EFFECTS OF MULTI-PASS BRINE SYSTEM ON THE ICE TEMPERATURE OF SKATING RINKS

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Abstract

Two approaches were developed to study the influence of the multi-pass brine system on the ice surface temperature: the first one is analytical based on a simple thermal circuit employing four nodes with isothermal boundary condition at a specified depth within the soil underneath the slab and the second one is a numerical three-dimensional model which employs the control volume method to solve partial differential equations that describe the heat transfer through the ice sheet, the brine and the different layers under the concrete slab. The model is tested by comparing its predictions with measured values. Profiles of ice surface temperature are presented and analyzed for the two-pass and four-pass circuits. The results show that the two-pass circuit results in a more uniform ice temperature.

1 Introduction

In most arenas, the ice rink is cooled by a brine solution circulated in a two-pass network of pipes embedded in a concrete slab. The brine pump often accounts for over 15% of the refrigeration system's total energy consumption. This energy may be reduced by different techniques. The City of Montreal has adopted the concept known as a four-pass brine system with chillers evaporators in series. Utilising this new method provides important energy savings but may affect the uniformity of the ice temperature. The low temperature brine solution that is circulated through the slab removes the cooling load resulting from heat transfer above the ice sheet (e.g., due to long-wave radiation between the ceiling and the ice sheet, convection and condensation), and from conduction in the soil below the slab. The literature review revealed very few studies treating in detail heat transfer through the ice rink floor. Bellache et al. (2006) used a commercial CFD code to analyse two-dimensional transient simultaneous heat and mass transfer in ice rinks. They extended their study up to 2m of depth in the ground by considering an average constant brine temperature. Daoud and Galanis (2006) used a zonal model to predict the heat fluxes in an indoor ice rink. They included different layers under the ice sheet by considering an average constant brine temperature. The present paper presents two approaches to study the influence of the multi-pass brine system on the ice surface temperature: the first one is analytical based on the electrical analogy and the second one is a numerical three-dimensional model which employs the control volume method to solve partial differential equations that describe the heat transfer through the ice sheet, the brine and the different layers under the concrete slab. The objective of this study is to show the effect of multi-pass brine systems on the ice temperature of skating rinks.

2 Description of a typical section through the ice rink floor

A typical section through the ice rink floor is composed of the following layers (Figure 1): the 0.0 25 m ice sheet; the 0.15 m concrete slab with polyethylene refrigeration pipes of 0.025 m diameter at 0.1 m centre-to-centre distance; the 0.1 m extruded polystyrene insulation layer; the 0.2 m sand layer; and the 1.5 m earth layer. The refrigeration pipes are located in the concrete slab at 0.025 m

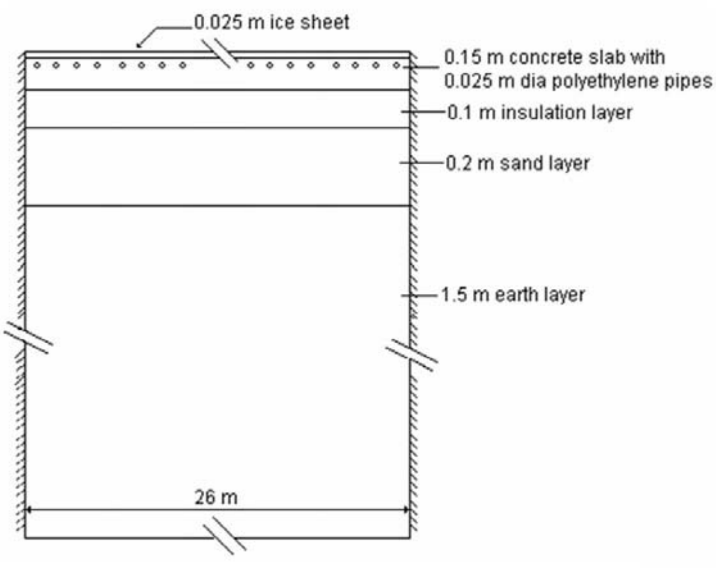

Figure 1: *Transverse cross- section of the ice rink floor.*

below the ice sheet. The ground at a depth of 2 m is assumed to have a constant temperature. In this figure, dashed lines are used to denote the surfaces that are insulated.

3 Methodology

Two design alternatives of ground-coupled floor slabs were considered in the model development and evaluation study.

Case no.1: the two-pass brine distribution system with chiller evaporators connected in parallel. The two-pass slab system used 296 polyethylene pipes spaced at intervals of 0.075 m, as shown in Figure 2. The brine header system is reversed-return, using 0.2 m, schedule 40 steel pipes. The brine was composed of aqueous calcium chloride. A single brine pump circulated the brine. The pump, driven by a 22 kW, 126m/s motor, possessed a capacity of 56.9 $10^{-3}m^3/s$ with a head pressure of 263 kPa. Two evaporators are connected in parallel, each evaporator using 28.5 10^{-3} m^3/s.

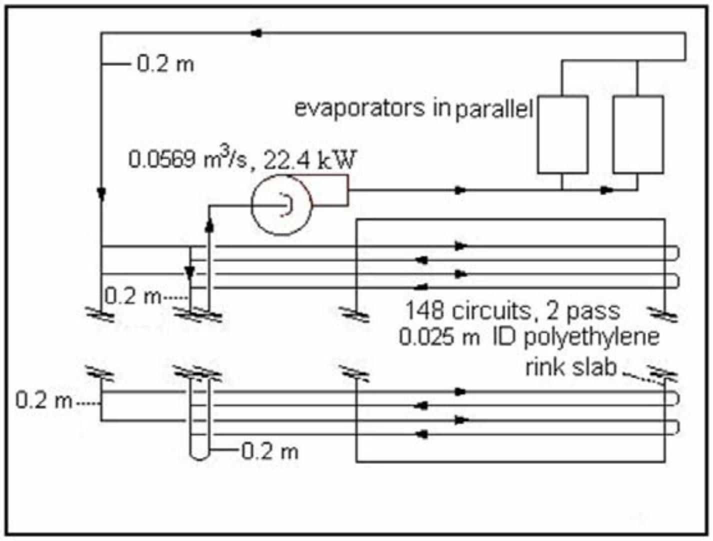

Figure 2: *Schematic of two-pass system with evaporators in parallel.*

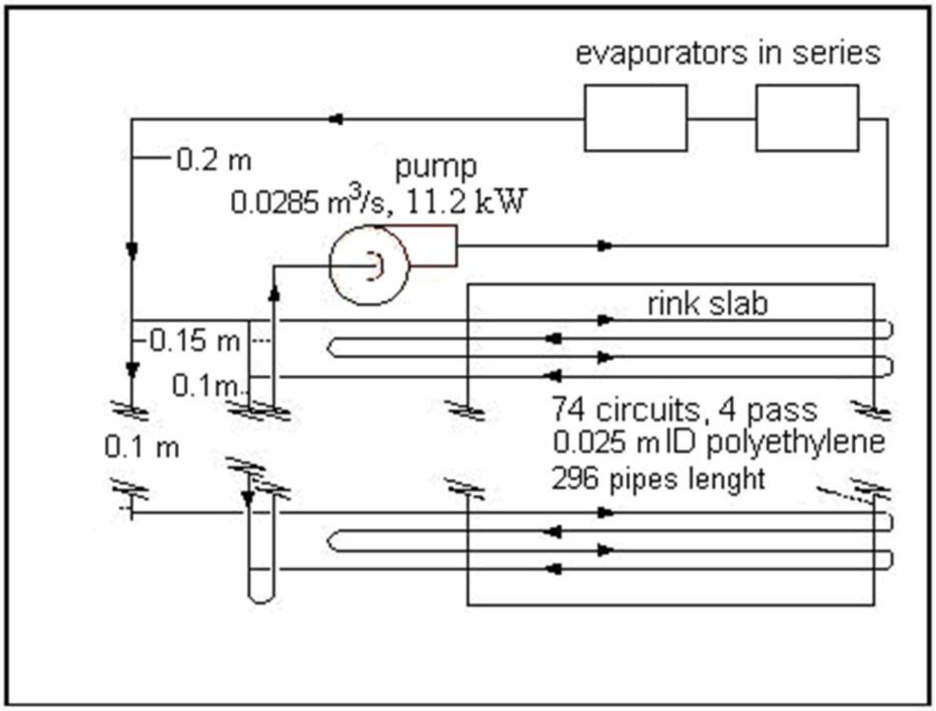

Figure 3: *Schematic of four-pass system with evaporators in serie*s.

Case no.2: the four-pass brine distribution system with the evaporators in series. This system enables the flow rate necessary for cooling the ice surface to be reduced by half. Utilising this new system resulted in reduction of 93000 kWh/yr of the energy consumption of the brine pump and refrigeration system. The original 0.2 m brine header system was replaced by a 0.15 m header system because brine flow decreased from 56.9 to 28.5 10^{-3} m^3/s. The evaporators are piped in series for a flow of 28.5 10^{-3} m^3/s each. The brine is circulated by a single pump sized for a brine flow rate of 28.5 10^{-3} m^3/s and a head pressure of 226 kPa, driven by a 11 kW high-efficiency motor rotating at 1,200 rpm. The analytical and numerical approaches have been applied for the two cases to study the influence of the multi-pass brine system on the ice surface temperature.

4 Modeling

Two approaches were developed to study the influence of the multi-pass brine system on the ice surface temperature:

4.1 Analytical approach

Based on the one-dimensional analysis, it uses a simple thermal circuit employing four nodes with an isothermal boundary condition at 2m underneath the slab. The energy balance for the brine can be approximated as follows:

$$\dot{m}_b \, c_{p_b} \left(T_{bout} - T_{bin}\right) = \dot{Q}_i + \dot{Q}_p + \dot{Q}_g \qquad (1)$$

Where

$\dot{Q}_i$ = heat transfer rate on top of the ice surface

$\dot{Q}_p$ = pumping heat load

$\dot{Q}_g$ = ground heat load

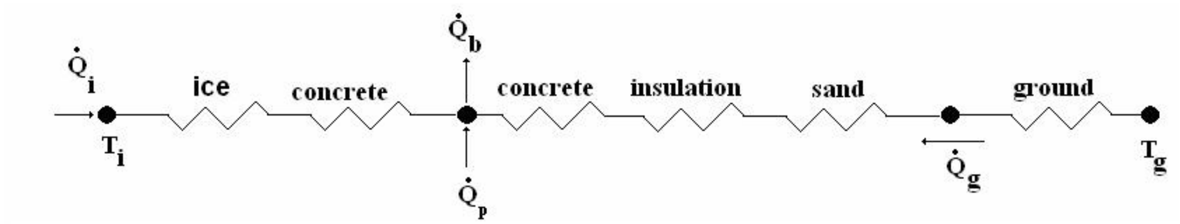

Figure 4: *Simplified four-node model for a one-dimensional ground-coupled floor in ice rinks.*

The heat load due to dissipation in the pipes and heat gains from the ground are calculated as follows (White, 2001):

$$\dot{Q}_p = \rho\, g\, \dot{V}\, H_{sys} \tag{2}$$

$$\dot{Q}_g = \frac{k_{g-b}}{\delta_{g-b}} A\left(T_g - \overline{T}_b\right) \tag{3}$$

With

$$\overline{T}_b = \frac{T_{bin} + T_{bout}}{2}$$

The heat flux on top of the ice surface is assumed to have a constant value.

By combining equations 1, 2 and 3, we obtain the outlet brine temperature:

$$T_{bo} = \frac{\dot{m}_b c_{p_b} T_{bi} + \dot{Q}_i + \rho\, g\, \dot{V}\, H_{sys} + \dfrac{k_{g-s}}{2\,\delta_{g-s}} A\left(2T_g - T_{bi}\right)}{\dot{m}_b c_{p_b} + \dfrac{k_{g-b}}{2\,\delta_{g-b}} A} \tag{4}$$

And the ice surface temperature is given by the following expression:

$$T_i = \frac{\dot{Q}_i\ \delta_{i-b}}{k_{i-b}\ A} + \overline{T}_b \tag{5}$$

4.2 Numerical approach

A three-dimensional model was developed for the two cases by using a CFD commercial code (Spalding, 1991). The calculation domain includes the solid layers of the slab and the brine solution which is circulating in the network of pipes embedded in the concrete slab.

4.2.1 Hypotheses

- The fluid flow and heat transfer in the ice slab are assumed to be steady state and turbulent.
- The heat transfer rate on top of the ice surface is uniform and constant.

4.2.2 Physical properties of each layer

1. Thermal conductivity of insulation $k = 0.029\ \mathrm{W\,m^{-1}K^{-1}}$; (Ashrae, 2005).
2. Thermal conductivity of concrete $k = 1.4\ \mathrm{W\,m^{-1}K^{-1}}$; (Incropera, 2002).
3. Thermal conductivity of ice $k = 2\ \mathrm{W\,m^{-1}K^{-1}}$; (Perry, 1973).
4. Thermal conductivity of sand $k = 0.27\ \mathrm{W\,m^{-1}K^{-1}}$; (Perry, 1973).
5. Thermal conductivity of earth $k = 2\ \mathrm{W\,m^{-1}K^{-1}}$; (Yunus, 2003).

4.2.3 Model equations

The equations which govern fluid flow and heat transfer are the conservation equations of mass, momentum and energy with the two equation model closure for turbulence. The calculation domain includes the layers of the slab and the brine solution which is circulating in the network of pipes embedded in the concrete slab. The equations of conservation are applied only in the fluid flow. In the solid, the equation of heat conduction is applied.

Continuity equation

$$\frac{\partial}{\partial x_i}\left(\overline{u}_i\right) = 0 \tag{6}$$

Momentum equations

$$\overline{\rho u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \mu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i^{'} u_j^{'}}\right) \tag{7}$$

Energy equation

$$\rho \overline{u}_j \frac{\partial \overline{T}}{\partial x_j} = k \frac{\partial^2 \overline{T}}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\rho c_p \overline{u_j^{'} T'}\right) + St \tag{8}$$

Transport equation of turbulence kinetic energy

$$\overline{u}_i \frac{\partial E_k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\nu_t}{Pr_k}\frac{\partial E_k}{\partial x_i}\right] + P_k + G_k - \varepsilon \tag{9}$$

Transport equation of dissipation rate

$$\overline{u}_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\nu_t}{Pr_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right] + \frac{\varepsilon}{k}\left(C_{1\varepsilon} P_k + C_{3\varepsilon} G_k - C_{2\varepsilon}\varepsilon\right) \tag{10}$$

The model constant are $Pr_k = 1$; $Pr_c = 1$; $\sigma_\varepsilon = 1.3$; $C_\mu = 0.09$; $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$; $C_{3\varepsilon} = 1$

4.2.4 Boundary conditions

The following boundary conditions are applied to the typical section
- The heat transfer rate on top of the ice surface is uniform and constant $q'' = 58\ W/m^2$.
- The ground temperature far below the concrete slab floor is uniform and constant at T = -4 ºC.
- There is no heat transfer through the left and right boundaries (i.e. the surfaces are insulated).

4.2.5 Calculation procedure

The numerical solution of the system of coupled partial differential equations has been carried out using the finite volume method, a staggered grid and the hybrid scheme for discretization of the convection terms. The SIMPLE algorithm was used for the pressure correction and the solution was obtained iteratively using the commercial CFD code. The number of grid points within the domain has been selected based on a preliminary analysis to ensure that the results are independent of their number. The discretization grid was always non-uniform with higher density near the brine inlets and outlets and near the interface ice-concrete. Numerical tests have also been carried out to ensure that the results are independent of the number of iterations. Under relaxation was often necessary to achieve convergence, which was declared when the cumulative residuals for each of the conservation equations were less than 10^{-6}. The results reported throughout this paper were calculated with 19 x 41 x 1035 grid points and 10000 iterations.

4.2.6 Validation

The following variables were measured: supply and return brine temperature, brine flow rate and ice surface temperature close to centre ice rink. Table 1 presents the comparison between the measured and calculated temperatures at the brine outlet and the ice surface. The numerical results are in better agreement with the measurements than the results of the analytical calculation. The return brine temperature calculated by the analytical method is close to the measurement value. On the other hand the corresponding difference for the ice temperature is significant, since we have used an average brine temperature for the calculation of heat flow between the ground and the brine and the energy balance in a 1-D model. The agreement between the measured and numerical data is acceptable, the maximum relative error is under 9% and may be attributed to the following factors:

- Model assumptions/simplification such as a uniform and constant heat flux on top of the ice surface.
- Measurement errors due to the instruments (temperature and mass flow).

Table 1: *Comparison between measured and calculated temperatures*

Multi-pass network	return brine temperature measurements (°C)	return brine temperature analytical calculation (°C)	return brine temperature numerical calculation (°C)	ice surface temperature measurements (°C)	ice surface temperature analytical calculation (°C)	ice surface temperature numerical calculation (°C)
2-pass	-	-8.5	-8.1	-6.3	-6.1	-6.5
4-pass	-7.3	-7.9	-7.4	-5.5	-5.9	-6.0

5 Results and discussion

The 2-D vertical temperature distribution in the section of 0.4 m wide, as predicted by computer simulations, is presented in Figure 5 (in color) for the two cases under consideration. The flow rate and supply brine temperature are equal 0.38 l/s and -9ºC respectively. The heat flux on top of the ice surface is 58 W/m^2 and the ground temperature far below the concrete slab floor is equal -4ºC. In the layers located below the concrete slab, i.e. from the insulation to the bottom of the domain, the isotherms are horizontal and practically identical for the two cases. On the other hand, in the concrete slab, the difference between the two cases is very significant. It is observed that the concrete slab with the two-pass network of pipes is colder than the one with the four-pass network of pipes.

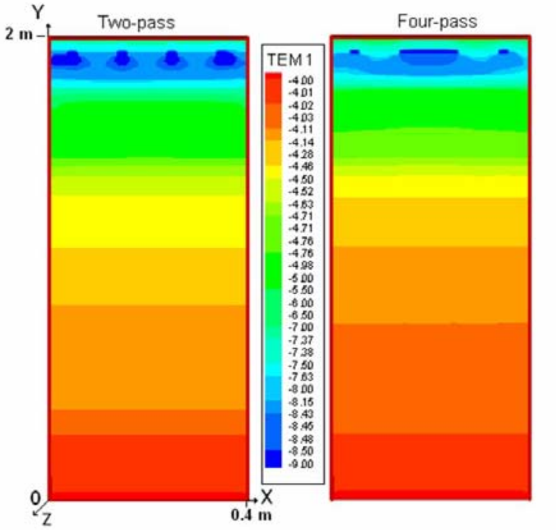

Figure 5: *Temperature Distribution in Cross.*

5.1 Ice surface temperature distribution

Figures 6 and 7 show the temperature distribution across the top surface of the ice calculated by the numerical model at position Z = 16 m. It is noted that the design of the multi-pass brine system influences significantly the temperature of the ice surface. The ice surface temperature of four-circuit is warmer for the same inlet cold fluid temperature and surface heat flux.

In the case of four-pass, we notice that the ice surface temperature fluctuation is important with X and would therefore result in non-uniform ice quality.

In the case of two-pass, the ice surface temperature fluctuation is significantly reduced with X. It is clear that the surface temperatures of ice are almost identical for the two cases in the first 10 centimetres, i.e. close to the inlet of the brine. Beyond 20 cm, the variation in temperature becomes increasingly important thus reaching 0.7 ºC close to the outlet of the brine.

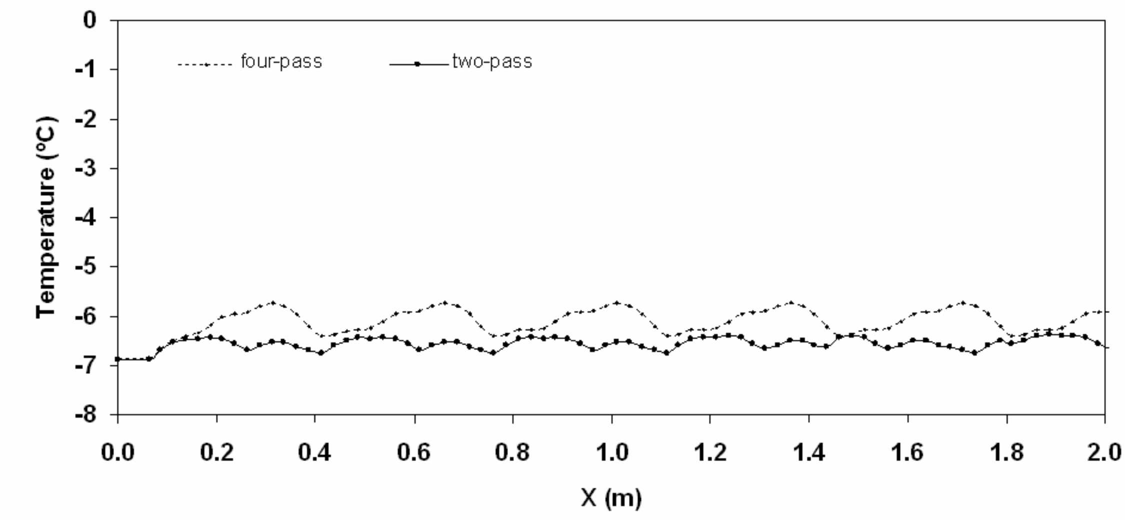

Figure 6: *Ice surface temperatures for two considered cases at Z = 16 m and 0<X<2m*

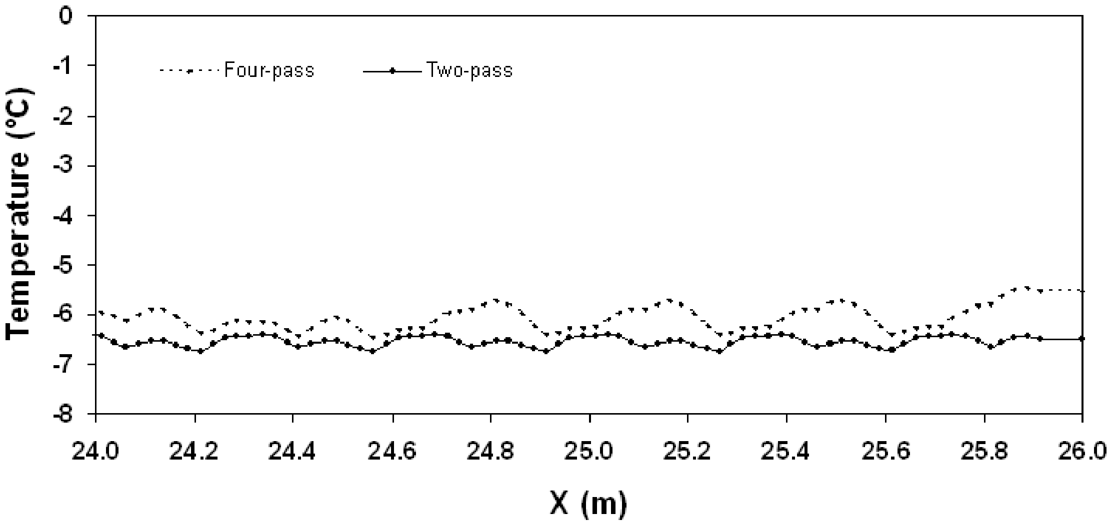

Figure 7: *Ice surface temperatures for two considered cases at Z = 16 m and 24<X<26 m*

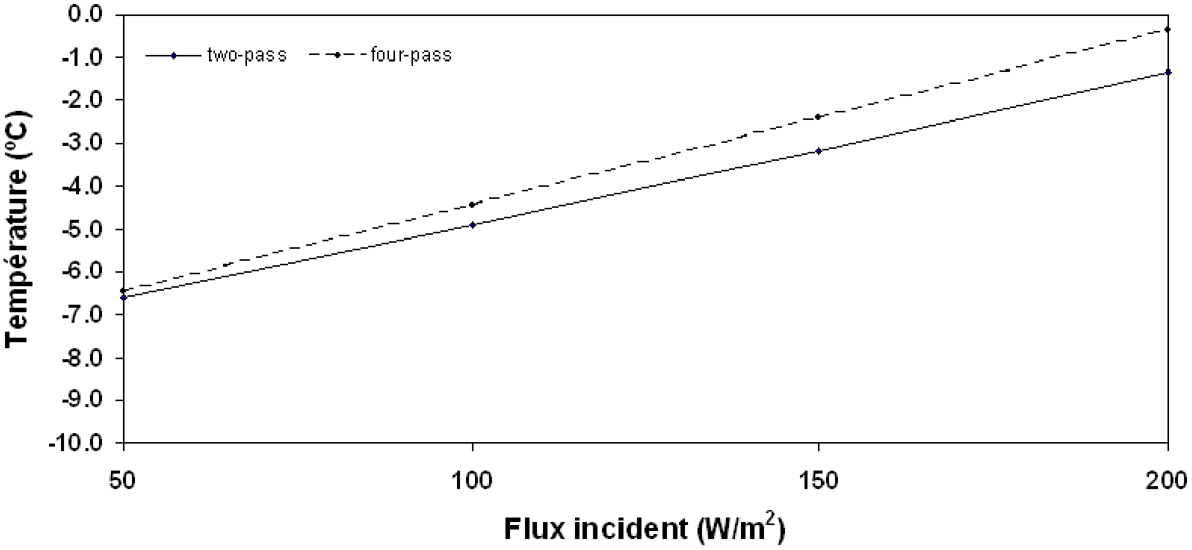

Figure 8: *Ice surface temperatures for varying heat fluxes*

Figure 8 shows the effect of the heat transfer rate on the top of the ice on the ice surface temperature. It indicates that the ice surface temperature is linear with the heat transfer rate reaching the ice surface. We note that the average ice temperature for four-pass systems is always higher than for two-pass systems. Their difference increases when the heat flux into the ice increases.

6 Conclusion

An analytical approach and a numerical method were used to study the effect of the brine distribution system on the temperature of the ice surface. The two approaches give results close to the corresponding measurements. The four-pass network results in higher average ice temperatures, larger differences between its maximum and minimum values and a significant deterioration of ice quality.

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