

Foundation Heat Exchanger Model and Design Tool Development and Validation

The attached document is the main body of the final report submitted to Oak Ridge National Laboratory. Many of the appendices (not included here) were either published papers or papers that were, in September of 2011, drafts of papers now published. A number of these papers are now available in the Publications section of our website, www.hvac.okstate.edu. If you have need of any of the appendices not available there, please contact Dr. Spitler (spitler@okstate.edu). As of January 2013, papers that are currently available include the following:

Lee, E.S., D.E. Fisher and J.D. Spitler. 2013. *Efficient Horizontal Ground Heat Exchanger Simulation with Zone Heat Balance Integration*. HVAC&R Research. In Press.
(DOI: 10.1080/10789669.2013.774887)

Fan, D., S. Rees, J. Spitler. 2013. *A dynamic thermal network approach to the modeling of Foundation Heat Exchangers*. Journal of Building Performance Simulation. 6(2): 81-97.

Xing, L., J.R. Cullin and J.D. Spitler. 2012. *Modeling of foundation heat exchangers — comparison of numerical and analytical approaches*. Building Simulation. 5(1):267-279.

Cullin, J. R., L. Xing, E. Lee, J. D. Spitler and D. E. Fisher. 2012. *Feasibility of foundation heat exchangers in ground source heat pump systems in the United States*. ASHRAE Transactions: 118(1):1039-1048.

Xing, L. J.R. Cullin, J.D. Spitler, D.E. Fisher, and P. Im. 2011. *Foundation Heat Exchangers for Residential Ground Source Heat Pump Systems - Numerical Modeling and Experimental Validation*. HVAC&R Research. 17(6):1059-1074.

Fan, D., S. J. Rees and J. D. Spitler. 2011. *Application of Dynamic Thermal Networks to the Modelling of Foundation Heat Exchangers*. Building Simulation 2011. Sydney, Australia, IBPSA.

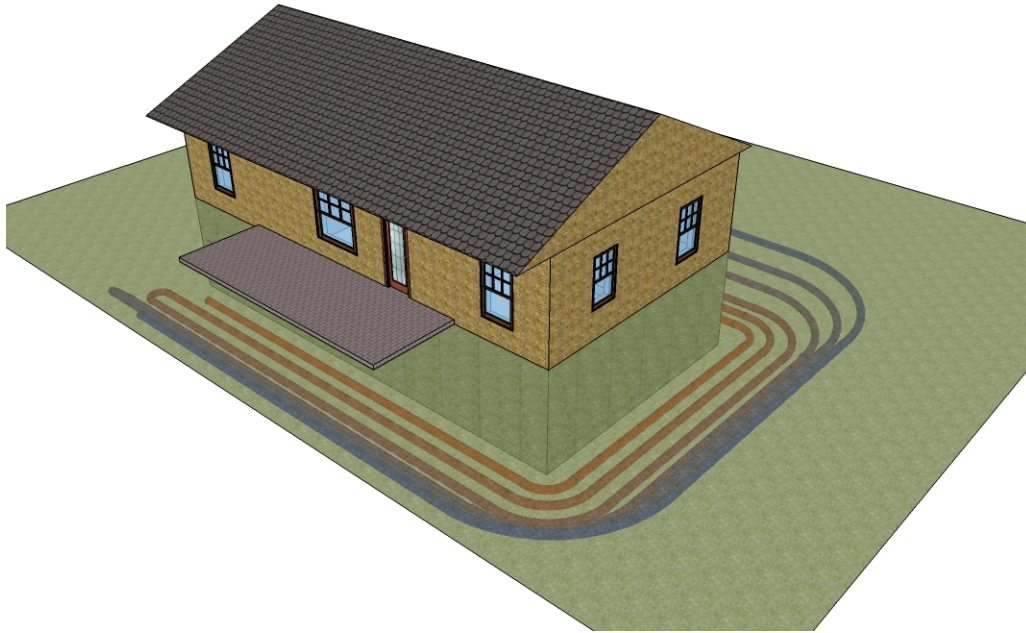
Xu, H. and J.D. Spitler. 2011. *Importance of moisture transport, snow cover and soil freezing to ground temperature predictions*. Proceedings of the Nordic Symposium on Building Physics. May 2011.

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Foundation Heat Exchanger Model and Design Tool Development and Validation



Final Report

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Executive Summary

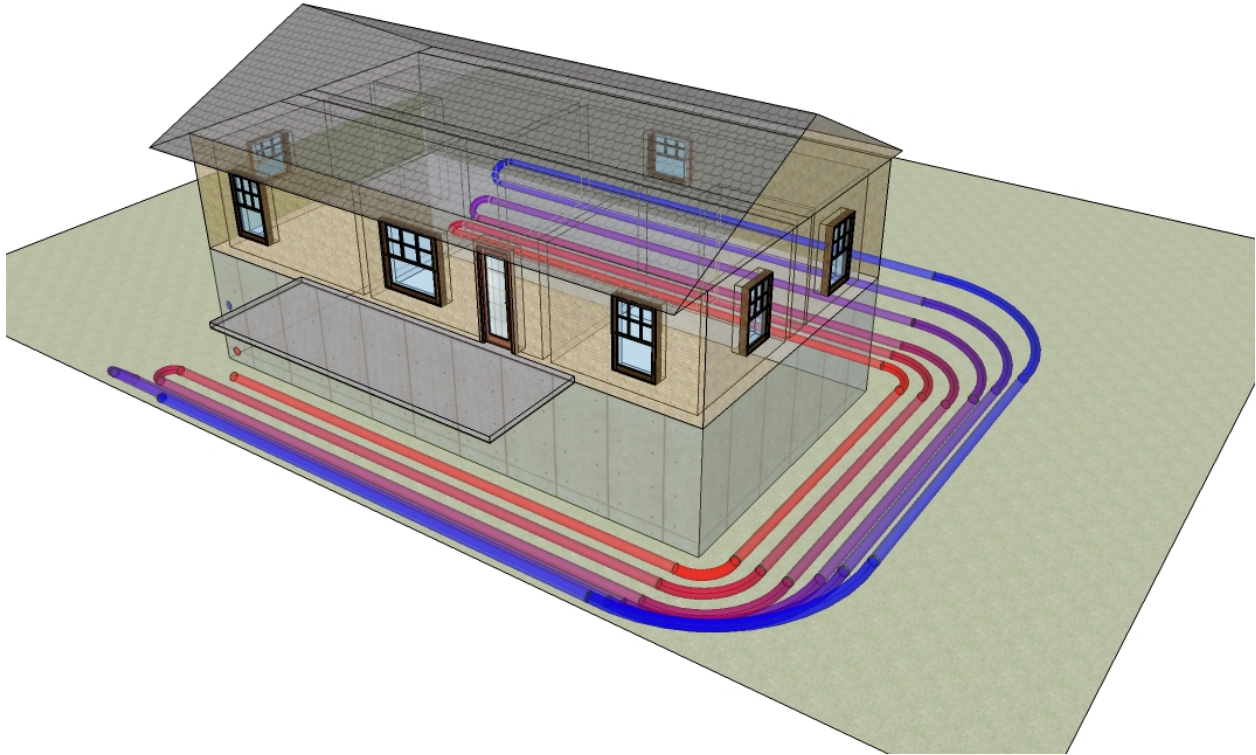


Figure 1 Foundation Heat Exchanger Concept

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. As shown conceptually in Figure 1, foundation heat exchangers (FHX) are placed within the excavation made for the basement and foundation. They may also be placed in the excavations used for utility trenching, as shown in Figure 2. 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 (Mueller 2009) recently.



Figure 2 FHX in a) basement excavation, b) extended into utility trench
(Courtesy: Piljae Im, ORNL)

This report describes a project aimed at developing validated models and design tools for foundation heat exchangers. The most important project results are summarized in this Executive Summary as follows.

- A detailed numerical model (Xing 2010; Xing et al. 2011) based on the finite difference method was developed. It was originally intended to utilize a coarse grid, yet as testing and validation went on, it became apparent that a finer grid, as shown in Figure 3 was needed. Although the model was really too slow for EnergyPlus implementation or use as a design tool, it was essential for determination of which phenomena needed to be modeled. The careful analysis required for experimental validation of the model also helped find problems in the experimental data acquisition and analysis that were then corrected. It was used in several parametric feasibility studies and in an investigation of the analytical solution. Although it was ultimately replaced by a more computationally efficient model implemented in EnergyPlus, it did serve as an extremely useful research tool.

This model was validated with one year of experimental data collected at an experimental house located near Oak Ridge, Tennessee. The model shows good agreement with the experimental data—heat pump entering fluid temperatures (EFTs) typically within 1 °C (1.8 °F)—with minor discrepancies due to approximations such as constant moisture content throughout the year, uniform evapotranspiration over the seasons, and lack of ground shading in the model. The model also predicts undisturbed ground temperature, pipe wall temperature and basement heat transfer reasonably well. Figure 4 plots the heat pump EFT, averaged over each day, for both the model and the experiment. There are discontinuities in both data sets; for the

experiment, this represents days in which the equipment was off, or for which the experimental data is missing (such as around days 10, 275, and 290). For the simulation, the pipe wall temperature is plotted when the system is off. Sample predictions of the temperature field are shown in Figure 5. This work is covered in a paper accepted for publication in the journal HVAC&R Research. (Xing et al. 2011)

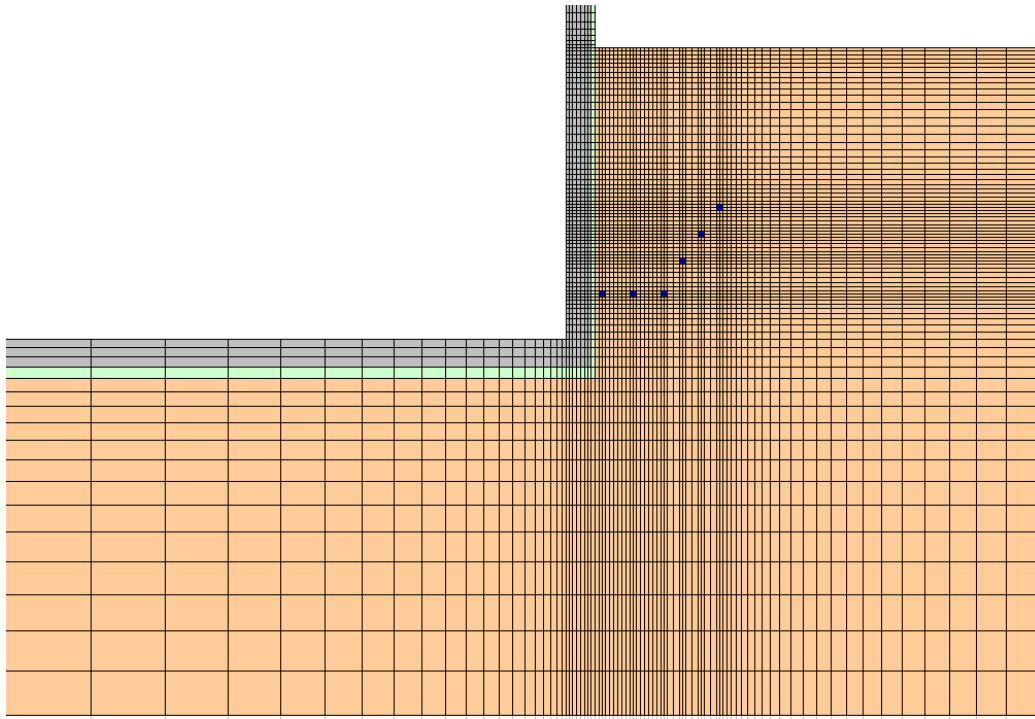


Figure 3 Actual grid used for two-dimensional finite difference model

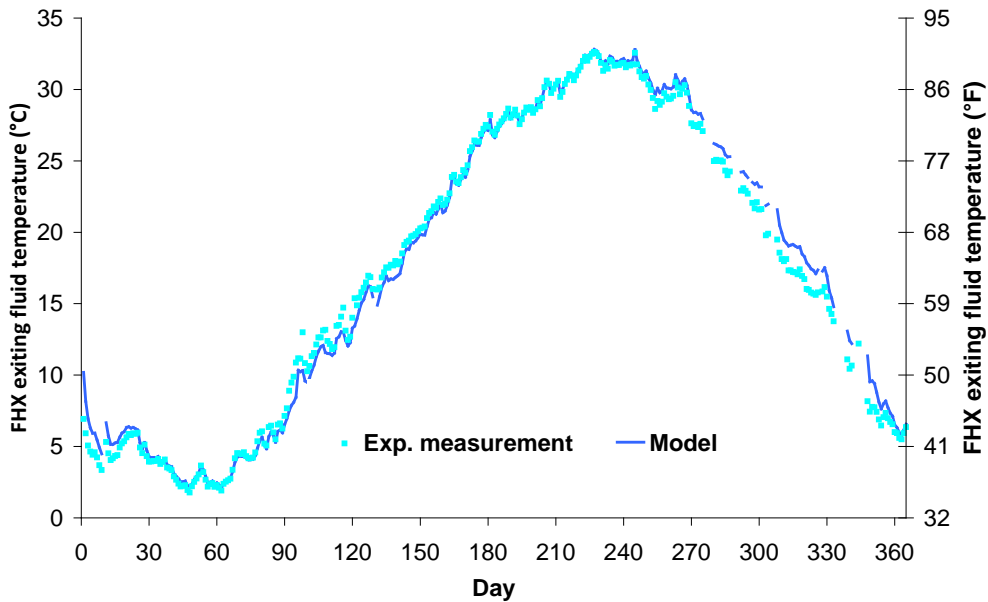


Figure 4 Validation of the Coarse Grid Model

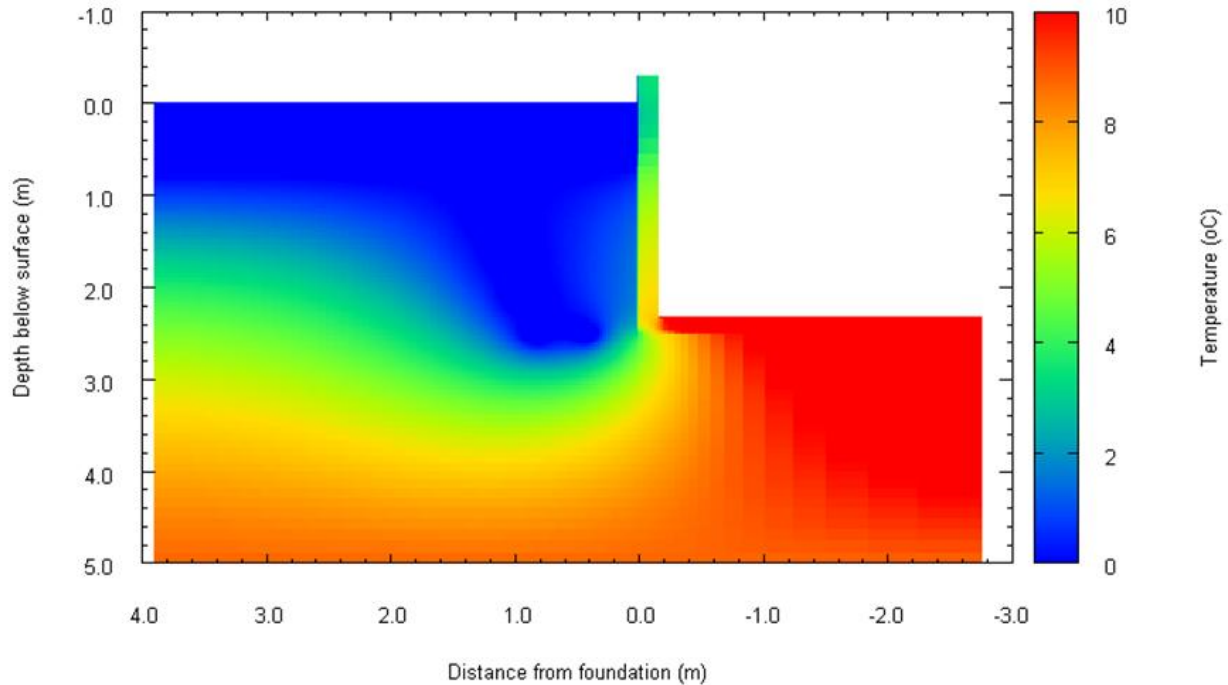


Figure 5 Temperature field surrounding basement for January 31 in Minneapolis

- A parametric study of GSHP systems using FHXs in Europe was performed for houses of both one and two stories with two different insulation levels in ten locations. The FHX for the single-story house with the higher insulation level produced heat pump EFTs that remained within the manufacturer's suggested limits, while systems in Reykjavík, Stockholm, and Tampere produced minimum EFTs below the design constraints. In all but one case in Tampere, an additional, reasonably-sized HGHX can be added onto the system to bring the minimum EFT up to a more desirable level. It should be noted that, for these simulations, freezing in the soil was not considered. This work was covered in a paper presented at the Clima 2010 conference. (Spitler et al. 2010)
- A detailed two and three-dimensional tool has been developed using a multi-block boundary fitted Finite Volume Method approach. This numerical method has been developed from that in the tool Gems2D previously used in a number of ground heat transfer projects (e.g. ASHRAE 1090-RP and 1119-RP). Rather than develop two tools – one being 2D and the other 3D – a single tool has been developed from the research tool Gems3D. This has ultimately been incorporated into a second EnergyPlus model (Rees 2011) that allows 3D representation of FHX.

The research tool Gems3D has been validated firstly (De Montfort University 2009) by application of the ground-coupling test cases developed for testing such software by IEA Annex 43. A second research tool has been developed as an intermediate stage between the Gems3D tool and the EnergyPlus model. Making annual simulations using 3D models is extremely challenging and so significant effort has gone into optimizing the speed of calculation. A speed

up of an order of magnitude has been achieved by a combination of measures (see progress report 8/11). Validation has been carried out with respect to one year of experimental data much as the two-dimensional model discussed above (Figures 3 and 4). An example of the model geometry and temperature field is shown in Figure 6. Model validation has been reported by Rees and Fan (2011). The model is able to reproduce the experimental temperature response and heat transfer rates satisfactorily. The validation exercise has also highlighted that there are some parameters relating to ground surface and environmental conditions that are relatively uncertain but nevertheless have an important affect on the validation results.

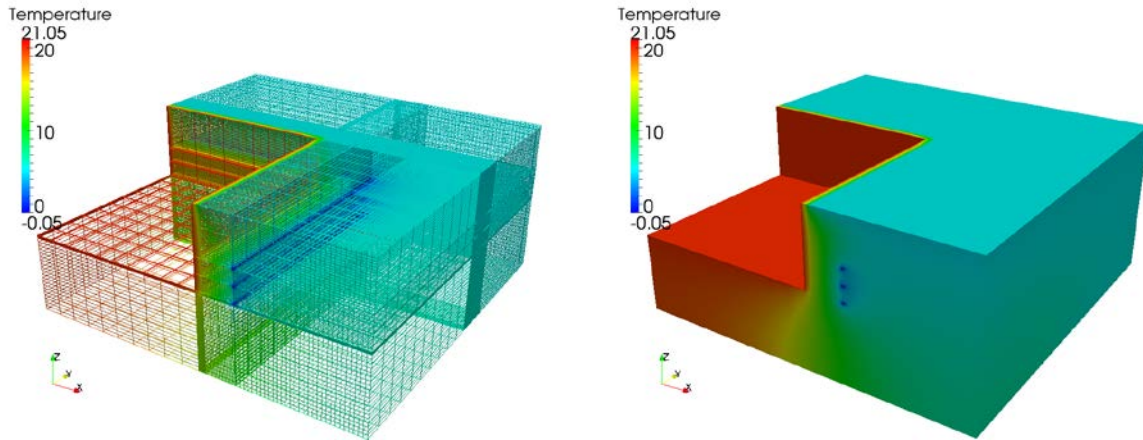


Figure 6. An example Three-dimensional model mesh and results for an outside corner FHX segment.

- Effective application of a three-dimensional numerical model depends on being able to generate meshes efficiently. This is particularly important in an energy simulation or design tool where minimum user interaction in the mesh building process is desired. Considerable effort has gone into development of a parametric meshing tool for a combination of FHX geometries. This allows generation of a wide range of mesh types automatically from a small number of FHX dimensions. This tool has more than one application in this project. Meshes generated using these algorithms have been used in the research numerical tool, Dynamic Thermal Network calculations (see below) and are also incorporated into EnergyPlus. It is possible to generate meshes representing FHX pipes parallel to the building, at an outside corner and also at an inside corner. Combining these meshes in a number of FHX model instances that are coupled together allows flexible representation of a variety of building floor plans and FHX layout. A combination of meshes/models is illustrated in Figure 7. This work is covered in an attached report. (Fan and Rees 2011b)

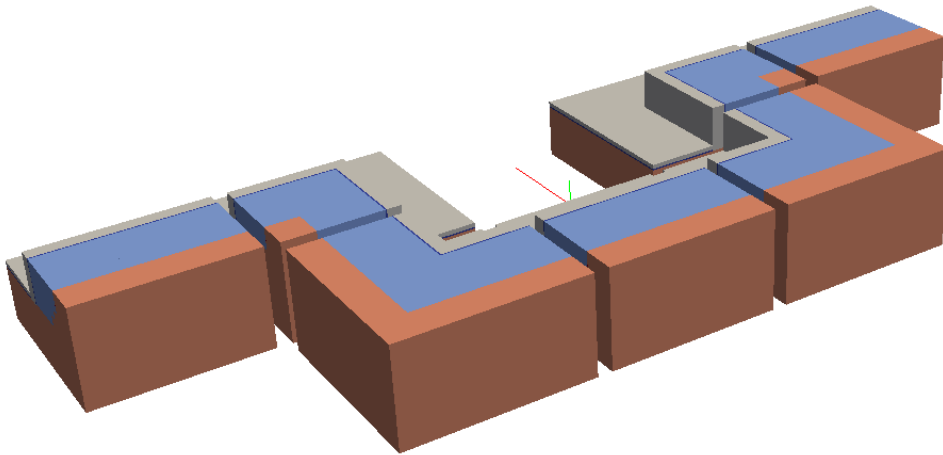


Figure 7. An example of a number of corner and parallel meshes used to represent a complex-shaped basement plan.

- Carrying out annual simulations of building basements and FHX using a three-dimensional numerical model was known to be impractical for the commercial user or practicing engineer. Although considerable speedup of the model used in this project has been possible carrying out annual simulations (i.e. at least 8760 time steps) must be regarded as only suitable for research studies. As this was apparent the team also became aware of a new approach developed at Chalmers University, Sweden, known as Dynamic Thermal Network modeling (PhD thesis by Wentzel (2005)). This approach can make use of a numerical model to derive a series of temperature weighting factors. Once these weighting factor series have been derived the model can be simulated very quickly. The significant advantage of this approach over other weighting factor methods is that complex three-dimensional geometries can be dealt with as easily as one-dimensional surfaces.

Application of this method has required development of tools to generate step response data from the numerical model and three-dimensional meshes. Further tools were developed to convert this data into the required weighting factors and finally to perform a simulation. It transpired that this method had the disadvantage that it could take a significant amount of time to run the numerical model to calculate the required step responses (it is necessary to simulate steps over approximately 100 years for an FHX problem). This approach, at this stage of development, could not therefore form the basis of a 3D EnergyPlus model without a library of response factor data being generated separately. Consequently this approach was not implemented in EnergyPlus. An example of the response factor data that characterizes a particular FHX is illustrated in Figure 8. This work is further described in a paper to be presented

at the Building Simulation 2011 conference (Fan et al. 2011) and a report. (Fan and Rees 2011b)

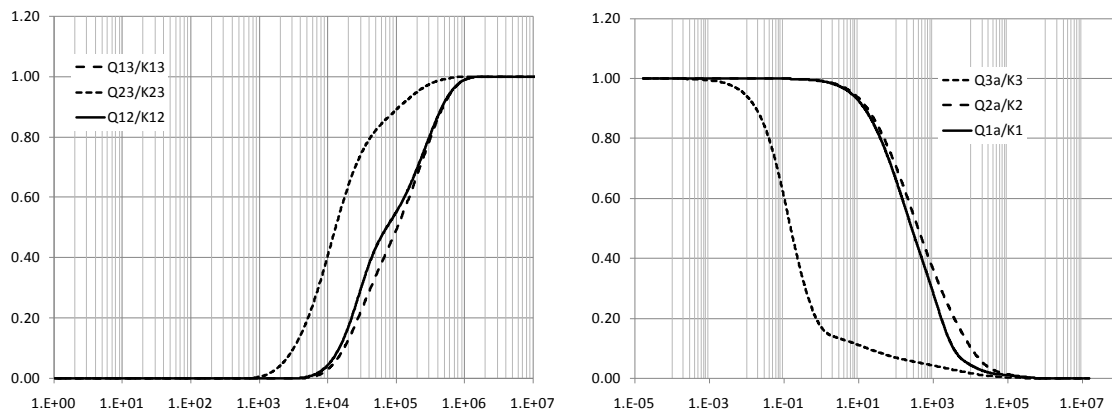


Figure 8. Example response factor data used in the Dynamic Thermal Network approach. This data highlights the faster response of the pipe to fluctuations in fluid temperature (Q3a in the right-hand figure) compared to the basement and ground surface conditions. The transmitted responses shown in the left-hand figure illustrate the extreme length of time required before steady state conditions would be achieved (approximately 106 hours).

- A computationally efficient heat transfer algorithm has been derived and implemented in EnergyPlus. The code has the capability of simulating foundation heat exchangers along with other configurations. The capabilities of the model include the possibility of placing a pipe under the slab, not just beside the slab. The model was initially developed and tested as a standalone model, but has since been approved by the EnergyPlus development team, and the code, example files, and documentation are packaged to be included with the EnergyPlus V7 release in October. The model has been validated within EnergyPlus using the loop demand as a boundary condition. The model data, when compared to data taken at the Oak Ridge test house, shows that the model is sensitive to initialization, but is able to predict peak operating temperatures quite well. A significant feature of this model is the calculation speed. The model's underlying derivation help the overall computational efficiency, and in addition, a large effort was made to cut the run time as low as possible. Currently, a basic FHX simulation can be simulated in about 2 minutes on a modern PC. This is in contrast to some of the other modeling efforts which may be of higher accuracy, but at the cost of significant computation time. This work is described by Lee (2011c; Lee 2011b).
- A study of the feasibility of FHXs for residential GSHP systems in the U.S. was performed by simulating FHX systems in 17 locations for houses with two different insulation levels. In only one instance (Minneapolis, with the lower of the two insulation levels) did the heat pump EFT exceed the design constraints after a 100 ft. HGHX was added to the system. From these results, a preliminary map (Figure 9) of the feasibility of FHX systems in the U.S. was generated, with

three different areas of feasibility identified. Additionally, this study demonstrated that the coupling between the above- and below-grade calculation domains was significant--on the order of 1°C--and that the FHX itself does not intensify freezing in the soil adjacent to the foundation. This work is described in a paper submitted to ASHRAE for publication in the ASHRAE Transactions. (Cullin et al. 2012)

- A design tool was implemented in Excel using VBA. The tool is based on an analytical model that utilizes superposition of line sources and sinks uses a hybrid monthly time step. The analytical model runs about 200 times faster than the detailed numerical model, but at the cost of some accuracy. Six cases at six different locations in the US were investigated and results of the analytical and numerical models were compared in the context of design. For all cases except Salem, Oregon the analytical model used by the design tool oversized the FHX between 17% and 19%. For Salem, the analytical model oversized the FHX by 29%. Given the inherent uncertainties in the inputs, e.g. building loads and soil thermal properties, this level of oversizing in a simplified design tool should be acceptable.
- All of the models were experimentally validated, as described in (Lee and Xing 2011; Rees and Fan 2011; Xing et al. 2011). Figure 10 shows a comparison of all three models to the experimental measurements of the FHX exiting fluid temperature.
- By way of dissemination, three conference papers have been written and accepted; two (Spitler et al. 2010; Xing et al. 2010) have been published and presented; the third (Fan et al. 2011) will be presented in November. Three archival papers have been written; one (Xing et al. 2011) has been accepted for publication and two (Cullin et al. 2012; Xing et al. 2012) are under review.

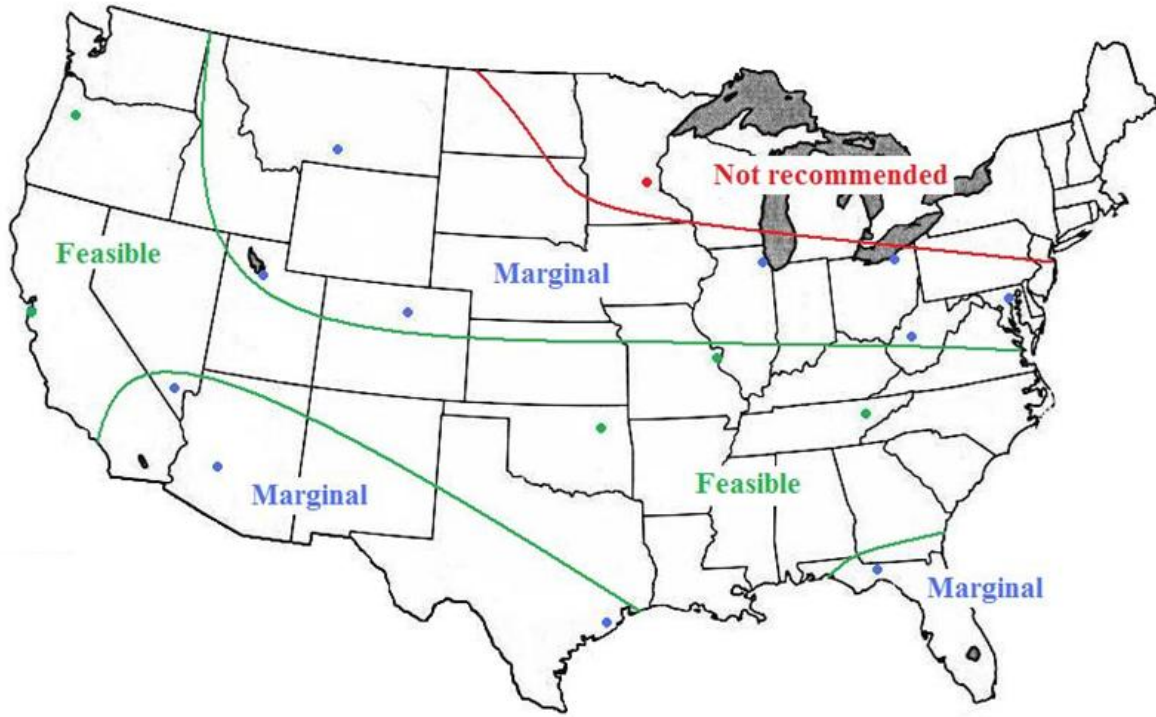


Figure 9 Preliminary feasibility map for FHX (Cullin et al. 2012)

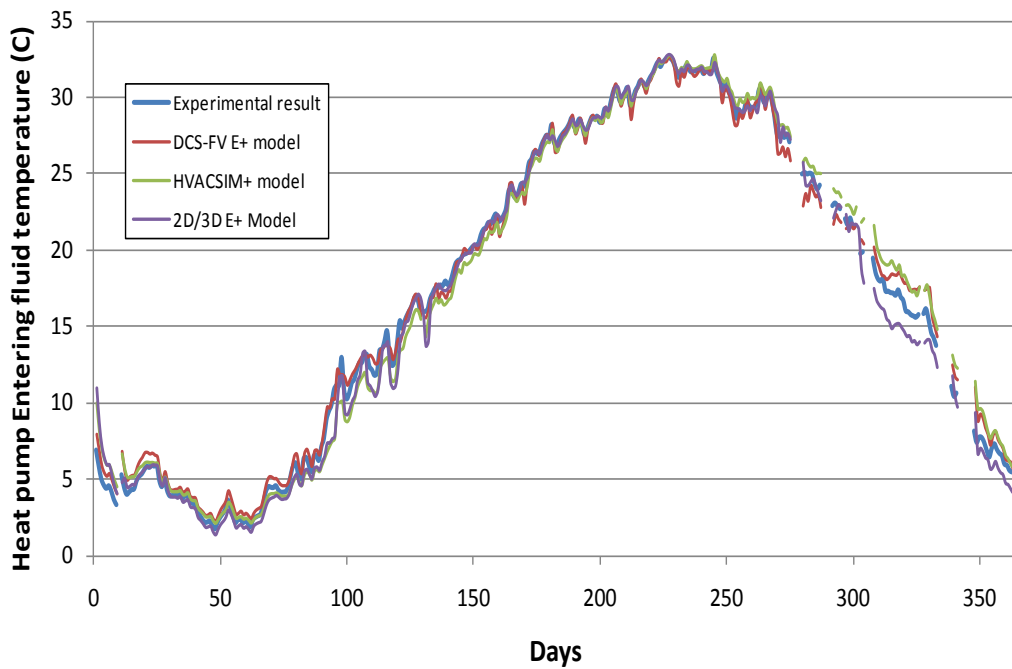


Figure 10 Three models compared to experimental measurements

Task-by-Task Summary

The Oklahoma State University (OSU) / DeMontfort University(DMU) team developed foundation heat exchanger (FHX) models for use in EnergyPlus along with a separate standalone design tool. Both models were validated against experimental data collected by the ORNL team. For purposes of organizing the project, the development of an EnergyPlus model and a design tool model were treated as two tasks (OSU-1 and OSU-2 below) though there was necessarily some overlap.

The results for each of the tasks and subtasks are described very briefly in the following sections. For each task and subtask, a very brief summary is given in this section, with pointers to the appendices where more detailed information is given. The appendices include an MS thesis, conference papers, journal papers and other reports, together covering all aspects of the project. The appendices are labeled using the Author-Date system rather than “Appendix A”. In the electronic version of the final report, the appendices are mostly given with as PDFs, with the file name matching the citation, e.g. “Xing_2010.pdf”. Source code is provided in a series of zip files as described below.

OSU-1 EnergyPlus FHX Model Development

The integrated design of near/net-zero-energy buildings (ZEBs) requires the use of energy calculation and design tools capable of accurately modeling state-of-the-art building technologies and their interactions with other building systems and with the environment. EnergyPlus (Crawley et al. 1999) was developed to provide the building design community with an energy analysis tool for ZEBs. In addition to EnergyPlus, specialized design tools are often required to size components to the accuracy required by ZEB design. The current release version of EnergyPlus cannot account for the thermal interaction between the building’s foundation, the soil, and the FHX-coupled heat pumps. However, an experimentally validated EnergyPlus model has been implemented in the development of the code and is scheduled for release in October 2011. The objective of this task was to develop and validate both the new EnergyPlus FHX models and the specialized design tools required to support research, development, and implementation of FHX-based GHP systems in ZEBs. Several different approaches were investigated:

- A coarse grid numerical model, first implemented in HVACSIM+ for testing purposes. This is reported in some detail by Xing, et al. (2011). The results from this model allowed us to choose which phenomena were modeled, e.g. evapotranspiration and soil freezing/thawing.
- The detailed numerical model (based originally on the GEMS 3D tool) has been developed in a number of stages during the project. Some effort has gone into improving efficiency and optimizing mesh generation. It was more effective to develop a combined two and three dimensional code (2D being a special case of a 3D geometry) rather than separate 2D and 3D models. Hence subtasks 1.3 – 1.5 were combined with 1.8 and 1.9 and are reported as such in Table 1.
- The work on application of the detailed numerical model to Dynamic Thermal Network representation of the FHX was not one of the original subtasks. This approach was investigated

because it has significant efficiency advantages for 3D models and makes use of the same underlying 3D numerical models and mesh generation tools as those developed for other aspects of the project (subtasks 1.8, 1.10). Development of this approach has been reported in several progress reports and is also summarized in the appendix (Fan, 2011b). The model derived taking this approach has been verified with reference to the three-dimensional numerical model. Although this approach proved very promising further work would be required before it could be incorporated into a tool like EnergyPlus.

- A computationally efficient 3D model (based on a dual coordinate system finite volume approach) was developed during the project and eventually implemented in EnergyPlus. The model is one of two approaches used for subtasks 1.7, 1.8 and 1.11 as it is a 3D implementation in EnergyPlus and has been validated against experimental data. This model has shown considerable speed advantages over other modeling work developed during this project, and is able capable of modeling some advanced configurations such as under-slab pipes.

Table 1 contains summaries for each of the subtasks, pointing to a more detailed report found in the appendices.

Table 1 Subtask Summaries

Subtask	Appendices
<u>Subtask 1.1.</u> Strategic literature review. Identify and analyze key literature, seeking analytical tests and potential verification and validation data.	This literature review is included as part of Xing (2010).
<u>Subtask 1.2.</u> Write an EnergyPlus new feature proposal for the FHX model. Revise as needed until final submission in July 2009.	Two new feature proposals (NFP) were submitted; one (Lee 2011d) covers generically pipes in the ground and the other (Lee 2011a) covers FHX more specifically.
<u>Subtask 1.3.</u> Develop a FHX and basement heat transfer research tool based on GEMS_2D.	The detailed numerical model research tool was developed as a 3D model (with 2D being treated as a special case). This task is reported with – see Subtask 1.8
<u>Subtask 1.4.</u> Develop a model of the experimental installation using the FHX and basement heat transfer research tool based on GEMS_2D.	Testing and validation of the detailed numerical model was carried out using the combined 2D/3D model – see Subtask 1.9

Subtask	Appendices
<p><u>Subtask 1.5.</u> Develop an implementation of the 2D research tool for integration in EnergyPlus including a parametric 2D mesh generation tool.</p>	<p>The detailed numerical model was implemented with a 2D and 3D capability – see Task 1.8. Initial validation of the numerical method was carried out by application of the IEA Annex 43 Ground Coupling tests (report included later).</p>
<p><u>Subtask 1.6.</u> Develop draft user and engineering documentation.</p>	<p>See (Lee 2011c) for the EnergyPlus documentation.</p>
<p><u>Subtask 1.7.</u> Compare the EnergyPlus FHX model to experimental data sets developed under Task 3.</p>	<p>See Subtask 1.11.</p>
<p><u>Subtask 1.8.</u> Extend the numerical model to three dimensions based on GEMS_3D. Investigate sensitivity to three dimensional features. Develop an implementation of this model in EnergyPlus.</p>	<p>The three dimensional numerical model (GEMS3D) was developed with respect to its efficiency and parametric mesh generation capabilities. The research tool code has been adapted (a new GHX3D research tool resulting) and integrated into EnergyPlus and allows both two and three dimensional representation of FHX. Sensitivity to three-dimensional features is discussed in Fan and Rees (2011a). The three dimensional mesh generation tools are described by Fan and Rees (Fan and Rees 2011b)</p>
<p><u>Subtask 1.9.</u> Compare the detailed EnergyPlus basement and slab model to experimental data sets developed under Task 3.</p>	<p>The FHX model included in EnergyPlus has been validated with respect to one year of data from the SIP experimental house. This is reported separately.</p>

Subtask	Appendices
<p><u>Subtask 1.10.</u> Refine 3D model parametric mesh generation to include complex geometries (e.g. walk-out basements).</p>	<p>Algorithms and tools were developed to allow parametric generation of both two and three dimensional FHX geometries. This mesh generation code has been included in EnergyPlus. Complex FHX geometries can be represented by modular combination of meshes of inside corners, outside corners and parallel sections. The three dimensional mesh generation tools are described by Fan and Rees (2011a)</p>
<p><u>Subtask 1.11.</u> Further validation against experimental data.</p>	<p>Final validation results for all three models are described in (Lee and Xing 2011; Rees and Fan 2011; Xing et al. 2011)</p>
<p><u>Subtask 1.12.</u> Develop and test design and simulation methodologies with particular reference to zero-energy housing using the detailed simulation tool.</p>	<p>This has been tested for a house in Colorado. See the report by Cullin (2011).</p>
<p><u>Subtask 1.13.</u> User and reference documentation. Prepare technical papers and other material for dissemination of the research.</p>	<p>See reference section of the report. The research has been disseminated through a number of papers and reports, in addition to the EnergyPlus documentation which will be released soon.</p>

OSU-2 Design Tool Development

The purpose of this task was to provide properly documented and validated design tools, methodologies, and algorithms supporting the deployment of FHX-based GHP systems. The initial tool could be used to predict peak entering fluid temperatures, given building loads and ground properties.

Because not all houses will have adequate ground heat exchanger capacity solely with an FHX, the design tool capabilities were expanded to account for additional horizontal ground heat exchanger (GHX) and/or additional heat rejection provided by a domestic water heating heat pump. The required additional horizontal GHX can be sized automatically with the design tool.

Table 2 contains summaries for each of the subtasks, pointing to a more detailed report found in the appendices.

Table 2: Development of the FHX Design Tool

Subtask	Appendices
<u>Task 2.1.</u> Develop approximation based on existing simplified methods for horizontal GHX — the initial, simple “simulation kernel.”	This approximation is described in the Design Tool Guide (Oklahoma State University 2011) and the paper by Xing, et al. (2010).
<u>Task 2.2.</u> Implement approximation in Excel spreadsheet with VBA; use DLL if necessary to achieve reasonable speed.	The implementation is described in the Design Tool Guide (Oklahoma State University 2011).
<u>Task 2.3.</u> Develop design methodology capable of determining how much auxiliary heat exchanger capacity is needed from either a) a horizontal GHX or b) a wastewater heat exchanger.	The design tool, as described in the Design Tool Guide (Oklahoma State University 2011) is capable of sizing an auxiliary horizontal GHX for systems with specified size FHX, with or without a heat pump water heater.
<u>Task 2.4.</u> Develop models of auxiliary heat exchangers as specified in Task 2.3. Implement models in the FHX kernel.	Models of two auxiliary heat exchangers are described in the Design Tool Guide (Oklahoma State University 2011): a heat pump water heater and an auxiliary horizontal GHX.
<u>Task 2.5.</u> Make comparisons of simple simulation kernel to detailed model developed in Task OSU-1. Determine needed refinements to simple simulation kernel, development of an intermediate level model using response factors or a hybrid numerical approach, or replacement with an adaptation of the detailed model.	This comparison is reported in detail in Xing, et al. (2010). The simplified design tool works adequately for design purposes. If more accurate results with less inherent safety factor are desired, one of the more detailed models, such as that implemented in EnergyPlus, may be utilized.
<u>Task 2.6.</u> Write preliminary FHX design guide and revise design tool user documentation.	See the Design Tool Guide (Oklahoma State University 2011).
<u>Task 2.7.</u> Based on the results of Task 2.5, either refine simple simulation kernel or replace with an adapted detailed model.	The refined simple simulation kernel is described in the Design Tool Guide (Oklahoma State University 2011).
<u>Task 2.8.</u> Further refine design methodology —improved accounting for heat transferred to the building, addition of one or more auxiliary heat exchangers such as domestic water heating heat pump and/or exhaust air heat exchanger.	See the Design Tool Guide (Oklahoma State University 2011).

Subtask	Appendices
<u>Task 2.9.</u> Revise design tool interface as needed; prepare design guide, program documentation, and papers.	See the Design Tool Guide (Oklahoma State University 2011) and Xing, et al. (2010).
<u>Task 2.10.</u> Based on analyses of buildings with and without FHX, make preliminary recommendations as to how FHX might be incorporated into design heating and cooling load calculations.	A preliminary analysis is contained in Spitler and Cullin (2011). In short, it seems unlikely that, with moderate basement insulation (R-13), it is necessary to revise cooling and heating load calculation procedures.

Source Code

Source code for the various aspects of the project are provided in zip files. These are summarized in Table 3.

Table 3 Summary of source code

File	Contents
DMU_EnergyPlus.zip	Source code for the EnergyPlus model implementation described by Rees (2011). An executable and example input files are included. This model allows both 2D and 3D representation of FHX. This model has some memory and computational overhead compared with the other models but can capture 3D effects at basement corners.
PGrid3DFHX.zip	This contains source code and example files for the utility described by Fan and Rees (2011a). It can be used to generate meshes for use in deriving DTN weighting factors.
GenerateStepResponses.zip	This contains source code and example files for a utility to generate the step response data required for deriving DTN coefficients as described by Fan and Rees (2011b).
CalDTNFactors.zip	This utility uses the step response data to calculate the DTN weighting factors (Fan and Rees 2011b).
FHX Design Tool_20110927_final.xls	Design tool. Source code is in the VBA modules.
OSU_Energyplus_Source.zip	Source code for the EnergyPlus model implementation described by Lee (2011c). This is the computationally efficient 3D model based on a dual coordinate system finite volume approach.
OSU_HVACSIM+_Source.zip	Source code for the HVACSIM+ models of the FHX and HGHX.

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