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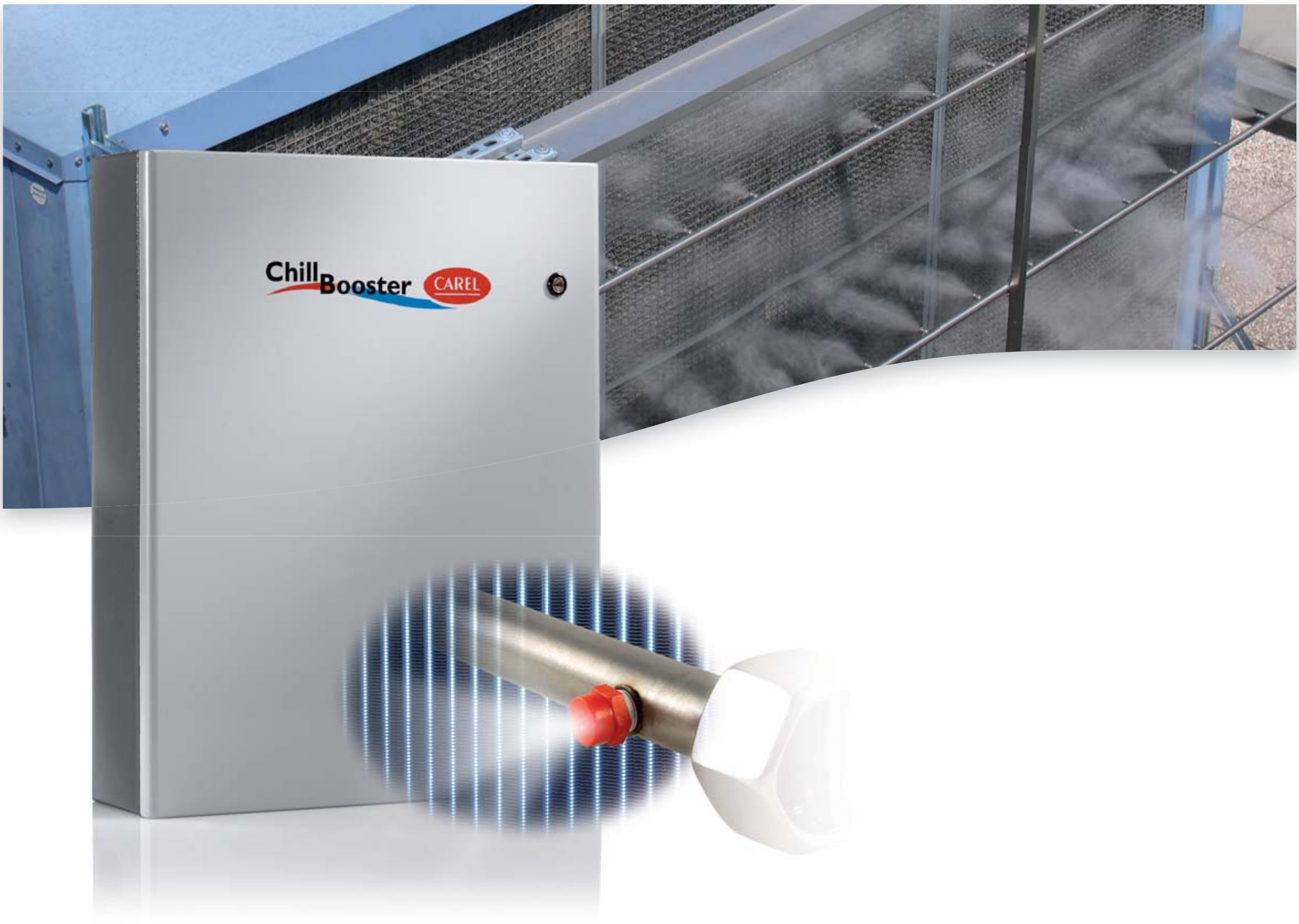

ENG

chillBooster:
story of a simple yet powerful product

humidification-for-life.com

Content

1. GOALS OF THIS PAPER

- Understanding how to invest in energy saving with a break-even point of a couple of months
- Understanding evaporative cooling by water on cooling coils for saving energy
- Understanding chillBooster and how cooling-coiled equipments can benefit from it

2. CHILLERS, CONDENSERS, DRY COOLERS AND ALIKE: BASIC INTRODUCTION

In many installations, all these equipments cool a refrigerant fluid by making it flow inside pipes in contact with the outdoor air: if the outdoor air is colder than the refrigerant, this rejects part of its heat towards the air; otherwise, the equipment is locked by a safety switch not to absorb additional heat. The pipes form the so-called cooling coils. The next picture gives an idea of what a dry cooler is; the other equipments are similar.

The heat rejection is sustained by:

- Coils made of materials with high thermal conductivity, like copper and aluminium
- Water sprayed on coils to boost their performance. Note that water quality has to be compatible with the coils material in order to minimize the mineral build-up or to avoid corrosion in case the water is demineralised
- Fans, that force the outdoor air to flow through the coils and to remove more heat than it would by natural flow (i.e., with fans off)
- The exposed surface between the pipes and the air: the wider the bigger the heat rejection
  - The length of the pipes is made as longer as possible, because the longer the pipes the wider the exposed surface
  - Fins (similar to small side wings) are added to the pipes all along their length to increase the exposed surface. As an example, a coil W x H = 7.2 m x 1.2 m (23.6 ft x 3.9 ft) can develop an exposed surface as wide as 1,600 m^2 (17,222 ft^2)[1]

V-shaped roof-top dry cooler with 5 fans

Cooling coil with pipes made of copper and fins made of aluminium

Chiller on CAREL Industries S.r.l.'s roof with 3 fans on top and water being sprayed counter-flow towards the cooling coil

In almost all installations heat rejection can be enhanced by evaporative cooling. This advantageous technique even makes the heat rejection possible when the outdoor air is so warm that the equipment would be locked out not to absorb heat without evaporative cooling present (safety switches are usually installed to stop the equipment when the outdoor air is warmer than the refrigerant).

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[1] *The actual values can be found on the data sheet supplied with the equipment*

3. WHAT IS CHILLBOOSTER?

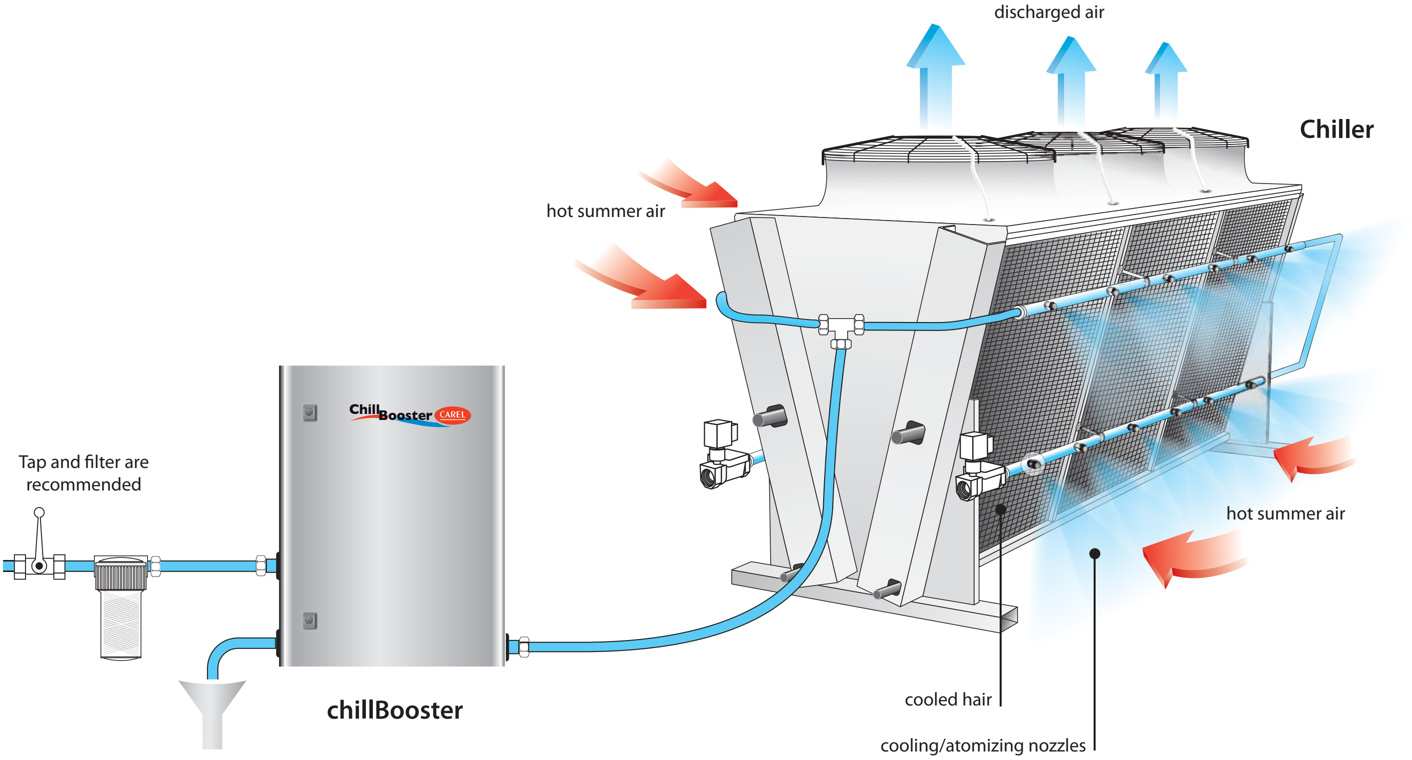
Why and how all this is possible is explained in the following sections.

This chapter covers the following topics:
1. Description, working principle and parts
2. Water quality
3. Installation
4. Maintenance

3.1 Description, working principle and parts

3.1.1 Description and working principle

chillBooster is a simple atomizer that sprays water in small drops, whose Sauter diameter is approx. 35 μm[1].
The typical structure and use of a chillBooster system is represented in the following picture, where chillBooster is shown to support the heat rejection of a dry cooler by exploiting the cooling effect of evaporating water (evaporative cooling):



Drops are usually sprayed against the air flow so that they partially evaporate before depositing on coils. Then, most of the deposited water evaporates from the coils, ***greatly enhancing*** the rejection of heat from the chiller; the part of the water that does not evaporate, drips, bringing away some more heat.
The phenomena that help to increase the heat rejection from the coils are, in order of occurrence:

1. **Water evaporation in air** reduces the air temperature by a few degrees (maximum), thanks to the evaporative-cooling effect. It is well known that 1 L of water evaporating in 1 hour absorbs approx. 700 W of heat from the surrounding air, which becomes cooler and more humid [700 W/(L/h) ≅ 1,000 BTU/hr per lb/hr of evaporating water]. Since cooling coils are sensitive to temperature, chillBooster gives a first advantage by the evaporative cooling of the air, that may boost the rejected heat by up to 20%[2]. An additional increase of the heat rejection comes from the evaporation of the water deposited on the coils, as explained hereafter.
2. Water drops not evaporated in air deposit on the fins of the coils and, immediately, water starts to evaporate into the air streaming through the coils. This **evaporation** is forced **by** the so-called **mass convection**[3]:
   a. As long as the air in the stream is not saturated at the temperature of the water on the fins, it will continuously absorb and bring away (mass convection) the vapour that is always present on the surface of the water present on the fins;

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[1] *The drops generated by any water atomizer are different from each other both in shape and dimensions. However, in order to make the study of their effects on the air simple, drops are idealized as spheres all having the same diameter: this is the so-called **Sauter diameter**. The Sauter diameter is calculated as the ratio between the total mass of all drops, M, and their total surface, S:* $d = \frac{6}{\rho} \times \frac{M}{S}$ *(ρ is the water density approximately equal to 1,000 kg/m^3 or 62.43 lbs/ft^3).*

[2] *The evaporative cooling of air continues also through the coils thanks to the carried-over drops. As a rule of thumb, an increment of 1* $g_{water}/kg_{dry\ air}$ *(7* $gr_{water}/lbs_{dry\ air}$*) by evaporative cooling generates a cooling effect of approx. -2.5 °C (-4.5 °F). Note that such decrement, only apparently small, may boost the reject heat by up to 20%. It is also important to point out that the actual temperature drop depends on the conditions of the outdoor air, the sprayed water flow and the distance between the nozzles and the coils; moreover, the real rejection enhancement depends also on the characteristics of the equipment.*

[3] *Refer to Appendix A for basic information on mass convection*

b. As a consequence, new water will evaporate to replace the vapour "stolen" from its surface and …

c. … the whole process will continue as long as there is water on the coils (loop to a)

Evaporation is a change of phase from liquid to vapour: it occurs by absorbing heat mainly from the coils, where water is deposited [approx. 700 W per L/h of evaporating water, 1,000 (BTU/hr)/(lb/hr)], and in a much smaller amount (actually, negligible) from the air stream. The heat absorbed by the evaporating water greatly increases the heat rejection, *as if the coils were operating with dry coils and the outdoor air were even 5-10 °C (9-18 °F) colder*. This way the heat rejection may further increase by 40% or more! It is worth pointing out that the total length of the fins along the air-stream direction plays an important role in the evaporation rate and in the evaporative-cooling effect: *given a certain area for the coils' exposed surface to the air, it is not worth having too long fins, since the overall evaporation (i.e., the evaporative cooling) does not increase significantly beyond a certain value of the lenght along the air-stream direction*. This concept is better explained in section 3.1.1.1 below.

3. Finally, the water not evaporated from the coils drips. chillBooster-like systems are usually oversized so that some water will always flush the coils to reduce the build-up of minerals. This is particularly important when spraying mains water because it may have a significant content of minerals (read also sect. 3.2). Note that the dripping water draws some heat but has a negligible effect on the total heat rejection compared to that guaranteed by the evaporation from the coil

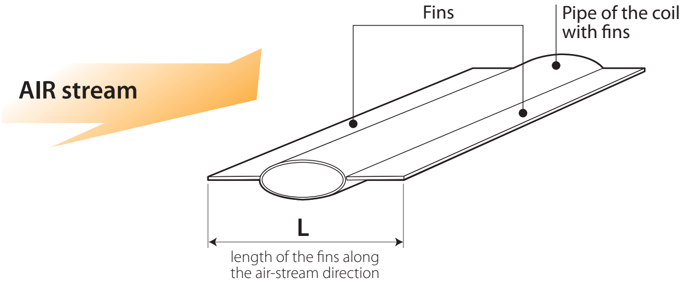
The three phenomena above increase the heat rejected by the chiller even by 40% or more depending on the following parameters:

- **Amount of water sprayed over the coils**
- **Outdoor air conditions**
- **Coils' characteristics that affect the evaporation. These are:**
  - **Design conditions: outdoor air temperature, refrigerant temperature, rejected heat, coils' total exposed surface to the air stream, length of the fins along the air direction, fins' efficiency**
  - **No. of coils**
  - **Total actual air flow through the coils**
  - **Percentage of the exposed surface wet by the sprayed water**
  - **Actual temperature of the fluid flowing inside the coils**

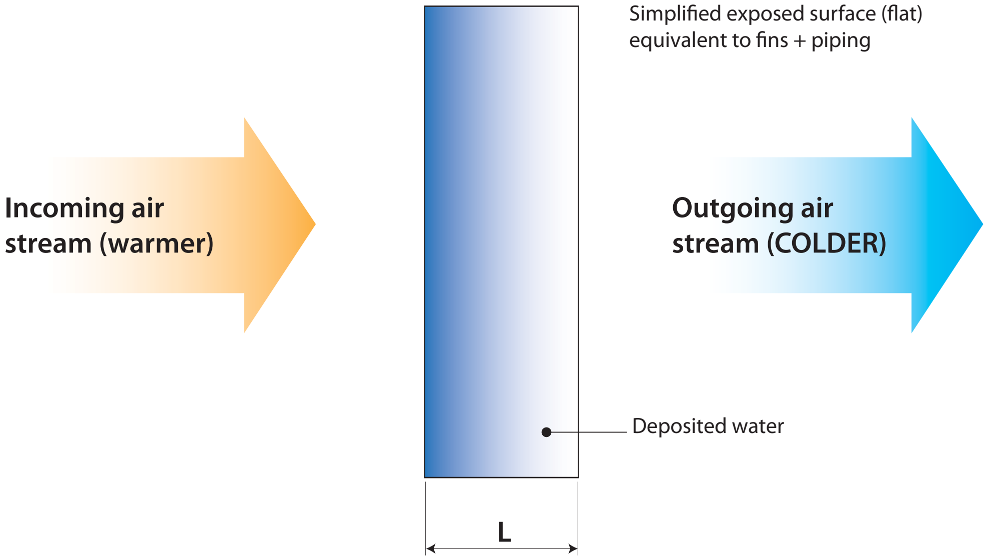
The enhancement of the heat rejection is equivalent to operating the equipment with dry coils and outdoor air even 5-10 °C (9-18 °F) colder than the actual temperature.

3.1.1.1 Fins need not be too long for a strong evaporative-cooling effect

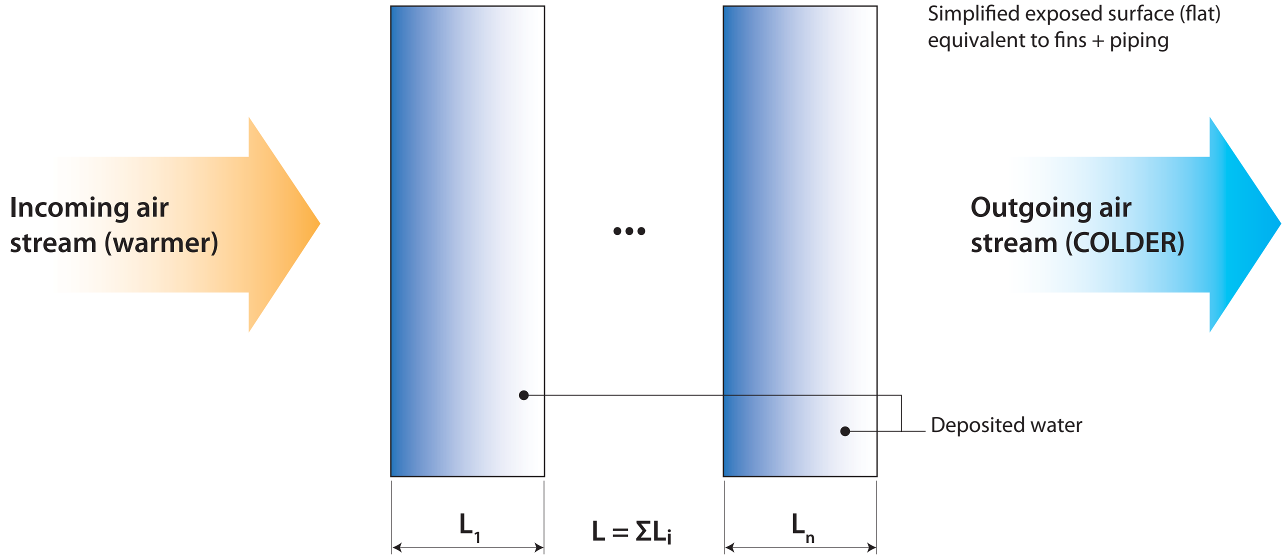
Tubes in the coils usually have fins to increase the exchange surface with the air:



The exchange surface is composed by that of the fins plus the outer surface of the coils' piping. It is curved, however, for sake of simplicity, the exchange surface can be approximated as a flat surface with extension (L) equal to the piping diameter plus the length of the fins along the air direction: L is hereafter called "total length of the fins along the air direction".



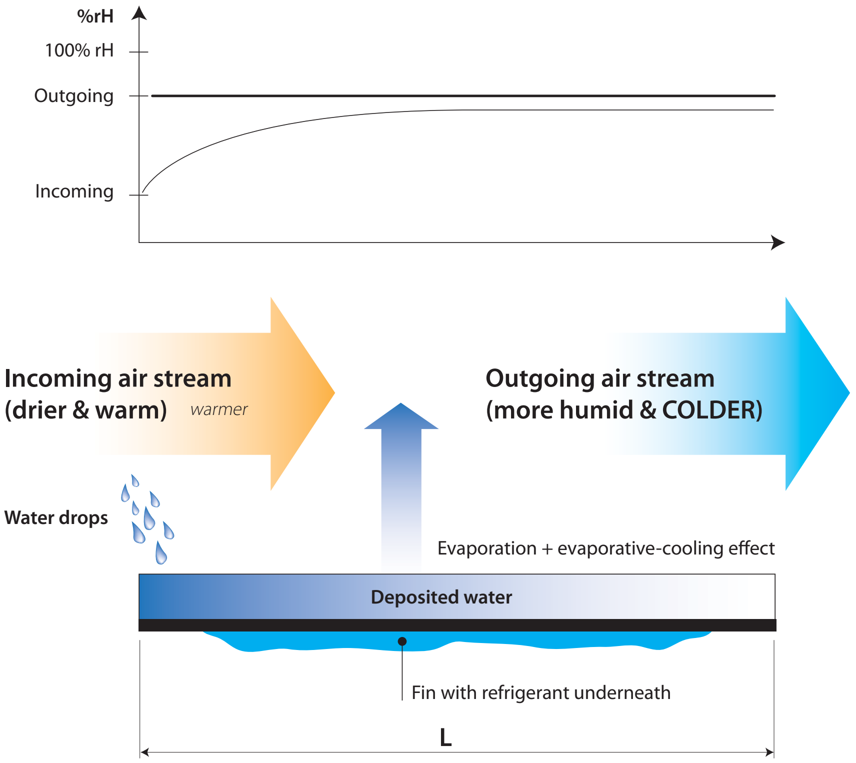
L, the total length of the fins, is the sum of the lengths of the fins in case there are coils one after the other along the air direction:



The air stream absorbs moisture from the evaporating water, hence increasing its humidity. The increment of humidity is not constant across length L because the more humid the air the less additional moisture it takes on: this means that the rate at which the relative humidity of the air grows decreases across length L. With reference to the following drawing, the inlet air, being "dry", is prone to absorb more moisture than the air at the end of length L (right-hand side of the drawing) because it is more humid down there having already absorbed moisture while flowing over the fins. This explains why the %rh curve becomes flatter towards the end of length L.

4. The logical consequence is that having long fins is not really worthwhile, since part of the deposited water might drip from the coils instead of evaporating. Instead, lenght-calibrated fins guarantee a bigger evaporation of the water (less will drip from the coils) and, consequently, a stronger evaporative-cooling effect.

It would be desirable to have optimally short fins and, consequently, very long piping. However, given a certain value of the exposed surface, which is a characteristic of the equipment, the shorter the fins the longer the whole piping of the coils should be; and it is also understandable that the length of the piping is also constrained by the equipment's dimensions. In other words, each equipment comes with what can be assumed to be the right compromises among all of its characteristics, piping and fins included.



3.1.2 Main parts of chillBooster

The components of a chillBooster system are depicted in the following pictures:

CABINET

Models available (refer to CAREL's literature for the available combinations):

- 100 L/h, 500 L/h and 1,000 L/h (634 GPD, 3170 GPD and 6340 GDP); 0.3 kW, 0.5 kW and 0.6 kW
- 230 VAC 50 Hz or 230 VAC 60 Hz
- With cabinet (shown above) or open-skid for wall-installation (not shown)
- With/without UV lamp
- For mains water above 30 μS/cm or demineralised water (≤30 μS/cm). In the former case, some components in contact with water are made of brass, whereas in the latter all parts in contact with water are made of AISI 304 stainless steel. You can read more on the supply water in sect. 3.2.

Description:

- Each cabinet has a vane pump (ref. 1: blue motor with pump at right) that pressurizes the water at around 10 bar (145 PSI) towards the fogging nozzles. The duty of the pump, hence of the whole chillBooster, is on/off upon a call from an external dry contact (also known as potential-free or relay-type): the control panel (ref. 2) starts/stops the pump according to the dry contact.
- Supply water enters through a solenoid fill valve (ref. 3) and a pressure controller with strainer (ref. 4) towards the pump. A minimum-pressure switch (ref. 5) stops the pump to avoid air-lock when the supply pressure is below 3 bar (40 PSI).
- If the optional UV lamp (ref. 6) is included, water will be sanitized by the lamp before being sprayed. The UV lamp's panel has a timer which alerts when maintenance is due (the panel is shown above the lamp, on the left). The drain valve at its bottom (with the blue cock) must be manually opened for drain before any long stop.
- Water may be by-passed inside the pump via the by-pass valve (ref. 7): the by-pass valve protects the pump and the piping downstream in case of potential over-pressure conditions above 10 bar.
- In case the operational conditions recommended in the manual are not respected, the by-pass flow may increase up to the point that the temperature of the water being by-passed becomes higher than 56°C/133°F. In such a circumstance, the thermostatic valve (ref. 8 with the red cap) opens to discharge a small amount of warm water: this will be automatically replaced by fresh supply water thus decreasing the water temperature, and the thermostatic valve will close.
- All cabinets have a solenoid drain valve (ref. 9) to drain as much water as possible when chillBooster is stopped; it makes the pair with the solenoid drain valve at the end of the nozzles-carrying pipes in case this is ordered (the end-of-line drain valve is an option; read more below).
- The cabinet also has inlet and outlet pressure gauges for commissioning and servicing.

A 5-μm water filter before the chillBooster is recommended to stop debris. A water tap before the chillBooster is also recommended for servicing.

AISI 304 STAINLESS-STEEL HOSES

They connect the cabinet to the pipes carrying the nozzles and can be also used to connect nozzles-carrying pipes. Being made of stainless steel, they are suitable for outdoor installation.

These hoses are available in different diameters and lengths:

- Diameter ½":
  - 0.4 m (16 in) with G½"F nut on both ends
  - 0.5 m (20 in) with G½"F nut on both ends
  - 1 m long (3.3 ft) with G½"F nut on both ends
  - 2 m long (6.6 ft) with G½"F nut on both ends
  - 10 m long (33 ft) with G½"F nut on both ends
- Diameter ¾":
  - 1 m long (3.3 ft) with G¾"F nut on both ends
  - 2 m long (6.6 ft) with G¾"F nut on both ends

NOZZLES-CARRYING UNTHREADED AISI 304 PIPES

Different lengths are available to suit the installation requirements and fit into the available installation space:

- 1.05 m (41.34 in) for 7 nozzles
- 1.96 m (77.17 in) for 13 nozzles
- 2.87 m (112.99 in) for 19 nozzles

All pipes' outer diameter is 20 mm (0.79 in). The holes are flow-drilled so that no residues are left inside the pipes or the holes themselves. Being made of stainless steel, they are suitable for outdoor installation without ageing problems or deterioration due to UV rays.

NOZZLES & CAPS

There are 3 available nozzles according to the water flow at 10 bar (145 PSI):

- Red: 5 L/h (31.1 GPD). This is available off the shelf.
- White/cream: 7.5 L/h (47.6 GPD)
- Black: 15 L/h (95.1 GPD)

The model is chosen as the best compromise between the required water flow and the available installation space (smaller space leads to bigger nozzles in order to have the same water flow and vice-versa).
All nozzles are made of acetylic resin and have a steel strainer inside (not replaceable). They are suitable for outdoor installation without ageing problems or deterioration due to UV rays.

Caps are used to close the unused holes according to the required water flow.

COMPRESSION FITTINGS FOR THE NOZZLES-CARRYING UNTHREADED AISI 304 PIPES

They are suitable for outdoor installation without ageing problems or deterioration due to UV rays.

END-OF-LINE SOLENOID DRAIN VALVES

The end-of-line solenoid drain valve is maintained opened by the cabinet while chillBooster is stopped so as to drain as much water as possible from the piping.

The models available are:

- Made of brass, for supply water above 30 µS/cm
- Made of AISI 304 stainless steel, for any type of supply water

Both are suitable for outdoor installation any type of without ageing problems or deterioration due to UV rays.

GASKETS AND FITTINGS

Both ½" and ¾" fittings are available to fit all hoses and pipes as well as the optional end-of-line drain valve. All are suitable for outdoor installation.

3.2 Supply water quality

Supply water for chillBooster can be either mains water or demineralised water. The distinction between the two types of water is as follows:

- Mains water: conductivity > 30 µS/cm. Brass components can be used
- Demineralised water: conductivity ≤ 30 µS/cm. AISI 304 stainless-steel components are recommended, because brass would be eaten away

It is important to point out that softened water is NOT demineralised water. In fact, demineralised water has part or all of its minerals removed by treatments like reverse osmosis, de-ionization and alike; instead, softened water is obtained from mains water by replacing its calcium and magnesium salts with sodium salts, so its mineral content remains unchanged or may even increase.

The following tables describes the advantages and disadvantages of the two types of water:

	MAINS WATER (conductivity > 30 µS/cm)	DEMINERALISED WATER (conductivity ≤ 30 µS/cm)
Availability and cost of the supply water	Mains water is readily available, so it's cheaper than demineralised water because this is produced through a dedicated treatment (demineralization) of the mains water.	Brass components should not be used because brass is deteriorated by demineralised water. Instead, AISI 304 (min) components have to be used with demineralised water. Demineralised water is more expensive because minerals are removed from mains water by dedicated filtering techniques (reverse osmosis, de-ionization beds, etc.)
	The cost of the supply water is purely the cost of the mains water, c_{mains}	Each of these techniques involves the waste of some water to drain the removed minerals away: the flow of drained water depends on the used technique and mains water quality, but may range from 50% to 80% of the mains water inlet flow. The remaining part is the usable demineralised water (20% to 50%, known as recovery factor, f_r). Consequently, the cost of the demineralised water becomes higher than that of the mains water and can be estimated by the following ratio: $c_r = \frac{c_{mains}}{f_r}$ in currency/unit of volume of sprayed water. Another cost item is the cost of the energy used by the treatment system per unit of sprayed water volume, c_{energy}. Also the additional cost of the maintenance of the demineralising system should be taken into account. It includes the costs of membranes to change, carbon filters to replace, mechanical filters to substitute, maintenance of the internal softener plus the costs of eventual spare parts and the labour cost of servicing. All these expenses should be related to the volume of treated water over a certain period (e.g., 1 year, 6 months) and summed to c_r and c_{energy} to get the overall cost of demineralised water in currency/unit of volume of sprayed water: $c_{demin} = \frac{c_{mains}}{f_r} + c_{energy} + \left.\frac{\text{maintenance costs}}{\text{volume of sprayed water}}\right\|_{\text{across the same period}}$
Minerals sprayed	Almost all minerals contained in the sprayed water deposit. This is particular detrimental with high-mineral-content waters sprayed on coils, that would see the build-up of mineral deposits, thus reducing the overall rejection efficiency. The consequence is more energy consumption, more maintenance to keep the coils clean and, anyway, the need of using more water than necessary to flush as much minerals as possible away from the coils. In regards of the cleaning of coils, some makers of chillers advice that coils might need to be cleaned every 200 hrs if mains water is sprayed onto them.	Demineralised water carries less minerals so the deposits will be reduced, if not negligible. This is advantageous for reducing the energy used by the equipment and the costs of removing the minerals. Some makers of chillers advice that coils might need to be cleaned every 900 hrs if demineralised water is sprayed onto them. The other side of the coin is that demineralised water is as more aggressive as less minerals it has. Therefore, coils need being made of resistant material or coated by a protective layer in order to stand the aggressiveness of demineralised water. This translates in a higher purchase cost of the equipment.
Components	Brass components can be used, leading to a lower price for the whole chillBooster system.	AISI 304 stainless-steel components are recommended, because brass may be quickly eaten away by demineralised water. This leads to a higher price for the whole chillBooster system.

3.3 Installation of chillBooster onto a chiller

The installation is very straightforward because no special expedients or skills are required for setting up the water distribution piping; additionally, the available set of fittings suits almost all the installation constraints that can be found on the field. Standard support bars, screws and nuts for the hoses and pipes may need to be sourced locally.

These are pictures of a real installation:

Standard support bars, screws and alike can be sourced locally

Nozzles-carrying pipes, nozzles, fittings and gaskets are supplied by CAREL.

Exclusively standard tools are required

Examples of real installations on a dry cooler (left) and a chiller (right):

3.4 Maintenance of a chillBooster system

Maintenance of a chillBooster system is easy and simple:

REFERENCE	Components	Frequency	Activities
(not shown)	Nozzles	Annual or in case they do not spray water	Check the conditions; eventually clean/replace
(not shown)	Water filter before chillBooster's cabinet	Annual	Check and clean/replace
4	Water filter inside chillBooster's cabinet	Annual	Check and clean/replace
(not shown)	Water connections inside and outside chillBooster's cabinet	At seasonal restarts or in case spraying is low and the pump is ok	Check for leaks and correct
6	UV lamp (if present)	Monthly	Check the red led on the lamp's panel: if ON, replace the lamp. ON = lamp exhausted. The red led is activated by the lamp's timer to alert the user.
		Every 5,000-7,500 hrs	It is usually time to replace the lamp if the red led on the lamp's panel is ON.
1	Pump	Whenever the outlet pressure does not reach 10 bar, even after adjusting the by-pass valve (ref. 7) AND there are no leaks downstream of the pump.	There is no preventive maintenance for the pump: it runs until it has to be replaced. A pump needs to be replaced when the outlet pressure does not reach 10 bar even after adjusting the by-pass valve (ref. 7), with no leaks downstream of the pump.

4. CONVENIENCE OF CHILLBOOSTER AS BOOSTER OF EXISTING CHILLERS AND SIMILAR EQUIPMENTS

IMPORTANT: The estimation method hereafter described can also be used for any water sprayers whose drops have a Sauter diameter greater than or equal to 10-15 µm, i.e. starting from humiFog.

This section covers the following topics:

1. Why and in which conditions is chillBooster convenient?
2. How much is it convenient?

4.1 Why and in which conditions is chillBooster convenient?

As explained in sect. 3.1.1, water evaporation from coils increases the heat rejected by the chiller or condenser even by 30% or more.
Water evaporation occurs by mass convection thanks to the air stream flowing over the water layer deposited on the fins: as long as the air in the stream is not saturated at the temperature of the water on the fins, it will continuously absorb and bring away (mass convection) the vapour that is always present on the surface of the water layer; as a consequence, new water will evaporate to replace the vapour "stolen" from its surface and the whole process will continue as long as there is water on the fins.

The interesting point is that the evaporation from the water layer is continuous and spontaneous <u>if the partial pressure of vapour in the air stream is lower than that of the water layer</u>. The partial pressure of vapour is a measure of the amount of vapour present in the fluid (either air or water): the higher the amount of vapour the higher its partial pressure, and vice versa. The idea that the amount of vapour generates a pressure helps to understand why the vapour moves spontaneously from the water to the air, causing water to evaporate: in fact, like gases, vapour diffuses spontaneously from locations with higher (vapour) pressure to locations with lower (vapour) pressure, until the pressures equalize. For this reason, since vapour pressure is usually higher over the water layer than in the air stream, vapour spontaneously transits towards the air stream, and this process continues as long as the incoming air has a vapour pressure lower than the water layer's.

So, everything works as long as the incoming air has a vapour pressure lower than the water layer's.
Now the question is: are there cases when the air's vapour pressure is higher than the water layer's? Yes, there are, and in those cases water will not evaporate. Luckily enough, these cases are rare.

The vapour pressure of the water layer depends on the water temperature: it increases when temperature increases, and vice versa[1]. The sprayed water absorbs heat from the coils, because these are usually warmer; an additional contribution comes from the incoming air if this is warmer than the sprayed water. These contributions warm the water up, so that temperatures close to those of the refrigerant are usual for the deposited water (e.g., 20 °C to 35 °C / 68 °F to 95 °F).
The second heat gain, that from the incoming air, is particular interesting: the warmer the air the warmer the water tends to be. This is extremely important in tropical areas, where the high humidity would mistakenly lead to the conclusion that the evaporation cannot take place: in fact, it does, because the high air temperature may increase that of the deposited water, hence its vapour pressure, thus sustaining the evaporation. One consequence is that, in some conditions, fog forms downstream of the fans when the amount of evaporated water exceeds the saturation of the outdoor air, i.e. mass convection may force the evaporation of more water than the air can carry just because this is "forced" evaporation, not "natural" (this is a similar fog that can be seen at the discharge of cooling towers).

Even in hot and humid climates (e.g., Tropics), chillBooster may be beneficial for chillers and alike.

4.2 How much is chillBooster convenient?

The estimation method described in the following can be used to see whether the application of a water sprayer like chillBooster can help the chiller to overcome peaks of cooling demand.
The estimated evaporative-cooling power can be seen as the additional heat rejected by the coils <u>on top</u> of that rejected when they are fully dry. For instance, when they are fully dry, the rejected heat = 100 kW; by spraying 150 L/h of water the evaporative-cooling power = 90 kW, so the total rejected heat becomes approximately equal to 190 kW. In case the total rejected heat estimated this way (190 kW in the example above) is higher than what actually needed (e.g., 180 kW), the difference (10 kW) generates a reduction of the electric energy used by the chiller.
The overall method is not exactly precise, but can be used as a quick assessment of whether or not the chillBooster is of any help for the chiller. More precise estimations can be made by CAREL.

The estimation of the convenience proceeds in 4 phases:

1. Assessment of whether or not the evaporation can occur
2. If it does, the estimation of the cooling power generated by the evaporating water follows
3. Sizing of the chillBooster system
4. Finally, the convenience (i.e., break-even point) of using chillBooster is estimated

The following sections explain them all.

4.2.1 Limit of the estimation method

- The method described hereafter yields approximated estimations due to the simplified way they are made: the error may be as much as ±20%. The results should not be used as supporting data for projects: for more precise estimates, please, refer to CAREL
- The method ***<u>estimates</u>*** only the evaporative-cooling power given by the evaporation of water both in the air and from the coils
- The method does NOT take into account the heat drawn by the water dripping from the coils, if any, and the heat rejected by the dry parts of the coils, if any
- This means that the evaporative-cooling power estimated by this method is a figure of how much heat can be rejected thanks to water evaporation; instead, it is NOT the total heat rejected by the coils because that given by the dry parts and the dripping water is not included. Ask CAREL for a comprehensive estimation that includes these missing parts

4.2.2 Data required for the estimation of the convenience

The data required for the assessment of the convenience are:

- Outdoor air conditions. IMPORTANT: the humidity ratio has to be expressed in kg_w/kg_{da} or lbs_w/lb_{da}
- Condenser or dry cooler:
  - Temperature of the refrigerant fluid inside the coils (°C). This can be found from its data sheet or by asking the maker
  - Total width and height (W_{coils} , H_{coils}) of the coils (m). Refer to the equipment's data sheet or ask the maker.
  - Air speed through the coils, v_{air} (m/s). Refer to the equipment's data sheet or ask the maker
  - Total exposed surface to the air, A (m^2). This is the contact surface between the air and the piping of the coils; it can be found from the equipment's data sheet or by asking the maker (it is of the order of hundreds or thousands of m^2; thousands or tens of thousands of ft^2)
  - <u>Total</u> length of the fins <u>along the air direction</u>, L (mm)

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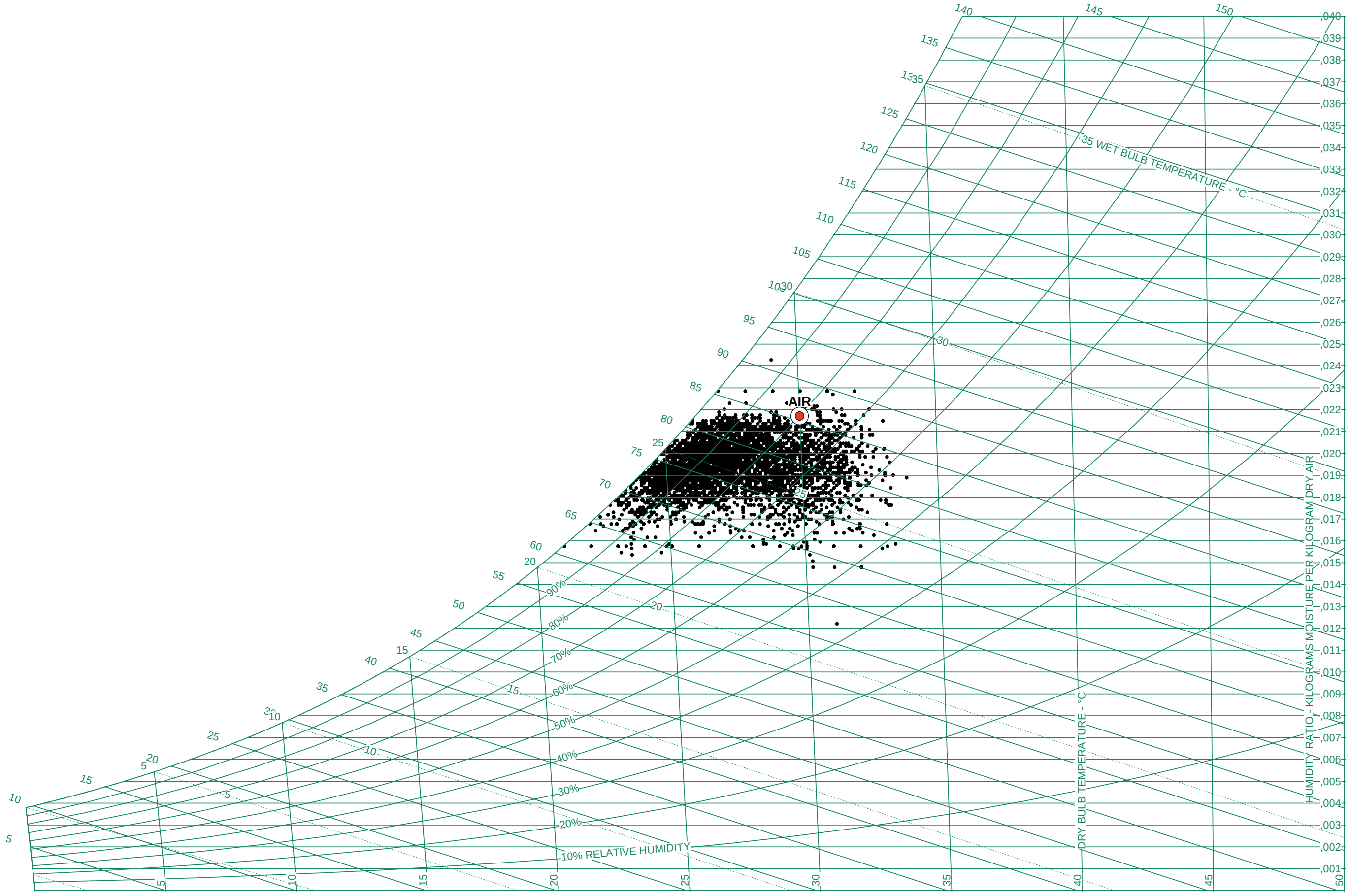
[1] *The relationship is totally non-linear*

4.2.3 1st phase - Manual procedure for assessing the evaporation

The manual (approximate) procedure for assessing whether evaporation takes place involves the use of the humidity ratio. This expresses the amount of moisture present in the air as mass of vapour, in kg, per kg of dry air and is 1:1 related to the partial vapour pressure of the air. The advantage of using the humidity ratio is that it is on the vertical axis of the psychrometric chart, so the psychrometric chart can show both the conditions of the outdoor air and whether water can evaporate from the coils.
The assessment of whether the deposited water evaporates from the coils is as follows:

1. Find the outdoor air conditions on the psychrometric chart. Let W_{air} be its humidity ratio. Example: Singapore 30 °C (86 °F), 80 %rh, W_{air} = 0.022 kg_w/kg_{da} (0.022 lbs_w/lb_{da})



2. Find the temperature of the fluid inside the chiller or condenser from its data sheet or by asking the maker. Example: 36 °C (97 °F)

3. Estimate the deposited water temperature as the arithmetic mean of the temperatures of the coils (assumed equal to the refrigerant's temperature) and that of the outdoor air decreased by 2 °C – 4 °F due to the evaporative cooling[2]. Example: 32 °C (90 °F) = [(30-2) + 36] / 2, (this is in °C)

4. Enter the psychrometric chart with the deposited water temperature just estimated up to the saturation line and find the corresponding humidity ratio above the water layer, $W_{water\ layer}$ (it is assumed that air right above the water layer is saturated at the temperature of the water layer itself). The red line shows how to find this humidity ratio starting from the water temperature. Example: 0.031 kg_w/kg_{da} (0.031 lbs_w/lb_{da})

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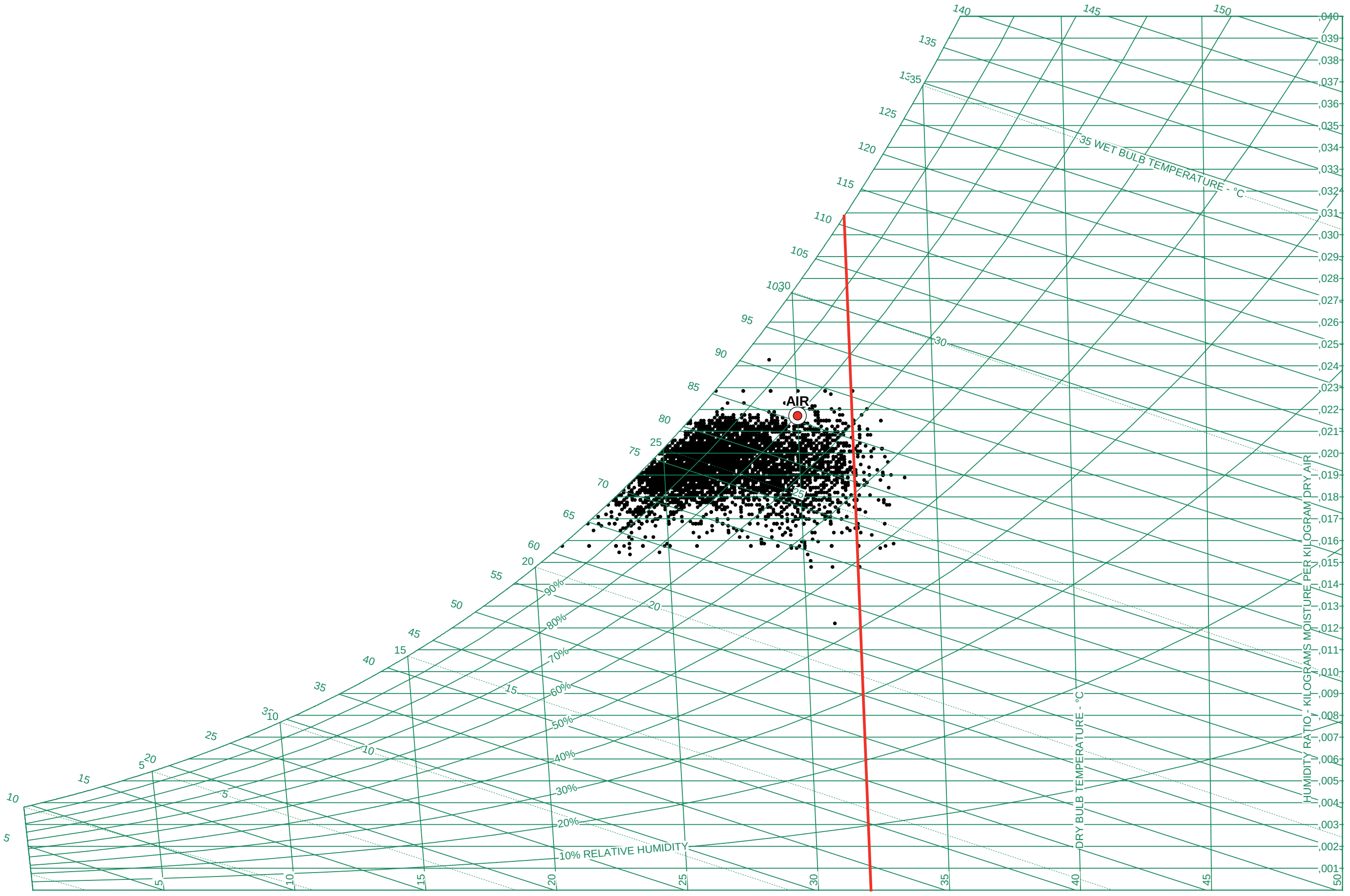
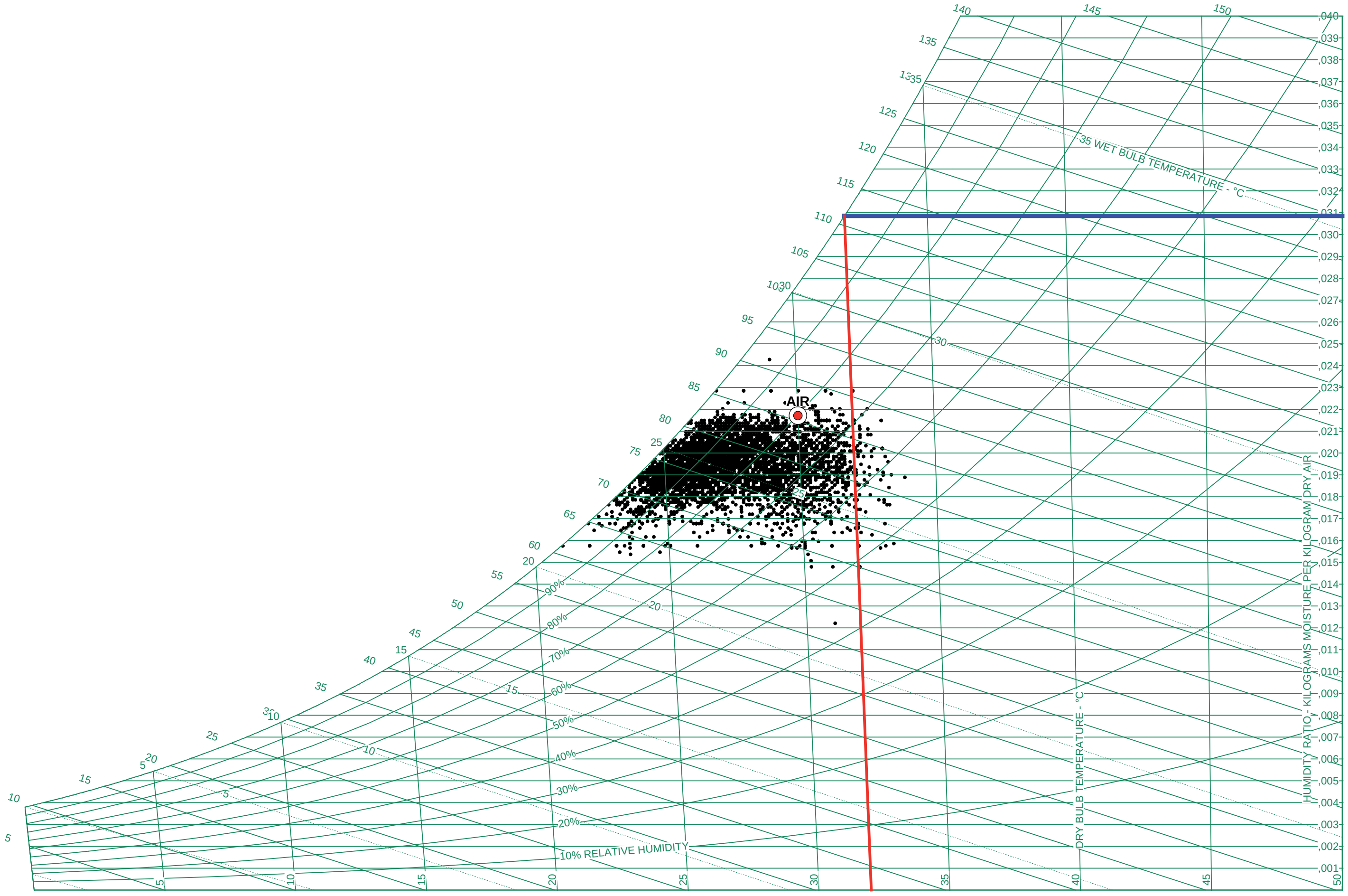
[2] 2 °C (4 °F) is an average value. The real one depends on the outdoor air conditions, air flow and sprayed water flow. Ask CAREL for more precise estimates.



5. Draw a horizontal line at the humidity ratio just found (in blue)



6. If the outdoor air is below the line, then evaporation will take place, so you can proceed to the estimation of the cooling power generated by the water evaporation (2nd phase); otherwise it will not start. In the example, even in the hot and humid Singapore chillBooster would be beneficial.

4.2.4 2nd phase - Estimation of the evap.-cooling power

The estimation of the evaporative-cooling power can be done only in case the humidity ratio above the water layer is higher than the humidity ratio of the outdoor air (i.e., in case the blue line is above the outdoor air's representative point in steps 5 & 6 above).

The estimation of the evaporative-cooling power is based on two main steps:

- Estimation of the maximum possibile evaporation rate from the coils
- Estimation of the evaporative-cooling power based on the real sprayed water flow rate

Consider that if the sprayed water flow is higher than the maximum evaporation rate, part of the sprayed water will drip from the coils. Since this method does not take into account the heat removed by the dripping water, the real sprayed water flow rate should be less than or equal to the maximum evaporation rate, otherwise the estimated evaporative-cooling power might be affected by larger approximation errors. Obviously, when the real sprayed water flow rate is less than the maximum evaporation rate, part of the coils will remain dry. The method does not estimate the heat rejected by the dry parts: it only estimates the heat rejected thanks to water evaporation by the wet parts. The evaporative-cooling value given by the method can be ***thought of*** as the additional heat rejected by the coils thanks to the evaporation of water: this additional heat sums up to that rejected by fully dry coils to give the overall heat rejection. As already stated, although this is not precise, it is a simple manual method for understanding how much more heat can be rejected by a cooling-coiled system thanks to the evaporation of sprayed water. CAREL can make more precise and comprehensive estimates if needed.

Proceed as follows (refer to Appendix A for more information on steps 7-9; formulas in steps 7-18 are valid in the SI system only):

7. Calculate the Reynolds number of the air stream over the water: $Re_f \cong 60 \times v_{air} \times L$
   - v_{air} is the air speed in m/s
   - L is the length of the fins along the air direction, in mm

   Example with v_{air} = 2 m/s and L = 30 mm: $Re_f \cong 60 \times 2 \times 30 = 3{,}600$

8. Calculate the Sherwood number of the limit layer:

$$Sh_f \cong \begin{cases} 4.3\times\sqrt{(v_{air}\times L)} \Leftarrow Re_f \le 500{,}000 \text{ (laminar flow over the fins)} \\ 0.8\times(v_{air}\times L)^{4/5} \Leftarrow Re_f > 500{,}000 \text{ (turbulent flow over the fins)} \end{cases}$$

   - v_{air} is the air speed in m/s
   - L is the length of the fins along the air direction, in mm

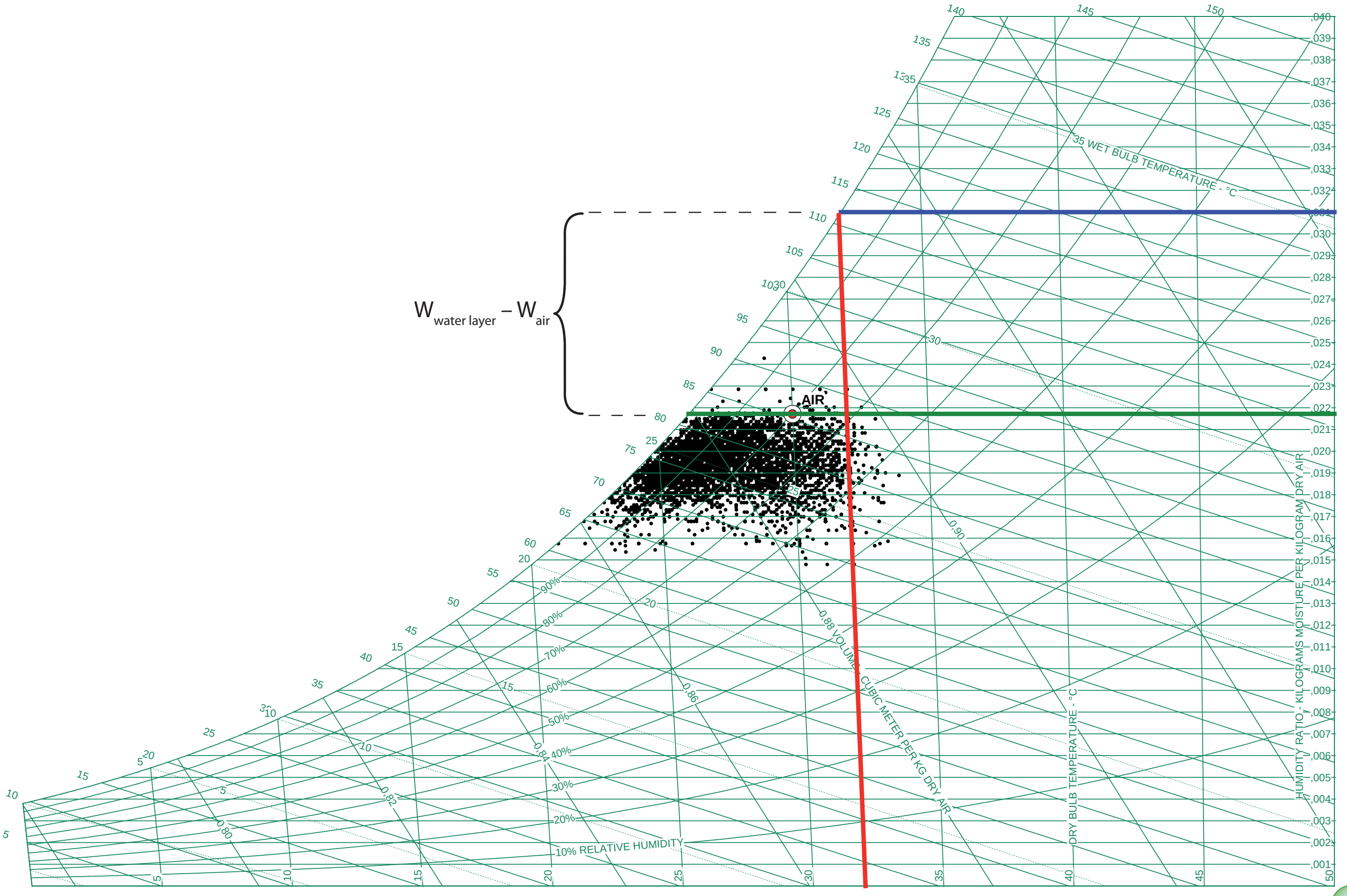
   Example with v_{air} = 2 m/s and L = 30 mm:
   - $Re_f \cong 3{,}600$ from above, so the air flow is laminar over the fins
   - $Sh_f \cong 4.3\times\sqrt{(v_{air}\times L)} = 4.3\times\sqrt{(2\times 30)} = 4.3\times\sqrt{60} \cong 4.3\times 7.7 \cong 33.1$

9. Calculate the mass convection coefficient in m/s: $h_M \cong \dfrac{0.03\times Sh_f}{L}$
   - L is the length of the fins along the air direction, in mm

   Example with v_{air} = 2 m/s and L = 30 mm $h_M \cong \dfrac{0.03\times Sh_f}{L} \cong \dfrac{0.03\times 33.1}{30} \cong 0.03$ m/s

10. Use the total exposed surface of the coils to the air, A, in m². This can be found from the data sheet of the equipment or can be asked for to the maker. Example: A = 1,000 m²

11. Calculate the difference $W_{water\ layer} - W_{air}$
    IMPORTANT: respect this order of the terms in the difference! This must be positive if in step 5 the humidity ratio above the water layer has been proved to be higher than that of the outdoor air.
    Example: $W_{water\ layer} - W_{air} = 0.031 - 0.022 = 0.009$ kg_w/kg_{da} (0.009 lbs_w/lb_{da})



12. Calculate the **maximum evaporation rate in kg/h**:

$$R_{\max} \cong 4{,}320 \times h_M \times A \times \left(W_{water,layer} - W_{air}\right)$$

Example:

$R_{\max} \cong 4{,}320 \times h_M \times A \times \left(W_{water,layer} - W_{air}\right) \cong 4{,}320 \times 0.03 \times 1{,}000 \times 0.009 \cong 1{,}166$ kg/h

13. If the sprayed water flow is less than R_{max} then all the sprayed water will evaporate, otherwise part of it will drip from the coils. This method does not allow to estimate the additional heat rejected when water drips from the coils, so in case the sprayed water flow is grater than R_{max} the following estimates may be approximated per defect (refer to CAREL for more prices values).

14. Set the **evaporation rate** $R_{evaporation}$ **from the coils** as follows (in kg/h):

$$R_{evaporation}: \begin{cases} \text{sprayed water} \le R_{\max} \Rightarrow R_{evaporation} = \text{sprayed water} \\ \text{sprayed water} > R_{\max} \Rightarrow R_{evaporation} = R_{\max} \end{cases}$$

IMPORTANT: the sprayed water flow MUST be expressed in kg/h

Example 1: sprayed water = 130 kg/h ➔ sprayed water ≤ R_{max} = 1,166 kg/h ➔ $R_{evaporation}$ = 130 kg/h
Example 2: sprayed water = 1,200 kg/h ➔ sprayed water > R_{max} = 1,166 kg/h ➔ $R_{evaporation}$ = 1,166 kg/h

15. Calculate the **estimated evaporative-cooling power in kW**:

$P_{evap.cooling} \cong 0.7 \times R_{evaporation}$ 0.7 is the latent power of evaporation, in kW, of 1 kg/h of evaporating water

Example 1: $P_{evap.cooling} \cong 0.7 \times R_{evaporation} \cong 0.7 \times 130 \cong 91$ kW

Example 2: $P_{evap.cooling} \cong 0.7 \times R_{evaporation} \cong 0.7 \times 1{,}166 \cong 816$ kW. This may be approximated per defect because it does not take into account the heat drawn by the dripping water.

16. At this point the heat rejected thanks to the evaporative cooling has been estimated

17. When the sprayed water flow is less than the maximum evaporation rate, its value can be added the heat rejected by fully dry coils to understand what is the total heat rejected by the chiller.
Examples:
    - Heat rejected by fully dry coils = 10 kW; evaporative-cooling power = 91 kW ➔ total rejected heat = 10 + 91 = 101 kW
    - Heat rejected by fully dry coils = -15 kW (i.e., the chiller would lock out); evaporative-cooling power = 91 kW ➔ total rejected heat = -15 + 91 = 76 kW. chillBooster allows the chiller to run, whereas it would stop without chillBooster!

18. When the sprayed water flow is equal to the maximum evaporation rate, then the total rejected heat is equal to the estimated evaporative-cooling power because the rejection is due only to the evaporation of the water. **Example:** heat rejected by fully dry coils = xxx kW; evaporative-cooling power = 816 kW → total rejected heat = 816 kW

The estimated values are not exact, however the method is quite reasonable for manual evaluation. In case more precise estimates are required, CAREL can do them.

4.2.5 3rd phase - Sizing the chillBooster system

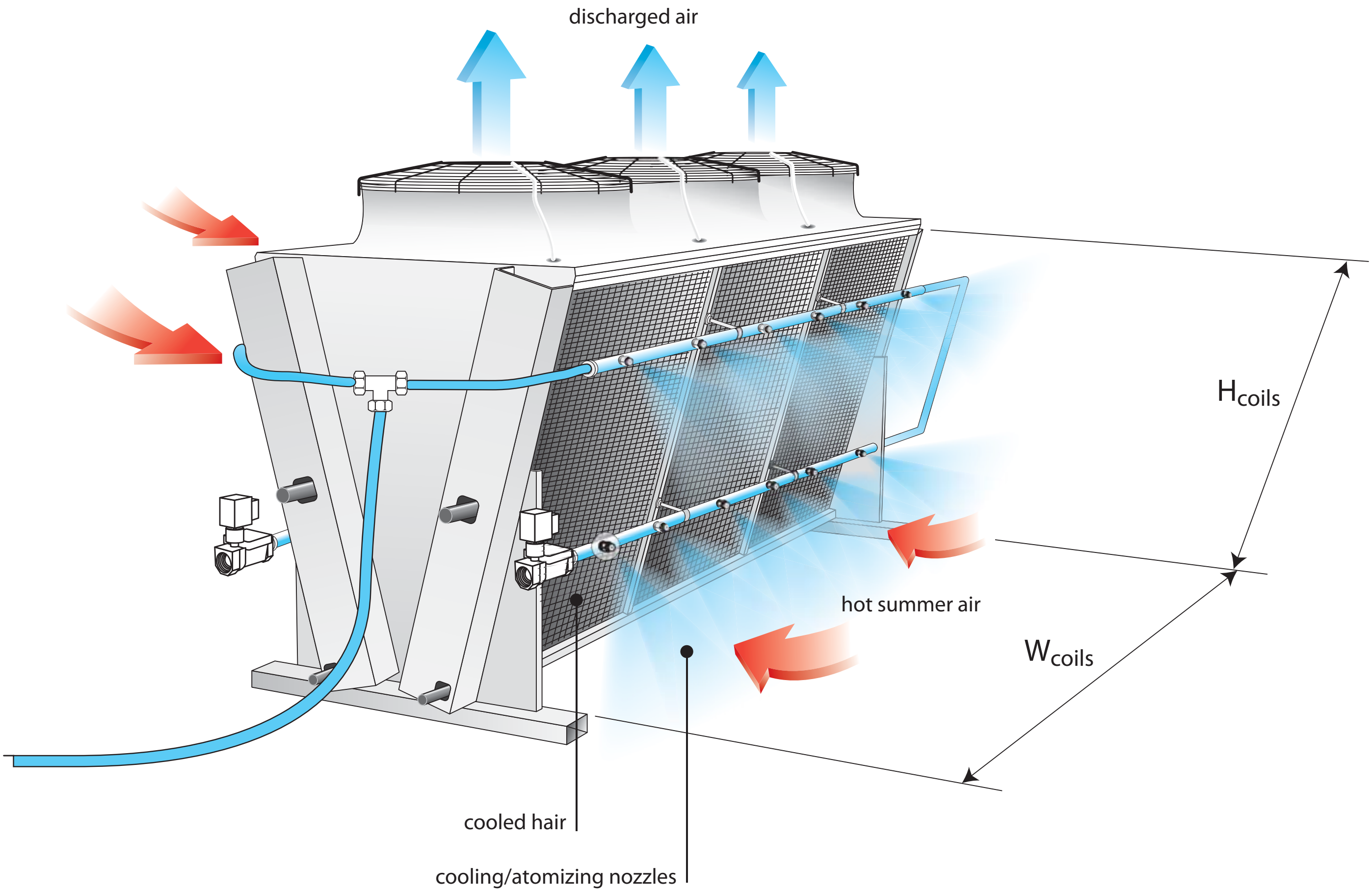
The steps for sizing a chillBooster systems are:

19. It is advisable to spray an amount of water that drips from the coils to wash away the minerals it contains: a 20% increment of R_{max} seems reasonable, although in many real cases even smaller sprayed flow rates may flush the coils. The resulting sprayed water flow, q_{water}, is the total water flow that **chillBooster has to spray: q_{water} = R_{max} + 20% (or whatever value that guarantees coils flushing).**
Note: that some minerals will anyway build up on the coils, making their periodic cleaning necessary; this can be reduced by spraying demineralised water, but care is required because demineralised water can corrode the coils (refer to sect. 3.2 for more information).
Example: q_{water} = R_{max} + 20% = 1,166 kg/h + 20% = 1,399 kg/h = 3,085 lbs/hr

20. **Bill of material of the chillBooster system:**

    IMPORTANT: the values given as examples change according to the real installation; for this reason the total list price is not calculated. Additionally, this step is informative: refer to the chillBooster manual and price list for properly sizing a chillBooster system or seek advice from CAREL.

    a. Start by defining the type of supply water, supply voltage (Vac and frequency), presence of UV lamp, closed cabinet or open-skid cabinet. **Example:** mains water, 230 VAC 50 Hz, UV lamp on board, closed cabinet.
    b. Choose the proper cabinet to guarantee at least water flow q_{water} calculated at step 19. If no cabinet is available (e.g., because q_{water} is too big), then either split q_{water} among more than 1 cabinet or choose the biggest available cabinet (the reduced sprayed water flow will generate a lower evaporative-cooling benefit). The choice between the 2 options can be made by estimating the break-even points and evaporative-cooling effects of both (do all the 4 phases described across this section 4.2 and then take a decision). **Example:** q_{water} = 562 kg/h, so we choose the 1,000-kg/h cabinet → cabinet AC100D0010 (also use the data defined in step 20.a above). Using the data of steps 14 and 15 above, $P_{evap\ cooling}$ = 0.7 x 562 = 393.4 kW
    c. Define the nozzles, nozzles-carrying pipes and caps:
        - Nozzles: the type available off the shelf is ACKNR00000 (kit with 10x 5-L/h nozzles); quantity $n_{nozzles}$ = 113 pcs. (= q_{water} / 5 = 562 / 5 = 112.4, rounded up to the closest integer = 113) è 12x ACKNR00000
        - Nozzles-carrying pipes: these hold the nozzles and must fit within the coils' dimensions. Select the longest pipe model that fits the coils' width (W_{coils}); this can handle a characteristic max. no. of nozzles (n_{max}). Then find out how many of such pipes are necessary by dividing $n_{nozzles}$ / n_{max} = n_{pipes}; they shall be installed horizontally within the coils' height (H_{coils}).
          Example:
            - W_{coils} = 3 m (9.8 ft) → longest pipe is ACKT019000 (2.87 m – 113 in) for n_{max} = 19 nozzles
            - No. of pipes n_{pipes} = $n_{nozzles}$/n_{max} = 113 / 19= 5.9 rounded to 6
            - H_{coils} 2 m (6.6 ft) → the 6 pipes shall be installed horizontally within the 2-m height, 1 every 40 cm (1.3 ft) = H_{coils} / (n_{pipes} – 1) = 2 m / (6-1)



- If the n_{pipes} pipes hold more nozzles than required, the surplus holes shall be closed by caps code ACKCAP0000: $n_{caps} = n_{pipes} \times n_{max} - n_{nozzles}$. The caps can be distributed across the pipes with no specific constraint because all pipes start/stop together.
  Example: $n_{caps} = n_{pipes} \times n_{max} - n_{nozzles} = 6 \times 19 - 113 = 1$ caps

d. Define the connections between the nozzles-carrying pipes:
  - Corrugated hoses: 1 between each pair of nozzles-carrying pipes, i.e. $n_{conn.\ hoses} = n_{pipes} - 1$. Different lengths are available, from 0.4 m (16 in) to 10 m (33 ft), so choose the best-fit one.
    Example: choose code ACKT1F0500 (0.5 m – 20 in) because the distance between pipes is 40 cm (1.3 ft); quantity: $n_{conn.\ hoses} = n_{pipes} - 1 = 6 - 1 = 5$
  - Joints between the corrugated hoses: code ACKRDM0000; quantity equal to 2 pcs. per nozzles-carrying pipe: $n_{joints} = 2 \times n_{pipes}$
    Example: code ACKRDM0000, $n_{joints} = 12$ pcs. (= 2 x 6)

e. End-of-line drain valve: the type depends on the type of supply water, mains or demineralised.
Example: code ACKRDM0000, 1 pc.

f. Connection between the cabinet and the nozzles: the type and no. of pipes/hoses depend on the location of the cabinet compared to that of the nozzles. Different pipes/hoses are available, so choose the best combination.
Example: the cabinet is installed some 8 m (26 ft) away from the coils, so corrugated hose ACKT1FA100 is chosen (10-m/33-ft long), 1 pc.

g. Gaskets: 1 gasket per joint is required (code ACKG100000 is a kit with 2 gaskets).
Example: code ACKG100000, 8 pcs. because there are 13 joints so 13 gaskets are necessary (8x ACKG100000 = 16 gaskets of which 3 are spares)

4.2.6 4th phase - Convenience of using chillBooster: break-even point

When chillBooster is added onto an equipment, there will be costs to sustain and savings to take advantage of:

1. Costs:
   - Non-recurring costs: purchase & installation of chillBooster (a)
   - Running costs:
     - Yearly cost of the sprayed supply water (w)
     - Yearly cost of the electric energy used by chillBooster (e)
     - Yearly cost of the preventive maintenance (m)
2. Yearly saving (s), granted by the electric energy (r) not used by the equipment because part of the cooling comes from the evaporation of water

chillBooster is convenient when the non-recurring costs are recovered within a reasonable time. The meaning of "reasonable" depends on the final user, but a 3-year payback time (max.) is usually considered reasonable.

The guide-lines for estimating the costs and savings above are as follows:

Parameter	Description	Comments	Equations	Example
T [hrs]	No. of hours of operation of chillBooster	A common strategy for using chillBooster consists in starting it when the outdoor temperature goes above a certain threshold (30-35 °C – 86-95 °F seems to be a common threshold). Using the climatic data of the site, it can be found for how many hours per year the outdoor temperature stays above the threshold: this number of hours is T. Refer to CAREL for the climatic data of many cities around the world		*According to the climatic data of Singapore, the dry-bulb temperature is above the threshold of 30 °C = 86 °F for T =* ***1,102 hrs/yr***
$P_{evap.\ cooling}$ [kW]	Representative evaporative-cooling power during period T	Go through phases 1 & 2 (sect.'s 4.2.3-4.2.5) to estimate $P_{evap.\ cooling}$ during period T	Refer to sect.'s 4.2.3-4.2.5	*$P_{evap.\ cooling}$ =* ***393 kW*** *from step 20.b above*

4.2.6.1 Costs

Parameter	Description	Comments	Equations	Example
Non-recurring costs				
a [currency]	Purchase & installation of chillBooster	The purchase cost depends on the model of chillBooster, piping and nozzles, so refer to the quotation made. The installation cost is site-dependent, so it has to be estimated in cooperation with the installer.	The purchase cost of the chillBooster system is determined by its bill of materials (refer to sect. 4.2.5)	5,000 EUR can be assumed to be the list price of the chillBooster system as defined in step 20 above; 300 EUR can be assumed to be the installation cost → **a = 5,300 EUR**
Recurring costs				
w [currency/yr]	Yearly cost of the supply water by chillBooster	During period T, chillBooster will spray continuously. The sprayed water-flow rate (q_{water}) is constant and equal to the sum of the nozzles' flow rates: multiply q_{water} by the water specific cost (c_{mains}) and by the time T to get the cost of water per annum (w)	$q_{water} = \sum(\text{nozzles' flow rates})$ $w = q_{water} \times T \times c_{mains}$	$q_{water} = n_{nozzles}$ x 5 = 565 kg/h = 1,245.6 lbs/hr c_{mains} = 0.80 EUR/m^3 **w** = 565 / 1,000 x 1,102 x 0.80 = **498.10 EUR/yr** q_{water} is divided by 1,000 to express it in m^3/h
e [currency/yr]	Yearly cost of the electric energy used by chillBooster	During period T, chillBooster will spray continuously, so its power consumption, P, will be constant (P depends on the model of chillBooster – refer to sect. 3.1.2 above). Multiply P by the time T and by the electric energy specific cost (c_{el}) to obtain cost of electric energy per annum	$e = P \times T \times c_{el}$	P = 0.6 kW for the chosen model AC100D0010 (step 20.b above) c_{el} = 0.20 EUR/kWh **e** = 0.6 x 1,102 x 0.20 = **132.24 EUR/yr**
m [currency/yr]	Yearly cost of the preventive maintenance	The preventive maintenance consists in checking the nozzles, cleaning the coils from minerals if mains water is used (with demineralised water the associated cost is negligible), replacing the UV lamp (if present), replacing the water filter before chillBooster. Refer to sect. 3.2 and 3.4 above for more information		Preventive maintenance consists in replacing the UV lamp. Its maximum lifetime is equal to 7,500 hrs (refer to sect. 3.4), so it will need to be replaced every 7,500 / 1,102 = 6.8 yrs. Since its list price is 180 EUR/pc. (2011 list price), the associated yearly cost of servicing is 180 / 6.8 = 27 EUR/yr → increased to 40 EUR if the labour cost is included (estimated). The cost for cleaning the coils from minerals has to be estimated, too. Assuming, like some chiller makers advice, that coils need cleaning every 200 hrs and that each cleaning costs 100 EUR (based on 3-hr labour time), the servicing cost is: 100 EUR x 1,102 / 200 = 551 EUR/yr. **m** = 40 + 551 = 591 EUR/yr → rounded up to **600 EUR/yr** to take into account other possible servicing

4.2.6.2 Savings

Parameter	Description	Comments	Equations	Example
SEER	Seasonal energy efficiency ratio of the equipment	SEER can be found on the equipment's data sheet or asked for to the maker		For instance, SEER = 2.9
r [kWh/yr]	Yearly electric energy not used by the equipment	The saving is granted by the evaporation of the water. Divide $P_{evap.\ cooling}$ by SEER, then multiply by T to get the yearly electric energy not used by the equipment (approximately)	$r = \frac{P_{evap.cooling}}{EER} \times T$	r = 393 / 2.9 x 1,102 **= 149,340 kWh**
s [currency/yr]	Yearly saving from the reduced consumption of electric energy	The saving is granted by the evaporation of the water. Multiply r by the electric energy specific cost (c_{el}) the yearly saved cost of electric energy	$s = r \times c_{el}$	s = 149,340 x 0.20 **= 29,868 EUR/yr**
n [yrs]	Break-even point	The purchase and installation cost of chillBooster is recovered by the net saving of electric energy granted by the evaporation of water. In order to get the no. of years (n) corresponding to the break-even point, divide the non-recurring costs (a) by the yearly net saving [s-(w+e+m)]. After the n-th year, the non-recurring cost (a) will be fully recovered by the net saving [s-(w+e+m)].	$n > \text{break even} = \frac{a}{s - (w + e + m)}$ If the right-hand side of the equation is negative, then chillBooster is convenient since the beginning	*n > 5,300 / [29,868 – (498.10 + 132.24 + 600)] = 0.2 years* ***= 2.5 months*** In this example chillBooster is convenient from the 3rd month of duty.

5. USING CHILLBOOSTER TO BUY A NEW, SMALLER CHILLER OR SIMILAR EQUIPMENT

Proceed as follows:

1. Choose the proper chiller (or similar equipment) that would be suitable for the application without spraying water, i.e. with dry coils
2. Go through sect. 4.1. It is informative and valid also in this case: read it thoroughly
3. Go through sect. 4.2.1. It is still valid: read it thoroughly
4. Go through sect. 4.2.2. It lists the data required for the next steps: do as described therein
5. Go through sect. 4.2.3: do the assessment as described therein
6. Go through sect. 4.2.4: estimate the evaporative-cooling power as per the instructions in that section.
   IMPORTANT!
   - The evaporative-cooling power is the additional heat rejected by the wet coils
   - So the chiller (equipment) model can be down-sized by the same amount
   - Set the sprayed water flow so as to choose the first smaller model of equipment (or even a smaller one depending on the need)

   Example:
   - The right chiller for an application without chillBooster has to reject 500 kW with dry coils; the first smaller model rejects 400 kW with dry coils
   - Using the data of the examples in sect. 4.2.4, in order to have $P_{evap.\ cooling} \geq 100$ kW, the sprayed water flow should be minimum 100 / 0.7 = 143 kg/h
   - Round up to at least 150 kg/h to be on the safe side
   - Verify that, when 150 kg/h of water are sprayed onto the 400-kW chiller, its total rejected heat is equal to at least 500 kW by applying the method in sect. 4.2.4. If this is the case, 150 kg/h of sprayed water allow to use the smaller chiller, otherwise the water flow rate will have to be increased until the requirement of 500 kW is achieved with the smaller chiller
   - Of course, if more water were sprayed, an even smaller chiller could be used
7. Sect. 4.2.5: size chillBooster as described in that section

Then, continue with the following section.

5.2.1 4th phase - Convenience of using chillBooster: break-even point

When chillBooster is used to reduce the size of an equipment, there will be costs to sustain and savings to take advantage of:

1. Costs:
   - Non-recurring costs: purchase & installation of chillBooster (a)
   - Running costs:
     - Yearly cost of the sprayed supply water (w)
     - Yearly cost of the electric energy used by chillBooster (e)
     - Yearly cost of the preventive maintenance (m)
2. Savings:
   - Non-recurring saving: reduction (z) of the purchase cost of the equipment
   - Yearly saving (s), granted by the electric energy (r) not used by the equipment because part of the cooling comes from the evaporation of water

chillBooster is convenient when the difference between the non-recurring costs and the non-recurring saving is recovered within a reasonable time. The meaning of "reasonable" depends on the final user, but a 3-year payback time (max.) is usually considered reasonable.

The guide-lines for estimating the costs and savings above are as follow

Parameter	Description	Comments	Equations	Example
T [hrs]	No. of hours of operation of chillBooster	A common strategy for using chillBooster consists in starting it when the outdoor temperature goes above a certain threshold (30-35 °C – 86-95 °F seems to be a common threshold). Using the climatic data of the site, it can be found for how many hours per year the outdoor temperature stays above the threshold: this number of hours is T. Refer to CAREL for the climatic data of many cities around the world		*According to the climatic data of Singapore, the dry-bulb temperature is above the threshold of 30 °C = 86 °F for* ***T = 1,102 hrs/yr***
$P_{evap.\ cooling}$ [kW]	Representative evaporative-cooling power during period T	Go through steps 4)-7) above to estimate $P_{evap.\ cooling}$ during period T	Refer to steps 4)-7) above	$P_{evap.\ cooling} = 100$ *kW from step 6) above*

5.2.1.1 Costs

Parameter	Description	Comments	Equations	Example
Non-recurring costs				
a [currency]	Purchase & installation of chillBooster	The purchase cost depends on the model of chillBooster, piping and nozzles, so refer to the quotation made The installation cost is site-dependent, so it has to be estimated in cooperation with the installer.	The purchase cost of the chillBooster system is determined by its bill of materials (refer to step 6) above)	*1,500 EUR can be assumed to be the list price of the chillBooster system as defined in step 6) above; 300 EUR can be assumed to be the installation cost →* ***a** = 1,800 EUR*
Recurring costs				
w [currency/yr]	Yearly cost of the supply water by chillBooster	During period T, chillBooster will spray continuously. The sprayed water-flow rate (q_{water}) is constant and equal to the sum of the nozzles' flow rates: multiply q_{water} by the water specific cost (c_{mains}) and by the time T to get the cost of water per annum (w)	$q_{water} = \sum(\text{nozzles' flow rates})$ $w = q_{water} \times T \times c_{mains}$	$q_{water} = n_{nozzles}$ *x 5* *= round up (150/5) x 5* *= 150 kg/h = 330.7 lbs/hr* c_{mains} *= 0.80 EUR/m*^{3} **w** *= 150 / 1,000 x 1,102 x 0.80 =* ***132.24 EUR/yr*** q_{water} *is divided by 1,000 to express it in m*^{3}*/hr*
e [currency/yr]	Yearly cost of the electric energy used by chillBooster	During period T, chillBooster will spray continuously, so its power consumption, P, will be constant (P depends on the model of chillBooster – refer to sect. 3.1.2 above). Multiply P by the time T and by the electric energy specific cost (c_{el}) to obtain cost of electric energy per annum	$e = P \times T \times c_{el}$	*P = 0.5 kW for the chosen model AC050D0010* c_{el} *= 0.20 EUR/kWh* **e** *= 0.5 x 1,102 x 0.20 =* ***110.20 EUR/yr***
m [currency/yr]	Yearly cost of the preventive maintenance	The preventive maintenance consists in checking the nozzles, cleaning the coils from minerals if mains water is used (with demineralised water the associated cost is negligible), replacing the UV lamp (if present), replacing the water filter before chillBooster. Refer to sect. 3.2 and 3.4 above for more information		*Preventive maintenance consists in replacing the UV lamp. Its maximum lifetime is equal to 7,500 hrs (refer to sect. 3.4), so it will need to be replaced every 7,500 / 1,102 = 6.8 yrs. Since its list price is 180 EUR/pc. (2011 list price), the associated yearly cost of servicing is 180 / 6.8 = 27 EUR/yr → increased to 40 EUR if the labour cost is included (estimated).* *The cost for cleaning the coils from minerals has to be estimated, too. Assuming, like some chiller makers advice, that coils need cleaning every 200 hrs and that each cleaning costs 100 EUR (based on 3-hr labour time), the servicing cost is:* *100 EUR x 1,102 / 200 = 551 EUR/yr.* **m** *= 40 + 551 = 591 EUR/yr → rounded up to* ***600 EUR/yr*** *to take into account other possible servicing*

5.2.1.2 Savings

Parameter	Description	Comments	Equations	Example
Non-recurring savings				
z [currency]	Reduction of the purchase cost of the equipment	This is the difference between the model of equipment without chillBooster and the smaller model that can be purchased thanks to the additional evaporative-cooling power given by the sprayed water.	Refer to the maker's prices list	*13,000 EUR, assuming 130 EUR/kW as the incremental cost of chillers and a reduction from a 500-kW to a 400-kW chiller*
Recurring savings				
SEER	Seasonal energy efficiency ratio of the equipment	SEER can be found on the equipment's data sheet or asked for to the maker		*For instance, SEER = 2.9*
r [kWh/yr]	Yearly electric energy not used by the equipment	The saving is granted by the evaporation of the water. Divide $P_{evap. cooling}$ by SEER, then multiply by T to get the yearly electric energy not used by the equipment (approximately)	$r = \frac{P_{evap.cooling}}{EER} \times T$	r = 100 / 2.9 x 1,102 = **38,000 kWh**
s [currency/yr]	Yearly saving from the reduced consumption of electric energy	The saving is granted by the evaporation of the water. Multiply r by the electric energy specific cost (c_{el}) the yearly saved cost of electric energy	$s = r \times c_{el}$	s = 38,000 x 0.20 = **7,600 EUR/yr**

Parameter	Description	Comments	Equations	Example
n [yrs]	Break-even point	The purchase and installation cost of chillBooster is recovered by the net saving of electric energy granted by the evaporation of water. In order to get the no. of years (n) corresponding to the break-even point, divide the non-recurring costs (a-z) by the yearly net saving [s-(w+e+m)]	s - (w + e + m) > 0 $n > \frac{a - z}{s - (w + e + m)} \text{ if } s - (w + e + m) > 0$ If the right-hand side of the equation is negative, then chillBooster is convenient since the beginning. s - (w + e + m) < 0 $n < \frac{a - z}{s - (w + e + m)} \text{ if } s - (w + e + m) < 0$ If the right-hand side of the equation is negative, then chillBooster is never convenient, otherwise it is convenient for the initial "n" years.	*(1,800 – 13,000) / [7,600 – (132.24 + 110.20 + 600)] = **-1.7 negative!*** *In this example chillBooster is convenient since the beginning.*

6. EXCEL FILE FOR ESTIMATING THE RETURN-ON-INVESTMENT

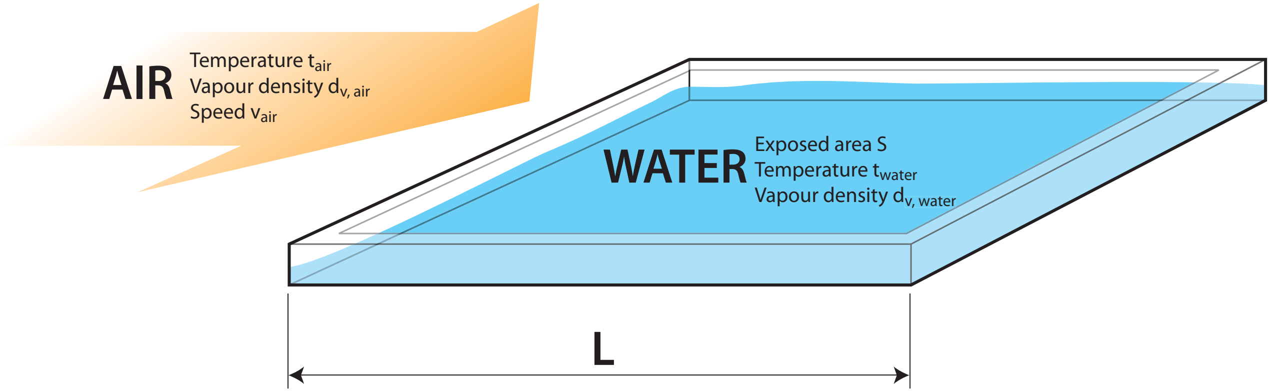
The following attached Excel file does the estimates described in sections 4 & 5.

7. APPENDIX A – MASS CONVECTION: BASICS (SI ONLY)

INFORMATION: This appendix is based mainly on 2009 ASHRAE Handbook – Fundamentals (SI), Chapter 6 MASS TRANSFER and, in particular, to its example 4 on page 6.6.

Mass convection is characterized by two fluids (A and B) in relative movement, with one of the two (e.g. B) moving over the other one (A).
Any fluid tends to diffuse into other fluids it is in contact with, so fluid A will diffuse into the moving fluid B. Fluid B, thanks to its movement, will continuously carry away the mass of fluid A diffused into it, thus sustaining the diffusion of A into B. This way, fluid A will see its mass continuously reduced.
If you replace A with "water over the coils" and B with "air streaming through the coils" you get the evaporation of water from the coils due to mass convection.

The basic law that rules the mass convection of water into air is the following:



$$q_{water} = h_M \times S \times \left(d_{v,water} - d_{v,air}\right)$$

where:

- q_{water} is the evaporation rate of water in kg/s
- h_M is the coefficient of mass convection, in m/s. It can be calculated as explained below.
- S is the area of the surface of water exposed to the air, in m². It has to be specified or calculated somehow.
- $d_{v,\,water}$ is the vapour density of water over its surface, in kg_{vapour}/m^3: It can be calculated by psychrometric formulas at the mean arithmetic temperature $(t_{air} + t_{water})/2$.
- $d_{v,\,air}$ is the vapour density of the air far away from the water, in kg_{vapour}/m^3. It can be calculated by psychrometric formulas given the temperature of the air far away from the water.

Estimation of the coefficient of mass convection h_M

The air above the water has "midway" characteristics between the water and the air far away from it. This layer of air is called "limit layer" and drives the evaporation of water (the limit layer is indicated by pedix "f" in the following).

1. Calculate the Reynolds number of the air over the limit layer (adimensional number): $\mathrm{Re}_f = \dfrac{\rho_f \times v_{air} \times L}{\mu_f}$:

   Where:
   - v_{air} is the mean air speed over the water, in m/s
   - ρ_f is the air density of the limit layer, in kg/m³
   - μ_f is the dynamic viscosity of the limit layer, in kg / (m x s)
   - L is the length, in m, of the exposed surface S along the air direction

2. Calculate the diffusion coefficient of water into the air:

   $$D_{v,w} = \frac{1}{10^6} \times \frac{0.926}{p/1{,}000} \times \frac{\left(t_f + 273.15\right)^{2.5}}{\left(t_f + 273.15\right) + 245}, \text{ in m}^2/\text{s}$$

   Where:
   - t_f is the temperature of the limit layer in °C, usually taken equal to $(t_{air} + t_{water}) / 2$
   - p is the absolute air pressure in Pa (e.g., 101,325 Pa at the sea level)

3. Calculate the Schmidt number of the limit layer (adimensional number):

   $$Sc_f = \frac{\mu_f}{\rho_f \times D_{v,w}}$$

4. Calculate the Sherwood number of the limit layer (adimensional number):

   $$Sh_f = \begin{cases} 0.664 \times \left(\mathrm{Re}_f\right)^{1/2} \times \left(Sc_f\right)^{1/3} \Leftarrow \mathrm{Re}_f \le 500{,}000 \text{ (laminar flow over the water)} \\ 0.037 \times \left(\mathrm{Re}_f\right)^{4/5} \times \left(Sc_f\right)^{1/3} \Leftarrow \mathrm{Re}_f > 500{,}000 \text{ (turbulent flow over the water)} \end{cases}$$

5. Finally, calculate h_M in m/s:

$$h_M : \begin{cases} d_{v,water} > d_{v,air} \Rightarrow h_M = \dfrac{Sh_f \times D_{v,w}}{L} \\ d_{v,water} \le d_{v,air} \Rightarrow h_M = 0 \end{cases}$$

Note that h_M is forced to 0 when the vapour density of the water is less than or equal to that of the air because the vapour in the air can diffuse to the water, but its diffusion coefficient is smaller than that of water into the air even by 3 orders of magnitude. Therefore the coefficient of mass convection of moisture into water can be considered negligible.

The formulas above can be approximated as follows:

- Set $\rho_f = 1.2$ kg/m^3 (average value)
- Set $\mu_f = 20 \times 10^{-6}$ kg / (m x s) (average value)
- Express L in mm
- Calculate $d_{v,\ water}$ and $d_{v,\ air}$ in kg/m^3 (formulas can be found in 2009 ASHRAE Handbook – Fundamentals (SI), Chapter 1 PSYCHROMETRICS). $d_{v,\ water}$ must be calculated at the mean arithmetic temperature $(t_{air} + t_{water})/2$

1. $$\mathrm{Re}_f = \frac{\rho_f \times v_{air} \times L}{\mu_f} \cong \frac{1.2 \times v_{air} \times L/1{,}000}{20 \times 10^{-6}} = 60 \times v_{air} \times L$$

   to be calculated

2. $D_{v,w} \cong 3 \times 10^{-5}$ m^2/s (average value)

3. $$Sc_f = \frac{\mu_f}{\rho_f \times D_{v,w}} \cong \frac{20 \times 10^{-6}}{1.2 \times 3 \times 10^{-5}} \cong 0.6$$

4. $$Sh_f = \begin{cases} 0.664 \times (\mathrm{Re}_f)^{1/2} \times (Sc_f)^{1/3} \Leftarrow \mathrm{Re}_f \le 500{,}000 \text{ (laminar flow over the water)} \\ 0.037 \times (\mathrm{Re}_f)^{4/5} \times (Sc_f)^{1/3} \Leftarrow \mathrm{Re}_f > 500{,}000 \text{ (turbulent flow over the water)} \end{cases} \Rightarrow$$

   $$Sh_f \cong \begin{cases} 0.664 \times (60)^{1/2} (v_{air} \times L)^{1/2} \times (0.6)^{1/3} \Leftarrow \mathrm{Re}_f \le 500{,}000 \text{ (laminar flow over the water)} \\ 0.037 \times (60)^{4/5} (v_{air} \times L)^{4/5} \times (0.6)^{1/3} \Leftarrow \mathrm{Re}_f > 500{,}000 \text{ (turbulent flow over the water)} \end{cases} \Rightarrow$$

   $$Sh_f \cong \begin{cases} 4.3 \times \sqrt{v_{air} \times L} \Leftarrow \mathrm{Re}_f \le 500{,}000 \text{ (laminar flow over the water)} \\ 0.8 \times (v_{air} \times L)^{4/5} \Leftarrow \mathrm{Re}_f > 500{,}000 \text{ (turbulent flow over the water)} \end{cases}$$

5. $$h_M : \begin{cases} d_{v,water} > d_{v,air} \Rightarrow h_M = \dfrac{0.03 \times Sh_f}{L} \\ d_{v,water} \le d_{v,air} \Rightarrow h_M = 0 \end{cases}$$

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