Cooling Towers and Freezing Weather

CONTROLLING ICE FORMATION

Forward

A properly designed cooling tower promotes the maximum possible contact between air and water — and does so for the maximum possible time period. This effort on the part of the designer results in an efficiency which, although greatly appreciated in the summertime, has the capability to produce performance-degrading ice formations during freezing weather operation. Therefore, means by which the cooling tower's efficiency can either be controlled, or can be made to work toward the management of ice formations, must be incorporated into its design, and must be properly utilized by the operator.

In addition to describing the basic concept of ice control, this paper will describe the potential for ice formations in various types of cooling towers — and will make specific recommendations for consideration.

Types of Ice

As on any outside structure, ice can form on a cooling tower in freezing weather purely by natural effect. In addition, being both a water cooling and an air moving device, a cooling tower can promote the formation of ice by its very operation.

In either case, whether caused by nature or by the cooling tower itself, the owner's concern for an ice formation on a cooling tower should be a reflection of both its location and its amount. Ice on exposed working platforms can be a personnel hazard, and should be corrected manually. Light random ice on the cooling tower louvers, structure, and the leading edges of the fill, is usually of minor concern. Ice allowed to form on the fans and other mechanical equipment — not to mention the shrouds and control devices associated with that mechanical equipment — can lead to catastrophe.

Generally speaking, acceptable ice is of relatively thin cross-section which may have formed on the louvers or air intake structure of an induced draft cooling tower. **Figure 1** shows what might be considered an acceptable amount of ice having formed inside the air intake structure of a counterflow cooling tower, and **Figure 2** indicates a relatively light curtain of ice on the louvers of a crossflow cooling tower. Since this amount of ice would normally have been anticipated in a cooling tower's design loading, it is customarily of little structural concern and,

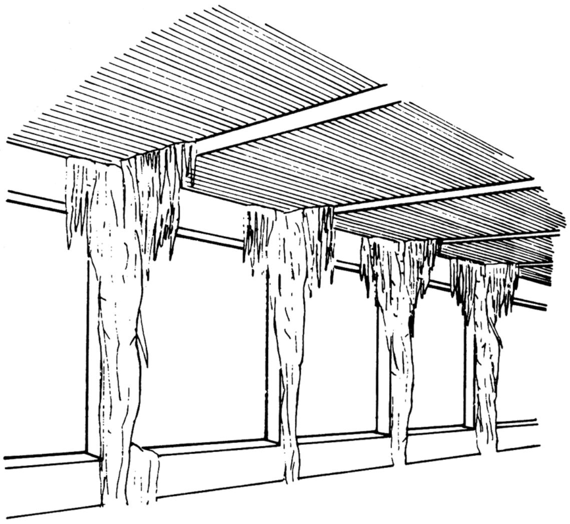

FIGURE 1 *"Acceptable" counterflow ice (viewed from the plenum)*

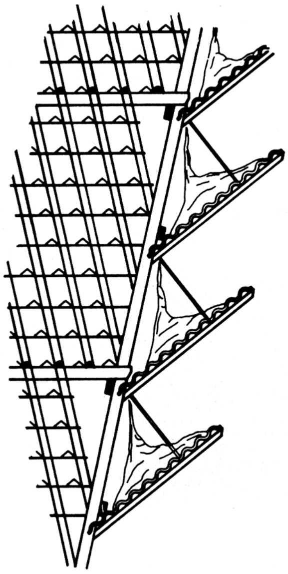

FIGURE 2 *"Acceptable" crossflow ice (louver cross-section view)*

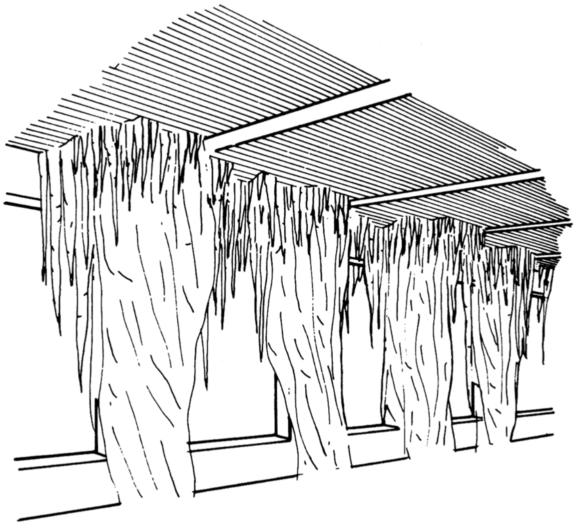

FIGURE 3 *"Unacceptable" counterflow ice*

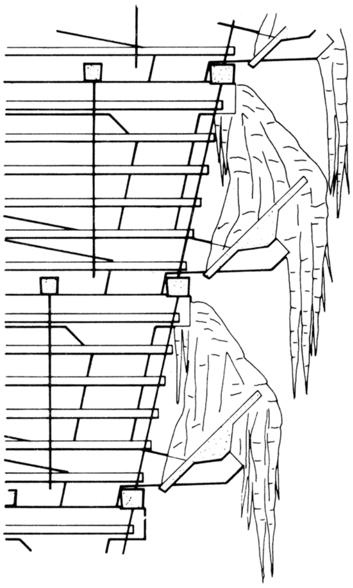

FIGURE 4 *"Unacceptable" crossflow ice*

in some cases, its retardation of air flow through the cooling tower achieves a result similar to the airside control procedures about to be discussed. However, although this ice may still be considered acceptable, it has proceeded to a point where measures for its limitation or removal should be undertaken.

If allowed to grow unchecked, ice can achieve massive cross-section, encroaching upon the fill — **Figure 3** or totally blocking air flow — **Figure 4**. Its weight alone can overload affected members and, when ice of such mass dislodges, it is obviously capable of doing significant damage.

Potential for Ice

Although the methods of ice control vary somewhat with the type of cooling tower, and the type of fill with which it is equipped — as well as the water distribution system and mechanical equipment arrangements — they are all based upon the following points of logic:

1 The potential for ice varies inversely with outside air temperatures. The lower temperatures become below freezing (32ºF wet bulb, which is often below dry bulb) the greater the probability of ice.

2 Within design limits, the potential for ice varies inversely with the amount of water flowing over the fill. A reduced water flow rate increases the probability of ice.

3 The potential for ice varies directly with the quantity of air flowing through the cooling tower. Reducing the air flow retards the formation of ice.

4 Where air flow is uncontrolled (as in the case of a natural draft cooling tower), the potential for ice formation varies inversely with the heat load imposed on the cooling tower. In that case, a reduced heat load will increase the probability of ice.

5 Where air flow is controlled to maintain a specific cold water temperature, the potential for ice varies directly with head load, and inversely with the selected cold water temperature. Increasing the heat load, or lowering the required cold water temperature, will increase the probability of ice. — see **Air-side Control**.

All mechanical-draft cooling towers permit some degree of air flow manipulation for controlling ice, the extent of which depends primarily upon the number of cooling tower cells, and the speed-change characteristics of the fan motors. Larger cooling towers designed to be operated in cold climates usually also include means by which to control the placement of water over the fill. In mechanical-draft cooling towers, airside and waterside control arrangements can be mutually supportive. However, natural draft cooling towers offer no reasonable opportunity for airside control and, for that reason, the methods will be discussed separately.

Air-side Control

Manipulation of the air flow (see *Cooling Tower Energy Management* available from SPX Cooling Technologies) is an invaluable tool, not only in the retardation of ice formation, but in the reduction or elimination of ice already formed. In addition to bringing less cold air into contact with the circulating water, reducing the entering air flow velocity alters the path of the falling water, allowing it to impinge upon (and melt) ice previously formed by random droplets which wind gusts or normal splashing may have caused to escape the protection of the relatively warm mainstream of water. This aspect will be clarified in the **Ice Characteristics versus Fill Behavior** section of this paper.

There are three choices available for controlling the air flow through a cooling tower. Single-speed fans afford the least opportunity for air flow variation, and cooling towers so equipped require maximum vigilance on the part of the user to determine the proper cyclic operation of the fans which will result in best ice control. Two-speed fan motors offer greater operating flexibility and should be considered the minimum level of control for cooling towers used in cold climates. Fans may be individually cycled back and forth between full-speed and half-speed as required to achieve balance between cooling effect and ice control, limited only by the maximum allowable motor insulation temperature which an abnormal number of speed changes per hour may cause to be exceeded. Since cooling tower capacity varies directly with the fan speed, while fan power varies with the cube of the speed ratio, operating all fans at half speed provides the same level of cooling as operation of half the fans at full speed, but uses only an eighth of the energy. On cooling towers having two or more fans evacuating a common plenum such as the round cooling towers depicted in **Figure 5**, those fans should be brought to the off position in unison to prevent a down draft of cold moisture-laden air from icing up the mechanical equipment of an inoperative fan. On multicell cooling towers (in-line configuration) equipped with a separate plenum for each fan, individual fans may be cycled as necessary to control ice. However, it must be understood that cycling the fan on a particular cell accomplishes nothing with respect to deicing of adjacent cells. Individual cell ice control must be accomplished independently. This is because of the temperature gradients about to be discussed.

Variable Frequency Drives (VFDs) offer the greatest level of flexibility, since they permit all fans to operate at the same speed for minimum energy consumption. In addition, all cells will then produce the same cold water temperature, eliminating the temperature gradient between cells.

Temperature Gradients

Understanding how to anticipate and control ice requires some knowledge of the water temperature gradients that occur in an operating cooling tower. Without such knowledge, operators often assume that controls which will automatically cycle fans to maintain a leaving cold water temperature well above freezing are sufficient insurance against the formation of ice. Occasionally, they are bewildered to find ice beginning to form even before the cold water basin temperature has depressed to that presumably "safe" level.

The reason, of course, is the aforementioned temperature gradients that occur transversely in all cooling towers, and longitudinally in multicell cooling towers where fans are cycled progressively. **Figure 6** indicates the typical transverse temperature gradients in a bank of crossflow fill. In this particular case, water is entering the cooling tower at 18°C and leaving at 7°C; temperatures which would seem to indicate to an operator that a 7°C "safe" zone exists between his operating point and freezing. Obviously, such is not the case. As can be seen, the net outlet temperature of 7° results from a mixture of water temperatures varying from about 12°C at the inboard edge of the fill to about .5°C at the outboard edge. Consequently, the real margin of safety is only about .5°C in this case.

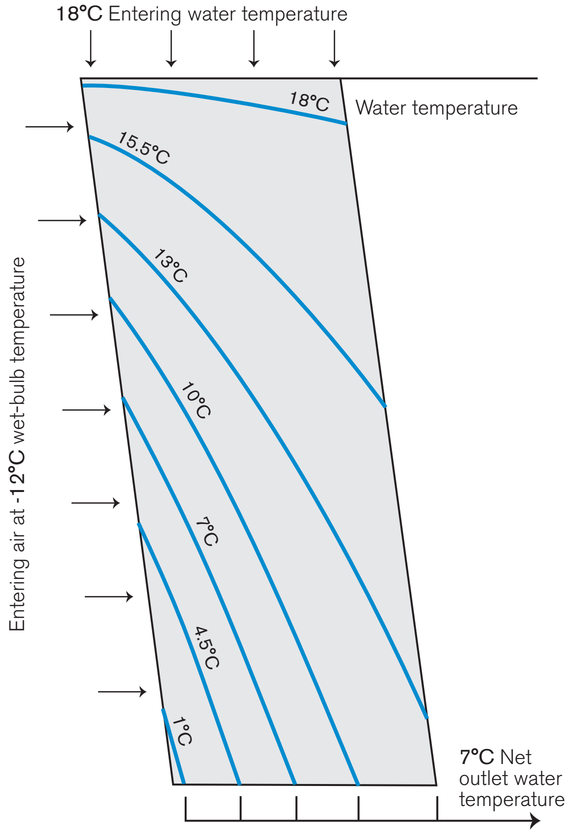

FIGURE 6 *Crossflow fill transverse temperature gradients*

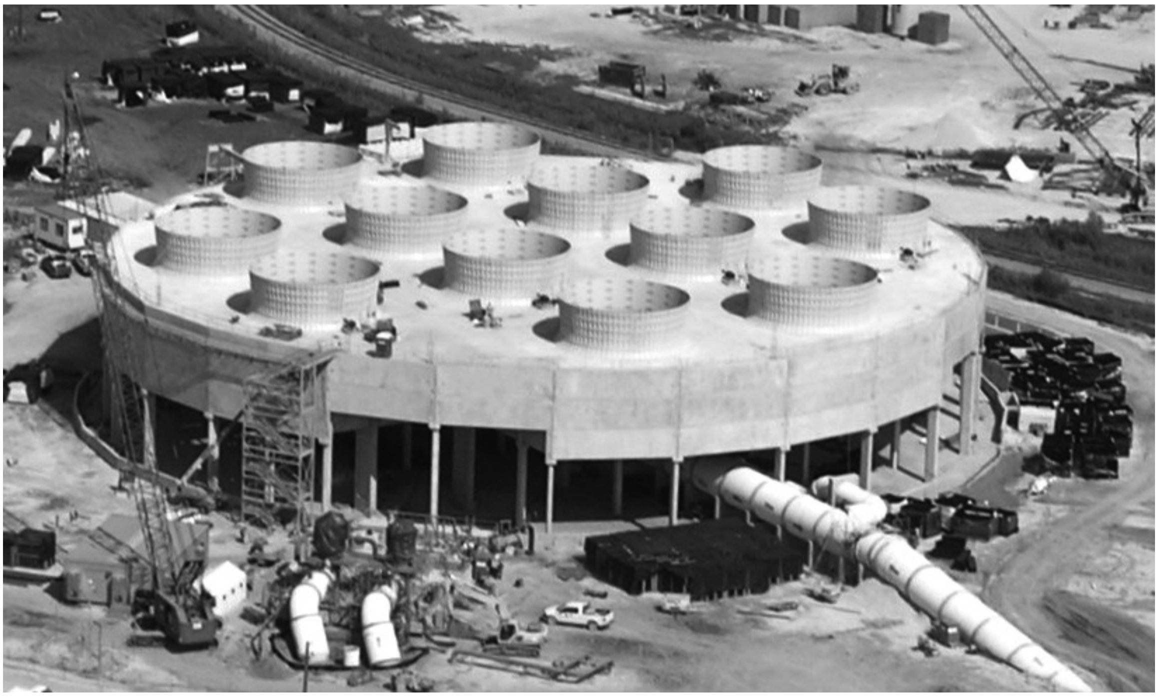

FIGURE 5 *Multifan common plenum cooling tower*

Do not assume from this that 7°C cold water temperature is the “magic” point of control for all operating situations. Water temperatures at the coldest point of the fill are very sensitive to the range (difference between entering hot and leaving cold water temperatures through which the cooling tower is cooling). At a given cold water temperature control point, reduced ranges (i.e. reductions in heat load at a constant water flow rate) will cause the water temperature at the coldest point of the fill to rise. Conversely, increased ranges (i.e. reductions in water flow at a fixed heat load) will cause water temperature at the coldest point of the fill to depress.

For example, if the cooling tower in which the **Figure 6** fill is installed were operating at a 5.5°C range (cooling the water from 12.5°C to 7°C), the entering wet-bulb temperature would be -1.7°C and the water temperature at the coldest point of the fill would be about 3.6°C. As wet-bulb temperature further reduces, measures would be taken to diminish air flow through the fill (by fan manipulation) and the coldest water in the fill would reduce only negligibly below that level.

There is also a longitudinal temperature gradient (actually, steps — rather than a gradient — as individual fans are manipulated) in a multicell cooling tower. This is because cells with fans operating at full speed contribute much more to the cooling tower’s overall cooling effect than do cells with fans either operating at reduced speed — or off. For example, if water were entering the cooling tower in **Figure 7** at 27°C and leaving at a net 15.5°C (one fan running-one off), the actual water temperature produced by cell #1 would be 10°C and water at the coldest point of its fill would be at or near freezing.

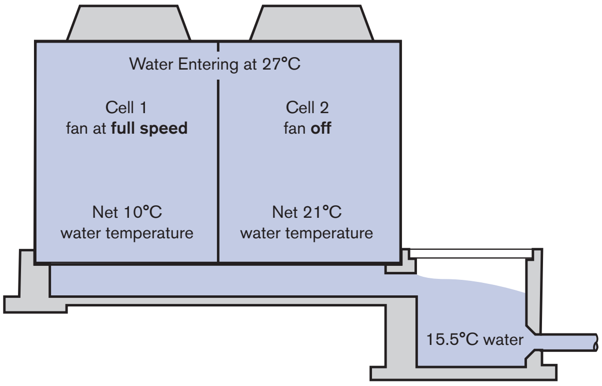

FIGURE 7 *Longitudinal temperature gradient*

Figure 8 and **Figure 9** indicate net performance — and thermal gradients — of a two cell cooling tower cooling through a 20°F range, equipped with single-speed and two-speed fans respectively. These curves are drawn on the premise that the operator will manipulate fans to prevent the net cold water temperature from going below 60°F, and the winter wet bulb temperature can routinely depress to 0°F. The solid line indicates the net water temperature sensed by the operator’s thermometers or control devices — the dashed line indicates the net water temperature from the cell operating at the greatest fan speed — and the dotted line indicates the coldest water temperature in the fill.

Looking at **Figure 8**, one can see that the situation depicted in **Figure 7** would occur at about a -2°F wet-bulb temperature for that particular cooling tower. Comparing **Figure 8** against **Figure 9**, one can also see the tremendous advantage afforded by two-speed motors — both in operating flexibility, and in the reduction of fill temperature gradients.

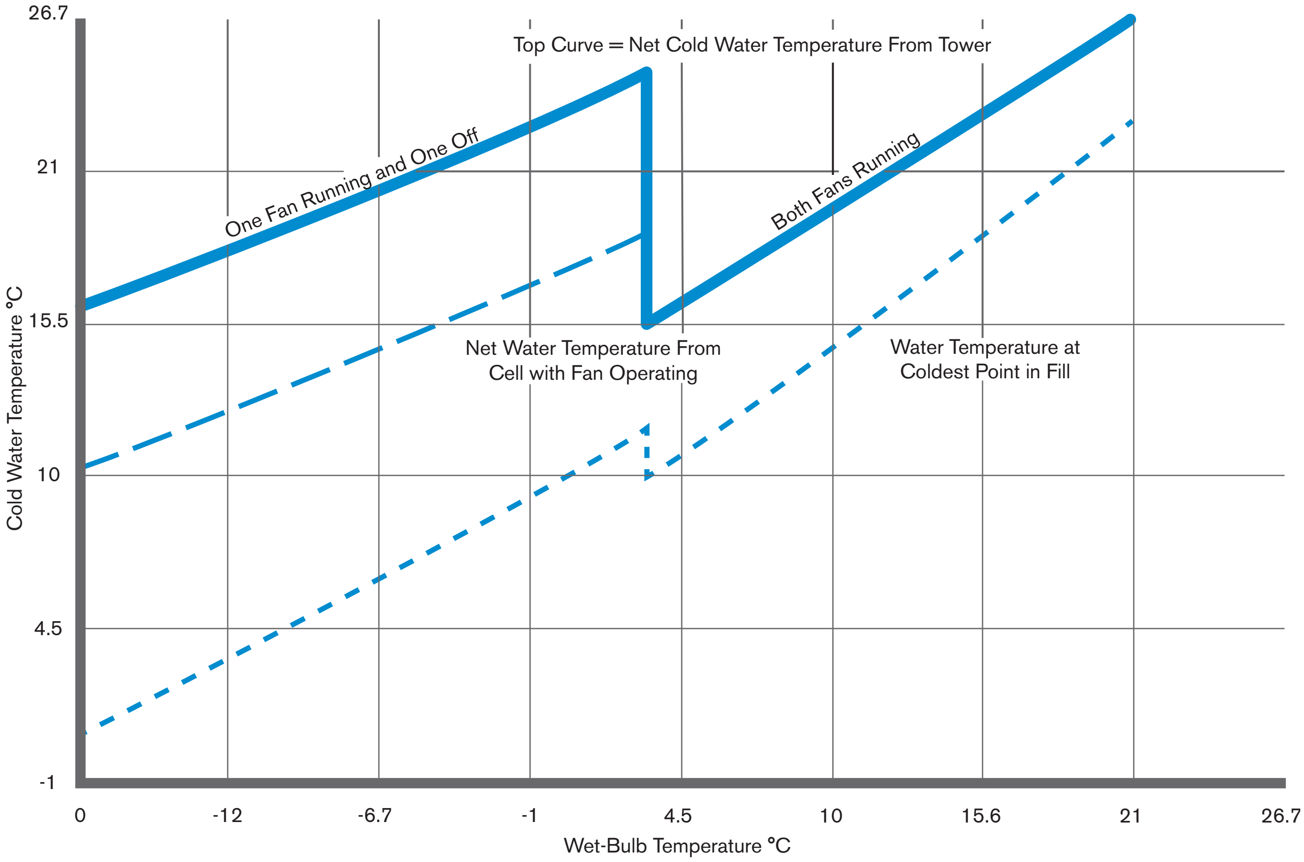

FIGURE 8 *Operating characteristics of a two-cell cooling tower with single-speed motors (11°C range)*

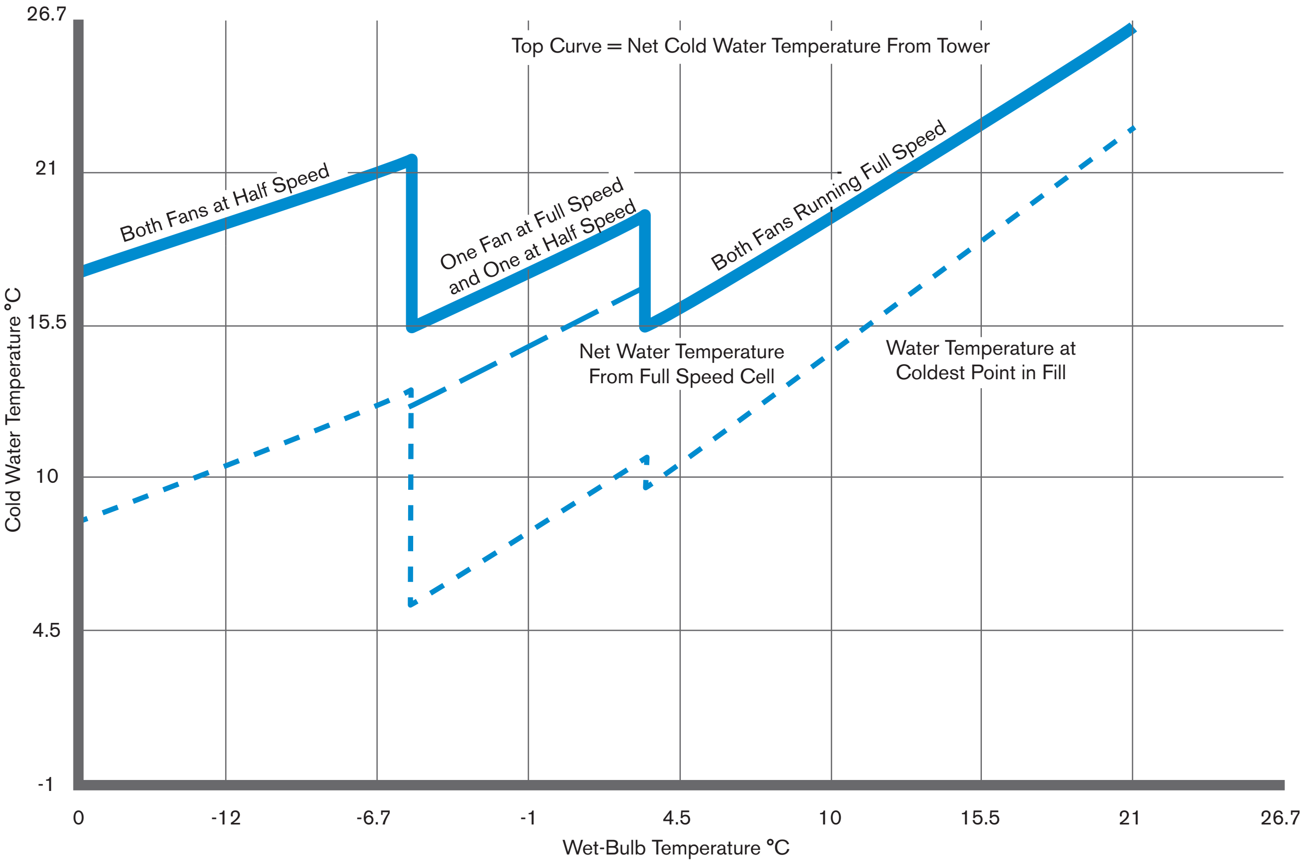

FIGURE 9 *Operating characteristics of a two-cell cooling tower with two-speed Motors (11°C range)*

Icing Characteristics versus Types of Fill and Types of Cooling Towers

The falling water pattern associated with various types of cooling towers has much to do with both the type of ice formed and its location. Crossflow cooling towers equipped with splash fill tend to form the louver ice depicted in **Figure 2** and **Figure 4**, wherein random water droplets generated by the splashing action may impinge upon the louvers and be frozen almost instantaneously. Ice typical of **Figure 2** can usually be controlled merely by reducing the fan's speed — or turning it off for a short period. The reduction in air velocity entering the louvers causes the water's pattern of fall to become vertical, and the louvers are subjected to a cascade of relatively warm water for deicing.

To the degree that such ice blocks air flow, it can oftentimes be self-limiting. Water behind a series of blocked louvers will fall vertically, and will effect a certain amount of deicing. Many wintertime operators of crossflow cooling towers will have observed the kaleidoscopic effect of this alternate freezing and thawing.

Left to progress to the magnitude indicated in **Figure 4**, such ice would require that the fans be reversed (on a mechanical draft cooling tower) for an interim of time, the extent of which must depend upon the tendency for ice to form on the fan cylinder and mechanical equipment. This reversal of air flow not only tends to inundate the louvers with warm water, but also bathes the louvers with warm exit air. In a natural draft crossflow cooling tower, where air flow reversal is impossible, removal of such ice would require a special distribution system whereby water could be periodically diverted to deluge the louvers.

Because of a typically "contained" flow pattern, random water droplets rarely escape film-fill crossflow cooling towers so equipped and tend toward little or no self-produced louver ice. In those cases, louver ice is usually the product of high winds, snow, sleet, and other natural forces.

Used in crossflow configuration, PVC film-fill also tends to limit the amount of ice that it will permit to form on the fill itself. In extended tests, conducted at zero heat load in freezing weather, attempts at forming significant fill ice have met with almost no success. In these tests, thin ice would form at the leading edge of the fill, turn to slush as air flow became blocked, and shortly disappear. This was particularly true of the configurations having louvers molded integrally with the fill. Therefore, given normal control measures, these cooling towers have proved to be quite civilized in their wintertime operation. This is especially true in the low-load, low-temperature situations encountered in "free cooling". Such cooling towers routinely deliver 4.4°C cold water at imposed ranges varying from 5.5°C to less than 1°C.

Since counterflow cooing tower fill is elevated appreciably above the cold water basin level, — **Figure 10** — the generation of random water droplets produced by this free fall tends to be irrespective of the type of fill utilized. Droplets which splash in an outboard direction will freeze on the basin curb and lower structure. Wind gusts cause falling water to momentarily encounter, and freeze upon, the intermediate structure (or louvers, if so equipped). Also, water which normally encounters the inside of the casing can continue down the inboard side of the exposed structure, where it becomes subject to freezing. The combination of these effects initially results in the formations typified by **Figure 1**. Given no concern (and a sufficiently low ambient), the formations will tend to grow toward that depicted in **Figure 3**, particularly where the normal fill temperature gradient results in water near freezing at the fill's coldest point.

Deicing measures for counterflow cooling towers are similar to those utilized for crossflow cooling towers, but tend to be somewhat less effective. The normally vertical sides of a counterflow cooling tower place air inlet areas beyond the reach of the falling water pattern with fans off. That operating mode, therefore, usually removes only that ice which has begun to encroach inward from the air inlets. Because of a counterflow cooling tower's structural nature, however, this limited deicing capability may prove to be enough in most cases. Peripheral ice of concern can be removed by fan reversal, but acceptable results may require several attempts. This is because air flow reversal can bring only a relatively minimal amount of warm water to bear on the ice. Therefore, warm air must accomplish most of the work, which slows down the process considerably. The number of attempts necessary, of course, depends on the tendency for icing of the mechanical equipment during backward air flow.

Many operators are reluctant to reverse fans on a counterflow cooling tower because of the small amount of water caused to escape the air inlets by the outward flow of air. This may produce sufficient ice in the immediate region of the cooling tower to be considered hazardous, requiring separate measures for its control.

Although fewer icing tests have been run on film-fill counterflow cooling towers, there is every reason to believe its response will be similar to that encountered in crossflow cooling towers. Fill icing is expected to be relatively little, with a tendency toward self-limitation.

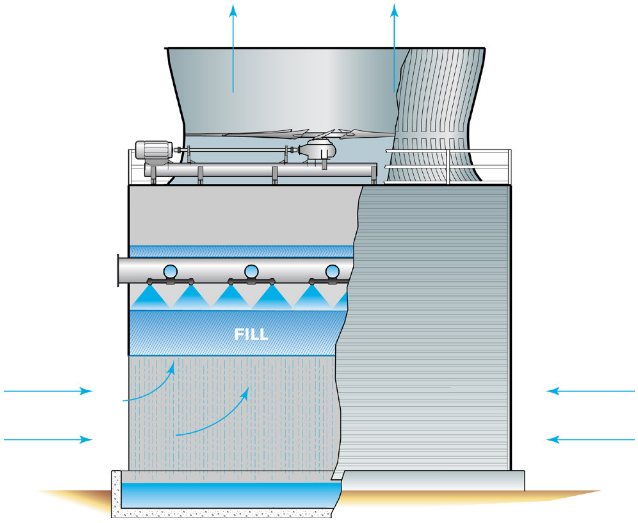

FIGURE 10 *Induced-draft counterflow cooling tower*

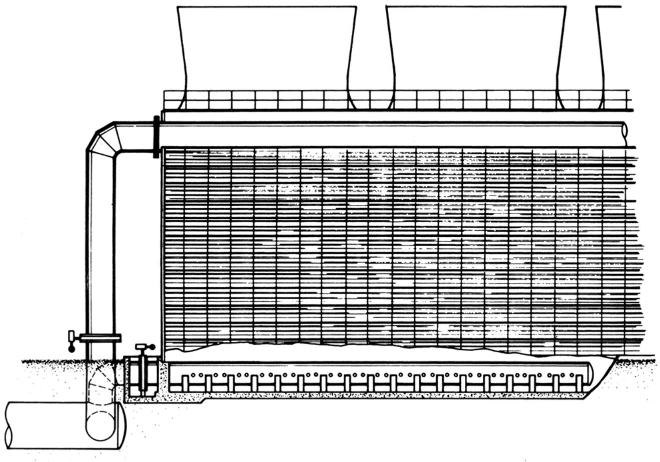

FIGURE 11 *Typical water bypass arrangement*

Water-side Control

Larger cooling towers designed for operation in freezing weather should be equipped with a water distribution system which can be manipulated to place the greatest concentration of flowing water nearest the air intakes of the cooling tower. This applies particularly to natural draft crossflow cooing towers, where no means of airside control is typically available, and the airflow rate actually increases with lower temperature due to the draft effect. Not only does this give the most difficult cooling job to the coldest air, but it also assures a rapid rise in air temperature to preclude freezing on the fill. Most importantly, it places the maximum amount of relatively warm flowing water in close proximity to the areas of greatest ice concern.

To provide for start-up and operating flexibility, provision for total water bypass directly into the cold water basin – **Figure 11** – is advisable on mechanical draft cooling towers, and should be considered mandatory on natural draft crossflow cooling towers. During cold weather start-up, the basin water inventory may be at a temperature very near freezing, at which time the total water flow should be directed back into the cold water basin upon return from the process load, without going over the fill. This bypass mode should be continued until the total water inventory reaches an acceptable temperature level (usually about 27°C), at which time the bypass may be closed to cause total flow over the fill.

Even during operation, combinations of low load, low ambient, and high winds can promote ice formations despite normal airside and waterside control procedures. In those cases, it may intermittently become necessary to divert to total bypass flow to build a heat content in the circulating water. Modulation of the bypass whereby a portion of the water flow is allowed to continue over the fill, must not be permitted on a natural draft crossflow cooling tower, and its utilization on mechanical draft cooling towers should be discouraged.

Where reduced flow rates cannot be avoided, either by pump manipulation or through bypass modulation, crossflow cooling towers can be provided with a longitudinal dam in the hot water basins to concentrate water outboard on the fill. The height and location of this dam would be based upon a predetermined minimum allowable water flow rate. At increased flow rates, the dam would become submerged, allowing water access to the inboard areas of the fill.

Comparison of Induced-Draft and Forced-Draft Cooling Towers

As indicated previously, of the two basic types of cooling towers utilized (counterflow and crossflow), neither can be considered to have an overriding advantage with respect to cold weather operation. Of far greater importance is the type of fan used, and its location with respect to air flow through the cooling tower. Consequently, the remainder of this paper will compare the icing characteristics of induced draft, propeller fan cooling towers and forced draft, blower fan cooling towers.

In the induced draft, propeller fan cooling tower depicted in **Figure 12**, cold air enters through the louvers at relatively low velocity—is heated by the water flowing over the fill—and exits through the fan at a relatively high velocity. This increased exit velocity assures that the amount of saturated air recirculating into the intake louvers will be minimal.

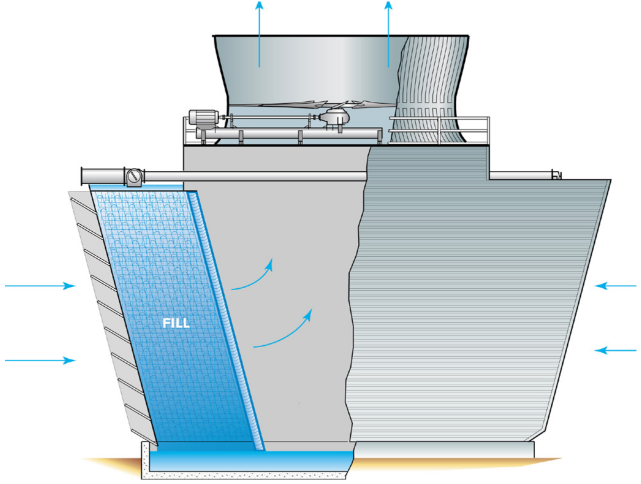

FIGURE 12 *Induced-draft crossflow cooling tower*

Therefore, only the passive air-intake area is subjected to any potential for ice formation related to cooling tower operation. The fan and mechanical equipment are exposed only to warmed air. This is true even when the fan is turned off. Convection currents induced by the warmth contained in the flowing water bathe the mechanical equipment with heated air.

Figure 12 also illustrates the fill-louver relationship in a crossflow cooling tower. Note that the space occupied by fill angles inward on the cooling tower from top to bottom. During full fan operation, water passing over the fill will tend to fall at that angle due to the velocity of the horizontal flow of air with which it is in contact. When the fan is slowed, or brought to a stop, the incoming air velocity reduces significantly and the water attempts to fall vertically. In doing so, the water impinges upon the louvers, cascading successively downward to the cooling tower basin. Except in the most severe situations, this cascade of warm water is usually sufficient to accomplish deicing.

In situations of extreme cold weather and/or a very light heat load, it may become necessary to reverse the direction of fan rotation. In this mode of operation, air flows downward through the fan — picks up heat passing through the fill—and exits through the louvers. This reverse passage of air shifts the falling water pattern outward causing an increased cascade down the louvers. The combination of warm water and warm air, of course, effects complete deicing.

Fan reversal should be limited to a time period of no more than one or two minutes at half speed to preclude excessive icing of the fan. Unless an inordinate buildup of ice has been allowed to accumulate, this is usually more than sufficient time to accomplish louver deicing. Monitoring is required to determine the time required to melt accumulated ice. Also, to prevent possible damage to the fan, drive train, and electrical system, an interval of no less than two minutes should exist between the instant that the motor is de-energized and the time it is restarted in the opposite direction. This allows the fan time to lose rotational momentum.

The least desirable cooling tower for operation in freezing weather is the forced draft, blower fan type, as depicted in **Figure 13**. Its lack of adaptability to cold weather operation stems primarily from the fact that the fans are located in the entering cold air stream, rather than in the warm leaving air stream. Because of the location of the fans care must be taken to ensure proper operation and orientation to prevent recirculation.

FIGURE 13 *Forced-draft counterflow cooling tower*

Recirculation is the reintroduction of a portion of the saturated leaving air stream back into the relatively dry entering air stream. In summertime, such a situation causes an undesirable elevation in cold water temperature by increasing the wet-bulb temperature of the air entering the cooling tower. In wintertime, the artificially-increased moisture content of the entering air quickly condenses and freezes on the cooling tower's coldest point — the air intake (fan) area.

Obviously, in any given wind condition, recirculation is a function of the relative velocities of the air entering and leaving the cooling tower. Where the exiting air velocity exceeds entering velocity, the cooling tower's tendency to recirculate is reduced. Conversely, higher entering velocities produce a localized zone of low pressure into which recirculation is induced (See *External Influences on Performance* available from SPX Cooling Technologies).

In the typical induced draft, propeller fan cooling tower — **Figure 12** — the average exit velocity is approximately 9.6 m/s, compared to an entering velocity of 3.5 m/s. This positive ratio exceeding 2.5/1 minimizes the potential for recirculation. In contrast, the air velocity at the fan region of a forced draft, blower fan cooling tower — **Figure 13** — is approximately 10 m/s, compared to a cooling tower exit velocity of about 3.4 m/s. This negative ratio exceeding 3/1 virtually assures some recirculation of saturated air back into the fan intakes.

An adverse wind condition compounds the problem, as seen in **Figure 14**. A wind velocity as little as 12 km/h (3.4 m/s) will deflect the exit plume an amount sufficient to insure entrapment within the negative pressure zone created by the fan's high entering velocity.

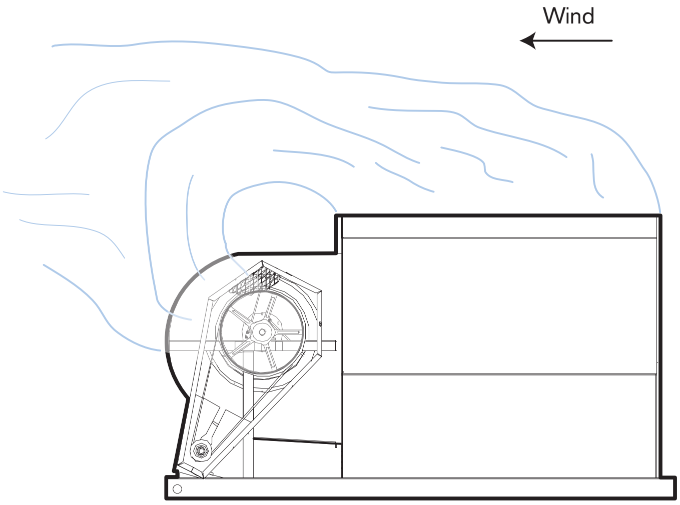

FIGURE 14 *Recirculation potential in a forced-draft cooling tower*

Under no circumstances should the direction of air flow be reversed in a forced draft cooling tower. (In the case of a centrifugal blower fan, the point is academic because it is impossible to do so.) Reversing the direction of air flow merely concentrates moisture on the mechanical equipment, which refreezes instantaneously upon return to normal air flow. Unfortunately, merely bringing the fan to a stop can also produce this unwanted situation. The spray-type water distribution system normally utilized in forced draft cooling towers causes a downward aspiration of saturated air, which exits through the inoperative fan. Although this movement of air is insufficient to effect deicing, it does contribute to further icing upon fan restart.

Finally, forced draft cooling towers can be operated in freezing weather, but extreme care must be taken to ensure proper operation and orientation to prevent recirculation.