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Modelling the Effect of Vertical Flow-Developer on Ice Cover

By:

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MANAGEMENT PERSPECTIVE

This extended abstract is our first reporting of a series of laboratory experiments that we have undertaken to study the efficiency of maintaining an ice-free patch in lakes by means of a submerged jet which lifts warmer water to the surface thereby melting the ice cover. We expect that this strategy will be employed in remediating lakes which winter fishkill is prevalant as oxygen may enter the lake by means of the open water and replenish the exhausted subsurface layers.

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Modelling the Effect of Vertical Flow-Developer on Ice Cover

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Abstract

Severe oxygen depletion causing massive fish kills in lakes and reservoirs occurs when ice cover prevents the replenishment of stored dissolved oxygen which has been depleted by biological demand and reduced oxygen production in the winter. Water quality of ice-covered, eutrophic lakes, can be improved by creating ice openings through which water could be aerated. A flow-developer creates an ice opening, or polynya, by circulating warmer water from the bottom of the lake. This study examines the performance of a submerged flow-developer which pumps water from a lake bottom vertically onto the ice cover.

The formulation of the polynya above a vertical flow developer is investigated numerically and experimentally. The numerical model is based on an integral jet formulation and heat-transfer properties of a turbulent jet impinging on a flat plate. The numerical model predicts the development of the polynya under transient, or steady state atmospheric conditions.

The laboratory experiment is carried out in a 1 m^3 tank. The tank is well-insulated and equipped with a chiller unit capable of cooling the air above the water to -30° C. Water is removed from the bottom of the tank, passed through a constant-temperature bath, and discharged back as a vertical submerged jet which impinges on the ice. The results of the experiment are presented in this paper and compared with numerical predictions of ice opening.

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Introduction

As dissolved oxygen levels in eutrophic lakes decrease to a level below which fish can live, a phenomenon known as winterkill occurs. This problem is caused by the presence of ice and snow cover in high latitude lakes which cuts off the supply of oxygen and light. It would thus be desirable to maintain an opening in the ice cover of these lakes during the winter months in order to promote oxygen transfer with the atmosphere. A method of achieving this is through the use of an artificial circulation device to move the warmer bottom water to the surface, thus melting and maintaining an ice-free zone known technically as a polynya. One method to create and maintain the polynya is the use of a vertical submerged jet. A horizontal jet type flow developer has been investigated by Eranti et al (1983). Study has also been devoted to the use of air bubble plumes (Ashton, 1979), and thermal bubblers (Baddour, 1989) to create a similar effect. The effect of artificial circulation on the heat budget of an ice covered lake has also been investigated in a field study (Rogers, 1992 and Rogers et al 1995).

Experimental Apparatus

The tank is of acrylic construction with all sides but the front heavily insulated with styrofoam. The front viewing window is two ply acrylic with an air gap between the panes to minimize heat losses. Water is removed from the bottom of the tank, passed through a constant temperature bath, and discharged as a vertical submerged jet impinging on the ice cover above. A rake of thermocouples connected to a data acquisition system was used to record the water and air temperatures during the experiment.

Numerical Model

The numerical procedure applies an entrainment model to predict the radius, and temperature of the jet near the impingement zone. At present, little is known about the characteristics of the heat transfer properties at the jet/ice interface. This model adapts studies done with air jets impinging on flat plates (Donaldson, et al, 1971) to determine the local variation of heat transfer from the jet to the ice through a Prantdl number transformation.

An ice growth/melting model is then used, with a constant heat transfer coefficient between the ice and air, and the varying heat transfer coefficient mentioned above for the jet/ice interface. Ice thickness is calculated at radial intervals for each time step. Eventually in time, the ice thickness near the jet centreline, where the local heat transfer coefficient is highest, will become zero, thus a polynya is established. With each time step the polynya size grows, gradually reaching a steady state or equilibrium size.

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Experimental Results and Observations

The experiments were conducted varying the distance, h of the ice sheet above the jet, and the Reynolds number of the jet flow. The diameter of the jet nozzle, d, was held constant at 2.5 mm for all tests. Two distinct melting regimes were observed. For the cases where the sheet of ice was relatively close to the jet nozzle, and jet momentum high, a cutting action was noticed. An initial opening in the ice was established quickly in this case, but thereafter melting was inefficient, with a large free surface disturbance above the jet. As the nozzle was moved away from the ice sheet, a more efficient melting was observed, with the surface disturbance above the jet minimal. In this case behaviour was similar to that of an impinging jet on a flat plate.

These two regimes can be seen when the experimental results are compared with the numerical predictions. Figure 1a shows the results for the case where h/d is the smallest. The experimental data shows no significant change in melting with increased Reynolds number while, the numerical predictions show that melting increases with Reynolds number, as would be expected. The case in Figure 1a with the lowest Reynolds number (Re = 1000) is quite accurately predicted by the numerical model. As Reynolds number is increased, the difference between predicted opening and observed opening become greater. Also it can be seen in this graph that there was more melting at lower Reynolds number than high, which is believed to be caused by the "cutting" action mentioned above.
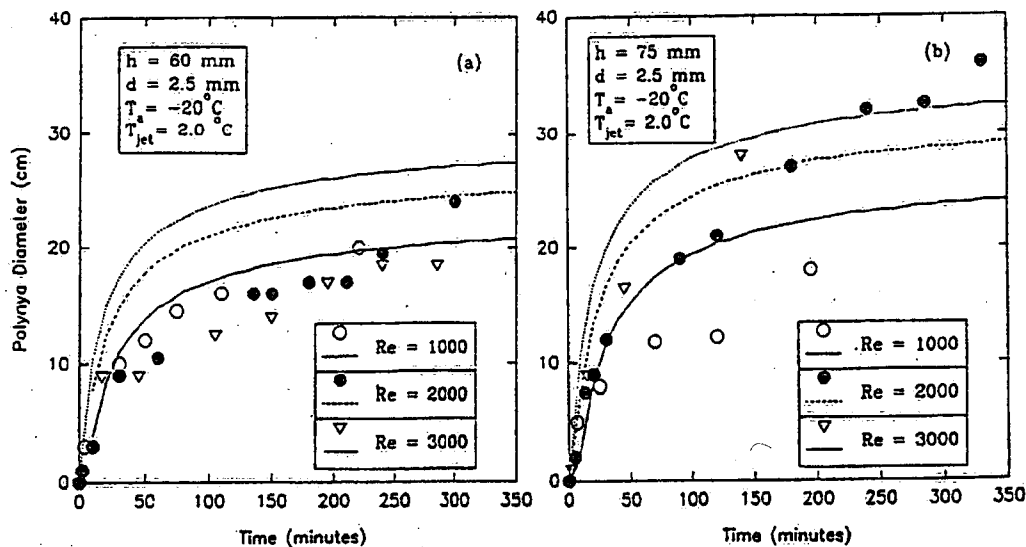

Figure 1 (a) and (b). Graphs of Polynya Growth With Time. Continuous curves are the numerical model whereas points are experimental results.

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In Figure 1b, with a greater distance between jet and surface, the agreement between observation and model opening prediction is still less than optimal. However, the expected trend of increased opening with increasing Reynolds number can be seen. The heat transfer analogy with a jet impinging on a flat plate deserves further investigation.

Initially the impinging jet model of heat transfer should be adequate, before the polynya is created. In this case we have a true impinging jet. Once an opening is formed, the flow dynamics are different from that of a flat plate impingement. The surface of the water cannot be considered rigid, as a plate, and a cavity is formed. The cavity changes the direction of the flow at the edge of the polynya and tends to separate the flow from the ice. It is also suspected that the disturbance created on the surface will increase heat transfer at the edge of the polynya due to the waves and increased turbulence caused by it. The ratio of jet submergence to the thickness of ice cover would also likely affect the polynya growth rate. The smaller this value is, the more pronounced the "cavity" effect would be, making the situation more remote from the impinging jet ideal.

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