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# An ice rink floor thermal model suitable for whole-building energy simulation analysis

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ABSTRACT

This paper presents a thermal model for an ice rink floor system that is integrated into EnergyPlus, a whole-building energy simulation tool, to improve design, evaluation, and operation of ice rink facilities. The developed ice rink floor thermal model, based on the conduction transfer function method, is validated against experimental data obtained under laboratory testing conditions. Two control strategies for indoor ice rink floor systems were modeled and evaluated including a brine temperature control strategy and an ice surface temperature control strategy.



## 1. Introduction

Ice rink arenas are among the most energy intensive entertainment facilities with annual energy consumption of 750 kWh/m$^2$, almost 3 times the energy use intensity of office buildings [1]. There are several thousands of indoor ice rinks in North America used for various spectator events and recreational activities such as hockey games, figure skating, or public skating. Most of the arenas are operated continuously for over 8 months to 11 months per year and thus consume significant levels of energy when compared to other recreational facilities. According to a DOE report, a typical indoor ice rink arena in Massachusetts had an average electric consumption of 730 MWh which accounted for $70,500 in 2010 for just a 7–8 months season [2]. Another study showed that the energy costs to operate an ice rink facility in Canada for 8 months are on average $86,000 [3]. According to the international ice hockey technical guides, the energy consumption by three ice skating rinks in Europe ranges from 900 to 1500 MWh/year and the average energy bill can range from $50,000 to $90,000 [4]. Unfortunately, there is no clear guidelines and analysis tools to help improve the energy performance of ice rinks. In particular, it is difficult to estimate refrigeration load and energy use of ice rinks using currently available whole-building energy simulations due to lack of detailed models for ice rink floor systems.

Early numerical and experimental analysis studies of indoor ice rink arenas were usually focused on indoor air quality [5]. Recently, ASHRAE has sponsored a research project to better estimate ice sheet cooling loads [6]. In particular, a numerical analysis was performed as part of this project to estimate daily heat flux profiles at the ice sheet surface under steady and periodic meteorological conditions [7,8]. As an extension of this ASHRAE project, a zonal model is developed to calculate thermal interactions between indoor air and ice sheet surface within an ice rink arena. This zonal model is used with TRNSYS to estimate annual energy consumption for ice arenas [9–11]. However, the model is a standalone algorithm and cannot be easily implemented in a whole-building simulation program.

The main objective of the work presented in this paper, is to develop a detailed heat transfer model for a typical ice rink floor suitable for integration within a whole-building simulation tool. While existing models [6–11] can estimate heat transfer along the ice sheet surface, they do not consider thermal coupling of the ice rink floor system with its surroundings. In this paper, a thermal model for the ice rink floor system is developed to account for thermal interactions between the floor system, ground, and ambient air of the indoor arena. Moreover, the developed ice rink floor system model was integrated into a state-of-the art energy analysis simulation program, EnergyPlus, to assess energy performance of ice rink facilities under various design and operating conditions.

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**Nomenclature**

| | |
|---|---|
| $A$ | area of brine pipe surface [$m^2$ ($ft^2$)] |
| Area | area of ice surface [$m^2$ ($ft^2$)] |
| $C_a$ | coefficients associated with the heat balance at the inside surface as defined in Equation (4) including solar, long wave radiation exchange, and conduction history terms, for example [°C (°F)] |
| $C_b$ | current cross Conduction Transfer Function term as defined in Equation (4) |
| $C_c$ | coefficients associated with the current heat source/sink as defined in Equation (4) [$m^2$ °C/W ($ft^2$ h °F/Btu)] |
| $C_d$ | coefficients associated with the heat balance at the outside surface as defined in Equation (5) including solar, long wave radiation exchange, and conduction history terms, for example [°C (°F)] |
| $C_e$ | current cross Conduction Transfer Function term as defined in Equation (5) |
| $C_f$ | coefficients associated with the current heat source/sink as defined in Equation (5) [$m^2$ °C/W ($ft^2$ h °F/Btu)] |
| $C_g$ | sum of temperature and source history terms at the source/sink location as defined in Equation (9) [°C (°F)] |
| $C_h$ | coefficients associated with the current heat source/sink as defined in Equation (9) [$m^2$ °C/W ($ft^2$ h °F/Btu)] |
| $C_i$ | inside term for the current inside surface temperature as defined in Equation (9) |
| $C_j$ | CTF outside term for the current outside surface temperature as defined in Equation (9) |
| $C_k$ | is defined as $C_k = C_g + \{C_i\,(C_a + C_b \cdot C_d) + C_j\,(C_d + C_e \cdot C_a)\}/(1 - C_e \cdot C_b)$ [°C (°F)] |
| $C_l$ | defined as $C_l = C_h + \{C_i \cdot (C_c + C_b \cdot C_f) + C_j \cdot (C_f + C_e \cdot C_c)\}/(1 - C_e \cdot C_b)$ [$m^2$ °C/W ($ft^2$ h °F/Btu)] |
| $Cp$ | specific heat for the brine [J/kg K (Btu/lb °F)] |
| CTF | conduction transfer function method |
| QTF | conduction transfer function method with heat source/sink |
| $F_m$ | flux CTF coefficient, $m = 0,1,\ldots,k$. |
| $m$ | brine mass flow rate [kg/s (lb/h)] |
| $q''$ | surface heat balance including radiation from other surfaces, solar radiation, and convection heat flux on the inside surface [W/$m^2$ (Btu/h $ft^2$)] |
| $q_{source}$ | heat flux from the heat source/sink (i.e., embedded pipes with the ice rink floor) [W/$m^2$ (Btu/h $ft^2$)] |
| $T_{b.in}$ | inlet brine temperature [°C (°F)] |
| $T_{b.out}$ | outlet brine temperature [°C (°F)] |
| $T_i$ | inside face temperature [°C (°F)] |
| $T_o$ | outside face temperature [°C (°F)] |
| $T_s$ | temperature at the location of the source/sink [°C (°F)] |
| $X_m$ | inside CTF coefficient, $m = 0,1,\ldots,M$. |
| $Y_m$ | cross CTF coefficient, $m = 0,1,\ldots,M$. |
| $W_m$ | QTF inside term for the heat source/sink, $m = 0,1,\ldots,M$. |
| $\varepsilon$ | effectiveness of the heat exchanger |

*Indices*

| | |
|---|---|
| i | inside |
| o | outside |
| b | brine |
| t | current time step |

## 2. Ice rink floor model description

An ice rink floor system model using the conduction transfer function (CTF) method was developed based on the low temperature radiation cooling system model currently available in EnergyPlus [12].

Similar to the EnergyPlus low temperature radiation cooling system model, heat sink terms were introduced to estimate the thermal load associated with the embedded pipes inside the ice rink floor. In order to form and maintain the ice sheet, the ice rink floor system was served by a refrigeration system that may include several chillers and pumps. The quality of the ice sheet was ensured through a control system to maintain the fluid inside the pipes within predefined set-point temperatures.

The ice rink floor system model differed from that of the low temperature radiation cooling system modeled in EnergyPlus in several aspects as noted below [12]:

- First, ice rink floor system used a brine solution with temperatures that were usually below zero. On the other hand, the low temperature radiation cooling system uses water with higher temperatures that are above 0 °C. In EnergyPlus, most systems are designed to use fluids operating above freezing temperatures.
- Second, low temperature radiation cooling systems are intended to control room air temperature. The ice rink floor model, however, is used to control ice layer surface temperature or outlet brine temperature.
- Third, a radiation cooling system includes HVAC equipment that is used to remove thermal load from one zone or several zones. However, the ice floor rink floor system was independent from the zone air control system and could actually contribute to the zone heating/cooling loads.

Due to these differences, several challenges needed to be considered when developing an ice rink floor system model suitable for integration into a detailed whole-building simulation program such as EnergyPlus. A brief outline of the developed ice rink floor model is provided in the following sections.

Like the low temperature radiant system model, the ice rink floor system model has two algorithms. The first algorithm calculates temperatures and heat fluxes through the floor structure including the heat sinks/sources. The second algorithm predicts temperatures and heat fluxes at the source/sink location.

The low temperature radiant system model integrated in EnergyPlus uses the conduction transfer function technique with heat sources or sinks as expressed in the following equations [11–13]:

$$q''_{i,t} = \sum_{m=1}^{M} X_m T_{i,t-m+1} - \sum_{m=1}^{M} Y_m T_{o,t-m+1} + \sum_{m=1}^{k} F_m q''_{i,t-m} + \sum_{m=1}^{M} W_m q_{\text{source},t-m+1} \tag{1}$$

From the above equation, the inner and outer surface temperatures can be estimated as follows:

$$T_{i,t} = \left( -\frac{1}{X_1}\sum_{m=2}^{M} X_m T_{i,t-m+1} + \frac{1}{X_1}\sum_{m=2}^{M} Y_m T_{o,t-m+1} - \frac{1}{X_1}\sum_{m=1}^{k} F_m q''_{i,t-m} + + \frac{q''_{i,t}}{X_1} - \frac{1}{X_1}\sum_{m=1}^{M} W_m q_{\text{source},t-m+2} \right) + \left(\frac{Y_1}{X_1}\right) T_{o,t} + \left(\frac{W_1}{X_1}\right) q_{\text{source},1} \tag{2}$$