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FRAZIL ICE CONCERNS FOR CHANNELS, PUMP-LINES, PENSTOCKS, SIPHONS, AND TUNNELS IN MOUNTAINOUS REGIONS

Robert Ettema and Gokhan Kirkil
Dept. of Civil & Environmental Engineering, and IIHR-Hydroscience & Engineering,
The University of Iowa, Iowa City, Iowa, USA 52242
robert-ettema@uiowa.edu, gokhan-kirkil@uiowa.edu

This paper discusses frazil ice concerns associated with water-conveyance systems located in mountainous regions. Such systems commonly comprise open-water channels (or reservoirs) linked to pressurized conduits (pump-lines, penstocks, siphons, and tunnels) that pass water down, up, over, or through steep terrain. The discussion addresses fundamental aspects of frazil formation and behavior in flows undergoing substantial pressure changes. An important consideration for such flows is that increased pressure depresses the freezing temperature of water. As flow pressure subsequently decreases (e.g., on passing through a turbine, or rising up a pump-line), water may become super-cooled and prone to form frazil. The melting of ice entering a pressurized conduit (e.g., a penstock) can cool water flowing through the conduit. Such cooling may occur even when there is no heat loss through the conduits wall. It is well known that water-conveyance systems in cold regions are prone to significant frazil-blockage problems at entrance trash-racks. Less well known, however, are that some pressurized conduits also are at risk of accumulating frazil within themselves, and others may disgorge bolus accumulations of frazil, possibly mixed with other ice, that then create blockage problems at a downstream section. Several case-studies are used to illustrate situations where frazil has posed problems for penstocks, siphons, and tunnels in mountainous regions.

1. Introduction

A noteworthy feature of water conveyance systems located in steep mountainous regions is the combined use of open-channel and pressurized conduits. The combinations occur in the form of reservoirs and channels linked to one or more of the following conveyance-structure components:

i. hydropower penstocks and turbines;
ii. pump-lines;
iii. siphons (inverted and regular); and,
iv. water-diversion tunnels.

Such conveyance components commonly comprise critical parts of water-conveyance systems that divert water from streams, and reservoirs in mountainous terrain. Figure 1 illustrates, for instance, a small canal conveying water to a tunnel at a water-diversion project in the Sierra Nevada Mountains, California. Siphons and tunnels enable water to be conveyed across, or through, steep terrain. Penstocks precipitously drop water down to hydropower turbines set a lower elevation. Pumps enable water to be lifted to higher elevations. Though these conveyance components are fairly common, there is little information about their performance in mountainous terrain subject to frigid-weather conditions and, thereby, to ice.

Figure 1. A small canal conveying water to a tunnel in mountainous terrain

Of particular concern are problems attributable to frazil. It can form in several situations. The lower air temperatures and higher wind in mountainous regions may cause water in mountain streams and reservoirs to cool more quickly than at lower elevations, thereby creating conditions hastening ice formation. Consequently, pump intakes, penstocks, siphons, and tunnels linked to mountain streams and reservoirs frequently convey frigid water during winter; the severity of conditions requires that some systems be drained during such winter. The concern for frazil formation is aggravated by the swift and turbulent flow conditions prevailing in many mountain streams and rivers. Further, flow pressures in water-conveyance conduits flowing full can vary over several orders of magnitude, and thereby alter the freezing temperature of water. Together, these aspects of water flow produce situations where frazil may form in sufficient concentrations as to pose difficulties for water-conveyance systems in mountainous terrain. This paper outlines and discusses the difficulties posed by frazil and other ice forms, including snow; mountainous regions often experience relatively large amounts of snow, as well as colder air.

There is scant literature on water-conveyance systems in frigid mountainous regions. Though Gemperline (1990) and Billfalk (1992) usefully summarizes ice considerations in the design and operation of water intakes for hydropower facilities, and Daly (1991) does the same for water intakes generally, none of these papers tackles the ice issues complicating the overall performance of conveyance systems subject to substantial pressure variations. Gilpin's comprehensive work on freezing of water flow in pipes flows (e.g., Gilpin 1981) gives useful insights, but only for small-bore pipes and modest pressure variation. Several anecdotal accounts, and sundry ad-hoc reports, however, indicate that larger-scale conveyance components in mountainous regions can encounter significant problems attributable to frazil ice and snow (e.g., Ettema 2005).

2. Variation of Freezing Temperature with Pressure

Blockage of water intake trash-racks by frazil and other ice forms is a well-known problem (e.g., Gemperline 1990, Daly 1991). Frazil accumulation can block the trash rack at the entrance to a penstock, pump-intake, siphon, and tunnel, as well as within them. Also, blockages may lead to overflow and further jamming of approach channels or pipes. Less well known are the ice problems attributable the changes in freezing temperature associated with the substantial pressure changes that water flows in pressurized conduits may undergo. The principal factor to be considered in this regard is the depression of freezing temperature as water pressure increases. This trend is illustrated in the phase diagram of water (Figure 2).

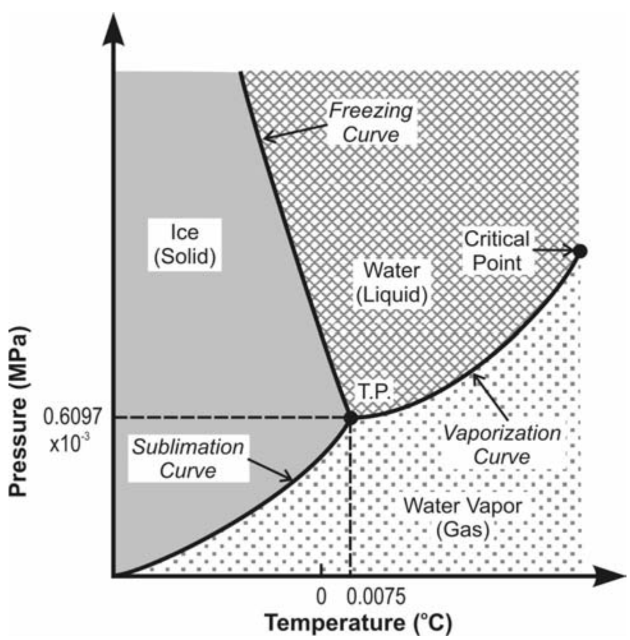


Figure 2. A portion of the phase diagram of water (T.P. is the triple point for water)

Pressure variation may delay or hasten freezing, and it may reconstitute ice pieces passing with water through pressurized conduits. The variation of melting/freezing temperature with gage pressure can be expressed, from the Clapeyron equation for ice-water,

$$\frac{dT_F}{dP} = T_F \frac{dV}{dH_F} \qquad [1]$$

in which T_F is freezing temperature, P is pressure, V is volume of water freezing, and H_F is latent heat of water fusion. For water, with T_F in degrees Kelvin and P in MPa, the trend expressed by Eq. (1) can be illustrated graphically using a curve such as in Figure 3. The curve itself can be expressed as

$$T_F = 273.16\left[1 - \left(\frac{P}{395.2}\right)\right]^{1/9} \qquad [2]$$

Here, temperature, T_F, is in degrees Kelvin, and gage pressure, P, is in MPa. Eq. (2) indicates that an increase of approximately 1MPa pressure decreases the freezing temperature of water by about 0.074^{o}K (or 0.074^{o}C); i.e., the freezing temperature of water becomes -0.074^{o}C. The average depression of freezing temperature for ice commonly found in nature (ice type 1h, Hobbs 1974) is 0.10^{o}C/MPa, over the pressure range associated with ice 1h, 0 < P < 209MPa. Pressure changes of the order of 0 to 2MPa magnitude are common in closed-conduit flows associated with hydropower penstocks, pumps, siphons, though perhaps less so in tunnels. An elevation difference of 100m produces a pressure difference of about 1MPa.

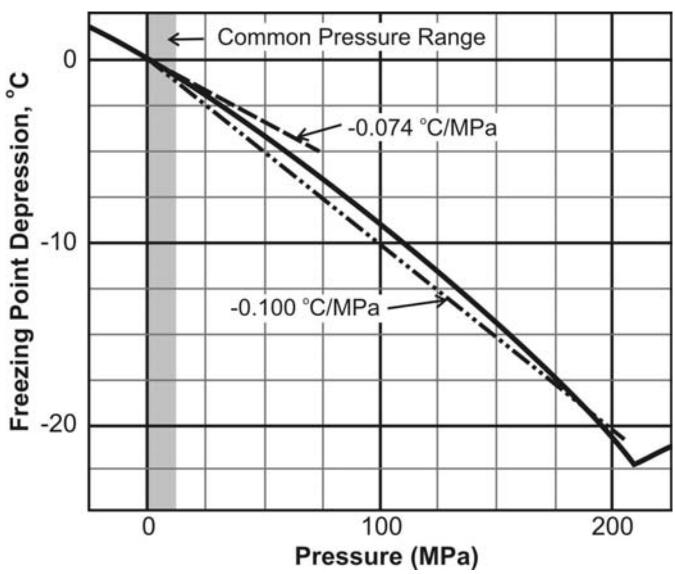


Figure 3. A portion of the relationship between freezing-point depression, ΔT_F and absolute pressure for water; common pressure range for hydraulic structures is indicated

The following two practical questions arise regarding the depression of water's freezing temperature for water flowing through hydropower penstocks, pump pipelines, and siphons:

i. Why should the depression of water's freezing temperature be of concern to the operation of these conduits?
ii. How can water in these conduits attain the depressed freezing temperature?

The depression of freezing temperature can result in super-cooling of water and frazil formation, with all its attendant problems of flow blockage. Accordingly, care is needed to minimize frazil formation in such conduits. To do this requires preventing water flow from actually dropping to its depressed freezing temperature, or below.

Water flowing down a conduit may cool owing to heat loss through the walls of the conduit, and through the melting of ice transported with flow into the conduits. As the freezing temperature decreases, the surface of ice melts, drawing heat from the water, thereby cooling it. The water cools to the extent that sufficient ice melts to cool the water to its freezing temperature. The amount of ice particles needed to cool frigid water from its initial freezing temperature to its adjusted freezing temperature can be calculated from the heat-balance relationship

$$\rho_{ice}\lambda(\Delta C_{ice}) = \rho_{water}C_p(\Delta T_F) \qquad [3]$$

where ρ_{ice} is ice density, λ is latent heat of melting ice, C_{ice} is frazil ice concentration, C_p is specific heat of water and T_F is freezing temperature of water, and $\Delta T_F = T_{F2} - T_{F1}$; here, T_{F1} is the freezing temperature at the higher elevation, T_{F2} is the freezing temperature at the lower elevation, and T_{F3} is the freezing temperature at the conduit's outlet. A freezing temperature drop $\Delta T_{F,water}$=0.1°K requires an ice-concentration reduction of ΔC_{ice} =1.03x10^{-3}. Assuming an initial freezing temperature, T_{F1} = 0°C, Eqs. 2 and 3 lead to a relationship between ΔC_{ice} and net head-drop through the conveyance structure. Figure 4 shows the relationship. For instance, the change of ice concentration given in the above example (ΔC_{ice} =1.03x10^{-3}) corresponds approximately to a 100m head-drop. Estimates of frazil concentrations in streams and reservoirs are in the order of 10^6 particles/m^3 (Daly, 1991). If frazil particles in flowing water are taken to be discoids, 2mm in diameter and 0.1mm thick (e.g., Chen et al., 2004), a nominal volumetric frazil concentration is about 1.6x10^{-3}, which means that typically there is enough frazil ice to super-cool water in the conveyance structures diverting water from the mountain streams and reservoirs.

Pressure-related super-cooling of water occasionally occurs in the natural environments. Alley et al. (1998), for example, describe how water flowing through or beneath a deep glacier can super-cool when eventually ascending a steep slope at the end of a glacier. The ascending super-cooled water may freeze to the glacier's floating base, as well as to other boundaries.

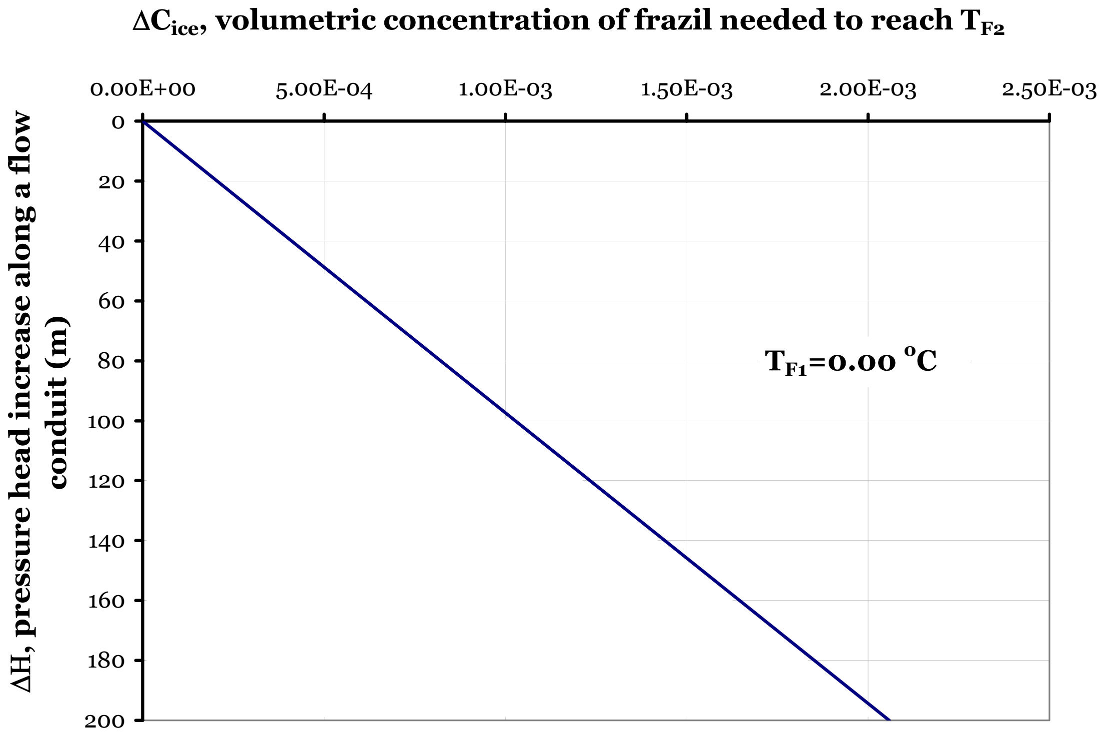


Figure 4. Variation of frazil concentration needed to reach final freezing temperature (T_{F2}) as a function of pressure-head increase (or elevation drop) along a conveyance structure; initial freezing temperature is T_{F1}

3. Frazil Formation in Hydropower Turbines and Draft-tubes

A penstock delivers water under pressure to a hydropower turbine, which then extracts much of the power associated with the water's flow rate and net head. For low and medium-head turbines, the water power is converted into mechanical power by means of flow momentum exchange; the flowing water remaining fully enclosed by the turbine and its draft tube, but at drastically reduced pressure. However, for high-head turbines, water surrounded by air at atmospheric pressure impacts the turbine runner, and is then discharged directly into a tailrace. Figure 5 shows that water pressure in a penstock increases as flow moves down the penstock. A corresponding decrease in freezing temperature accompanies the pressure increase. As the water emerges from the penstock and passes through the turbine, its pressure decreases abruptly, with the consequent increase in freezing temperature, and the flow of super-cooled water out of the turbine. Super-cooled water is in an unstable state, and eventually (through nucleation by ice fragments in the flow) will adjust itself so as to be in a stable state. When that occurs, water releases its latent heat of fusion, and there occurs a rapid growth of frazil, which initially is in an active state. Frazil may be swept out into the tailwater channel. If the concentration of frazil is large, and the tailwater quite small, the frazil can congest the tailwater, eventually accumulating back up into the turbine, possibly eventually choking flow through the turbine. Few studies have been conducted of turbine operation when water flow is at the freezing temperature and frazil is at the verge of forming, or actually forming.

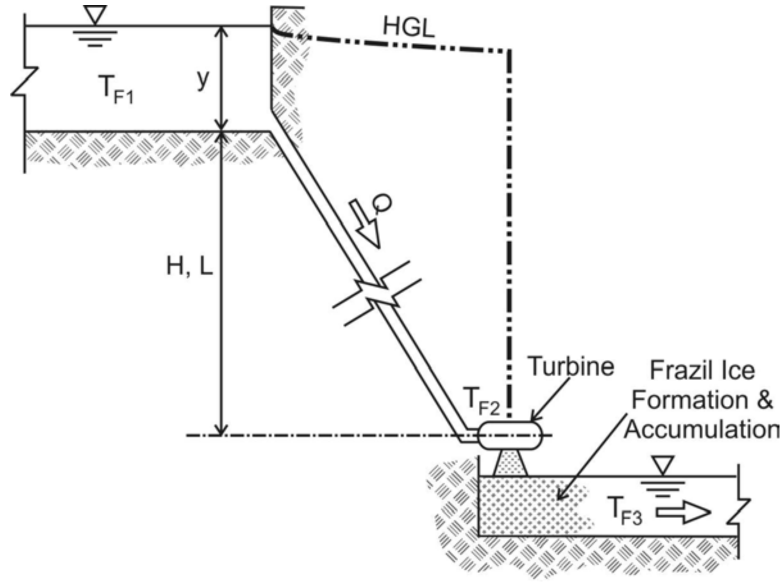


Figure 5. Frazil formation and accumulation within a turbine and its outlet; freezing temperatures $T_{F1} = T_{F3} = 0.00^oC$; $T_{F2} < 0.00^oC$

The length, or inclination, of a penstock plays a role with respect to cooling of flow through a penstock in frigid winter conditions. For a given drop in elevation, penstock length directly influences flow duration through a penstock. Greater flow duration provides more time for water to cool, by means of ice melting or heat-loss through the penstock. Accordingly, all else being equal, a longer penstock produces more frazil.

4. Frazil Formation in Pump Lines

When passing through a pump, water pressure suddenly rises to head H_p, as indicated in Figure 6, and then reduces along the pump-line to about the equivalent of the flow depth at the flow outlet. The freezing temperature drops correspondingly as the hydraulic grade line rises above the pipe, causing the water potentially to be super-cool and the ice to melt. Actual super-cooling depends on there being sufficient time for water to cool. The freezing temperature rises as the hydraulic grade line drops and approaches the water surface at the outlet. Flow along the declining grade line is prone to form frazil. The volume of frazil formed approximately equals the volume of ice melted, and depends on additional heat loss through the conduit's walls. The frazil in super-cooled water is initially in an active state whereby it can adhere to the remaining ice pieces conveyed with the flow, and agglomerating as a bolus, of ice pieces or slush that may disgorge at the outlet of the pump line. The increased flow resistance produced by the agglomerating slush may, with time, increase the flow resistance encountered by the pump. Information on ice agglomerates or boluses, discharging from a pump line is not available presently. There evidently are no document reports of their occurrence.

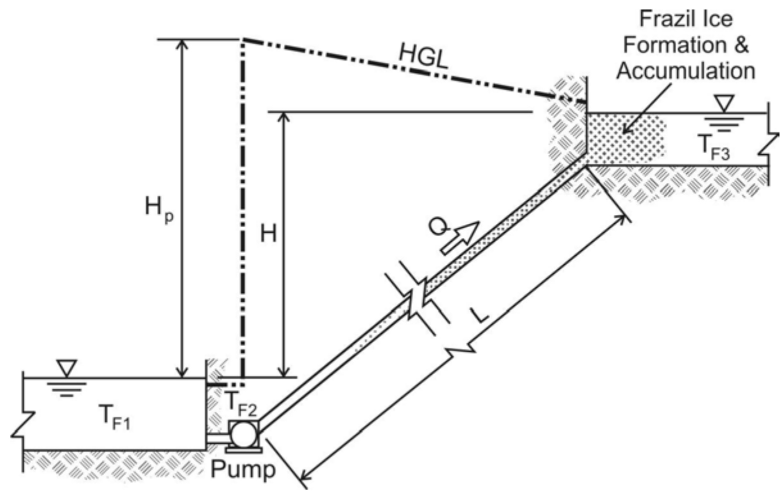


Figure 6. Frazil formation in a pump-line pipe: $T_{F1} = T_{F3} = 0.00^oC$; $T_{F2} < 0.00^oC$

5. Frazil Formation in Siphons

The changes in pressure and, thereby, of freezing temperature in siphons combine the changes occurring for flow in pump discharge lines. The formation of frazil and ice agglomerates essentially is the same as for a long pump line. As described above for pump lines, and penstocks, the freezing temperature declines as pressure increases (on the siphon's downward arm), and increases as pressure decreases (on the upward arm). Provided that the water attains the reduced freezing temperature, the flow in the upward flow is super-cooled. Inverted siphons are not uncommon for mountainous terrain; the siphon has an overall U-shape form, as indicated in Figure 7. Ice entering the siphon may largely pass through the siphon, though some ice may accumulate in the bottom, especially at locations where flow separation occurs, notably at the first bottom bend where ice in the separation region may rest against the upper side of the siphon pipe (Figure 8).

As water descends an inverted siphon, water pressure increases and the freezing temperature of water is depressed. Water has to cool before attains its freezing temperature. In this regard, frazil and ice pieces (as well as snow) entering the siphon may partially (or entirely) melt, the heat need to melt ice being drawn from the flowing water and cooling the water. An argument can be made that the more ice entering each siphon, the greater the internal heat sink provided for the flow to super-cool. The dropping water then cools, even when there is no heat transfer to the pipe and air around the pipe. The heat generated by flow friction would be negligible compared to the heat consumed in melting ice as water drops in the siphon and flows within the siphon.

A longer siphon (all other factors equal) provides more time for water to cool more, and thereby for more frazil to be generated. The relatively long bottom section of the siphon enables considerable melting of ice entering the siphon, thereby enabling the water to attain its new freezing temperature. A longer bottom section can enable more ice to rise and accumulate along the conduit, as sketched in Figure 8. Greater accumulation of ice would increase flow resistance, and decrease flow rate, through the siphon, thereby compounding the frazil concern.

The location where frazil first forms in each siphon depends on the air temperature and rate of heat loss from each siphon, as well as on water flow rate, and the amount of ice entering the siphon. For example, under milder weather conditions and less ice entering the siphon, frazil will form closer to the end of the siphon, and will emerge as a rather thin slush. But under more frigid weather conditions, and more ice entering the siphon, ice forms more quickly along the siphon, and would emerge from the siphon as a more agglomerated, clumpy bolus of ice.

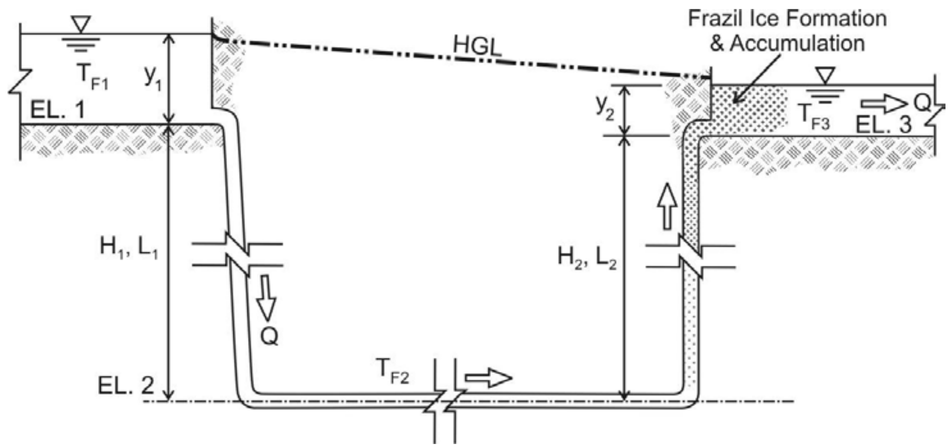


Figure 7. Frazil formation in an inverted siphon; $T_{F1} = T_{F3} = 0.00^oC$; $T_{F2} < 0.00^oC$

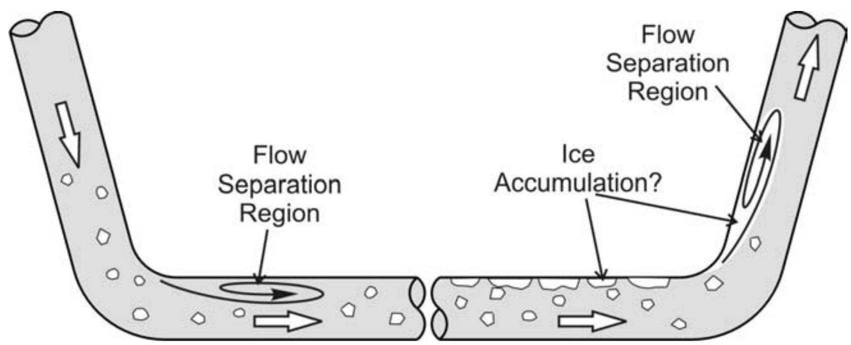


Figure 8. Flow separation at the base of an inverted siphon, and flow along the base may increase ice accumulation

6. Frazil and Other Ice in Diversion Tunnels

Flow in most tunnels flowing full usually do not experience the great pressure fluctuations experienced by flow in penstocks, pump-lines, and siphons. For most tunnels, the elevation drop is relatively modest (typically much less than 100m), unless the tunnel includes a vertical drop. Also, tunnel-wall temperature (in tunnels flowing full) is above the freezing temperature, and warms frigid-water flows. Wall temperatures typically are between the water temperature (about 0^oC for frigid water) and the temperature of the rock at some distance from the crown of the tunnel. Rock temperatures often are estimated to be at about the yearly average air temperature of the region in which the rock is located.

Nevertheless, tunnels still can be prone to ice problems, notably –

i. ice blockage of tunnel-entrance racks;
ii. accumulation of ice pieces drifting into a tunnel;
iii. accumulation of frazil formed by flow turbulence within the intake entrance; and,
iv. aufeis formed by freezing of water seeping into a tunnel drained during winter.

The problem of entrance-rack blockage is essentially the same as that for water intakes generally, and is well documented (e.g., Billfalk 1992, Daly 1991, Gemperline 1990). However, a complication for tunnel entrances in steep mountainous regions, especially in remote regions, is that the usual methods for controlling frazil blockage of intakes along rivers and lakes are infeasible or much more difficult to implement. The usual methods (e.g., Daly 1991) include facilitating the formation of an intact ice cover on the approach channel immediately upstream of the entrance, the use of warm water to heat the entrance rack, and back-flushing of flow through the entrance rack. The more practical option presently is to mechanically break-up ice accumulating at a rack, and sluice it sideways out of the approach channel.

There are few reports (or studies) documenting concerns caused by ice accumulation within water-diversion tunnels, though such problems are known to occur. An operational difficulty is that access difficulties hinder the viewing of ice accumulations in tunnels. Ettema (2005), though, describes one instance where ice, largely frazil, accumulated in a tunnel. This instance is briefly elaborated below as a case-study example.

Lia and Carstens (1998) describe the problems caused by aufeis formation in water diversion tunnels for several Norwegian hydropower plants. The problem can be substantial for unlined tunnels in rock whose water-table lies above the tunnel. Frigid air passing through such tunnels freezes water seeping from fissures in the rock.

A related further problem is snow-drift accumulation at the entrance and outlet of tunnels. Lia and Carstens 1998) describe large accumulations that practically dammed tunnels at Norwegian hydropower plants. Heavy snow falls and substantial winds can result in the formation of snow drifts. For tunnels in mountainous regions with perennial snow, the drifts can exist for several winters and consolidate.

7. Case-Study Examples

Briefly described here are three case-study examples of frazil concerns encountered by a penstock, a siphon, and a tunnel in mountainous regions. Each example illustrates the difficulties that frazil may pose for these conveyance structures. Usefully documented examples are quite rare, and the full circumstances associated with them usually unclear. Also, several scale considerations hamper laboratory simulation of the case-study examples, or similar situations. The difficulties include the physical chemistry of water, along with the flow lengths and large pressures involved. These factors are almost prohibitively challenging to reproduce in the usual hydraulics laboratory.

Frazil in a Turbine and Tailrace. A case-study example illustrating frazil formation and accumulation at the end of a penstock is that of a micro-hydro plant at King Cove, Alaska. The plant draws water from a glacier-fed stream, and has a gross head of 90m, and a net head of 74m (giving $\Delta T_F \approx$ -0.06°C). Early during its operation, a large quantity of frazil formed in the turbine and in the plant's outflow channel. Figure 9 shows frazil being excavated from the outflow channel.

(a) (b)

Figure 9. King Cove micro-hydro plant, Alaska (a); excavation of frazil from the plant's small tailrace channel (b) (Photos courtesy of King Cove Hydro)

Frazil in an Inverted Siphon. The difficulties of siphon operation in frigid winter conditions are illustrated by a siphon conveying water across an approximately 100m-deep ravine in the Sierra Nevada Mountains, California. Figure 10 shows the layout of the siphon. The siphon's operators observing flow discharging from the siphon describe how it intermittently ejects a large bolus of ice slush that adversely affects the capacity of the outlet channel to convey water. Though the literature lacks information about the formation of an ice "bolus," the size, shape, and intermittent features of a representative bolus suggests that it forms initially in flow-separation zones within the siphon; e.g., at the downstream side of the bends at the bottom of the siphon, as indicated in Figure 8. The ice boluses tumble, consolidate, and grow within the flow separation region until reaching a size large enough to be caught by the flow and swept along the siphon, eventually emerging (whale like, as the observers report) at the siphon's outlet channel.

It is possible that several smaller boluses may merge as a single glob, and that the they collect further slush as they rise relatively rapidly up the rising arm of the siphon. Bolus buoyancy, added to flow drag, propel the bolus ("like a breaching whale," as one operator characterized it) out of the siphon's outlet. There are no direct observations of how an ice bolus forms. There are reports (from the siphon's operators) of rumblings in the siphon's bottom section at times when the siphon is passing ice. These noises suggest, as indicated in Figure 8, that the initial ice accumulation forms along the tunnel's crown and in the flow-separation regions. Flow then drags the accumulating bolus of ice along the siphon.

(a)

(b)

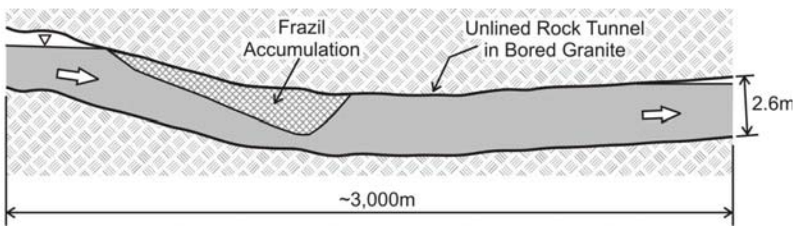
Figure 10. A siphon for a water-conveyance system in the Sierra Nevada Mountains, California (a); ice boluses disgorged at the siphon's outlet, and blocking the siphon's outlet channel (b)

Flow through the siphon is driven by the difference in water surface elevation between the siphon's inlet and the outlet. As this elevation difference decreases, such as when ice severely reduces flow through the channel, flow passes more slowly through the siphon. It is possible therefore that ice difficulties in the channel become aggravated as they progress, because flow slows through the siphon, ice in the siphon forms larger boluses, which in turn have greater difficulty in passing through the channel.

Frazil Accumulation in a Diversion Tunnel. As is likely with frazil accumulation in most tunnels, the general circumstances associated with frazil passage into the tunnel described here are known in only approximate terms. The tunnel's entrance is shown in Figure 1. Direct observations of the processes resulting in the accumulation are incomplete, for various reasons including a lack of observations about ice conditions along the canal conveying water to the tunnel. The manner whereby ice passage and accumulation in the tunnel, nonetheless, can be inferred from the data obtained from several sources, and from what is known in the literature about the formation of similar accumulations in rivers and streams. The frazil accumulation was akin to a hanging frazil "dam," such as described in Ashton (1986) or Beltaos (1995). A couple of differences from hanging frazil dams being that –

i. The accumulated frazil rested against the tunnel's rock crown; and,
ii. As the frazil accumulation thickened, the constrained flow path narrowed and velocities increased.

A construction problem had resulted in the tunnel not following a steady downward invert grade that would have facilitated the free-surface flow of water along its entire length. The tunnel's initial gradient was over-steep, and an alignment correction was needed. Accordingly, the tunnel had a mild kink at about its mid-point, where the tunnel's grade became mildly upward so that the tunnel would reach the required exit at an outlet channel location. Frazil entering the tunnel, and possibly forming in an initial portion of tunnel, accumulated near the location where the tunnel's slope begins to arc gently upwards towards its outlet. In this region, the free-surface flow of water along the downward reach of the tunnel gradually occupies practically the full flow cross section of the tunnel. The approximate extent of the accumulation is indicated approximately in Figure 11. The accumulation profile is based on observations reported by an inspection crew who entered the tunnel drained for a scheduled inspection. The frazil accumulation did not block flow, which continued to pass through the tunnel. Considerations related to critical velocity for erosion of accumulated frazil slush infer that the tunnel likely would not block owing to frazil accumulation.



(a)

(b)

Figure 11. Frazil accumulation in a water-diversion tunnel: (a) approximate profile of frazil accumulation in the tunnel; (b) a view of frazil deposited on the invert of the drained tunnel

8. Conclusions

Frazil ice often is an under-appreciated concern for many water-conveyance systems, but none more so than systems in mountainous terrain. Mountainous terrain is more likely to have colder weather, swift-flowing streams, and to have limited accessibility. The combined considerations of temperature and flow speed increase the likelihood of frazil formation. Limited accessibility aggravates the concern.

Also, because water-conveyance systems in mountainous terrain often entail the combined use of open-channel and pressurized conduits, a further mechanism compounds frazil difficulties in mountainous terrain. The mechanism arises when frigid water flowing in a conduit undergoes major pressure increase, and then reduction. Increased pressure depresses water's freezing temperature, and thereby results in the super-cooling of water that subsequently flows with decreasing pressure. If the water cools to the depressed freezing temperature, frazil quickly forms when water flows at reduced pressure. Flows through a penstock and hydropower turbine, a pump line, or a siphon, produce cycles of increased then decreased pressure, thereby exposing these flow components to frazil. Water flowing at increased pressure may cool as ice transported in the water melts, and also by heat loss through the conduit walls. A longer conduit (all else equal) provides more time for water to cool to its depressed freezing temperature. Also, more ice entering a pressurizing flow enables water to cool more quickly to the depressed freezing temperature.

The practical consequence is that frazil can readily pose substantial difficulties for hydropower and water-supply facilities in mountainous terrain. Frazil accumulations and blockages potentially can occur in the approach channels, as well as block trash racks at entrances to flow components like and penstocks, pumped water lines, siphons, and tunnels. Extensive amounts of frazil may form at the outlet of turbines. Moreover, frazil and other ice may accumulate within the flow components themselves. Agglomerations of ice may form in a pump line or an inverted siphon, hampering flow passage, and be disgorged as a bolus of ice that may block flow downstream of a pump or siphon outlet.

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