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"free" cooling using
Water Economizers

from the editor ...
In past newsletters, we addressed the ability to accomplish "free" cooling by artfully rearranging traditional cooling equipment [1] and other ways to achieve byproduct cooling virtually for free.[2] We've also provided newsletters that discussed air economizers and energy code requirements.[3]

In this EN, Susanna Hanson (Trane applications engineer) focuses on the traditional methods of water-side economizing and associated energy code requirements.

Let's start with some definitions.

Economize: V. Tr. To use or manage with thrift: the need to economize scarce energy resources.
- economizer n.

The variety of ways to be thrifty with HVAC energy explains why there are so many components of equipment and systems called "economizers". For the purposes of this discussion, we will focus on the water economizer as defined by ASHRAE Standard 90.1-2007 (Standard 90.1) section 3.2.

Economizer, water: A system by which the supply air of a cooling system is cooled indirectly with water that is itself cooled by heat or mass transfer to the environment without the use of mechanical cooling.

Why economize?

There are times of the year when a system can use outdoor conditions to cool the building or process using the standard cooling components to distribute its cooling effect.

The most prevalent technique is an air economizer. When the temperature, or enthalpy, of the outdoor air is low, cooler outdoor air is used to reduce the temperature (or enthalpy) of air entering the cooling coil. This can reduce or eliminate mechanical cooling for much of the year in many climates.

Why water economize? Some applications reduce or negate the benefits of air economizers or simply make them impractical. In these cases, a water economizer can reduce compressor run hours and energy use. Some examples include:

- Minimum humidity requirements - bringing in additional cold, dry outdoor air can increase humidification loads.
- System limitations - some air handling units are easily equipped with economizers while others are not. This can be related to space, distance to the outside air intake, increased return or exhaust fan sizing, duct routing, or duct space.
- Dedicated outdoor air systems - a separate outdoor air unit is typically sized to serve only the ventilation loads. Another system to handle other building loads may be served by chilled water.

Standard 90.1 requirements

The following sections of the Standard 90.1 prescriptive path are relevant for water economizers.[4]

Section 6.5.1 Economizers. "*Each cooling system…*" over the size thresholds shown below "*that has a fan shall include either an air or water economizer.*" There are nine exceptions: small individual fan cooling units, spaces humidified above 35°F (2°C) dew point for processes, systems with condenser heat recovery, some residential applications, and systems with minimal hours or cooling loads. There is also an option to use higher efficiency equipment in lieu of an economizer for unitary system sizes below 760 kBtu/h (63 tons). There is no high efficiency trade-off option for applied systems.

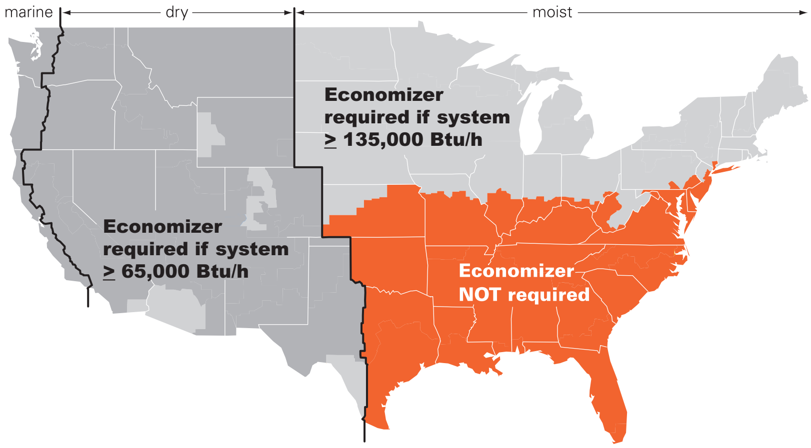
The requirements vary by system size and climate zone (Table 6.5.1 and Figure 1).

Table 6.5.1 Minimum system size for which an economizer is required

Climate zones	Cooling capacity for which an economizer is required
1a, 1b, 2a, 3a, 4a	No economizer required
2b, 5a, 6a, 7, 8	≥135,000 Btu/h
3b, 3c, 4b, 4c, 5b, 5c, 6b	≥65,000 Btu/h

Section 6.5.1.2.1 Design Capacity. The section states that "*water economizer systems shall be capable of cooling supply air by indirect evaporation and providing up to 100% of the expected system cooling load at outdoor air temperatures of 50°F (10°C) dry bulb/45°F (7°C) wet bulb and below.*" unless dehumidification loads cannot be met in which case, the water economizer system "*must satisfy 100% of the expected system cooling load at 45°F dry bulb/40°F (4°C) wet bulb.*"

Figure 1. Standard 90.1 regional economizer requirements based on cooling system capacity



Expected building loads can vary widely for a given dry-bulb and wet-bulb combination (e.g. night versus day, occupied versus unoccupied), so this requirement is somewhat unclear. A reasonable assumption is that the intent of the Standard is 100% of the normal daytime operation cooling load.

Section 6.5.1.2.2 Maximum Pressure Drop. "*Precooling coils and water-to-water heat exchangers used as part of a water economizer system shall either have a water-side pressure drop of less than 15 ft of water or a secondary loop shall be created so that the coil or heat exchanger pressure drop is not seen by the circulating pumps when the system is in the normal cooling (noneconomizer) mode.*"

A sidestream application (see Figure 3) has no maximum pressure drop, since it is not seen by the circulating pumps when in normal cooling mode.

Section 6.5.1.3 Integrated Economizer Control. *"Economizer systems shall be integrated with the mechanical cooling system and be capable of providing partial cooling even when additional mechanical cooling is required to meet the remainder of the cooling load."*

This is only *required* in climate zones 3b, 3c, 4b, 4c, and 5c. However, integrated control is worth considering even in cases where it is not required.

Types of water economizers

Strainer cycle. In this system, the condenser and chilled-water systems are connected. When the outdoor wet-bulb temperature is low enough, cold water from the cooling tower is routed directly into the chilled-water loop.

Although the strainer cycle is the most efficient water economizer option, it greatly increases the risk of fouling in the chilled-water system and cooling coils with the same type of contamination that is common in open-cooling-tower systems. A strainer or filter can be used to minimize this contamination, but the potential for fouling prevents widespread use of the strainer-cycle system.

Indirect evaporative precooling coil. For water-cooled, self-contained direct-expansion (DX) systems (like floor-by-floor systems), a precooling coil upstream of the refrigerant coil is supplied with cold water from the cooling tower. This indirect evaporative precooling-coil circuit is similar to the strainer cycle because it interfaces an open circuit directly with the air delivered to the zones.

Indirect evaporative cooling-coil circuits, connected directly to an open cooling tower, must be maintained properly to minimize fouling, microbial growth and corrosion. Maintaining this circuit involves frequently providing the same proper water treatment as the cooling tower.

Evaporative cooler with air-cooled chiller. A variation on the water economizer for air-cooled chillers is to use an evaporative cooler in series with the air-cooled chiller. The air-cooled chiller will come on once the evaporative cooler can no longer handle the load by itself.

Dry cooler with air-cooled chiller. Another variation for air-cooled chillers is a dry cooler, or closed-circuit cooling tower, in series with the air-cooled chiller.

Because of their high approach temperature, dry coolers may not be able to meet the requirement of 100% of the cooling load at either 50ºF/45ºF or 45ºF/40ºF (see previous discussion of Section 6.5.1.2.1).

Plate-and-frame heat exchanger. In this type of water economizer, the water from the cooling tower is kept separate from the chilled-water loop by a plate-and-frame heat exchanger. This is a popular configuration because it can achieve high heat-transfer efficiency without cross-contamination. With the addition of a second condenser-water pump and proper piping modifications, this heat exchanger can operate simultaneously with the chiller. As much heat as possible is rejected through the heat exchanger while the chiller handles the rest of the cooling load.

Plate-and-frame heat exchangers isolate the building loop from the water in the open cooling tower loop, but they must be cleaned, typically annually. The labor and parts for cleaning and reassemby (e.g. gasketing) is an expense that should be factored into the life-cycle cost of this option.

Free-cooling chiller. Another method of "free" cooling is to transfer heat between the cooling tower water and the chilled water inside a centrifugal chiller through the use of refrigerant migration, also known as a thermosiphon. When the temperature of the water from the cooling tower is colder than the desired chilled-water temperature, the compressor is turned off and automatic shutoff valves inside the chiller refrigerant circuit are opened. Because refrigerant vapor migrates to the area with the lowest temperature, refrigerant boils in the evaporator and the vapor migrates to the cooler condenser. After the refrigerant condenses, it flows by gravity back to the evaporator.This allows refrigerant to circulate between the evaporator and condenser without the need to operate the compressor.

Depending on the application, it is possible for refrigerant migration in a centrifugal chiller to satisfy many hours of cooling load without operating the compressor. Free cooling chillers serving systems that can tolerate warmer chilled-water temperatures at part-load conditions can produce over 60% of the rated capacity without compressor operation.

There are no cooling coil fouling concerns because the cooling-tower water flows through the chiller condenser and is separate from the chilled-water loop. There is no additional expense for cleaning, as the condenser tubes are the same as those used for normal cooling mode and should already be on a maintenance schedule. In addition, fewer pipes, pumps and fittings and no heat exchanger are required.

For example, a 1000-ton chiller supplied with 35°F tower water can create a maximum 638 tons at 45°F chilled-water temperature. Assuming the same water flows, the same chiller supplied with 40°F tower water would create 638 tons at 50°F chilled water. These numbers are representative and vary based on the chiller selection.

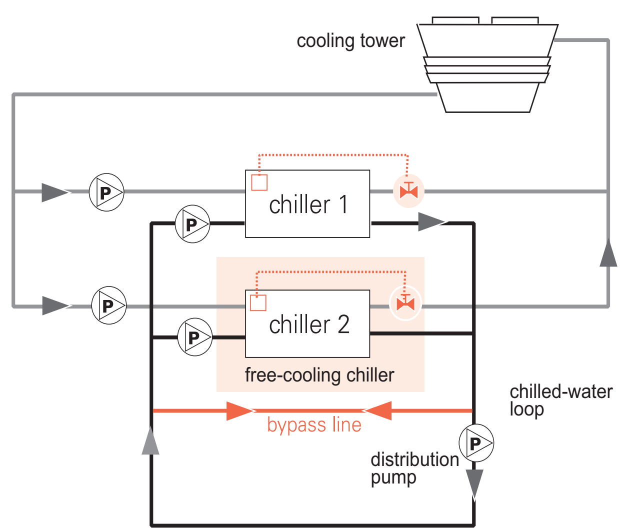
If the free-cooling chiller is part of a traditional parallel chiller lineup, simultaneous operation is not possible without blending leaving chilled-water temperatures. It is common for designers to embrace a heat exchanger in series with a chiller but less common to embrace chillers in series. If simultaneous operation is desired, the free-cooling chiller should be installed in the same location as the heat exchanger in Figure 3.

System configuration and control

Parallel configuration. In this arrangement, the placement of the water economizer is similar to an additional chiller in a parallel plant arrangement, Figure 2.

The water economizer must either create the leaving chilled-water setpoint, or the plant must mix colder-than-required water from the operating chiller with warmer water from the economizer to satisfy the chilled-water setpoint. This is seen as undesirable as it may use as much energy as it saves. The chiller uses 1.0 to 2.5% more energy per degree of colder water created. In this case, since the temperature is then raised by the warmer water from the economizer, no pump energy savings are available to balance the increased chiller energy. Thus, the parallel arrangement is often considered an "all or nothing" design. That is, if the water economizer cannot meet the entire load, the plant controller stops the economizing cycle and reverts to standard mechanical cooling. The number of hours suitable for water-side economizing is thereby reduced.

Figure 2. Water economizer piped in parallel with chillers



Series configuration. To resolve the need for mixing during simultaneous operation (and to meet ASHRAE 90.1's integrated operation requirement where required), a water economizer is often piped in series or sidestream with the rest of the chiller plant, Figure 3.

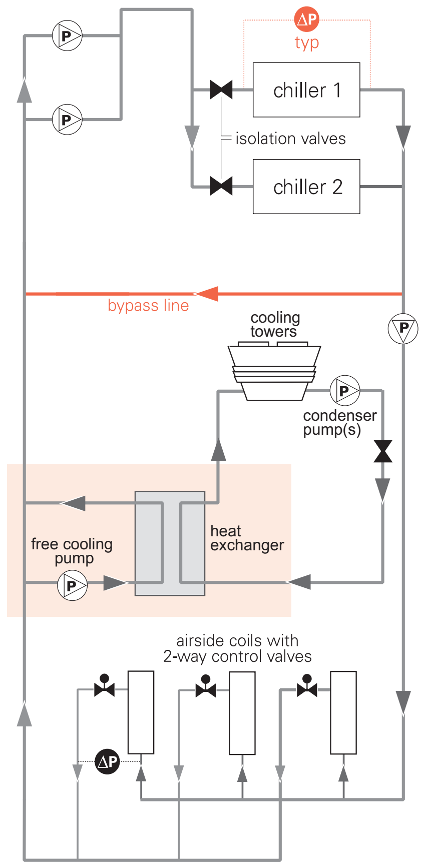
Water cooled by the economizer can be further cooled by one or more active chillers. More hours are suitable for water-side economizing in this arrangement than the parallel arrangement, and integrated economizing is accomplished without mixing. Control at transition is also simpler with the series arrangement.

One common concern about piping water economizers in series with chillers is that the touted benefits—integrated, simultaneous operation and simplified transitions—requires that the chiller be able to operate at colder-than-normal condenser water temperatures.

There are several methods for condenser water temperature control. For example, a condenser bypass lets the chiller compressor heat the condenser water enough to meet minimum chiller requirements. Some chillers may even have this feature as standard. Another technique is to dedicate a separate tower loop to the chiller when running simultaneous free cooling. This could be a back-up tower that is typically idle, or created through valves and extra piping.

One side-effect of having the chiller and the water economizer on the same cooling tower circuit is that the chiller compressor will increase the tower load by its motor heat. This will, in turn, cause tower approach and leaving-water temperature to increase. But with an economizer still operating, we would prefer that the tower water stay as cold as possible (as cold as it would have been without the chiller on).

Figure 3: Water economizer piped in side stream (series) arrangement



For this reason, towers or tower cells for the economizer or free cooling chiller are often separated from those serving operating chillers, so that the chiller requirements and the economizer requirements do not conflict during simultaneous operation. In addition, the tower fans serving the chiller can be optimally controlled to minimize chiller-plus-tower energy.[5]

Alternatively, a small air-cooled chiller sized for the excess load may be advantageous if the tower circuits cannot be separated.

Control implications. The series arrangement has less risk of disrupting cooling during system transition—primarily when going from mechanical to free cooling. For the parallel arrangement, it is more difficult to develop automated algorithms for predicting the proper switch-over point to minimize system disruption. Without automation, the process can be based on the operator's intuition and past knowledge. But the operator is typically not there between 10pm and 3am when the mode will most likely work. A poorly conceived automatic system during initiation of all-or-nothing free cooling will likely be disabled.

With the series configuration, the control system can try to initiate free cooling and if it doesn't meet all the load, the now partially-loaded chiller will meet the rest. The decision can then be made to either remain in partial economizer, or revert back to full mechanical cooling. (Generally if load or wet-bulb temperature are dropping, remaining on economizer mode is advantageous.)

When to initiate free cooling. Free cooling mode in a series arrangement can be initiated as soon as the tower water can be made cold enough for the system to benefit. For best system efficiency, the tower is not likely to be producing its coldest possible water when the decision to enter free cooling mode is made.[5] Therefore, it is necessary to predict if cold enough tower water could be produced, so that the chiller or chiller compressor can be turned off.

So, how can we predict potential tower performance before attempting switch-over? Imagine a system with the water economizer in sidestream position (Figure 3) and the following design criteria:

42°F leaving-water temperature
48°F maximum chilled-water temperature
12° chilled-water delta T
5°F tower approach (constant)
3°F heat exchanger approach

The simplistic control would enter economizing mode whenever the outdoor wet bulb is 40ºF or less (40+5+3 = 48). One problem with this control is that the tower approach is not constant—it varies both with load and wet-bulb temperature.

Tower performance. There are three problems with predicting tower performance by assuming a constant tower approach to wet bulb. It understates the number of hours available for economizing at warmer wet-bulb temperatures and overstates the cooling effect available at low wet-bulb temperatures. It also incorrectly predicts the chiller energy consumption. These errors lead us to seek a better method.

A reputable energy analysis program, tested in accordance with ASHRAE Standard 140, will probably model the tower adequately. Table 1 shows tower performance at various tower load and wet-bulb conditions typical during water economizer operation, which assumes that there is no compressor heat to be rejected. The tower was selected with 85°F design leaving water, 7°F design approach and a 10°F range.

The tower has to work harder to reject the same amount of heat as the wet bulb drops, and it also works harder as the load goes up. If we take that one step further, as the wet bulb falls or the load goes up, the tower approach goes up. Due to the increase in approach temperature, tower fan energy will increase. System energy savings are diminished and free cooling becomes less desirable.

Based on this information (as shown in Table 1), you can predict the wet-bulb temperature at which the water economizer can reduce the return-water temperature enough to initiate free cooling.

How many hours? Standard 90.1 requires that full capacity must be achieved by the water economizer when the outdoor temperature is 50°F DB and 45°F WB (unless there are dehumidification issues). So, if the economizer design is correct, a simple perusal of the hours below 45°F WB is a good initial guess.

But are there any more hours available? It depends. Is the desired threshold cooling capacity or maximum chilled-water setpoint? More hours are available if the chilled-water temperature is allowed to float upward until a zone humidity or space temperature alarm terminates free cooling or starts a supplemental chiller.

In free cooling mode, there is no heat of compression or motor heat to reject to the cooling tower, so tower load and tower approach will be lower than for mechanical cooling mode at the same hour. So if the tower is in free cooling-only mode, the tower load equals the building cooling load.

Approach is the temperature difference between what is being produced and the "power source" that creates the product. In the case of a cooling tower, the "product" is cold water leaving the tower and ambient wet bulb is the driving force that creates the cold water. If a cooling tower produces 85°F cold water when the ambient wet bulb is 78°F, then the cooling tower approach is 7°F.

Table 1. Tower approach temperature at various load and wet-bulb temperatures

	wet-bulb temperature										
% building load	48	46	44	42	40	38	36	34	32	30	28
30	4.4	4.8	5.2	5.6	6.0	6.3	6.7	7.2	9.2		
25	3.9	4.3	4.6	4.9	5.2	5.5	5.9	6.1	8.1		
20	3.5	3.8	4.0	4.1	4.3	4.7	5.0	5.1	7.1		
15	2.8	4.0	3.1	3.2	3.4	3.7	4.0	4.2	6.2		
10	2.1	2.2	2.3	2.4	2.5	2.8	2.9	3.3	5.3	7.3	9.3
5	2.1	2.2	2.3	2.4	2.5	2.8	2.9	3.3	5.3	7.3	

Note: Shaded combinations were not present in the building model used.

In an office building in Chicago a simulation showed that there were 730 hours when the wet bulb was between 28°F and 48°F and there was a call for cooling. In contrast, a simulation of a hospital in Chicago found 1,980 hours in that wet-bulb range. Surely not all of these will be candidates for water-side economizing, but many will. Table 2 builds on Table 1 to show the coldest water that could be supplied to the free cooling device.

The next step is to apply the performance (approach) of the water economizer to determine the heat exchanger leaving-water temperature (Table 3).

Alternatively use the thermosiphon chiller performance to determine the temperature of water it could produce (Table 4).

The final step is to compare the temperature leaving the water economizer with the maximum chilled-water reset value. If it is lower, then the load can be met and the system could initiate free cooling. If it is higher, then in a series arrangement, free cooling could be attempted and the chiller would stay on to handle the rest of the load. In parallel operation, free cooling would not be attempted.

What about optimization? It may be possible to press free cooling to the point where it consumes more system energy. Depending on the climate and how oversized the tower is, there could be many hours when free cooling can save substantial energy. Conversely there are hours when water-side economizing offers no benefit. But what about the marginal hours and what is their value in energy dollars? To optimize operation you must balance the condenser pump, tower fan, chilled-water pump and fan energy to develop the right scheme. This optimization takes design time, commissioning time, and tuning time.

Table 2. Tower-leaving temperature at various load and wet-bulb temperatures

	wet-bulb temperature										
% building load	48	46	44	42	40	38	36	34	32	30	28
30	52.4	50.8	49.2	47.6	46.0	44.3	42.7	41.2	41.2		
25	51.9	50.3	48.6	46.9	45.2	43.5	41.9	40.1	40.1		
20	51.5	49.8	48.0	46.1	44.3	42.7	41.0	39.1	39.1		
15	50.8	50.0	47.1	45.2	43.4	41.7	40.0	38.2	38.2		
10	50.1	48.2	46.3	44.4	42.5	40.8	38.9	37.3	37.3	37.3	37.3
5	50.1	48.2	46.3	44.4	42.5	40.8	38.9	37.3	37.3	37.3	

Tower modeled with 85°F design leaving water, 7°F design approach and a 10°F range

Note: Shaded combinations were not present in the building model used.

Table 3. Heat exchanger leaving temperature at various load and wet-bulb temperatures

	wet-bulb temperature										
% building load	48	46	44	42	40	38	36	34	32	30	28
30	55.4	53.8	52.2	50.6	49.0	47.3	45.7	44.2	44.2		
25	54.9	53.3	51.6	49.9	48.2	46.5	44.9	43.1	43.1		
20	54.5	52.8	51.0	49.1	47.3	45.7	44.0	42.1	42.1		
15	53.8	53.0	50.1	48.2	46.4	44.7	43.0	41.2	41.2		
10	53.1	51.2	49.3	47.4	45.5	43.8	41.9	40.3	40.3	40.3	40.3
5	53.1	51.2	49.3	47.4	45.5	43.8	41.9	40.3	40.3	40.3	

Heat exchanger approach assumed constant at 3°F and tower temperatures from Table 2

Note: Shaded combinations were not present in the building model used.

Table 4. Free-cooling (thermosiphon) chiller leaving temperature at various load and wet-bulb temperatures

	wet-bulb temperature										
% building load	48	46	44	42	40	38	36	34	32	30	28
30	57.2	55.8	54.2	52.7	51.2	49.4	47.8	46.4	46.4		
25	56.4	54.7	53.0	51.3	49.7	47.9	46.4	44.6	44.6		
20	55.2	53.6	51.7	49.9	48.1	46.5	44.9	43.0	43.0		
15	54.0	53.2	50.4	48.6	46.8	45.1	43.4	41.6	41.6		
10	52.2	51.2	49.0	47.0	45.0	44.0	41.6	40.0	40.0	40.0	40.0
5	51.5	50.3	48.5	46.5	44.5	43.1	41.0	39.5	39.5	39.5	

Based on performance of Trane centrifugal chiller using free-cooling option and tower temperatures from Table 2

Note: Shaded combinations were not present in the building model used.

When to exit free cooling. Exiting free cooling is more simple than initiating, because the free cooling effect on the system is already known. The decision can use any of the following criteria.

For simultaneous free cooling:

1 when the return water temperature is reduced by less than 2°F
2 based on expected time-of-day scheduled load patterns
3 based on ambient wet-bulb temperature

For stand-alone free cooling:

1 when humidity or temperature control is compromised
2 based on expected time-of-day scheduled load patterns
3 based on ambient wet-bulb temperature

The second and third criteria could also be set up as lock-outs to prevent the initiation of free cooling when it is unlikely to work, or when tighter system control is required.

Closing thoughts

Water-side economizing—whether by plate-and-frame heat exchanger, chiller thermosiphon cycle, or another method—can provide limited amounts of cooling when ambient wet-bulb temperatures are low. Chilled-water temperature as high as 50°F is often acceptable during this type of cooling because cooling load is lower and latent load does not exist at these conditions. The elevation of chilled-water temperature aids this type of cooling as heat follows its natural tendency toward colder areas: from the air side, to chilled water, to tower water, to ambient air, without the aid of a compressor. If supply-air temperature must be lower, or as ambient wet-bulb temperature climbs, the driving force for free cooling is reduced.

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