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Simulation Based Investigation on the Design of Hydronic Snow Melting System

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ABSTRACT

Hydronic heating systems that circulate a heated fluid through pipes embedded in a bridge deck or roadway may be used to eliminate or reduce dangerous driving conditions caused by snow and ice. The first important task in sizing such a system is determining the required heat flux. Current guidance in the ASHRAE HVAC Applications Handbook for required surface heat fluxes is based on a one-dimensional steady-state heat balance of the snow-melting surface. For a range of locations, the required heat flux to maintain a specified surface condition for a statistically-determined percentage of hours with snow fall has been tabulated. This approach is limited by the fact that real systems are almost never operated continuously through the winter. Also, two-dimensional effects, such as pipe spacing and bottom losses are clearly important, but neglected by the procedure used to develop the design heat fluxes.

This paper describes a parametric study to investigate the impact of idling time, heating capacity, pipe spacing, bottom insulation, and control strategies on system snow melting performance. An experimentally validated hydronic snow melting system simulation has been run for several different North American locations, using up to ten years of weather data. With all parametric variations, 528 simulations were run.

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 6-12 in. (150-300mm) at a depth of 2 to 3 in (50-75mm). Nominal pipe diameters are commonly ¾ or 1 inch (20 or 25 mm).

Determining the heating capacity is the first important task in the design of the hydronic snow melting system. Current guidance in the ASHRAE HVAC Applications Handbook *(1)* for required surface heat fluxes is based on a one-dimensional steady-state heat balance *(2)* 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%.

This approach is limited by the fact that real systems are almost never operated continuously through the winter due to the energy cost implications. Rather, the systems are turned on when a pavement sensor detects the presence of snow or ice. It is also possible that the systems may be turned on a few hours in advance of a snowfall event. While not common practice, such a control system is the topic of an ongoing research project *(3)*.

Also, two-dimensional effects, such as pipe spacing and bottom losses are clearly important, but neglected by the procedure used to develop the design heat fluxes. The pipe spacing, pipe depth, and slab insulation can all have a significant effect *(4)* on the heating capacity required to achieve a certain snow-melting performance. 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 tabulated values. The aim of this paper is to provide a preliminary evaluation of the impacts of transient and two-dimensional effects on the snow melting performance. Instead of using a one-dimensional steady-state heat balance on the snow-melting surface, a simulation of the hydronic snow melting system is utilized, which employs a transient and two-dimensional model for snow melting on the hydronically-heated slab and uses ten years of actual weather data. The simulation has been experimentally validated *(5,6)* and is used in a parametric study to investigate the effects of idling time, pipe spacing, slab insulation, etc. on the system performance.

ASHRAE SNOW-MELTING HEAT FLUX REQUIREMENT

Tabulated surface heat flux requirements for 46 North American cities in the ASHRAE Handbook of HVAC Applications *(1)* are based on the results from a recent ASHRAE research project *(2)*. The algorithm for calculating the surface heat flux requirements was based on the steady-state energy balance for required total heat flux (heat flow rate per unit surface area) q_o at the upper surface of a snow-melting slab during snowfall:

$$q_o = q_s + q_m + A_r(q_h + q_e) \tag{1}$$

where, q_s is the heat flux required to raise the temperature of snow falling on the slab to the melting temperature plus, after the snow has melted, to raise the temperature of the liquid to the assigned temperature of the liquid film; q_m is the heat flux required to melt the snow; heat flux q_h includes convective losses to the ambient air and radiative losses to the surroundings; q_e is the heat flux needed for evaporating the melted snow. A_r, the snow-free area ratio, is defined as the ratio of the snow free area of a surface to the total area of the surface. The snow free area is assumed to be covered only with a thin liquid film, and devoid of any ice crystals. The procedures for evaluating each of the terms are described in references 1 and 2. In the calculations, the slab surface temperature was assumed to be uniform at 0.6°C (33°F). Based upon the frequency distribution of hourly heat fluxes, which were calculated with weather data for the years 1982 through 1993, the design heat flux was chosen to maintain certain surface snow-free area ratios for a percentage of snowfall hours.

"Idling" operation was described *(1)* as supplying heat to the slab anytime the ambient temperature is below 0°C (32°F) and it is not snowing. The purpose of such idling operation is to maintain the slab surface temperature above the freezing point of water, so that snow can be melted immediately at the beginning of snowfall with the steady-state heat flux. However, as illustrated by the data presented in the same handbook, the annual energy requirement for idling can be more than 20 times greater than that for snow melting. Obviously, such idling operation is not energy efficient and is seldom done in practice.

As reviewed previously, there are two primary limitations on the surface heat fluxes presented in the ASHRAE handbook: the first is that the calculation was based on steady state heat balance on the surface of a slab, and therefore, the transient effects of weather and operation were not taken into account; the second is that the slab surface temperature was assumed to be uniform, and therefore, the effect of the arrangement of the pipes was not considered. Since snow-melting systems generally have heating elements embedded in material of significant thermal mass, transient effects should not be neglected in determining the required surface heat flux. A two-dimensional transient analysis of the snow melting system *(4)* has shown that, for particular storm conditions, heat fluxes up to five times greater than those indicated by steady-state analysis need to be delivered to the slab in order to keep its surface clear from snow during the early hours of the snowfall when the heating system is just starting to operate. On the other hand, continuous idling of the system as described in the handbook can eliminate the transient effect but will consume too much energy to be practical. Utilizing weather forecasts and local weather data *(3)*, it may be possible to predict snow events several hours in advance with reasonable accuracy. This will significantly reduce the idling operation but may also require higher heating capacity than that calculated from the steady-state heat fluxes to achieve the desired snow melting performance. Therefore, the relationship between the idling duration and the snow melting performance is important to reach the optimal balance between the system heating capacity and the operating costs.

OBJECTIVES

The primary objective of this investigation is to evaluate the performance, under realistic transient operating conditions, of snow melting systems designed with the heat fluxes given in the ASHRAE handbook. In addition, the impact of idling time, heating capacity, pipe spacing, bottom insulation and control strategies on snow melting performance will be investigated.

SIMULATION APPROACH

A simple hydronic snow melting system is simulated in this work. 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 1. The heater, when operating, provides a constant heat input to the slab. The fluid temperature will rise to the necessary level to provide the specified heat input, 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 or when the slab surface is clear from snow. This number of hours is referred to as the idling time. This perfect control is accomplished by looking ahead in the weather file. In practice, an imperfect forecasting tool would be used. The work in this paper will be useful in determining the requirements for a successful forecasting controller. i.e., how many hours in advance does the system need to be turned on?

The system simulation was implemented in the HVACSIM+ *(7)* environment, using component models of a hydronically-heated slab, a circulating pump, a heater and a controller, connected together in a graphical user interface *(8)*.

Modeling Snow Melting on a Hydronically-Heated Slab

A number of models for snow melting on hydronically-heated slabs have been previously presented. A complete review is beyond the scope of this paper. For a detailed review, the reader is referred to reference *(9,16)*. In short, previously developed models are unsuitable for the task at hand in that they are: steady-state, and therefore incapable of modeling transient effects *(10,11)*; or incapable of accounting for snow accumulation *(12,13)*, or did not account for the insulating effects of the snow *(14)*, or too detailed and requiring an infeasible amount of computational effort for ten year simulations *(4)*.

The model used in this work is developed from an existing model described in detail by Chiasson, et al. *(14)*. 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 distribution of snow/ice and slush over the surface, and subsequently, the snow free area ratio A_r can be predicted. In this model, solar radiation absorbed by the slab surface is considered in addition to the heat flux terms utilized in equation (1). In addition, an improved model for calculating the equivalent sky temperature *(15)* is employed in the model to calculate the radiative heat loss from the slab surface to the sky. The bottom condition of the slab can be specified as either adiabatic or exposed to surrounding environment with or without insulation. 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. A detailed description of this model can be found in reference *(16)*.

This model has been validated with monitored data from a medium scale (20' x 60', 6.1m x 18.3m) experimental hydronic bridge snow melting system *(5,6)*. Monitored weather conditions, entering fluid temperature and flow rate are used as inputs to the model. Predicted average bridge surface temperature, exiting fluid temperature and surface snow free area ratio A_r compare favorably to the corresponding experimentally measured values.

Weather Data

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. In the calculations which led to the tabulated ASHRAE design heat fluxes, the weather data for the years 1982 to 1990 were taken from the Solar and Meteorological Surface Observation Network (SAMSON)*(17)*, while the data for 1991 through 1993 were taken from DATSAV2 *(18)*. Since the DATSAV2 data were not available to the investigators when the work was done, SAMSON data from 1981-1990 were used in the simulations. The average hours of snowfall were compared for the two periods; they are close (within 6 %) for six of the ten locations. For Minneapolis, OKC, Spokane and Reno, the differences are 8%, 9%, 10% and 11% respectively.

The following measurements were extracted from the SAMSON data:

- Hourly values of the precipitation amount in equivalent depth of liquid water
- Precipitation type
- Ambient air dry-bulb temperature
- Dew-point temperature
- Wind speed
- Total solar radiation incident on a horizontal surface
- Cloud cover fraction in the sky
- Cloud height

In addition to the data used in the calculation of the ASHRAE design loads, two additional measurements, total horizontal solar radiation and cloud height, are utilized in the current research in order to account for solar radiation and more accurately compute the thermal radiative exchange between the slab top surface and the sky.

ORGANIZATION AND METHODOLOGY OF PARAMETRIC STUDY

The immediate goal of the parametric study is to find the actual snow melting performance of systems with given heating capacity, idling time and slab design at particular locations. Following the ASHRAE design procedure, the snow melting performance is expressed here by the percentage of hours when the system can keep the slab surface clear from snow during snowfall. In this study, the heating capacity of the system is specified as a parameter of the heater and determined by multiplying the heated area with the surface heat fluxes tabulated in the ASHRAE Handbook, corresponding to percentage of snowfall hours not to be exceeded (75%, 90%, 95%, 98%, 99% and 100%). In addition to the location and heating capacity, other parameters to be varied include the idling time (0,1,3,5 hours), pipe spacing, and bottom boundary condition.

One of the aims of the current study is to investigate the performance of snow melting systems designed with the heat fluxes given in the ASHRAE handbook. Specifically, to what degree will a system designed with the tabulated heat fluxes be able to give the indicated snow melting performance? Therefore, most of the work has been done with a simple control strategy, referred to as “snow only.” This control strategy turns the system on at its full design capacity during snowfall and during the idling period. This strategy may not be energy efficient and will often result in excessively high fluid temperatures when the system is operated in relatively mild weather conditions.

In addition, a more practical control strategy, referred to as “snow and surface temperature” has been evaluated. This control strategy turns the system on during the same times (during snowfall and idling) as the “snow only” control strategy. However, the system output is modulated so that the temperature on the surface midway between pipes is not higher than 3°C. This is implemented with a deadband control strategy. During idling or snowfall, the controller will turn on the heater if the surface temperature between the two adjacent pipes is lower than 2.5 ºC; and turn off it if the temperature is higher than 3 ºC. In addition, if any snow remains after the snowfall is over, the controller will continue to maintain the surface temperature within the specified range.

The parametric studies are divided into four sets of cases, as shown in Table 2. In the first two sets of cases, the bottom of the slab is assumed to be perfectly insulated (adiabatic). The first and second sets are identical, except that the pipe spacing is 6” (150 mm) in the first set and 12” (300 mm) in the second set. (Also, only five locations are simulated.) In the third set of cases, the bottom of the slab is fully exposed to the environment without any insulation. The pipe spacing of 6” (150 mm) is specified in this set of cases. In the first three sets of parametric studies, the “snow only” control strategy is used. The fourth set, which uses the “snow and surface temperature” control strategy, has utilized only five years (1981-1985) for two locations -- Chicago and SLC. In total, there are 528 different cases in the parametric study. The computational time for each case (10 year simulation) is around 40 minutes on a Pentium 4, 2.8G HZ personal computer. Batch files are used to automate the parametric study.

RESULTS AND DISCUSSION

The simulation results were analyzed to characterize the relationship between the idling time, heating capacity and snow melting performance of a hydronic snow melting system. In addition, the effects of the arrangement of the pipes, bottom insulation and control strategies on this relationship are also investigated.

Relationship among the Idling Time, Heating Capacity and Snow Melting Performance

Figure 1 is an attempt to show the results of the first set of parametric study cases all on one plot. 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.

This difference can be seen more clearly in Figures 2 and 3, which show results for Chicago and Salt Lake City. The bars in these figures indicate the snow melting performance predicted by the simulation. For Chicago, five hours of idling gives performance similar (but not quite equal) to that expected from the steady state heat balance. However, for Salt Lake City, three hours of idling gives results that are close to or exceed that expected from the steady state heat balance. To try to understand this phenomenon, a number of measures of the weather data were calculated. For hours coincident with snowfall, average values of dry bulb temperature, solar radiation flux, wind speed and snowfall rate were considered. At present, the best explanation seems to be that the average dry bulb temperature coincident with snowfall is comparatively high at Salt Lake City and Reno. This can be seen in Figure 4. Given the higher dry bulb temperature it is likely that the slab temperatures are also naturally higher, on average, at the start of each snowfall event. Therefore, less energy is required to raise the slab temperature above freezing. The higher dry bulb temperature also means less convective and radiative heat loss from the top surface of the slab. As a result, the surface heat flux requirements at Salt Lake City and Reno are significantly lower than those at other locations as can be seen in the ASHRAE surface heat fluxes *(1)*.

Effects of Slab Parameters

Three combinations of pipe spacing and bottom condition have been simulated for a range of locations, heating capacities, and idling times in the first three sets of parametric studies, which use the “snow only” control strategy. However, due to space limitations, only the results of Chicago and Salt Lake City are shown in Figure 5 and Figure 6 respectively. Each figure gives the actual performance vs. the design performance for four different idling times and 6” (150 mm) and 12” (300 mm) pipe spacing with adiabatic bottom condition, and 6” (150 mm) pipe spacing with exposed bottom condition.

As can be seen, either increasing the pipe spacing or eliminating the bottom-side insulation degrades the performance of the system. Increasing the pipe spacing makes it more difficult to uniformly heat the top surface of the slab. Furthermore, this analysis assumes that the same heat flux is achieved with either spacing. However, increasing the pipe spacing requires higher fluid temperatures, some of which are infeasible.

Effects of Control Strategies

As discussed above, most of the simulations have been implemented with a “snow only” control strategy. In addition, 48 five-year simulations have been run with the “snow and surface temperature” control strategy. Figure 7 and 8 show the snow melting performance and maximum entering fluid temperatures to the slab resulting from different combinations of control strategy and pipe spacing in Chicago.

It can be seen in Figure 7 that using the “snow and surface temperature” control strategy degrades the snow melting performance compared with the “snow only” control. The decrease in performance is due to the lower surface temperatures maintained with the “snow and surface temperature” control strategy. Increasing the pipe spacing from 6” (150 mm) to 12” (300 mm) further degrades the performance.

Although the “snow only” control strategy would seem to perform better, it often requires impractically high fluid temperatures, as can be seen in Figure 8. Likewise, even with the “snow and surface temperature” control strategy, a 12” (300 mm) spacing requires very high fluid temperatures to deliver the design heat fluxes. The heat source, piping material, and working fluid place limitations on the maximum fluid temperature. For example, a heat pump system typically cannot exceed 55°C (131 °F). Crossed-link polyethylene piping used in radiant heating systems typically has an upper temperature limit of 82°C (180 °F). Water/anti-freeze solutions may be able to exceed 100°C (212°F), but it is not clear that using such high temperatures is advisable.

This raises the question of whether or not the system performance can be satisfactory if a reasonable maximum fluid temperature is a constraint to the design. As can be seen in Figure 7, with 6” (150 mm) pipe spacing, five hours of idling and the "snow and surface temperature" control strategy, the 99% design requires a maximum fluid temperature of 70°C (163°F), but yields snow-free surface conditions for only 88% of the snowfall hours. However, it should be kept in mind that "snow-free" means no ice crystals at all, whether they are in snow or slush. Presumably, conditions that are not snow-free, but mostly snow-free are safer than conditions where the roadway is completely snow-covered.

CONCLUSIONS AND RECOMMENDATIONS

A computer simulation of the hydronic snow melting system 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. In addition, the impact of idling time, heating capacity, pipe spacing, bottom insulation, and control strategies on snow melting performance has been investigated. Conclusions drawn from this study include:

- 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;
- Preheating the slab with full heating capacity before snowfall can significantly improve the snow melting performance; however, it may result in excessively high fluid temperatures in mild weather conditions. These high fluid temperatures may not be achievable with typical system design constraints.
- Idling the system in advance of the snow event significantly improves the snow melting performance and is more energy efficient comparing with the continuous idling operation described in the ASHRAE Handbook, particularly in colder climates. Therefore, forecasting-based control systems should be utilized in snow melting systems.

Recommendations for future research include the following:

- In this study, the snow melting performance is expressed by the percentage of hours when the surface is completely clear from snow ($A_r = 1$) during snow fall hours. However, it might be much more important to know the performance based on times when the surface is mostly clear of snow. One previous work *(19)* suggested that a 50% snow-free condition would be "reasonable for most traffic conditions."
- As shown in this study, many factors can affect the heating capacity required to achieve a desired snow melting performance. It is possible that this information might be distilled to a set of design tables. It is perhaps more feasible and useful to develop a simulation-based procedure and computer implementation to facilitate the design of the hydronic snow melting system.

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List of Tables and Figures

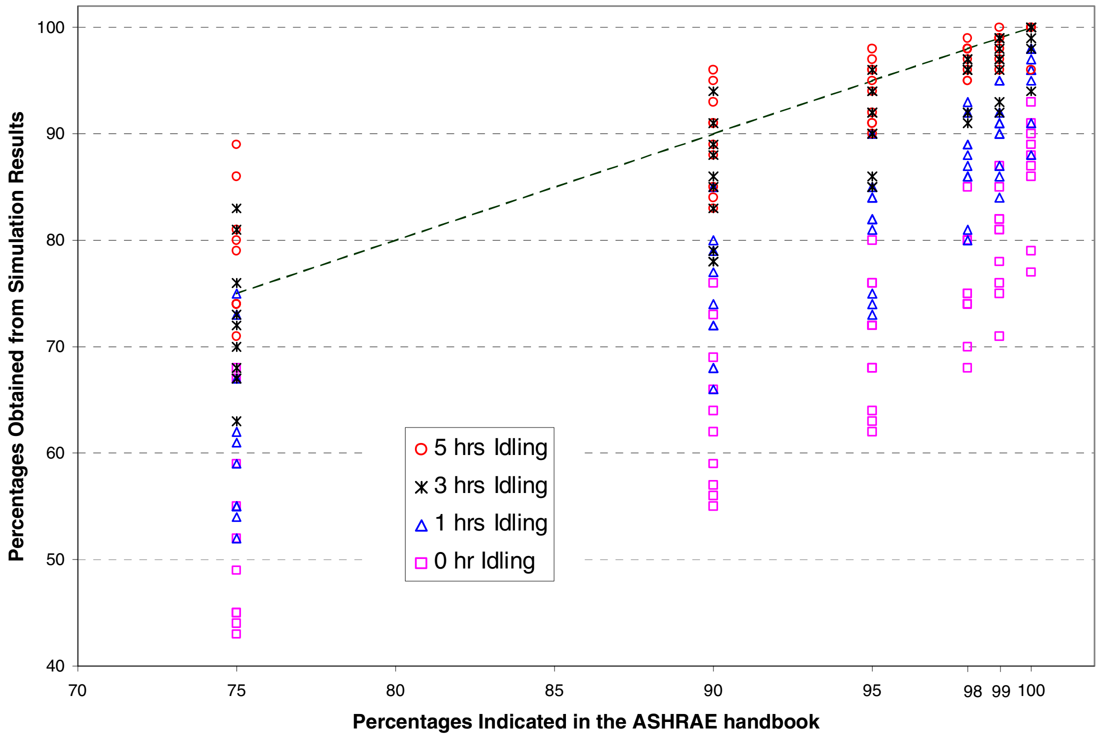

FIGURE 1 Snow melting performances obtained from the simulation results of the first set of parametric study (Adiabatic bottom and edges with 6" (150 mm) pipe spacing).

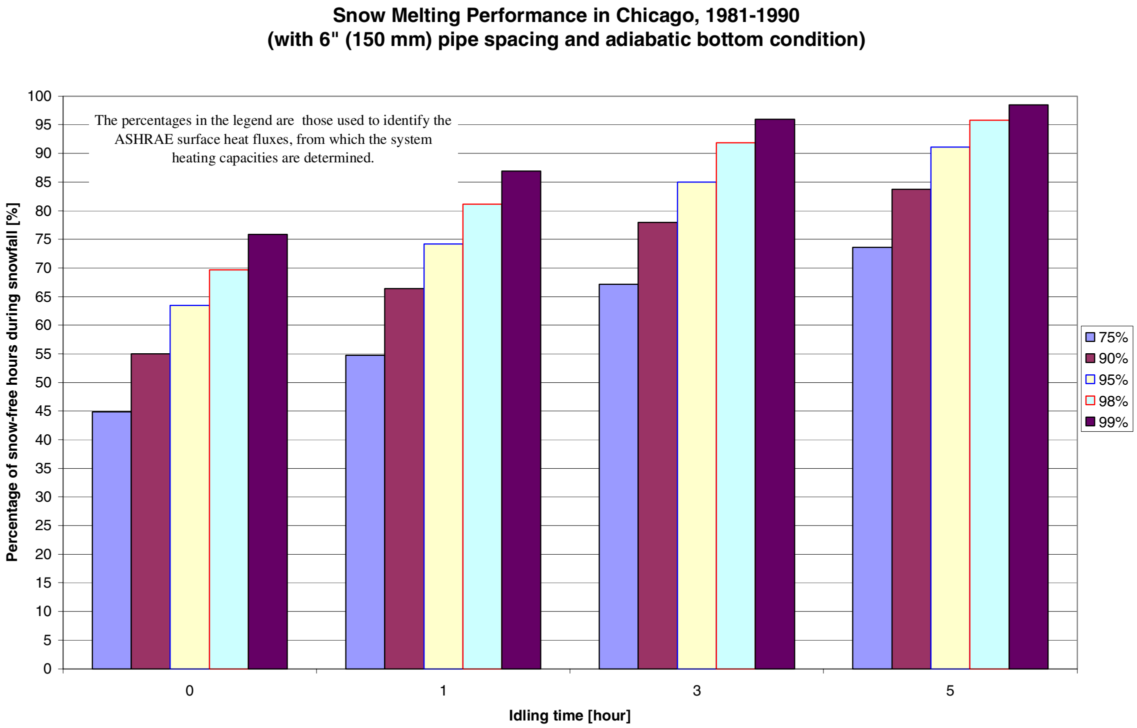

FIGURE 2 Relationship among the idling time, heating capacity and snow melting performance at Chicago.

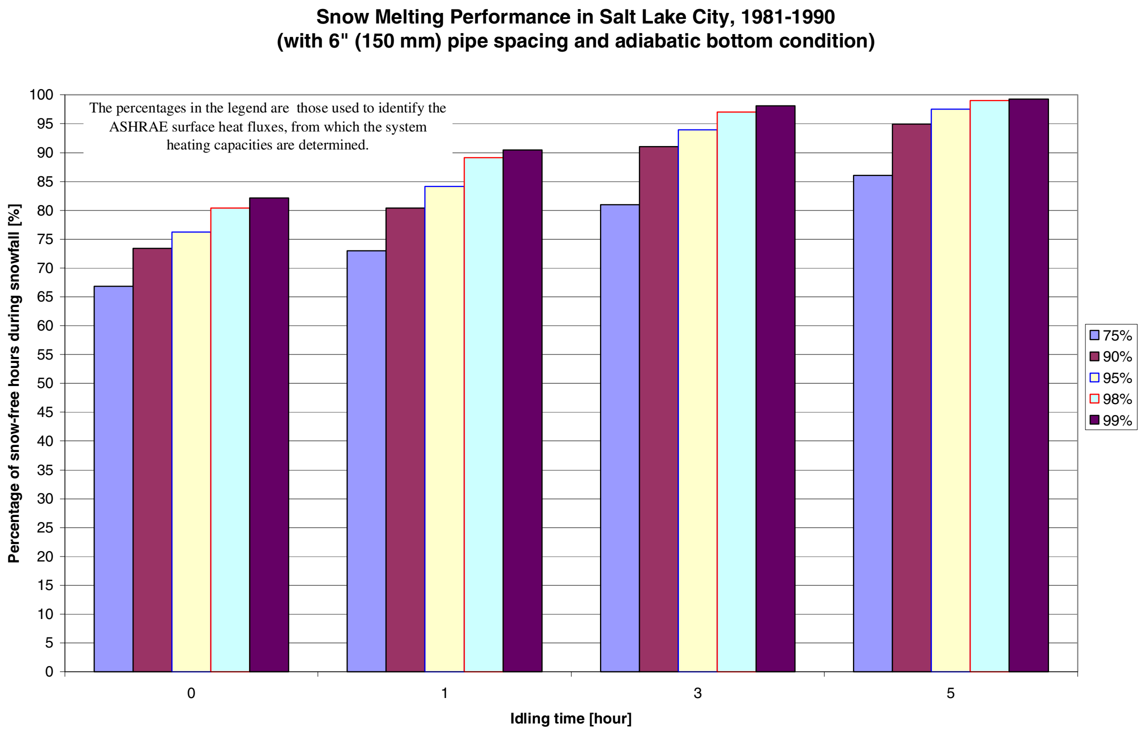

FIGURE 3 Relationship among the idling time, heating capacity and snow melting performance at Salt Lake City.

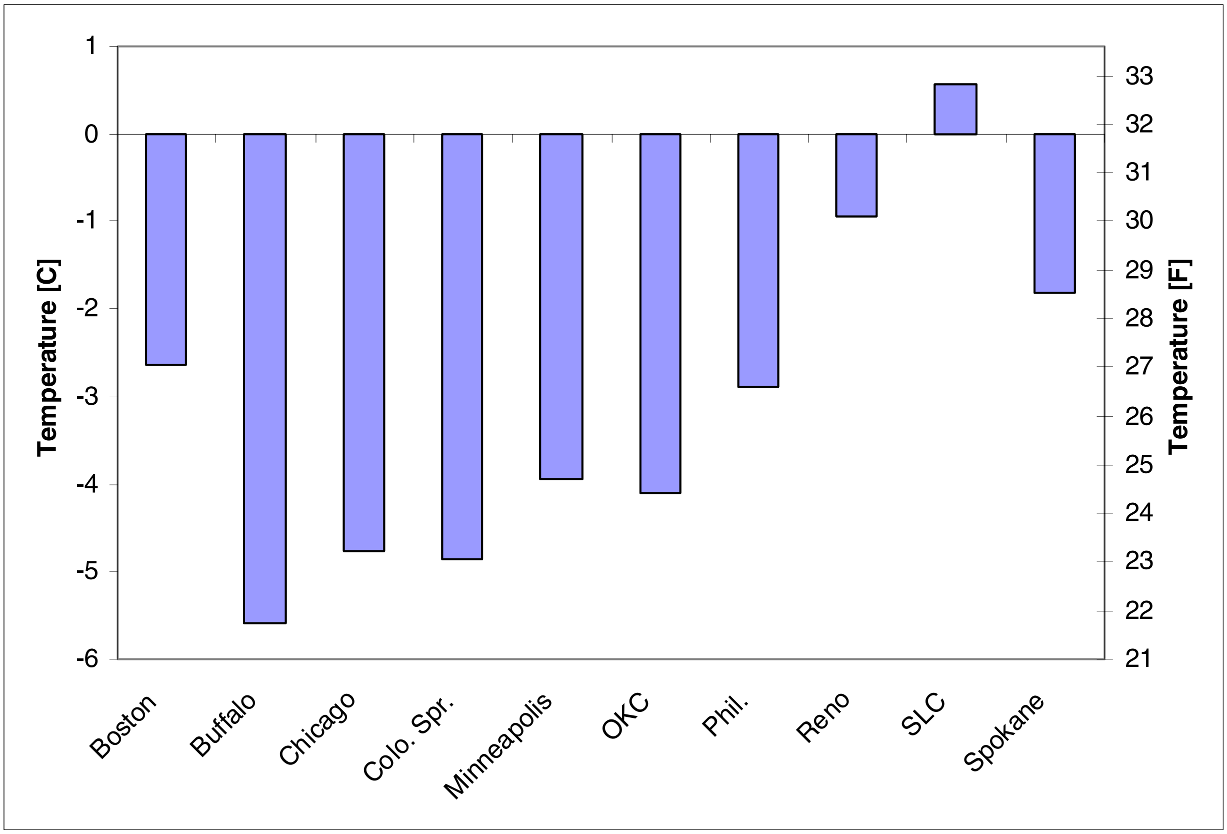

FIGURE 4 Average coincident air dry-bulb temperature during snowfall.

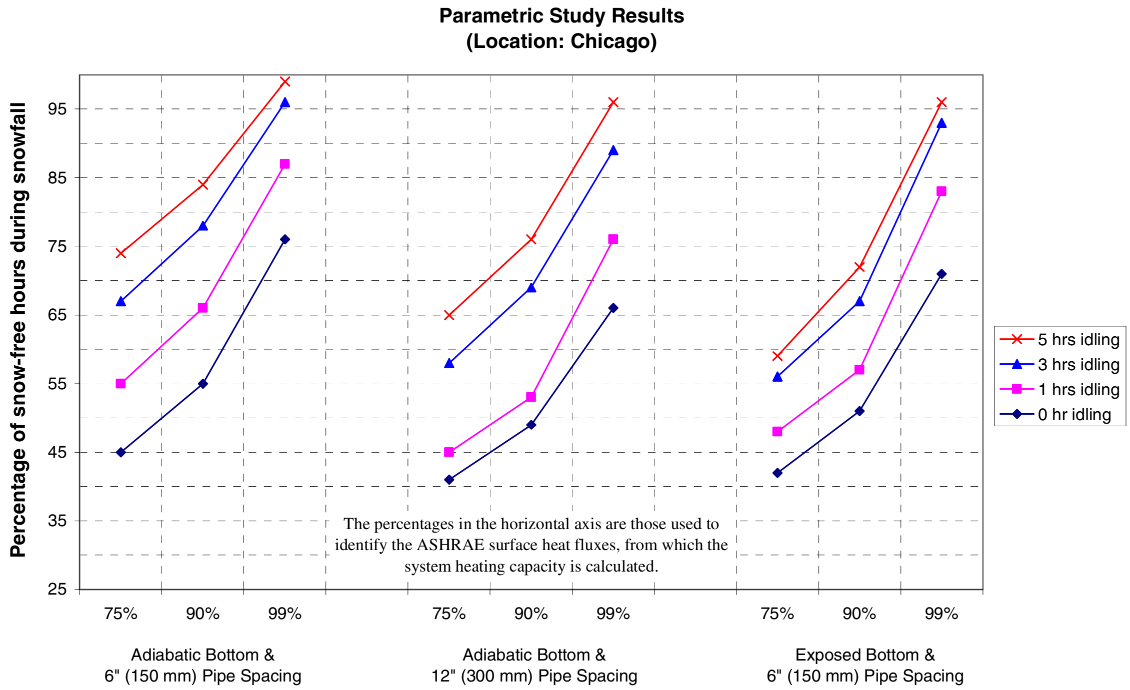

FIGURE 5 Parametric study results (with "snow only" control strategy) - Chicago.

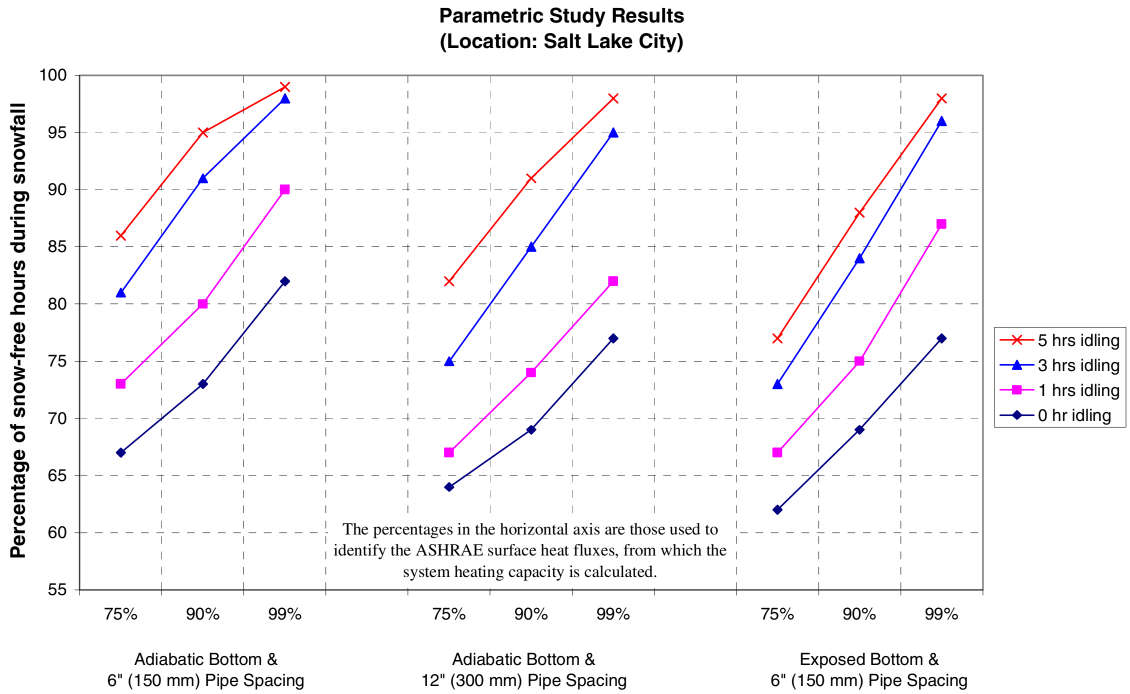

FIGURE 6 Parametric study results (with "snow only" control strategy) – Salt Lake City.

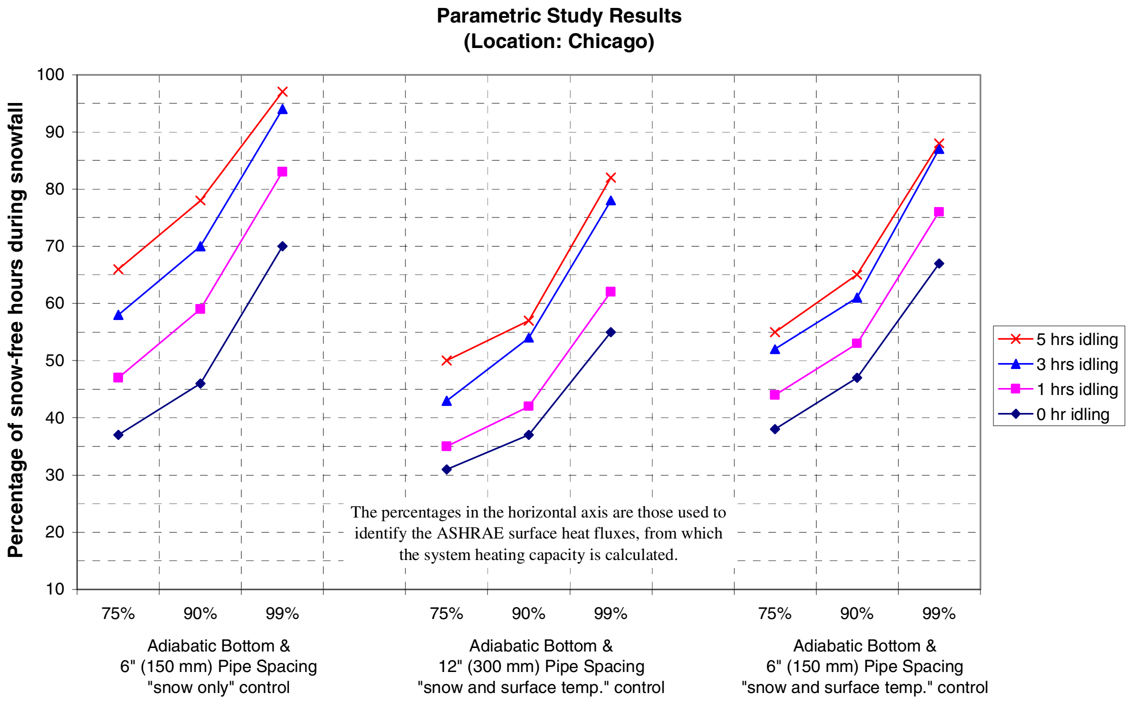

FIGURE 7 Comparison of snow melting performance resulting from different combinations of control strategy and pipe spacing - Chicago.

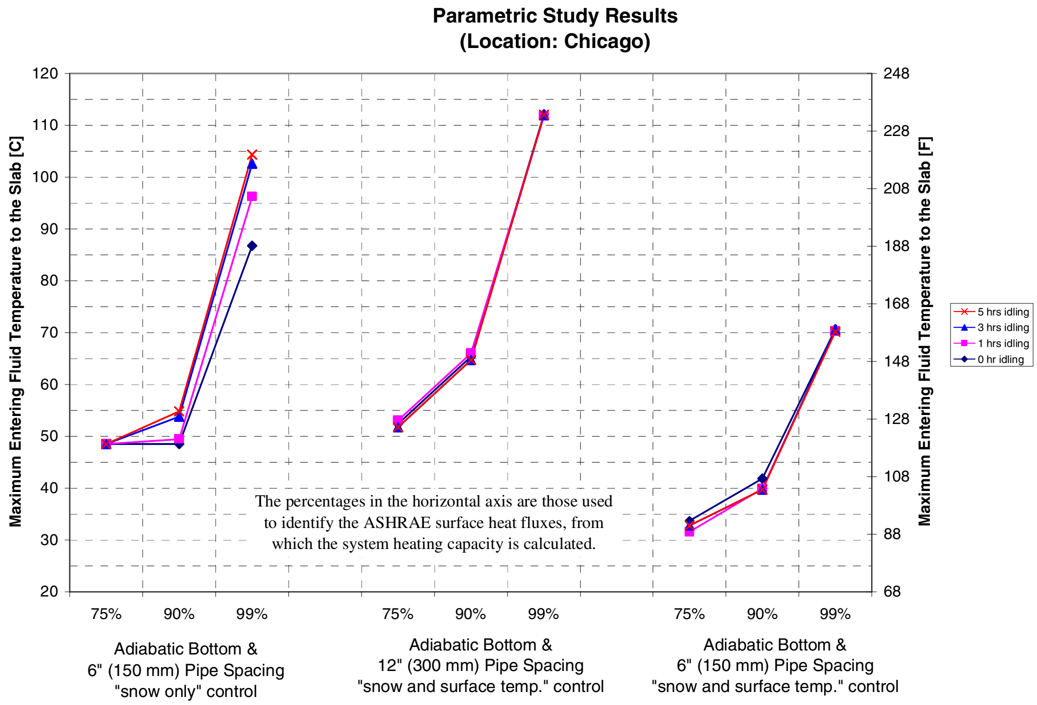

FIGURE 8 Comparison of the maximum entering fluid temperature to the slab resulting from different combinations of control strategy and pipe spacing - Chicago.

TABLE 1 Parameters of the Hydronically-Heated Slab

Design Parameters	Parameter Value (SI Units)	Parameter Value (IP Units)
Slab Thickness	203 mm	8 in
Slab Thermal Conductivity	1.4 W/m.K	0.81 Btu/hr.ft.^{o}F
Slab Volumetric Heat Capacity	2200 kJ/m^{3}.C	32.8 Btu/ft^{3}.^{o}F
Slab Surface Solar Absorptance	0.6	
Pipe Spacing *	152 mm	0.5 ft
Pipe Depth Below Surface	76 mm	3 in
Pipe Diameter	25mm	1 in
Pipe Wall Thickness	2 mm	0.0625 in
Pipe Wall Thermal Conductivity	0.39 W/m.K	0.23 Btu/hr.ft.^{o}F
Bottom Insulation *	Adiabatic	
Heat Carrier Fluid	Propylene Glycol (42% concentration by mass)	

* Varied parameters in the parametric study; values given are for the base case.

TABLE 2 Organization of Parametric Study

	Parameter levels	Number
Set 1	Location: Spokane, Reno, SLC, Colorado Springs, Chicago, OKC, Minneapolis, Buffalo, Boston and Philadelphia	10
	Heating capacity *: 75%, 90%, 95%, 98%, 99%, 100%	6
	Idling duration: 0,1,3,5hours	4
	Pipe spacing: 6 inches (150mm)	1
	Bottom condition: Adiabatic	1
	Control strategy: "Snow only"	1
Set 2	Location: Chicago, Minneapolis, Philadelphia Reno and SLC	5
	Heating capacity *: 75%, 90%, 95%, 98%, 99%, 100%	6
	Idling duration: 0,1,3,5hours	4
	Pipe spacing: 12 inches (300mm)	1
	Bottom condition: Adiabatic	1
	Control strategy: "Snow only"	1
Set 3	Location: Chicago, Minneapolis, Philadelphia Reno and SLC	5
	Heating capacity *: 75%, 90%, 95%, 98%, 99%, 100%	6
	Idling duration: 0,1,3,5hours	4
	Pipe spacing: 6 inches (150mm)	1
	Bottom condition: Exposed	1
	Control strategy: "Snow only"	1
Set 4	Location: Chicago and SLC	2
	Heating capacity *: 75%, 90% and 99%	3
	Idling duration: 0,1,3,5hours	4
	Pipe spacing: 6 inches (150mm) and 12 inches (300mm)	2
	Bottom condition: Exposed	1
	Control strategy: "Snow and surface temperature"	1

* The heating capacity is calculated by multiplying the heated area with the ASHRAE surface heat fluxes, which are loads that was not be exceeded during certain percentage of snowfall hours from 1982 through 1993 according to the steady state analysis.