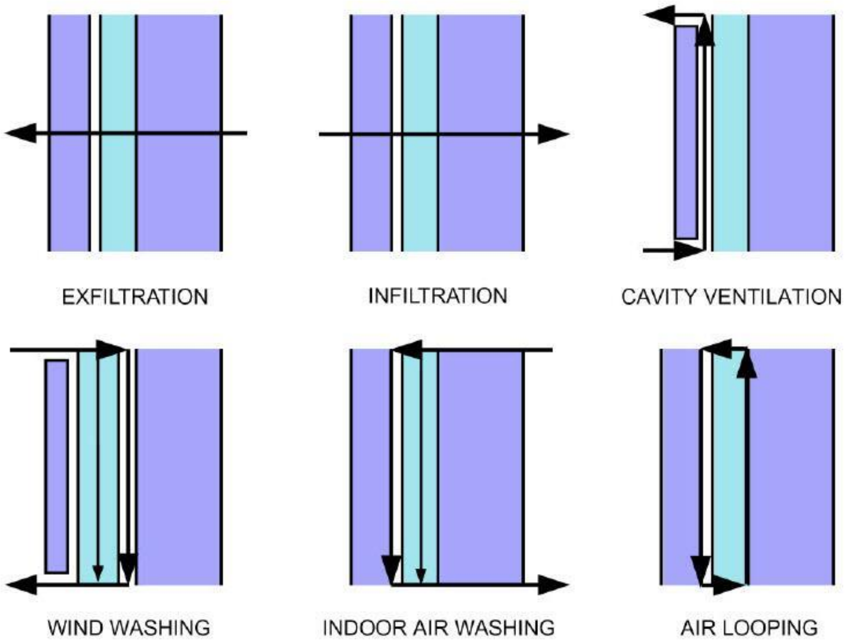

NERIS – Del 3

Moisture transport in ice rinks – mechanisms and physics

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Summary

The project name NERIS is an acronym for Nordicbuilt: Evaluation and Renovation of Ice halls and Swimming halls. NERIS is led by the department of Civil Engineering at the Royal Institute of Technology (KTH) in Stockholm, Sweden.

This report is part three in a series of four, which will address moisture handling in ice rinks. Together these reports will not only provide with fundamental knowledge on how to design the dehumidification function, but they will also give general recommendations regarding the structures that separate the indoor climate from the outdoor as well as the choice of proper materials for the building envelope. Part three gives a structured walkthrough regarding the different physical mechanisms that impact the moisture sources as well as the moisture sinks of an ice rink.

The design of a dehumidifier in an ice rink has traditionally been done with outdated and often misleading assumptions. Certain aspects such as internal sources have been overestimated while more important ones such as air leakages have in turn been underrated. A number of field measurements have been carried out in selected ice rinks in order to analyze and estimate air leakages. The results confirm that this source has the highest magnitude and is much more dominating than what has been assumed in the past. For an arena room of around 25 000 m^3, which represents the bulk of Swedish ice rinks, it appears that leakages are normally within 5-15%, i.e. the air volume that leaks in per hour with respect to the total arena room volume.

The internal sources normally consist of skaters and spectators who release water vapor to the air. Due to the fact that ice rink users in general are fairly well clothed, it can be concluded that most of the moisture released is absorbed by the clothing. For dimensioning purposes, the moisture load has often been taken as 350 g/h per person, while if only respiratory vapor release is considered the load can be as low as 8 g/h per spectator and 40 g/h per skater.

Water vapor diffusion through the walls and roof has a relatively low contribution to the total load and can in general be neglected as a moisture source. However, it is important that the diffusion through the building envelope is well managed, otherwise condensation may occur in parts of the structure which in the worst case may lead to roof collapse but more commonly causes moisture damage and mold problems.

Nominally the total moisture load in a normal training/public ice rink sums up to around 20 kg/hour. For the majority of the time when an ice rink is used the internal loads are very small, which means that the load is mostly due to air leakages. In the worst-case scenario, i.e. when the outdoor air is the wettest, leakages can lead to a total load of 30 kg/hour and internal loads at design conditions can be around 5 kg/hour. But such a high level of moisture load is typically only short term in a normal ice rink, and therefore there is usually no need to design the dehumidification capacity up to such levels.

The two main moisture sinks, i.e. mechanisms that remove moisture from the indoor air, are the ice slab and the dehumidifier. The ice slab can be responsible for removing tens of kilograms of water per hour through moisture condensation/freezing onto its cold surface. A higher temperature difference between the ice slab and the air increases the moisture transport from the air to the ice surface.

The dehumidification system plays the most important role in the moisture handling and should have a design capacity of around 20 kg/hour. Point loads can be up to 30-35 kg/hour but this study concludes that a design capacity of up to 20 kg/hour is normally enough. The air volume in the arena room as well as inner surface materials act as buffers to some extent during the peak load periods.

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1 Introduction

1.1 Background and scope of the NERIS project

The project name NERIS is an initial abbreviation for Nordicbuilt: Evaluation and Renovation of Ice halls and Swimming halls. NERIS is led by the Department of Building Science at the Royal Institute of Technology (KTH) in Stockholm, Sweden. Financial support has been received from Formas (The Research Council for the Environment, Land Industries and Community Development) and the Energy Agency. The purpose of the project is to "propose methods to be able to inspect and evaluate the functionality of these types of buildings and report various renovation measures that can improve performance". This means that one wishes to achieve an information bank regarding moisture management in ice rinks and swimming pools. The NERIS project started in 2014 and will be completed in 2018.

This report is the third part in a series of four whose task is to treat moisture in ice rinks. Together, the four reports will analyze and explain the mechanisms of moisture in ice rink facilities. Initially, the ice rink technology will be explained and how the moisture problem in a building can arise with this type of application. The idea is to then build a logical sequence of reports in which moisture-related challenges such as moisture sources and other building physical properties together with dehumidification methods and their energy use impact are described in ice rink applications. The goal is that the various parts of this report series should be able to complement each other and be able to provide practical advice and instructions regarding the dimensioning and planning of dehumidification systems in ice rinks.

1.2 Scope of NERIS - Part 3: Moisture transport in ice rinks - mechanisms and physics

Part 3 of NERIS will deal with how moisture transport in ice rinks works. This knowledge is very fundamental partly for being able to dimension the dehumidification equipment but not least for how the climate shell and its constituent materials should be constructed. The work and material in the present document is a combination of literature compilation but above all analysis of results from field measurements.

Knowledge of the sources of the moisture that de facto enters an ice rink is rather vaguely mapped in the literature. There are many accounts of the potential sources but few have attempted to put these sources into perspective, ie. estimated their absolute and relative sizes. In the present work, the sources have been estimated computationally and compared with measurements and results from real plants.

It turns out that dimensioning has traditionally been based on somewhat incorrect assumptions. Certain factors such as internal moisture loads have been overestimated while air leakage has been underestimated. Within the framework of this work, for example, measurements have been made in a number of ice rinks to estimate air leakage. These results have confirmed the picture that this particular source is larger and more dominant than previously thought.

In the same way, it is interesting and important to understand where the moisture that has entered the ice rink goes. That the dehumidifier takes care of moisture is obvious, but how much condenses on the ice? Calculations have also been made for the removal of moisture, which have been verified with data from the field. All with the aim of understanding how ice rinks with associated dehumidification function should best be constructed and dimensioned. In Neris part 4, the knowledge from previous parts will be summarized in recommendations for construction and dimensioning.

2 Moisture transport through the ice rink's climate shell

Part 3 of NERIS will deal with how moisture transport in ice rinks works. This knowledge is very fundamental partly for being able to dimension the dehumidification equipment but not least for how the climate shell and its constituent materials should be constructed. The work and material in the present document is a combination of literature compilation but above all analysis of results from field measurements.

In building physics, the mechanisms of moisture transport are usually divided into four main groups:

- Movement of water vapor due to air flow, ie. convection.
- Diffusion of water vapor due to partial pressure gradients in the water vapor.
- Surface diffusion and capillary movement of aqueous liquid in porous building materials.
- Fluid flow that occurs due to gravity, fluid or air pressure.

The degree to which the various forms of moisture transport occur in a building's climate shell depends on its structure and use. However, the most relevant forms of transport in this context are usually convection and diffusion of water vapor.

The amount of water vapor that is transported depends on the prevailing air properties at the respective sides of the climate shell and the structure of the climate shell, which acts as a barrier to air and moisture transport. The transport direction itself is determined by the relationship between the local outdoor climate and the intended indoor climate. In the case of ice rinks, the moisture problem usually arises when moisture is transported from the ambient air into the facility where the main source of moisture is convection through the ice rink's climate shell, i.e. air leakage.

The reason for the above-mentioned moisture problems is due to striving to keep the indoor climate of the ice rink constant according to dimensioned conditions. This is maintained as long as the capacity of the facility's building structures and installations is sufficient. In practice, the density of the building and the installed dehumidifier capacity determine how well you manage to maintain the desired climate. As previous reports within Neris stated, the geographical location affects the conditions through the temperature and humidity levels of the ambient air, which of course also change during the year. These conditions and the air's natural tendency to try to even out climate differences lay the foundation for the moisture problem that exists in an ice rink.

2.1 Air leakage – Convection through the climate shell

Air carries water vapor with it, which can leave the air and be absorbed by or condense on other surfaces, where the latter happens when the temperature of the surface is lower than the air's dew point. In the typical moisture problem of ice rinks, ambient air is transported into the facility and then takes moisture with it. This moisture can then be absorbed or condensed on various surfaces and lead to problems in the indoor climate if the facility's moisture management is deficient.

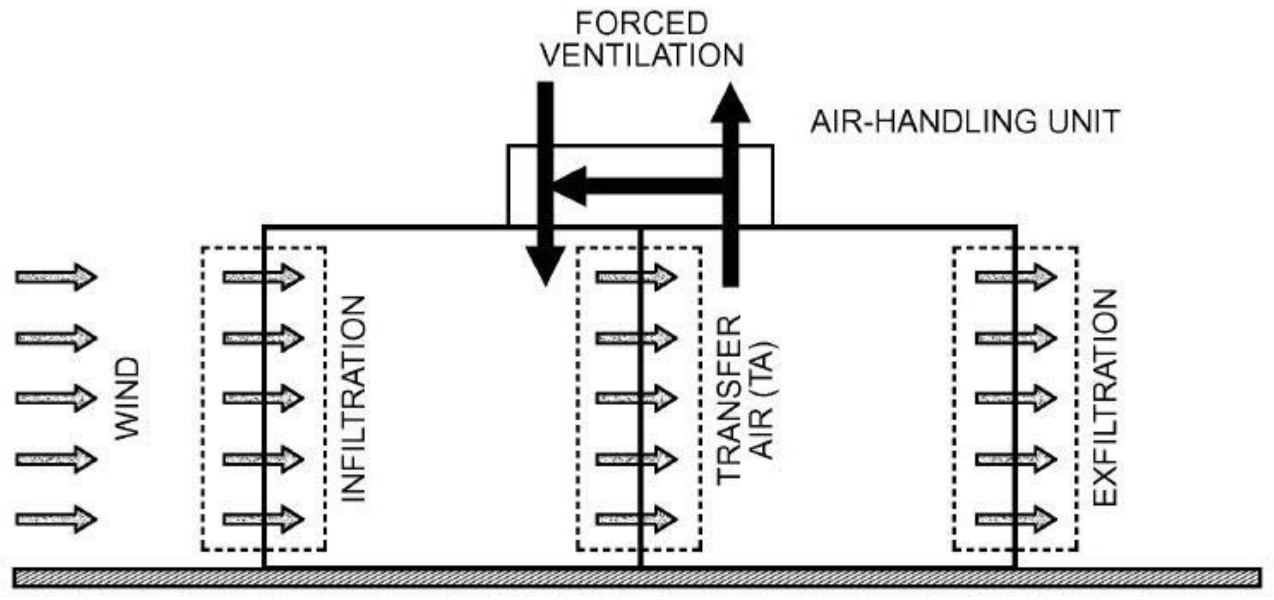


Figure 1. Different types of air transport through a climate shell.(ASHRAE, 2017a)

Figure 1 shows the distribution of air flows into and out of a building. Air leakage refers to infiltration or exfiltration, depending on the direction of the leakage, while the rest of the air exchange is taken care of by installations that deliver intentional ventilation. Air exchange between internal spaces is called overhead air.

Buildings cannot normally be fully airtight, and that is usually not the goal either, as it can lead to excessively high investment costs. National building regulations often require air tightness for different types of buildings from an energy use perspective, but for colder indoor climates such as ice rinks, air tightness also affects the dehumidification requirement significantly. As previously mentioned, air leakage is the main source of moisture in ice rinks, which can be observed when comparing the ratio between the absolute humidity of the surroundings and the dehumidification demand in the facility throughout the season. Figure 2 illustrates this, where it can be seen that changes in the moisture level of the indoor air follow the same trend as changes in the ambient air.

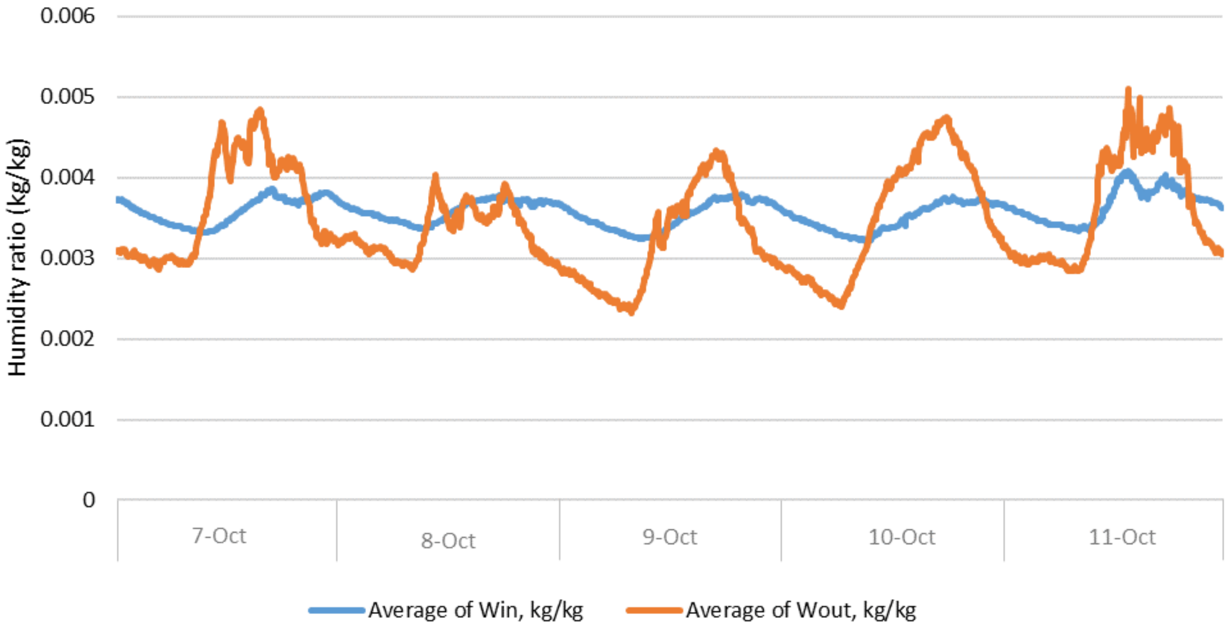
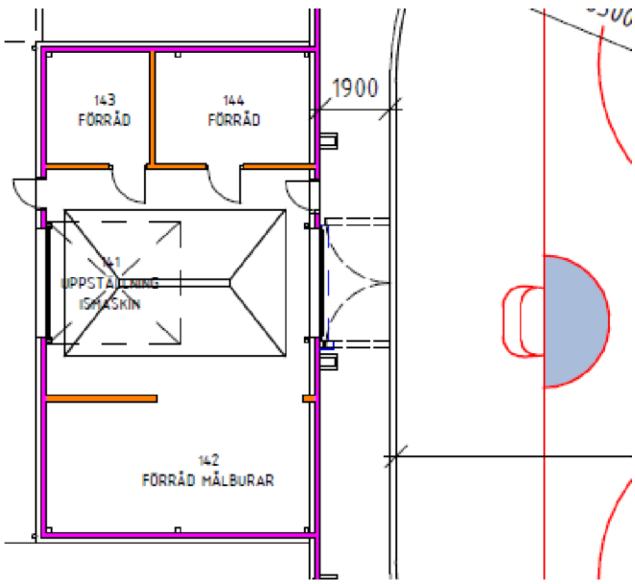


Figure 2. The steam ratio inside and outside an ice rink.

In order to minimize air leakage, it is important to make the ice rink's climate shell as airtight as possible and ensure that there are no unwanted openings in the constructions. Despite these measures, intentional openings, e.g. doors, through use cause large air leaks that introduce a lot of moisture. The ice machine needs to remove ice scraps and top up with laying water, usually outside the arena room. This happens several times during the day to be able to maintain the ice quality, which means that even the door of the ice machine can become a noticeable source of moisture. Gates and doors that separate the arena room of the ice rink from the surroundings must therefore be closed as much as possible. A more sustainable solution to minimize air leakage via intentional openings is to create airlocks that separate the arena space from the surroundings. These spaces can also be used for other purposes, where for example an ice machine garage is a good example as shown in the figure below. The garage is then provided, advantageously, with automatic doors



that can be operated by the ice machine driver so that these are never open at the same time.

Figure 3. Example of how an ice machine garage forms a "lock" between the arena room and the surroundings in an ice rink.

Air flows through and inside the climate shell occur due to the total pressure difference between the indoor and outdoor climates. This is a result of the temperature differences, ie. the density differences, between the different climates but also the pressure difference that wind can bring. Mechanical equipment, such as air handling systems, can cause further variations in pressure, but normally these are balanced, meaning that exhaust air is replaced by the same amount of outside air.

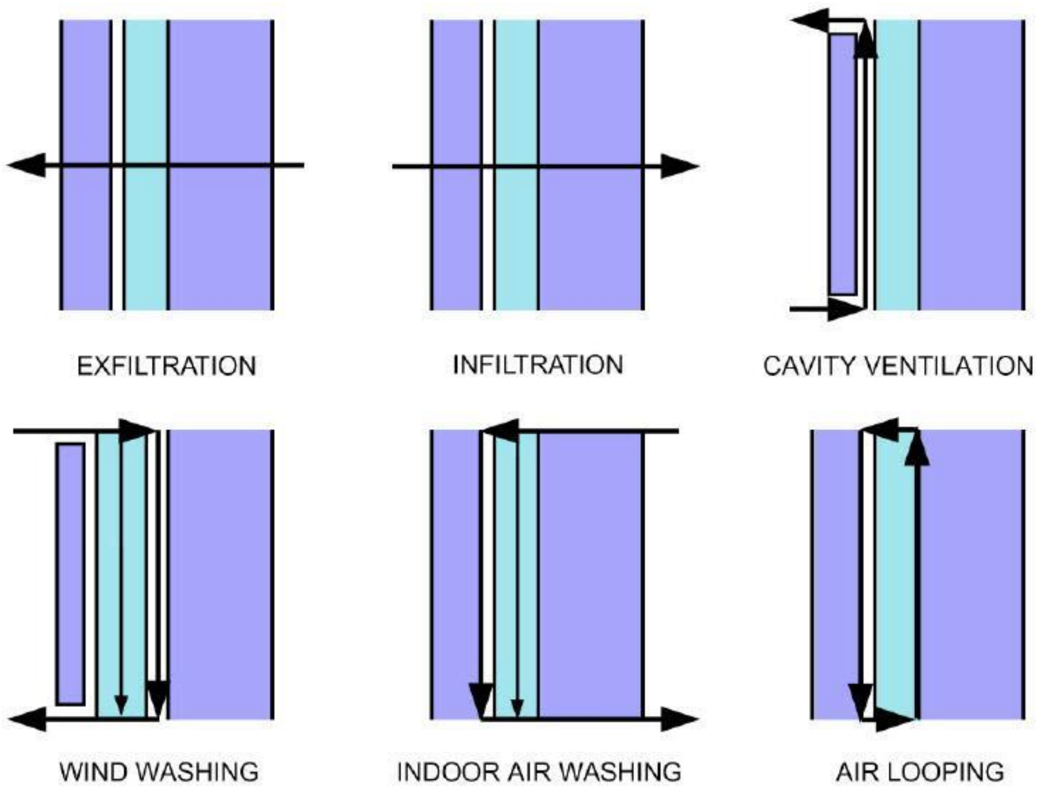


Figure 4. Example of air flows in a climate shell.(ASHRAE, 2017b)

Air can move in different ways in a climate shell, Figure 4 shows the principles of these different types of flows. In reality, these usually take place in combination with each other, resulting in complex air flows. If an ice rink's climate shell leaks, i.e. air infiltrates or exfiltrates, it becomes difficult to maintain the indoor climate according to dimensioned values due to uncontrolled air flows inward or outward. This also affects the cooling demand in the facility, as a large amount of warm ambient air then leaks in during the warm part of the season and increases the convective and latent heat load on the cooling system.

Increased cooling demand means higher capacity demands on the cooling system, which results in higher investment costs and increased energy use. To avoid this, a layer can be installed in the structure of the climate shell that acts as an air barrier. This type of layer has continuously low air permeability and can noticeably reduce the unwanted air flow that reaches the indoor climate. In homes and other common buildings, it is common for the air barrier to also be a vapor barrier placed on the inside of the structure, but in the case of ice rinks, this solution is not necessarily recommended, which will be discussed later in this report.

2.1.1 Pressure differences and the chimney effect

The air is distributed so that at sea level it has a density that decreases as you move upwards, which occurs in correlation with the decreasing air pressure. For reference, it can be mentioned that air at an altitude of 1500 m has a density that is approx. 20 percent lower than at sea level. The density of air is also changed by its temperature, which explains why cold air falls downwards while warm air rises. A 20 percent change in density can be observed when comparing the properties of air at temperatures of -30 and +20 °C. The effect of moisture on the density of air is virtually insignificant, but in tropical climates it can be observed that the air becomes slightly lighter due to moisture (the water molecule has a lower molecular weight than dry air). The density of the air depending on temperature and humidity level can be seen in Figure 5.

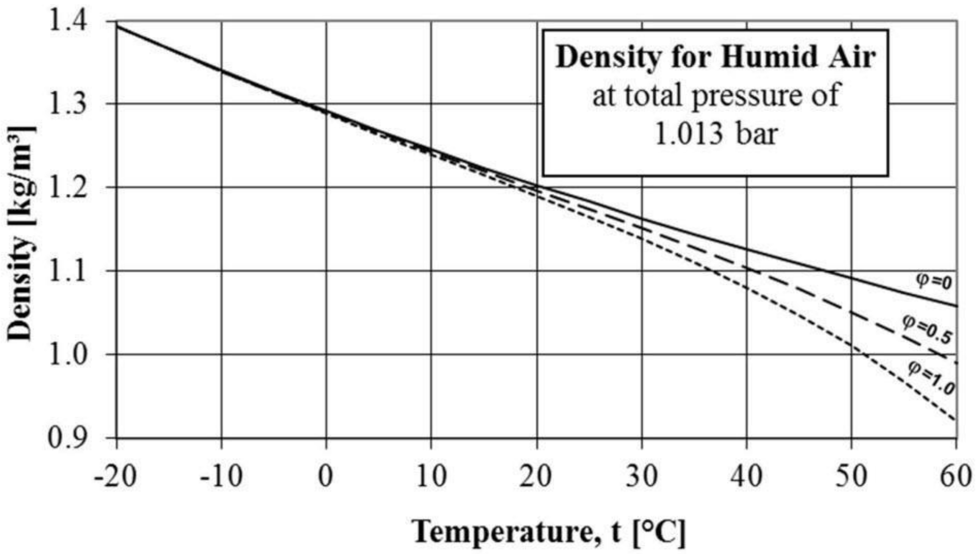


Figure 5. Air density in relation to temperature and relative humidity.

Buildings can be said to function like chimneys where warm air rises and disappears through openings in the upper parts of the house while cold air is drawn in at the floor to replace the warm air. This is called the chimney effect and causes hydrostatic pressure differences on the climate shell. Even in ice rinks, warm air rises towards the ceiling, while colder, higher-density air is held down. However, what separates ice rinks from most other buildings is that the temperature of the arena room can be colder than the surroundings for a long time, which means that the cold air at the bottom of the ice rink creates a higher pressure against the lower part of the climate shell than the ambient air does. As a result of this pressure difference, the cold air leaks out (exfiltrates) from the bottom of the ice rink through the climate shell to replace the warmer ambient air that rises upwards. At the same time, warm ambient air penetrates through the ice rink's upper part of the climate shell due to the negative pressure caused by the exfiltrated cold air.

Figure 6 illustrates the above description. Furthermore, it should be noted that wind can shift the ambient pressure conditions and lead to increased infiltration through the upper part of the climate shell and reduced exfiltration through the lower part. The part of the climate shell where the pressure conditions of the ice rink and the surroundings are at the same level is called the neutral pressure line, which can be used to indicate which parts of the climate shell are exposed to negative or positive pressure. In Figure 6 it can be observed that the further down the neutral pressure line moves, the greater the infiltration through the upper part of the climate shell.

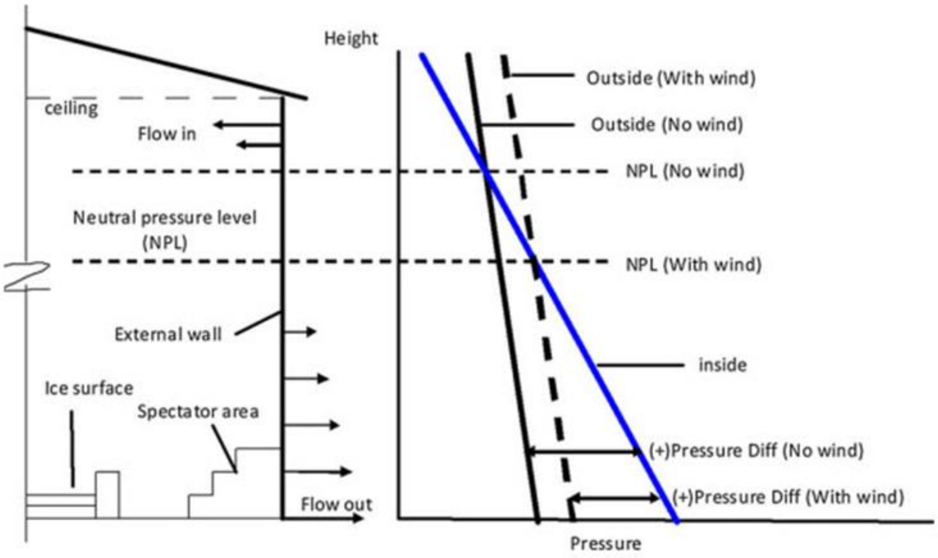


Figure 6. The chimney effect in an ice rink.(Lin & Chuah, 2010)

The chimney effect is a contributing cause of air leakage and therefore plays a major role in moisture transport in ice rinks. When the indoor air has a lower absolute humidity than the outdoor air, this means that the infiltrating air brings moisture into the facility. Since the infiltrated air replaces the air that was exfiltrated on the other side of the neutral pressure line, one can calculate the humidity increase in the ice hall by multiplying the volume of the infiltrated air with the difference of the absolute humidities of the outdoor and indoor air. In a functioning facility, it is mainly the dehumidifier that removes this supplied moisture in the arena room or it is "captured" by the ice via diffusion.

During periods when the outdoor air is drier than the indoor air, the reverse occurs, i.e. moisture is taken out of the ice rink via exfiltration. If an acceptable humidity level can be maintained in the ice rink and its climate shell via this natural process, there is no need for the dehumidifier to be in operation.

The ventilation system can, like the wind pressure, affect the chimney effect in the facility, but in normal cases the ventilation system is operated so that the ratio of supply and exhaust air is balanced, which means that it does not have a contributing effect.

2.1.2 Results from previous studies of air leakage

There are only a few previous studies that have attempted to measure and/or evaluate air leakage in ice rinks. One of them was performed in an ice rink in Taipei, which is located in a subtropical climate zone. The results showed that the air change per hour due to air leakage in the 49,000 m^3 the large arena was between 0.43 and 0.51 (ie between 21,000 and 25,000 m^3/hrs). It will turn out that this is a very large air leak and the reason is the big difference between the hot and humid surroundings and the relatively cold and dry air in the arena room. The differences in moisture ratio were as large as up to 14 gH2O/kg, air, which creates both large operating forces but above all a large moisture addition (Lin & Chuah, 2010).

In another study in a Swedish ice rink with an internal arena room volume of approx. 25,000 m3, they used the dehumidifier's operating data, and were able to calculate that the air leakage in the facility was 7067 m^3/hrs. This corresponds to an air turnover of 0.28 turnovers per hour (Rogstam & Mazotti, 2014a).

Calculation tools from suppliers of dehumidification systems give an indication of how much dehumidification capacity it thinks is needed in an ice rink! By studying a couple of current tenders including dimensioning calculations, it has been established that the air leakage in the current cases was assumed to be between 5 and 8 percent of the arena room's volume per hour, i.e. an air turnover corresponding to 0.05 and 0.08.

2.1.3 Analysis and measurement method and results of air leakage in ice rinks

Measuring air leakage under relevant conditions in an ice rink is a rather delicate task. Therefore, this study has concentrated on "indirectly" measuring and then analyzing the air leakage. First, basically the same method as Rogstam & Mazzotti 2014 was used, where the dehumidifier is allowed to act as a mass flow meter. In the next step, CO2 concentration measurement and its decay time are used as a measure of air turnover.

The first method to be able to calculate the air leakage is based on the moisture balance in the arena room of an ice rink. In the equation below, the moisture sources are on the left side and the moisture sinks are on the right side.

$$\dot{m}_{infiltration} + \dot{S}_{internally} + \Delta\dot{m}_{ventilation} = \dot{m}_{diffusion} + \dot{m}_{dehumidification} + \dot{m}_{exfiltrating}$$

In an ice rink where the indoor climate is controlled towards absolute humidity, an analysis based on the equation above can be carried out. To accomplish this, data has been collected in a facility where the absolute humidity is constant, between 3.8 and 3.9 g of water vapor per kg of air. In the calculations, the moisture transport to the ice via diffusion is assumed to be constant, since the ice temperature is also constant throughout the season. The internal moisture source, i.e. the one that arises from the use in the facility, it is also considered to be constant and even if this is not completely correct, from an overall point of view it is a matter of short-term deviations which should not significantly affect the results. Normally, the ventilation system should not need to bring in fresh air, as it is assumed that air leakage is sufficient to maintain the necessary CO_2-levels in the facility, which means that this too can be disregarded in the equation.

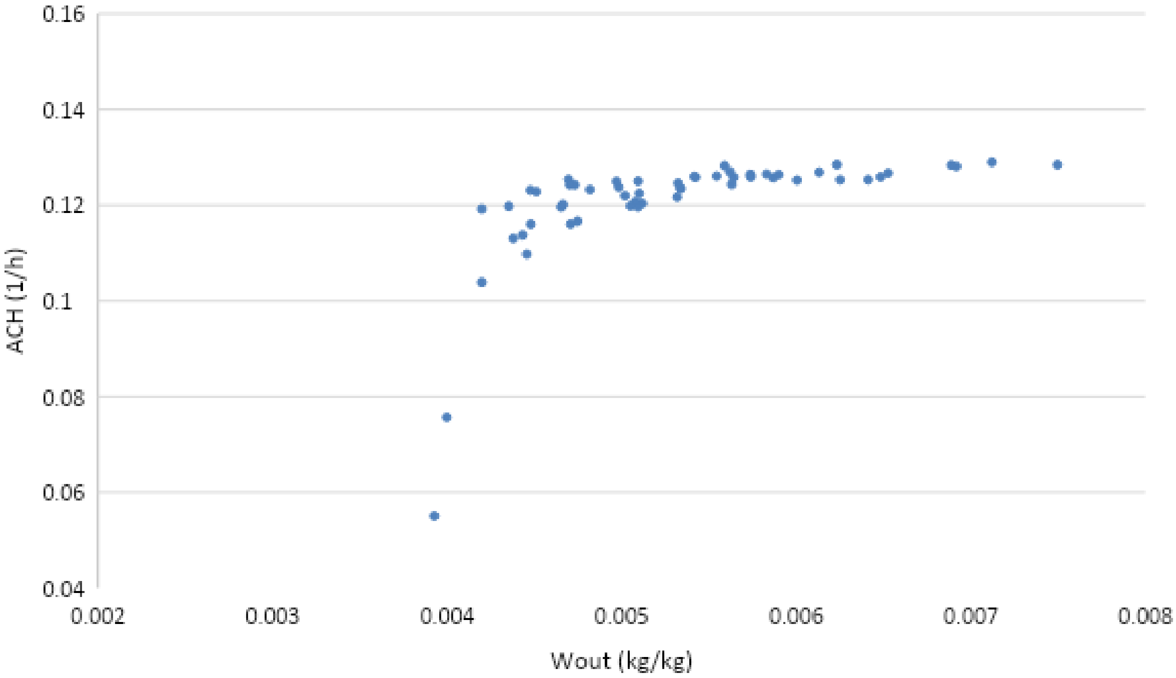


Figure 7. Air change per hour due to air leakage in a studied ice rink.

The remaining variables that, under these assumptions, can still change are $\dot{m}_{infiltration}$, $\dot{m}_{dehumidification}$, and $\dot{m}_{exfiltrating}$. With available data regarding internal and external moisture levels as well as from the operation of the dehumidifier, the air leakage in the ice rink can be analysed. Figure 7 shows the result from the calculations based on the aforementioned assumptions where each point represents the daily mean value.

In Figure 7, it can be observed that when the external moisture levels lead to a need for dehumidification in the facility, an amount of air is treated in the dehumidifier that corresponds to an air change of up to 0.13 per hour in the arena room of the ice rink. This can be interpreted as the air leakage in the space and is estimated to be around 3000 m^3/h, as the total volume of the arena room is approx. 23,000 m^3. As the humidity of the outdoor air approaches the state of the indoor air, the calculation goes towards infinity and therefore the curve "dives" when it approaches approx. 3.9 g of water vapor per kg of air.

The second method mentioned above is the one based on CO2 concentration measurement of the air in the arena room. This type of measurement is quite easy to perform for a given period of time where then variations that follow the activity in the facility can be clearly followed.

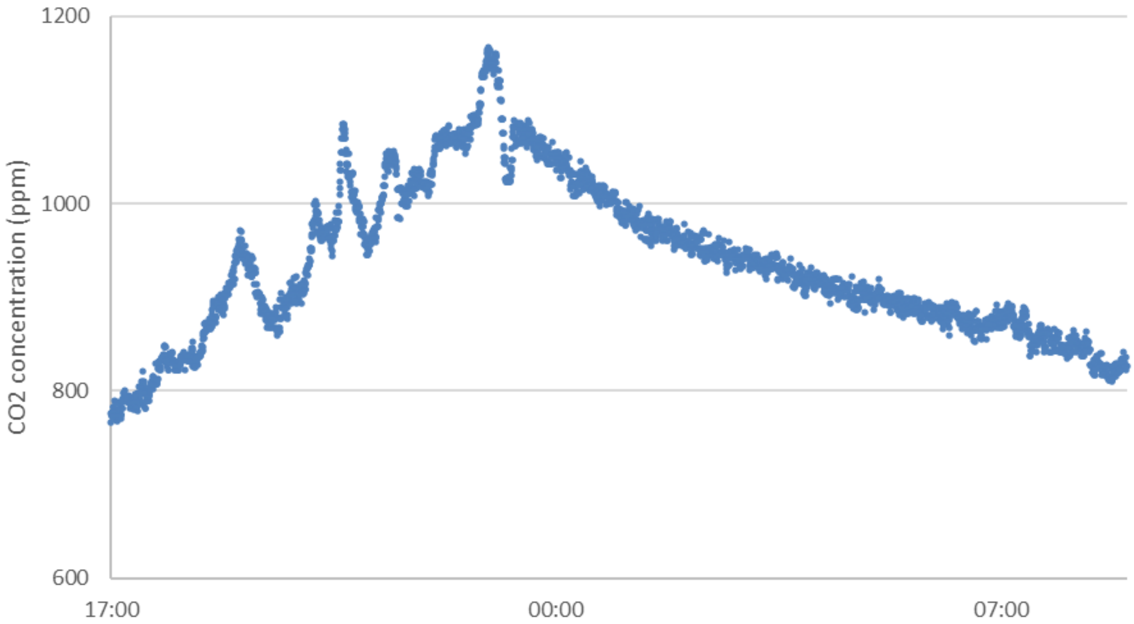


Figure 1 CO2 concentration in an ice rink during and after activity time.

As an example, Figure 1 shows measurement data where the clearly increasing CO2 concentration is visible during activity time (in the evening), while it fades away during the night. The fact that the concentration decreases (fades) is then due to the fact that there are no more people in the premises and that the air leakage, which is assumed to be constant, then gradually dilutes the higher indoor concentration. If one makes the assumption that the period after activity is still representative of the rest of the time when the facility is in operation, the decay process can be analyzed. To calculate the air exchange/leakage, a method is used where the CO2 concentration in the indoor and outdoor air is analyzed over a limited time. (Schibuola, Scarpa, & Tambani, 2016). The outdoor air, which replaces the indoor air, is assumed here to have a constant CO2 concentration of about 400 ppm.

Below is the equation and parameters used:

$$BUT = -\frac{3600}{t} \cdot ln\left(\frac{C(t) - C_{ext}}{C_0 - C_{ext}}\right)$$

Where the following parameters are used:

ACH - Air Change per Hour	[h^{-1}]
t – Time period	[s]
C(t) - CO2 concentration after time interval t	[ppm]
C_0 - CO2 concentration before time interval e.g	[ppm]
C_{ext} - CO2 concentration in the surroundings (outdoors)	[ppm]

The results from the methods reported above as well as a number of measurements carried out in some ice rinks are included in the table below. Table 1 contains different types of facilities and that these are analyzed with different methods, which explains the large spread in the results. Not unexpectedly, it can be seen that the leakage tends to increase with increasing building volume. However, the data are too limited to draw any far-reaching conclusions. What we can say is that for arena rooms around 25,000 m3, which corresponds to the bulk of Swedish ice rinks, the leakage normally appears to be within 5-15%.

Table 1 Calculated air leakage in some ice rinks of different types and sizes.

	Type	Volume (m^3)	The building's internal surface (m^2)	Air leakage	
				BUT (h^{-1})	l/s per m^2 wall and ceiling surface (internal surface)
Ice rink 1		23 500	4400	0.13	0.19
Ice rink 2		25 200	4140	0.064	0.11
Ice rink 3		No information	No information	0.15	-
Ice rink 4		54 000	No information	0.27	-
Ice rink 5		16 700	No information	0.08	-
Ice rink 5		108 000	10480	0.14	0.40
Ice rink 6		49 000	6800	0.45	0.90

2.2 Diffusion through the climate shell

Diffusion through the climate shell, see Figure 8, is another type of moisture transport that occurs in parallel with air leakage. This type of moisture transport occurs in the vapor phase through different materials, where water vapor diffuses from higher vapor content to lower vapor content to equalize the concentrations. The driving force is thus the difference in vapor content, which creates differences in the partial vapor pressure. The magnitude of this type of moisture transport through the climate shell depends on how large the diffusion resistance of its material layer is.

Compared to air leakage, diffusion through the climate shell is a much slower process, which means that its role as a source of moisture in an ice rink becomes significantly less. In a study that compared different wall constructions in an ice rink, it was possible to conclude from the calculated results that diffusion through the wall of an ice rink has an insignificant effect on the humidity level in the arena room. In one example, it has been calculated that during the month of August, when the difference in moisture level is greatest, 135 g of water per hour is transported via diffusion into the ice rink. This result provides a strong argument that diffusion through the climate shell does not need to be taken into account when calculating the moisture balance in an ice rink (Yousif & Douglah, 2017).

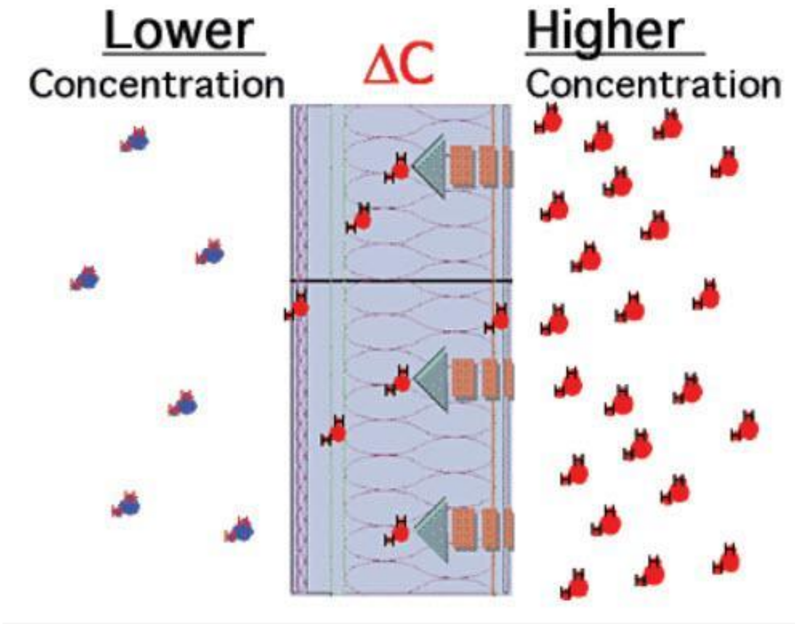


Figure 8. Moisture transport through a climate shell via diffusion.(BNP Media, 2006)

However, diffusion can have a much more serious effect on the climate shell itself, if it has not been dimensioned for the local climate or due to flaws in the construction. There is then the risk that moisture condenses or that the relative humidity becomes too high in one of the layers of the climate shell, which creates favorable conditions for, for example, microbial damage, which in the worst case can lead to structural problems. To avoid this, one should be able to determine in which direction the diffusion usually takes place and, based on this information, dimension the construction so that the relative humidity does not become too high in any of its layers. When dimensioning, you should analyze the risk of moisture damage in the structure from a year-round perspective, where you use data for the current ambient climate and the dimensioned indoor climate in the ice rink. Although there is a risk of condensation in walls and ceilings under certain climate conditions, a solution can be approved if it is a question of short periods and if it has time to dry out in drier climate conditions.

In part 1 of the NERIS project, three climate areas in Sweden and their moisture levels were analysed. These climate areas were chosen to be able to represent the northern part (Kiruna), middle part (Stockholm), and southern part (Malmö) of Sweden. A clear trend in terms of absolute humidity could be observed where in the northern climate range it was in the range 1.0 – 6.3, in the middle range 2.5 – 9, and in the southern range 3.5 – 9.6 g water vapor per kg dry air. This suggests that the direction of diffusion in an ice rink's climate shell will partly depend on geographical location but mainly on time of year. For most of the season in most of the country, moisture transport will be from the outside in. At the same time, the moisture content in the hall drops when it drops outside, see Figure 2, so it is seldom that the moisture content is lower inside than outside. When this happens, the differences are small and the levels are low, which is why the consequence in the form of moisture transport in the "wrong direction" is minimal.

3 Moisture transport within the ice rink

The previous section discussed how moisture gets in and out of an ice rink. This section will explain what happens to the moisture sim found in the arena room. Since the moisture level of the ambient air is higher than that of the arena room, the ventilation system and air leakage will bring more moisture into the arena room than is taken out. This moisture will burden the moisture sinks in the ice rink, which basically consist of the surface of the ice that absorbs moisture from the air through frost formation and the dehumidifier. Furthermore, there are additional sources of moisture inside the ice rink which further increase the load.

Moisture inside the arena space moves so that the moisture balance between moisture sources and moisture sinks is maintained, and involves the following mechanisms:

- Water vapor released from user(s) and water surfaces.
- Water vapor adsorbed and desorbed by any hygroscopic material present.
- Water vapor that condenses on surfaces colder than the dew point of indoor air and condensed moisture that evaporates from these surfaces.
- Water vapor removed by the dehumidifier.

Below, the most important mechanisms are explained in more depth and their absolute and relative orders of magnitude are reported.

3.1 Diffusion to the ice surface

When moist air in the arena meets the cold ice surface, condensation occurs and frost forms on the ice surface, which means that this type of moisture transport from air to ice also involves a phase change. In order for this to happen, the ice temperature must be lower than the dew point of the air, which is usually the case and especially during the warmer part of the ice season when the humidity levels in the arena room are often at their highest.

This form of moisture transport brings a cost to the ice rink operation, as the condensed moisture increases the heat load on the cooling system. Furthermore, condensation/frost has a negative impact on the ice quality as the ice becomes rough from the frost. However, it is not enough to lower the dew point of the indoor air to below 0 °C with the help of the dehumidifier, as the ice temperature is below the freezing point and condensation inevitably occurs anyway. The goal is therefore to ensure that the condensation does not cause too much stress on the ice and its quality, instead of stopping it altogether.

There are several calculation methods to be able to estimate the amount of moisture that is transferred from the air to the ice surface. When calculating the diffusion flux, it is important to remember that the physical process involves the transfer of both mass and heat in order to correctly predict the magnitude of the moisture transport. Figure 9 shows the results of a study where two different methods were used to calculate the amount of moisture that condenses on the ice, with the area of 1800 m^2, depending on its surface temperature. Assumptions were made regarding the air velocities in the arena room, where higher air velocity increases the flux of both heat and mass transfer.

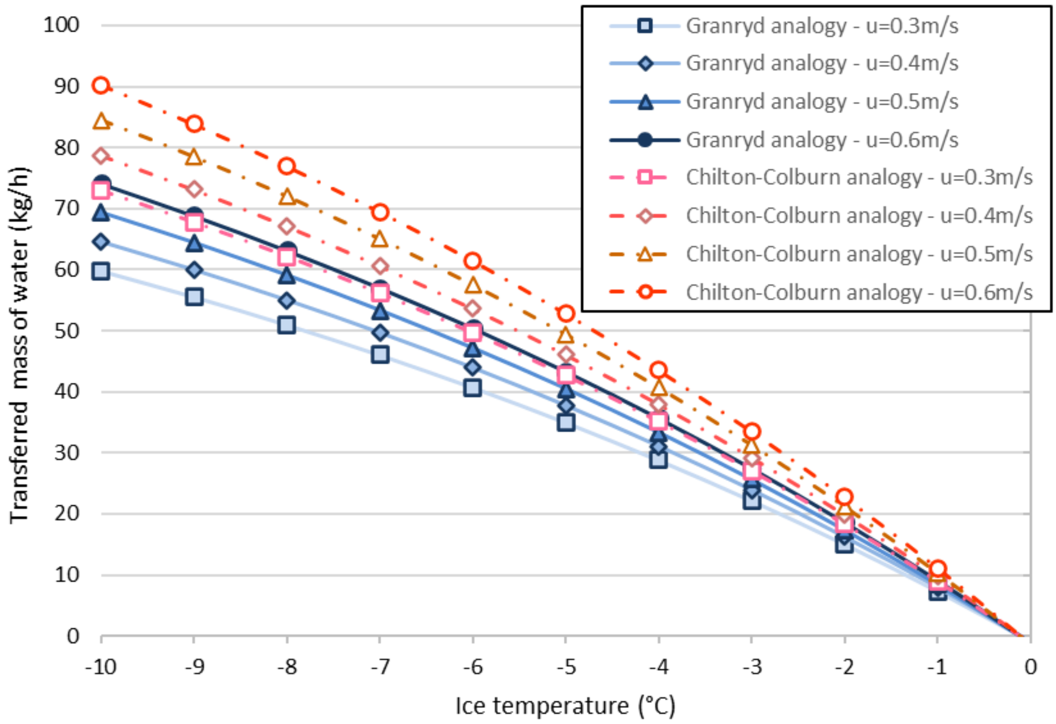


Figure 9. The amount of water transferred from air to ice via the diffusion process. (Rogstam & Mazzotti, 2014b)

It can be noted that the transfer process increases as the ice temperature is lowered, and that it is very sensitive to changes in the driving force. When you e.g. comparing the mass transport at -3 °C and -6 °C, at an air speed of 0.5 m/s and calculations according to Granryd's analogy, the calculation indicates that the amount almost doubles, in this case from 20 to 40 kg/hour. In practice, the air movements are probably lower, which is why the moisture transport to the ice is normally lower than this calculation shows. This study has so far not delved further into refining the calculation but leaves it to future studies.

In order to be able to estimate the amount of moisture that diffuses to the ice in an ice rink, the dimensioned climate conditions in the arena room and the ice temperature must be known. The more humid the indoor air is in the arena room, the greater the mass transfer of water to the ice surface. In the performed calculations, it has been assumed that the air just above the surface of the ice has a dew point of around -0.1 °C.

Figure 10 is based on the previous calculations and assumptions made and shows the latent and sensible heat flow that occurs when the air's moisture diffuses to the ice surface. Here you can see that the dehumidification of the indoor climate that the ice cream contributes to has a cost, i.e. it causes a heat load on the cooling system, which can have consequences in terms of the cooling system's energy use and capacity, as well as a generally deteriorating effect on the ice quality.

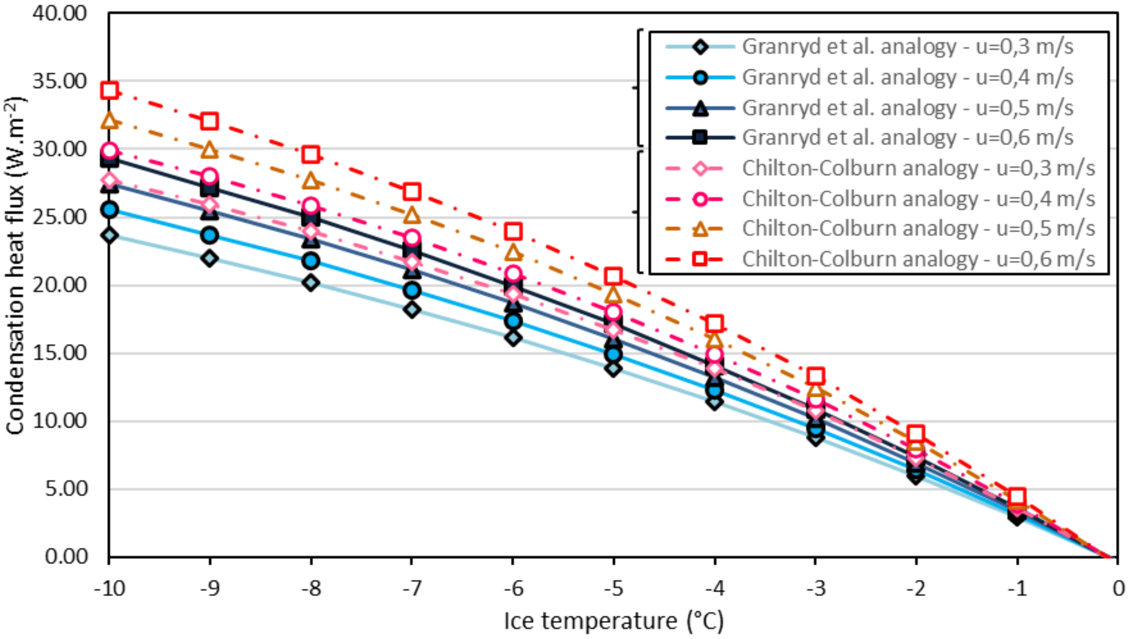


Figure 10. Heat flow that occurs due to the condensation process from the air to the ice surface.

As can be seen in Figure 10, the calculation shows that at, for example, an ice temperature around -3°C, which is normal, the diffusion gives a heat load of about 10 W/m2. This in turn gives a total load of around 18 kW, which is about 20% of the total load on the cooling system.

3.2 Moisture load from ice rink users

Ice rinks are usually public spaces and depending on the type of facility, different events are organized where the audience can be large. This personal load, together with the players' sporting activity, causes a short-term moisture load in the arena room that deserves further investigation to understand its size in the facility's moisture balance.

Water vapor is emitted from humans via sweat and exhaled air. Since ice rink users are generally well dressed with clothes, equipment, etc. that cover most of the body, it can be assumed that most of the sweat will be absorbed by the clothing. Since it is a question of a relatively short load time, the diffusion process from the clothing to the indoor air in the arena room can be assumed to be quite low and sweat as a source of moisture therefore becomes insignificant. In references on the dimensioning of dehumidifiers, the moisture load of 0.35 kg/hour and person has often been used, while if only the contribution of exhaled air is included, the load is as low as 8 g/hour for spectators and 40 g/hour for practitioners.

On the other hand, the breathing air transfers moisture directly to the indoor climate of the arena. ASHRAE proposes a calculation method for estimating the amount of moisture generated by the breathing process in Chapter 9.4 of the ASHRAE Fundamentals handbook, where the type of activity form plays a large role. With a typical case in Sweden as an example, it can be assumed that a hockey match has around 500 spectators and 40 players. According to the calculation method, the total moisture load from the spectators and players at the ice rink is estimated to be 3.9 and 1.5 kg of water vapor per hour respectively, i.e. in total, there will be approximately 5.4 kg of water per hour.

The calculated amount of moisture is noticeable, but since it is a question of a relatively short-term load, no conclusions can yet be drawn as to whether it can lead to moisture-related problems in the arena room. Furthermore, it is not a question of frequent "spikes", as these types of events do not usually take place several times during the day. This source of moisture therefore most likely accounts for a short-term peak in the moisture level of the indoor climate, which can last for a couple of hours and then via e.g. dehumidification return to the normal level determined by the other moisture sources in the arena room of the ice rink.

Another factor that should also be taken into account in these situations is the adsorption capacity of the internal wall and ceiling surfaces, the material of which can temporarily store moisture and thus even out the short-term moisture load. This will be discussed in more depth later in this report.

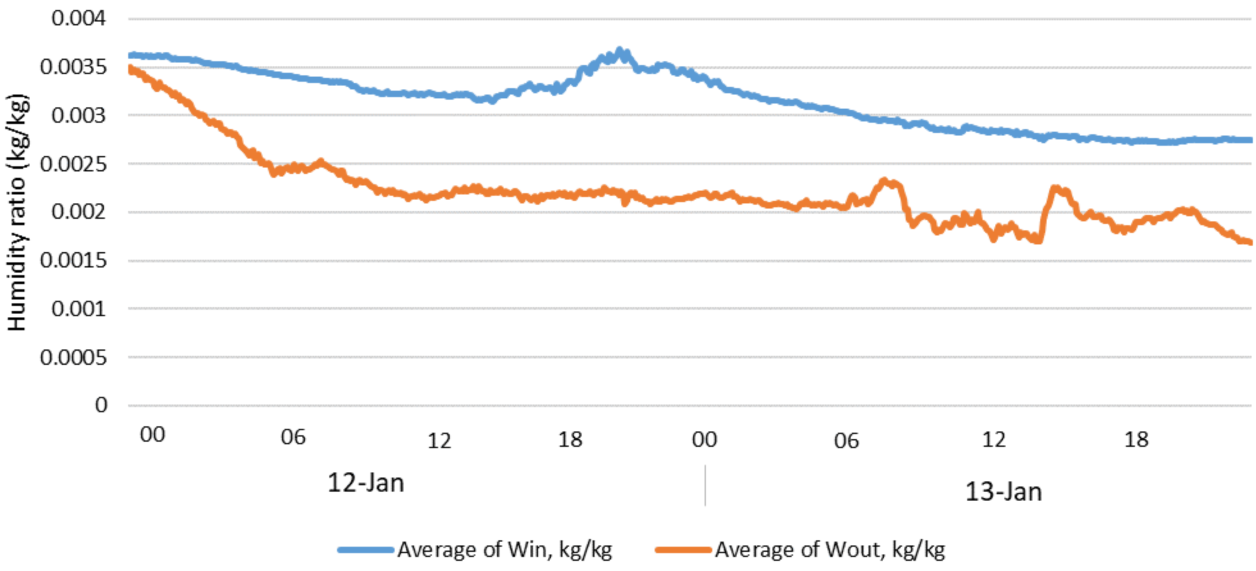


Figure 11. Absolute humidity inside and outside an ice rink over two days.

In cases where the ambient climate is more humid than the arena space of the ice rink, it becomes more difficult to trace the sources that generate moisture inside an ice rink, as they have a significantly smaller impact on the moisture level than the moisture flow caused by the infiltrated air leakage through the climate shell. A practical approach to be able to analyze the moisture load caused by users is to look at the arena room's moisture levels from a 24-hour perspective as in Figure 11, where two days with a dry outdoor climate have been analyzed. Under these conditions, the only noticeable source of moisture should be the ice rink's users, which can be observed on January 12th between 6pm and 9pm when the humidity level rises despite the drier surrounding climate. This indicates that some event, e.g. a hockey match with several spectators, has taken place in the arena room at this time.

The analysis estimates that during these three-hour time intervals, approx. 3.1 kg of water vapor was generated per hour, which is at the same size level as the previously described typical case where the calculations were made with assumptions of 500 spectators and 40 players. However, the calculations carried out in this case are not precise, because under these conditions, exfiltration of moisture out of the plant also took place. More credible results could be obtained if one analyzed a period when the internal and external moisture levels were identical, but with the available data, no temporary moisture loads could be observed in the arena space under such circumstances.

3.3 Dehumidification – Moisture control of the indoor climate

Since starting with artificially frozen ice, it took a while before the importance of dehumidification in an ice rink was understood. In connection with the increased popularity of ice hockey, the season began to be extended, which led to moisture problems beginning to arise in several ice rinks during warmer and more humid periods. In the beginning, they tried to move the air above the ice with the help of fans, but this led to a deterioration of the ice quality and increased heat load. Then they tried to blow out the air from the arena room, but this increased the humidity level further as the blown out air was replaced by more humid air that infiltrated into the facility. Gradually, ice rinks began to be equipped with dehumidifiers, which in today's situation are considered essential if you want to guarantee the ice and air quality in the arena room.

3.3.1 Moisture control within appropriate levels

The purpose of the dehumidifier is to avoid moisture problems in the ice rink. But its control strategy can also significantly affect the facility's energy efficiency, i.e. incorrect settings can lead to unnecessary operation and wasted energy. To avoid over-drying, it should be taken into account that the bed water when applied on top of the ice does not freeze immediately, but will have a temperature of 0°C for a few minutes. If the dehumidifier is set to maintain a humidity level where the dew point of the air becomes lower than 0°C, the bed water will begin to evaporate during the freezing period. In practice, this means that the dehumidification system creates its own load, and that the need for flushing with an ice machine becomes more frequent. Therefore, there is considered to be a strong case for ensuring that the lowest dew point level in the arena space does not fall below 0°C. At least not with the help of the dehumidifier!

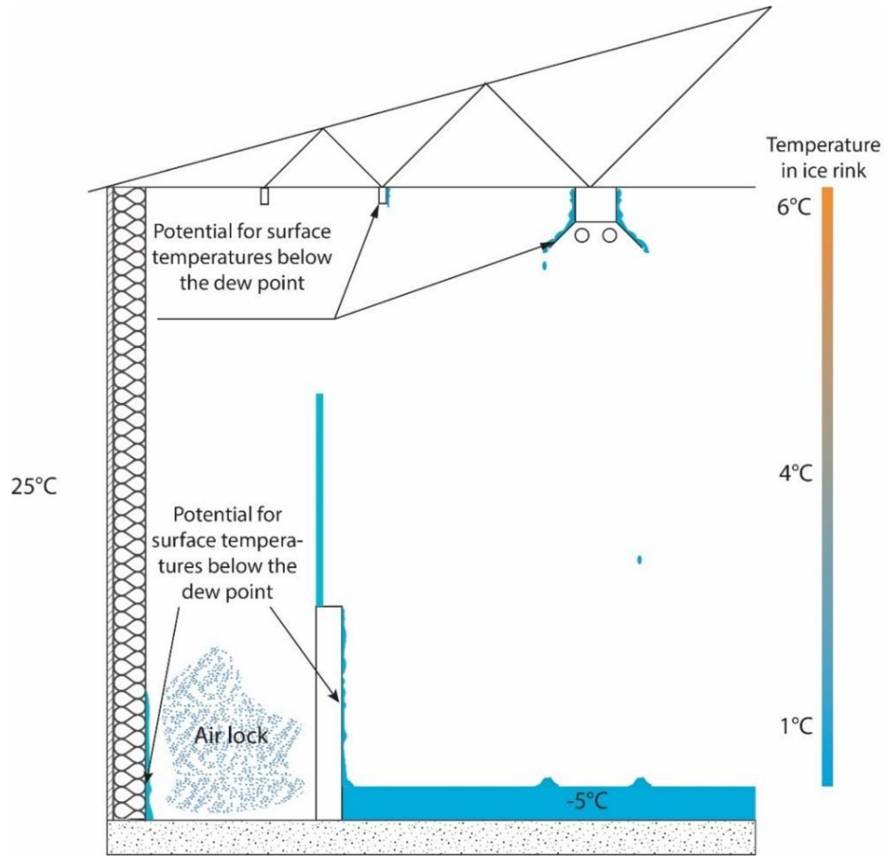


Figure 12. Potential risk zones for condensation in an ice rink.

As the lowest acceptable dew point level is based on the facility's energy efficiency, the highest acceptable level must ensure that moisture problems do not occur in the facility. Figure 12 illustrates the biggest risk zones where condensation can occur in an ice rink. Here it should be noted that metal surfaces, often beams or lighting fixtures, above the ice can have low surface temperatures due to the heat radiation towards the ice. If the air's dew point level exceeds the surface temperature of, for example, these metal surfaces, the moisture will condense on these surfaces. This in turn can lead to microbial damage, rust damage and reduced ice quality, as the condensate often drips onto the ice.

Another surface that is often exposed to the risk of condensation is the edge, whose surface temperature becomes low due to the heat radiation to the ice and because the air near the ice is the coldest. If frost forms on the surface, it can disrupt the game on the ice, as the bounce of the puck against the rim risks becoming unpredictable.

Between the edge and the outer wall, there is a risk of an air pocket arising, if this space is not sufficiently ventilated or lacks heating. This can lower the surrounding surface temperatures further and increase the risk of condensation, especially at the climate shell.

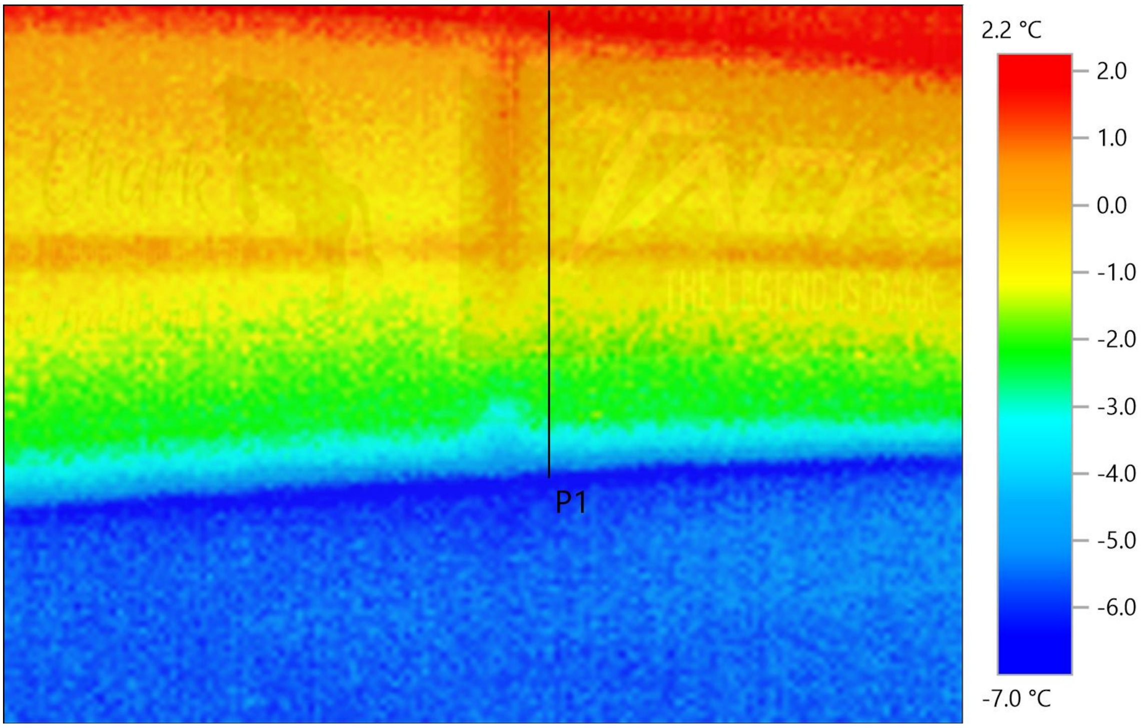


Figure 2 Temperature profile on the inside of the edge In an ice rink with an air temperature of approx. 7°C.

In order to dial in a suitable control interval for dehumidifiers in ice rinks, an upper limit is also needed. Figure 2 shows results from an IR thermography of an (insulated) edge in an ice rink whose air temperature is about 7°C. Even though the air temperature is as "high" as 7°C, the edge's surface temperature is significantly below 0°C. This clearly illustrates where condensation and frost formation will occur and the higher the moisture content (dew point) you have in the hall, the greater the problems. A well-known part of the work in ice rinks is called "ice knocking", which means that you have to manually and mechanically knock away ice from the kick bar and the lower part of the edge. In order to avoid too much ice build-up or condensation on the rim, based on these measurements, the reasoning above and practical observations, it is recommended that the dew point of the arena room is not allowed to be higher than +2°C. In the case above, the upper edge of the edge and the protective glass are about 2°C, which is why condensation would occur there if the dehumidification was not controlled to a lower temperature.

3.3.2 Dehumidifier capacity

Part 2 of the NERIS Project investigated dehumidification techniques, where it emerged that sorption dehumidifiers are best suited to the dehumidification needs of an ice rink and have therefore become the most common solution. In this section, the capacity requirements of a dehumidifier will be examined, as one wants to avoid overinvesting in dehumidification systems to maintain the desired climate conditions in the arena room. At the same time, it is important to install the necessary capacity as the consequences of a lack of dehumidification function can be costly.

In order to be able to analyze the capacity and performance of the dehumidification system, field measurements have been made in several ice rinks. Explicitly measuring the removed moisture/water is possible but difficult and therefore this study has chosen to start from the dehumidifiers' manufacturer data. With said data and measurement of some key parameters which are presented below, the capacity can be calculated.

Available data ie. indoor and outdoor temperatures, as well as the dehumidifier's electricity and heat data, were collected from an ice rink during an entire season. From the dehumidifier's data sheet, you could read out information regarding the calculated dehumidification capacities depending on the properties of the process air, which are illustrated in Figure 13. By interpolating between the respective lines, the estimated capacity can be calculated.

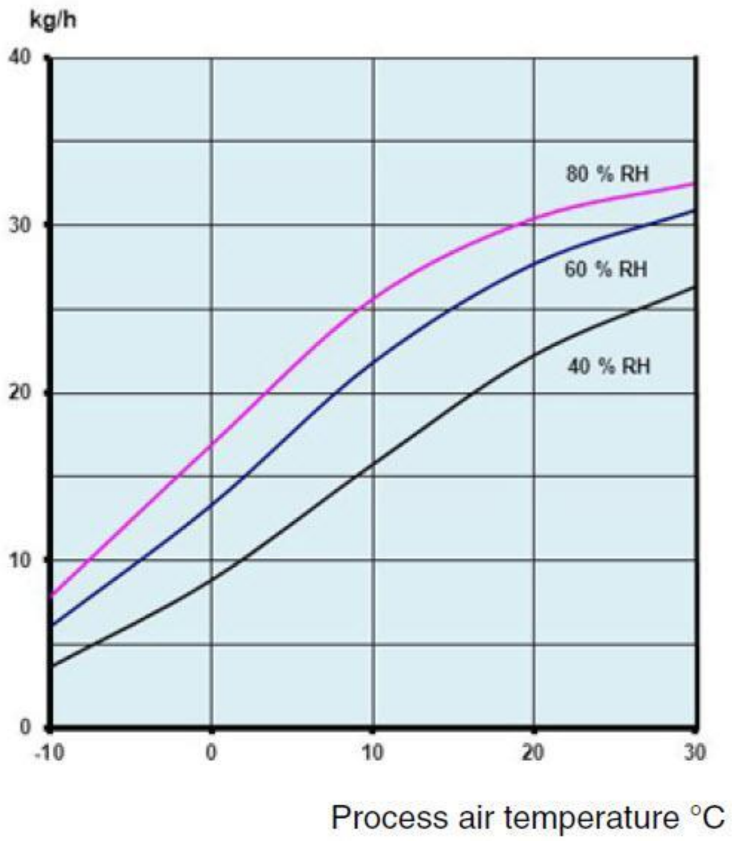


Figure 13. The dehumidification capacity of a dehumidifier depending on the properties of the process air (Munters 2013).

The given specification in Figure 13 shows data at full power operation of the dehumidifier, which does not always have to be the case. The actual degree of dehumidification is therefore calculated in proportion to the ratio of the actual drive power to the designed power. Furthermore, it should be noted that the dehumidification capacity drops the drier the process air is, despite the same heat capacity being delivered to the sorption wheel.

Figure 14 shows the daily average value of the dehumidification capacity in two ice rinks during an entire season, which in this case is shown against the outdoor temperature. From previous reasoning, not least in Neris 1, it has been shown that higher air temperature normally also means higher moisture content in the air. Consequently, the results are logical as the need for dehumidification increases with increasing outside temperature. In ice hall 1, the dehumidifier is regulated based on dew point/absolute moisture content - in this case 3.9 g/kg (dew point approx. 0.4°C). This means that when the moisture content in the outside air approaches this value, the need for dehumidification decreases and, as shown in Figure 14, dehumidification stops at outside temperatures below 0°C. For ice rink 2, which is controlled by relative humidity, the dehumidifier continues to operate even though it is not needed. In the figure below, operating points below -5°C outdoor temperature can be noted.

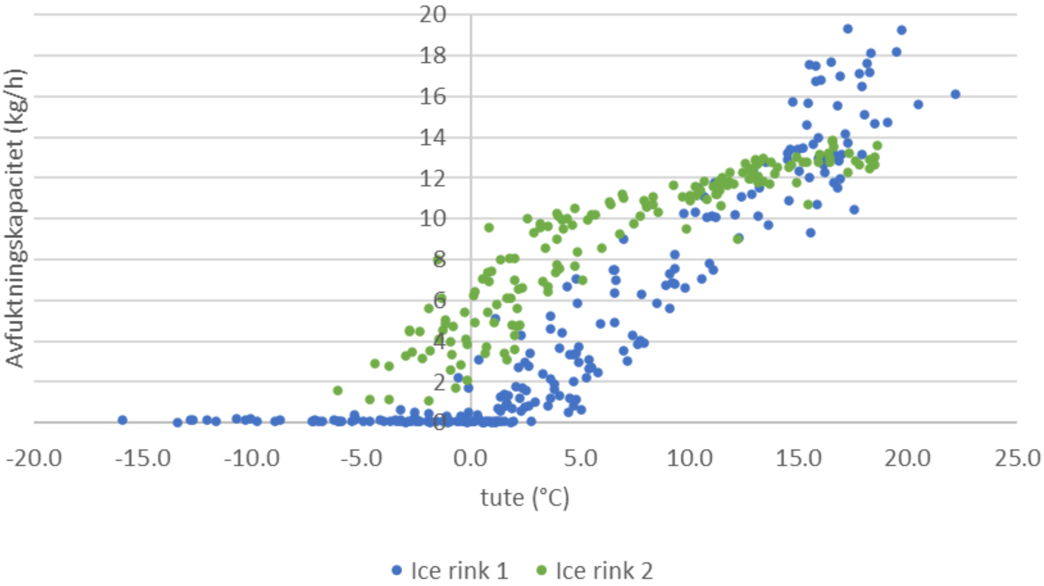


Figure 14. Dehumidification capacity of the dehumidifier in two ice rinks.

The dehumidification capacity of ice rink 1 reaches a maximum of almost 20 kg of water per hour. However, this is not enough during the hottest and most humid time of the season, in these cases during certain days between the end of July and the end of September. Figure 15 shows that the absolute humidity in Ice Hall 1 can then rise up to 5.2 g/kg, which corresponds to a dew point of 4.5 °C.

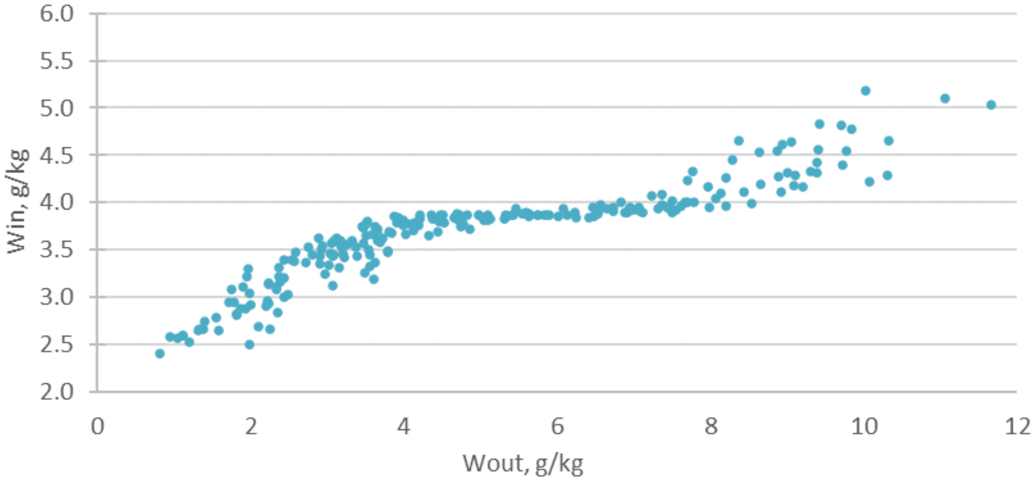


Figure 15. Absolute humidity in the indoor and outdoor air for Ice Hall 1.

With the reasoning from earlier, a maximum acceptable dew point level of approx. 2°C was recommended to avoid condensation and frost problems. This limit is exceeded for a number of days, as the dehumidification capacity is not sufficient to fully handle the moisture load from air leaks and internal sources.

Figure 16 shows the dehumidifier's capacity profile in ice hall 1, where the dew point level of the indoor air can be used as an indicator of the dehumidifier's capacity. It can be noted that when the ambient climate is humid, the capacity of the dehumidifier is not sufficient to keep the indoor climate stable at the desired humidity level. The dew point rises during some short periods and reaches levels of about 4.5 °C. Higher capacity of the dehumidifier would be advantageous in this case. As the ambient climate becomes drier, the required dehumidification capacity drops until it is no longer necessary to keep the dehumidifier in operation.

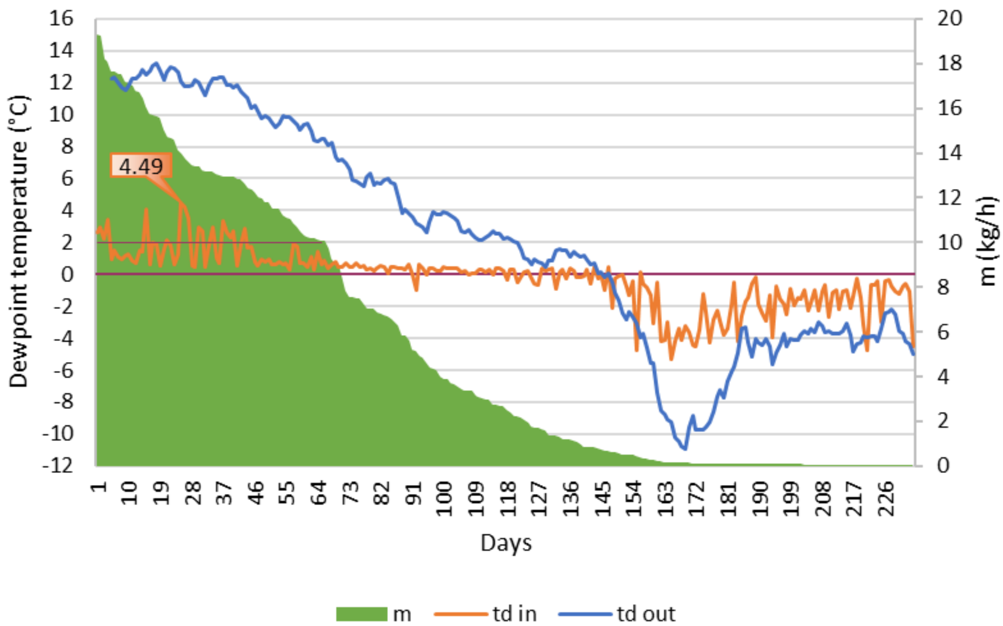


Figure 16. The dehumidification capacity (m) in relation to the dew point (e.g_d) during a full season of operation.

In order to be able to estimate the dehumidification capacity needed, data from the interval where the ice rink's dehumidifier can meet the dehumidification requirement is used. Figure 15 shows this range, i.e. where an almost constant level of the moisture level of the indoor climate can be maintained until the moisture level of the ambient climate becomes too high for the dehumidifier. Figure 17 has compiled the data where the humidity level in the ice rink is kept constant and compares the dehumidification capacity with the absolute humidity of the surrounding climate. Here you can see a trend that can be further extrapolated if you assume that the dehumidification requirement continues to be linear up to the highest measured moisture level in the ambient climate, 12g moisture per kg of air. As a result, the dehumidifier's capacity requirement would then need to be 28 kg per hour to be able to cover the dehumidification needs throughout the season. However, it should be noted that this linear estimation does not take into account changes in the infiltration rate which at higher moisture levels potentially increases, due to higher temperature differences at the climate shell. In that case, this would increase the moisture load in the arena space further - in addition - to what was assumed in this case.

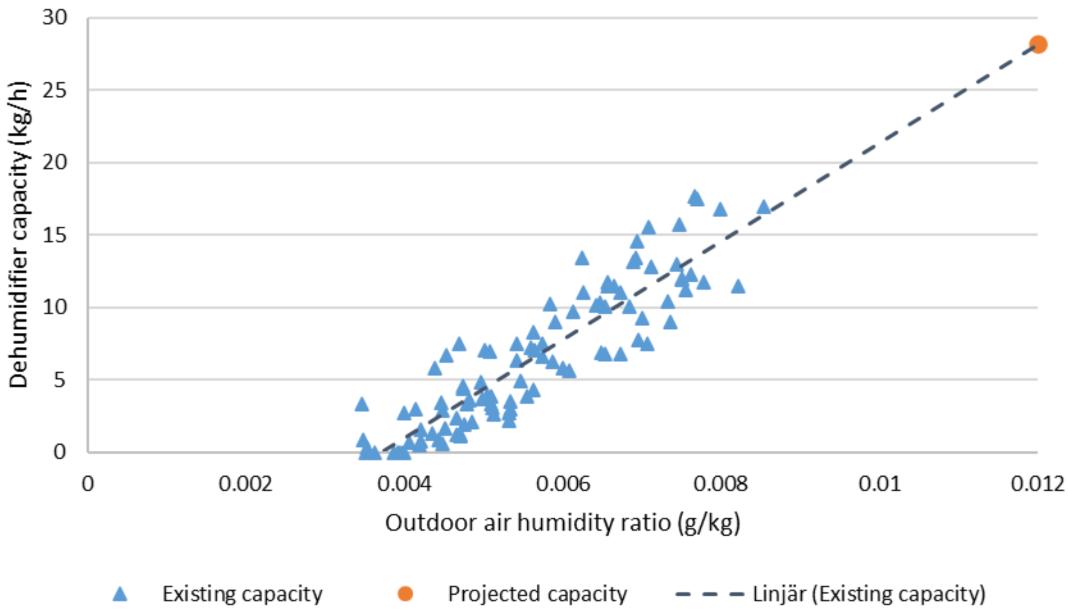


Figure 17. Estimated capacity requirement for the dehumidifier to be able to cover needs throughout the season.

In the ice rink studied, the dew point level of the indoor air exceeded the limit value for around 20 days in total, i.e. about 10% of the entire season. If you want to increase the capacity to cover the dehumidification needs during all the hours of the season, an approx. 30% larger dehumidifier is required. All technical systems are not dimensioned for maximum need, but you "have to live" with certain market values not being maintained in all situations. How important this is and what "degree of coverage" you wish to have with your system is up to everyone to judge. It is also difficult to decide in this situation how many hours a certain "excess humidity" can be accepted. This can be investigated further but is deemed to be outside the scope of this project.

The conclusion from this section is central to this investigation and is summarized by the fact that the capacity requirement for dehumidification in an ice rink of normal to smaller dimensions, i.e. approx. 25,000 m3 volume, is 20-30 kg/hour. In the next part of Neris (4) sizing and specification of dehumidifiers will be discussed.

3.4 Adsorption of moisture in building materials

An additional theoretical moisture sink in an ice rink is adsorption of moisture in its building materials. The impact and potential effect of the building materials as a moisture buffer is briefly touched upon here.

When choosing a building material, its heat and moisture insulation properties are usually among the most important ones examined. Building materials also have different capacities when it comes to storing moisture, which can have a significant effect on the moisture balance of the indoor climate depending on which materials are chosen for the surrounding structures and how the space is used.

During the production of a building material, its porosity is usually examined in a laboratory, which describes the percentage of voids in the material. This void can act as storage space for moisture. Moisture/steam can also be adsorbed directly in the cell wall, as in e.g. wood. The amount of moisture that these hygroscopic, or moisture-absorbing, materials carry is related to the relative humidity of the surrounding air, i.e. when the relative humidity rises, moisture is adsorbed in hygroscopic materials and when the relative humidity falls, desorption of stored moisture from the materials occurs. A hygroscopic material can therefore act as a buffer to handle moisture changes. Fluctuations in the moisture content of the surrounding climate as well as internal moisture sources directly affect the moisture load of the indoor climate, but with a moisture buffer these spikes in the moisture load can be smoothed out. Moisture control in an ice rink can therefore potentially be achieved by applying the dehumidification system in combination with the moisture buffers that hygroscopic materials in the facility potentially provide, such as the climate shell, furnishings and furniture in the arena room.

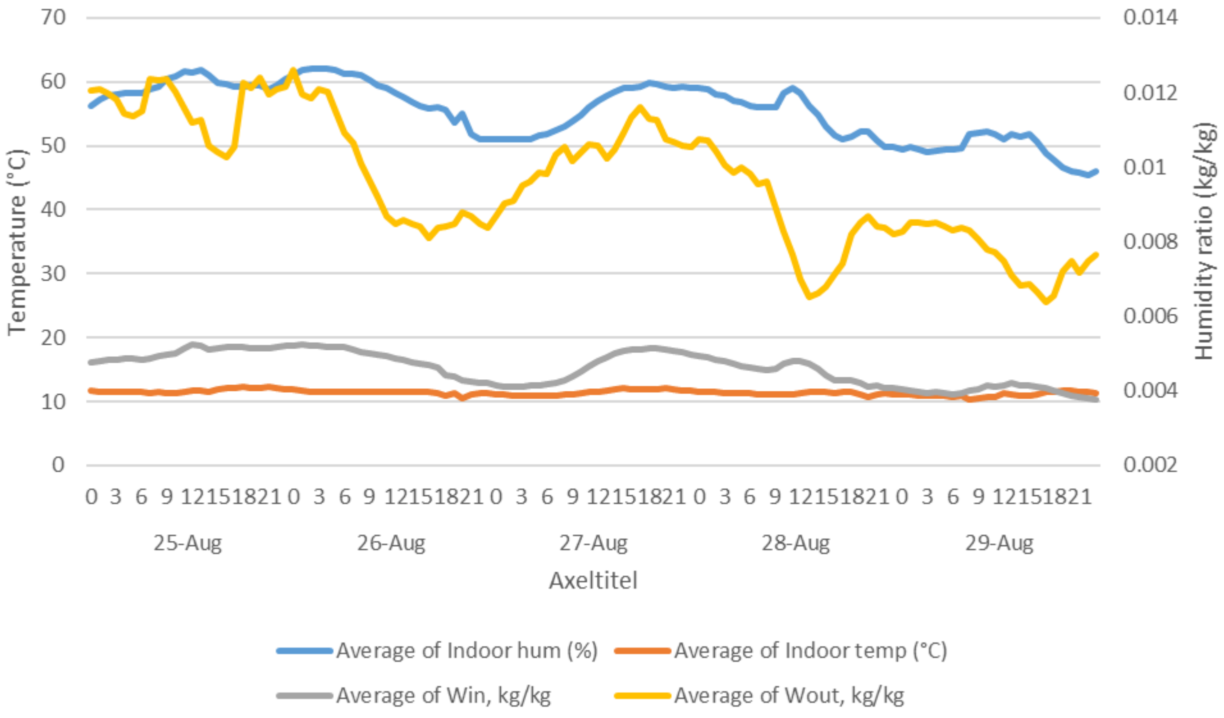


Figure 18. Air parameters that affect the relative humidity inside and outside an ice rink.

Figure 18 shows the air parameters that determine the relative humidity inside and outside an ice rink, where the temperature level of the arena room is kept more or less constant. This means that variations in the humidity of the indoor climate depend on changes in the absolute amount of moisture. From this information it is not possible to calculate the size of the ice rink's moisture buffer, but it can be noted that the fluctuations in the arena room's moisture levels are more evened out than the ambient climate, which can be explained to some extent by the structures' ability to store moisture but also by the air volume itself.

4 Discussion and results regarding moisture loads and moisture management

This study has gone through the various physical mechanisms in a structured way that contribute both to moisture loads and later also to moisture sinks. The potential sources of moisture were listed and analyzed in chapter 2, where calculation bases and assumptions for these were also studied. Previous assumptions found in the literature have been critically reviewed and in some parts revised. In chapter 3, the internal management of moisture in the ice rink was studied by looking at the risk and magnitude of condensation on building parts but also on the ice.

When the sources and sinks have been analysed, these have, where possible, been matched against measurements. Although the study has access to a larger number of field measurements, it is not always obvious to connect theory and practice. In most cases, trends, orders of magnitude, etc. have been able to be verified, which is very valuable in an area where there are few studies and the theoretical connections have large uncertainties.

4.1 Moisture load

To summarize the discussion and the analysis that has been made regarding the loads, these have been illustrated in the figure below. This is to put the contributions in relation to each other, which comes from the fact that in the literature and in practice there is very different information about the size of the various parts. The source of the variations comes from very different assumptions, especially regarding air leakage and internal loads. This study has tried to analyze the loads theoretically in a nuanced way and then put them in relation to the field measurements made to verify the calculations.

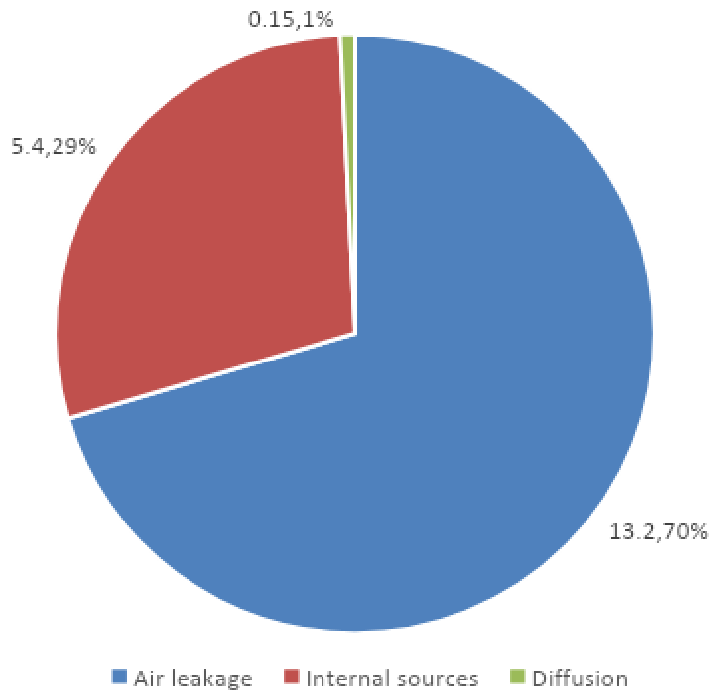


Figure 19. The moisture loads at maximum internal loads and in other nominal conditions an ice rink.

Note: Automatic translation – See original document in Swedish.

In this case, it has been assumed that the indoor/outdoor temperature is 7/15°C, the air leakage is 13% which contributes to the external load and that 500 spectators and 40 players account for the internal loads. As noted earlier, the diffusion through walls and ceilings accounts for a vanishingly small percentage, but it is included to put it in perspective. As can be noted, the total loads amount to just under 20 kg/hour and then the internal loads are at their highest level. During most of the ice rink's usage time, the internal loads are basically 0, which means that the load consists of the air leakage, which in this case would mean about 13 kg/hour.

If, for the same facility, one were to assume the worst case when there is the highest possible humidity in the outdoor air, i.e. 12 g H2O per kg of air, the contribution of the air leakage part would rise to close to 30 kg/hour. The dimensioning internal loads are the same, i.e. about 5 kg/hour, which gives a total contribution of about 35 kg/hour. Now, these levels of load are short-lived in such a facility, which is why you normally do not need to design for these levels.

4.2 Moisture sinks

The two main moisture sinks, ie the ways in which moisture in the ice rink's air is removed, are the ice surface and the dehumidifier. The ice surface is a bigger "dehumidifier" than you might think. The calculations in chapter 3 give by law that the capacity is about 10 kg per hour - depending on the moisture content of the air and the temperature of the ice. The greater the difference in saturation state between the ice surface, i.e. its temperature and the air's moisture content - the greater the mass transport from the air to the ice surface. The calculations made are quite sensitive because they depend on the prevailing conditions in terms of air speeds, air temperature, moisture content, etc. These quantities, apart from the air speed, which is not measured but only assumed, have been measured in the "bulk volume" of the ice rink, i.e. at a great distance from the ice surface. Consequently, the conditions can be quite different, which of course strongly affects the calculation. This area is interesting to continue investigating in the future as it potentially accounts for a relatively large proportion of the moisture transport.

The second and perhaps most interesting part of moisture management is of course the dehumidifier, and it was found that capacities of the order of 20 kg/hour are required when operating during the hottest part of the season. The point loads in terms of moisture in a training or audience hall can be upwards of 30-35 kg/hour at the highest possible moisture content in the outdoor air in combination with the maximum number of spectators. Now it is relatively unlikely that these two maximums coincide, which is why this study assesses that dimensioning capacities up to approx. 20 kg/hour are normally sufficient. In the next part of Neris – part 4 – recommendations for dimensioning dehumidification units but also distribution systems will be dealt with.

5 Conclusions

This part of NERIS has dealt with how moisture transport in ice rinks works. This knowledge is very fundamental partly for being able to dimension the dehumidification function but also for how the climate shell and its constituent materials should be constructed. The study has gone through the various physical mechanisms in a structured way that contribute to both moisture loads and moisture sinks.

It has been shown that the sizing of dehumidifiers in ice rinks has traditionally often been based on somewhat incorrect assumptions. Certain factors such as internal moisture loads have been overestimated while air leakage has been underestimated. Within the framework of this work, measurements have been made in a number of ice rinks to estimate e.g. air leakage. These results have confirmed the picture that this particular source is larger and more dominant than previously thought. It can be seen that leakage tends to increase with increasing building volume but the available data are too limited to draw any far-reaching conclusions. What can be said is that for arena rooms of around 25,000 m3, which corresponds to the bulk of Swedish ice rinks, the leakage normally appears to be within 5-15%.

The internal loads normally consist of users/practitioners and the public who emit water vapor via sweat and exhaled air. Since rink users are generally well dressed, it can be assumed that most of the sweat will be absorbed. For the dimensioning, the moisture load of 0.35 kg/hour and person has often been used, while if only exhaled air is included, the load is as low as 8 g/hour for spectators and 40 g/hour for practitioners. Diffusion through walls and ceilings accounts for a very small percentage and can be considered negligible when it comes to total moisture load. On the other hand, it is important to manage the diffusion during dimensioning, material selection, etc. when walls and ceilings are constructed, otherwise condensation can occur in the construction, which can have very serious consequences. Moisture accumulation in the construction has, in the worst case, led to roof collapse, but moisture damage and mold are more common.

Nominally, the total moisture loads in a normal training/audience hall amount to just under 20 kg/hour and then the internal loads are at their highest level. During most of the ice rink's useful life, the internal loads are very small, which means that the moisture load consists of the air leakage, which in this case would mean about 13 kg/hour. Worst case when there is the highest possible humidity in the outdoor air, i.e. in a summer case, the contribution of the air leakage part would rise to close to 30 kg/hour. The dimensioning internal loads are about 5 kg/hour, which gives a total contribution of about 35 kg/hour. Now, these levels of load are short-lived in such a facility, which is why you normally do not need to design for these levels.

The two main moisture sinks are the ice surface and the dehumidifier. The ice surface has a greater effect than you might think and can transport away 10s of kg of water per hour. A greater difference in temperature between ice and air increases moisture transport from the air to the ice surface. The most important part of moisture management is the dehumidifier and it is about capacities of the order of 20 kg/hour. The point loads can be upwards of 30-35 kg/hour, but this study assesses that dimensioning capacities up to approx. 20 kg/hour are normally sufficient. In the next part of Neris – part 4 – recommendations for dimensioning dehumidification units but also distribution systems will be dealt with.

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