ICE COVER PROGRESSION IN THE CHAUDIERE RIVER

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I- Introduction

This paper deals with the morphological aspects of ice formation on various stretches of the Chaudiere River. Observations were made during the winters of 1963-64 and 64-65 on the physical aspects of ice during its formation, on the mechanism of its formation and on the progression of the solid ice cover.

Although no precise measurements were made of the velocities permitting the progression of the cover it was found, by computations, that an ice cover will form in that river for any flow velocity unless thermal conditions are unable to freeze up warm stretches.

2- Basic mechanisms of ice formation in rivers

There are two mechanisms of ice cover formation in rivers that are quite distinct. The first one might be called the frazil ice evolution process and the second one the border ice growth process.

(1) The first process has been well described elsewhere (1,2,3,) and we will comment on it briefly here to give further details on some of its aspects. The frazil ice process is responsible in the Chaudiere River, as probably everywhere else, for the covering with ice of most of the river's surface especially in the zone of fluvial flow.

This process starts with the supercooling of water which is at the origin of frazil formation. In turbulent flow, the supercooling effect is extended in depth to the whole flow cross-section, so the crystallisation process takes place in the whole section. Frazil crystals then agglomerate into flocks (plate 1) which after a while flow up to the water's surface. Water imprisoned between crystals freezes at the surface, and soon the upper parts of the flocks form solid ice crusts. Those ice cakes, by hitting each other and the banks while moving with the current, have a tendency to adopt a more or less circular shape and develop an edge which stands higher than the center part: in other words they evolve into the well known form of pancake ice (plate 2).

Aside from frazil crystals snow may be at the origin of pancake ice formation: during a heavy snow fall, flocks of snow crystals do not melt after they have fallen in the river. They are transported by the current in spongy masses and, like flocks of frazil crystals, finally develop into pancake ice. Pancake ice floes, if they are transported long enough in fluvial stretches, may further develop into ice plates (plate 3) consisting of individual floes frozen one to another. The concentration of floes or plates

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PLATE 1

PLATE 2

PLATE 3

increases at river singularities like contractions, meanders, etc. When the concentration gets heavy enough flocks or plates will cover the whole width of the section and, being held up by the banks, constitute an ice bridge from which the ice cover progresses upstream. Depending on hydraulic conditions, the oncoming ice will either stop at the upstream edge of the cover or be carried under it.

A particular aspect of ice behavior during cover formation is created at the foot of uncovered rapids, when the fluvial stretches upstream and downstream of it are covered. In that case the oncoming ice, because of the relatively short distance under which it travels and the great turbulence of the water, mostly consists of frazil flocks. At the foot of the rapids those flocks, due to the high velocity of the flow, are carried under the cover until they reach a section of sufficiently low velocity where they are deposited on the underside of the cover. The local accumulation of frazil thus developed narrows the flow section until the water gains enough speed to carry the flocks further downstream. Considerable amounts of frazil thus accumulate over great distances under the cover.

In the Chaudiere river (4), the first process of ice cover formation is completely developed in the middle part of the river, where the slope and velocity are very low for a stretch of about forty miles. Frazil flocks gradually become pancake ice floes, which in turn agglomerate together to form larger ice plates. Ice bridges are formed at specific singularities, from which the ice cover progresses upstream. Plates 4 and 5 are representative of such conditions.

Even in fluvial stretches where pancake ice develops, a certain amount of frazil flocks exist at times. The ice cover progression in zones of fluvial flow is then not entirely due to ice floes. A great percentage of the covering up with ice on those stretches is done by frazil flocks. Because of their very small density, they are carried even in low velocity zones underneath an ice cover whose upstream edge is perpendicular to the flow direction or forming a wide angle with it. But along the edges of border ice which run parallel to the current or form a small angle with it, the water follows the edge instead of rushing under it and consequently the flocks are carried alongside it. Because of the spongy nature of frazil flocks and the irregular aspect of border ice edges, there is a great tendency for the flocks to cling to those edges. Border ice thus gradually extends towards the middle of the river, narrowing the free surface flow. In some cases, for example when there is a narrowing in the river itself, both sides will meet at a certain point, forming an ice bridge from which the process will continue as long as the edges upstream of the bridge remain at a small enough angle with the flow direction. Plate 6 shows a case where an ice cover has progressed with frazil flocks, successive rows forming V shapes. At plate 7, frazil flocks are seen to concentrate and stop along the edge of a local extension of the border ice; that local extension was caused by the presence of rock boulders around which border ice was developed and frazil flocks filled up open areas between these patches of ice. Plate 8 shows an extension of border ice provoked by frazil ice flocks at the right-hand bank in a meander: because of inertia, flocks have a tendency to concentrate at the concave side of the meander. At the left-hand bank appears a local patch of ice provoked by a sand-shoal.

PLATE 4

PLATE 5

PLATE 6

PLATE 8

PLATE 7

PLATE 9

PLATE 10

(2) Not much has been said in the literature on the second process of ice formation in rivers, the border ice growth process. Although this process does not account for the production of large quantities of ice it is important because it provides the means for the covering of zones in rapid flow of small rivers, where hydrodynamical conditions of equilibrium (5-6) are not possible. Because this process is slow compared to the frazil ice evolution process it takes a long time to cover the surface of strong rapids unless the winter meteorological conditions are very severe.

Border ice is the first type of ice to appear in a river in areas of laminar flow along the banks. Because in laminar flow there is no intermixing of the top layer with the bottom layers, the temperature differences are important either in the vertical direction or in the horizontal one away from the banks. The top layer adjacent to the bank will go through undercooling considerably while the average temperature of water in the middle of the river will still be much above freezing point. Ice will be nucleated starting right in contact with the colder (because more conductive) material of the banks and this nucleation will propagate on the surface towards the middle of the flow, forming a clear and solid ice sheet.

The edge of this ice sheet will finally come in contact with the turbulent water and its further progress will depend only on the thermal atmospheric exchange as compared to the temperature and turbulence of the water. By no means will the growth process be stopped only because the water is warmer than freezing point.

Let us consider, Fig. A, the case where the edge of the border ice is parallel to the direction of the flow. There will be a velocity gradient in a direction x normal to the edge along the top surface layer. The velocity will be zero at the boundary and will attain a reference value outside the boundary layer. Very close to the edge there will be a laminar sublayer followed by the turbulent layer.

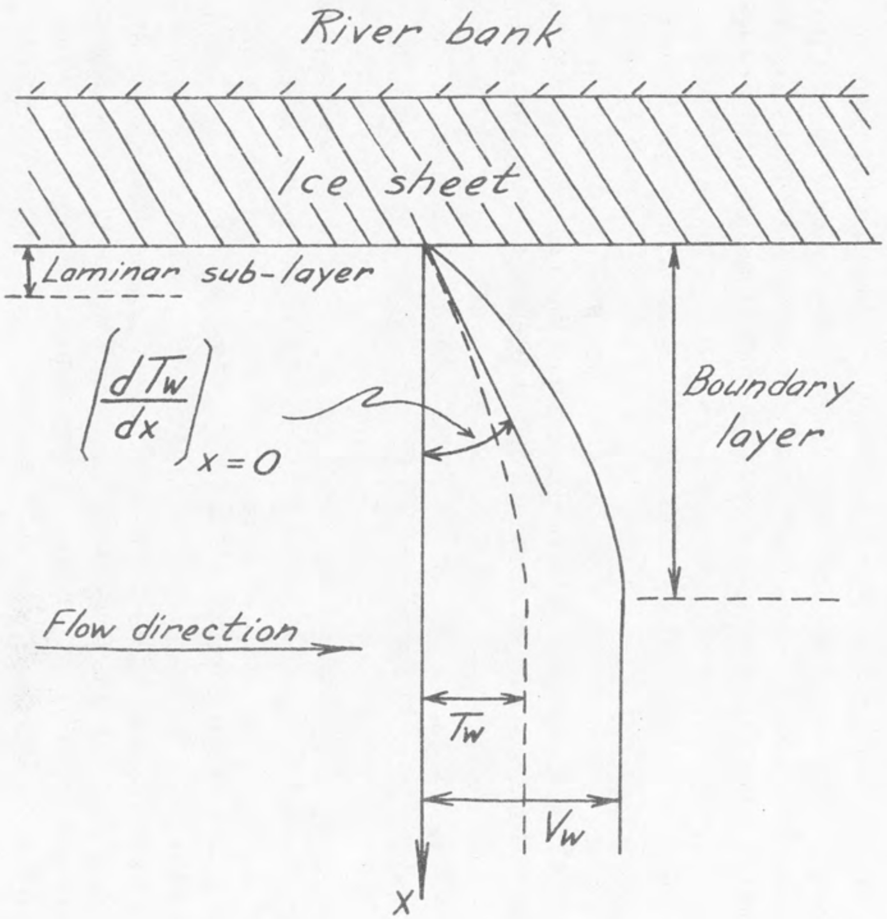
Because of the Reynolds similitude of heat transfer to velocity distribution, if the water temperature is higher than the freezing point, there is also a temperature gradient of similar form from the warm water temperature at the reference point outside the boundary layer to the freezing point temperature at the ice boundary.

The quantity of heat that the warm water is giving to the boundary is:

$$Qw = k_w \left(\frac{dTw}{dx} \right)_{x=0}$$

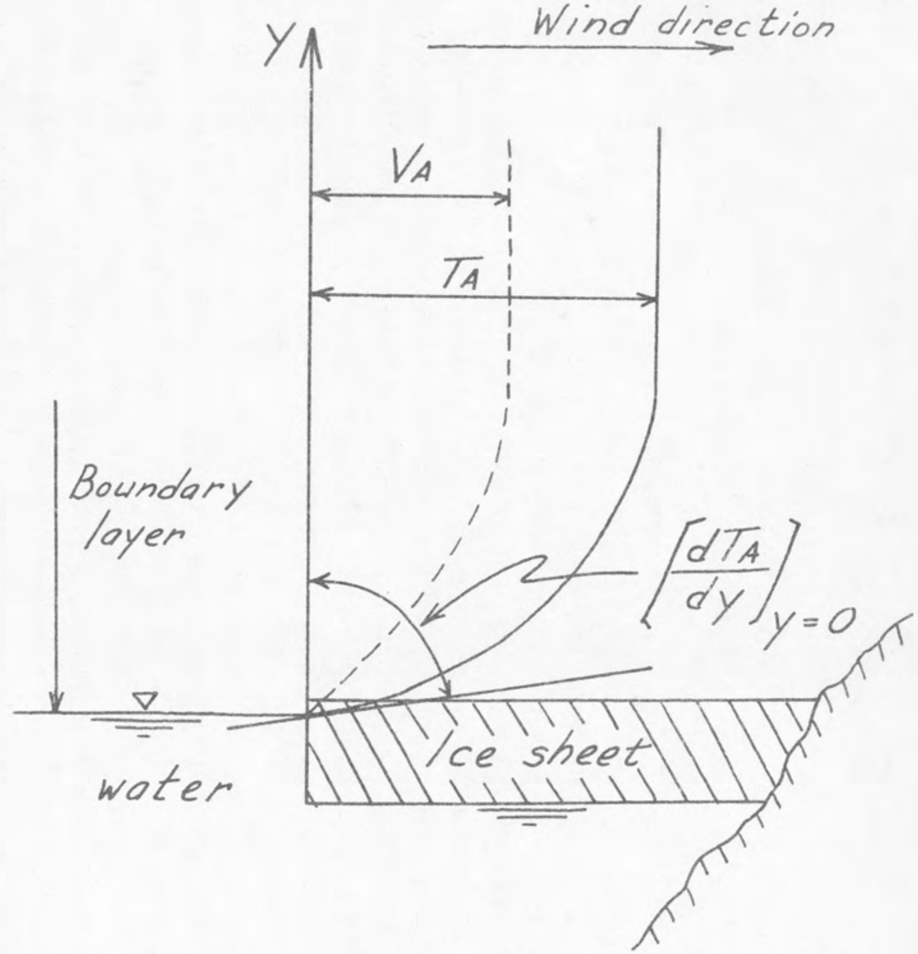
where k_w is the thermal conductivity of water.

Consider now, in a direction normal to the ice sheet at the ice boundary, the wind velocity profile in air (Fig.B). Without taking into account the heat extraction from water by radiation or evaporation, the quantity of heat taken out by convection from a thin surface film of water at the ice boundary will be, for similar reasons:



V_W: water velocity
T_W: water temperature.

FIGURE A.



V_A: air velocity (wind).
T_A: air temperature.

FIGURE B.

$$Qa = k_a \left(\frac{dTa}{dy} \right)_{y=0}$$

where k_a is the thermal conductivity of air.

The ice border will grow if Qa is higher than Qw. Because of the values of kw and ka it means that the air temperature gradient at the boundary has to be 25 times higher in air than in water. But wind velocities and air temperature differences below freezing are often so much higher in winter than water velocities and water temperature above freezing that the border ice will progress even in warm water if the weather is cold enough. Of course this growth will be accelerated if the water temperature in the turbulent flow itself is already at the freezing point.

The Chaudiere River (4) includes two other stretches with high velocity flow, upstream and downstream of the fluvial zone previously mentioned. The upstream stretch is in general straight, free of obstacles and in torrential flow; the lack of singularities makes it hard for ice bridges to form, and the high velocity and turbulence of the flow prevents pancake ice from having time to develop. Consequently the stretch stays, for most of its length, uncovered for quite a while and produces great quantities of frazil. Flow conditions also prevent, although not completely, frazil flocks from clinging to border ice edges. That upper stretch is finally covered up in the following way: border ice growth is responsible for the covering up of an important part of the surface, and the ice cover is completed when the concentration of frazil flocks gets so heavy that individual flocks gradually cling together in large masses which are stopped at narrow restrictions between border ice edges, in spite of the velocity of the flow. Large areas are thus finally covered quickly. Plate 9 shows such a concentration of frazil flocks, with border ice appearing at the bottom of the plate.

The downstream stretch includes zones of relatively low velocity flow and quite a few rapids with very high velocity current. This stretch also scarcely produces any pancake ice floes, and those developed in the preceding stretch are stopped there. The zones of relatively low velocity flow are covered up in a manner similar to ice cover progression with frazil flocks in the preceding fluvial stretch. In the rapids the ice cover progresses almost uniquely from border ice growth caused by thermal exchanges with little help from frazil ice flocks: specially in the strong rapids, practically no flock can cling to the edge. In that part of the river, many rock boulders emerge in the rapids and greatly help to cover them up, border ice growing around those boulders (plate 10). One of the rapids in that part of the river includes a drop of 4 feet over a distance of about 100 feet, which is still free of ice after an ice cover exists upstream and downstream of it. The total width of the river at the drop is about 700 feet. Discharge conditions at that point are usually around 2000 cfs and the water velocity about 7 feet per second by the end of December, time at which an ice cover starts to form over the drop. In January this cover is completed and open patches appear again at the end of February.

3- Conclusion

The observations of the ice cover formation on the Chaudiere River show that it follows two distinct processes:

The well known frazil ice evolution process where frazil particles become flocks, then ice pancakes which form rapidly an ice cover by juxtaposition of these floes in stretches of fluvial flow. At the foot of rapids frazil ice and flocks have had no time to consolidate into solid ice floes and pass under the cover to form underhanging dams, progressing downstream.

The less well known border ice growth process which might be divided into border ice extension by frazil flocks, and border ice growth by thermal exchanges only. The first one provides rapid extension of the border ice, often producing ice covers over the whole width of the river. The second one is responsible for the covering up of high velocity rapids: the solid ice sheet grows from the shore and around emerging boulders.

In rivers of the type and size of the Chaudiere River, it can be seen that border ice growth plays a major role in the ice cover progression.

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