PHYSICAL PROCESSES IN ICE RINKS STUDIED WITH SMALL-SCALE MODELLING

Pär Carling M.Sc.
Building Services Engineering, KTH, Stockholm, SWEDEN

ABSTRACT

The study reported in this paper is concentrated on the estimation of the heat transfer from air to ice due to convection. Together with measurements of temperature and moisture profiles, air movements have been visualised in a small-scale model of a planned indoor ice rink. Some field tests concerning moisture content and temperature also have been realized in two different ice rinks.

The study indicates that a low emissivity layer in the ceiling decreases the risk for ceiling condensation, decreases the heat radiation on the ice and decreases the driving force for air mixing. The convective heat exchange coefficient was estimated to 1.0 W/m^2·°C by measuring the frosting rate on the ice. The warm, humid and contaminated air from the gallery streams next to the ceiling and mixes with the air over the rink.

KEYWORDS

Convective heat transfer, Model experiments, Public buildings, Temperature gradient

INTRODUCTION

Ice skating rinks are common in many European and North American countries. Sometimes serious problems occur in these buildings. High energy usage and operating costs, high humidity leading to unsatisfactory ice conditions as well as decay of materials and poor comfort for the spectators are common examples. Blades (1992) has presented recommendations for promotion of more energy efficient, cost effective and improved ice skating rinks. A common strategy for solving the condensation problems is to apply a coating of low emissivity in the ceiling which has been proved useful by computer modelling by Korsgaard and Forowicz (1986). In order to decrease the energy use the heat transfer from air to ice must be lowered. Hayashi and Aoki (1977) examined the frost layer structure appearing under different conditions and state that frost formation should be treated as a simultaneous heat and mass transfer problem. The total heat transfer from air to ice consists of radiation, convection and sublimation (Bäckström 1946). When calculating moisture balance in an ice rink the convective heat transfer coefficient can be set to 1 W/m^2·°C according to Glas (1984). In an earlier report Glas (1966) calculated a theoretical value for an ice rink, 80 meters long with a temperature difference of 10 degrees to be 0.27 W/m^2·°C.

The study reported in this paper is concentrated on the estimation of the heat transfer due to convection and sublimation. Measurements of temperature and moisture profiles in a small-scale model of a planned indoor ice rink are presented together with smoke visualisation of air movements. Field measurements of moisture content and temperature profiles in two ice rinks are also reported.

EXPERIMENTAL SET-UP AND PROCEDURE

The small-scale model (see fig. 1) was built in the scale 1:100 with the dimensions 1.2*0.9*0.23 m^3 (L*W*H). The bottom is a concrete slab equiped with cooling pipes in which an ethyleneglycol-water solution is circulated. The walls and ceiling are made of wooden boards that are insulated against heat.

On the sides of the concrete slab are water tanks from which water evaporates in order to simulate the moisture contribution from the spectators. The water temperature can be adjusted with an immersion heater. One of the gables are made of plexiglas which together with lighting in the ceiling of the model makes it possible to follow the tests by sight. Just above the rink three wires are mounted. On each wire six round pieces of aluminium foil are fixed. The wires are attached to a rotating handle on an electric engine which makes the aluminium pieces move with an average speed of 0.56 m/s. The device is meant for simulating skating movements. The inside of the ceiling and the walls have been painted with low permeable paint in order to decrease the moisture transport between the model and the surroundings. Tests have also been made with a layer of aluminium foil in the ceiling. In the model the temperatures have been measured with 21 copper-constantan thermocouples at some fixed points. The moisture content has been measured, at different levels, with a hygrometer through a premade hole in the roof. In the field tests a combined hygrometer and thermometer has been used for the measurements. To measure the frosting rate in the model a plastic foil with a defined area has been applied to the ice surface. The amount of frost on the plastic foil has been weighed after finishing a test. When the frosting rate is known, the convective heat transfer coefficient can be estimated from

$$M_f = \frac{\alpha \cdot A_f \cdot (x_{air} - x_{surface})}{c_{pa}} \tag{1}$$

where

M_f = frosting rate (kg/s)
α = convective heat transfer coefficient (W/m^2·°C)
A_f = plastic foil area (m^2)
x_{air} = moisture content in the air volume next to the ceiling (kg moisture/kg dry air)
$x_{surface}$ = moisture content next to the ice (kg moisture/kg dry air)
c'_{pa} = specific heat of dry air (kJ/kg·°C)

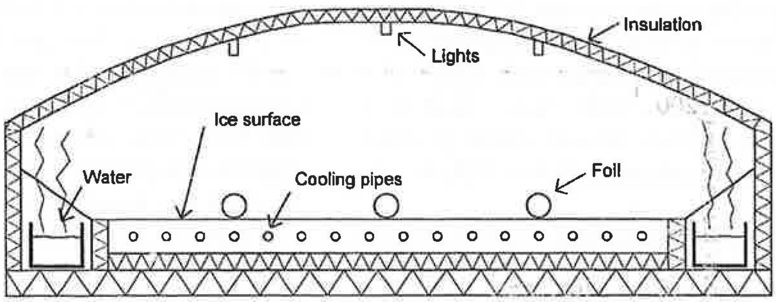

Figure 1 Outline diagram over the small-scale model.

The air movements have been visualised by smoke injected under the gallery

The model has not been constructed with the intention to to fulfil all the rules of small-scale modelling. The aim has rather been to do a qualitative analysis of the air movements and to see the relative influence of the air movements on the heat transfer.

TEMPERATURE AND MOISTURE PROFILES

Close to the ice, that is from the surface up to approximately 2 meters above the surface, a stable cold air layer was established in the real ice rinks studied. In this layer hardly no air movements occur. In the model the corresponding value was about 30 millimeters. In an ice rink the air temperature will increase all the way up to the ceiling and if the surface of the ceiling has a low emissivity layer, the ceiling will be warmer than the air (fig. 2). However if the ceiling has high emissivity the temperature will be lower on the surface than in the air just below the ceiling (fig. 3). The difference in surface temperature is caused by differencies in heat transfer due to radiation. A higher ceiling emissivity causes a larger heat transfer from the ceiling to the ice. Temperature profiles from field measurements have a similar appearance as the profiles from the model. In figure 4 temperature profiles from two ice rinks are presented. In these measurements only the temperature profiles up to 2.5 meters above the ice surface were measured.

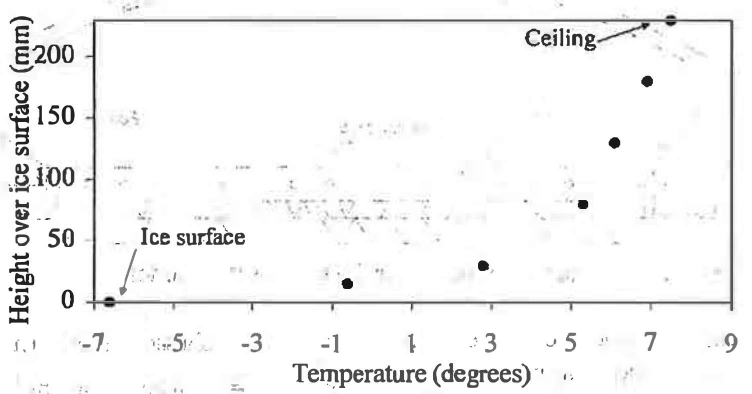

Figure 2. Temperature profile in the small-scale model when the ceiling emissivity was low (aluminium foil). The measurements are done in the center of the model.

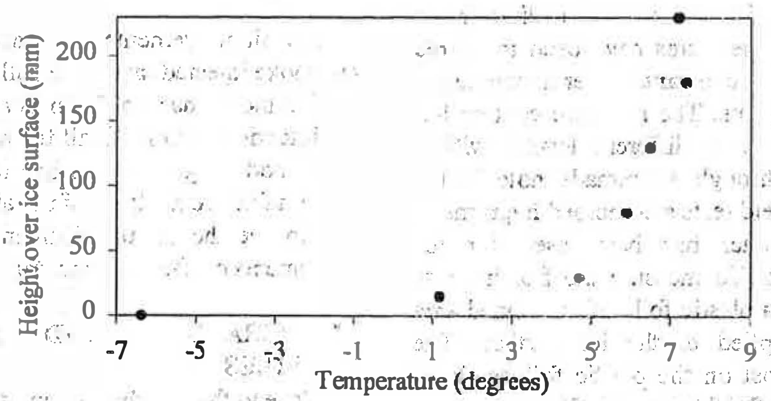

Figure 3. Temperature profile in the small-scale model when the ceiling emissivity was high (white paint). The measurements are done in the center of the model.

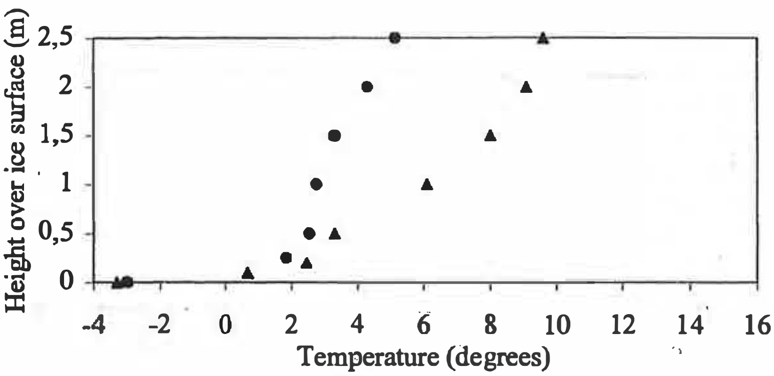

Figure 4. Temperature profiles up to 2.5 meters above the ice surface in two ice rinks.

Concerning the moisture profiles they clearly show that the moisture transportation goes downwards. On the ice, moisture will become frost and the air will be dried. In figure 5 moisture profiles from the same ice rinks as in figure 4 are presented. Moisture profiles in the small-scale model where also measured (fig. 6). However it seemed like a difficult task to measure the moisture content next to the ice. Therefore a theoretical value of the moisture content next to the ice was calculated based on the assumption that the water vapour concentration was saturated.

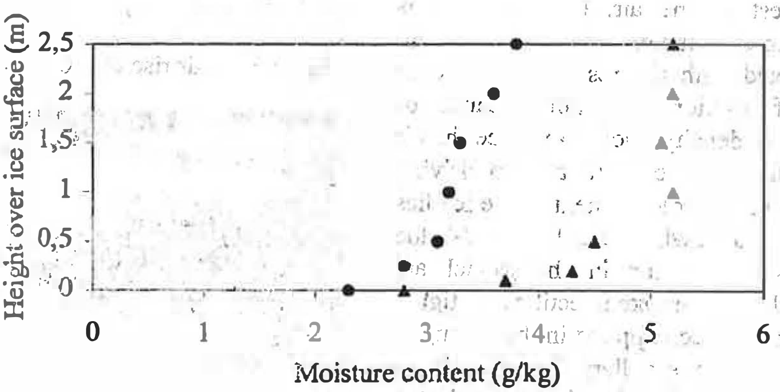

Figure 5 Moisture profiles in two icerinks. The measurements where done at the same occasions as in those referred to in figure 4.

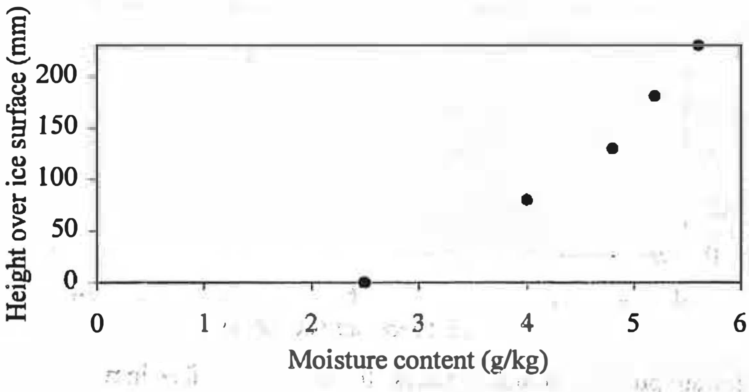

Figure 6 Typical moisture profile in the small-scale model.

AIR MOVEMENTS IN THE MODEL

The air that is humidified, contaminated and warmed by the spectators rises up from the gallery and streams close to the ceiling where some turbulence occur because of friction. If the ceiling is colder than the air next to it, the airstream will be cooled and will soon fall down into the volume and mix with the rest of the air. If the ceiling is warmer than the air next to it, the airstream will be mixed with the rest of the air only because of friction and not because of differences in density. Next to the ice the air will not stir because there are no driving forces. The heavy cold air next to the ice lies like water in a bowl. In the figures 7-9 the movements of the air in the model are visualised through smoke injections. In figure 10 a curtain has been applied in the ceiling at the front edge of the gallery in the model in order to stop the humid air to reach the volume over the ice. Behind the curtain exhausting grills could be mounted.

Figure 7 Air rise up from the gallery

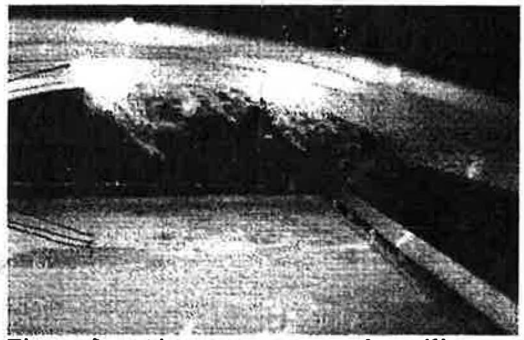

Figure 8 Air streams next to the ceiling and due to friction some turbulence occur.

Figure 9 The air from the gallery is mixed with the air over the rink

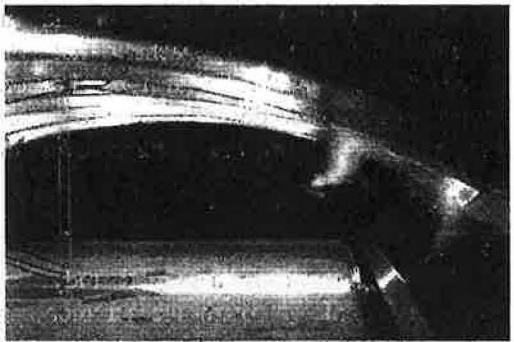

Figure 10 Example of a possible device for preventing the humid air from the gallery to reach the ice. In this case a plexiglass curtain have been placed over the gallery.

CONVECTIVE HEAT TRANSFER COEFFICIENT

If the air above the ice is completely still the heat transfer between air and ice only consists of conduction and the heat transfer coefficient can be calculated by

$$\alpha = \frac{\lambda}{d} \qquad (W/m^2 \cdot °C) \qquad (2)$$

where

λ = conductivity for the air ($W/m \cdot °C$)
d = thickness of the stable layer (m)

In the model the layer thickness was approximately 0.030 m and the conductivity for air (0°C) is 0.0245 ($W/m \cdot °C$) which means that α because of conduction is about 0.8 ($W/m^2 \cdot °C$).

In table 1 measured frosting rates and moisture differencies are shown together with convective heat transfer coefficients calculated by equation (1).

Under the round pieces of aluminium foil that were used for inducing air movements an increased amount of frost could be discovered when the simulators of skaters were used. The extra frost accomplished by air movements seemed to have less density than the frost accomplished by the moisture transport due to diffusion (fig. 11).

Comparing the heat transfer coefficients from the measurements with and without simulating skaters, the heat transfer coefficients during simulations were approximately 10% higher.

Table 1 Results from the model measurements

Test	Moisture difference (g/kg)	Frosting on the area 0.04 m² (kg/s)	Simulation of movements	Time of testing (min.)	Convective heat transfer coeff. ($W/m^2 \cdot °C$)
1	1.8	$1.04 \cdot 10^{-7}$	No	1120	1.48
2	3.3	$0.98 \cdot 10^{-7}$	No	1090	0.76
3	3.5	$1.08 \cdot 10^{-7}$	No	4275	0.79
4	2.4	$1.15 \cdot 10^{-7}$	Yes	450	1.23
5	3.0	$1.29 \cdot 10^{-7}$	Yes	375	1.10
6	2.7	$1.01 \cdot 10^{-7}$	Yes	1260	0.96
7	4.0	$1.26 \cdot 10^{-7}$	Interrupted	1380	0.81
				Mean value:	1.02
				Standard deviation:	0.25

However the measured values were few and more measurements are required to verify the results.

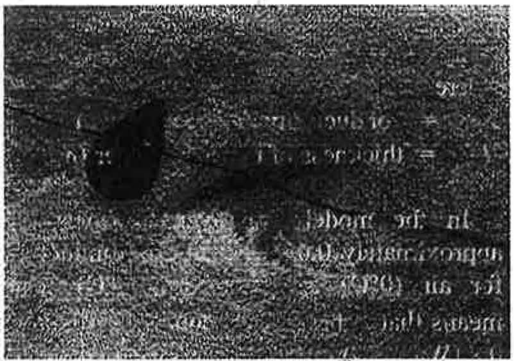

Figure 11 Locally increased frosting due to forced convection.

DISCUSSION

Clearly a low emissivity layer at the ceiling is useful. It will not only rise the temperature of the ceiling in order to decrease the risk for condensation but also decrease the heat radiation to the ice and therefore save energy. Furthermore the driving force for air mixing will decrease which means that the convective heat load to the ice will be smaller. Since the air mixing decreases the transportation of moisture will go slower which means less frosting on the ice.

The estimation of the convective heat transfer coefficient is based on only a few values. Nevertheless it is interesting to notice that the air movements caused by the simulation of skaters seem to have a small influence on the calculated value of the heat transfer coefficient. The values are scattered probably due to measuring errors. It would have been interesting to do more tests also including different speeds of the movement. Even if the "local" frosting was to small to detect it is obvious that the heat transfer due to convection increased when there were movements over the ice.

It seems, both from observations at field tests and small-scale modelling tests, that the movements of the skaters do not have much influence on the stable air layer next to the ice. Even if there are air movements the temperature profile do not need to fluctuate, on the contrary it seems to be quite stable in icerinks.

When designing the ventilation system of an icerink one strategy could be to divide the hall into two different zones. One zone around the gallery where humid and contaminated air could be evacuated quite near the spectators. To put some sort of curtains in the ceiling at the front edge of the gallery would hinder the air to stream out over the rink. A curtain like that must be combined with exhaust grills behind the shield. Another way of reaching that two-zone strategy would be to turn the roof construction upside down in order to get the air evacuated from the volume over the gallery.

SUMMARY

The study was made as a pilot study for a planned icerink. Through measurements of the temperature, moisture content and frosting rate in a model, both with and without simulated skating movements, the convective heat transfer coefficient has been estimated. The air movements have been visualised through smoke injections in the model.

The study indicates that a low emissivity layer in the ceiling is good. The convective heat transfer coefficient was estimated to 1.0 $W/m^2 \cdot °C$ and movements from skaters seemed to have little influence on the heat transfer. One way of solving the ventilation problem is to design a two-zone system.

ACKNOWLEDGEMENTS

This study was part of my diploma project at the Division of Building Sciences Engineering, KTH, Stockholm. I would like to thank Mr C Hansson at the consulting company EWR-Wahlings, Sweden for his valuable points of view on this report.

REFERENCES

Blades R.W. (1992) Modernizing and retrofitting ice skating rinks. *ASHRAE Journal.* April:34-42

Bäckström M. (1946) *Kylteknikern,* 379-380. Stockholm.

Carling Pär. (1997) Studie av fysikaliska processer i ishallar. Diploma thesis. Divison of Building Sciences Engineering, KTH, Stockholm, Sweden.

Glas L-O. (1966) Värmeövergång från horisontella ytor vid egenkonvektion och vid forcerad konvektion. Division of Applied Thermodynamics and Refrigeration, KTH, Stockholm, Sweden.

Glas L-O. (1984) Värmeåtervinning från kylanläggningen till Björkängshallen i Huddinge. *BFR-rapport* R84:1984

Hayashi Y., Aoki K. (1977) Heat and mass transfer by natural convection under frosting condition. The International Institute of Refrigeration (IIF/IIR), Commissions B1, B2, E1, Belgrad, Yugoslavia.

Korsgaard V., Forowicz T. (1986) *Building research and practice*, 6, 342-347.