Bridge Deck Deicing using Geothermal Heat Pumps

JEFFREY D. SPITLER, PH.D., P.E.,
MAHADEVAN RAMAMOORTHY
Oklahoma State University
Stillwater, OK, U.S.A.

KEY WORDS

Ground source heat pump systems, ground loop heat exchangers, bridge deck deicing system.

ABSTRACT

Several research projects at Oklahoma State University have investigated bridge deck deicing systems that utilize a ground source heat pump system to provide heating. This paper describes simulation methodology; the design of a system planned for installation on a bridge deck near Weatherford, Oklahoma; and results from system simulations of the proposed bridge deck.

System simulations of the bridge deck heating system have been developed in two component-based modeling environments: TRNSYS and HVACSIM+. Component models of the hydronically-heated bridge deck, vertical ground loop heat exchanger, and water-to-water heat pumps have been developed and validated separately. They will be presented briefly in the paper.

A heating system has been designed for a bridge deck on Interstate Highway 40 (I-40), located just east of Weatherford, Oklahoma. This bridge deck on the westbound section of the roadway spans a county road, a creek, and a railroad. The new bridges are approximately 213 m long by 12 m wide. The design process, described in the paper, required iterative application of both a ground loop heat exchanger design tool, and the system simulation to find a suitable combination of minimum entering fluid temperature, number and configuration of the heat pumps, and ground loop heat exchanger size. A system with 16 heat pumps of nominal 30-ton capacity and 250 boreholes, each 76 m deep, was selected.
.
The system also circulates fluid from the bridge deck directly to the ground loop heat exchanger in the summer in order to “recharge” the ground. Results from the system simulation showing operation both in the winter heating mode and summer recharge mode are presented.

INTRODUCTION

Travel is hazardous in the late fall, winter, and early spring, during periods of snow, sleet and freezing rain. Perhaps the greatest danger along this line is the frequent occurrence of preferential icing of bridges, where bridge decks become icy and slick while adjacent roadways remain clear. Some drivers crossing preferentially iced bridges lose control of their vehicles, resulting in single or multiple vehicle accidents. The risk of mishap is worse when other non-ideal conditions exist such as during low visibility conditions and bridge/roadway maintenance operations.

Therefore, it is highly desirable that preferential icing be prevented.By far, the most frequent responses to bridge deck icing are the applications of salt and/or sand or other gritty material. Salt applied to a bridge deck prior to icing can prevent preferential icing. Timing of the application of salt and sand is often problematic. Furthermore, salt is corrosive and eventually penetrates down to the reinforcing steel. When it corrodes, the bridge deck life is reduced. Some alternative, non-corrosive substances are available, but they are significantly more expensive.

One alternative method for preventing preferential icing is described in this paper. This system makes use of hydronic heating in the bridge deck, with the heat source being a ground-source heat pump. In order to make the system economically feasible, it is necessary to operate it only when needed. The "just-in-time" control strategy is one of the topics of ongoing research. Some of the work that has been done to date, including the design of a full-scale (215 m x 12 m) heated bridge deck system is presented in this paper. Much of it is simulation based, although a small-scale (1 m x 3 m) geothermally-heated bridge deck was operated for several years (1) at Oklahoma State University. In addition, a recently constructed medium-scale (6m x 17 m) bridge deck will also be used in the future for validation purposes.

COMPONENTS AND COMPONENT MODELS

The system simulations have been implemented in two component-based system simulation environments: TRNSYS (2) and HVACSim+ (3). In these environments, the bridge deck, heat pumps, ground loop heat exchanger, circulating pumps, etc., are all modeled as individual components and then connected together to form a system simulation. In the design procedure, some of the individual component models were used separately. Accordingly, the individual components are described briefly below.

Hydronically-heated Bridge Deck

The heat demanded by the snow-melting system represents the thermal load. The pipe, commonly cross-linked polyethylene, is embedded in a serpentine configuration as shown in Figure 1. Typical pipe spacing ranges from 150 to 300 mm and is usually buried between 50 and 75 mm deep. Nominal pipe diameters are commonly 18 to 25 mm. Heat transfer in pavement slabs has been addressed for snow melting applications by many sources including Adlam (4), Chapman (5), Kilkis (6), ASHRAE (7), and Ramsey, et al. (8). Heat transfer mechanisms acting upon the pavement slab are shown schematically in Figure 2.

Heat transfer within the slab itself is by conduction. Internal sources of heat are due to convection from flow of the heat transfer fluid through the pipes. Heat fluxes at the pavement surface are due to a number of environmental interactions and include convection, solar radiation, thermal (long-wave) radiation, sensible heat transfer from precipitation, and latent heat transfer from melting snow and evaporating water. In the case of a bridge deck where the slab bottom is exposed, heat transfer from the bottom surface is by convection and radiation to the surroundings.

The component model used here has been described in detail by Chiasson(9). Transient heat transfer in the slab is represented in the model in two-dimensional (2-D) cross-section using the Cartesian coordinate system. Each of the heat transfer mechanisms shown in Figure 2 is represented in the model.

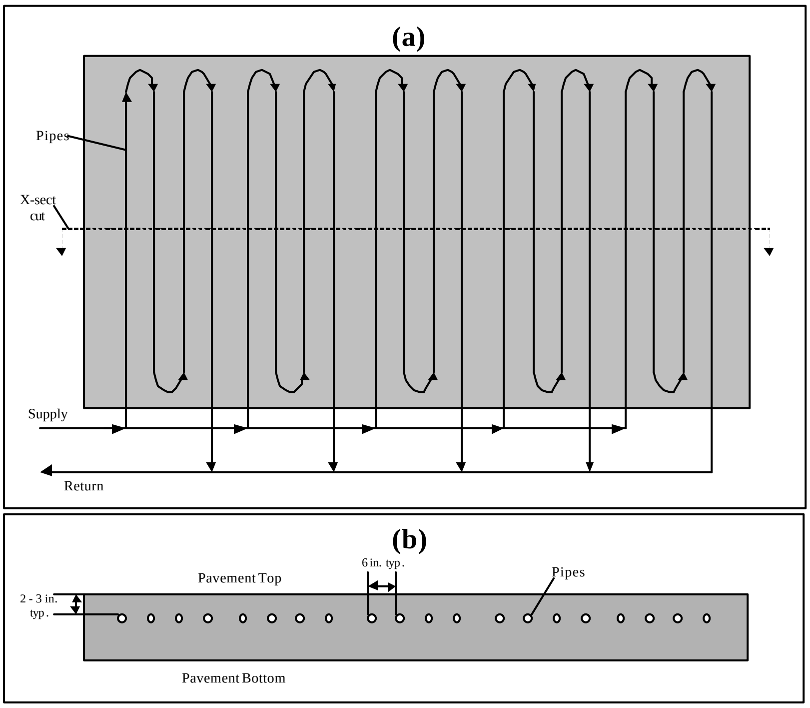

Figure 1: Typical Construction of a Hydronic Snow-Melting System in (a) Plan View and (b) Cross-Sectional View.

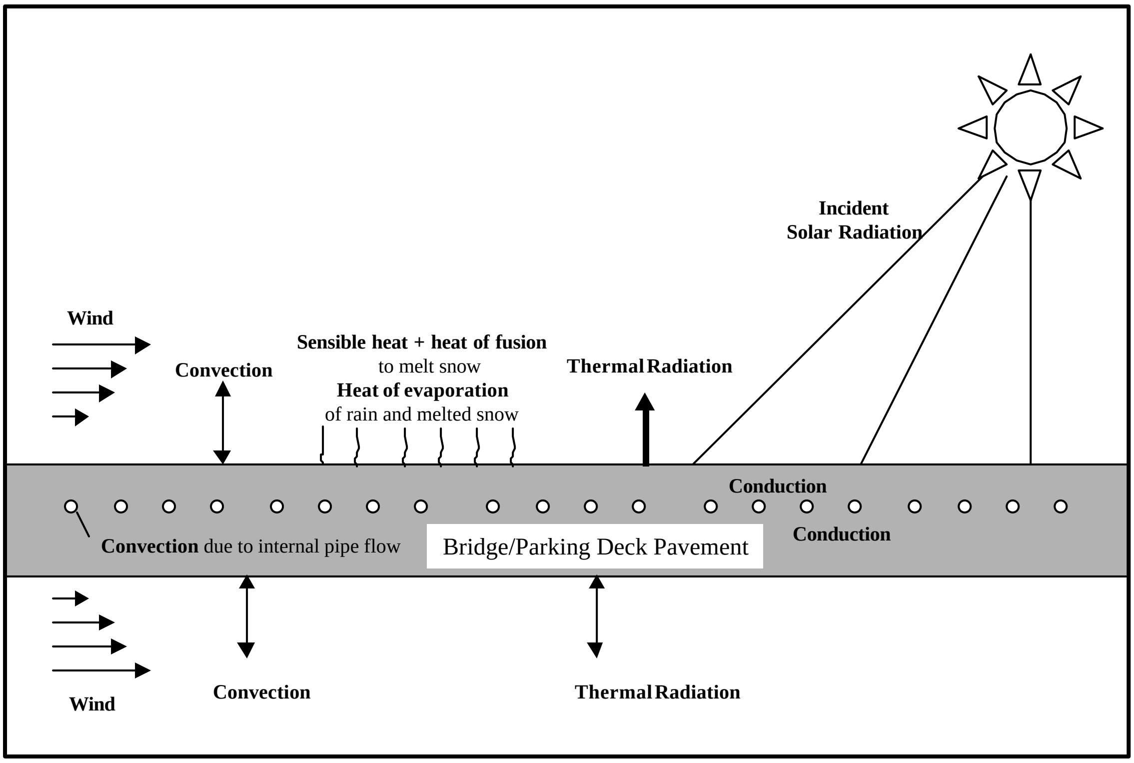

Figure 2: Heat Transfer Mechanisms in a Hydronically-Heated Bridge Deck

Ground Loop Heat Exchanger

Several types of ground loop heat exchanger (GLHE) configurations can be installed at a particular site, depending on the site conditions. In this work, we selected the vertical closed-loop ground-coupled type, which can be installed at any location where drilling and earth trenching are feasible.

The GLHE model (10) used here is capable of accounting for both long-term and short-term transients. The model uses the results of Eskilson (11), who used a finite difference model to solve for the temperature distribution in borehole fields of various configurations in response to a step heat extraction or rejection rate. The temperature distribution over time was then converted to a series of non-dimensional response factors known as "g-functions". These g-functions were extended to short time steps by Yavuzturk and Spitler (10), who also developed a model which, with moderate efficiency, utilize the g-functions to predict hourly exiting fluid temperatures of a ground loop heat exchanger, given the hourly entering fluid temperatures and mass flow rates.

Water-to-water heat pumps

A parameter-estimation-based water-to-water heat pump model has been developed by Jin and Spitler (12). This model makes use of the manufacturers' catalog data and a multi-variable optimization routine to calculate the optimal values of parameters that describe the overall performance of the heat pump. The objective function in the optimization routine is formulated from the basic thermodynamic laws of the conservation of mass, energy, and momentum that describe the behavior of the compressor, the evaporator, the condenser, and the refrigerant. Once the optimal values of the performance parameters have been determined, the model can accurately simulate the performance of the heat pump over its full operating range.

Because the heat pump in a simulation may be occasionally subjected to conditions for which it is not intended to operate, several checks are placed in the component model to turn the heat pump off if the entering fluid temperature exceeds 48.8ºC or the mass flow rate is unacceptably low. These checks mimic the pressure cut-off switches that will shut the heat pump off if pressure is too high.

For a large bridge deck, a number of heat pumps may be necessary. For the Weatherford bridge deck, 16 heat pumps are utilized, arranged as eight serially-connected[1] pairs. These were combined into a single component model, referred to as a "gang of heat pumps" and illustrated in Figure 3. A separate controller can control the number of pairs of heat pumps on at any one time.

[1] They are connected in serial on the load side; on the source side, they are connected in parallel.

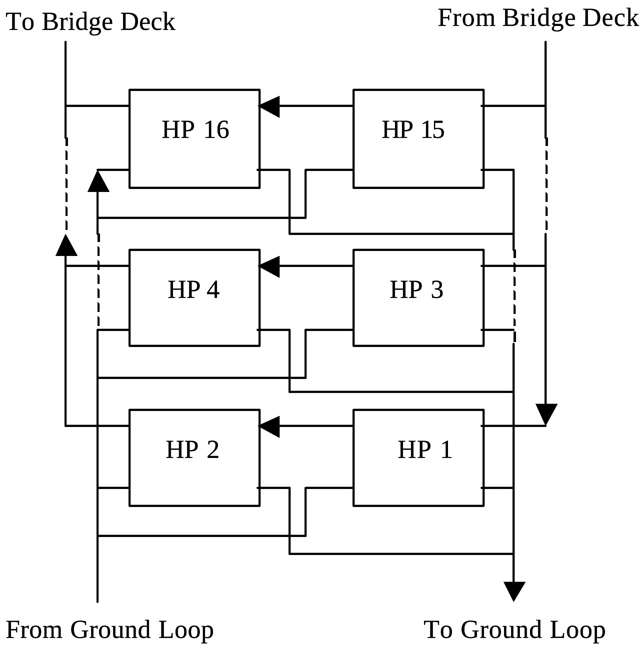

Figure 3: Gang of 16 Heat Pumps

Controller

With respect to making the system economically feasible, the controller may eventually be the most important part of the system. At present, only very simple control strategies have been tested. More sophisticated control strategies are a topic of current research.

The current control strategy is somewhat artificial in that it "reads ahead" in the weather file and, if there is to be snow or freezing rain, turns on the heating system. Once the heating system is turned on, the number of serially-connected pairs turned on is controlled by the bridge deck surface temperature. At or above 2.67ºC, one pair is turned on. Below 0ºC, all eight pairs are turned on. In between, the number of pairs that are on is linearly controlled.

For recharging the ground in the summer, the controller bypasses the heat pump by sending control signals to the diverters and directs the flow to the ground loop heat exchanger. Fluid is circulated directly between the bridge deck and the ground loop heat exchanger whenever the bridge deck surface temperature exceeds a user specified set point; 32.2ºC has been used so far as the setpoint.

WEATHERFORD, OKLAHOMA BRIDGE DECK DESIGN

The bridge deck described in this paper is a section of Interstate Highway 40 (I-40), located just east of Weatherford, Oklahoma. This particular section of I-40 consists of eastbound and westbound bridges that span over a county road, a creek, and a railroad. The highway bridges are scheduled to be replaced by new bridges approximately 215 m long by 12 m wide. Only the westbound bridge is to be heated by the GSHP system.

THE SYSTEM DESIGN PROCESS

The system design procedure is described in some detail in another paper (13). Briefly, it was completed in four phases: (1) establish the required heat flux to the bridge surface, (2) estimate the bridge heating loads, (3) estimate the energy available for thermal recharge of the ground, and (4) size the GLHE. None of these phases are completely independent; the final design decisions were the result of iterations of the four phases, each of which are described in the following subsections. A flow chart summarizing the design process is shown in Figure 4.

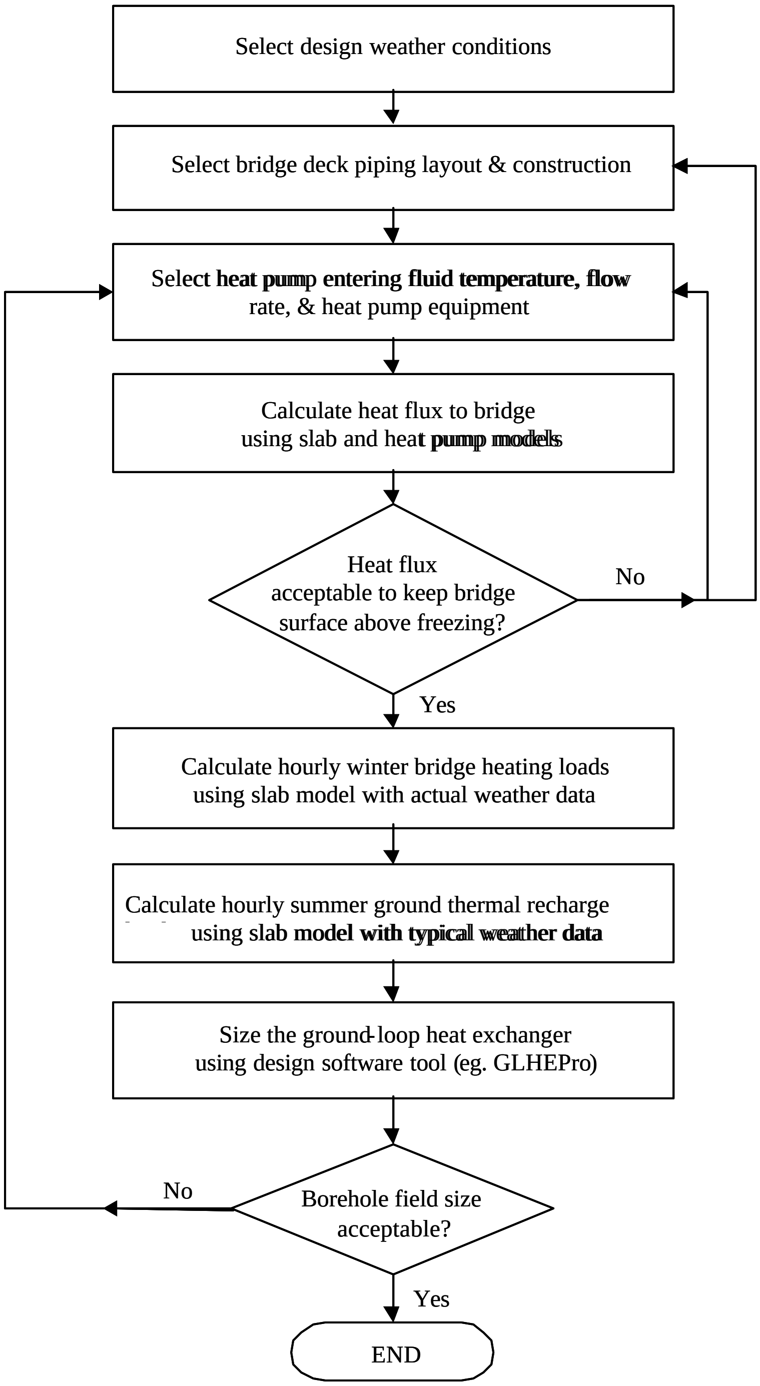

Figure 4: Summary of the Design Process for Ground-source Heat Pump Bridge Deck Heating System.

The design procedure is, necessarily, somewhat simpler than the system simulation. At present, the system simulation takes much too long (say, 3 hours on a 500 Mhz. Pentium III) to run iteratively in a design procedure. Therefore, a number of simplifications were made to complete the design.

The Heat Flux to the Bridge

The heating requirement of a snow-melting system is commonly described in terms of a heat flux. The heat flux required for successful operation of the system depends upon many factors including: (1) environmental heat transfer mechanisms (as shown in Figure 2), (2) bridge deck construction (materials, thickness, area, and orientation), (3) hydronic tubing construction (material, diameter, spacing, and burial depth), (4) system flow rates, (5) heat transfer fluid properties (density and thermal properties), and (6) the fluid supply temperature. The following design conditions were chosen:

Weather Conditions:

- air temperature = -9.4°C
- wind speed = 22.5 km/hr
- snowfall rate = 250mm./day

Bridge Deck and Hydronic System Design:

- pipe diameter = 18 mm nominal
- pipe depth = 75 mm. below road surface
- pipe center spacing = 300 mm.
- deck thickness = 200 mm
- deck area = 2475 m^2
- heat transfer fluid = 42% propylene glycol @ a flow rate of 22 l/s
- heat pump model = Water Furnace, Spectra SXW 360 (nominal capacity 30 tons or 106 kW)

The objective of the design heat flux was to keep the average bridge surface temperature above freezing under the weather conditions listed above. These design weather conditions were selected based on a compromise between system feasibility and a realistic winter storm scenario. Determination of the design heat flux required quantification of the heat transfer mechanisms shown in Figure 2. However, this depended on knowledge of the heat pump performance, which at this stage of the design process could not be reliably determined by conventional means. The conventional practice is to estimate the heating load and use manufacturers' catalog data to estimate load-side and source-side entering fluid temperatures to the heat pump by assuming the temperature decrease across the load is the same as listed in the catalog. In this case, none of the input parameters (entering fluid temperatures and flow rates) match any of the catalog data, making even interpolation of the catalog data difficult. Therefore, it was decided that it would be ideal to be able to predict the heat pump performance in response to a dynamic heating load, and hence the need for a system modeling approach.

To determine the heat flux, the heat pump model was coupled to the slab model and the design conditions described above were used as inputs to the models. Design parameters such as minimum heat pump entering fluid temperature, number of heat pumps, and flow rate were varied with the models and several potential designs were considered. Bridge deck average surface temperatures and the corresponding heat flux are plotted versus source-side heat pump entering fluid temperature for 8 heat pump pairs in Figure 5. This figure shows, for a given heat pump configuration, under design weather conditions, both the heat flux that can be produced, and the average surface temperature that can be maintained.

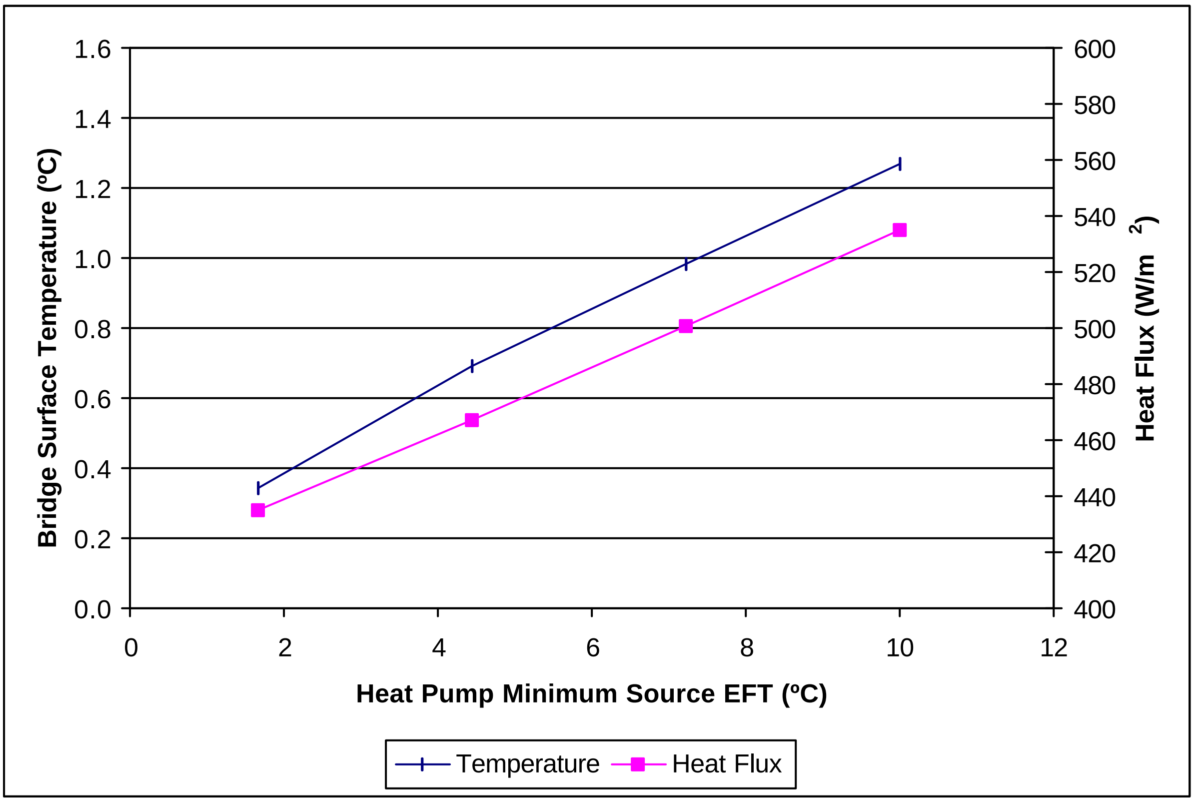

Figure 5. Bridge surface temperature and corresponding heat flux under design weather conditions versus the source-side heat pump entering fluid temperature (EFT) for 16 (8 pairs) of heat pumps.

The performance of 9 pairs and 10 pairs of heat pumps was also simulated, but these arrangements were rejected from consideration because the model results showed that the entering fluid temperature to the second heat pump in each pair exceeded the manufacturer's rating.

The Bridge Heating Loads

The design heat flux only represents the maximum potential output of the system. It yields no information regarding the actual energy use of the system over the course of a heating season, since the heat flux is determined for extreme weather conditions only. As previously stated, the performance of the GLHE depends upon the short-term loads on the heat pump. It is therefore necessary to estimate the hourly heating loads on the heat pump in order to design a reliable and cost-effective GLHE. Such estimates of the heating loads require the use of reliable weather data.

The heating loads on the heat pump for the various cases were estimated using the design heat fluxes shown in Figure 6 and actual hourly climatic data for Oklahoma City for the years 1982 through 1992. Actual hourly weather data are desirable to properly simulate storm events. Included in the data sets are the hours when rain or snow was falling along with the quantity of precipitation in equivalent inches of water.

For each year from 1982 to 1992, the numerical bridge deck model was used to predict the bridge surface temperature under the actual climatic conditions for the given year.

In order to design the ground loop heat exchanger, it was necessary to estimate both the winter heating loads, and the summer recharge rates. The estimate for the heating loads was done with a rough and conservative approximation. It was assumed that the bridge will call for heating 12 hours before and 12 hours after a freezing precipitation event. The bridge heating load was then assumed to be linearly proportional to its surface temperature: heating load = 0% of the design flux at 1.67°C and heating load = 100% of the design flux at –6.7°C. When more advanced control strategies are available, which include forecasting and variable rate heating, a better prediction of the bridge deck heating loads may be made using the simulation tool. The year 1983 was chosen as the "design year" since that year exhibited the highest heating requirement. Monthly bridge heating loads for 1983 are summarized graphically in Figure 6.

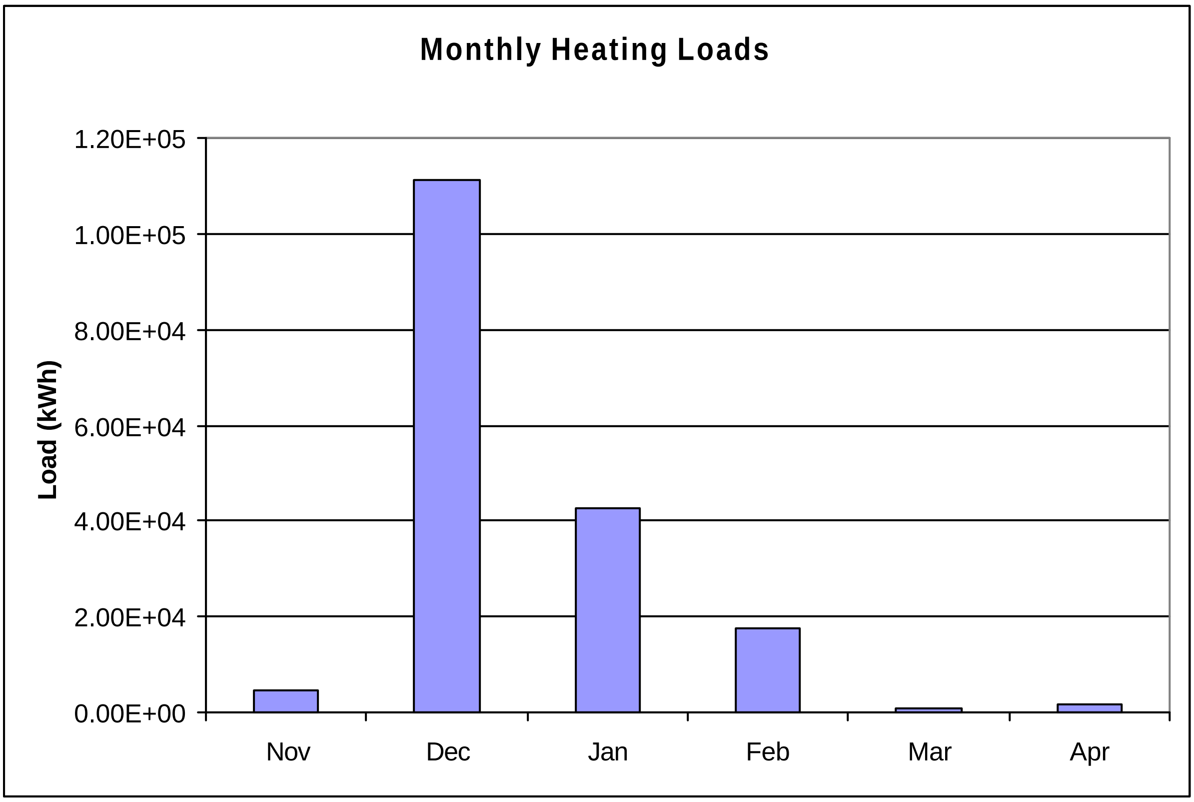

Figure 6. Bridge monthly heating loads for the "design year" 1983.

Ground Thermal Recharge

Thermal recharge of the ground is necessary to effectively balance the thermal loading to the ground over the annual cycle, and hence reduce the size and therefore the cost of the GLHE. Thermal recharge is analogous to the cooling load of a building since heat is rejected to the ground in both cases. Therefore, as with the heating load, thermal recharge loads need to be estimated on an hourly basis in order to design a reliable and cost-effective GLHE.

Potentially available energy for recharging the ground was estimated using the numerical bridge deck model and "typical" weather data for Oklahoma City. The weather data were of the Typical Meteorological Year (TMY) format, produced by the National Climatic Data Center. A TMY record for a particular location represents a long-term statistical average of various weather parameters. TMY data were used for estimating the recharge loads rather than actual weather data because the TMY data are more representative of the long-term weather conditions over the life cycle of the bridge.

The recharge strategies investigated with the model included circulating fluid from the bridge deck to the ground loop when the bridge surface exceeds some specified temperature. A surface temperature of 32.2°C was found to be adequate. The hourly thermal recharge rates were computed by the slab model using an overall energy balance on the heat transfer fluid. The monthly thermal recharge rates are shown graphically in Figure 7. Note that the available energy for recharging exceeds the total winter heating load. Therefore, the circulating pumps could be run for fewer hours, while still balancing the annual load. The advantage of summer recharge is seen in the next subsection.

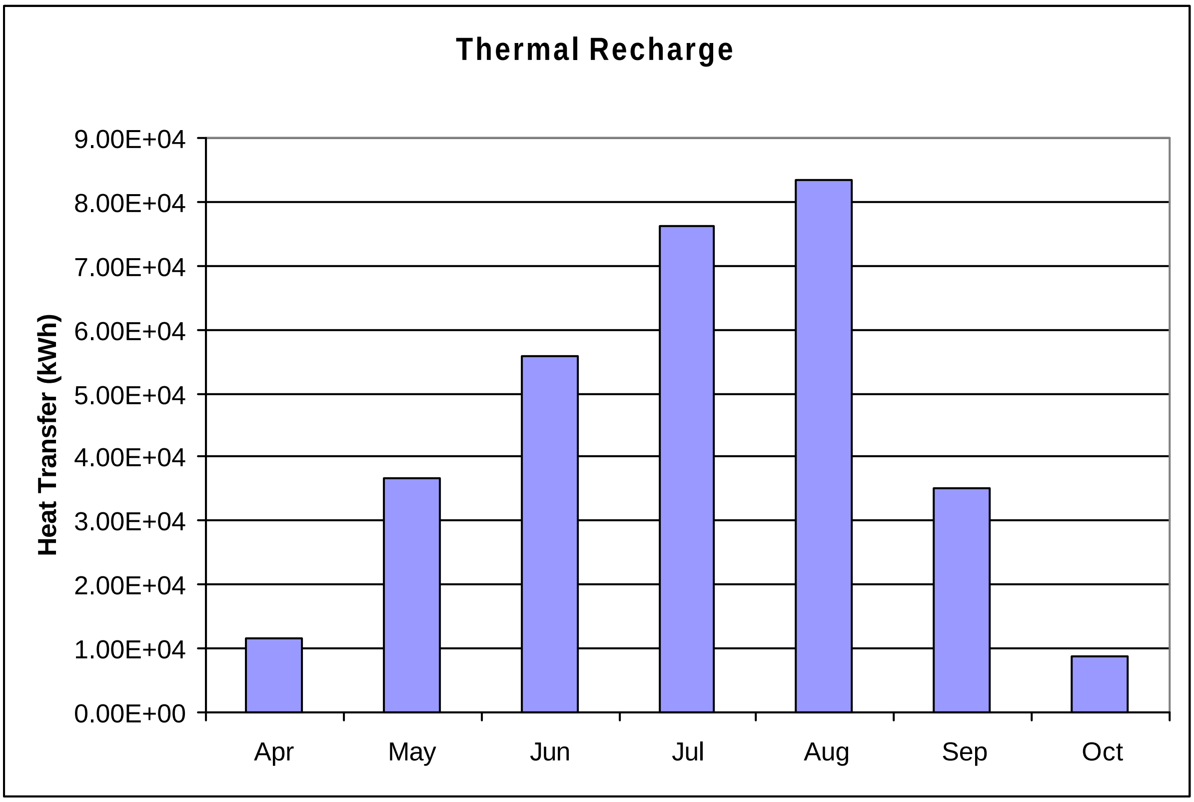

Figure 7. Estimated monthly energy available for thermal recharging of the ground.

The Ground-Loop Heat Exchanger (GLHE)

The GLHE was sized using design software developed by Spitler, et al. (14). Inputs to the model included the heating loads, the thermal recharge rates, a description of the ground thermal properties, a description of the borehole geometry, the fluid physical and thermal properties, and a description of the heat pump. A 42% propylene glycol solution was specified as the heat transfer fluid with a total flow rate of 57 l/s. A borehole diameter of 125 mm, HDPE U-tubes with a nominal diameter of 18 mm, and thermally enhanced grout were also specified.

All borehole fields considered in the design process were rectangular-shaped with 76 m deep bores on 4.6 m spacings and were sized for 25 years of operation. Figure 8 shows the relationship between the design minimum entering fluid temperature to the heat pump and the required number of boreholes for cases with and without summer recharge. The impact of the entering fluid temperature as well as using summer recharge on the borehole field size are evident.

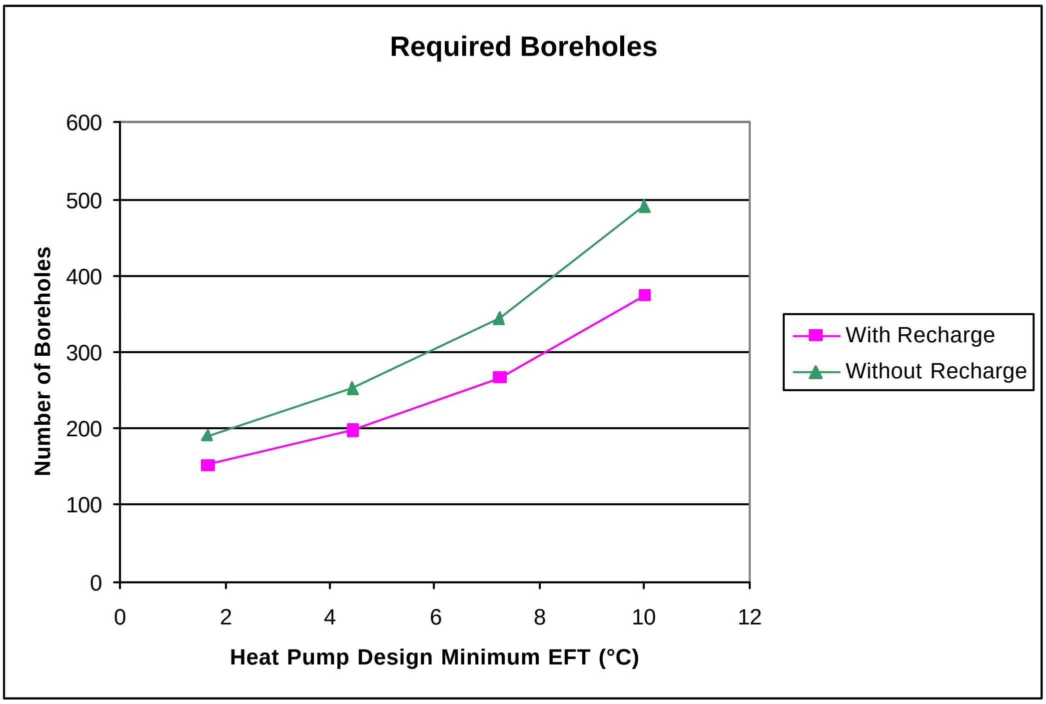

Figure 8. Number of boreholes required to meet minimum heat pump source-side entering fluid temperature (EFT) with and without summer recharge, when 16 heat pumps are used.

The Final Design

The final system design consists of 16 heat pumps arranged in 8 pairs such that the fluid flow is in parallel on the source side and in series on the load side. The heat pumps will supply fluid to the bridge deck at approximately 50°C with a total flow rate of 22 l/s. The borehole field configuration selected consists of 250 boreholes, each 76 m, deep, that uses summer recharge. The borehole field will supply fluid to the heat pumps at a minimum temperature of 6.7°C with a total flow rate of 57 l/s.

DISCUSSION OF RESULTS

With the system modeling and simulation approach, key design parameters could be easily varied and the performance of several possible designs could be examined in order to obtain a workable solution. There is a trade-off between the number of boreholes that make up the GLHE and the number of heat pumps required to provide the heating load. In other words, fewer heat pumps could have been chosen, but the GLHE length would approach an extremely large value. Therefore, the size of the GLHE is traded off against the size and number of heat pumps required. The modeling approach allows a suitable combination to be found.

The advantages of the modeling effort can be summarized by conducting a simple cost analysis. Given that a typical cost for drilling, grouting, and installing pipe in a borehole is approximately $1,000 per borehole, a borehole field with no summer recharge supplying 10°C fluid to 16 heat pumps (Figure 7) would cost about $490,000. A borehole field taking advantage of summer recharge supplying 6.7°C fluid to 16 heat pumps (Figure 7) would cost about $250,000.

WEATHERFORD, OKLAHOMA BRIDGE DECK SAMPLE RESULTS

To provide some understanding of the hour-to-hour operation of the bridge deck, results are presented for a single day in the winter when there is snowfall and a single day in the summer when the system is storing heat in the ground. The system was simulated with 1983 Oklahoma TMY weather data. Again, neither the winter control strategy nor the summer recharge strategy is yet optimized, but the results are of some interest. Figure 9 shows the surface temperature, ambient air temperature, and snowfall for January 1, when the snowfall starts late in the afternoon.. Under these relatively mild conditions, only one pair of heat pump operates. The heat pumps become operational six hours before the snow event at hour 13. The spike in the surface temperature at 14th hour indicates that the heat pump has been switched on. Figure 10 shows the first heat pump entering fluid temperature (EFT), the second heat pump entering fluid temperature, and the exit fluid temperature (ExFT) from the gang of heat pumps. It is quite a bit lower due to mixing with the fluid flowing through the heat pump pairs that are off. This seems likely to be less than ideal; a future research topic is to optimize the fluid circulation through the mechanical room.

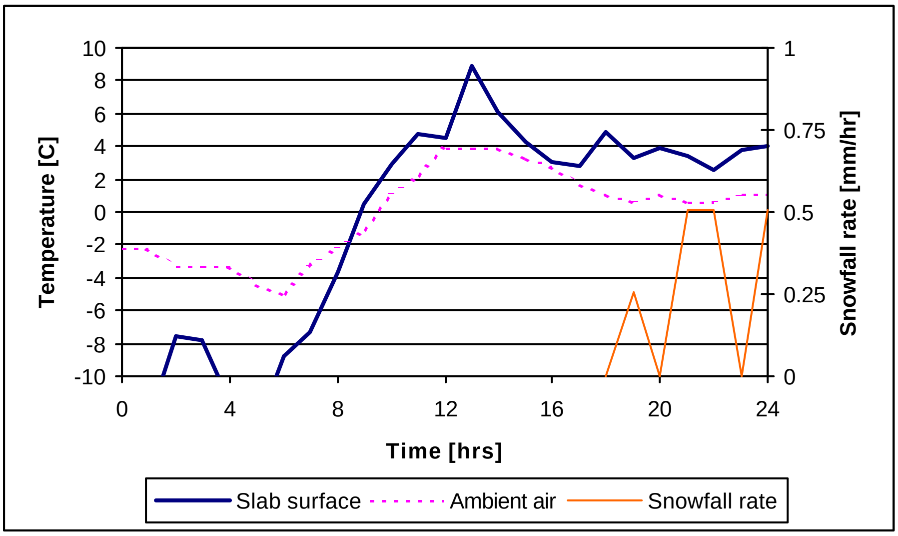

Figure 9: Surface Temperature, Ambient Temperature, and Snowfall Rate

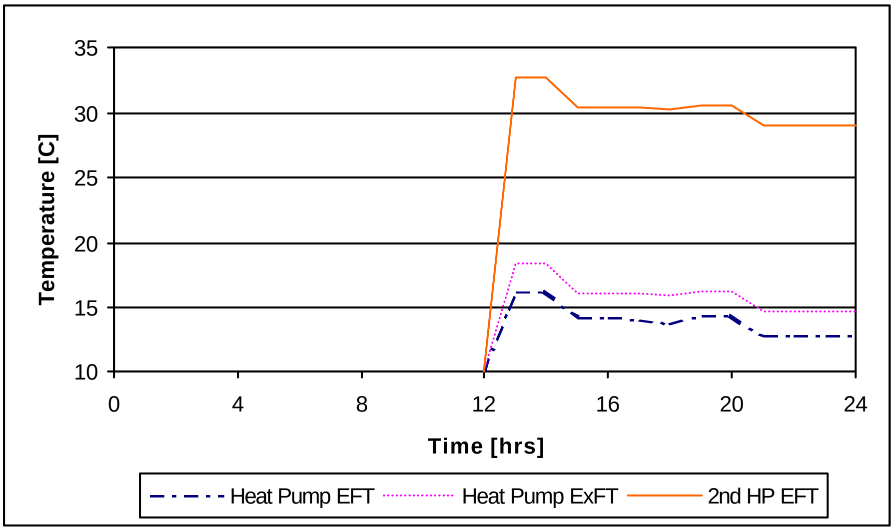

Figure 10: Heat Pump Fluid Temperatures on the Condenser Side (Winter Heating Mode)

Figure 11 shows the weather conditions and slab surface temperature for a July day when the system is recharging the ground. The loop temperatures for the day are shown in Figure 12, and the actual recharge rate is shown in Figure 13. A significant amount of heat can be extracted from the hot bridge deck during summer and stored in the ground for use in winter. Again, neither the winter control strategy nor the summer recharge strategy is yet optimized.

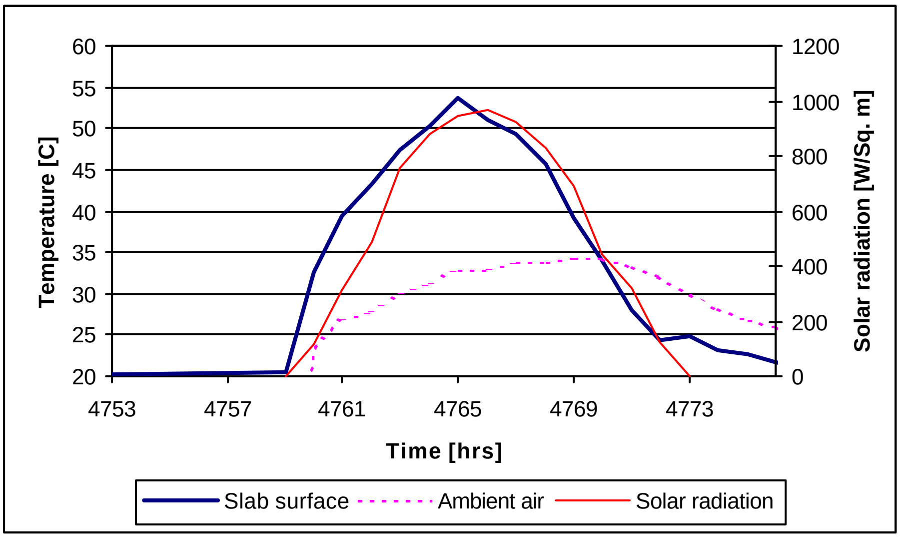

Figure 11: Surface Temperature, Ambient Temperature, and Solar Radiation during summer day

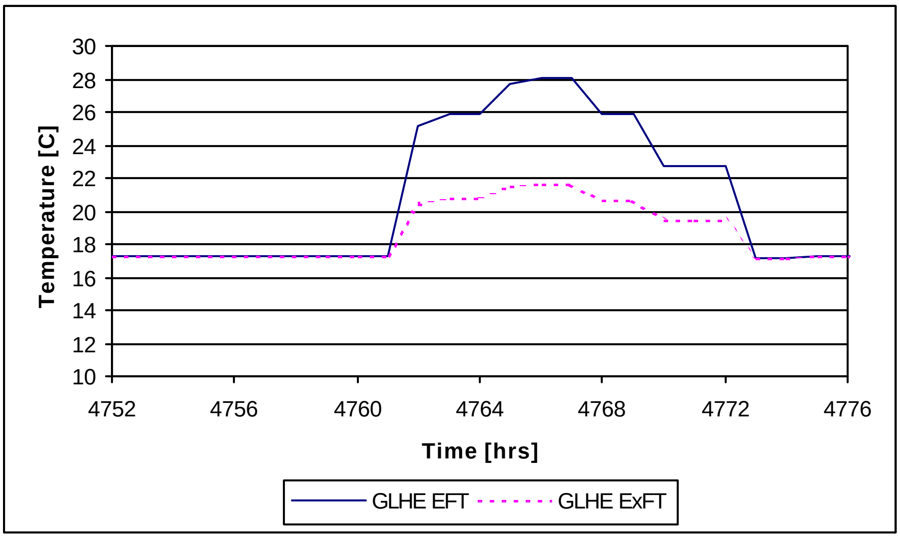

Figure 12: Ground Loop Entering and Exiting Fluid Temperatures (Recharge Mode)

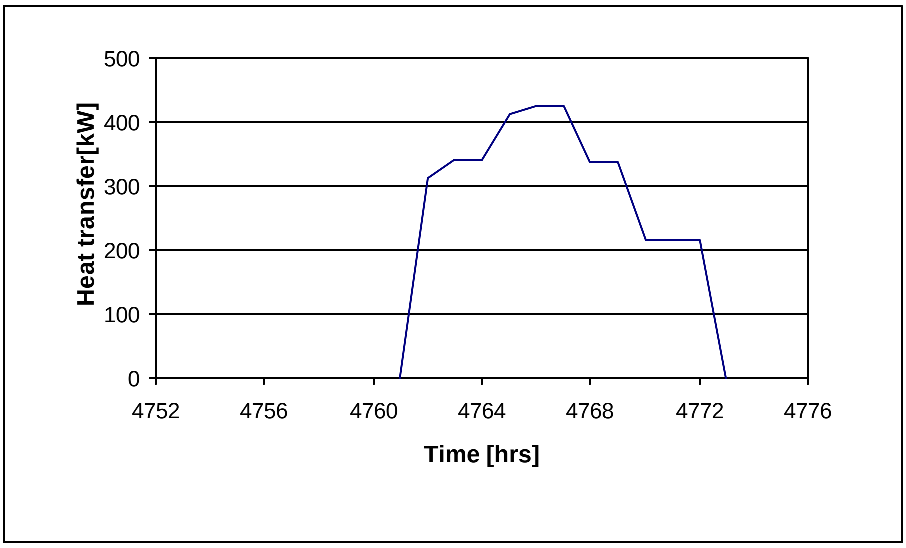

Figure 13: Recharge Heat Transfer Rate

CONCLUSIONS

The design of a bridge deck heating system for a bridge deck on Interstate 40, East of Weatherford, Oklahoma has been presented. The design procedure made use of existing design tools and recently developed component models of hydronically-heated bridge decks, water-to-water heat pumps, and ground loop heat exchangers. In addition, preliminary results from research in progress on system simulation of the entire system have been presented. A significant amount of research is yet to be done on the topic of control and operating strategies. In addition, validation of the models against a medium-scale(6m x 17 m) hydronically heated bridge deck located in Stillwater, Oklahoma is planned.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Federal Highway Administration under Grant No. DTFH61-99-X-00067. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the Authors and do not necessarily reflect the view of the Federal Highway Administration. Earlier funding that helped establish the basis of this work by the Oklahoma Department of Transportation and the U.S. Department of Energy is gratefully acknowledged.

REFERENCES

1. Wadivkar, O. 1997. An Experimental and Numerical Study of the Thermal Performance of a Bridge Deck De-icing System. M.S. Thesis. Oklahoma State University School of Mechanical and Aerospace Engineering.
2. Solar Energy Laboratory (SEL). 1997. *TRNSYS, A Transient Systems Simulation Program, User's Manual, Version 14.2.* University of Wisconsin-Madison.
3. Clark, D.R. and W.B. May. 1985. *HVACSim+ Building System and Equipment Simulation Program – Users Guide.* National Bureau of Standards.
4. Adlam, T.N. 1947. *Radiant Heating*. The Industrial Press, New York, NY.
5. Chapman, W.P. 1952. Design of Snow Melting Systems. *Heating and Ventilating*. April, pp. 96-102

6. Kilkis, I.B. 1994. Design of Embedded Snow Melting Systems: Part 1, Heat Requirements – An Overall Assessment and Recommendations. *ASHRAE Transactions*, 100(1):pp. 423-433.
7. ASHRAE 1999. *ASHRAE Handbook*, *HVAC Applications*. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA.
8. Ramsey, J.W., M.J. Hewett, T.H. Kuehn, and S.D. Petersen. 1999. Updated Design Guidelines for Snow Melting Systems. *ASHRAE Transactions*, 105(1).
9. Chiasson, A. 1999. Advances in Modeling of Ground-Source Heat Pump Systems. M.S. Thesis, School of Mechanical and Aerospace Engineering, Oklahoma State University. Also available at: http://www.mae.okstate.edu/Faculty/spitler/pdfs/chiasson_thesis.pdf.
10. Yavuzturk, C., J.D. Spitler. 1999. A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers. *ASHRAE Transactions*. Vol. 105, No. 2. pp. 475-485.
11. Eskilson, P. 1987. *Thermal Analysis of Heat Extraction Boreholes.* Doctoral Thesis, University of Lund, Department of Mathematical Physics. Lund, Sweden.
12. Jin, H. and J.D. Spitler. 2000. A Parameter Estimation Based Model for Water-to-Water Heat Pumps. Submitted for publication to *The International Journal of HVAC&R Research.*
13. Chiasson, A., J.D. Spitler. 2000. *A Modeling Approach To Design Of A Ground-Source Heat Pump Bridge Deck Heating System*. Accepted for Publication in Proceedings of the 5th International Symposium on Snow Removal and Ice Control Technology. Roanoke, VA. September 5-8, 2000
14. Spitler, J. D., C. Marshall, R. Delahoussaye, and M. Manicham. 1996. *Users Guide of GLHEPRO*, School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK