cases in locations with significant basement heating loads. The results for a below-grade insulation thermal resistance value of 2.26 m^2K/W are shown in Figure 5.

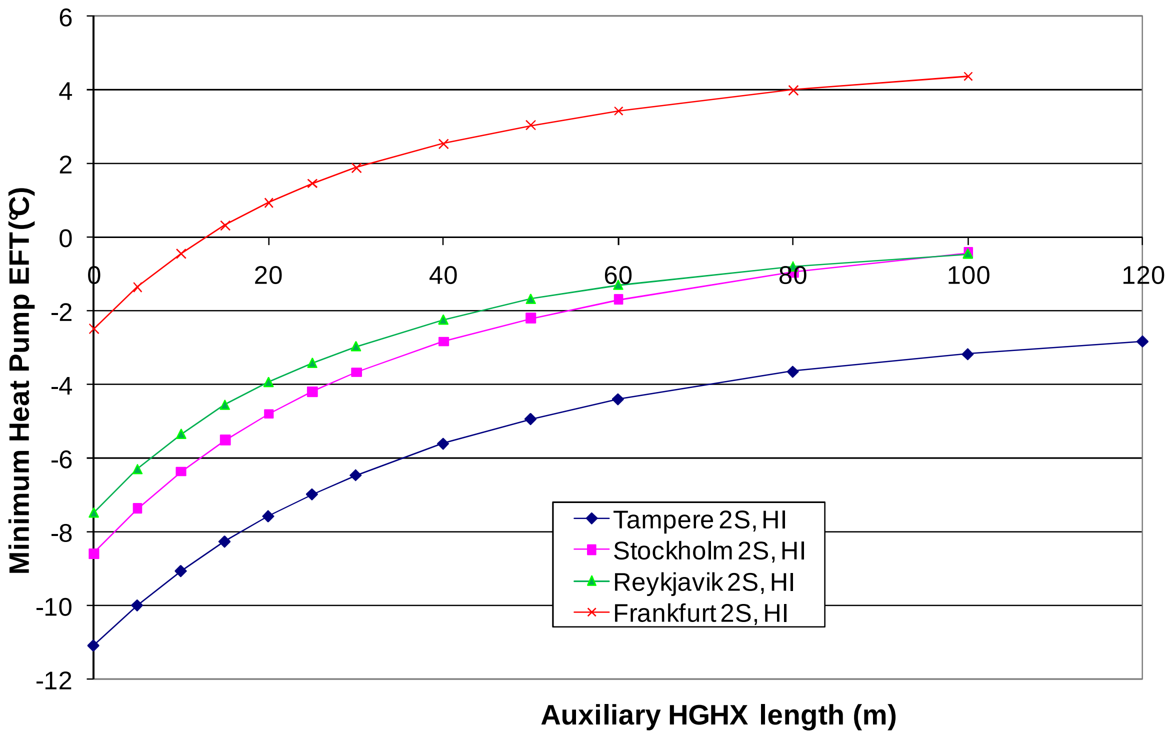

Figure 4. Effect of HGHX length on minimum heat pump EFT

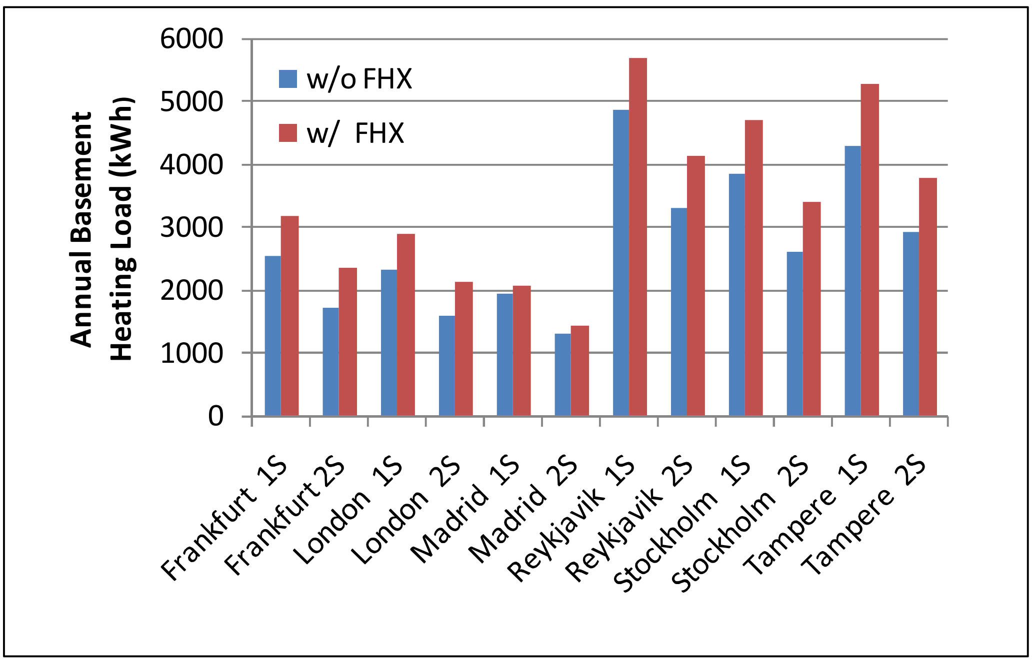

Figure 5. Basement Heating Loads

The short-circuiting effect might be approximated as the difference between the with-FHX and without-FHX annual basement heating loads. Several observations may be made – first, the basement heating loads are quite high compared to the house heating loads; the values shown in Figure 5 represent between 33% and 82% of the above-grade annual house heating load. The higher percentages are for the warmest climates, suggesting that, in practice, if the basement were not conditioned that the temperature would just remain lower than the 20ºC setpoint utilized in this study. However, for colder climates, even though the percentages are lower, the total heating load would be significant if the basement were conditioned. Likewise, the short-circuiting will be more severe for colder climates and is on the order of 12% of the above-grade house heating load. If the basement were to be conditioned, a higher insulation level and/or more spacing between the insulation and the piping would be desirable. A preliminary check of the sensitivity to insulation thickness showed that doubling the thermal resistance of the insulation reduced the basement heating load without an FHX by 36% and that with an FHX by 34%.

DISCUSSION

A preliminary investigation of the feasibility of using foundation heat exchangers in ground-source heat pump systems is reported above. As shown in Table 2, for detached houses sited such that the FHX can cover the entire perimeter, the FHX appears to be a suitable alternative to conventional ground heat exchangers used with residential ground-source heat pump systems for a remarkably wide range of climates. Using the heat pump manufacturer's design temperature limits, only houses in Tampere, Stockholm, and Reykjavik would require additional horizontal ground heat exchanger. These are also the three locations in the study where significant snowfall and snow coverage duration may have an important effect that is not included in the current model.

As is always the case with ground heat exchanger designs, the size is sensitive to the difference between the constraining design entering fluid temperature limit and the undisturbed ground temperature. This is shown in Figure 4, where the required length of an auxiliary heat exchanger increases as the minimum entering fluid temperature approaches the undisturbed ground temperature.

The possible problem of short-circuiting is partially analyzed here; a fuller investigation will require an integrated model of the house, basement, and foundation heat exchanger. At present, though, it appears that short-circuiting is most severe for the coldest climates.

ACKNOWLEDGEMENT

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