Heat-driven show production applying ejector and natural refrigerant

Ailo Aasen
Snow for the Future – final workshop
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Technical snowmaking

- Artificial snowmaking is used in 90% of ski resorts
- Many of today's snowmaking technologies rely on cold ambient temperatures
  - *Temperature-dependent* snowmaking
- Global warming yields fewer cold days
  - Length of snow season decreasing 5 days/decade since 1970
- Desirable properties of snowmaking
  - Low environmental footprint, e.g. low electricity consumption
  - Possibility to function at ambient temperatures above $0\ ^{o}\mathrm{C}$
  - Should only involve natural working media

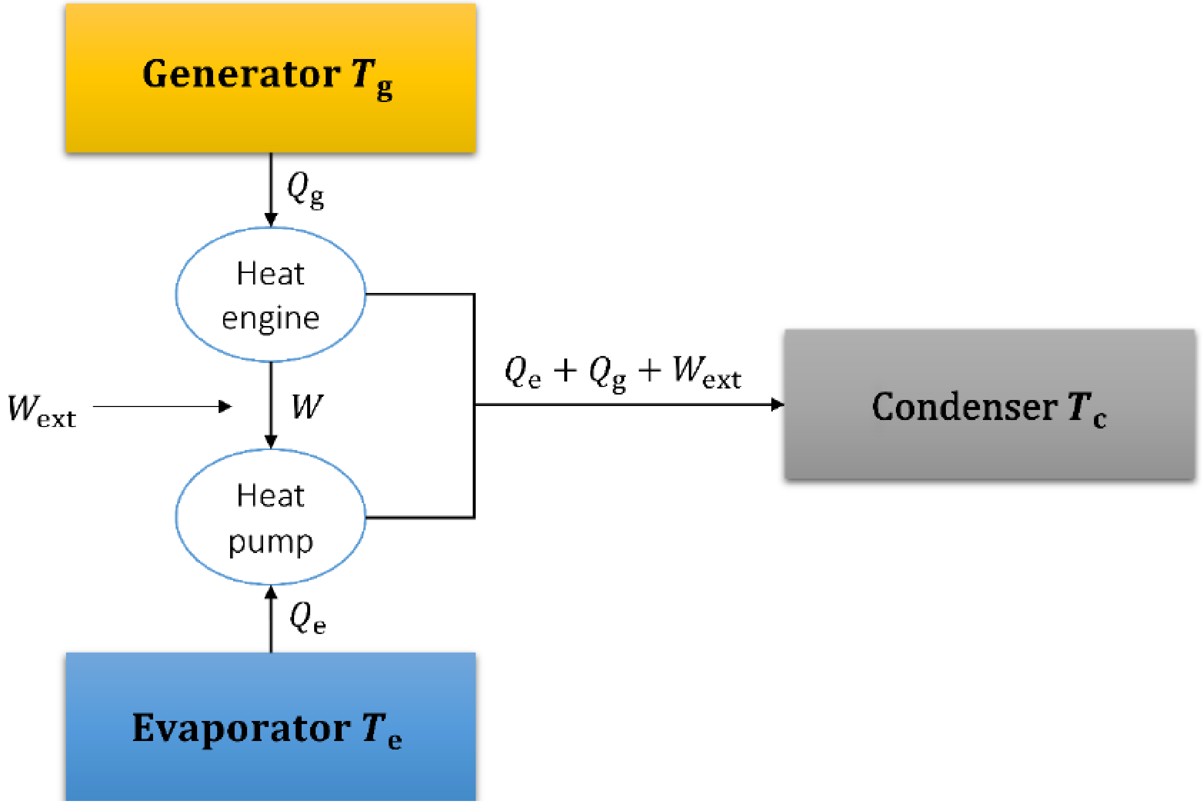
Temperature-independent snowmaking

- Systems that produce snow at any ambient temperature
- Two general approaches:
  1. Chilling water below the freezing point using some closed-cycle chiller, e.g. vapor-compression chiller
  2. The vacuum ice slurry method, where cooling happens by drawing off water vapor until the triple point is reached
- The vacuum method enables using a heat-driven chiller, which dramatically lowers electricity consumption compared to vapor-compression chillers

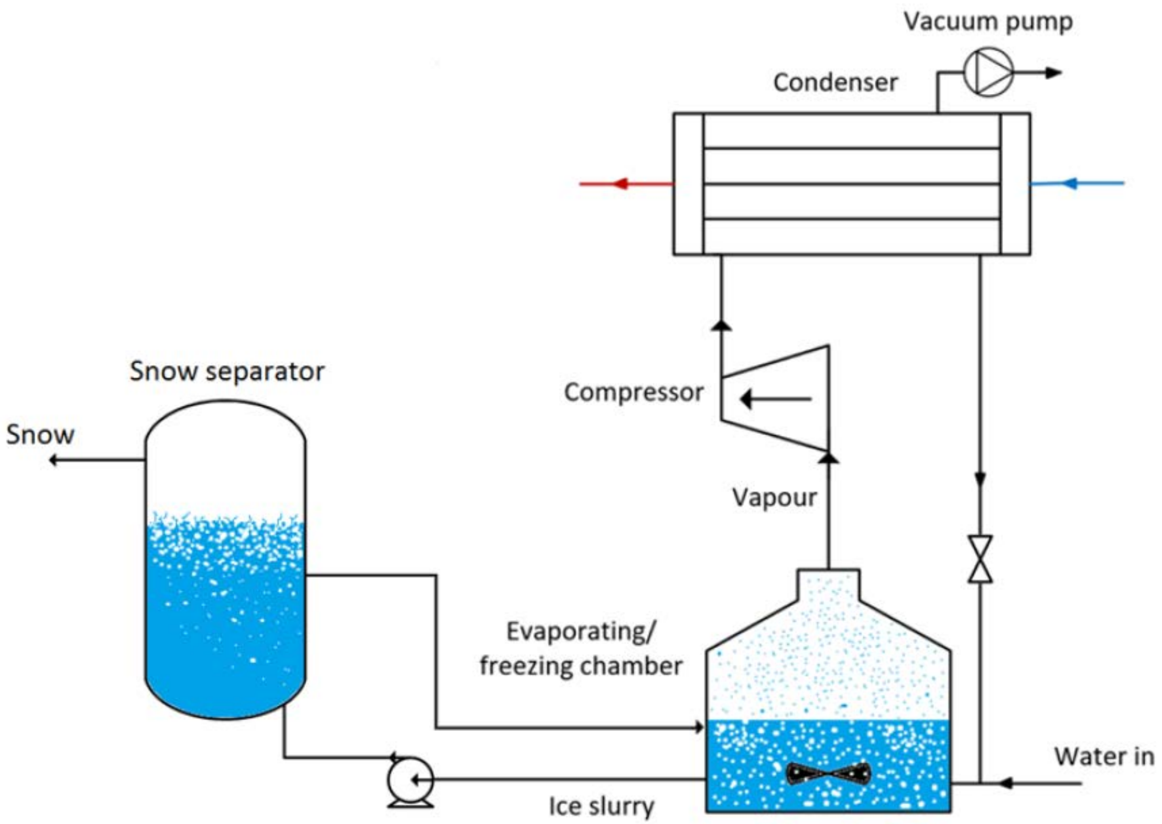
Heat-driven chillers – basic idea

- Combination of
  - Heat engine
  - Heat pump
- Mediated by some external work W_{ext}
- Reversible coefficient of performance:

$$\text{COP}_{\text{id}} = \frac{Q_e}{W_{\text{ext}} + Q_g} = \frac{T_e}{T_c - T_e} \frac{T_g - T_c}{T_g}$$



Vacuum ice freezing technique

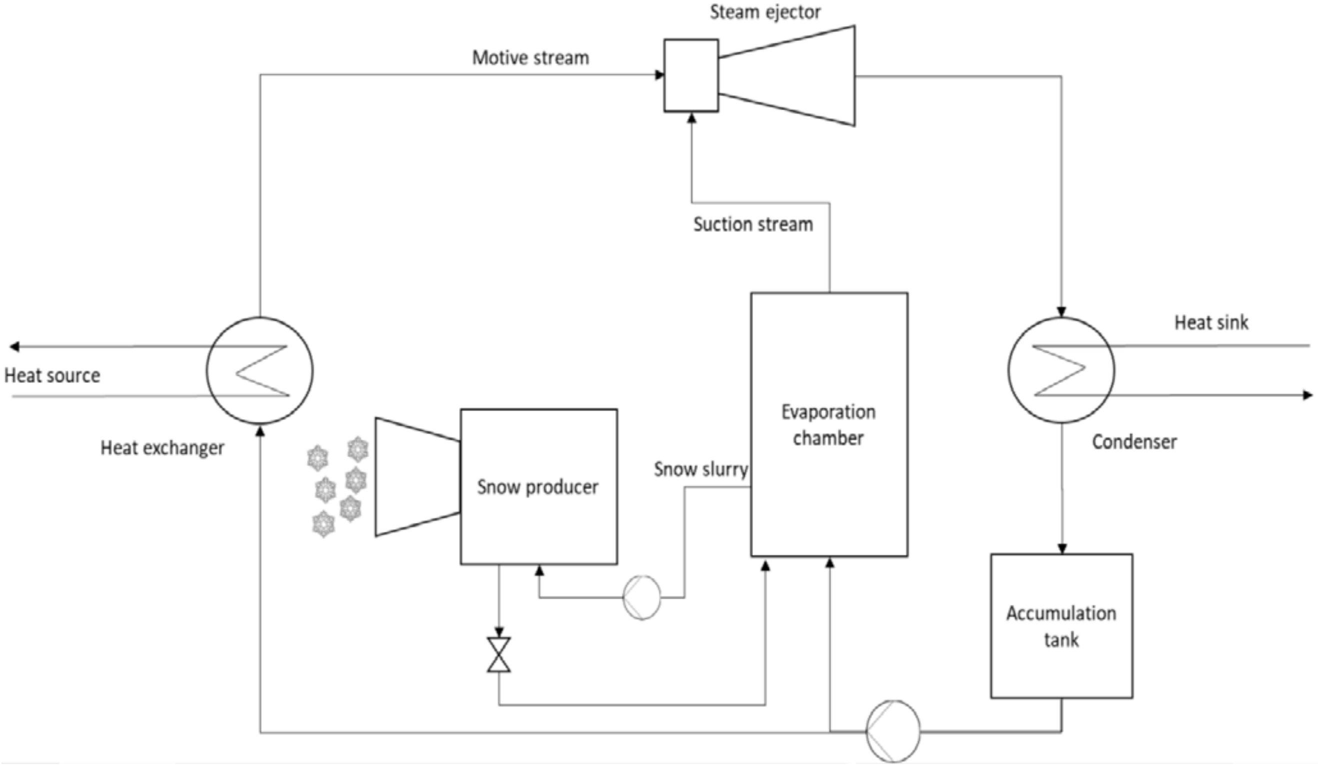


- Snowmaking based on an open cycle
- Triple point: $T = 0.01\ ^{\mathrm{o}}\mathrm{C}, P = 611\ \mathrm{Pa}$
- Enthalpy balance in freezing chamber yields the ratio of mass flows:

$$\frac{\dot{m}(\mathrm{ice})}{\dot{m}(\mathrm{vapor})} \approx 7$$

- Low pressures ⇒ large vapor volumes and expensive compressors

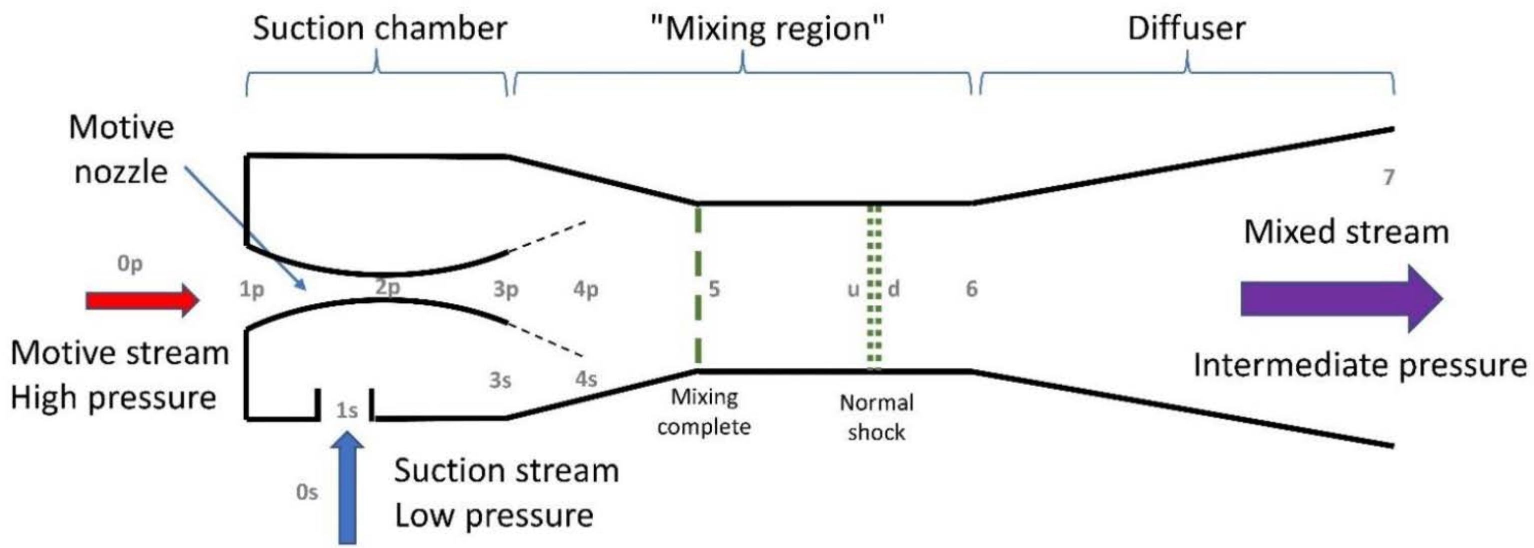
Vacuum ice freezing using ejector



- Compressor replaced by ejector
  - Lower CAPEX, OPEX
  - More reliable due to no moving parts
- Process integration
- OPEX depends on
  - Cost and temperature of heat source
  - Cost and temperature of cooling water
- **How does COP depend on the heat source and cooling water temperatures?**

Ejector model

- State-based model
- Homogeneous thermodynamic equilibrium at each state
- Both streams choke prior to mixing
- Transition from supersonic to subsonic flow in a single, normal shock



From heat source

To condenser

From vaccum freezing chamber

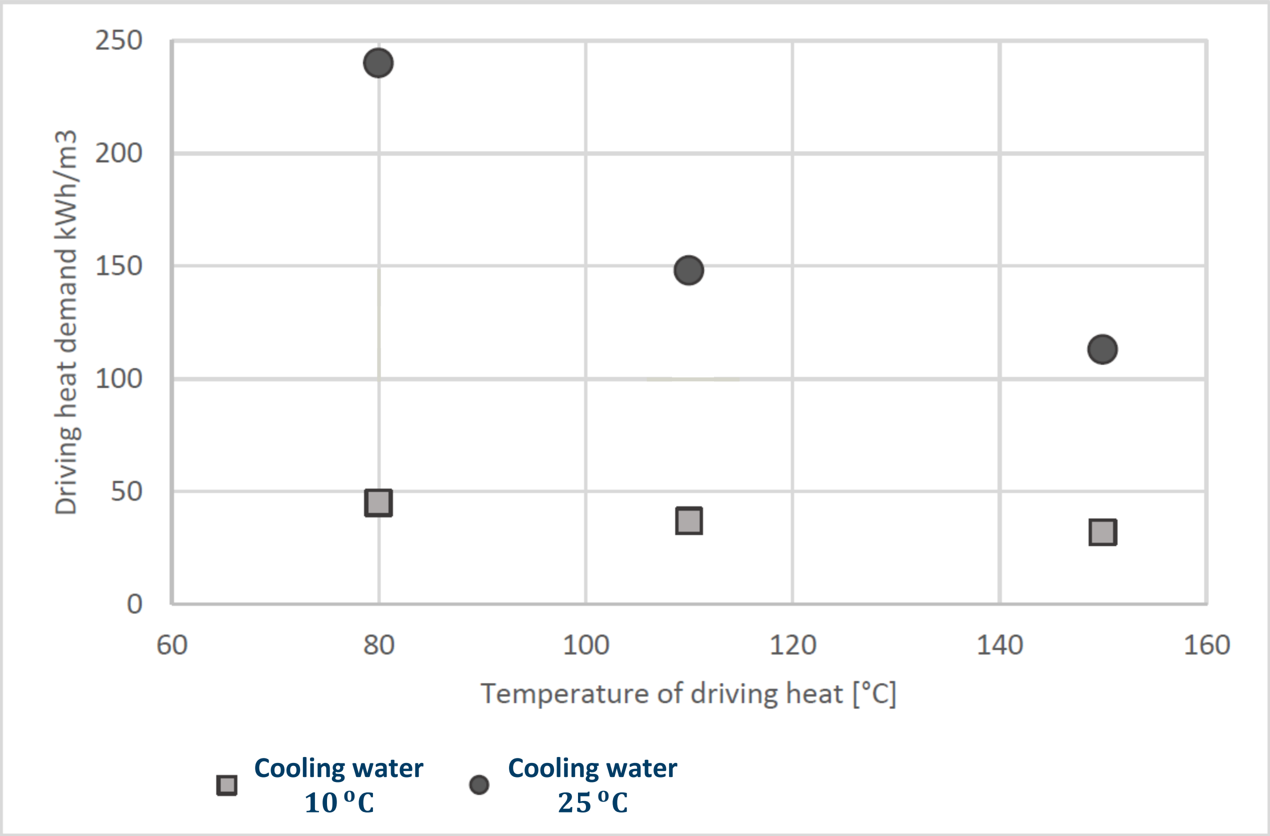
Modelling assumptions

- 5 K temperature difference in heat exchangers

- Two condenser temperatures: 30 °C, 15 °C
  - Corresponding to cooling water at 25 °C, 10 °C

- Three generator temperatures: 150 °C, 110 °C, 80 °C

Results of simulating ejector freezing cycle

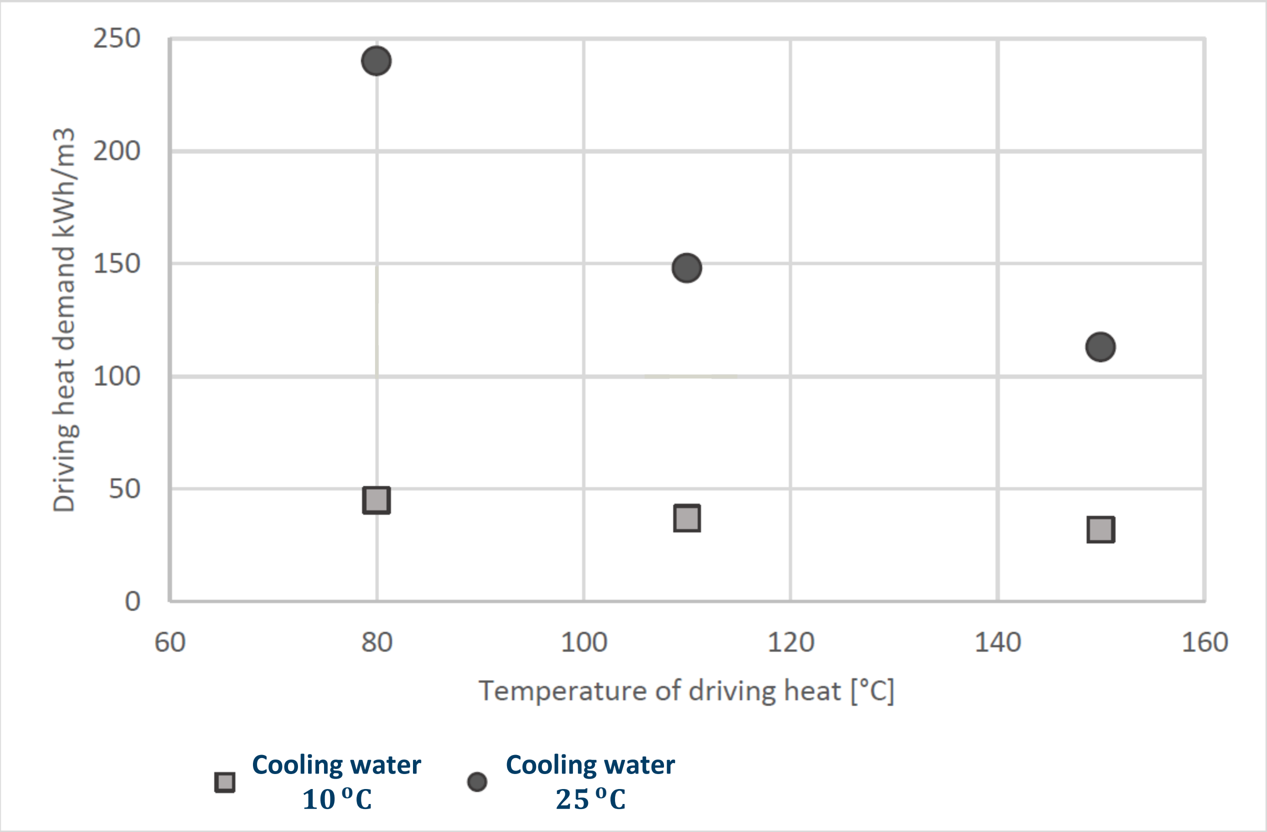


Heat demand vs heat temperature, for two condenser temperatures

Cold cooling water is extremely important

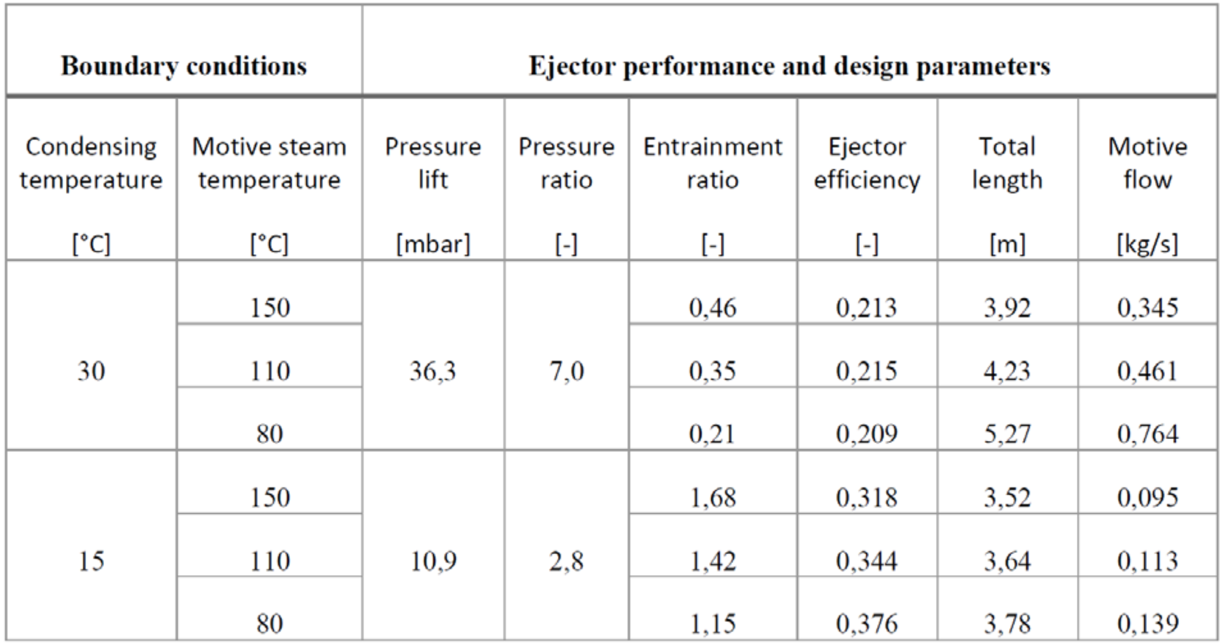
Temperature of heat input is less important

Results of simulating ejector freezing cycle



Heat demand vs heat temperature, for two condenser temperatures

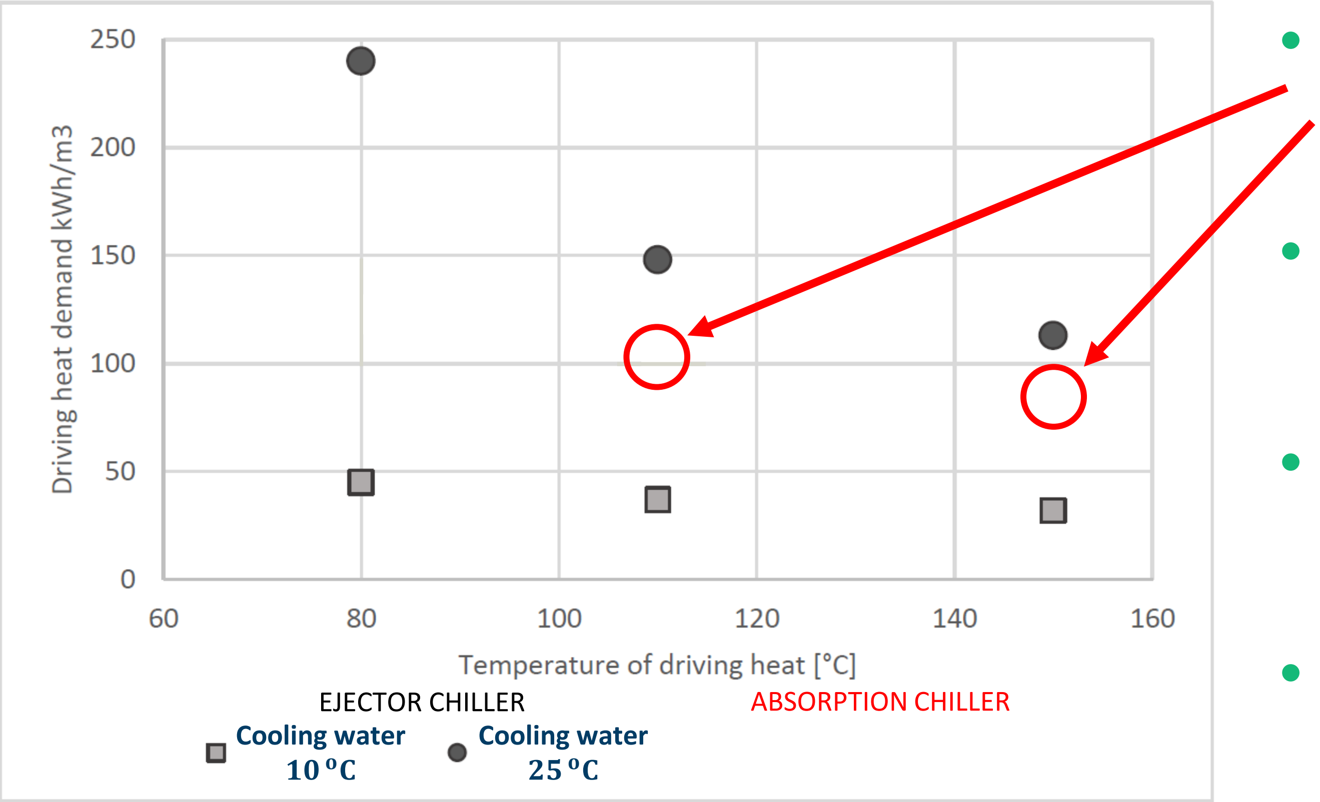
Ejector characteristics



Boundary conditions		**Ejector performance and design parameters**					
Condensing temperature [°C]	Motive steam temperature [°C]	Pressure lift [mbar]	Pressure ratio [-]	Entrainment ratio [-]	Ejector efficiency [-]	Total length [m]	Motive flow [kg/s]
30	150	36,3	7,0	0,46	0,213	3,92	0,345
	110			0,35	0,215	4,23	0,461
	80			0,21	0,209	5,27	0,764
15	150	10,9	2,8	1,68	0,318	3,52	0,095
	110			1,42	0,344	3,64	0,113
	80			1,15	0,376	3,78	0,139

Entrainment ratio: $\frac{\dot{m}(\text{suction vapor})}{\dot{m}(\text{motive steam})}$

Comparison to commercial absorption chillers



Heat demand vs heat temperature, for two condenser temperatures

- Absorption chiller is weakly dependent on cooling water temperature
- Absorption chiller has highest COP when using 25 °C cooling water
- The situation is reversed if sufficiently cold cooling water is available:
- Ejector system has highest COP when using 10 °C cooling water

Summary

- Growing demand for environmentally friendly, temperature-independent snow production
- An ejector can be process integrated in vacuum ice slurry production
- Ejector chiller COP is highly dependent on condenser temperature
  - Becomes highly efficient for cooling water temperature of $10\ ^{\text{o}}\text{C}$ and below
  - Even outcompetes absorption chillers
- Ejector chiller COP is weakly dependent on generator temperature
  - Highly efficient even with generator temperatures as low as $80\ ^{\text{o}}\text{C}$
  - Enables use of low-grade surplus heat from a range of industrial processes

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Thank you.