A Simulation Tool for the Hydronic Bridge Snow Melting System

Xiaobing Liu Jeffrey D. Spitler[1]

ABSTRACT

The design of hydronic heating systems for bridge snow melting requires assessment of long-term performance under expected future weather conditions, especially when geothermal energy is used as the heat source. This is important to be able to predict the snow melting performance, analyze the economics, and investigate the effects of controls and design parameters on the system performance. A simulation tool for modeling hydronic bridge snow melting systems using ground source heat pumps (GSHP) or other heat sources has been developed to facilitate the design. In this paper, a numerical model of the hydronically-heated bridge deck and the experimental validation results of the model predictions are described. In addition, the structure and features of the simulation tool are presented. As an application of the simulation tool, the ASHRAE guidance for required surface heat fluxes for snow melting is evaluated with a simulation-based parametric study.

INTRODUCTION

Melting snow with a hydronic heating system can eliminate the need for snow removal by chemical or mechanical means and provide greater safety for pedestrians and vehicles. As a result, a large number of snow melting systems have been installed, including sidewalks, roadways, ramps, bridges, runways and parking spaces for the handicapped. Hydronic heating systems circulate a heated fluid through a pipe network embedded in the slab to melt snow and ice on the surface of the slab. The pipe network consists of number of circuits, which are usually laid in a serpentine configuration. The pipe material is usually either cross-linked or high-density polyethylene. Typical pipe spacing ranges from 150 to 300mm at a depth of 50 to 75mm. Nominal pipe diameters are commonly 18 to 25 mm. A variety of fluids, including brine, oils, and glycol-water, are suitable as heat carrier fluids in hydronic heating systems. Freeze protection is essential since most systems will be operated intermittently in subfreezing weather. A number of heat sources can be used for such systems, including boilers, electrical heater, ground water, and ground source heat pump.

Design of hydronic snow melting systems is a topic of current and recent research. Current guidance in the ASHRAE handbook (ASHRAE 2003) for required surface heat fluxes is based on a one-dimensional steady-state heat balance (Ramsey, et al. 1999) of the snow-melting surface. This approach is limited by the fact that real systems are almost never operated continuously through the winter, nor do weather conditions remain constant. Accordingly, the large thermal mass of the bridge deck requires that transient performance be considered. In addition, two-dimensional effects, such as pipe spacing and depth, are clearly important, but neglected by the procedure. Furthermore, the required heat fluxes were all computed assuming that there would be no contribution from solar radiation. This is a conservative approximation but its effect is not well understood. Given the transient, two-dimensional and solar effects, it is unclear how an actual snow melting system performance might compare to the ASHRAE guidance.

[1] Oklahoma State University, School of Mechanical and Aerospace Engineering, spitler@okstate.edu

The design will be more complicated if a GSHP system is used as the heat source. This is due to the need to consider the long-term changes in performance of the ground heat exchangers. It is usually necessary to model the performance of the ground heat exchangers over a period of as long as 25 years in order to ensure an adequate design. It is accordingly necessary to consider, not static design conditions, but the time varying nature of heating loads over these periods. Proper consideration of these complexities requires some reliance on system simulation in the design process.

This paper describes a numerical model of the hydronically-heated bridge deck and the experimental validation results of the model predictions. In addition, the structure and features of a simulation tool of the hydronic bridge snow melting system using ground source heat pump (GSHP) or other heat sources are presented. As an application of the simulation tool, the ASHRAE guidance for required surface heat fluxes for snow melting is evaluated with a simulation-based parametric study.

MODELING SNOW MELTING ON A HYDRONICALLY-HEATED SLAB

The process of melting snow on a hydronically-heated bridge deck is complex. Heat transfer mechanisms involved in the snow melting process include the phase change of water (melting and evaporation), solar radiation, thermal radiation, convective heat transfer on the surface, and the conductive heat transfer from the pavement slab. Furthermore, snow is a porous material composed of ice crystals and air, and its melting is characterized by the permeation of melted water due to capillary action. Depending on the water permeation through the porous structure of snow and the refreezing of permeating water, the snow can be fully saturated with water, which is usually called slush; or retain its air-filled porous structure, which is recognized as dry snow. While dry snow can significantly reduce the heat loss from the surface, the slush has little “insulating effect”. Due to the variation of weather conditions and the discrete layout of the embedded pipes, the surface conditions can vary both temporally and spatially. Different surface conditions are associated with different heat transfer mechanisms. Figure 1 shows a cross-section view of the pavement slab while snow is melting on it.

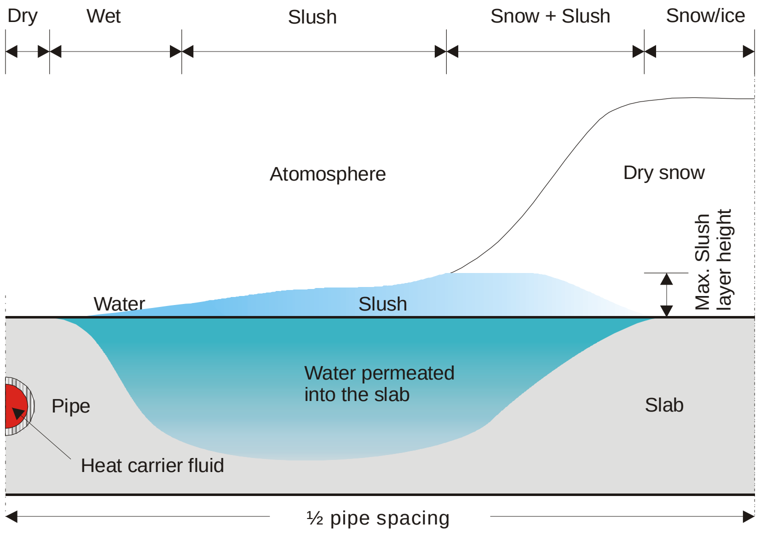

FIGURE 1 Variation of surface conditions in snow melting -- a cross-section view of the slab while snow is melting on it.

A number of models for snow melting on hydronically-heated slabs have been previously presented. However, previously developed models are unsuitable for facilitating the design in that they are: steady-state, and therefore incapable of modeling transient effects

(Schnurr and Rogers 1970; Kilkis 1994); or incapable of accounting for snow accumulation (Leal and Miller 197; Schnurr and Falk 1973), or did not account for the insulating effects of the snow (Chiasson, et al. 2000), or too detailed and requiring an infeasible amount of computational effort for multi-year hourly or sub-hourly simulations (Rees et al. 2002).

The model adopted in the simulation tool is developed from an existing model (Chiasson, et al. 2000). While the transient conduction heat transfer in the slab is still modeled using the two-dimensional finite difference method, the modeling of the snow melting process occurring on the surface has been significantly revised. The mass of snow is tracked along with the surface temperature at each surface node. Thus, the condition at each surface node can be identified and the distribution of snow/ice and slush over the surface can be predicted. The coupling between the surface heat balance and the conduction heat transfer in the slab is processed with a modified "time marching" method to deal with the phase change of water involved in the snow melting process. In addition, an improved model for calculating the equivalent sky temperature (Brown 1997) is employed in the model to calculate the radiative heat loss from the slab surface to the sky. This model may also be useful for modeling electric resistance heating systems and predicting the road surface temperature. Detailed description of this model is given in the paper of Liu and Spitler (2004).

EXPERIMENTAL VALIDATION

Individual component models and system simulation of a GSHP based hydronic bridge snow melting system have been validated with experimental data. The experimental facility consists of an 18.2 m x 6.1 m bridge deck with a 9.1 m x 6.1 m area hydronically heated by a GSHP system. The facility and data collection procedures were reported in a previously published paper (Liu, et al. 2003). In the previous work, surface condition measurements were not available to validate model predictions of the ratio of the snow-free surface area to the total surface area. In this paper, the comparison between the predicted and actual variation of the snow free area ratio (SFAR) will be presented. The actual SFAR is estimated from images of the bridge surface, which was taken and recorded with a digital camera at 30-minute intervals. A completely snow-free surface leads to a snow free area ratio of 1; a completely snow covered surface leads a ratio of zero; and "striping" leads to intermediate values.

The event selected for validation occurred in Stillwater, Oklahoma on December 23, 2002. It started with rainfall at about 6:00 in the morning; the rainfall changed to snow around 9:00 am and the snowfall ceased at about 4:30 pm. The total amount of precipitation in equivalent water was 29 mm during the whole event. In this event, the heating system was activated 1 hour after the snowfall began because of a problem with the automatic control system. Although unintentional, it provided a good scenario for validating the simulation performance.

As can be seen in Figure 2, SFAR falls to zero at the beginning of snowfall, and then rises to one as the system heats the bridge; the predicted snow free area ratios satisfactorily match the actual surface conditions. Measured and predicted bridge average surface temperatures during the heating operation are also compared in the same figure. As illustrated in Figure 2, the surface temperature dropped immediately after snowfall began at 9:00 am and stayed at about 0.7 °C until the heating system was started at 10:00 am. From then on, the bridge surface temperature began to increase continuously. At about 1:00 pm, snow on some areas of the bridge surface was completely melted and "stripes" began to appear (SFAR > 0). Since heat flux required for snow melting is reduced, the speed of the temperature rise increased significantly. Good agreement between measured and predicted values of the average bridge surface temperatures is observed before the snow free area ratio reaches 1; after that, the predicted surface temperatures deviate further from the measured values. This may be partially due to the variation of the thermal properties of the concrete, as it is saturated with water and gradually dries out following the snow melting process, and partially due to snow drifting from the unheated portion to the heated portion of the bridge. These phenomena can either reduce the heat conducted to the surface or introduce additional heat fluxes for snow melting and water evaporation on the surface and thus decrease the average surface temperature.

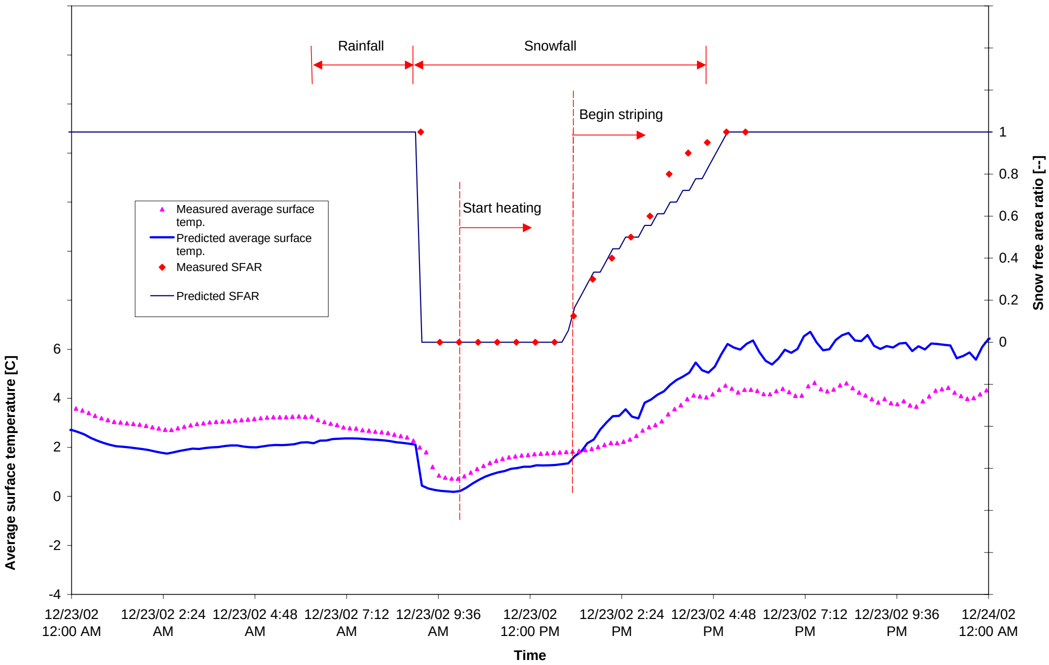

FIGURE 2 Comparison between measured and predicted bridge average surface temperature and snow free area ratio.

STRUCTURE OF SIMULATION TOOL

The simulation tool consists of a collection of component models of the hydronic bridge snow melting system, a system simulation tool, HVACSIM+ (Clark 1985), and utility programs to generate required input files of the simulation and to analyze the simulation results. Table 1 categorizes the currently available component models. A parameter-estimation-based model developed by Jin and Spitler (2002, 2003) is used for the water-to-water heat pump. The various parameters of the model are estimated from the manufacturers' catalog data by applying a multi-variable optimization algorithm. The model for the vertical ground loop heat exchanger (VGLHE) was developed by Yavuzturk and Spitler (1999), which extends the g-function method proposed by Eskilson (1987) and thus is able to predict both the short and long term performances of a field of VGLHE.

TABLE 1 List of Component Models

Heating Element	Heat Source	Controller	Accessories
Hydronically-heated bridge pavement	Water-to-water heat pump	Linear proportional control	Circulating pump
	Vertical ground loop heat exchanger	On-off control with dead band	Conduit
	Electric heater		Valve

Boiler

The simulation is implemented with a graphical interface (Varanasi 2002) for HVACSIM+(Clark 1985), which is a public domain dynamic simulation program developed at the National Institute of Standards and Technology (NIST). This simulation program employs a hierarchical, modular approach that allows the component models to be connected together in a flexible way (and also facilitates investigation of novel system configurations). In the system simulation, the mass flow rates of the heat carrier fluid can either be treated as constants or solved explicitly. To explicitly solve the mass flow rates, the flow-pressure problem of the fluid network and the thermal problem of the system may be solved subsequently at each simulation time step. Thus, the variation of mass flow rates resulting from the changes of the fluid viscosity can be accounted. However, it increases the complexity and computational time requirements of the simulation.

Weather data required in the system simulation include: ambient temperature, effective sky temperature, humidity ratio of air, wind speed, wind direction, solar radiation, solar angle, snowfall rate, and rainfall rate. A utility program has been developed to convert weather data from various sources, including SAMSON (NCDC 1993), Oklahoma Mesonet (Elliot et al. 1994), and NVDS (2002), to the boundary condition file required by the simulation. The g-function data used in the VGLHE model and the parameters of the water-to-water heat pump model are generated separately with special utility programs prior to the simulation.

APPLICATION OF THE SIMULATION TOOL

As an application of the simulation tool, a preliminary evaluation of the ASHRAE guidance for required surface heat fluxes for snow melting is conducted by a simulation-based parametric study. Current guidance in the ASHRAE handbook (HOA 2003) for required surface heat fluxes is based on a one-dimensional steady-state heat balance (Ramsey et al. 1999) of the snow-melting surface. For 46 North American locations, the required heat flux to maintain a specified snow free area ratio for a statistically-determined percentage of hours with snow fall has been tabulated. Required heat fluxes are given for snow free area ratios of 0, 0.5, and 1, and for percentage-of-snowfall-hours-not-exceeded of 75%, 90%, 95%, 98%, 99% and 100%. For intermittently operated systems, these heat fluxes would be correct only for systems that could instantaneously transmit their heating capacity to the road surface. However, it is desirable to estimate the percentages for transient operation with the tabulated heat flux capacities, and the use of the simulation tool to do so is described in this section.

A simple hydronic snow melting system is simulated. This system consists of a hydronically-heated slab, a circulating pump, a heater and a controller. The parameters of the hydronically-heated slab are intended to be typical for a heated bridge deck application and are summarized in Table 2. The heater, when operating, provides a constant heat input to the slab. The heat provided by the heater is specified to be the multiple of the heated area and the tabulated ASHRAE surface heat fluxes. To provide the specified heat input, the fluid temperature will rise to the necessary level although this may sometimes result in unfeasibly high fluid temperatures. Since the purpose of this simulation is to evaluate the surface heat flux, neither thermal mass nor transport delay is considered in the heater model. The controller is assumed to be perfect – it will turn on the heating system a certain number of hours in advance of the snowfall, and will turn it off at the end of the snowfall. This number of hours is referred to as the idling time. This perfect control is accomplished by looking ahead in the weather file.

Since the weather conditions associated with snow events vary widely, it is desired to investigate the snow melting performance with a number of years of weather data in order to draw more reliable conclusions on the effect of transient weather/operation conditions on the snow melting performance. We have chosen ten different North American locations to represent a range of climates: Spokane, Reno, SLC, Colorado Springs, Chicago, OKC, Minneapolis, Buffalo, Boston and Philadelphia. SAMSON data from 1981-1990 for each of the locations were used in the simulations. The computational time for each 10-year hourly simulation is around 40 minutes on a Pentium 4, 2.8G HZ personal computer.

TABLE 2 Parameters of the Hydronically-Heated Slab

Parameter Name	Parameter Value
Slab Thickness	203 mm
Slab Thermal Conductivity	1.4 W/m.K
Slab Volumetric Heat Capacity	2200 kJ/m^3.C
Slab Surface Solar Absorptance	0.6
Pipe Spacing	152 mm
Pipe Depth Below Surface	76 mm
Pipe Diameter	25mm
Pipe Wall Thickness	2 mm
Pipe Wall Thermal Conductivity	0.39 W/m.K
Bottom Insulation	Adiabatic
Heat Carrier Fluid	Propylene Glycol (42% concentration by mass)

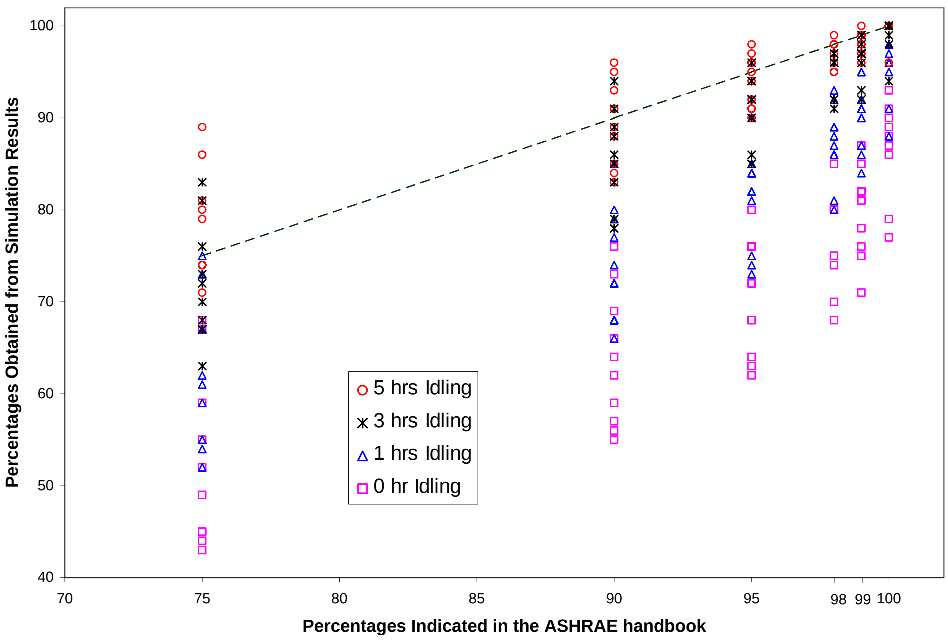

FIGURE 3 Comparison of snow melting performance between predictions of the 2-D transient simulation and those indicated in ASHRAE handbook

The predicted snow melting performance is shown in Figure 3. The horizontal axis represents the percentage of snowfall hours where the surface would be snow free, based on the tabulated ASHRAE surface heat flux values, which vary with location. The vertical axis represents the percentage of snowfall hours where the surface would be snow free, based on transient simulation results of the systems with heating capacity corresponding to the ASHRAE surface heat flux. The diagonal line represents a one-to-one match between the performance of the system calculated with the transient simulation and the performance calculated based on a steady state heat balance. A point on this line would represent a case where the actual performance is as good as that predicted with the ASHRAE steady state heat balance analysis. In the plot, different symbols refers to cases with different idling times; individual data points with same symbol show the system performance at different locations.

As expected, the performance increases increasing idling times. For zero hours idling, i.e. the system is turned on when snowfall starts, the performance for all locations falls substantially below that predicted with a steady state heat balance. For most locations, approximately 5 hours of idling will give system performance similar to that expected from the steady state heat balance. However, it may be noted that a few data points show good performance for even one hour of idling, and performance exceeding that expected from the steady state heat balance with three hours of idling. These data points correspond to Reno and Salt Lake City where the average dry bulb temperature coincident with snowfall is comparatively high.

The simulations results illustrate that, for the system investigated in this parametric study, preheating the slab 3-5 hours before snowfall with the full heating capacity obtained from the ASHRAE surface heat flux requirement is necessary to achieve the desired snow melting performance. Such operation is considerably more energy efficient than the continuous idling operation described in the ASHRAE Handbook, which is to maintain the slab surface temperature at 0.6 °C by supplying heat to the slab anytime the ambient temperature is below 0°C and it is not snowing. Therefore, forecasting-based control systems should be utilized in the hydronic snow melting systems.

CONCLUSIONS AND RECOMMENDATIONS

The dynamic nature of the hydronic bridge snow melting systems requires that the long-term seasonal performance be assessed in their design. This design exercise can most conveniently be undertaken by the application of simulation methods.

A numerical model for the snow-melting process occurring on a hydronically-heated surface has been developed. Various surface conditions encountered during the snow melting process have been identified and modeled with a simplified approach to achieve a balance between model accuracy and computational time requirement. Experimental validation results have shown that the model is able to predict bridge deck surface temperature and SFAR sufficiently accurate for the purposes of system design and performance analysis.

A simulation tool for the hydronic bridge snow melting systems has been developed. It consists of component models, the modular simulation environment HVACSIM+, a graphical user interface, and associated utility programs. The simulation tool allows the convenient analysis of hydronic bridge snow melting systems with various configurations.

The simulation tool has been used to evaluate the performance, under realistic transient operating conditions, of snow melting systems designed with the heat fluxes given in the ASHRAE handbook. Simulation results demonstrate that the heating capacity calculated directly from the tabulated ASHRAE surface heat fluxes is not enough to achieve the expected snow-melting performance without idling, even if the heat loss from back and edges of the slab are eliminated. However, idling the system in advance of the snow event can significantly improve the snow melting performance. It is more energy efficient compared with the continuous idling operation described in the ASHRAE Handbook. Therefore, forecasting-based control systems should be utilized in the hydronic snow melting systems.

To achieve an economically feasible and technically reliable hydronic bridge snow melting system, a systematic design procedure and proper optimization algorithm are recommended for future development of the simulation tool.

ACKNOWLEDGEMENTS

This material is based on work supported by the FHWA. Earlier funding, that helped establish the basis of the work, was provided by the Oklahoma Department of Transportation and U.S. Department of Energy and is gratefully acknowledged.

REFERENCES

ASHRAE. Handbook of HVAC Applications 2003 (IP). Chapter 50. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Brown, D.F. 1997. An Improved Methodology for Characterizing Atmospheric Boundary Layer Turbulence and Dispersion. Ph. D. Thesis, UIUC, IL.

Chiasson A.D., J.D. Spitler, S.J. Rees, and M.D. Smith. 2000. A model for simulating the performance of a pavement heating system as a supplemental heat rejecter with closed-loop ground-source heat pump systems. ASME Journal of Solar Energy Engineering. November 2000. 122:183-191

Clark, D.R. HVACSim+ Building System and Equipment Simulation Program – Reference Manual. NBSIR 84-2996, National Bureau of Standards, 1985.

Elliot, R.L., F.V. Brock, M.L. Stone, and S.L. Sharp. 1994. Configuration decisions for an automated weather station network. Applied Engineering in Agriculture, 10(1): 45-51.

Eskilson, P. 1987. Thermal Analysis of Heat Extraction Boreholes. Doctoral Thesis, University of Lund, Department of Mathematical Physics. Lund, Sweden.

Jin, H. and J.D. Spitler. 2002. A parameter estimation based model of water-to-water heat pumps for use in energy calculation programs. ASHRAE Transactions. 108(1): 3-17.

Jin, H. and J.D. Spitler. 2003. Parameter estimation based model of water-to-water heat pumps with scroll compressors and water/glycol solutions. Building Services Engineering Research and Technology. 24(3):203-219.

Kilkis, I.B. 1994. Design of embedded snow melting systems: part 2, heat transfer in the pavement – a simplified model. ASHRAE Transactions, 100(2): 434-441.

Leal, M. and P.L. Miller. 1972. An analysis of the transient temperature distribution in pavement heating installations. ASHRAE Transactions, 78(2): 61-66.

Liu, X., S.J. Rees, J.D. Spitler. 2003. Simulation of a geothermal bridge deck anti-icing system and experimental validation. Proceedings of the Transportation Research Board 82nd Annual Meeting, Washington, D.C. January 12-16, 2003

Liu, X. and J.D. Spitler. 2004. Development and experimental validation of a numerical model for the hydronic bridge snow-melting system. Submitted to Journal of Applied Thermal Engineering.

NCDC (National Climatic Data Center). 1993. Solar and meteorological surface observation network 1961-1990 (SAMSON) (CD-ROM), Version 1.0.

NVDS (National Virtual Data System). 2002. 2. Hourly cloud cover data is obtained from the National Virtual Data System at the following URL:
http://nndc.noaa.gov/?http://ols.ncdc.noaa.gov/cgi-bin/nndc/buyOL-002.cgi

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): 1055-1065.

Rees, S.J., J.D. Spitler and X. Xiao. 2002. Transient analysis of snow-melting system performance. ASHRAE Transactions, 108(2): 406-423.

Schnurr, N.M. and M.W. Falk. 1973. Transient analysis of snow melting systems. ASHRAE Transactions, 79(2): 159-166.

Schnurr, N.M. and D.B. Rogers. 1970. Heat transfer design data for optimization of snow melting systems. ASHRAE Transactions, 76(1): 257-263.

Varanasi, A. Development of a Visual Tool for HVACSIM+. M.S. Thesis. Oklahoma State University, Stillwater, OK, 2002. (http://www.hvac.okstate.edu/pdfs/THESIS_AdityaV.pdf)

Yavuzturk, C., J.D. Spitler. 1999. A short time step response factor model for vertical ground loop heat exchangers. ASHRAE Transactions. 105(2):475-485.