Simulation of a Geothermal Bridge Deck Anti-icing System and Experimental Validation

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ABSTRACT

The design of heated bridge deck anti-icing systems requires assessment of long-term performance under expected future weather conditions. A method of simulating the performance of such a system has been developed. The system studied in this work uses a bridge deck with embedded hydronic tubing and a ground-coupled heat pump system with vertical borehole heat exchangers as a heat source. The models of each component and their integration into the simulation of the whole system are described. Validation of the simulation method has been attempted by making use of operating data collected from an experimental heated bridge deck installation. The collection of data, estimation of the model parameters, and comparison of the simulation results with the measured data is discussed. Results indicate that the system simulation of the heated bridge deck is able to predict performance with reasonable accuracy under a range of weather and operating conditions.

INTRODUCTION

Preferential icing of bridge decks not only results in higher traffic accident rates but also poses considerable engineering problems. Traditional anti-icing treatment by application of salt/sand to bridge decks is less successful than application to the adjacent highway due to the preferential nature of the icing process and associated difficulty in predicting the onset of icing. Of further concern to both highway engineers and funding agencies is the deterioration of bridge deck life due to increased corrosion rates induced by the application of salt.

The heating of bridge decks has been proposed as an alternative means of providing protection against preferential icing. Such a system can potentially offer improved road safety and increased bridge deck life. A number of heat sources have been proposed for such systems, including heat pipes, natural gas boilers and electric cables *(1)*. Ground coupled heat pump systems and hydronic heating offer improved energy efficiency over other systems. Such systems consist of hydronic tubing embedded in the bridge deck with hot water circulated from a number of water-to-water heat pumps that, in turn, extract heat with the ground via vertical U-tube borehole heat exchangers (Fig.1). This geothermal bridge deck technology has been the subject of a recent federally funded research project at Oklahoma State University.

Application of geothermal bridge deck anti-icing technology has been discouraged by higher initial costs, but also lack of reliable design procedures, modeling methods and software tools. Ground-coupled heat pump systems require a different approach to design than other forms of heating system. This is due, primarily, 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 much 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. Similarly the large thermal mass of the bridge deck requires that transient performance be considered. (This partly explains why adequate design methods have not previously been developed). Proper consideration of these complex time-varying boundary conditions requires some reliance on system simulation in the design process.

This paper describes the models used in simulating a geothermal hydronic bridge deck anti-icing system and their incorporation into a model of the whole system. The collection of operating data, and corresponding weather data, from a medium scale geothermal bridge anti-icing system is described. These data have been used in the validation of the component models and the whole system simulation. The results of this validation process are further discussed and will show the ability of this simulation approach to successfully predict the performance of the system under a wide range of operating and weather conditions.

MODELING OF THE BRIDGE HEATING SYSTEM COMPONENTS

In order to simulate the operation of the geothermally heated bridge deck system it is necessary to model the following system components:

- The bridge deck with embedded hydronic tubing
- The water-to-water heat pumps
- The system controls
- The circulating pumps
- The ground-loop heat exchanger

These models are discussed in the remainder of this section.

Hydronically-Heated Bridge Deck Model

The heated bridge deck is an otherwise standard construction, with small diameter piping embedded. This pipework consists of number of circuits laid in a serpentine configuration perpendicular to traffic flow on the bridge. The pipe material in the deck 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). The pipe can often be arranged so that it can be simply clipped to the steel reinforcement prior to pouring the concrete.

The model of the hydronic-heated pavement used in this work is based on the finite difference model described in detail by Chiasson *et al. (2)*. In this model transient conduction heat transfer in the pavement is modeled using a two-dimensional finite difference method. Symmetry enables the conduction through the bridge deck to be limited to calculation using a geometry that includes half a single pipe and surrounding concrete up to a distance of half the pipe spacing (Fig. 2). Heat and mass transfer at the upper surface of the deck, under the wide variety of possible weather conditions, is complex. Heat transfer by the following modes are modeled:

- Solar radiation heat gain
- Convective heat transfer to the atmosphere
- Long-wave thermal radiation to the sky,
- Sensible heating of snow and rain,
- Melting of the snow and ice
- Evaporation of rain and melted ice/snow.

At the bottom surface of the bridge heat transfer by convection and long-wave radiation to the environment are also considered. Mass transfer by melting of the snow/ice, runoff from the surface and evaporation is tracked throughout the simulation. As the variation in temperature and heat flux over the surface can be calculated it is also possible to calculate the variation in ice and snow thickness between the pipes. The modeling of the snow-melting process is discussed further in Rees *et al.(3)* and Hockersmith *(4)*.

Ground Loop Heat Exchanger Model

Vertical ground loop heat exchangers have seen widespread application in building heating and air-conditioning installations and are well suited to geothermal bridge heating systems. Such heat exchangers consist of pipes in a 'U-tube' formation inserted and grouted into a small diameter borehole. Heat is exchanged with, and stored in, the surrounding ground by circulating fluid in a closed loop from the heat pumps. The boreholes have typical diameters of 3 in (75 mm) to 5 in (125 mm) and depth of 50 ft (10 m) to 600 ft (180 m). The typical diameters of the U-tube pipes are in the range from ¾ in (20 mm) to 1.5 in (35 mm).

The huge thermal mass of the ground enables significant amounts of energy to be extracted (or rejected) and stored. This large thermal mass means that if the bridge deck were continuously heated the temperature of the ground around the heat exchangers would progressively reduce over the life of the system. The system fluid temperatures would change correspondingly, which in turn would result in degradation in heat pump efficiency. It is these long-term effects, in fact, that make long-term simulations necessary to evaluate the design of this type of system.

For any thing but the smallest heating capacities it is necessary to use a 'field' of vertical ground-loop heat exchangers. In the borehole field the heat transfer rates and operating temperatures of each heat exchanger are influenced by the neighboring heat exchangers. As a consequence, performance of the gound-loop heat exchanger installation depends on the spacing and geometric configuration of the boreholes. A method of dealing with different geometric arrangements and the long-term heat storage effects in vertical ground-loop heat exchangers was developed by Eskilson *(5)*. This relies on the fact that the temperature response of the heat exchangers can be represented as the response to a series of heat pulses, and calculated from a non-dimensional function unique to each configuration. This method has been extended, and implemented, as a model that is able to calculate fluid temperatures by Yavuzturk and Spitler *(6)*. It is this model that has been used in this work.

Water-to-water Heat Pump Model

A number of 'water-to-water' heat pumps are used as the primary heating source. Their function is to extract heat from the fluid circulated through the ground-loop heat exchangers and transfer this heat to the fluid circulated through the bridge deck. The fluid circulating the ground-loops is at a temperature close to the average ground temperature (63^{o}F [13.2 ^{o}C] in Oklahoma) and is raised to a temperature of 110-130^{o}F (40-55 ^{o}C) in the fluid circulating through the bridge deck. Such operating temperatures are generally sufficient to ensure sufficient heat output at the bridge surface to control snow and ice precipitation in storm conditions. The circulating fluids are typically water-propylene glycol anti-freeze mixtures.

A parameter-estimation-based water-to-water heat pump model developed by Jin and Spitler *(7)* has been used in this work. This model uses a thermodynamic analysis of the refrigeration cycle, simplified heat exchanger models, and a detailed model of the refrigerant compressor. The various parameters of the model are estimated from the manufacturers' catalog data by applying a multi-variable optimization algorithm. Once the optimal values of the performance parameters have been determined, the model can accurately simulate the performance of the particular heat pump over its full operating range.

System Controls Model

To effectively and reliably prevent the preferential ice formation, the system has to be controlled such that there is sufficient heat output at the deck surface at the start of snow precipitation or before possible freezing of accumulated surface water. It is a further objective of the control system to minimize energy usage by overheating the bridge or operating for excessive periods. During initial system simulations conducted for design purposes (system sizing) simplified control strategies have been implemented in a controller model. An important objective of the research project is to develop sophisticated control methods that are able to optimally heat the bridge deck and take account of forecast weather conditions. This 'Smart Bridge' control technology is discussed in a companion paper *(8)*. The heated bridge deck model discussed above has also been used to test these control strategies.

SIMULATION OF THE GEOTHERMAL HYDRONIC BRIDGE ANTI-ICING SYSTEM

In order to simulate the operation of the whole anti-icing system, the inputs and outputs of each system component model have to be coupled together, and the resulting set of differential and algebraic equations solved. The component based simulation environment HVACSIM+ was selected for this task *(9)*. This simulation tool 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). HVACSIM+ is capable of solving the non-linear differential-algebraic systems of equations that are involved in simulating fluid flow and heat transfer problems *(10,11)*. This simulation environment is also designed to deal with complex combinations of time varying boundary conditions, such as weather data, and includes convenient libraries of fluid properties.

In order to make comparisons between the simulation results and measured experimental data, realistic estimates of the various model parameters have to be established. The principal uncertainties in the model parameters are associated with the bridge deck model. Parameter sensitivity analysis of this model has shown that the solar absorptance of the bridge deck surface, the thermal properties of the concrete, and modeling of long-wave radiation are the most significant. The estimation of these parameters is discussed below.

Bridge Surface Solar Absorptance

The solar absorptance is the most sensitive parameter in the prediction of bridge surface temperature, particularly in summer conditions when the heating system is off and the bridge collects solar energy (so called 'recharge mode'). However, the literature and data concerning on the solar absorptance of concrete is limited. Published values are in the range 0.6 to 0.8 and are not specific to particular concretes. A more accurate value of solar absorptance was estimated from additional experiments. In these experiments incoming solar radiation and solar radiation reflected from the bridge deck surface were measured using a four-component net radiometer. Data was collected between sunrise and sunset under mostly clear sky conditions. The solar absorptivity was found to be approximately constant at a value of 0.62.

Bridge Deck Thermal Properties

Prediction of conduction heat transfer in the bridge deck is sensitive to the thermal conductivity and specific heat of the deck construction materials. The concrete used in the bridge was sampled and the thermal conductivity measured with the guarded hot plate method. The average of measured value was found to be 0.95 Btu/hr.ft.˚F (1.65 W/m.K). Review of the available data shows that moisture content is an overriding determinant of the specific heat of concrete *(13, 14)*. The specific heat and density of the concrete was accordingly measured at various levels of moisture content *(12)*. In order to arrive at a final estimation of the thermal properties, some account was also taken of the presence of the steel reinforcement by calculating mass-weighted values from the respective material properties.

Sky temperature

Long wave radiation between the bridge deck surface and the environment can be the most significant driving heat flux under nighttime conditions. Calculation of this radiant flux relies strongly on the estimate of effective sky temperature. A number of empirical models for the calculation of time varying sky temperatures have been published *(15, 16, 17, 18)*. These have the limitation of being applicable only under certain sky conditions and give a wider range of predictions at locations other than that at which the empirical data was collected. Comparison of measured data – collected at the experimental bridge deck using a net radiometer – with predictions from a number of models, showed the Brown model *(15)* to be the best candidate, and was subsequently adopted for the simulations.

THE EXPERIMENTAL GEOTHERMAL BRIDGE ANTI-ICING SYSTEM

An experimental medium-scale bridge deck with a geothermal anti-icing system has been constructed as part of this research project. This bridge deck forms a test bed for the technology and provides a means of collecting experimental data for the purposes of model validation under operating conditions.

The bridge and anti-icing system installation

The system comprises a bridge deck with embedded heat exchanger pipe loops, a single water-to-water heat pump, a six-borehole vertical ground loop heat exchanger, along with circulating pumps and control system. Fig. 1 is a schematic diagram of the system. The experimental bridge deck is 60 feet (18.3 m) in length and 20 feet (6.1 m) in width. The bridge structure consists of two pre-cast double-T beams and a steel-reinforced fiber-mesh concrete deck. The embedded pipe-work consists of cross-linked polyethylene (PEX) pipe bound to the reinforcement mesh. The parameters of the bridge deck and the embedded piping system are summarized in Table 1.

The vertical closed-loop ground source heat exchanger installation is comprised of 6 boreholes with a diameter of 5.25 inch (0.13 m) that are in a 2 by 3 configuration with 25 ft (7.62 m) spacing. Each borehole contains an HDPE U-bend pipe loop with nominal diameter of 1 in (25 mm), and is grouted with a mixture of 4020 sand and bentonite. The effective thermal conductivity and surrounding clay/sandstone formation were estimated from *in situ* test data. The parameters of the ground loop heat exchanger installation are summarized in Table 3.

A single water-to-water heat pump with nominal cooling capacity of 10 tons (35 kW) is used in the system to transfer heat from the ground to the bridge deck. The output temperature of the fluid circulated through the bridge deck is designed to be in the range 100 - 130°F (38 – 55°C). A fluid mixture of water and propylene glycol is circulated at a rate of approximately 21 GPM (1.3 l/s) through the ground-loop system, and 8 GPM (0.5 l/s) through the bridge deck.

The Data Acquisition and Control System

A custom data acquisition system has been developed to record experimental data from the system at 5-minute intervals. The system instrumentation consists of 60 thermistors embedded in the bridge deck, four fluid system thermistor probes, two flow meters and three kWh meters as indicated in Fig. 1. The following types of data are collected:

- Leaving and entering fluid temperature in both source and load side of heat pump
- Temperatures within and at the surface of the deck
- Flow rates in both source and load side
- Power consumption of heat pump and circulating pumps

The bridge anti-icing system has initially been operated with on-off control of the heating system. The objective has been to control the bridge surface temperature in the range of 40-42°F (4.4-5.5°C) when there is a risk of icing or snowfall. In summer – when it is possible to replenish the thermal energy stored in the ground by collecting solar energy from the bridge – fluid is circulated directly from the bridge to the ground heat exchangers when the surface temperature is higher than 90°F (32.2°C) and is switched off when the temperature falls to 88 °F (31.1°C).

Weather Data Collection

The weather data for the validation exercise were obtained by combining cloud cover data from the National Virtual Data System with the data from the Oklahoma Mesonet (*meso*scale *net*work), which is a network of weather stations throughout Oklahoma (*19*). The local Mesonet weather station is approximately 1 mile (1.6 km) from the experimental bridge site. As accurate precipitation data in freezing conditions is not available from the automated weather station, data were also collected from a heated tipping-bucket rain gauge installed at the bridge site.

MODEL AND SYSTEM SIMULATION VALIDATION

The validation process reported here has consisted of comparison of measured bridge deck temperatures, system heat transfer rates and fluid temperatures, with model predictions. The objective has been to validate each component model individually, as well as the whole system simulation.

Component Model Validation

As the heat pump model has been validated as part of a separate exercise and reported elsewhere *(20)*, validation efforts have focused on the bridge deck and ground loop heat exchanger models. The validation of the bridge deck and ground-loop heat exchanger models was conducted by using the measured entering fluid temperatures and weather data as inputs to each model, and examining the predicted surface temperatures and heat transfer rates.

Validation of The Hydronically Heated Bridge Model

Measured and predicted bridge average surface temperatures and exiting fluid temperatures during recharge (summer) operation, are compared in Fig. 3 and Fig. 4 respectively. A number of cycles of operation – corresponding to daylight hours – are shown. The calculated surface temperatures follow the experimental data well but show some over prediction of the peak temperatures. The maximum average surface temperature shown (Fig. 3) is approximately 3.6 ˚F (2 ˚C) above that of the measured surface temperature. The over prediction of the surface temperature in these conditions is thought to be due to the uncertainties in the calculation of long-wave radiation and convective heat fluxes. Similarly, the peak exiting fluid temperatures (Fig.4) have the largest differences with the experimental data (0.9 ˚F [0.5 ˚C]).

Measured and predicted bridge average surface temperatures and exiting fluid temperature, during a number of cycles of heating (winter) operation, are compared in Fig. 5 and Fig. 6 respectively. The first cycle of operation corresponds to the arrival of snowfall and start of bridge deck heating. There is good agreement between measured and predicted values of both the bridge surface and exiting fluid temperatures. In this simulation, sky temperature under snowfall conditions was approximated by the ambient temperature following the recommendations of Ramsey *(16)* and ASHRAE *(21)*.

The degree of snow cover during this period is indicated by the ‘snow free area ratio’ shown in Fig. 6. This is a ratio of the snow-free surface area with the total surface area. Hence, a snow free area ratio of 1 indicates a completely snow-free surface, a ratio of zero indicates a completely snow covered surface, and intermediate values indicate patches of snow (striping). During the snowfall event the calculated snow free area ratio can be seen to initially fall to zero, and rises to one as the system heats the bridge. Later in this period predicted surface temperatures deviate further. This may be partly due to the additional uncertainties in the thermal properties of the concrete and solar absorptivity of the surface as the concrete is saturated with water and gradually dries out following the snow melting process.

Validation of The Vertical Ground Loop Heat Exchanger Model

Predicted exiting fluid temperatures from the ground loop heat exchanger model are compared with measured data in Fig. 7 and Fig. 8 for recharge and heating modes respectively. Acceptable agreement with the measured data is shown over most of the operating cycle. The largest differences (approximately 1.1 ˚F [0.6 ˚C]) occur in heating mode at the end of each cycle. This is a small temperature difference, but represents a more significant difference in heat transfer rate.

System Simulation Validation

In order to evaluate the performance of the simulation of the whole bridge deck anti-icing system, only measured weather data, system flow rates and recorded operating periods (not fluid temperatures) were used as inputs to the simulation. The validation of the system simulation in recharge operating mode was made with experimental data recorded in the period 8/01/00 to 8/14/00. Data used in the validation exercise for heating mode was collected in the period 12/30/2001 that included a period of snowfall.

System Operation In Recharge Mode

The amount of heat that can be injected to the ground is of primary interest in the recharge mode of operation. Accordingly, the measured and predicted heat transfer rates have been compared in Fig. 9. Although there are noticeable differences at peak conditions the differences in accumulated energy are less than 2%.

System Operation In Heating Mode

The objective of the whole system simulation is to be able to predict the presence of frozen precipitation on the bridge deck surface. Accordingly, in the simulation of the geothermal bridge anti-icing system operated in heating mode, prediction of bridge deck surface temperature is of primary concern. The measured and predicted surface temperatures during the winter test period are compared in Fig. 10. The corresponding ground loop heat exchanger exiting fluid temperatures are also shown.

Again, the first cycle of operation corresponds to the first period of snowfall. The predicted maximum and minimum bridge deck surface temperatures are in good agreement with the measured data. However, the predicted data shows some time shift relative to the measured data.

CONCLUSIONS AND RECOMMENDATIONS

The dynamic nature of geothermal heated bridge deck 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.

Models of the principal components of a geothermal bridge deck anti-icing system have been developed and used to simulate operation of the system. Experimental data have been collected from an operational medium-scale system installation. The most sensitive model parameters have been identified and further experiments have been conducted to establish values applicable to the experimental installation.

A validation exercise that has compared predicted temperatures and heat transfer rates with measured data has been conducted. Both the individual component models and whole system simulation predictions have been examined. Results of the validation exercises have shown that the simulation is able to predict bridge deck surface temperature and system fluid temperatures sufficiently accurately for the purposes of system design and performance analysis.

ACKNOWLEDGEMENTS

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List of Tables and Figures

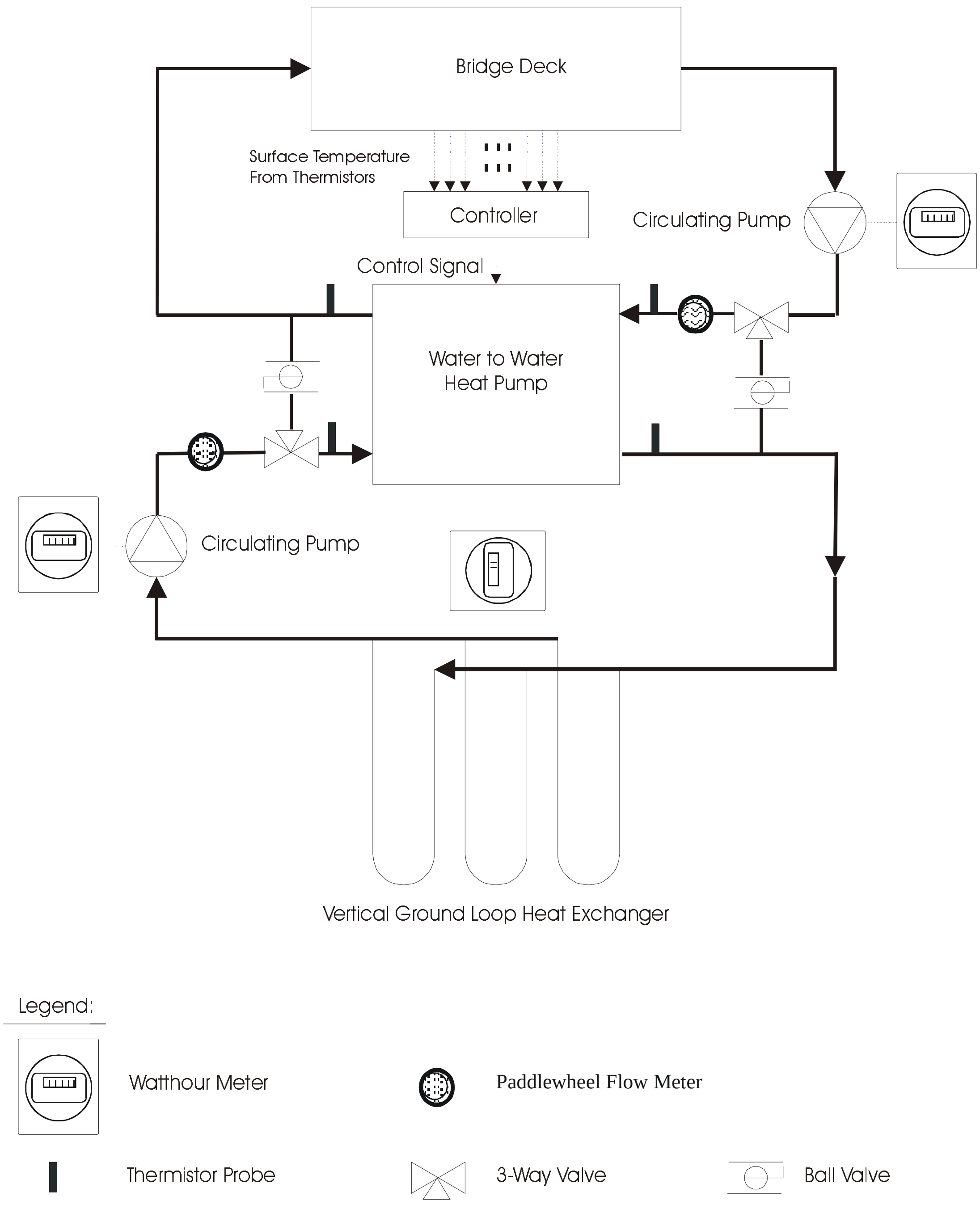

FIGURE 1 Schematic diagram of the experimental bridge deck anti-icing system.

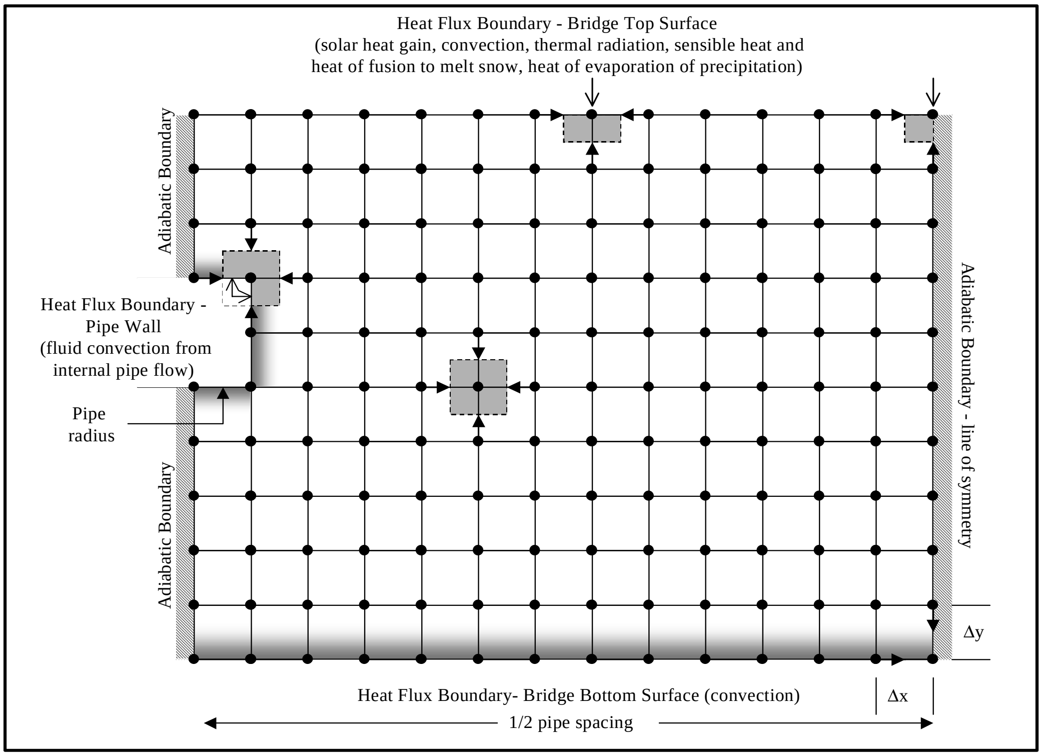

FIGURE 2 The bridge deck model domain showing the finite-difference grid and boundary conditions.

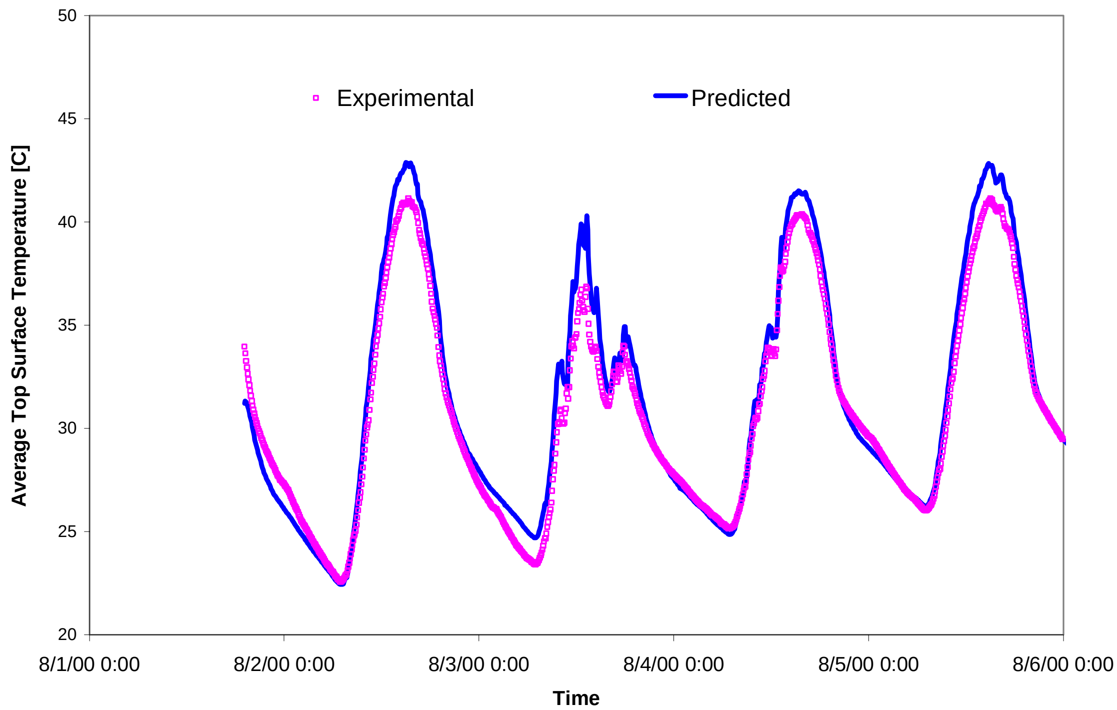

FIGURE 3 Measured and predicted bridge surface temperatures – recharge operating mode.

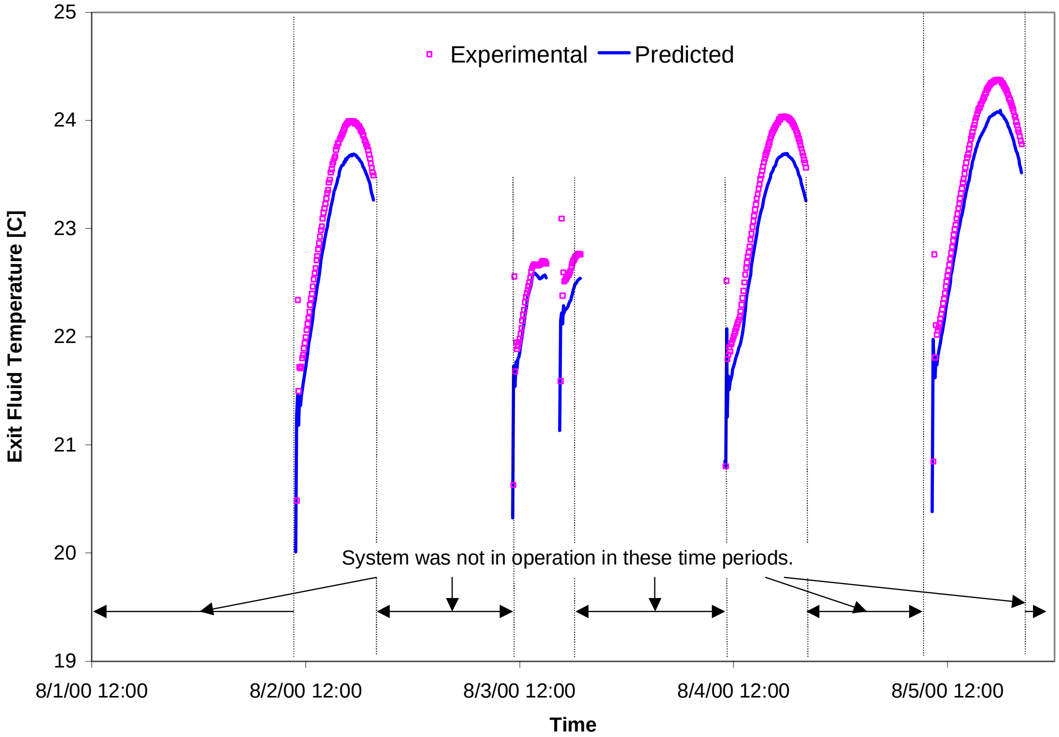

FIGURE 4 Measured and predicted bridge exiting fluid temperatures – recharge operating mode.

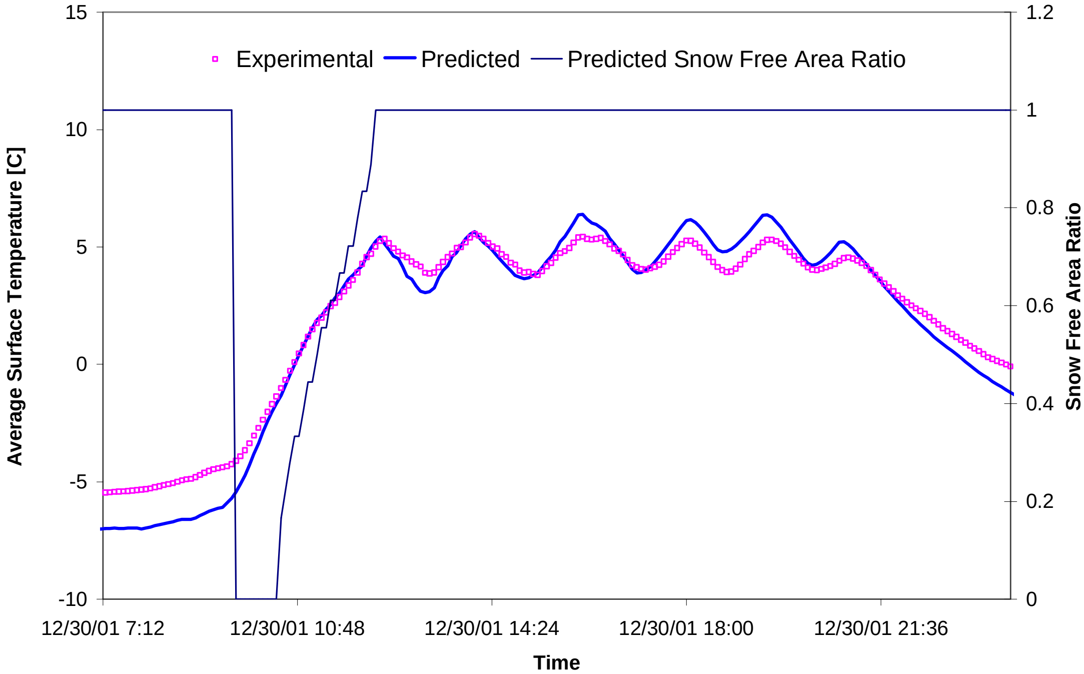

FIGURE 5 Measured and predicted bridge surface temperatures – heating operating mode. Presence of snow on the bridge surface is indicated by the Snow-Free-Area-Ratio data.

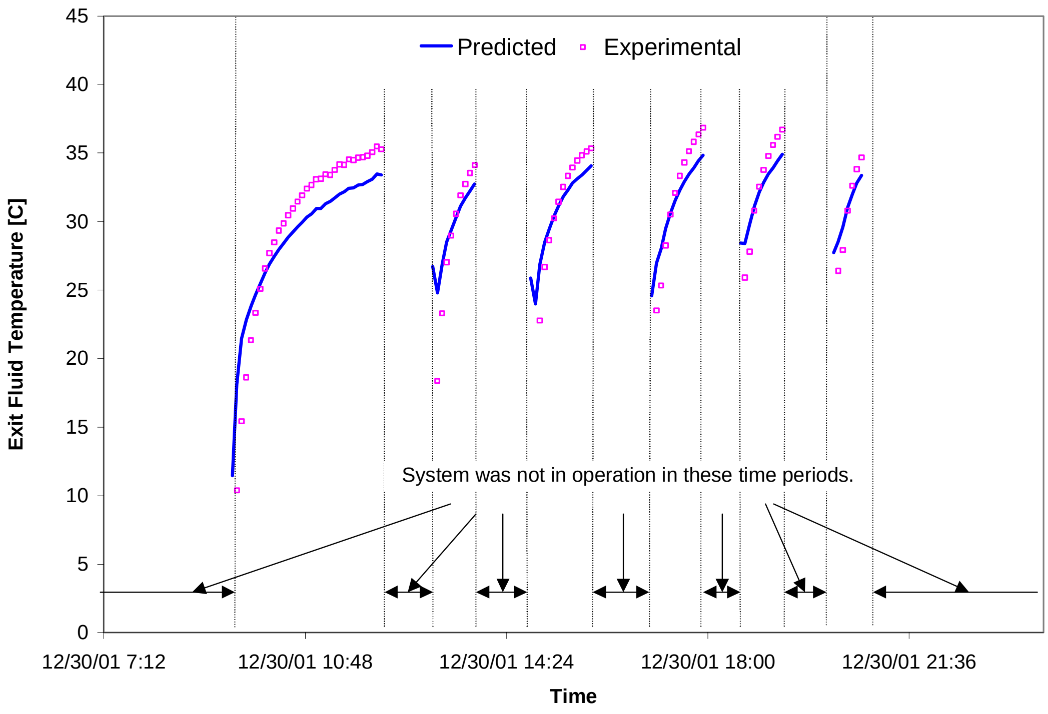

FIGURE 6 Measured and predicted bridge exiting fluid temperatures – heating operating mode.

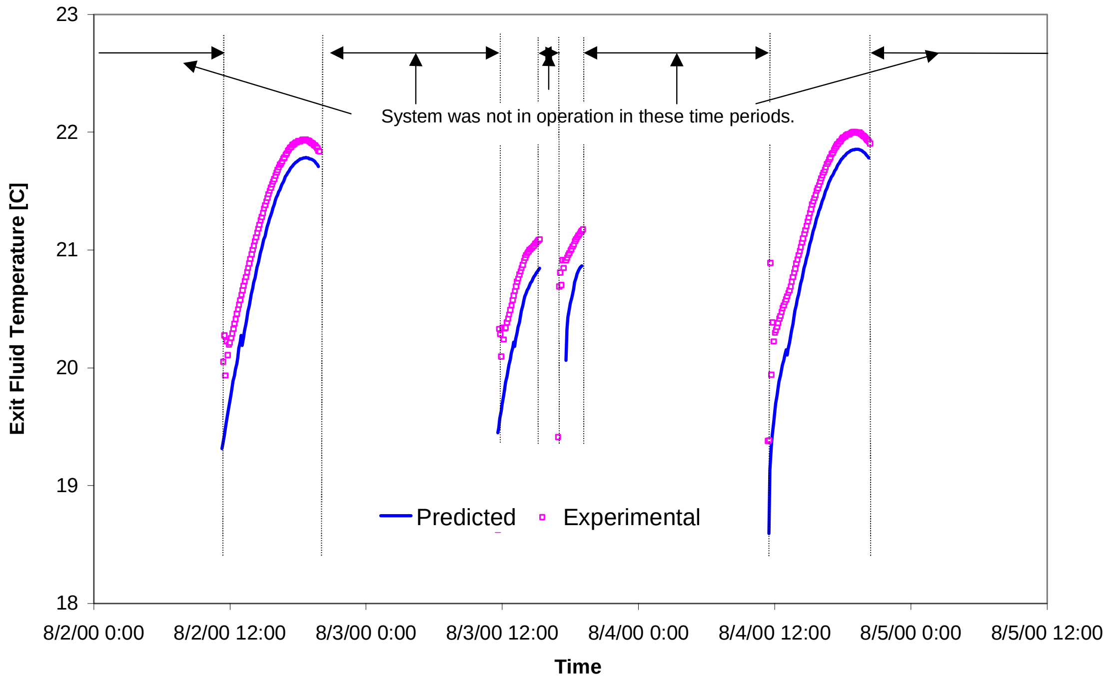

FIGURE 7 Measured and predicted exiting fluid temperatures for the ground loop heat exchanger – recharge operating mode.

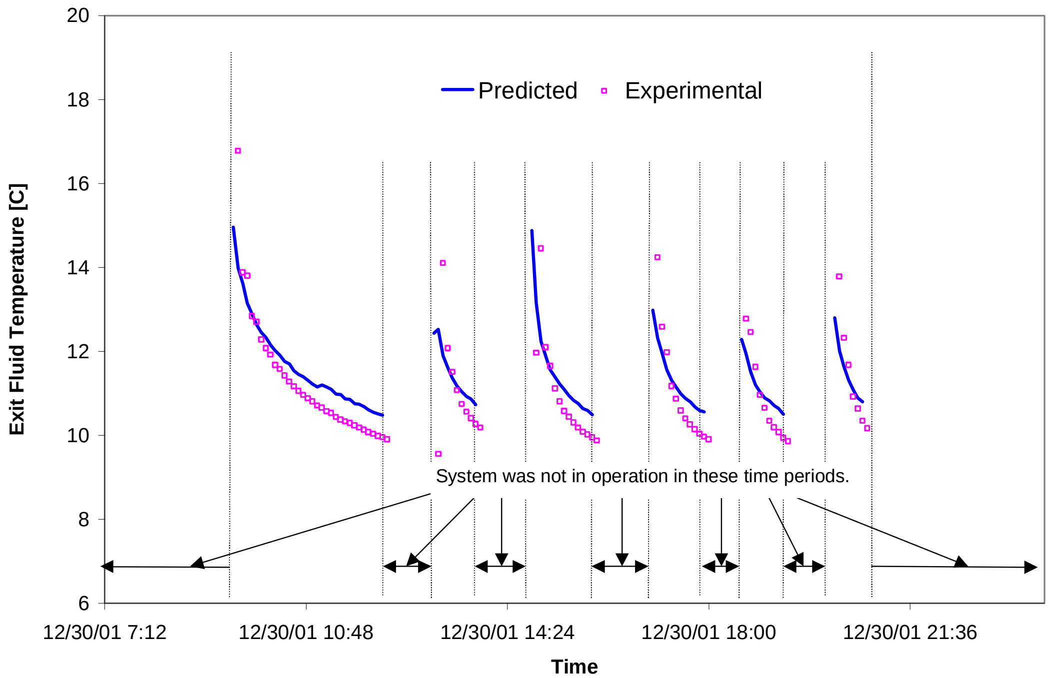

FIGURE 8 Measured and predicted exiting fluid temperatures for the ground loop heat exchanger – heating operating mode.

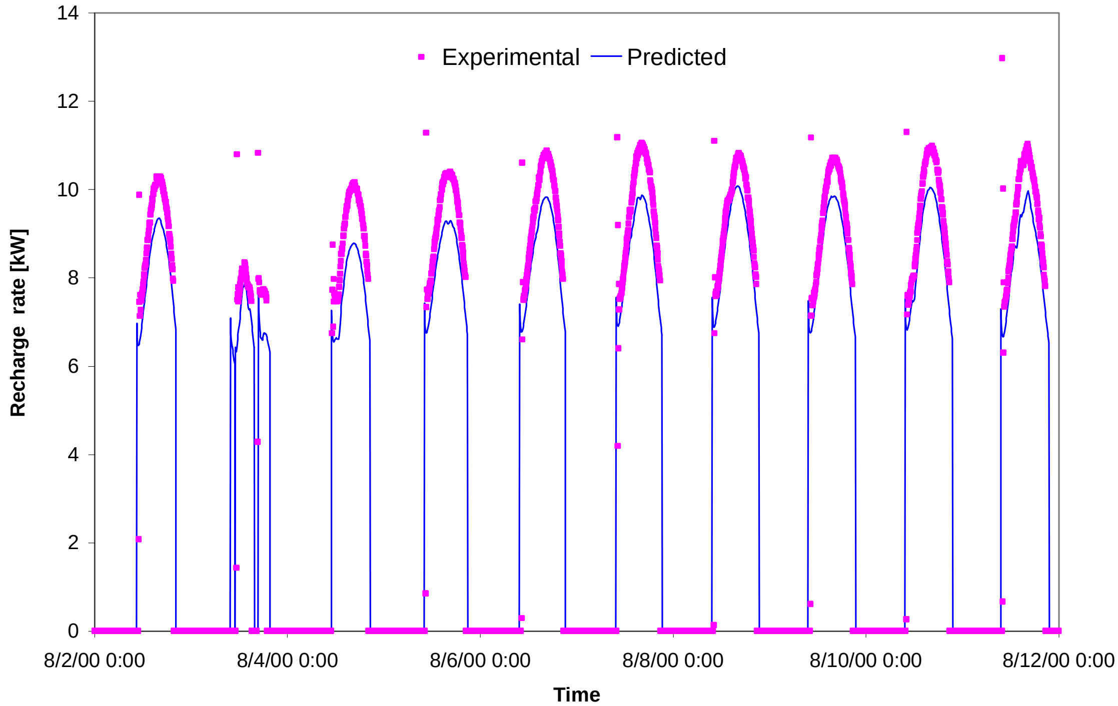

FIGURE 9 Measured and simulated heat transfer rates – recharge operating mode.

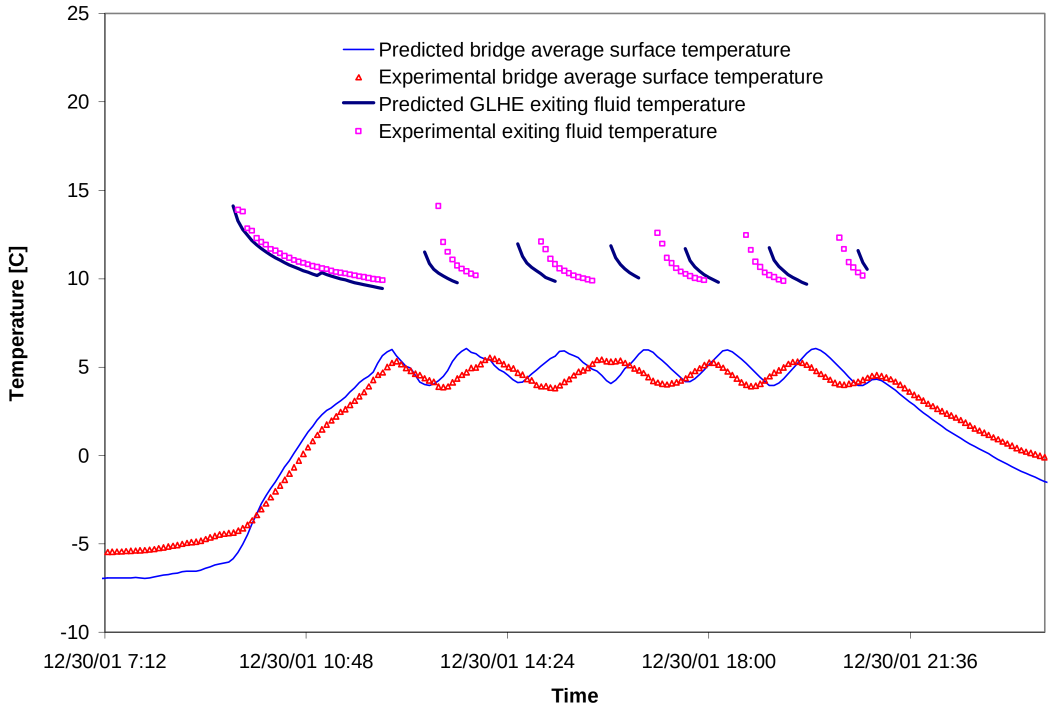

FIGURE 10 Measured and simulated surface and GLHE exiting fluid temperatures – heating operating mode.

TABLE 1 Bridge Deck Heating System Design Parameters

Design Parameters	Parameter Value (SI Units)	Parameter Value (IP Units)
Heated Pavement Length	9.1 m	30 ft
Pavement Width	6.1 m	20 ft
Azimuth (from North)	6 degrees	6 degrees
Pavement Thickness	152 mm	6 in
Pipe Spacing	0.305 m	1 ft
Pipe Diameter	19 mm	0.75 in
Pipe Depth Below Surface	89 mm	3.5 in
Pipe Wall Thickness	2 mm	0.0625 in
Pipe Thermal Conductivity	0.45 W/m.K	0.26 Btu/hr.ft.^{o}F
Number Of Circuits	10	10
Length Of Pipe Per Circuit	19.8 m	65 ft
Thermal Conductivity	2.87 W/m.K	0.952 Btu/hr.ft.^{o}F
Volumetric Heat Capacity	2200 kJ/m^3.C	32.8 Btu/ft^3.^{o}F
Density	2474 Kg/m^3	154.6 lbm/ft^3
Heat Carrier Fluid	Propylene Glycol (42% concentration by mass)	

TABLE 2 Ground Loop Heat Exchanger Design Parameters

Design Parameters	Parameter Value (SI Units)	Parameter Value (IP Units)
Number Of Boreholes	6	6
Borehole Length	66.1 m	217 ft
Borehole Radius	67 mm	2.625 in
Ground Thermal Conductivity	2.34 W/m.K	1.351 Btu/hr.ft.^{o}F
Ground Volumetric Heat Capacity	2350 kJ/m^3.K	35.1 Btu/ft^3.^{o}F
Undisturbed Ground Temperature	17.2 C	63 ^{o}F
Grout Thermal Conductivity	1.61 W/m.K	0.933 Btu/hr.ft.^{o}F
Pipe Thermal Conductivity	0.39 W/m.K	0.226 Btu/hr.ft.^{o}F
Pipe Wall Thickness	3 mm	0.119 in
Pipe Outer Diameter	33 mm	1.31 in
Pipe (U-Tube) Spacing	67 mm	2.62 in
Heat Carrier Fluid	Water	