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Report

Temperature independent snow production

State of the Art

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ABSTRACT

Both the reliability of natural snow and the number of potential snow production days with traditional snowmaking equipment are decreasing due to a warmer climate. This is especially the case at lower altitudes. To maintain conditions suitable for winter sports close to cities and highly populated areas in the future, it may be necessary to use snow storage and temperature independent snow production. These techniques are already in use by several ski resorts, but they are both expensive and energy demanding. It is therefore necessary to develop a new approach to snowmaking that allows snow to be made in an energy efficient and environmentally friendly way at temperatures above 0 °C. Utilization of the heat produced in TIS machines, or the use of waste heat for snow production are among the proposed methods to achieve this.

This report begins with a brief description of the currently most used methods for snow production. This is followed by a description of ice production technologies that can be used in temperature independent snow machines, a review of existing TIS systems, and a comparison of these. A summary of two master theses about TIS systems and utilization of the produced surplus heat written in cooperation with the "Snow for the future" project is then given. The report ends with a discussion and conclusions regarding TIS systems.

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APPENDICES

1 Introduction

This report is part of the "Snow for the future" project, and discusses current technology used for snow production with a focus on temperature independent snow (TIS) machines. The purpose of the report is to lay a foundation for the development of more energy efficient and environmentally friendly snow production systems.

The background for the project is the decreasing reliability of natural snow and number of potential snow production days with traditional snowmaking equipment. The annual mean temperature in Norway increased by approximately 1°C from 1900 to 2014, and is expected to continue to rise towards the end of this century. In the report "Climate in Norway 2100", the authors have found that due to climate change, the snow season is projected to become shorter in the entire country, with the greatest reduction in the lowlands. The maximum snow depth is also predicted to decrease for most regions. However, the maximum amount of snow may increase in some areas at higher elevation because the precipitation is expected to increase and much of this will come as snow (Hanssen - Bauer, Førland et al. 2015). The changes in the annual maximum snow-water equivalent (SWE) and number of days with snow cover from 1971-2000 to 2071-2100 for the RCP4.5 and RCP8.5, median projection, are illustrated in Figure 1 and Figure 2.

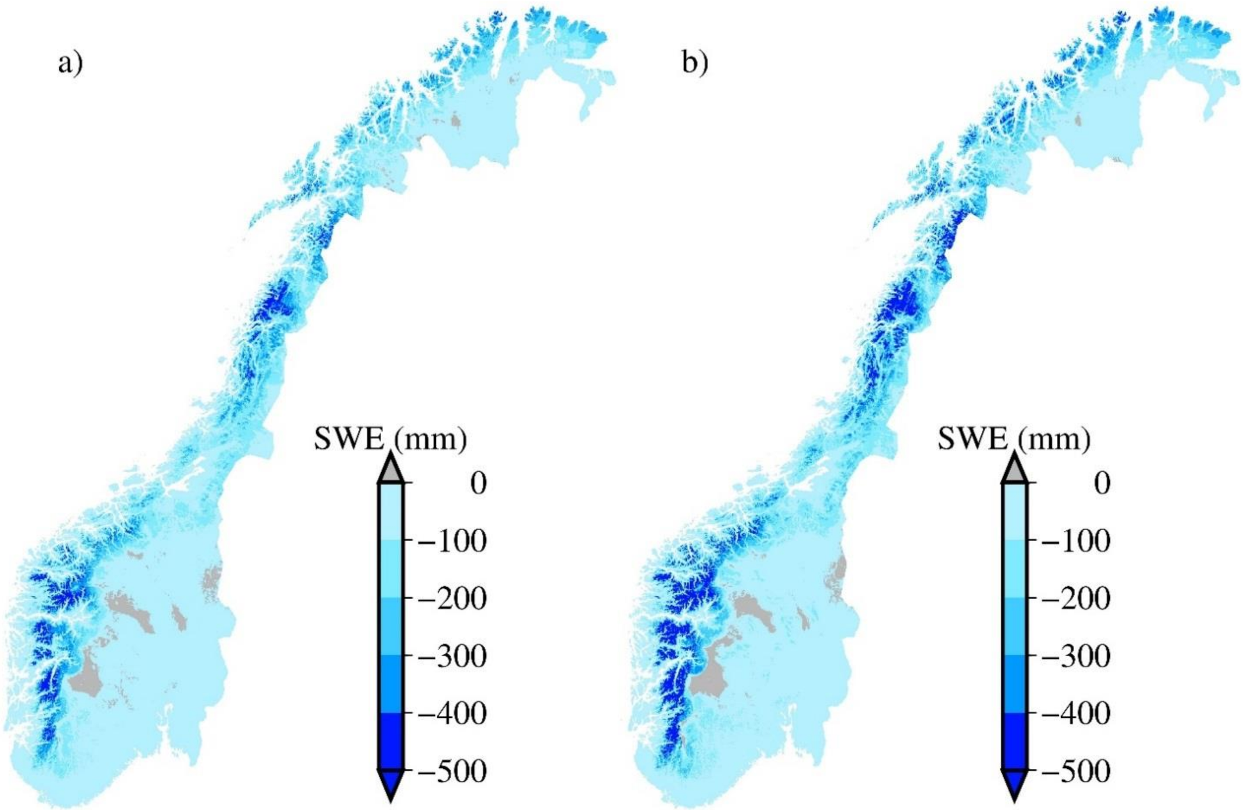


Figure 1: Changes in the annual maximum snow-water equivalent (mm) of the snow reservoir from 1971-2000 to 2071-2100 for a) RCP4.5 median projection and b) RCP8.5, median projection. The figure is taken from the report "Klima i Norge 2100" and reproduced with permission (Hanssen - Bauer, Førland et al. 2015).

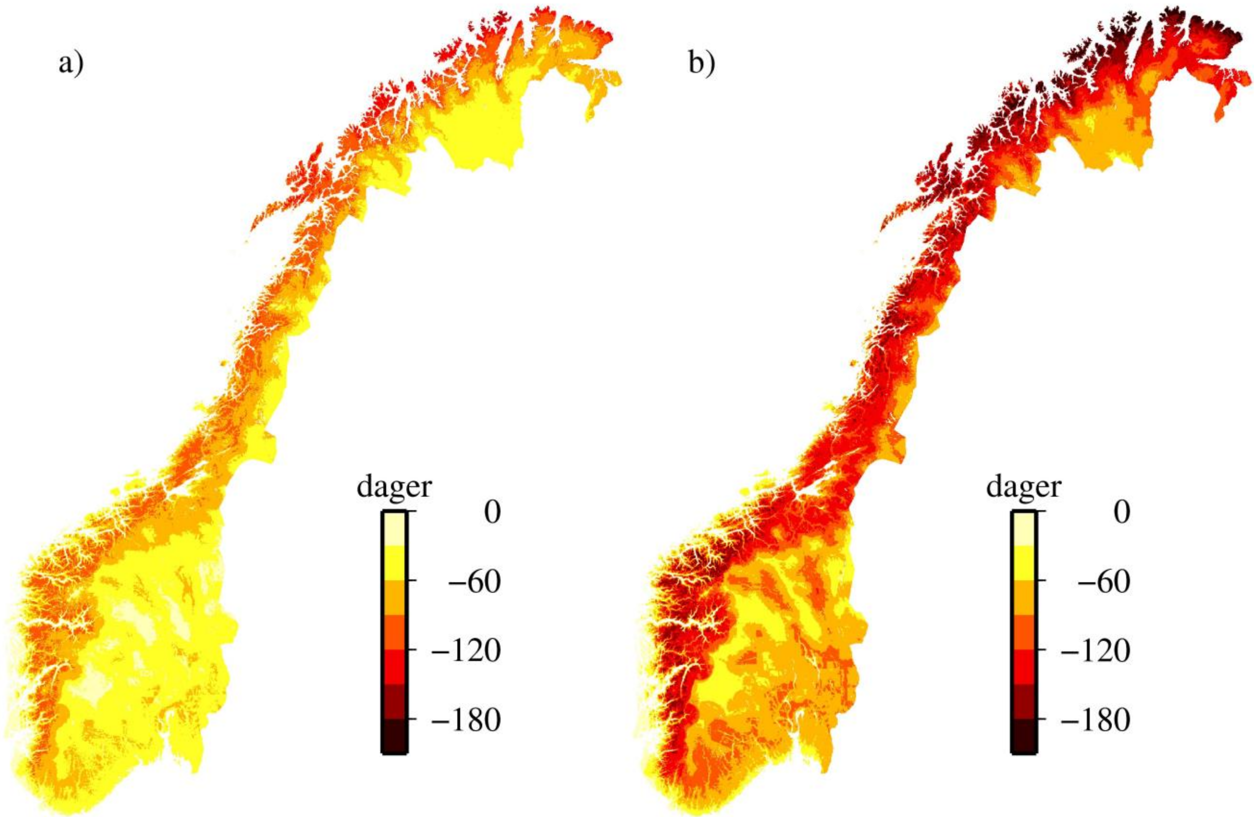


Figure 2: Changes in the annual number of days with snow cover from 1971-2000 to 2071-2100 for a) RCP4.5 median projection and b) RCP8.5, median projection. The figure is taken from the report "Klima i Norge 2100" and reproduced with permission (Hanssen - Bauer, Førland et al. 2015).

There have been several studies on the variability and trends of the Alpine snow cover due to the importance of snow for hydrology and tourism in the European Alps, and the relatively dense network of measurement stations available in some Alpine countries (Christoph 2011). Since the end of the 1980s, there have been anomalous warm winter temperatures, and a general decrease in snow depth and snow cover duration have been observed for low-laying stations. Models for future snow cover with a 2 °C increase in temperature climate scenario have estimated a significant reduction in snow depth below 1800 m, a reduction in snow cover duration of 4 – 6 weeks, and a rise of the snow line by about 300 – 500 m (Christoph 2011).

The strategy of most ski area managers for adapting to the projected climate change is to use temperature dependent snowmaking (TDS) (Steiger and Mayer 2008). However, this method requires temperatures around freezing to produce snow, and several studies have found that this may not be a suitable strategy beyond the short term period (Spandre, François et al. 2016).

There are currently a few TIS machines on the market, but these are very energy demanding. It is therefore necessary to develop a new approach to snowmaking that allows snow to be made in an energy efficient and environmentally friendly way at temperatures above 0 °C. Utilization of the heat produced in TIS machines, or the use of waste heat for snow production are among the proposed methods to achieve this.

This report will briefly describe TDS, which is the leading technology of today for artificial snow production. This is followed by a description of ice production technologies that can be used in TIS machines, a review of existing TIS systems, and a comparison of these. A summary of two master theses written in cooperation with the "Snow for the future" project about TIS systems and utilization of the produced surplus heat is then given. The report ends with a discussion and conclusions regarding TIS systems.

2 Temperature dependent snow production

Artificial snow is used to cover ski runs where natural snow is missing or uncertain and inside indoor centres for skiing. It is also necessary for laboratory experiments to simulate snow and avalanche processes. The first snowmakers were invented and patented in the 1950s to produce snow for ski runs in the United States (de Jong 2011). These were based on the principle of blowing small water droplets through freezing air, such that they freeze before reaching the ground. In Europe, artificial snow was first introduced in the 1970s. Today, 90 % of all ski resorts produce artificial snow (Ofner and Pauly 2006), and many ski runs rely entirely on artificial snow for part of their season. Artificial snow for approximately 166 km^2 are produced annually for ski resorts in the Austrian Alps with a water consumption of about 300 000 m^3/km^2 and a power consumption of around 250 GWh per year (Professional Association of the Austrian Cable Cars 2017).

The most commonly used technologies for snow production are based on the principle of atomizing water in cold air by forcing pressurized water and some amount of compressed air through nozzles. The water droplets will then freeze before reaching the ground if the conditions are right. There are two main types of snowmaking machines using this technique. The first is low-pressure snow guns, where water under pressure is sprayed through nozzles into an air jet produced by a fan, illustrated in Figure 3(left). The second is high-pressure towers, where pressurized water and a larger amount of compressed air is forced through nozzles and atomized, illustrated in Figure 3 (right) (Fauve and Rhyner 2004).

Figure 3: TechnoAlpin's TF10 Fan gun (left) and Borax lance (right) (TechnoAlpin.com 2017). Used with permission from TechnoAlpin.

Three conditions must be satisfied to produce snow with these methods. There must be sufficient energy exchange with the surrounding air to freeze the entire droplet, a freezing nuclei that triggers the freezing process must be present, and the flight time must be long enough for the freezing of the droplet (Fauve and Rhyner 2004). The freezing process is illustrated in Figure 4.

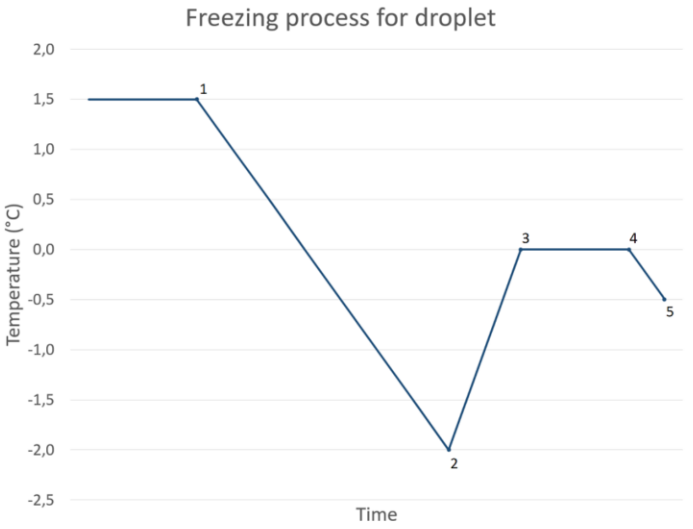


Figure 4: Freezing of water droplet. 1. Water exits nozzle 2. Nucleation temperature reached 3. Droplet partially frozen 4. Droplet totally frozen.

Convective heat transfer with the surrounding air and evaporative cooling reduces the temperature of the droplet. At air temperatures above about – 7 °C the evaporative cooling predominates, while the convective cooling becomes more important at lower temperatures (Chen and Kevorkian 1971). Chemically pure water can remain a liquid down to below – 40 °C, but if it contains freezing nuclei (microscopic particles in the water) it can turn to ice at much higher temperatures. Additives are therefore sometimes added to increase the number of nucleates. The most commonly used additive is Snomax, a natural protein that helps to initialize crystallization (de Jong 2011). When the freezing process starts, heat is liberated and the temperature of the droplet rises to 0 °C. The temperature drops again when the entire droplet is frozen. This process is described in more detail by (Fauve and Rhyner 2004).

Snowgun manufacturers have indicated that a wet-bulb temperature of -2°C is required to produce snow. The wet-bulb temperature is a combination of the relative humidity (RH) and air temperature (dry-bulb temperature), and is always lower (RH < 1) or equal (RH = 1) to the dry-bulb temperature. The efficiency of the snowmakers improves at lower temperatures (Spandre, François et al. 2016). A snowmaking chart that shows the relationship between the wet-bulb temperature, dry-bulb temperature and relative humidity is given in Figure 5.

Dry bulb Temperature (°C) \ Relative humidity (%)	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
4	-2,4	-2,0	-1,6	-1,3	-0,9	-0,6	-0,2	0,2	0,5	0,9	1,2	1,6	2,0	2,3	2,6	3,0	3,3	3,7	4,0
3	-3,1	-2,7	-2,3	-2,0	-1,7	-1,3	-1,0	-0,6	-0,3	0,0	0,4	0,7	1,0	1,4	1,7	2,0	2,4	2,7	3,0
2	-3,7	-3,4	-3,1	-2,7	-2,4	-2,1	-1,7	-1,4	-1,1	-0,8	-0,5	-0,2	0,1	0,4	0,8	1,1	1,4	1,7	2,0
1	-4,4	-4,1	-3,8	-3,5	-3,1	-2,8	-2,5	-2,2	-1,9	-1,6	-1,3	-1,0	-0,7	-0,5	-0,2	0,1	0,4	0,7	1,0
0	-5,1	-4,8	-4,5	-4,2	-3,9	-3,6	-3,3	-3,0	-2,7	-2,5	-2,2	-1,9	-1,6	-1,3	-1,1	-0,8	-0,5	-0,3	0,0
-1	-5,8	-5,5	-5,3	-5,0	-4,7	-4,4	-4,1	-3,9	-3,6	-3,3	-3,1	-2,8	-2,5	-2,3	-2,0	-1,8	-1,5	-1,3	-1,0
-2	-6,5	-6,3	-6,0	-5,7	-5,5	-5,2	-5,0	-4,7	-4,5	-4,2	-4,0	-3,7	-3,5	-3,2	-3,0	-2,7	-2,5	-2,2	-2,0
-3	-7,3	-7,0	-6,8	-6,5	-6,3	-6,0	-5,8	-5,6	-5,3	-5,1	-4,8	-4,6	-4,4	-4,1	-3,9	-3,7	-3,5	-3,2	-3,0
-4	-8,0	-7,8	-7,6	-7,3	-7,1	-6,9	-6,6	-6,4	-6,2	-6,0	-5,7	-5,5	-5,3	-5,1	-4,9	-4,6	-4,4	-4,2	-4,0
-5	-8,8	-8,6	-8,3	-8,1	-7,9	-7,7	-7,5	-7,3	-7,1	-6,8	-6,6	-6,4	-6,2	-6,0	-5,8	-5,6	-5,4	-5,2	-5,0
-6	-9,5	-9,3	-9,1	-8,9	-8,7	-8,5	-8,3	-8,1	-7,9	-7,7	-7,5	-7,3	-7,1	-7,0	-6,8	-6,6	-6,4	-6,2	-6,0
-7	-10,3	-10,1	-9,9	-9,7	-9,6	-9,4	-9,2	-9,0	-8,8	-8,6	-8,4	-8,3	-8,1	-7,9	-7,7	-7,5	-7,4	-7,2	-7,0
-8	-11,1	-10,9	-10,7	-10,6	-10,4	-10,2	-10,0	-9,9	-9,7	-9,5	-9,3	-9,2	-9,0	-8,8	-8,7	-8,5	-8,3	-8,2	-8,0
-9	-11,9	-11,7	-11,6	-11,4	-11,2	-11,1	-10,9	-10,7	-10,6	-10,4	-10,3	-10,1	-9,9	-9,8	-9,6	-9,5	-9,3	-9,2	-9,0

Good snow quality — Poor snow quality — No snowmaking

Figure 5: Snowmaking chart, based on chart from (Eikevik 2017).

The characteristics of artificial snow differs from natural snow. While natural snow grains grow by condensation of water vapor on the grains, leading to a dendritic shape, machine-made snow results from the rapid freezing of water droplets from the surface to the core. This gives a spherical shape and a grain size of 0.05 to 2 mm, which is much smaller than that of natural snow (0.2 to several mm) (de Jong 2011). Due to the rapid freezing from the outside, high pressure can build up when the core starts to freeze. This often leads to building of air pockets that bulge on the surface or fractures of the grains, which results in abrasive behaviour (Fauve and Rhyner 2004). Freshly made artificial snow has a density between 300 and 500 kg/m^3, which is around four times more than new natural snow and close to that of groomed snow (Fauve and Rhyner 2004, de Jong 2011). The high density, small grains and temperature near 0 °C accelerates the sintering process. Machine-made snow therefore quickly acquires a very high strength (Fauve and Rhyner 2004).

3 Temperature Independent snow production

Temperature independent snow is made by producing small grains of ice. There are several methods to do this, and the main technologies are described in this section.

Manufactured ice is used for many different applications such as food processing, storage and transportation, manufacturing and thermal storage. The use of ice is the traditionally most used method for conserving fish during transport, and large amounts of ice are produced in Norway every year. The fish is stored in crates where 25 to 30 % of the weight is ice (Ellingsen, Emanuelson et al. 2009). In 2015, 1 380 841 tons of fish and shellfish was sold from Norwegian fish farms (SSB.no 2017). If we estimate that 1 000 000 tons of the fish was transported on ice, this means that 250 000 tons of ice was produced. That is enough to cover a 200 km long, 5 m wide and 0.5 m deep ski track.

Different kinds of ice can be produced according to the type and size required for the particular application. Ice machines can be classified according to how the ice is produced and whether it is dry subcooled ice, wet ice or an ice slurry (Graham, Johnston et al. 1992). Dry and wet ice are usually produced in systems where heat is transferred from water to a refrigerant through a wall. There are two main disadvantages with this. The first is that ice has a low thermal conductivity, such that the heat transfer rate will decrease as the ice is building up. The second is that the ice easily sticks to the cold wall. An ice removal cycle is therefore usually necessary to remove the ice form the refrigerated surfaces and restore the heat transfer capacity. In machines that produce subcooled ice, the ice is usually removed from the cooling surface by mechanical means, while wet ice is usually removed by a defrosting procedure where the ice is partially thawed. Both methods will decrease the efficiency of the system. This can be avoided in some ice slurry machines (Stamatiou, Meewisse et al. 2005). Most commercial ice is produced by either flake, tubular or plate ice machines (ASHRAE 2014).

3.1 Refrigeration cycle and refrigerants

Ice machines are dependent on a refrigeration cycle. A short introduction of refrigeration cycles and refrigerants are therefore given before the different ice making technologies are described.

3.1.1 Refrigeration cycle

A refrigeration cycle transfers thermal energy from a heat source with low temperature, T_C, to a heat sink at a higher temperature level, T_H. A basic refrigeration cycle consists of an evaporator, a compressor, a condenser and an expansion valve, as seen in Figure 6. The refrigerant enters the evaporator as a liquid, and absorbs heat from the cold side as it evaporates. It exits the evaporator as a saturated or slightly superheated vapor. The vapor is then compressed to the condensing pressure in the compressor before it enters the condenser. Heat is rejected to the heat sink as the refrigerant condenses. The refrigerant is then expanded to the evaporation pressure, and the cycle is completed.

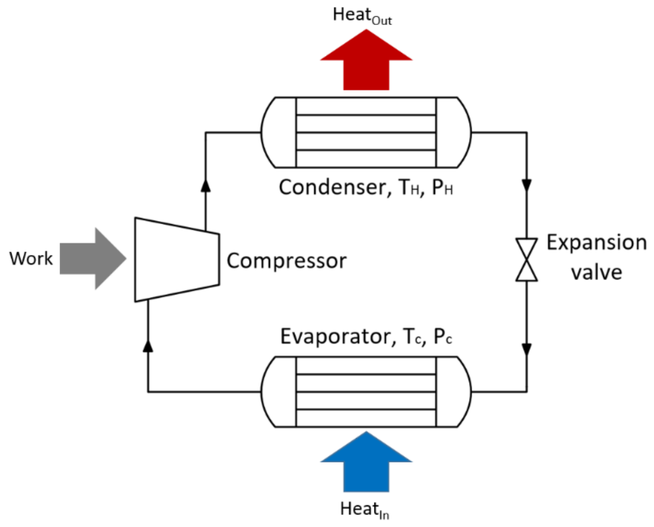


Figure 6: Refrigeration cycle

The performance of refrigeration cycles are usually described by the coefficient of performance (COP), defined as:

$$\text{COP} = \frac{\text{Useful refrigerating effect}}{\text{Net energy supplied from external source}}$$

The energy supply is usually in the form of mechanical or electrical work for mechanical vapor compression cycles. An ideal reversible refrigeration cycle operating between two reservoirs has the maximum possible COP. One such cycle is the Carnot cycle. The Carnot COP is defined as:

$$\text{COP}_{\text{Carnot}} = \frac{T_C}{T_H - T_C}$$

Hence, the maximum possible COP decreases with increasing temperature difference between the cold and the hot side. The departure of an actual cycle from an ideal reversible cycle is given by the refrigerating efficiency:

$$\eta_R = \frac{COP}{COP_{\text{Carnot}}}$$

3.1.2 Refrigerants

Refrigerants are the working fluids in refrigeration cycles, and absorb heat from one area and rejects it to another, usually through evaporation and condensation, respectively. Several factors must be considered when selecting which refrigerant to use. These include thermophysical properties, chemical stability, safety, environmental impacts, cost, availability, efficiency, regulations and compatibility with materials. No single fluid fulfills all the desired attributes, so it is a trade-off when selecting which refrigerant to use (ASHRAE 2013).

Two of the most important environmental parameters are the ozone depletion potential (ODP) and global warming potential (GWP). ODP is a measure of a materials ability to deplete stratospheric ozone relative to R-11, which is set to 1.0. GWP is a measure of a materials ability to trap radiant energy relative to CO_2 (R-744). Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have a high ODP and GWP, and are to be phased out of production under the Montreal Protocol (ASHRAE 2013). Hydrofluorocarbons (HFCs) have a low ODP, and have been used to replace CFCs and HCFCs. They are however powerful greenhouse gases, and account for 2 % of EU's overall greenhouse gas emissions (European-Commision 2017). The amount of HFCs on the European marked will therefore gradually be capped and phased out according to the EU F-Gas Regulations (EU 2014). Hence, it is desirable to use natural refrigerants with ODP and GWP close to zero.

As seen in the examples of commercially available ice making systems in later sections, many of them are offered with refrigerants such as R22 (HCFC), R404A (HFC), R507 (HFC), R134A (HFC) and R717 (natural). Other natural refrigerants that can be considered include hydrocarbons, R744 (CO_2) and water for some of the systems. Data and safety classifications for some selected refrigerants are given in Table 1.

Table 1: Refrigerant data and safety classification for selected refrigerants (ASHRAE 2013). * Sublimes.

Refrigerant number	Chemical name	Chemical formula	Molecular mass	Freezing point (°C)	Normal boiling point (°C)	Critical Temperature (°C)	Critical Pressure (kPa)	Safety group	ODP	GWP
R717	Ammonia	NH_3	17.0	-77.6	-33.3	132.3	11 333	B2L	0	<1
R718	Water	H2O	18.0	0.01	100.0	374.0	22 064	A1		
R744	Carbon dioxide	CO2	44.0	-56.6	-78.4*	31.0	7377	A1	0	1
R170	Ethane	CH3CH3	30.1	-182.8	-88.6	32.72	4872.2	A3		
R290	Propane	CH3CH2CH3	44.1	-187.6	-42.11	96.7	4251	A3		20
R22	Chlorodifluoromethane	CHClF2	86.5	-157.42	-40.8	96.1	4990	A1	0.04	1790
R134a	1,1,1,2-tetrafluoroethane	CH2FCF3	102.0	-103.3	-26.1	101.06	4059.3	A1	0	1370
R404a	R-125/143a/134a (44/52/4)		97.6		-46.2	72.0	3729	A1	0	3700

The safety classifications are from ASHRAE Standard 34 and indicate if the refrigerant is toxic and/or flammable. The leading letters A and B signify “lower” and “higher” toxicity, based on occupational exposure limits. The numbers 1, 2 and 3 indicate “no flame propagation, “lower flammability”, and “higher flammability”, respectively. Group 2 is subdivided based on burning velocity, with 2L implying those more difficult to ignite.

The theoretical calculated performance of some refrigerants for a standard cycle are given in Table 2.

Table 2: Comparative refrigerant performance per kW of refrigeration. Reproduced with permission from ASHRAE. ©ASHRAE, www.ashrae.org. 2013 ASHRAE Handbook—Fundamentals (ASHRAE 2013). *Superheat required.

Refrigerant No.	Refrigerant Chemical Name or Composition (% by mass)	Evaporator Pressure, MPa	Condenser Pressure, MPa	Compression Ratio	Net Refrigerating Effect, kJ/kg	Refrigerant Circulated, g/s	Liquid Circulated, L/s	Specific Volume of Suction Gas, m^3/kg	Compressor Displacement, L/s	Power Consumption, kW	Coefficient of Performance	Compressor Discharge Temp., °C
Evaporator −31.7°C/Condenser 30°C												
744	Carbon dioxide	1.349	7.213	5.35	132.1	7.57	0.0128	0.0285	0.2160	0.5892	1.698	91.3
170	Ethane	1.012	4.655	4.6	153.6	6.51	0.0236	0.0548	0.3567	0.5947	1.681	57.9
1270	Propylene	0.199	1.305	6.57	269.1	3.72	0.0075	0.2266	0.8422	0.3471	2.88	49.1
507A	R-125/143a (50/50)	0.199	1.460	7.34	101.1	9.89	0.0097	0.0949	0.9360	0.3887	2.573	38.1
404A	R-125/143a/134a (44/52/4)	0.190	1.421	7.46	104.9	9.54	0.0093	0.1005	0.9565	0.3853	2.595	38.9
502	R-22/115 (48.8/51.2)	0.183	1.304	7.14	97.8	10.22	0.0086	0.0924	0.9470	0.3651	2.739	41.3
22	Chlorodifluoromethane	0.152	1.192	7.81	155.3	6.44	0.0055	0.1448	0.9326	0.3369	2.967	65.4
717	Ammonia	0.110	1.167	10.61	1079.1	0.93	0.0016	1.0425	0.9643	0.3327	3.007	140.9
Evaporator −6.7°C/Condenser 30°C												
744	Carbon dioxide	2.909	7.213	2.48	129.5	7.72	0.0130	0.0127	0.0977	0.2845	3.514	61.3
170	Ethane	2.024	4.655	2.3	163.1	6.13	0.0222	0.0263	0.1612	0.2786	3.588	46.6
32	Difluoromethane	0.653	1.928	2.95	258.6	3.87	0.0041	0.0563	0.2178	0.1690	5.924	59.7
410A	R-32/125 (50/50)	0.643	1.886	2.94	170.9	5.85	0.0057	0.0406	0.2381	0.1728	5.78	46.6
507A	R-125/143a (50/50)	0.503	1.460	2.9	114.9	8.70	0.0085	0.0385	0.3349	0.1798	5.564	34.2
404A	R-125/143a/134a (44/52/4)	0.486	1.421	2.92	118.8	8.42	0.0083	0.0405	0.3410	0.1785	5.598	34.6
1270	Propylene	0.476	1.305	2.74	294.4	3.40	0.0068	0.0986	0.3359	0.1675	5.975	39.3
502	R-22/115 (48.8/51.2)	0.457	1.304	2.86	109.5	9.13	0.0077	0.0386	0.3527	0.1724	5.799	35.4
22	Chlorodifluoromethane	0.399	1.192	2.99	165.9	6.03	0.0051	0.0584	0.3520	0.1637	6.105	47.8
407C	R-32/125/134a (23/25/52)	0.396	1.267	3.19	167.1	5.98	0.0053	0.0588	0.3518	0.1686	5.93	43.9
290	Propane	0.385	1.079	2.8	288.6	3.47	0.0072	0.1180	0.4093	0.1669	5.987	34.9
717	Ammonia	0.332	1.167	3.51	1113.0	0.90	0.0015	0.3689	0.3313	0.1599	6.254	82.1
1234yf	2,3,3,3-Tetrafluoropropene*	0.250	0.783	3.13	120.5	8.30	0.0077	0.0718	0.5954	0.1715	5.835	30.0
134a	Tetrafluoroethane	0.228	0.770	3.37	153.0	6.54	0.0055	0.0880	0.5745	0.1650	6.063	34.8
1234ze(E)	trans-1,3,3,3-Tetrafluoropropene*	0.168	0.578	3.44	139.6	7.16	0.0063	0.1086	0.7798	0.1658	6.03	30.0
600a	Isobutane*	0.123	0.405	3.29	278.0	3.60	0.0066	0.2984	1.0723	0.1620	6.171	30.0

Ammonia (R717) is a widely used refrigerant in industrial systems. As seen in Table 1 and Table 2, it performs very well and has a low ODP and GWP, which makes it environmentally friendly. The operating pressures are comparable to other common refrigerants and it has a relatively high normal boiling point. Ammonia also has a high volumetric capacity, which leads to small pipe line sizes and compressor volume (Danfoss.com 2017). Other advantages include a good tolerance for mineral oils, low sensitivity to small amounts of water in the system, simple leak detection, good availability and low price (Lorentzen 1995). Ammonia is however both toxic, flammable and incompatible with materials that contain copper. Installations can therefore be relatively expensive since they require steel tubing, semi hermetic compressors and several safety devices (Danfoss.com 2017).

A number of hydrocarbons, such as propane, isobutane and propylene, are commonly used refrigerants. They have an ODP of zero and a low GWP. Operating pressures, pressure ratios and discharge temperatures are similar to that of other common refrigerants. They have excellent thermodynamic and good transport properties. The commonly used hydrocarbons are compatible with standard lubricating oils and machine-building materials, except propylene, which is not compatible with neoprene (Danfoss.com 2017). Hydrocarbons are readily available, inexpensive and non-toxic. The main disadvantage is their high flammability. The cost of commercial and industrial hydrocarbon systems can be relatively high due to the need for safety equipment (Danfoss.com 2017).

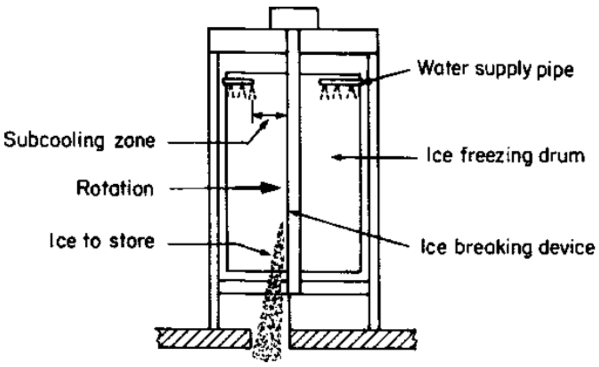
Carbon dioxide (R744) is both environmentally friendly, non-toxic and non-flammable. It was commonly used as a refrigerant from the late 1800s and well into the 1900s (Lorentzen 1995). Lately, it has become a common refrigerant to achieve low temperatures in food and refrigeration industry due to its favourable thermodynamic and transport properties (Bansal 2012). CO_2 requires a high operating pressure for efficient operation, but has a low compression pressure ratio. The low compression ratio improves the volumetric efficiency and allows compressors with smaller swept volumes to be used. CO_2 has a low critical temperature of 31 °C and is used in both sub-critical and trans-critical refrigeration cycles. Sub-critical systems is reported to perform well with respect to energy efficiency compared to other refrigerants (Nekså 2002). Trans-critical systems can be particularly well suited when a strongly gliding temperature for the heat discharge is desired. CO_2 is compatible with common lubricants and machine construction materials, is easily available and inexpensive. Due to higher pressures in trans-critical systems or increased complexity in both trans-critical and sub-critical systems, CO_2 systems tend to be more expensive than traditional systems (Danfoss.com 2017).

Water can be used as the refrigerant for heat pumps and refrigeration cycles down to an evaporator temperature of 0 °C. The benefits of water include that it is environmentally friendly, non-toxic and non-flammable. Its thermophysical properties makes it somewhat less efficient than conventional refrigerants for simple cycle configurations. By using water as both refrigerant and heat transfer fluid, direct contact heat transfer in the evaporator and/or condenser can be used with potential energy savings. This way, the power consumption can be less than for systems with conventional refrigerants (Van Orshoven, Klein et al. 1993). However, low operating pressure results in a very large specific volume (large compressor), and a high compression ratio is required. This combination puts a high demand on the compressor, which has prevented water from being used as the refrigerant in mechanical systems. Due to the vacuum operating conditions, the pressure difference between the evaporator and condenser is small, leading to small aerodynamic forces on the compressor. This allows for a light construction and the possibility to use unconventional materials which can lower the cost (Van Orshoven, Klein et al. 1993). Large centrifugal compressors with a diameter of 2.6 m, titanium alloy steel blades, a blade thickness of 1.5 mm, and a pressure ratio between 2 and 3 are used in vacuum ice makers (Ophir 2008). The investment costs of water based refrigeration cycles is much higher than for HFC based refrigeration cycles, according to (Lachner, Nellis et al. 2007).

3.2 Ice machines

3.2.1 Flake Ice

Flake ice machines are available in cylindrical drum and disk type designs. The ice is produced by applying water on either the inner or outer surface of a refrigerated cylindrical drum, as seen on the left in Figure 7, or on a refrigerated disk (Figure 7, right). The drum type is available in both vertical and horizontal arrangements. Some models have a rotating drum and a stationary scraper on the outside that removes the ice from the cooling surface. Others have a stationary drum and a rotating scraper on the inside. The removed ice falls into a bin below the ice machine and can then be further processed and transported to storage. The disk type is available in a vertical arrangement and rotates about a horizontal axis (ASHRAE 2014).



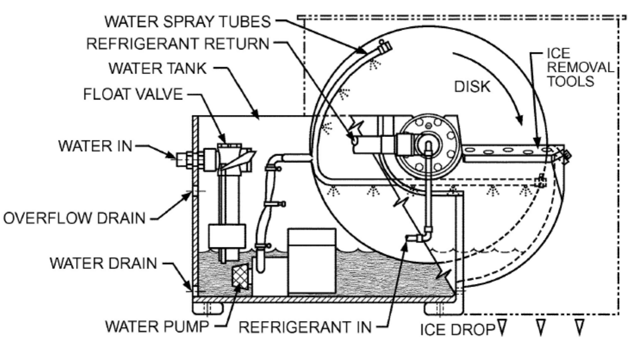


Figure 7: Drum type (left) and disk type (right) flake ice machines. Drum type illustration from (Graham, Johnston et al. 1992), reproduced with permission. Disk type reproduced with permission from ©ASHRAE, www.ashrae.org. 2014 ASHRAE Handbook—Refrigeration (ASHRAE 2014).

The rotational speed, evaporator temperature, and water flow in the ice machines are variables that can be adjusted to regulate the capacity and thickness of the produced ice. The thickness ranges from 1.0 to 4.5 mm and the ice is usually harvested as dry subcooled flakes of 100 to 1000 mm^2 in area. The degree of subcooling depends on several factors, but the evaporating temperature and time for the ice to reach the subcooled temperature are the most important. The subcooling region is immediately before the scraper, where no water is added, allowing the ice to reach a subcooled temperature (Graham, Johnston et al. 1992, ASHRAE 2014).

Flake ice machines usually operate with an evaporator temperature of -20 to -25°C, which is substantially lower than in other types of ice machines. This is necessary to produce ice at a high rate and keeping the machines small and compact. The lower evaporating temperature results in an extra power requirement in the refrigeration cycle. This is somewhat compensated for by the fact that the flake ice is produced continuously without an intermittent defrost cycle, such that no additional refrigeration load is incurred for releasing the ice from the cooling surface. The unit capacity of flake ice machines ranges from 0.5 to 60 tons/24 hrs. When high capacity is required, it can be convenient to use two or more units in parallel, rather than a single unit. That way the flexibility for operating at reduced capacity is improved and the risk of a complete breakdown is reduced. This is also applicable for other types of ice machines (Graham, Johnston et al. 1992).

As an example of commercially available flake ice machines, the North Star Ice Equipment Corporation delivers ice machines with an enclosed vertical drum design. They report a refrigeration requirement of 4.67 kW of refrigeration per ton of ice (i.e., 112.1 kWh/ton) if the makeup water is 5 °C and 5.91 kW with 27 °C makeup water. The capacity of their different models ranges from 2.7 to 52.8 tons/ 24 hrs. Specifications for North Star's Model 90 CS flake ice machine is given in Table 3 (NorthStar.com 2017).

Table 3: Specifications for North Star's Model 90 CS flake ice machine (NorthStar.com 2017).

Producer	**North Star Ice Equipment corporation**
Model	Model 90 CS
Capacity (tons/ 24hrs)	44.1
Refrigerant	R-717
Evaporator temperature (°C)	- 26
Water supply temperature (°C)	15.5
Refrigeration/ton of ice (kW/ton)	5.02
Refrigeration/ton of ice (kWh/ton)	120.5

Flake ice is the most commonly used snow substitute (Paul 2002). Several manufacturers can deliver snowmakers based on flake ice machines. TechnoAlpin, North Star Ice Equipment Corporation and Focusun are described in Section 4.4, 4.6 and 4.7. Technical specifications for some commercial self-contained flake ice systems are given in Table 4.

Table 4: Specification for some commercially available flake ice machines, including flake ice drum, refrigeration cycle and cooling of water (Focusun.com 2017, Icesta.com 2017, kingfit.cc 2017, Snowkey.com 2017).

Producer	Fujian Snowman Co.	Fujian Snowman Co.	Kingfit	Kingfit	Focusun	Focusun	Icesta
Model	F200W	F600W	QFI-20S	QFI-50S	FIF-500W	FIF-600W	IF30T-R4W
Type	Flake ice	Flake ice	Flake ice	Flake ice	Flake ice	Flake ice	Flake ice
Capacity (tons/ 24 hrs)	20	60	20	50	50	60	30
Flake ice thickness (mm)	1.5 – 2.2	-	-	-	1.5 – 2.5	1.5 – 2.5	1.5 – 2.2
Refrigeration capacity (kW)	126.4	362	108.7	273.3	286	350	202.0
Power consumption (kW)	54.8	183.9	63	147.4	176.3	214.9	108.4
Power consumption (kWh/ton)	65.8	73.5	75.6	70.8	84.6	85.6	86.7
Compressor	-	-	-	-	2 x 125 HP	1 x 350 HP	-
Refrigerant	R404A, R507A, R717	R22, R404A, R717	R22, R404A	R22, R404A	R404A	R404A	R404A
Cooling medium			Water	Water	Water	Water	Water
Ambient temperature (C)	25	25	40	40	35	35	25
Water temperature	16	16	16	16	20	20	16
Water consumption (l/hr)	833	2500	-	-	-	-	1950
Evaporator temperature	-23	-27	-20	-20	-	-	-20
Condensing temperature	38	38	40	40	-	-	40

3.2.2 Tubular Ice

Tubular ice is produced either on the inner or outer surface of vertical tubes. When ice is produced on the outside, there is a falling film of water on the outer surface and an evaporating refrigerant on the inside of the tubes. The freezing cycle usually takes between 8 and 15 minutes, and produces an ice layer of 5 to 13 mm (ASHRAE 2014). During the cycle, the ice layer builds up, and the evaporating temperature is therefore continuously lowered from an initial temperature of about -4 °C to a terminal suction temperature of -12 to -26 °C. A hot discharge gas is introduced in the tubes at the end of the freezing cycle to release the ice by melting the inside of the ice tubes. The defrosting cycle usually takes around 30 seconds. The tubes of ice will then slide down into a cutter or crusher before it can be transported to storage. After the defrosting procedure, the machine returns to the freezing cycle. Units with capacities of 9 tons/ 24 hrs or higher normally operate with R-717 (ASHRAE 2014). Operating parameters for a typical unit at two different suction pressures are given in Table 5.

Table 5: Tubular ice machine specifications (ice produced on the outer surface) (ASHRAE 2014)

Tubular ice machine	17.5 tons/ 24hrs	37.7 tons/ 24hrs
Refrigerant	R-717	R-717
Suction pressure (kPa)	265	145
Water supply temperature (°C)	21	21
Refrigeration/ton of ice (kW/ton)	7.2	7.5
Refrigeration/ton of ice (kWh/ton)	172.8	180

When the ice is produced on the inner surface of the vertical tubes, as seen in Figure 8, the tubes are surrounded by an evaporating refrigerant. Hollow cylinders of ice are produced with a wall thickness of 10 to 12 mm (Graham, Johnston et al. 1992). These can be harvested as cylinders or crushed ice.

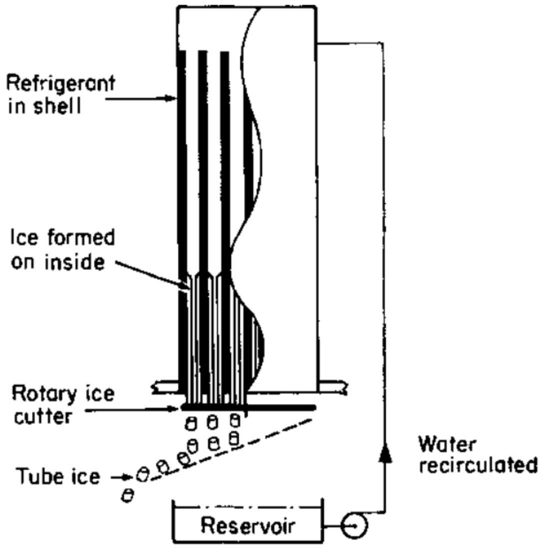


Figure 8. Tube ice machines (Graham, Johnston et al. 1992), reproduced with permission.

The freezing cycle is usually between 13 and 26 minutes. Due to the growing ice layer, the evaporator temperature continuously drops from an initial suction temperature of -4 °C to between -7 and -21 °C at the end of the freezing cycle. The ice is released by introducing a hot discharge gas on the refrigerant side, thus melting the outer surface of the ice cylinders. The cylinders will then slide down into a cutter or crusher before being transported to storage. After the defrosting procedure, the unit returns to the freezing cycle. Operating parameters for a typical unit at two different suction pressures are given in Table 6. An advantage of tubular ice machines is that they can produce ice at a higher suction pressures than other types of ice machines (ASHRAE 2014).

Table 6: Tubular ice machine specifications (ice produced on inner surface) (ASHRAE 2014)

Tubular ice machine	**39 tons/ 24hrs**	**60 tons/ 24hrs**
Refrigerant	R-717	R-717
Suction pressure (kPa)	275	210
Water supply temperature (°C)	21	21
Refrigeration/ton of ice (kW/ton)	6.7	7.9
Refrigeration/ton of ice (kWh/ton)	160.8	189.6

Technical specifications for some commercial tube ice systems are given in Table 7.

Table 7: Specifications for some commercially available tube ice systems, including tube ice machine, refrigeration cycle and cooling of water (Focusun.com 2017, Icesta.com 2017, kingfit.cc 2017, Snowkey.com 2017)

Producer	**Fujian Snowman Co.**	**Fujian Snowman Co.**	**Kingfit**	**Focusun**	**Icesta**	**Icesta**	**Berg Chilling systems**
Model	TIM200A	TIM300A	QTI-20T	FIT-500	IT30T-R2W	IT80T-R2W	Shell ice maker
Type	Tube ice	Tube ice	Tube ice	Tube ice	Tube ice	Tube ice	Tube ice
Capacity (tons/ 24 hrs)	20	30	20	50	30	80	9.1 - 45
Ice tube diameter (mm)	29	29	22-35	22 – 35	28	28	-
Refrigeration capacity (kW)	132.3	189.9	-	371.5	227	485	-
Power consumption (kW)	59.4	81.5	53.2	177	98.5	205.5	-
Power consumption (kWh/ton)	71.28	65.2	63.84	85	78.8	61.65	44 – 47[1]
Compressor	-	-	-	5 x 50 HP	-	-	35 HP – 2 x 125 HP
Refrigerant	R404A, R507A, R717	R404A, R507A, R717	-	R22, R404A	R22, R404	R22, R404	-
Cooling medium	-	-	-	Water	Air	Air	Water
Ambient temperature (°C)	33	33	-	35	25	25	26.7
Water temperature (°C)	20	20	16	20	20	20	15.5
Water consumption (l/hr)	916.6	1375	-	-	-	-	-
Evaporator temperature (°C)	-15	-15	-15	-	-	-	-
Condensing temperature (°C)	43	43	40	-	-	-	-
Ice temperature (°C)	-2	-2	-	-	-	-	-

3.2.3 Plate Ice

In plate ice machines, liquid water flows by gravity over refrigerated vertical plates to produce ice, as illustrated in Figure 9. The refrigerant in the circuits inside the plates usually has a temperature in the range -7 to -21 °C. The freezing cycle can be from 12 to 45 minutes, producing ice with a thickness of 6 to 20 mm. Water is applied in excess over the plates and the water that does not freeze is collected and recirculated (ASHRAE 2014).

[1] It is uncertain which components are included in this power consumption.

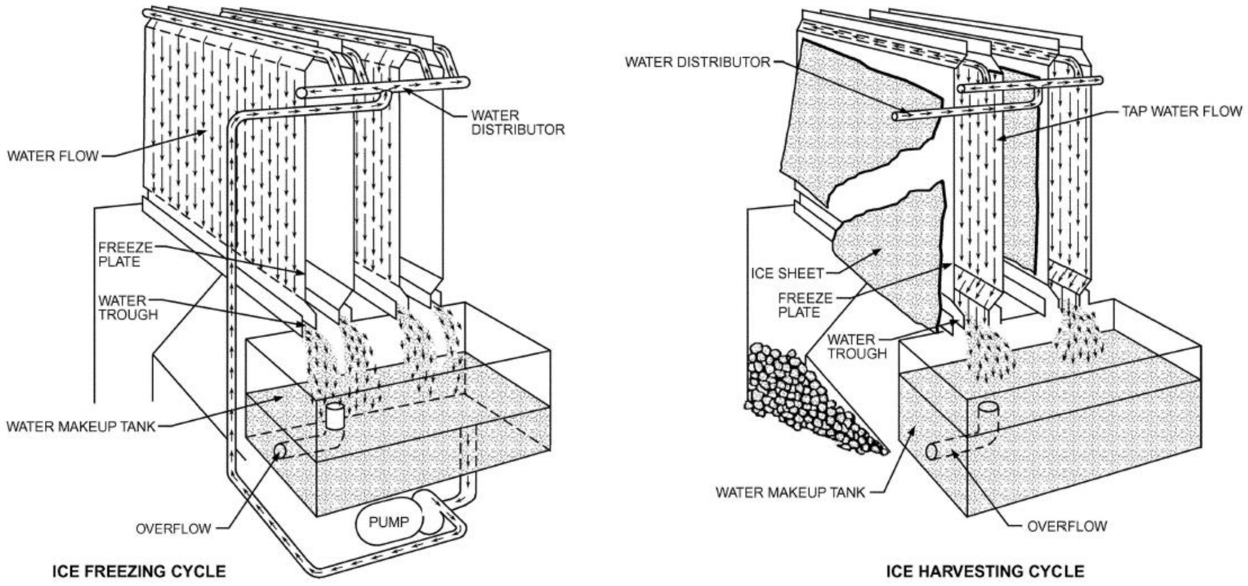


Figure 9: Plate ice machine, reproduced with permission from ©ASHRAE, www.ashrae.org. 2014 ASHRAE Handbook—Refrigeration (ASHRAE 2014).

There are two different methods for harvesting the ice. One method is to produce ice on one side of the plates and release it by running warm water on the other side during the defrosting cycle. The warm water must be heated if it is less than about 18 °C, such that the defrosting period is not too long. The defrosting water is collected and used as precooled water for producing ice in the next freezing cycle. The other method is to use an internal defrosting procedure where hot gas is applied to the refrigerant circuit to heat the plates, causing the ice surfaces touching the plates to melt. When this method is used, ice can be produced on both sides of the plates. During the defrosting cycle, the ice is released and falls into a cutter or crusher before reaching the storage (ASHRAE 2014).

The refrigeration requirement per unit mass of produced ice is higher for plate ice machines than for flake ice machines due to the defrosting cycles. However, plate ice machines can operate at higher evaporating temperatures, and the required power per kW of refrigeration is therefore normally lower (ASHRAE 2014).

SnowMagic and FrioNordica offers plate ice machines and crushers to produce artificial snow (see Section 4.8 and 4.9). Technical specifications for some commercial plate ice machines are shown in Table 8.

Table 8: Specifications for some commercially available plate ice systems, including plate ice machine, refrigeration cycle and cooling of water (Focusun.com 2017, kingfit.cc 2017, Snowkey.com 2017).

Producer	Fujian Snowman Co.	Fujian Snowman Co.	Kingfit	Focusun	Focusun
Model	P200W	P250W	QPI-20T	FIP-320W	FIP-480W
Type	Plate ice	Plate ice	Plate ice	Plate ice	Plate ice
Capacity (tons/ 24 hrs)	20	25	20	32	48
Ice thickness (mm)	3 - 20	-	2 – 30	10 – 15	10 – 15
Refrigeration capacity (kW)	138.2	172.8	-	238.4	357.6
Power consumption (kW)	74.7	85.9	63	124	189.1
Power consumption (kWh/ton)	89.64	82.46	75.6	93	94.55
Compressor	-	-	-	2 x 75 HP	3 x 75 HP
Refrigerant	R404A, R507A	R404A, R507A	-	R22, R404A	R22, R404A
Cooling medium				Water	Water
Ambient temperature (°C)	33	33	-	35	35
Water temperature (°C)	20	20	16	20	20
Water consumption (m3/hr)	316 l/h ice making	1052.1 l/h	-	-	-
Evaporator temperature (°C)	-18	-18	-15	-	-
Condensing temperature (°C)	38	38	40	-	-

3.3 Ice slurries

An ice slurry is a mixture of small ice particles and a carrier liquid. The liquid can be pure water or water mixed with a freezing point depressant, such as ethanol, ethylene glycol, propylene glycol or various salts such as sodium chloride (Kauffeld, Wang et al. 2010). Depending upon the additives and the generation method, the ice crystals typically range from 0.01 to 1 mm in diameter. Without a freezing point depressant, the ice slurry crystals are normally larger (Stamatiou and Kawaji 2005). The ice fraction in ice slurries are usually below 50 %, but for specialized applications mixtures of up to 80 % ice can be successfully pumped (ASHRAE 2014).

The size, shape and roughness of the ice particles are important for the fluidity and handling characteristics of ice slurries. Depending on the production method and required quality of the ice slurry, chemical and/or thermal smoothing of the particles can be used to improve the characteristics. In chemical smoothing, the surface roughness on individual ice particles are smoothed by adding freezing point depressants, which reduces particle entanglement and allows higher ice loading. Thermal smoothing is done by adding measured amounts of warmer coolant to the ice slurry during production. Ice particles produced and suspended in pure water generally have a poor fluidity (Kauffeld, Wang et al. 2010).

Ice slurries have a high energy storage density due to the latent heat of fusion, a large heat transfer area, the ability to maintain a constant low temperature during the cooling processes, and provides higher heat transfer coefficients than single-phase liquids (Kauffeld, Wang et al. 2010). This makes ice slurries beneficial for many applications, such as indirect refrigeration systems, thermal storage systems, comfort cooling of buildings and mines, process cooling of breweries, dairies and produce, and direct contact cooling of various food products. Ice slurries can also be an excellent type of artificial snow as they can be produced with less power consumption and provide a better skiing surface than other commonly used snow substitutes

(Kauffeld, Kawaji et al. 2005). Additional applications are described in "Ice slurry applications" (Kauffeld, Wang et al. 2010).

There are several methods for producing ice slurries. The method should be selected based on the application and type of ice particles required. Some of the most important methods are described in this report. The reader is referred to the "Handbook on Ice Slurries: Fundamentals and Engineering", (Kauffeld, Kawaji et al. 2005), for other production methods and a more thorough review of ice slurries.

3.3.1 Scraped surface ice slurry machines

Scraped surface ice slurry machines are currently the most used and technically developed method for producing ice slurries (Stamatiou, Meewisse et al. 2005). The process usually consists of tube-in-tube type heat exchangers and a refrigeration cycle, as illustrated in Figure 10, but plate type heat exchangers are also used in some models.

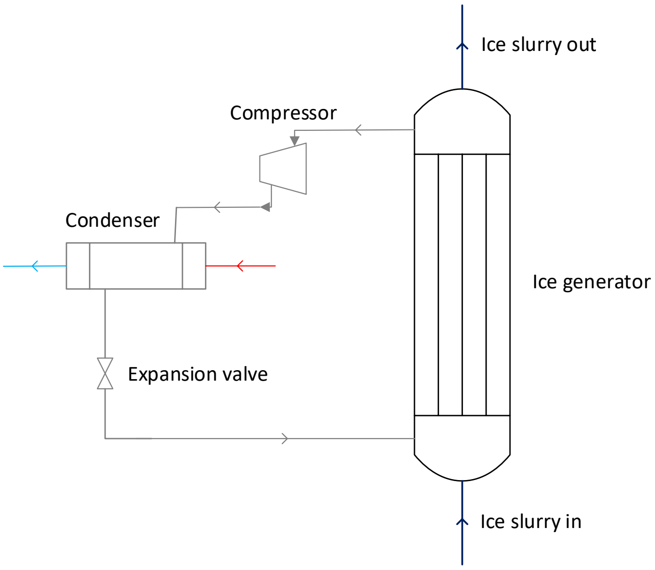


Figure 10: Principle diagram of scraped surface ice slurry generators.

For the tube-in-tube type models, the ice slurry is generated on the inner tube side, while the refrigerant is evaporated on the outer side (Figure 11, left). Rotating spring loaded scrapers inside the tubes, orbital rods, or rotary screws prevent ice from depositing on the inner surface. These ice generators are available in both vertical and horizontal arrangements. For the plate type models, the plates are stationary and cooled by an evaporating refrigerant on the inside, while the ice slurry is produced on the outside (Figure 11, right). Rotating scrapers prevent ice from depositing on the plates. The rotating scrapers also function to induce turbulence in the ice slurry flow for both types of scraped surface ice slurry generators, thus enhancing the heat transfer rates and facilitating the production of a homogenous ice slurry mixture (Stamatiou, Meewisse et al. 2005). Scraped surface ice machines require a minimum concentration of a freezing point depressant in the water to prevent freeze-up of the machine. This reduces the heat transfer rate and affects the ice slurry temperature. Existing systems work well with a minimum concentration corresponding to a -2 °C freezing point. Orbital rod evaporators (OREs) are vertical falling-film type scraped surface ice slurry machines. The falling film acts as a lubricant and ensures that the rod does not contact the wall. The component wear is reported to be minimal in ORE systems (Kauffeld, Kawaji et al. 2005).

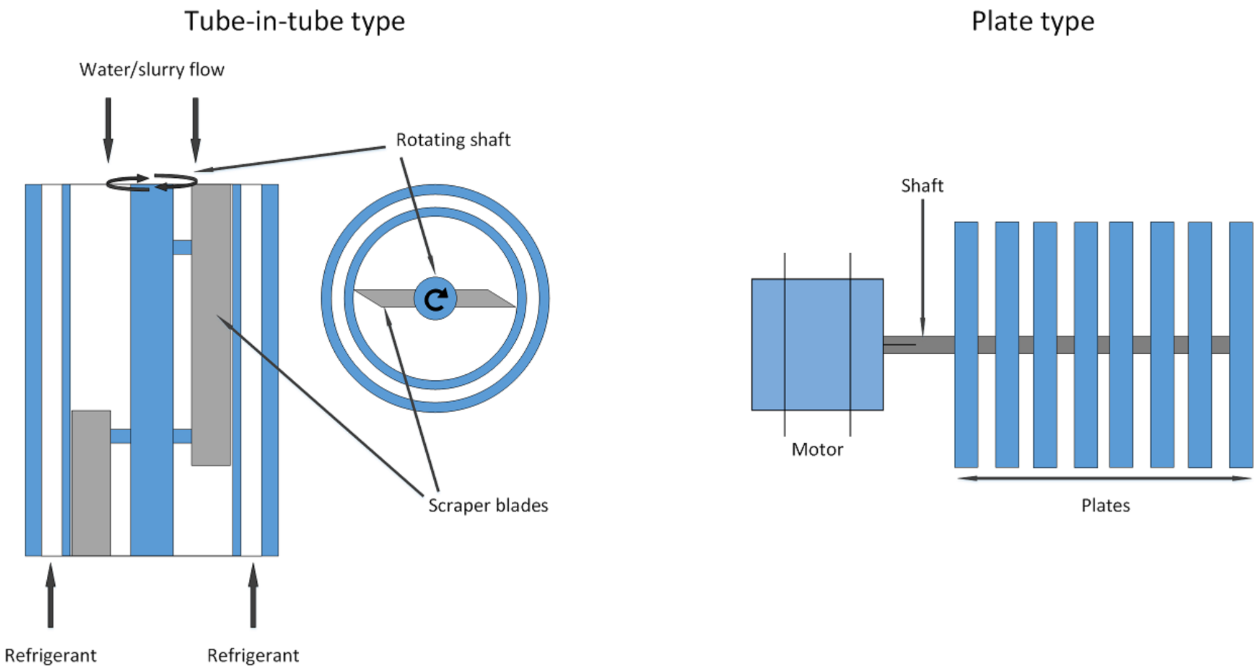


Figure 11: Tube-in-tube type (left) and plate type (right) scraped surface ice generators.

The ice crystallization process in the scraped surface ice-slurry generator is not fully understood. Some studies claim that the rotating scraper blades prevent the formation of ice crystal deposits on the refrigerated surfaces, and that there is a spontaneous nucleation in the bulk liquid that initiates the growth of ice crystals as the liquid is supercooled. Others conclude that the ice is formed near the refrigerated tube walls and is dispersed to the centre by the rotating scrapers. Typical rotation speed for the scraping blades is about 450 rpm (Kauffeld, Kawaji et al. 2005).

Scraped surface ice slurry generators can produce ice slurries with ice fractions ranging from 0 to 35 %. Higher fractions can be achieved with different kinds of concentrators. The produced slurry is homogenous with fine ice crystals ranging from 0.025 to 0.25 mm, depending on operating conditions and additives for scraped surface generators, and 0.050 to 0.100 mm for OREs (Stamatiou, Meewisse et al. 2005).

The main disadvantages of scraped surface ice generators are the high amount of mechanical work required by the scrapers, a high investment level, high maintenance costs and that a minimum concentration of a freezing point depressant is required (Li, Zhang et al. 2009) (Bédécarrats, David et al. 2010) (Kauffeld, Kawaji et al. 2005).

The production capacity of scraped surface ice generators is typically in the range 3 to 400 tons of ice per day, at a cost of around 1500 to 2000 US$ per ton of ice production capacity (Kauffeld, Kawaji et al. 2005). OREs costs about 550 US$ per ton of ice production capacity. Technical specifications for two commercial ice slurry systems are given in Table 9.

Table 9: Technical specifications for commercial ice slurry machines (Stamatiou, Meewisse et al. 2005).

Producer	**Sunwell**	**Mueller**
Model	ModuPak	MaxICE
Ice slurry side		
Tube material	304 stainless steel	304 stainless steel (NH_3) or copper 122 (HCFC)
Freezing point depressant	NaCl, EtOH, glycol	Ethylene glycol, propylene glycol, urea, ethanol
Crystal size (µm)	250 - 500	20 - 100
Inner tube diameter (m)	0.15	0.040 x 1.6 (mm) wall
Tube length (m)	1.8 – 2.4	1.2
Heat transfer area per tube (m^2)	0.85	0.13
Flow rate per tube (l/min)	10 – 23	6
Ice fraction change per tube (wt%)	15	6 - 8
Typical cooling heat flux (kW/m^2)	28	22 Copper, 16 SS
Nominal cooling load capacities (kW)	21 - 85	10 – 1800
Agitation mechanism	Plastic scraper blades	Stainless steel orbital whip rods
Agitation speed	450	850
Power requirement per heat transfer area (kW/m^2)	1.2 – 1.8	0.22
Scraper power consumption[2] (kWh/ton)	7.4	1.13
Refrigerant side		
Evaporator type	Shell and tube, flooded	Shell and tube, flooded
Refrigerant	R22, R404, R717	R22, R717, R134a
Evaporating temperature (°C)	-10 and -19	-10 to -8, SS. -10 to -4.4, Copper
Cost ($\$US/kW_{refrigeration\ capacity}$)	300 – 600	160

3.3.2 Vacuum Ice machines

The direct contact heat transfer vacuum freeze process is the most efficient method to produce an ice slurry (Kauffeld, Kawaji et al. 2005). The main components of vacuum ice machines typically include a vacuum freeze evaporator, a compressor, a condenser and a vacuum pump, as shown in Figure 12. The vacuum freeze evaporator operates at the triple point, where the vapor pressure of water is 611 Pa and the temperature is 0.01 °C. The vessel is well insulated such that the energy transfer during evaporation causes some of the remaining water to freeze. The heat of vaporization at the triple point is ~2500 kJ/kg, while the heat of fusion is ~333 kJ/kg. This means that the mass of ice produced is 7.5 times larger than the mass of vaporized water (Van Orshoven, Klein et al. 1993). To keep the process going the produced vapor must be removed. This can be done by drawing out the vapor with a compressor. Usually a centrifugal compressor is used, but ejector technology is also applied in some cases. After the compression, the vapor is condensed in a condenser and can be returned to the evaporation chamber. The low operating pressure results in a very large volume flow and a high demand on the compressor. A vacuum pump is used to create an initial vacuum and deaerate the system for air that is introduced to the system through the feed water. Another option for maintaining the vacuum is to deposit the vapor on refrigerated plates within the evaporator. The evaporation temperature of the refrigerant is reported to be around -6 °C in such systems (Van Orshoven 1991). The ice layer formed during the process is removed periodically by a defrosting procedure. The

[2] Calculation and assumptions in Appendix A.2.

water/slurry in the evaporator should be agitated to create a larger surface area for evaporation and to obtain a good ice crystal quality (Ophir, Rojanskiy et al. 2009). This results in a slurry of fine ice particles that is readily pumpable (Van Orshoven, Klein et al. 1993).

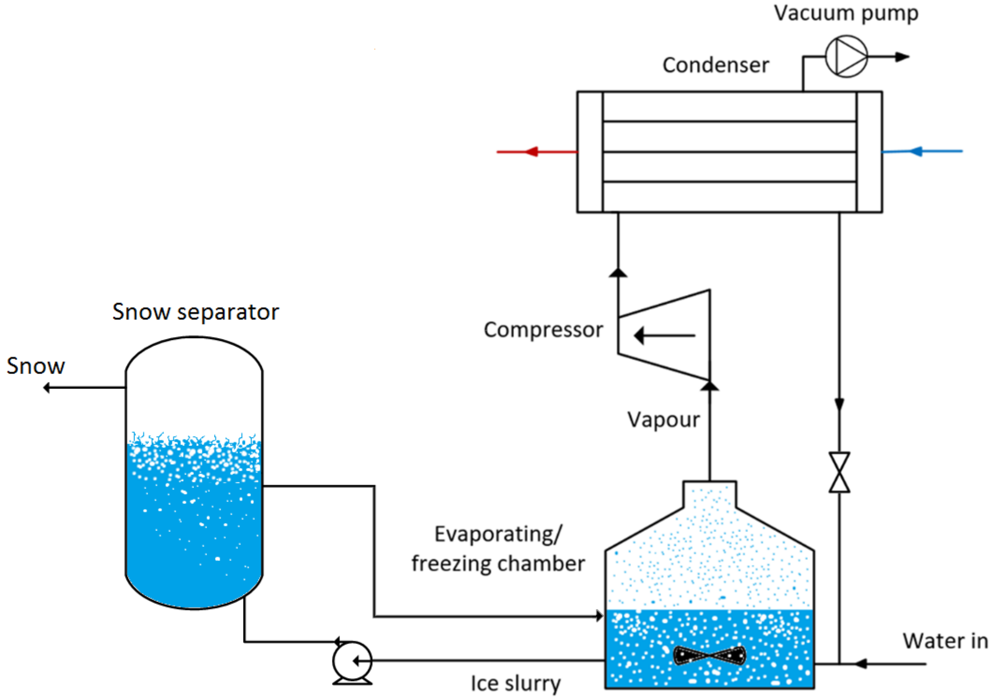


Figure 12: Principle schematic of a vacuum ice machine.

Currently, the majority of vacuum ice systems are used for mine cooling in South Africa. In areas where the temperature of the available cooling medium is high, cascade systems with a conventional refrigeration cycle as the upper stage is used. The installed systems have refrigeration capacities in the range 150 kW to 3 MW (Kauffeld, Kawaji et al. 2005). DemacLenko and IDE Technologies offer artificial snow machines based on vacuum ice makers (see Sections 4.1 and 4.2).

Freezing point depressants have been suggested to reach temperatures lower than 0 °C in vacuum ice machines. Asaoka, Saito et al. have studied the use of an ethanol solution to produce ice slurry as a thermal storage material (Asaoka, Saito et al. 2009). The system is similar to the vacuum ice maker with pure water, except that before the condensed vapor is returned to the evaporator, the liquid is diluted in a concentration control unit. An advantage of using an ethanol solution or other volatile solutes is that the saturation pressure is higher such that the work done by the compressor is reduced. For non-volatile solutes, such as salts, the vapor pressure of the solution is below that of pure water (Lugo, Fournaison et al. 2006). In the study, Asaoka, Saito et al. measures the vapor-liquid equilibrium data for ethanol solutions at 20 °C and at the freezing temperature. At the freezing temperature they find that the saturation pressure decreases as the concentration of ethanol increases. They state that this is because the effect of the lower freezing temperature is larger than that of the increase of ethanol concentration in the liquid. In a follow-up paper, Asaoka, Saito et al. investigate the evaporation characteristics for the ice slurry production and estimate the COP of the system (Asaoka, Saito et al. 2009). They conclude that the method can be used for ice slurry generation, and that it may have a higher COP than traditional systems using a refrigeration cycle. In (Lugo, Fournaison et al. 2006), the ice-liquid-vapor equilibria of ammonia and ethanol solutions applied to the production of ice slurries are investigated. For an ammonia solution, they find a maximum equilibrium pressure of 1.8 kPa at about – 18 °C with an ammonia molar fraction of 0.12. For ethanol solutions, the maximum saturation pressure is found to be only slightly higher than for pure water at a low ethanol concentration. Lugo, Fournaison et al. conclude that the use of aqueous solutions of salts should be limited to temperatures near 0 °C because of the low operating pressures, while ammonia and ethanol solutions can be considered for applications requiring much lower temperatures.

3.3.3 Dehumidification

The dehumidification ice producing method is very similar to vacuum ice making. The system consists of an ice producing chamber, a dehumidification unit and a refrigeration cycle. Cold low humidity air, with a vapor pressure less than 611 Pa, is introduced into the ice producing chamber. This produces an environment where the wet-bulb temperature is below 0 °C. At the same time, water above 0 °C is pumped from a water tank and sprayed into the chamber. Evaporative cooling thus supercools the water droplets, and the droplets' temperatures approach the wet-bulb temperature of the air. A temperature of - 2 °C or lower is suggested as a reliable supercooled degree for ice slurry production (Li, Zhang et al. 2009). The produced supercooled water is then released with a supercooled water releaser, and some of the water turns to ice. A separator can be used to separate the water and the ice. The air leaving the ice-producing chamber has increased its temperature and humidity. It is therefore first sent to a dehumidifier and then cooled on the evaporator side of a refrigeration cycle. The air can then return to the ice producing chamber. Heat from the condenser side of the refrigeration cycle can be used for regeneration in the dehumidification cycle. This double effect of the refrigeration cycle can increase the performance of the system (Li, Zhang et al. 2009). A schematic of a dehumidification ice slurry cycle is shown in Figure 13.

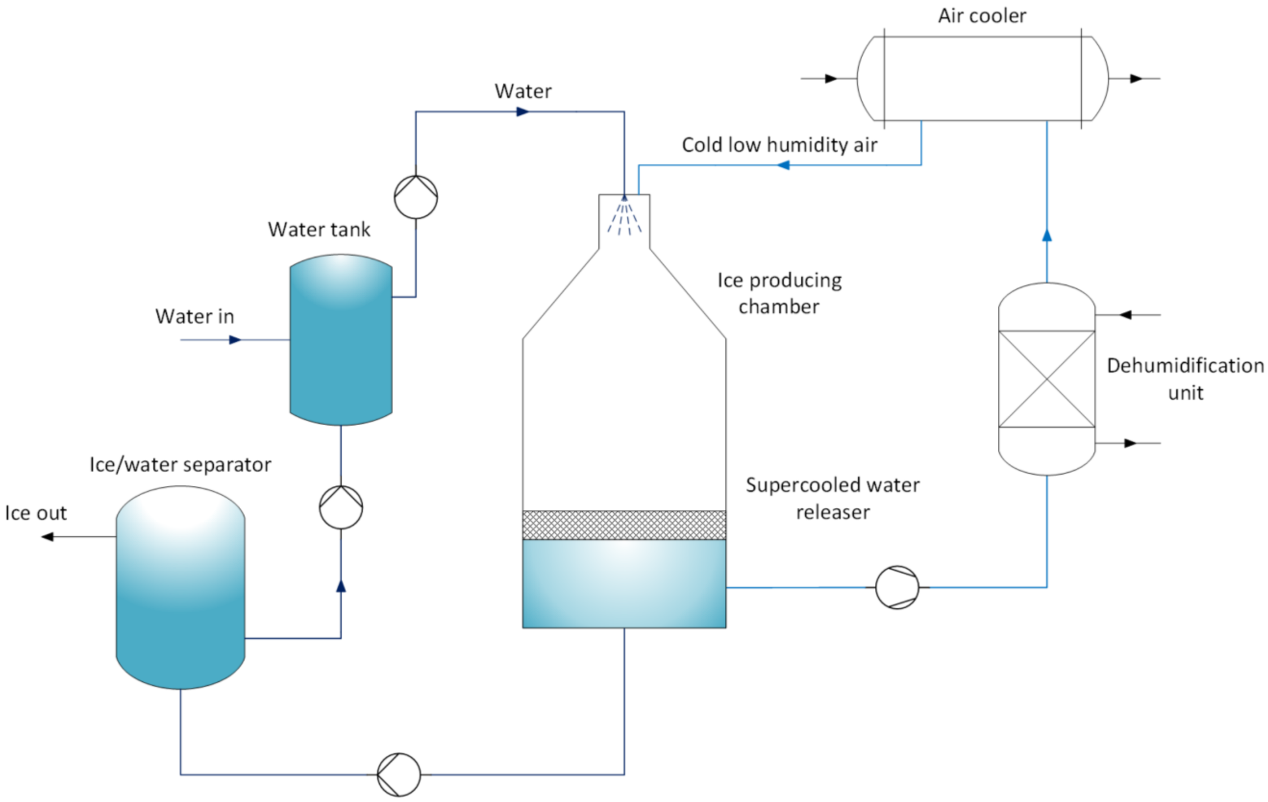


Figure 13: Principle schematic of dehumidification type ice slurry process.

3.3.4 Direct contact generators with immiscible refrigerants

Evaporation of a primary refrigerant directly in water to produce ice is investigated for some industrial applications and has been applied successfully for desalination of sea water (Kauffeld, Kawaji et al. 2005). This can be done at low pressure with water as the refrigerant, described in 3.3.2 Vacuum Ice machines or with the use of an immiscible primary refrigerant. An ice slurry generator system with an immiscible primary refrigerant is illustrated in Figure 14. The evaporated immiscible refrigerant is compressed, condensed and expanded before it is injected into the evaporator, where it evaporates through the water. The water is thus cooled and ice crystals are formed. It is important to design the injectors such that no ice is formed in the injectors themselves, as this could lead to blockage of the system. The injectors should also induce turbulence to promote the formation of a homogenous ice slurry mixture. The system is usually operated at pressures above atmospheric, which makes it challenging to extract the ice slurry from the evaporator while leaving the refrigerant in place (Kauffeld, Kawaji et al. 2005).

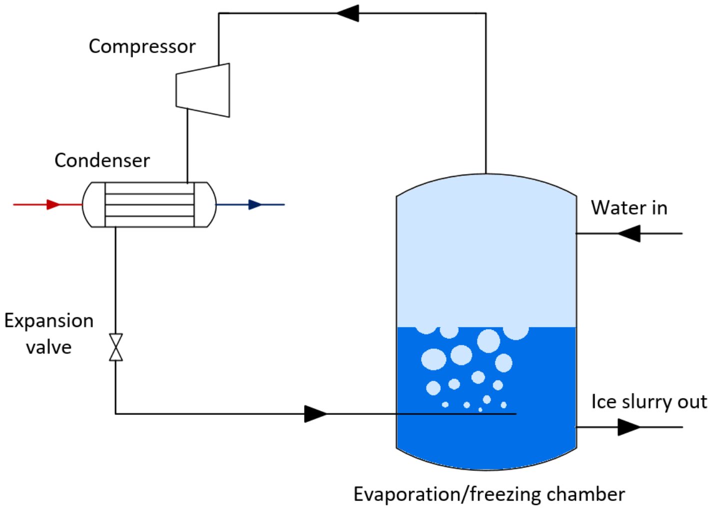


Figure 14: Direct contact evaporation ice slurry generator.

The direct contact heat exchange between the primary refrigerant and the water leads to good heat transfer rates, and results in a lower power consumption in the refrigeration cycle than for ice slurry generators that have a separating wall. The investment costs are also reduced as a heat exchanger is avoided. The injection nozzles may reduce the efficiency slightly and some power may be required to agitate the slurry. Exact power consumption for ice generators of this type has not been reported (Kauffeld, Kawaji et al. 2005).

Operating problems can include blockage of the injection nozzles due to freezing, and leakage of refrigerant with the ice slurry due to solubility of the refrigerant in water. The latter can cause safety and environmental hazards depending on the refrigerant in addition to the refrigerant losses. Furthermore, a small amount of refrigerant is usually trapped inside the ice particles regardless of how insoluble the refrigerant is in water. The same is the case for lubrication oil from the refrigeration cycle (Kauffeld, Kawaji et al. 2005).

Suitable refrigerants include hydrocarbons, most HFCs, and other refrigerants that are insoluble in water. Additives that do not evaporate easily can be used in the water. The system can produce ice slurries with an ice fraction of up to 40 % (Kauffeld, Kawaji et al. 2005).

Direct contact ice slurry generators with a liquid immiscible secondary refrigerant is also an option. This is illustrated in Figure 15. A heavy liquid refrigerant is cooled by a primary refrigeration cycle and is then sprayed into the water in the ice slurry generation tank, in a similar manner as for the direct evaporation systems. The secondary refrigerant should have a higher density and a lower freezing point than water. As the refrigerant is injected, the water is cooled and ice particles are formed. The ice particles rise upwards while the heavy refrigerant sinks to the bottom and is then pumped back to the heat exchanger. A disadvantage with this ice generator is that an extra refrigeration cycle is required such that both power consumption and investment costs increase. It is also difficult to find suitable liquids to be used as the secondary refrigerant. A benefit is that it is possible to use refrigerants that are soluble in water as the primary evaporating refrigerant (e.g. ammonia) (Kauffeld, Kawaji et al. 2005).

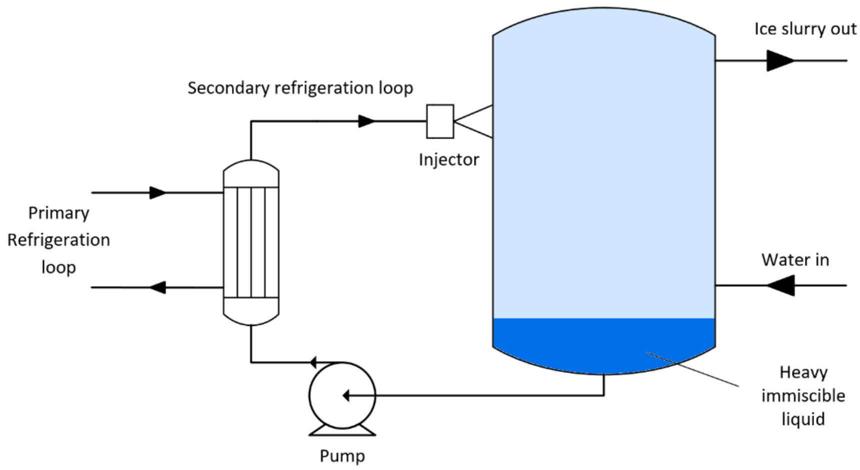


Figure 15: Direct contact ice slurry generator with a liquid immiscible refrigerant.

3.3.5 Supercooling method

Ice slurry generators based on the supercooling method usually consist of the following main components; a refrigeration cycle, a supercooling heat exchanger, a releaser, an ice slurry storage tank and pumps, as seen in Figure 16. The water is pumped from the ice slurry tank to the supercooling heat exchanger. Before entering the supercooler, the water runs through a filter or is preheated to about 0.5 °C to make sure no ice particles enter the supercooler. These could act as seeds for ice crystal growth and cause blockage. The water is then supercooled to a temperature below the melting temperature, usually – 2 °C, before entering the releaser where the water is disturbed and small ice particles are formed (Kauffeld, Kawaji et al. 2005). The releaser could use ultrasonic waves, mechanical vibration, additional cooling, directing the water perpendicularly into a wall or similar methods to trigger the ice formation. During crystallization the temperature rises to the melting temperature. The ice fraction can be estimated by:

$$X_{ice} = \frac{C_{P,l} * \Delta T_S}{L_f},$$

where $C_{P,l}$ is the specific heat capacity of liquid water, ΔT_S is the supercooled degree, and L_f is the heat of fusion (Castaing-Lasvignottes, David et al. 2006). This gives an ice fraction of 2.5 % for a supercooling degree of -2 °C. After the releaser, the produced ice slurry is returned to the ice slurry tank where the ice particles rise to the top and are collected. Sieves or centrifugal techniques can also be used for ice concentration (Egolf and Kauffeld 2005). A challenge with the system is ice blockage due to freezing inside the supercooling heat exchanger (Li, Zhang et al. 2012).

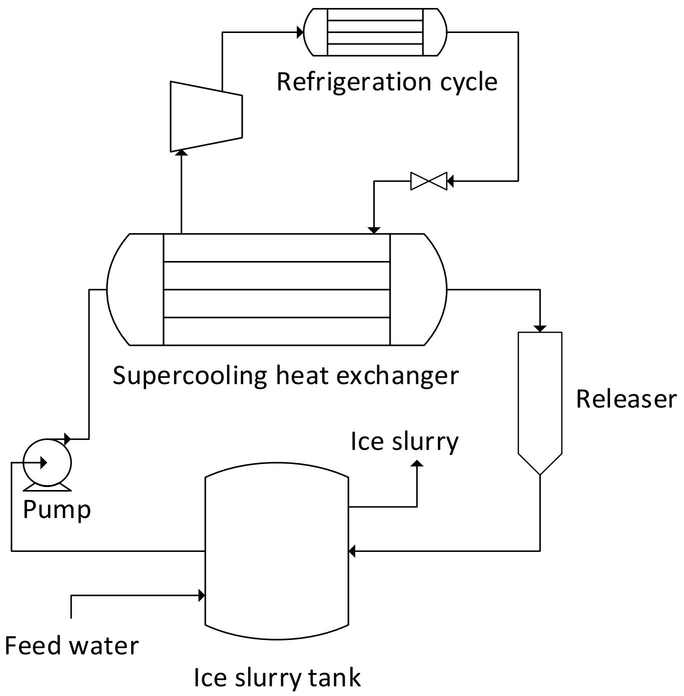


Figure 16: Principle diagram for supercooling ice slurry generator.

Ice generators using the supercooling method have been developed and installed in air-conditioning systems by several companies in Japan. Large ice storage systems with refrigeration capacity of 35 MW and more is installed (Kauffeld, Kawaji et al. 2005).

3.3.6 Other ice slurry generators

Several other ice slurry generating methods are investigated and tested in lab scale. Detailed descriptions of the systems are given in (Kauffeld, Kawaji et al. 2005). These include:

- Fluidized bed ice slurry generators. A refrigerant is evaporated on the shell side of a shell-and-tube or tube-in-tube heat exchanger, such that ice is formed inside the tubes. To prevent ice from building up on the surfaces, a fluidized bed is contained in the tubes. Small steel or glass particles (of size1 to 5 mm diameter) are fluidized by the upward flowing water, continuously impacting the walls and preventing the build up of an ice layer. The particles also disturb the heat exchanging boundary layer and improve the heat transfer rates. The particles can be separated out and recycled after exiting the heat exchanger.

- Ice slurry generation where ice is removed from the evaporator surface by increasing the ice slurry flow velocity and evaporator temperature when ice crystals are detected. Special coatings can also be used to prevent adhesion of ice on the surfaces.

- High pressure method. The freezing point of water is decreased by raising the pressure, and the water/solution is then cooled. Ice crystals are formed when the pressure is released.

- Cyclic removal of ice form the evaporator surfaces by defrosting or mechanical crushing devices.

4 Existing temperature independent snowmakers

4.1 IDE Technologies

The Israeli company IDE Technologies, established in 1965, use vacuum ice makers (VIM) to produce ice slurry. Their systems are used for snowmaking, deep mine cooling, district heating and thermal energy storage. For snowmaking purposes, they produce both mobile and stationary systems. Their first TIS was the stationary VIM 850, developed in 2005. In the following years, they developed the VIM 400 in 2009, and their first mobile snowmaker, the VIM 100 in 2013. Their systems consist of a vacuum ice maker that produces a slurry which is pumped to a snow concentrator where the snow is separated from the water (as shown in Figure 12). The produced artificial snow is reported to be of high quality (ide-snowmaker.com 2017).

The VIM 100 is a mobile containerized system that just needs to be connected to a power and water supply. It is delivered as one 40' container, one 20' container and a snow concentrator. In this system, the vacuum in the freezer is maintained by depositing the vapor on cold plates inside the vessel. The plates need to be frequently defrosted to maintain continuous heat rejection in the freezer. The VIM 400 and VIM 850 are stationary systems. In these, a centrifugal compressor is used to evacuate the vapor to maintain vacuum in the freezer. IDE have installed more than 400 VIM systems for different applications. Stationary snowmaking systems (VIM 400) have been installed in Zermatt, Switzerland and Pitztal, Austria. Specifications for IDE's three models are given in Table 10.

Table 10: Specifications for IDE technologies' VIM 100, VIM 400 and VIM 850 (ide-snowmaker.com 2017)

Model	VIM 100	VIM 400	VIM 850
Principle	Vacuum ice slurry	Vacuum ice slurry	Vacuum ice slurry
Type	Mobile	Stationary	Stationary
Cooling capacity (kW)	350	1 750	3500
Snowmaking volume[3] (m^3/day)	200	860	1720
Snowmaking mass (ton/day)	112	560	1 120
Designed Power Consumption[4] (kW)	190 (<250)	235	397
Power/mass[4] (kWh/ton)	40.7 (max 53.6)	10	8.5
Power/volume[4] (kWh/m^3)	22.8 (max 30)	6.6	5.5
Snow density (kg/m^3)	560	600 – 700	600 – 700
Snow quality		"Spring snow"	"Spring snow"
Snow Grain Size (mm)	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Recommended feed water temperature[5] (°C)	2 – 6	2 – 6	2 – 6
Nominal feed water flow rate (m^3/h)	4.7	23.3	46.6
Cooling water flow rate (m^3/h)		480	670
Refrigerant		Water	Water
Size	1 x 40' + 1 x 20' container + snow separator		

IDE's VIM technology can also be used for district heating with a natural body of water as the heat source. The water vapor is then condensed at around 10 °C, and a standard heat pump is used to further increase the temperature to between 40 and 70 °C depending on the application. The produced ice slurry is discharged back to the water source. This system is installed in Augustenborg, Denmark (ide-snowmaker.com 2017).

[3] Considering average snow density of 560 kg/m3 for VIM 100 and 650 kg/m3 for VIM 400 and VIM 800.
[4] The power consumption is for the VIM unit only and does not include a supporting cooling system.
[5] The snow production is reported to decrease by 1.5% for every 1 °C increase in feed water temperature.

4.2 DemacLenko

DemacLenko took over the startup company NeveXN in 2016, and now offers a temperature independent snowmaker. The snowmaker is called Snow4Ever and is based on vacuum ice technology. This is a mobile system that can produce 48 – 96 m^3/day depending on ambient conditions. Technical specifications for the system is given in Table 11 and a principle process diagram is shown in Figure 17.

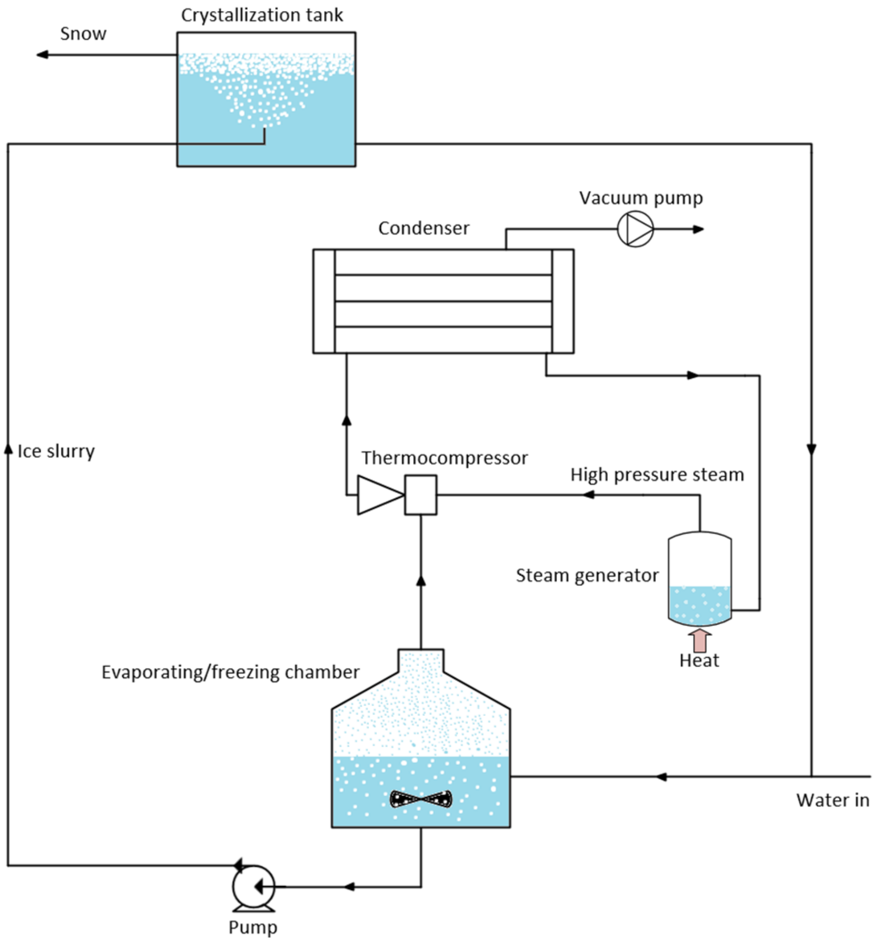


Figure 17: Principle process diagram for DemacLenko's Snow4Ever.

The following process description is based on NeveXN's patent application. There are some alternative configurations described in the document, so the exact configuration of the Snow4Ever system is not known. Water enters an evaporation/freezing chamber and is brought to triple point conditions. The produced vapor is drawn out of the chamber and compressed by a thermocompressor/ejector. After the compression, the vapor is condensed in a condenser. Subcooled water from the condenser enters a steam generator where steam for the thermocompressor is generated. A rotating mixer in the evaporation/freezing chamber stirs the slurry to increase the surface area for evaporation and to avoid packing of the crystals. The produced ice slurry is pumped to a crystallization tank where the snow is collected and ejected by a snow gun. Water returns to the evaporation/freezing chamber. All components can be contained in a single casing, making the system compact. No additives are used in the water (BESANA 2015). The snowmaker may use thermal energy to produce snow, which can come from renewable sources such as solar panels and biomass boilers. A prototype of the machine was installed at the Lago di Tesero Cross Country Stadium in Val di Fiemme in October 2014 (NeveXN.com 2017).

Table 11: Technical specifications for (DemacLenko.com 2017)

Model	Snow4Ever
Principle	Vacuum ice slurry
Type	Mobile
Production capacity (20 – 10 °C ambient temperature) (m3/day)	48 – 96
Max. power consumption (kW)	180 (Boiler: 160, Cooling tower: 10, Other: 10)
Required steam temperature	150 °C
Condenser temperature	10 °C
Power consumption (kWh/m3)	45 - 90
Snow density (kg/m3)	450
Grain size (mm)	0.2 – 0-5
Refrigerant	Water
Size	1 x 20' container + cooling tower

4.3 SnowTek

The Finnish company SnowTek produces two temperature independent snowmaking systems called SnowGen SI and SnowGen FI. The SI system is based on plate type scraped surface ice slurry generators from IceGen Inc.(see Figure 11). Snow is separated from the ice slurry in a snow separator. About 2.5 % salt is added to the water to increase the number of nucleates. The FI system is based on flake ice makers. Technical data for the systems are given in Table 12.

Table 12: Technical data for SnowTek's SnowGen system (Wright Bergwitz-Larsen 2017).

Model	SnowGen SI	SnowGen FI
Principle	Scraped surface ice slurry	Flake ice
Type	Mobile	Stationary
Production capacity (m3/day)	181	222
Power consumption (kW)	280	230
Power consumption (kWh/m3)	37.1	24.9
Snow density (kg/m3)	~ 550	~ 450
Feed water (°C)	8	8
Ambient temperature (°C)	10	10
Refrigerant	R404a, R507, R717	R404a, R507, R717
Size	1 x 40' container + snow separator	1 x 40' container

Torsby Ski Tunnel, Sweden, Änglagården Ski Hall, Sweden and the Kivikko Ski Hall in Finland all use the SnowGen system. Three SnowGen units were also used to produce snow for the ski jumping and Nordic combined competition venues at the Sochi Olympic Games in 2014 (Rykkje Dieseth 2016, allweathersnowtek.com 2017).

4.4 TechnoAlpin

TechnoAlpin delivers both fan guns, lances, and a temperature independent snowmaking system called Snowfactory. The Snowfactory system consists of flake ice makers from KTI-Plersch Kältetechnik GmbH, a refrigeration system, an ice crusher and a transport and delivery system. The produced ice is subcooled to a temperature of -5 °C, and is produced without any additives. Since the ice is dry, it can be distributed by conveyor belts or fans. TechnoAlpin reports that a variety of models and sizes of the Snowfactory can be produced depending on the customers requirements. Technical specifications for the SF100 and SF220 models are given in Table 13. The snowmakers are delivered in containers and only need to be connected to power and water supply to be ready for operation. The Snowfactory is not intended to substitute traditional snowmaking equipment, but to complement it (TechnoAlpin 2017).

Table 13: Technical data for TechnoAlpin's machines (Rykkje Dieseth 2016).

Model	SF100 (2014)	SF220 (2014)
Principle	Flake ice	Flake ice
Type	Mobile	Stationary
Size	1 x 40' container	2 x 40' container + evaporative condenser
Cooling Capacity (kW)	206	640
Capacity (m^3/day)	100	220
Power consumption (kW)	130	230
Water consumption (l/s)	0.8	1.5
Power consumption (kWh/m^3)	31.2	25.1
Evaporator temperature (°C)	-30	-30
Feed water temperature (°C)	5	5
Ambient temperature (°C)	15	15
Operating air temperatures (°C)	-5 to +25	-5 to +25
Refrigerant	R404A (HFC)	R717
Price	~ 4 million SEK (Idre Fjäll)	~ 6 million NOK (Sjusjøen)

TechnoAlpin reports that in the 2016/2017 season, 18 machines have been delivered for use in 11 different countries. Geilo, Sjusjøen, Idre Fjäll and the German Ski Association (DSV) are among the customers. DSV have two mobile units that are used to produce snow at competition venues in Germany (TechnoAlpin.com 2017).

4.5 Supersnow

Supersnow is a Polish company established at the end of the 1990s. They deliver snow cannons and snow making systems to facilities in Europe and Asia (supersnow.pl 2017). Supersnow offers two temperature independent snow machines, All Weather Snow (AWS) 55 and 110. The systems consist of flake ice makers, a refrigeration system, an ice crusher and a transport and delivery system installed in two 40' containers. Specifications for the two models are given in Table 14. The produced ice is subcooled to a temperature of -5 °C. Supersnow currently has installed two AWS systems in Szczyrk, Poland, and are developing and testing a new version that will be installed in Wisła, Poland to ensure snow for the ski jumping world cup in 2017. The new version is intended to be installed in a single container and be more easily movable (Supersnow 2017).

Table 14: Technical data for Supersnow's All Weather Snow systems(Supersnow 2017)

Model	AWS 55	AWS 110
Principle	Flake ice	Flake ice
Type	Mobile	Mobile
Size	2 x 40' container	2 x 40' container
Capacity (m^3/day)	55	110
Power consumption (kW)	133	210
Max water consumption (l/s)	0.57	1,03
Power consumption (kWh/m^3)	58.0	45.8
Feed water temperature (°C)	10	10
Ambient temperature (°C)	25	25
Operating air temperatures (°C)	0 to +40	0 to +40
Snow density (kg/m^3)	450 - 550	450 - 550
Grain size (mm)	1.5 - 2	1.5 - 2
Refrigerant	R507A (HFC)	R507A (HFC)

4.6 North Star Ice Equipment

North Star has installed ice production equipment for snowmaking at several ski resorts, theme parks and attractions. The ice is produced without additives by their industrial flake ice makers. The produced ice is subcooled and can be moved using mechanical or pneumatic systems. North Star delivers both movable containerized ice plants that incorporates ice makers, ice storage, ice rakes and delivery systems, as well as stationary systems (NorthStar.com 2017). Their largest single unit flake ice makers can produce 52.8 tons/ 24 hrs (based on 15.5 ºC make-up water and R717 refrigerant), which is about 110 m^3 /24 hrs of snow. These machines have a refrigeration requirement of 5.02 kW per ton ice.

4.7 Focusun

Focusun Outdoor Snowmaking system consists of flake ice makers, an ice crusher, and an air conveying system (Focusun.com 2017). The specifications for their artificial snow system is estimated based on their containerized flake ice plants (Table 15).

Table 15: Technical specifications for Focusun's containerized flake ice plants (Focusun.com 2017).

Model	FIF-600WC
Principle	Flake ice
Type	Mobile
Capacity (tons/ 24 hrs)	60
Capacity (m^3/ 24 hrs)[6]	120
Refrigeration capacity (kW)	342
Power consumption (kW)	204.9
Power consumption (kWh/ton)	82.0
Power consumption (kWh/m^3)	41.0
Refrigerant	R404A
Cooling medium	Water
Ambient temperature (°C)	35
Water temperature (°C)	20

[6] Assuming a density of 500 kg/m^3

4.8 SnowMagic, INC.

SnowMagic, Inc. produces temperature independent snowmaking systems based on plate ice machines (Rykkje Dieseth 2016). They deliver snow for outdoor and indoor applications, and have delivered their systems to several ski resorts in Japan in the 1990s and early 2000s, as well as to other venues in among others, Saudi Arabia, USA and Mexico. The snow is produced without any additives and distributed by a distribution hose (Snowmagic.com 2017). Technical data for their four different models are given in Table 16. The power consumption is based on 24 hours of production at maximum capacity.

Table 16: Technical data for SnowMagic (Rykkje Dieseth 2016, Snowmagic.com 2017)

Model	50	100	150	200
Principle	Plate ice	Plate ice	Plate ice	Plate ice
Type	Mobile	Mobile	Stationary	Stationary
Capacity (tons/day)	50	100	150	200
Capacity (m^3/day)	102	204	300	408
Power (kW)	151	248	362	545
Power consumption (kWh/m^3)	35.5	29.2	28.9	32.1
Ambient temperature (°C)	21	21	21	21
Average grain size (mm)	0.1 – 0.3	0.1 – 0.3	0.1 – 0.3	0.1 – 0.3
Snow density (kg/m^3)	490	490	490	490
Water supply (l/s)	0.8	1.6	2.4	3.1

4.9 FrioNordica

FrioNordica is a Norwegian industrial refrigeration company with extensive experience within cooling solutions for fishing, fish processing and aquaculture industry. They can also offer temperature independent snow production systems. These are based on either their flow-ice system, that uses scraped surface ice slurry technology, or a system based on plate ice machines. Specifications for the two systems are shown in Table 17. The power consumptions do not include distribution, crushing or washing (for flow-ice). FrioNordica estimates the power consumption for crushing to 0.5 kWh/ton ice and below 1.0 kWh/ton ice for distribution.

Table 17: Specifications for FrioNordica's snow production systems (Including freezing, scraping/defrost, pumps, condenser fans and pre-cooling of water).

Model	Flow-ice system	Plate ice system
Principle	Scraped surface ice slurry	Plate ice
Type	Mobile	Mobile
Electric power consumption (kWh/ton)	32	42
Electric power consumption (kWh/m^3)	16	21
Capacity (tons/day)	60	60
Capacity (m3/day)	120	120
Evaporator temperature (°C)	-10	-12
Condenser temperature (°C)	30	30
Feed water temperature (°C)	12	12
Refrigerant	R-134a, R-717	R-717
Size	1 x 40' container + 10' container	1 x 40' container + 10' container

The flow-ice system consists of flow-ice generators with individual drive motors, a refrigeration system, water pre-cooler, a snow separator and a delivery system, as shown in Figure 18. It is also possible to add heat pumps to utilize the produced heat. The system is available with R-134a or R-717 as refrigerant. The capacity of the system depends on the number of flow-ice generators (the cylinders seen in Figure 18).

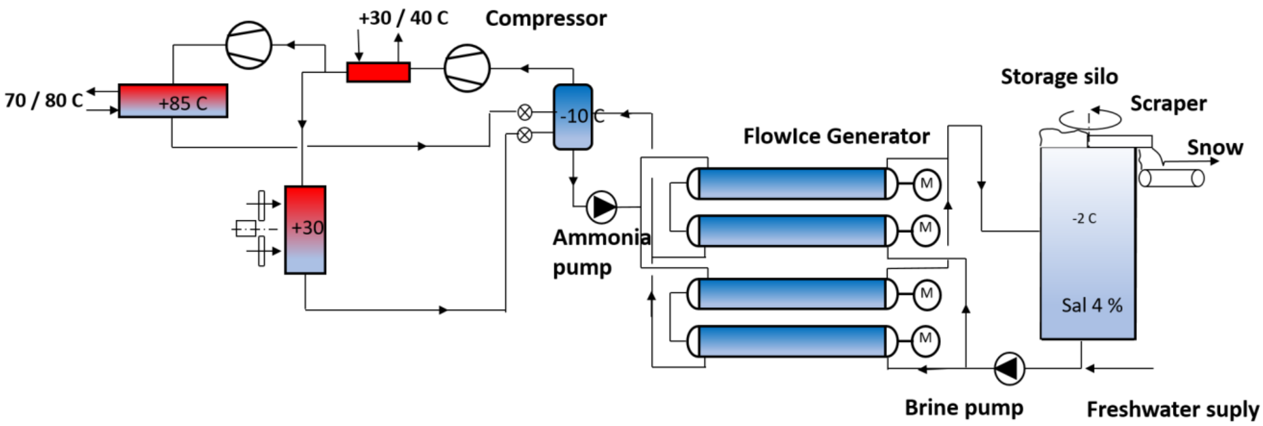


Figure 18: FrioNordica's flow-ice machine in snow production system.

The plate ice system consists of a plate ice machine, refrigeration system, water pre-cooler, ice crusher and delivery system, as shown in Figure 19. It is possible to add heat pumps to utilize the produced heat. The system is available with a R-717 refrigerant.

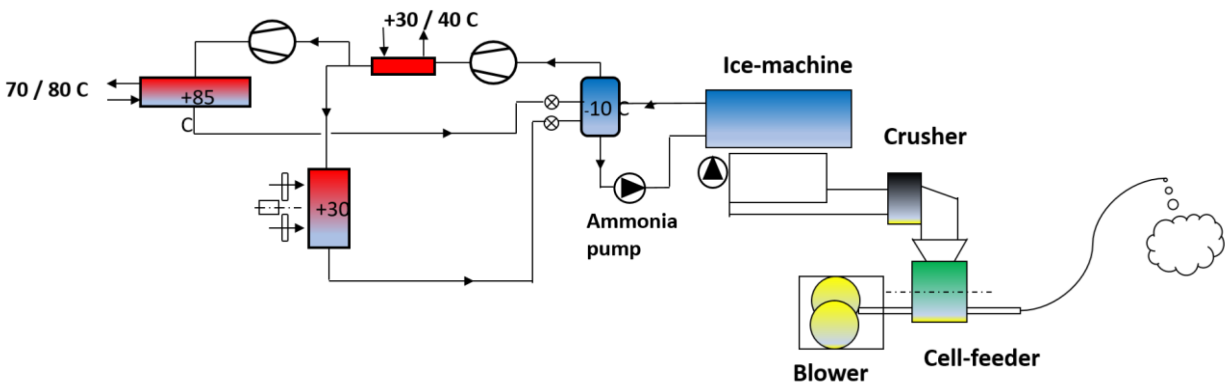


Figure 19: FrioNordica's snow production system with plate ice machine

FrioNordica has delivered a snow production facility in Japan, consisting of five snow production stations. Each station contained three plate ice machines (TS8) with a combined capacity of 50 tons/day, a crusher and a distribution system. R-22 was used as refrigerant, but the plate ice machines can also be set up with R-717.

4.10 Production with nitrogen

Snow can be produced by expanding compressed air together with water and liquid nitrogen. The method is similar to traditional snow guns described in Section 2, except that the droplets are frozen by the evaporating liquid nitrogen instead of the ambient air. This method is mostly used for indoor centers (de Jong 2011). Polar Technologies Europe is a supplier of such systems, and states that they can produce up to 200 m^3/hr of high quality snow (Polareurope.com 2017). In 2016, they produced about 1100 m^3 snow for The X Games in Oslo, Norway. Approximately 400 tons of liquid nitrogen were required for this production, so the operating costs were high (Haugsvær 2016). However, the investment costs are generally low.

4.11 Comparison of existing systems

Table 18 and Table 19 show the specifications for the different snow making systems in the 100 m^3/day and 200 m^3/day capacity range. The producers of the systems have provided specifications with different components included and for different operating parameters, so care should be taken when comparing them.

Table 18: Comparison of systems in the 100 m^3/ 24 hrs range.

Producer	**DemacLenko**	**TechnoAlpin**	**Supersnow**	**SnowMagic**	**Focusun**	**FrioNordica**	**FrioNordica**
Model	Snow4Ever	SF100	AWS 110	Model 50	FIF-600WC	Flow-ice[7]	Plate ice[7]
Principle	Vacuum ice slurry	Flake Ice	Flake ice	Plate ice	Flake ice	Scraped surface slurry	Plate ice
Type	Mobile	Mobile	Mobile	Mobile	Mobile	-	-
Size	1 x 20' container + cooling tower	1 x 40' container	2 x 40' container	1 x 40' container		1 x 40' container + 10' container	1 x 40' container + 10' container
Cooling capacity (kW)		206			342		
Snowmaking volume (m^3/day)	48 – 96[8]	100	110	102	120	120	120
Designed Power Consumption (kW)	180[9]	130	210	151	204.9	80	105
Power consumption[10] (kWh/m^3)	90 - 45	31.2	45.8	35.5	41	16	21
Snow density (kg/m3)	450	450	450 – 550	490	500	500	500
Snow Grain Size (mm)	0.2 – 0.5		1.5 – 2	0.1 – 0.3			
Refrigerant	Water	R404A	R507A		R404A	R-717	R-717
Ambient temperature (°C)	20 - 10	15	25	21	35		
Condenser temperature (°C)	10					30	30
Evaporator temperature (°C)	0.01	-30				-10	-12
Feed water temperature (°C)		5	10		20	12	12
Feed water flow rate (l/s)		0.8 l/s	1,03	0.8 l/s			
Operating temperature (°C)		-5 to +25	0 to +40				

[7] Specification only for ice machine and pre-cooling of feed water.
[8] 48 m^3/day for 20 °C and 96 m^3/day for 10 °C ambient temperature.
[9] 160 kW can be provided in the form of heat in the boiler.
[10] The power consumption per m^3 is calculated from stated maximum power consumption and production capacity unless stated otherwise.

Table 19: Comparison of systems in the 200 m^3/ 24 hrs range

Producer	IDE Technologies	SnowTek	SnowTek	TechnoAlpin	SnowMagic
Model	VIM 100[11]	SnowGen SI	SnowGen FI	SF220	Model 100
Principle	Vacuum ice slurry	Scraped surface slurry	Flake ice	Flake ice	Plate ice
Type	Mobile	Mobile	Stationary	Stationary	Mobile
Size	1 x 40' + 1 x 20' container + snow separator	1 x 40' container + snow separator	1 x 40' container	2 x 40' container + evaporative condenser	
Cooling capacity (kW)	350			640	
Snowmaking volume (m³/day)	200	181	222	220	204
Designed Power Consumption (kW)	190 (<250)	280	230	230	248
Power consumption[12] (kWh/m³)	22.8 (max 30)	37.1	24.9	25.1	29.2
Snow density (kg/m3)	560	550	450	450	490
Snow Grain Size (mm)	0.5 – 1.0				0.1 – 0.3
Refrigerant	Water	R404a, R507, R717	R404a, R507, R717	R717	-
Ambient temperature (°C)		10	10	15	21
Condenser temperature (°C)	5				
Evaporator temperature (°C)	0.01			-30	
Feed water temperature (°C)	2 – 6	8	8	5	
Feed water flow rate (l/s)	1.3	1.4		1.5	1.6
Operating temperature (°C)				-5 to +25	

In an effort to compare the systems, the coefficient of performance (COP) is estimated and plotted in Figure 20. The Carnot COP divided by 2, with an evaporator temperature of 0 °C and a varying condenser temperature given along the x-axis is plotted in the same figure. The COP calculations for the different machines are given in Appendix A.2. The temperature lift is taken to be the difference between the ice temperature and the ambient temperature.

The COP is defined in Section 3.1.1. For all systems, except DemacLenko's Snow4Ever, it is calculated as:

$$COP = \frac{\dot{Q}_{ice}}{\dot{W}},$$

where $\dot{Q}_{ice}$ is the heat that is removed to cool the feed water to 0 °C, freeze it, and optionally supercool the ice. $\dot{W}$ is the power consumption provided by the manufacturer.

In the Snow4Ever system, it is possible to use heat as the main energy source. The COP is therefore calculated as:

$$COP = \frac{\dot{Q}_{ice}}{\dot{W}+\dot{E}_x},$$

where $\dot{E}_x$ is the the exergy content of the heat Q at the temperature T, calculated as (Gundersen 2011):

$$E_x = Q * (1 - \frac{T_0}{T}),$$

where T_0 is the temperature of the surroundings.

[11] The power consumption is for the VIM unit only and does not include a supporting cooling system. The snow production capacity is reported to decrease by 1.5% for every 1 °C increase in feed water temperature
[12] The power consumption per m^3 is calculated from stated maximum power consumption and production capacity unless stated otherwise

The assumptions that have been made due to the limited information provided by some of the manufacturers are stated below:

- The temperature of the produced ice is assumed to be 0 °C unless a degree of supercooling is stated in the manufacturers specifications. The real temperature can be somewhat lower for SnowGen SI and FrioNordica's flow-ice system due to addition of salt to the feed water.

- For SnowMagic's systems it is assumed that the feed water temperature is 5 °C.

- For SnowGen FI it is assumed that the produced ice is at -5 °C.

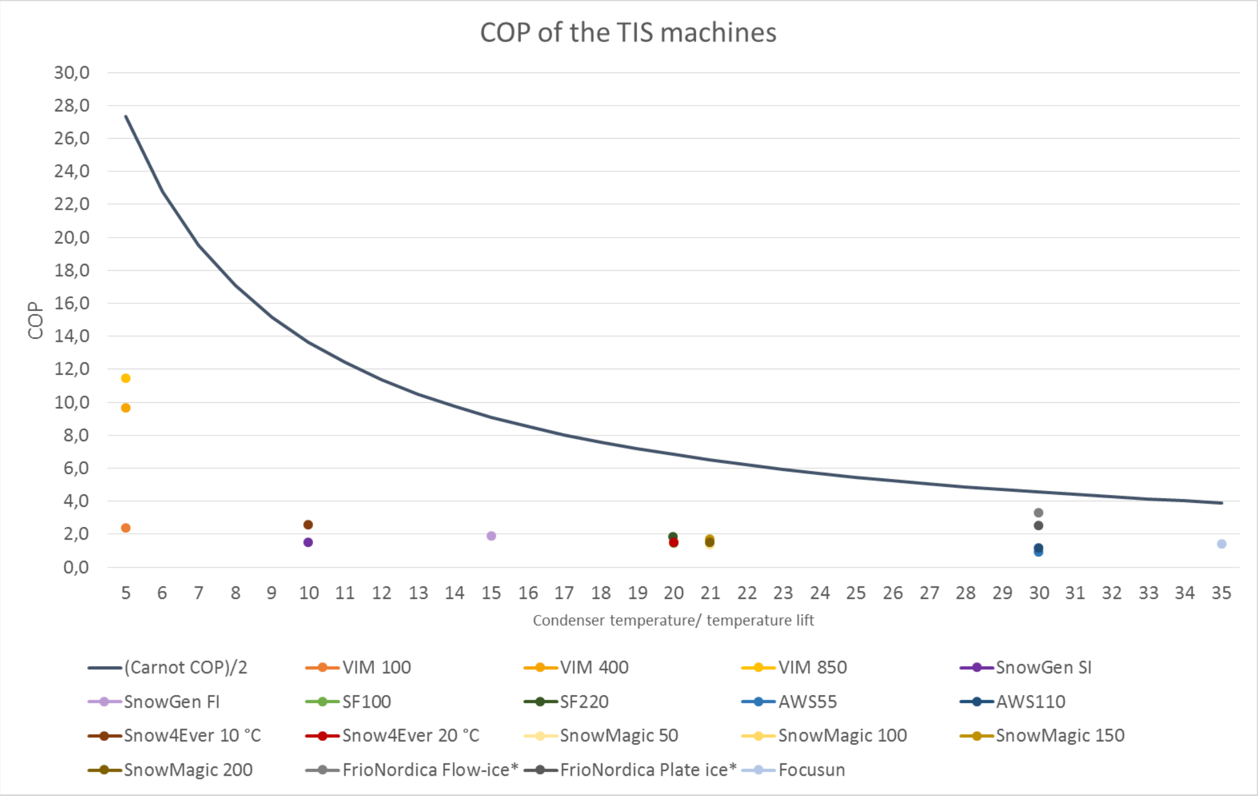


Figure 20: COP vs. condenser temperature for the different snowmakers. *Does not include crusher/separator or delivery system.

By inspecting Figure 20, it is clear that there is a potential for improvement with regard to energy efficiency for the different TIS machines, as they are all well below the $COP_{Carnot}/2$ line. The COP of the VIM 400 and 850 stand out as much higher than the rest. The temperature lift is however only 5 °C and the system size and capacity is much larger than for the other systems. Additionally, pre-cooling of the feed water or cooling of the cooling water is not included. The COP/COP_{Carnot} is 0.18 and 0.21 for VIM 400 and 850, respectively. This is in the same range as for many of the other systems. In (Ophir 2008), a VIM 850 used for mine cooling is stated to have a COP of 4.02 when the cooling water is 22 °C and 5.2 when it is 14.5 °C. FrioNordica's systems also have a high COP and a COP/COP_{Carnot} of 0.37 and 0.28 for the Flow-ice and plate ice systems, respectively. The power consumption for these systems does not include the snow separator (Flow-ice), crusher (plate ice) or delivery systems.

5 Snow quality

The desired snow quality depends on what the snow is intended for. The snow can be produced wet when it is used as a base layer or will be stored in depots for a period before use. When the snow will be used for events right away, it should have a density of about 300 – 400 kg/m^3, and be a little wet such that it is easily formed. Snow produced to supplement worn parts of the ski runs should on the other hand be dry. The desired snow quality also depends on the user. As an example, the snow should be as dry and light as possible for amateur alpine skiers, while it should be much harder and compact for experienced alpine skiers (Gjerland and Ødegaard Olsen 2014).

As described in Section 2, "Temperature dependent snow production", the artificial snow from traditional snowmakers has a density of 300 – 500 kg/m^3, which is around four times denser than new natural snow and close to that of groomed snow. The dryness and quality of the snow may to some extent be adjusted by changing the settings on the snow guns.

Snow from temperature independent snowmaking can be divided into dry and wet snow. The dry ice makers, such as flake ice machines can produce a supercooled dry snow with a density around 500 kg/m^3. The wet ice machines, such as the plate, tubular or slurry ice machines produce wet snow, also with a density around 500 kg/m^3, and the quality is often referred to as spring snow. Both the dry and wet ice are described as good skiing surfaces.

6 Master theses

Two Master students have written their theses on subjects within this project. Their main findings are summarized in this section.

6.1 Snow Production Equipment at Ambient Temperatures above Zero Degrees Celsius

Rykkje Dieseth did a literature review on existing temperature independent snowmakers, and made a simulation tool for ice production where he simulated production of flake ice and vacuum ice (Rykkje Dieseth 2016). Six cases were investigated for a production capacity of 50 tons/day. The ice production was based on the daily average temperatures from the Voll observation station in Trondheim for the period September 1st to November 1st. Three cases were investigated for the vacuum system; vacuum ice with two compressor stages (TVS), vacuum ice with one compressor stage (SVS), and vacuum ice with a CO_2 cascade arrangement, providing a constant 5 °C condensing temperature. For the flake ice system, two cases were investigated; single-stage compression (SCS) and two-stage compression (TCS) in a CO_2 refrigeration cycle. The average power consumptions and operating costs for the simulated two-month period are shown in Table 20.

For the vacuum ice system, Rykkje Dieseth finds that the two-stage system is slightly more efficient than the single-stage system regardless of the ambient temperature. However, the investment cost of a two-stage system is estimated to be around 50 % higher. The compressor outlet temperature of the SVS is much higher than for the TVS due to the high pressure ratio. At ambient temperatures above 11 °C, a single-stage compressor is unable to achieve the required pressure ratio. The CO_2 cascade system is more energy intensive than both the SVS and TVS system. The calculated power consumption for the vacuum ice makers are much less than for IDE's VIM100 system and somewhat lower than for the VIM 400 and 850. It is, however, difficult to compare the systems directly since the configuration of the existing machines are unknown.

For the flake ice makers, the single stage-system consumes less energy than the two-stage system when the ambient temperature is below 14 °C. The compressor outlet temperature limits the operation of SCS to a maximum ambient temperature of 18.7 °C. At this point the compressor outlet temperature reaches 150 °C, which is the maximum. Both the SCS and TCS are found to be more efficient than TechnoAlpin's SF100. However, some simplifications are made in this model and it does not include all the necessary components.

The vacuum system is found to be significantly more energy efficient than the flake ice system, and the operation costs are much lower. However, the investment costs for a vacuum ice system is much higher than for the flake ice system. The vacuum system size is estimated to be larger than the flake ice system.

Table 20: Power consumption and operating cost for the six cases (Rykkje Dieseth 2016)

System	Vacuum ice, single stage (SVS)	Vacuum ice, two-stages (TVS)	Vacuum ice, cascade	Flake ice, single stage (SCS)	Flake ice, two-stage (TCS)
Average power consumption (kWh/m^3)	5.8	5.6	12.8	24.5	27.1
Operating cost (NOK/m^3)	4.6	4.5	10.2	19.6	21.7

6.2 Utilization of surplus heat from snow producing machines

Haver Vagle has done a literature study on snowmaking, ice production, snow storage and heat recovery, and investigated four cases for snow supply under the condition that a 5 km ski track is guaranteed from November to the end of April at the Nordic Ski Arena in Granåsen, Norway (Haver Vagle 2016). The following four cases are evaluated based on cost and power consumption:

Case A: Snow storage
Case B: Temperature independent snowmaking with direct heat recovery
Case C: Indoor snowmaking with direct heat recovery
Case D: Temperature independent snowmaking with indirect heat recovery

A CO_2-heat pump that delivers water at 70 °C to three planned buildings at the ski arena, either directly or indirectly through a borehole thermal energy storage system is used to implement heat recovery.
Haver Vagle finds that snow storage is the cheapest option, with an estimated cost of 2.1 million NOK. The other cases are in the range 17.2 – 32.0 million NOK. The operating costs for all cases are above 0 NOK per m^3 of snow due to the costly process of distributing the snow on the track. With a more cost efficient snow distribution method, the total operating costs for the cases including heat recovery would be below 0 NOK/m^3.

Haver Vagle concludes that snow storage is the best suited option for Granåsen among the cases considered. This is because the estimated heat demand in Granåsen is too low to utilize the potential of the cases with heat recovery. The efficiency of these would be better with a continuous operation if a sufficiently large heat demand was present, and the costs related to distribution was decreased. He concludes that Case C, possibly in combination with Case D, is most promising in this regard. This could produce 12 GWh/yr of heat, about 200 000 m^3/yr of snow, and savings of 7.1 million NOK/yr. If the investment costs were held fixed, this would lead to a payback period of less than 5 years. Ski resorts should therefore be considered located near heat demanding industry, shopping malls or similar. A summary of the results for the four cases is given in Table 21.

Table 21: Summary of the results for the four cases (Haver Vagle 2016).

	Case A	Case B	Case C	Case D
Estimated investment cost (MNOK)	2.1	17.2	32	27.1
Operating costs (KNOK/yr)	714	288	345	122
Cost/m^3 produced snow (NOK/m^3)	59.48	24.01	16.96	10.2
Energy/ m^3 produced snow (kWh/m^3)	15.3	-27.0	-35.8	-44.2
Produced snow volume (m^3/yr)	12 000[13]	12 000	20 335	12 000

7 Discussion and conclusions

Due to a warmer winter climate, the snow season is becoming shorter and the maximum snow depth is decreasing. This is especially the case at low altitudes. New methods to ensure snow for ski and winter activities close to cities and highly populated areas are therefore necessary. One approach is to utilize TIS machines. There are already a few on the marked that are used to facilitate early openings of ski resorts, guarantee snow for competition venues, and to provide snow for the lowermost parts of ski slopes and similar applications. Most of these are based on flake ice machines, but snowmakers based on plate ice and ice slurries are also available. The existing systems are very energy demanding and have a low production capacity compared to traditional TDS machines. As an example, IDE's VIM 100 consumes about 22.8 kWh/m^3 produced snow, which results in a cost of 22.0 NOK/m^3 based on an electricity price of 0.965 NOK/kWh (SSB.no 2017). In comparison, a large fan gun consumes about 1.42 kWh/m^3 (including compressor, fan, heating and water pump) (Haver Vagle 2016), which results in an electricity cost of 1.40 NOK/m^3. It should be kept in mind that the fan gun requires a wet-bulb temperature of minimum -2 °C and several degrees lower to produce at full capacity.

The production capacity of most mobile TIS systems are around 100 m^3/ 24 hrs, while larger stationary TIS systems can have larger capacities. The largest installed TIS machine is IDE's VIM 400, with a capacity of 860 m^3/ 24 hrs. The VIM 850 has twice the capacity, but has not been installed for snowmaking applications so far. For comparison, fan guns can have production capacities in the range 100 m^3/hr.

The COPs for the existing TIS systems plotted in Figure 20 shows that the potential for improving the energy efficiency is high. This could be done by improving the ice production process and the components in the snowmakers. The vacuum technology seems to be a good candidate with regard to energy efficiency. The investment costs for such systems are reported to be high, however. The efficiency can also be improved by utilizing the surplus heat from snow production for district heating or similar. This can be done by lifting the temperature of the produced heat with heat pumps. Alternatively, snow can be produced from waste heat if a suitable heat source, providing heat at 150 °C or higher, is available.

[13] At the end of the snow storage period

Due to the lower capacities of TIS systems compared to TDS and the higher power consumption, the current TIS technology is not suited to replace TDS, but rather to act as a supporting system together with TDS and snow storage.

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A COP calculation

A.1.1 Machines in the 200 m³/ 24 hrs range

Example calculation for VIM 100:

VIM 100	T_hot	5 (°C)	278,15	Cooling water temperature
Power (kW)	190	250		
Capacity (tons/24hr)	112		1,30	kg/s
Tfeed (°C)	4,5		277,65	K
Tice (°C)	0		273,15	K
hif (kJ/kg)	332,4			
Cp (kJ/kgK)	4,22			
Q, ice	455,51			
COP (190)	2,40			
COP (250)	1,82			
COP_carnot	54,63			
COP(190)/COP_carnot	0,04			
COP(250)/COP_carnot	0,03			

Specific heat for water from (Çengel, Cimbala et al. 2012), latent heat of fusion and specific heat of ice from (Kauffeld, Kawaji et al. 2005)

$$COP_{Carnot} = \frac{T_C}{T_H - T_C} = \frac{273.15}{278.15 - 273.15} = 54.63$$

$$\dot{Q}_{Ice} = \dot{m}_{Ice} * (C_p * (T_{feed} - T_{ice}) + h_{if}) = 1.30 * (4.22 * (277.65 - 273.15) + 332.4) = 455.51$$

Where $\dot{Q}_{Ice}$ is the required heat removal too cool the feed water and the heat of fusion to produce the ice, C_p is the specific heat for water, T_{feed} is the feed water temperature, T_{ice} is the temperature of the produced ice and h_{if} is the heat of fusion.

$$COP = \frac{455.5}{190} = 2.4$$

$$COP = \frac{455.5}{250} = = 1.8$$

SnowGen SI	T_hot	10	283,15	Ambient temperature
Power (kW)	280			
Capacity (tons/24hr)	100		1,16	kg/s
Tfeed	8		281,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	423,80			
COP	1,51			
COP_carnot	27,32			
COP/COP_carnot	0,06			

SnowGen FI	T_hot	10	283,15	Ambient temperature
Power (kW)	230		*Assumed	
Capacity (tons/24hr)	100		1,16	kg/s
Tfeed	8		281,15	K
Tice*	-5		268,15	K
hif	332,4			
Cp	4,22			
Cp_ice	2,12			
Q, ice	436,06			
COP	1,90			
COP_carnot	17,88			
COP/COP_carnot	0,11			
SF220	T_hot	15	288,15	Ambient temperature
Power (kW)	230			
Capacity (tons/24hr)	110		1,27	kg/s
Tfeed	5		278,15	K
Tice (brochure)	-5		268,15	K
hif	332,4			
Cp	4,22			
Cp_ice	2,12			
Q, ice	463,55			
COP	**2,02**			
T_air	15			
T_evap_r	-30			
COP_carnot	13,41			
COP/COP_carnot	0,15			
SnowMagic 100	T_hot	21	294,15	Ambient temperature
Power (kW)	248		*Assumed	
Capacity (tons/24hr)	100		1,16	kg/s
Tfeed*	5		278,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	409,14			
COP	**1,65**			
T_air (web page)	21			
T_evap_r	-			
COP_carnot	13,01			
COP/COP_carnot	0,13			

A.1.2 Machines in the 100 m^3/ 24 hrs range

		10	283,15	Condenser temperature		
Snow4Ever	t_hot	20,00	293,15	Condenser temperature		
Power (kW)	180					
Capacity (tons/24hr)	21,6	43,2	0,25	kg/s	0,5	kg/s
Capacity (m3/24hr)	48	96				
Density (kg/m3)	450					
Tfeed	10		283,15	K		
Tfeed	20		293,15	K		
Tice	0		273,15	K		
hif	332,4					
Cp	4,22					
Q, ice_10	187,30					
Q, ice_20	104,20					
COP_10	**1,04**					
COP_20	**0,58**					
T_air	10 - 20					
T_evap_r	0					
COP_carnot_10	27,32					
COP_carnot_20	13,66					
COP(10)/COP_carnot	0,04					
COP(20)/COP_carnot	0,04					
Exergy						
T_0						
Q	160,00	kW				
T_Q	150	423,15	K			
W	20,00	kW				
Ex_10	52,94	kW				
Ex_20	49,16	kW				
COP_10ex	2,57					
COP_20ex	1,51					

COP based on exergy for the case of 10 °C ambient temperature:

$$\dot{E}_x = 160\ kW * \left(1 - \frac{283.15}{423.15}\right) = 52.9\ kW$$

$$COP = \frac{187.3}{20 + 52.9} = 2.57$$

SF100	T_hot	15	288,15	Ambient temperature
Power (kW)	130			
Capacity (tons/24hr)	45		0,52	kg/s

Tfeed	5		278,15	K
Tice (brocure)	-5		268,15	K
hif	332,4			
Cp	4,22			
Cp_ice	2,12			
Q, ice	189,6			
COP	**1,46**			
T_air	15			
T_evap_r	-30			
COP_carnot	13,41			
COP/COP_carnot	0,11			
AWS55	T_hot	25	298,15	Ambient temperature
Power (kW)	133			
Capacity (tons/24hr)	27,5		0,32	kg/s
Tfeed	10		283,15	K
Tice	-5		268,15	K
hif	332,4			
Cp	4,22			
Cp_ice	2,12			
Q, ice	122,60			
COP	**0,92**			
T_air	25			
T_evap_r				
COP_carnot	8,94			
COP/COP_carnot	0,10			
AWS110	T_hot	25	298,15	Ambient temperature
Power (kW)	210			
Capacity (tons/24hr)	55		0,64	kg/s
Tfeed	10		283,15	K
Tice	-5		268,15	K
hif	332,4			
Cp	4,22			
Cp_ice	2,12			
Q, ice	245,21			
COP	**1,17**			
T_air	25			
T_evap_r				
COP_carnot	8,94			
COP/COP_carnot	0,13			
SnowMagic 50	T_hot	21	294,15	Ambient temperature
Power (kW)	151			*Assumed
Capacity (tons/24hr)	50		0,58	kg/s

Tfeed*	5		278,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	204,57			
COP	**1,35**			
T_air	21			
T_evap_r	-			
COP_carnot	13,01			
COP/COP_carnot	0,10			
FrioNordica Flow-ice	T_hot	30	303,15	Ambient temperature
Power (kW)	80			
Capacity (tons/24hr)	60		0,69	kg/s
Tfeed	12		285,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	266,00			
COP	**3,33**			
T_air	30			Info from presentation
T_evap_r	-10			
COP_carnot	9,11			
COP/COP_carnot	0,37			
FrioNordica Plate ice	T_hot	30	303,15	Ambient temperature
Power (kW)	105			
Capacity (tons/24hr)	60		0,69	kg/s
Tfeed	12		285,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	266,00			
COP	**2,53**			
T_air	30			
T_evap_r	-12			
COP_carnot	9,11			
COP/COP_carnot	0,28			
Focuson	T_hot	35	308,15	Ambient temperature
Power (kW)	204,9			
Capacity (tons/24hr)	60		0,69	kg/s
Tfeed	20		293,15	K
Tice	0		273,15	K
hif	332,4			

Cp	4,22			
Q, ice	289,44			
COP	**1,41**			
T_air	35			
T_evap_r	-			
COP_carnot	7,80			
COP/COP_carnot	0,18			

A.1.3 Large capacity machines

VIM 400	T_hot	5	278,15	Cooling water temperature
Power (kW)	235			
Capacity (tons/24hr)	560		6,48	kg/s
Tfeed	4,5		277,65	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	2277,53			
COP	9,69			
COP_carnot	54,63			
COP/COP_carnot	0,18			
VIM 850	T_hot	5	278,15	Cooling water temperature
Power (kW)	397			
Capacity (tons/24hr)	1120		12,96	kg/s
Tfeed	4,5		277,65	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	4555,06			
COP	11,47			
COP_carnot	54,63			
COP/COP_carnot	0,21			
SnowMagic 150	T_hot	21	294,15	Ambient temperature
Power (kW)	362			
Capacity (tons/24hr)	150		1,74	kg/s
Tfeed	5		278,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	613,72			

COP	**1,70**			
T_air	21			
T_evap_r	-			
COP_carnot	13,01			
COP/COP_carnot	0,13			
SnowMagic 200	T_hot	21	294,15	Ambient temperature
Power (kW)	545			
Capacity (tons/24hr)	200		2,31	kg/s
Tfeed	5		278,15	K
Tice	0		273,15	K
hif	332,4			
Cp	4,22			
Q, ice	818,29			
COP	**1,50**			
T_air	21			
T_evap_r	-			
COP_carnot	13,01			
COP/COP_carnot	0,12			

A.2 Calculation of power consumption for commercial ice slurry machines

Producer	Sunwell	Mueller
Model	ModuPak	MaxICE
Heat transfer area per tube (m^2)	0.85	0.13
Flow rate per tube (l/min)	10 – 23	6
Ice fraction change per tube (wt%)	15	6 - 8
Power requirement per heat transfer area (kW/m^2)	1.2 – 1.8	0.22

Sunwell ModuPak

Assumptions:

- Density = 1000 kg/m^3

$$\frac{\text{Ice production}}{\text{tube}} = 23\left(\frac{\text{l}}{\text{min}}\right) * 1.0\left(\frac{\text{kg}}{\text{l}}\right) * 0.15 = 3.45\,\frac{\text{kg}}{\text{min}} = 0.207\,\frac{\text{ton}}{\text{hr}}$$

$$\frac{\text{Power requirement}}{\text{tube}} = 1.8\left(\frac{\text{kW}}{\text{m}^2}\right) * 0.85\ \text{m}^2 = 1.53\ \text{kW}$$

$$\frac{\textbf{Energy consumption}}{\textbf{ton}} = \frac{\textbf{1.53 kWh}}{\textbf{0.207 ton}} = \textbf{7.39}\,\frac{\textbf{kWh}}{\textbf{ton}}$$

Mueller MaxICE

$$\frac{\text{Ice production}}{\text{tube}} = 6\left(\frac{\text{l}}{\text{min}}\right) * 1.0\left(\frac{\text{kg}}{\text{l}}\right) * 0.07 = 0.42\ \frac{\text{kg}}{\text{min}} = 0.0252\frac{\text{ton}}{\text{hr}}$$

$$\frac{\text{Power requirement}}{\text{tube}} = 0.22\left(\frac{\text{kW}}{\text{m}^2}\right) * 0.13\ \text{m}^2 = 0.0286\ \text{kW}$$

$$\frac{\textbf{Energy consumption}}{\textbf{ton}} = \frac{\mathbf{0.0286\ kWh}}{\mathbf{0.0252\ ton}} = \mathbf{1.13}\frac{\mathbf{kWh}}{\mathbf{ton}}$$

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