SUPERCOOLED-WATER AND FRAZIL-ICE WITHDRAWAL BY LAKEBED INTAKES

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Though it is well known that lakebed water-intakes in cold regions are prone to blockage by frazil ice, little is known about how buoyant supercooled water and the fine-sized crystals of frazil ice can be drawn down to the depths at which lakebed intakes typically are located. This paper shows, through estimates of Monin-Obukhov length, that wind-induced turbulence is the primary process for dispersing supercooled water and frazil crystals downwards to substantial depths in the U.S. Great Lakes, and that intake-induced current subsequently reinforces that downward dispersion.

Most lakebed intakes in the Great Lakes are located in the nearshore zone, where the well-mixed surface layer of water intersects the coastal marine or lake bed. Depending on bathymetry, the nearshore zone extends outward from the shoreline to depths ranging from 9 to 30m. In cold regions, the nearshore zone normally becomes ice covered, often developing a so-called nearshore ice complex (NIC) of level ice floes and ridged ice along the shoreline. Though many water intakes are located beyond the NIC to avoid direct contact with ice, blockage by frazil ice is a real threat.

Supercooled water forms when the lake's water surface cools to below 0°C through heat transfer to the atmosphere. While it is not common to think of liquid water at temperatures below 0°C, the only mechanism limiting the magnitude and duration of supercooling is the latent heat released by growing ice. Accordingly, the presence of supercooled water implies a lack of sufficient growing ice to counterbalance the heat loss to the atmosphere. There may be a considerable lag in time before sufficient ice is present to overcome the heat loss to the atmosphere and warm the water back to 0°C. Supercooled water is found only where little or no ice is present prior to the onset of heat loss. As a result, supercooling can occur only when little or no surface ice is present, which means it can be created only before an ice cover forms or after winds, water currents, or melting remove the cover. The amount of supercooling is very small; it usually is no more that about -0.01°C.

An important question concerns the mechanism by which supercooled water formed at the lake surface descends to the lakebed elevation of intakes. Supercooled water is less dense than the warmer water below, and remains at the surface unless actively transported. Heat transfer from the water surface during the formation of supercooled water is a stabilizing buoyancy flux into the water, leading to a stratified water column with the coldest and least dense water at the surface and the initial ice formation limited to a thin surface layer.

Two processes can potentially overcome such stratification: wind mixing, and intake drawdown of water. As withdrawal of the surface layer is avoided for most intakes through the careful design of caps and covers over the tops of the intakes, shear stress created by wind is the mechanism that disrupts and mixes the surface layer into the upper water column. Of importance is the wind speed needed to overcome the stable stratification of the water column.

Given that the nearshore zone is well mixed, the wind speed need not be great. The Monin-Obukhov length provides an estimate of the depth that turbulent mixing can penetrate by overcoming the stable stratification of the water column. This length is the depth beneath the surface at which the turbulent mixing flux (inversely proportional to depth) equals the buoyancy flux. If this depth is equal to or greater than the nearshore depth, the water column will be supercooled to the depth of the intake. Straightforward calculation of the Monin-Obukhov length as a function of the wind speed and air temperature, assuming typical wintertime meteorological and lake conditions for the Great Lakes at night with clear skies (air pressure: 1000mb; relative humidity: 70%; air temperature between -5°C and -20°C; and initial water temperature of 0°C), indicates that moderate winds (7m/s or greater) can mix supercooled water to depths of 30m, enough to reach the bed of the entire nearshore zone.

The extent to which the nearshore lakebed is in contact with supercooled water has never been measured directly. However, diver records of intake blockages suggest that the extents range from spatially isolated, relatively small patches of lakebed to very large areas encompassing the entire nearshore zone for many kilometers along a shoreline. Outside the nearshore zone, in deeper water, the wintertime temperature structure of the lake (water becoming warmer with depth below the colder epilimnon) inhibits the occurrence of supercooled water at depth.

It is significant that the frazil build up on lakebed intakes is paralleled by the formation of anchor ice on the nearshore lakebed of the Great Lakes. The similarity between anchor ice and the frazil ice build up on intakes has not been remarked upon heretofore. It reflects especially the greater level of supercooling, the lesser levels of turbulence dissipation, and diminished seeding rate, in a large lake than occurs in a river. There is nothing known about the seeding rate for frazil formation in a lake, but the rate of energy dissipation by turbulence can be estimated approximately, and show that, in lakes, the comparatively low levels of turbulence lead to relatively low concentrations of crystals available for deposition; relatively high levels of supercooling, and thus the growth of larger crystals. This finding is consistent with the different forms of anchor ice and frazil build up seen on intakes in rivers and lakes.