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Numerical prediction of ventilation patterns and thermal processes in ice rinks

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Abstract

A numerical simulation of the heat and mass transfer phenomena in a ventilated ice rink has been carried out using the standard $\kappa-\varepsilon$ turbulence model. The complexity of the geometry has been taken into account by considering elements such as the plastic protection panels which have a significant effect on the flow field. The results calculated for four different configurations show the flow pattern, the isotherms and the lines of constant absolute and relative humidity. Values of the effective draft temperature are presented for several positions in the zone occupied by the spectators. The heat losses through the walls and ceiling as well as the latent, convective and radiative heat flux into the ice are presented and analyzed.

Keywords: Numerical simulation; Turbulent mixed convection; Ice rinks; Ventilation; Heating; Thermal comfort; Humidity; Radiation; Refrigeration load; Heat losses

1. Introduction

Canadian ice rinks use approximately 3500 GWh of electricity annually and generate 5×10^5 tons of gases contributing to the greenhouse effect. The potential for improvement in both areas is substantial. However, no concerted effort has been undertaken to develop design procedures and specify operational guidelines which would reduce energy consumption and gas emissions while maintaining the quality of the indoor air and ice as well as the comfort of skaters and spectators. The challenge is great because of the diversity of size and configuration of the buildings, and the differences in heating and ventilation systems in use. This complexity and the coupling between air movement, heat transfer through the building envelope, heat and mass transfer between the air and ice surface, radiation exchanges between the surfaces, pollutant and water vapour dispersion in a large irregular domain, explain the lack of design and operation norms.

The development of reliable CFD codes offers the potential for systematic analysis of the velocity, temperature, pollutant and/or vapour concentration distributions in ice rinks and other large buildings. Such numerical studies have been undertaken in 2D and 3D configurations by Chen et al. [1], Yang [2], Nielsen et al. [3], Jones and Whittle [4]. However, these studies do not generally take into account the interaction between convection, radiation, vapour diffusion and mass transfer between the ice surface and the air. They do not include the influence of these phenomena on heat losses through the envelope. Furthermore, previous studies have not evaluated the effect of these heat and mass transfer processes on the refrigeration load. Finally, no CFD study has evaluated systematically the effect of different ventilation and heating systems on energy consumption and thermal comfort.

In view of this situation, the present project aims to develop a model for ice rinks which takes into account

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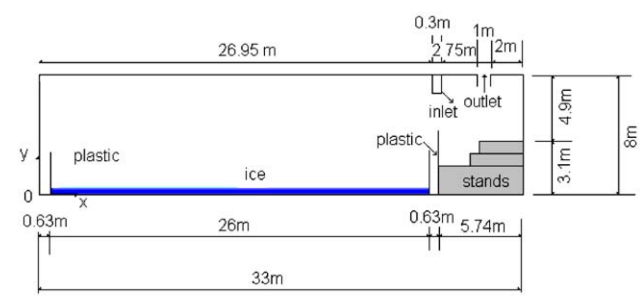
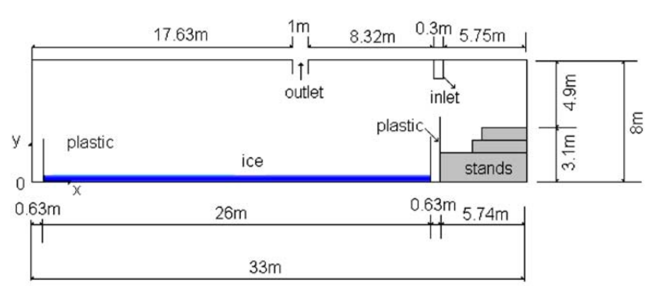
Nomenclature

C absolute humidity (kg/kg)
$(C\varepsilon_1, C\varepsilon_2, C\varepsilon_3, C\mu, C_d)$ turbulence model constants
D_{in} characteristic length (m)
g acceleration of gravity (m/s^2)
G_B buoyancy production of κ
G stress production of κ
H_{in} height of the inlet (m)
L_{in} width of the inlet (m)
P static pressure (Pa)
Pr_t turbulent Prandtl number
q_i heat flux for each element i of the envelope (W)
q_{ci} convective flux between the air and inside surface of the element i (W)
q_{ri} net radiative heat flux (W)
q_{li} heat latent (W)
T temperature (°C)
T_c average (control) space dry bulb temperature (°C)
t time (s)
U_{in} inlet velocity (m/s)
$\vec{V}$ velocity vector
u,v components of velocity (m/s)
S_ϕ source term
x horizontal coordinate (m)
y vertical coordinate (m)
β_T coefficient of thermal expansion (K^{-1})
β_c coefficient of mass expansion
Γ_ϕ diffusion coefficient
ε dissipation rate of turbulent kinetic energy (m^2/s^3)
κ turbulent kinetic energy (m^2/s^2)
μ dynamic viscosity (kg/m s)
v kinematic viscosity (m^2/s)
ρ density (kg/m^3)
$\sigma_t, \sigma_\varepsilon, \sigma_\kappa$ turbulence model constants
ϕ general field variable

all of the above phenomena and predicts energy consumption as well as ice and comfort conditions. For this purpose, we have calculated results for winter conditions and a particular ice rink in Montreal, Canada using the standard $\kappa-\varepsilon$ model to simulate the flow field and taking into account radiation exchanges between the inside surfaces of the envelope and the ice. In an earlier paper [5], we have presented numerical predictions for the velocity and temperature fields as well as comfort conditions and heat fluxes through the building envelope for four different combinations of inlet air conditions (temperature and direction of the ventilation air). In the present paper, we extend the formulation by including mass transfer between the ice surface and the air. Four different configurations of the ventilation system are considered and results with and without vapour diffusion and condensation are presented and compared in each case.



(a)



(b)

Fig. 1. (a,b) Cross section of the ice rink under consideration.

2. Modeling and calculation procedure

A schematic representation of a cross-section of the ice rink is shown in Fig. 1. Since the length of the building is considerable (64 m) the flow field far from the end walls is considered to be two-dimensional (no velocities perpendicular to the shown cross-section). As shown in Fig. 1, three rows of stands run the whole length of the building on one side. A narrow corridor encircles the ice surface. Protective transparent barriers separate the corridor and stands from the skating surface. Heating and ventilation for the spectators is provided by blowing $Q_{in} = 6.75\,\mathrm{m^3/s}$ of air through eight regularly spaced inlets (0.3 m × 1 m, each at a height of 6 m, above the ice surface). Air is extracted through a single outlet on the ceiling but for the purposes of this study we have considered that there are eight smaller openings at the same Z coordinate as the inlets. Therefore, the flow field in the X–Y plane midway through each set of inlets and outlets can be considered