Technical article

Influence of heat exchanger design on dehumidification and frost formation

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Main topics:

- Influence of different factors on dehumidification (Factors: Outside and inside heat transfer, tube arrangement)
- Description of influence of frost formation on performance
- Which influence does the heat exchanger surface have on frost formation?
  Relation between size of surface and thickness of ice and/or frost formation
- Presentation of advantages of high-efficiency evaporators with sufficiently large heat exchanger surface and the correspondingly reduced driving temperature difference; resulting cost savings

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With air coolers, dehumidification and frost formation are almost unavoidable side effects, which are generally undesirable. Dehumidification has a detrimental effect on the quality and shelf life of goods that are displayed openly, such as fruit and vegetables and, for this reason should be kept to an absolute minimum. At evaporation temperatures below the freezing point dehumidification also causes frost formation on the fins and thus directly or indirectly causes increased energy consumption.

The design of an air cooler, especially the structure of the fins and the arrangement of the tubes, has a major effect on dehumidification and frost formation on the fins. However, the operating parameters, such as air temperature, humidity and evaporation temperature can also make a big difference. Often, the influence of the air cooler is assessed wrongly and air coolers with bad heat transfer coefficients are used deliberately instead of changing the operating parameters accordingly. On the other hand, in many cases, highly efficient and, consequently, inexpensive air coolers are used in conditions for which they are not suitable.

This article aims to give an insight into the connections between the heat exchanger design, the operating parameters, ice-up and dehumidification and help those concerned make the right choice.

1 Dehumidification

1.1 *Theoretical fundamentals*

When air cools on a cold surface, the absolute humidity initially remains constant; in other words, the relative humidity increases. But eventually when the surface temperature falls below the dew point temperature of the air, humidity starts to condense. Thus, the requirement for humidity to be separated is that the temperature of this surface is below the dew point temperature.

With an air cooler this surface is the fin. In other words, if the temperature of the fin surface is below the dew point temperature of the incoming air, humidity is separated. However, the air at the outlet does not necessarily have to be saturated because not the entire air flow actually touches the fin. Therefore, in the model we split the air flowing through the cooler into two parts: The one part touches the fin and cools to the surface temperature of the fin. The second partial flow, on the other hand, flows through the air cooler unhindered. Behind the air cooler the two partial flows are mixed together again (Figure 2).

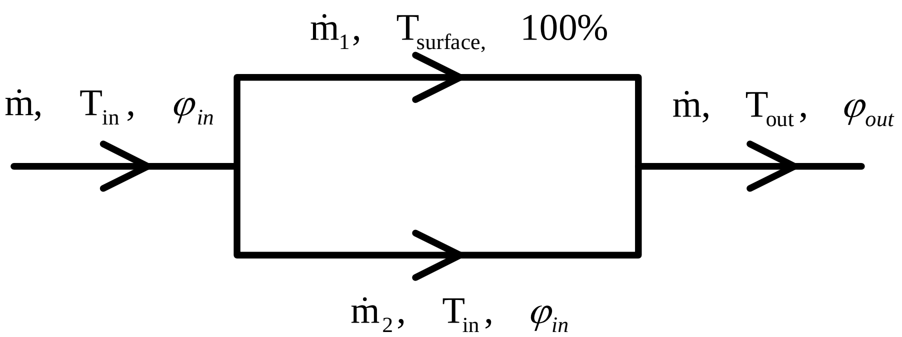

Figure 1: Model for partial air flows in an air cooler

If the surface temperature $T_{surface}$ is below the dew point temperature, the air of partial flow 1 must be saturated; in other words its humidity φ_1 = 100%. The mixture of the two partial flows then leads to the outlet state of the air. This state in the hx diagram is on the mixture line.

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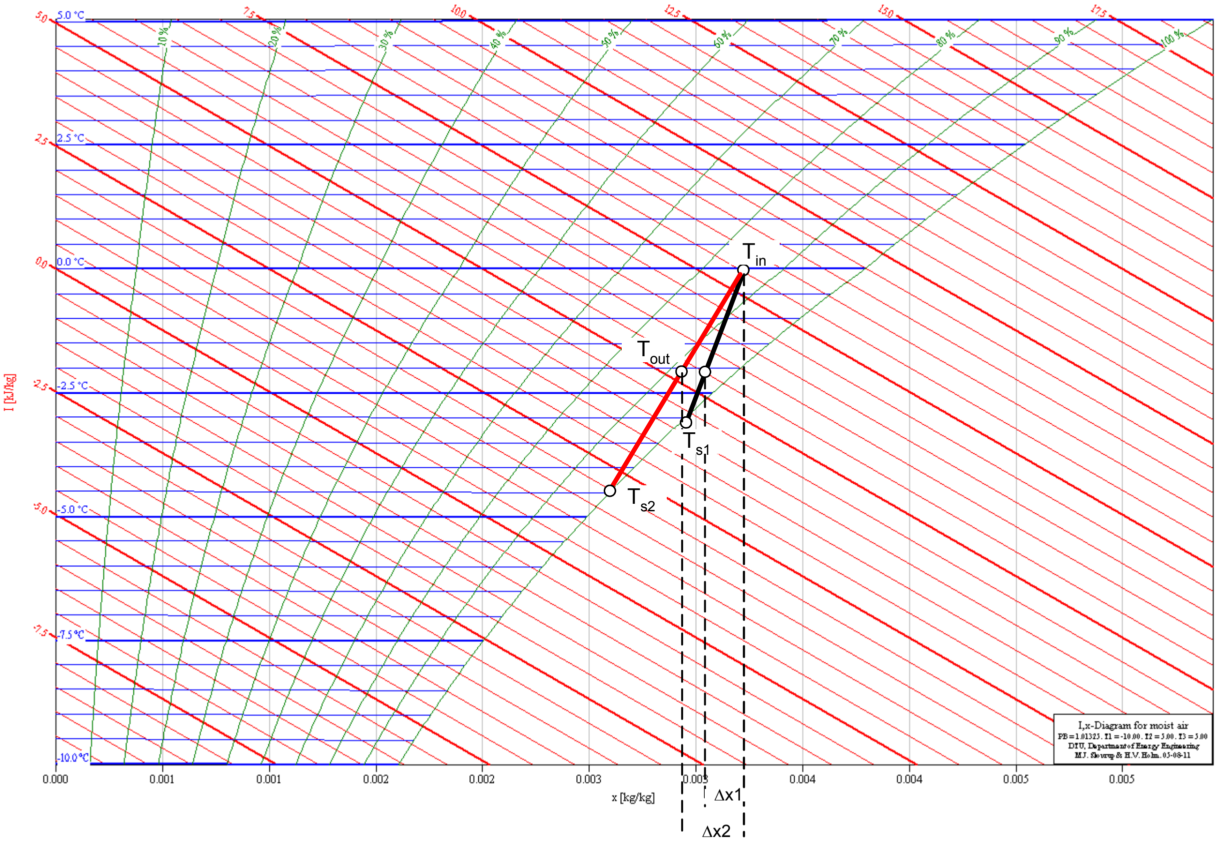

Figure 2: Dehumidification shown in the hx diagram

Figure 2 shows this mixture line for two different surface temperatures T_{s1} and T_{s2}. In the first case the surface temperature is –3°C and in the second case –4.5°C. The incoming air temperature in both cases is 0°C, relative humidity is 85% and the outgoing air temperature is –2°C. You can see that dehumidification is higher in the second case simply because of the lower surface temperature.

The dehumidification causes a power increase because the condensation on the fin produces a high heat transfer coefficient. But in actual fact, this extra power is useless because it does not help cool the air. We therefore distinguish between the latent refrigerating capacity, which is produced solely by condensation, and sensitive refrigerating capacity, which takes place through cooling the air. Ideally, the condensation is provided additionally without any adverse effects on the sensitive refrigerating capacity, but in actual fact, the sensitive refrigerating capacity is slightly less.

1.2 Influence of external heat transfer on dehumidification

As explained above, the surface temperature of the fin plays an important part in dehumidification. With a more effective fin; that is, a fin with high heat transfer coefficients, the surface temperature can be increased with the same power density on the air cooler. This can be explained by the following consideration (Figure 3):

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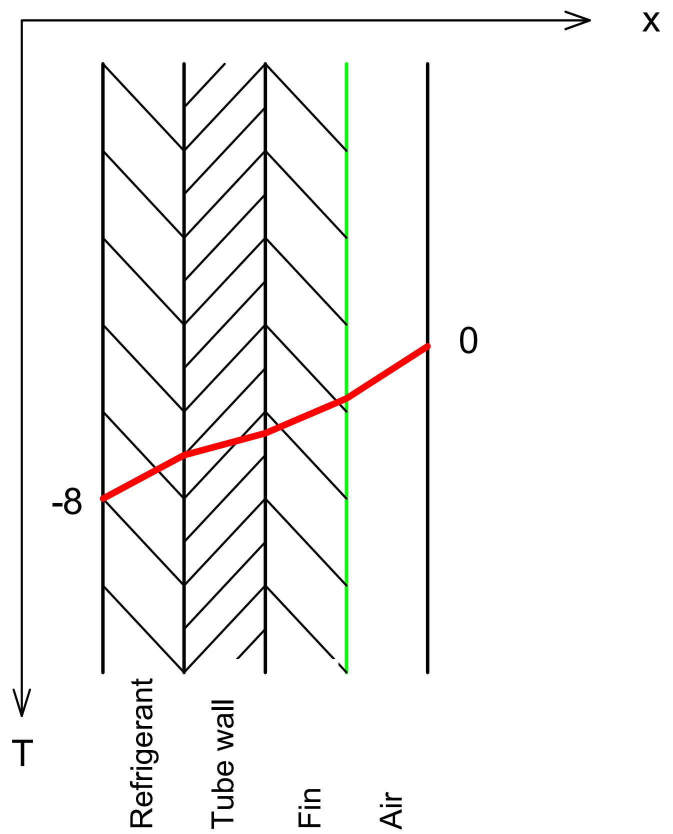
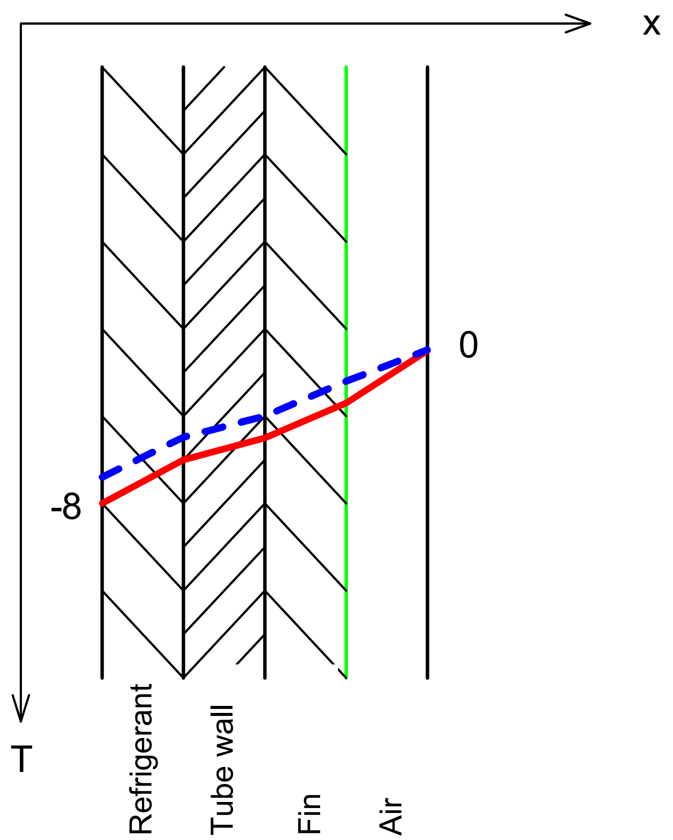


The heat has to overcome several resistances in an air cooler: First, from the air on the fin, then from the fin to the outer wall of the tube, through the wall of the tube and, finally from the inside of the tube wall to the refrigerant.

The higher the resistance or the smaller the heat transfer coefficient through a layer, the higher the temperature gradient must be, assuming the same power density; in other words, the temperature profile is steeper.

If you now increase the outer (= air side) heat transfer by making the fin thicker, for instance, the same power can be transferred per surface area with smaller temperature gradients (broken line in Figure 4).

Figure 3: Heat resistance values in a finned heat exchanger

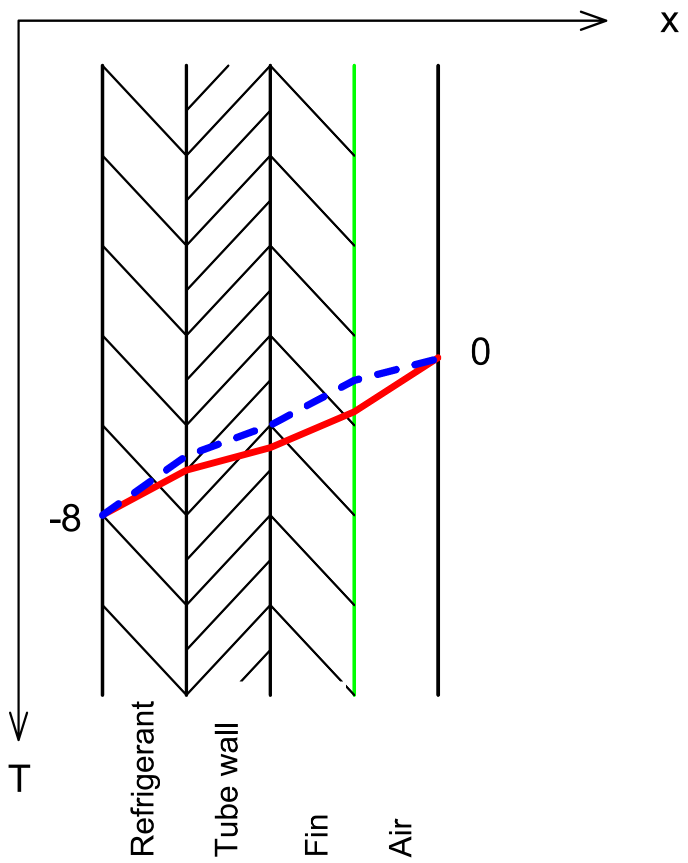


As nothing has changed with any of the other heat resistances and the same power per surface area has to be transferred, in this area the line must simply move upwards parallel to the other.

The result is a higher evaporation temperature, which is advantageous for the COP of the refrigeration system. But the higher surface temperature also reduces dehumidification.

In practice, improvements to the heat transfer coefficient are usually used to increase the power density of the air cooler. Generally, you can assume that a more efficient air cooler is used with the same temperature difference as the inefficient one. Hence, an increase in external heat transfer due to a more efficient fin will lead to a higher power density.

Figure 4: Temperature profile at increased external heat transfer value and constant power density



A higher power density can be transferred from the refrigerant to the tube and through the subsequent heat resistances only if the temperature gradient increases, as nothing has changed as regards the heat transfer here. This explains the course of the broken line in Figure 5. In spite of a higher power density the temperature of the fin surface rises and dehumidification is reduced.

We can thus say that a more effective fin reduces dehumidification even with the same temperature difference and thus an increased power density. More dehumidification through more efficient fins can happen only if the absolute power of the air cooler is also increased with the volume of air remaining constant because in this case the air cools more and, as a consequence, the average surface temperature can also decrease.

Figure 5: Temperature profile at increased external heat transfer and increased power density

1.3 *Influence of internal heat transfer on dehumidification*

The influence of internal heat transfer on the surface temperature and thus on dehumidification can be described with the same symbols. If the internal heat transfer is increased, for example, through internally grooved tubes, you can use this either to reduce the temperature difference with the same power density or, which is unfortunately more often the case, to increase the power density of the air cooler. However, even without a symbolic presentation it can easily be determined that without changing the external heat transfer the same power density can be achieved only with the same temperature difference between the air and the fin and thus with the same surface temperature. In the same way, an increase in power density can lead only to a lower surface temperature

In other words, increasing the internal heat transfer can never reduce dehumidification. If this increases the power density of the air cooler, this will increase dehumidification.

As an overall result the influence of internal and external heat transfer is shown in Figure 6, where the surface temperature of the fin is shown in comparison to the ratio of internal and external heat transfer.

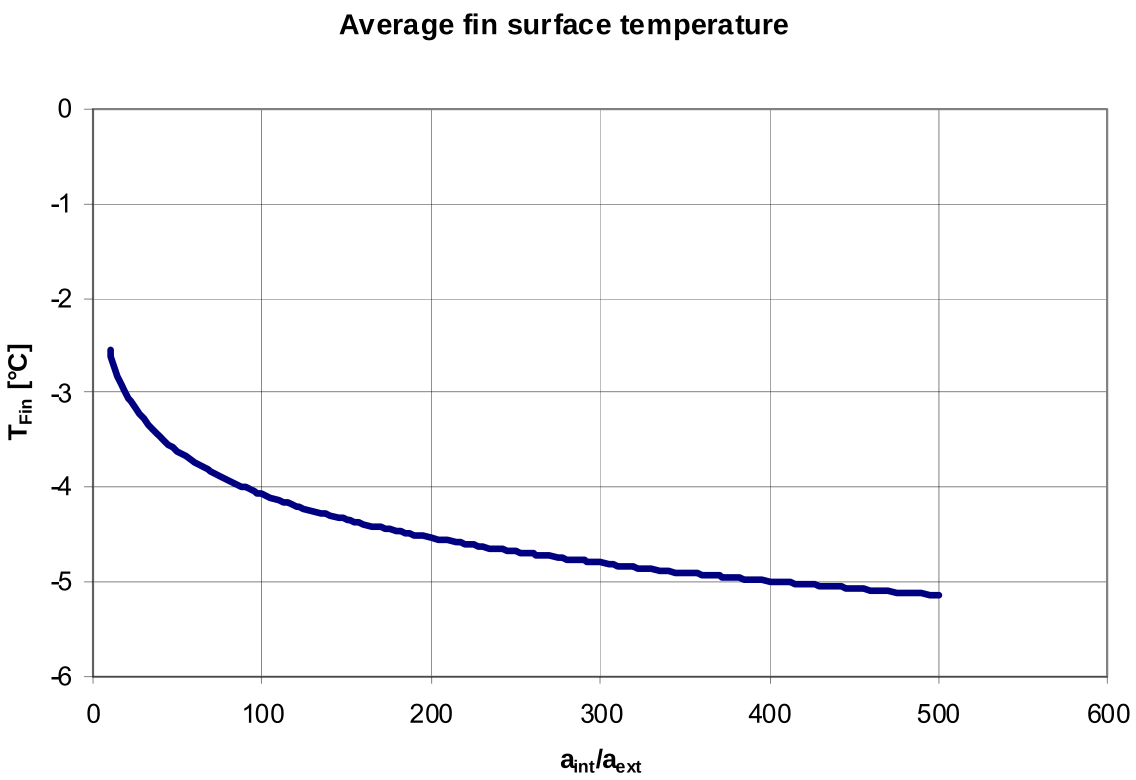


Figure 6: Influence of internal and external heat transfer on the surface temperature

1.4 *Influence of tube arrangement on dehumidification*

If the other conditions remain constant, dehumidification can be reduced only if the surface temperature of the fin is increased. Of course, this can always be achieved by reducing the temperature difference. However, all measures associated with the design of the air cooler can lead only to an increase in the surface temperature if the heat transfer on the air side is increased.

But increasing the air-side heat transfer can be done in various ways; for example with the structure of the fin or through the arrangement of the tubes. A smaller distance between the tubes and a staggered tube pattern has greater air-side heat transfer than an aligned tube pattern with large distance between the tubes. However, changing the tube pattern has two contrary consequences for dehumidification.

If, for example, you change an aligned tube pattern with a large distance between the tubes to a staggered tube pattern with a small tube distance, this changes the efficiency of the fins. In the symbolic presentation in Figures 3 to 5 this would lead to a situation where with a higher power density the fin surface temperature would have to be lower to transfer the increased power. But this is offset by the increased heat transfer coefficient of the staggered fin. Consequently, it is not possible to make a general statement about whether a staggered fin pattern reduces or increases dehumidification more or less than an aligned tube pattern. But if you consider the basic rule that an increase in the heat transfer coefficient should never be used to increase power density but only to reduce the driving temperature difference, a staggered tube pattern is undoubtedly better.

2 Frost formation

If the surface temperature of the fin is below 0°C, the condensed air humidity freezes and a layer of ice or frost gradually forms on the fin. The consistency of this ice layer also depends on the fin temperature – the lower the temperature, the lower the density of the ice. This ice layer has an insulating effect, which means that as the ice becomes thicker the heat transfer is reduced. In addition to this, the air-side pressure loss increases, resulting in a reduction in the volume of air. Both of these effects cause the evaporation temperature to fall slowly and thus increase the energy consumption of the compressor. Depending on the fin spacing, a certain thickness of ice can be tolerated before it has to be defrosted.

With small air coolers this defrosting is usually done electrically, which also uses energy. Consequently, on the one hand, the frost formation causes increased energy consumption directly due to the reducing evaporation temperature and also indirectly as a result of the electrical energy needed to thaw the ice and the energy that is needed after defrosting to remove the defrosting energy.

But for most system operators even more annoying than the energy consumption is the long downtime while the ice is being defrosted. Usually, a defrosting cycle takes between 30 and 40 minutes. During this time, nothing can be cooled and the goods are at risk. Therefore, defrosting should be necessary only rarely, which means that frost formation should be kept to a minimum.

2.1 *Influence of the heat exchanger surface on frost formation*

As explained in Section 1, the amount of separated condensate depends on the air temperature, the humidity, the volume of air and the average surface temperature of the fins. Of course, the same connection also applies to frost formation; although the surface of the heat exchanger also plays an important role in this respect. The smaller the cooler, the smaller the surface that is available for the total frost layer, which means that the ice or frost becomes thicker faster. Hence, if it produces the same output under the same conditions, a highly efficient air cooler will ice up much faster than a corresponding air cooler with less heat transfer. But on the other hand, for pure dehumidification the surface of the heat exchanger doesn't play any role at all.

This unfavourable frost formation behaviour of highly efficient air coolers has led to a situation that even today air coolers with bad heat transfer coefficients are often used. But with careful consideration this is quite silly, since instead of choosing an air cooler that is ineffective and large, you would be much better using an efficient air cooler with the same size and reducing the driving temperature difference. This can be seen in the simple example below that compares different types of heat exchangers:

Heat exchanger A: A = 100 m²; k = 20 W/m²K

Heat exchanger B: A = 50 m²; k = 40 W/m²K

Heat exchangers A and B produce the same refrigeration capacity under the same conditions. If, for example, the average logarithmic temperature difference is 10 K, both have 20 kW power. With just 50 m² heat exchanger B is certainly the less expensive solution. However, heat exchanger B has exactly the disadvantages that are attributed to a highly efficient air cooler: Rapid frost formation and frequent defrosting, which causes many people to choose a type B heat exchanger. But instead of spending a lot of money on an inefficient surface, it would be much more sensible to invest this money in an efficient heat exchanger, such as type C:

Heat exchanger C: A = 100 m²; k = 40 W/m²K

These heat exchangers cost only slightly more than type A, but reach an output of 20 kW at only half the temperature difference. That means that the evaporation temperature can be increased. In other words, the same surface area is available for frost formation as with type A but dehumidification and, consequently, frost formation are much lower than with type A, because the evaporation temperature and thus the surface temperature of the fin are much higher.

The assumption that a highly efficient air cooler ices up faster, applies only if it is used incorrectly; in other words, if it is operated under the same conditions, and the highly efficient air cooler is thus much smaller. But if you compare the same surface areas, the more efficient air cooler not only dehumidification is lower, it also ices up much slower.

3 Summary

Apart from the operating conditions, dehumidification is primarily caused by the surface temperature of the fins. The higher the surface temperature the less the dehumidification. High surface temperatures can be achieved only with high heat transfer coefficients on the air side; that is with highly efficient fins. All other improvements in the heat transfer coefficient, such as internally grooved tubes, increase dehumidification if they are used to increase power density.

As regards frost formation, apart from the amount of condensate, the size of the surface area also plays an important role: The bigger the surface area, the slower the ice layer forms. However, this is not a reason to use inefficient air coolers, rather highly efficient air coolers should be used to keep the temperature differences on the air cooler as small as possible. This allows dehumidification to be reduced most effectively and also saves energy.

Keywords:

Dehumidification, frost formation, air cooler, fin surface temperature