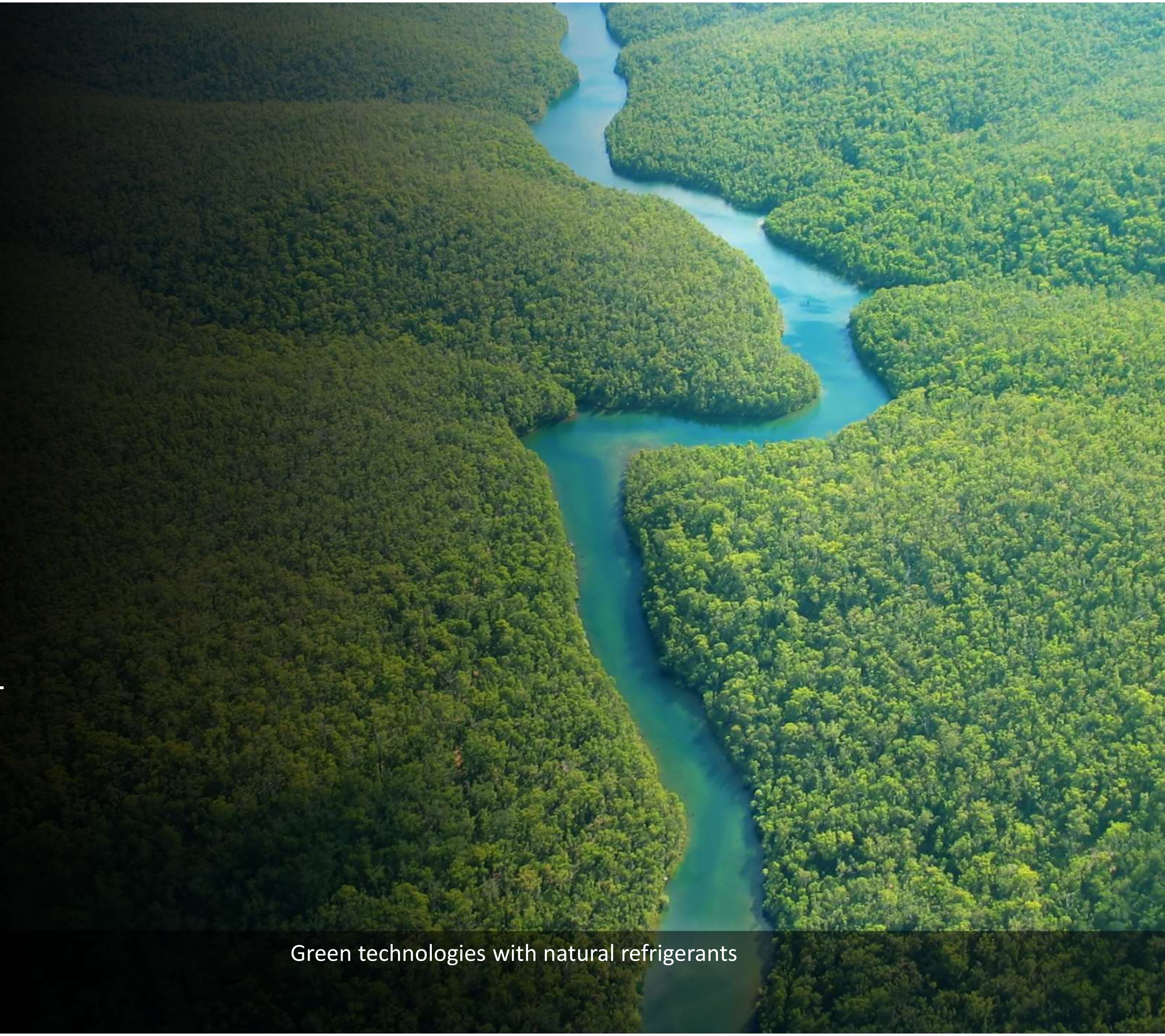
Modeling of CO_2 systems with novel two-stage evaporator

Mihir Mouchum Hazarika, NTNU



Green technologies with natural refrigerants

Outline

- **Introduction**
- Goal: to design flooded evaporator configurations
- Working principle: novel two-stage evaporator
- Objective
  - Modeling of gravity-fed evaporator loop
  - Modeling of two-stage evaporator loop
  - Test-rig with two-stage evaporator
  - Validation of numerical model
- Goals for further investigations
- Summary

Introduction

Heat transfer rate during evaporation:

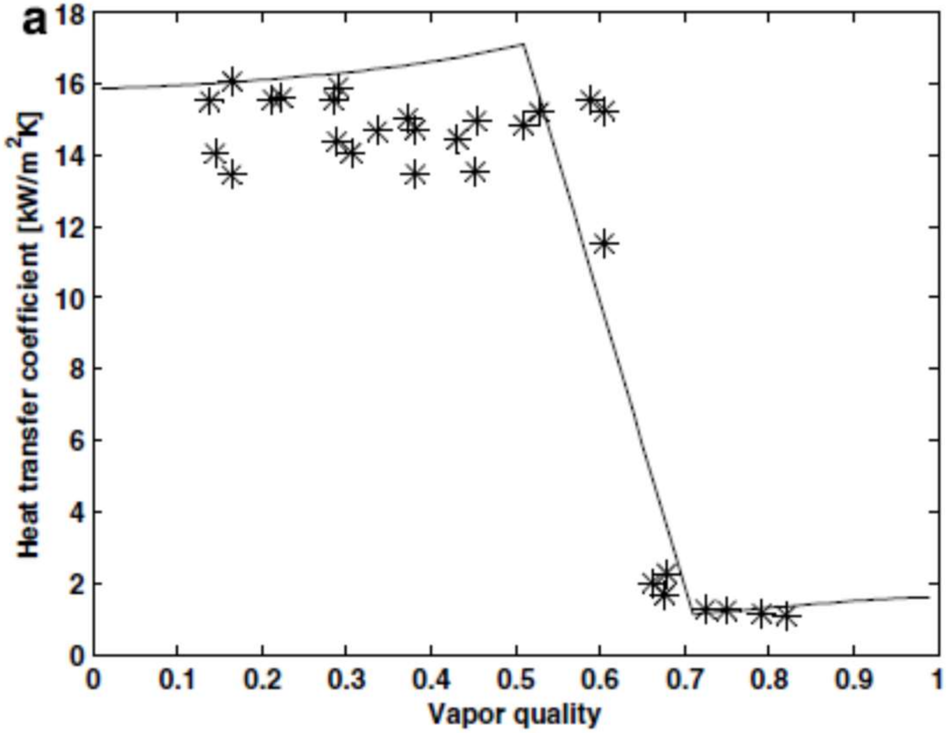
- Increases for higher heat transfer coefficient
  - ❖ Lower vapor fraction (larger liquid contact with evaporator surface)

This leads to:

- Better overall performance
- Compact heat exchanger design

Goal:

- To design flooded heat exchangers



Heat transfer coefficient of CO_2 during evaporation, d = 1 mm, G = 720 kg. m^{-2}. s^{-1} [1]

Introduction

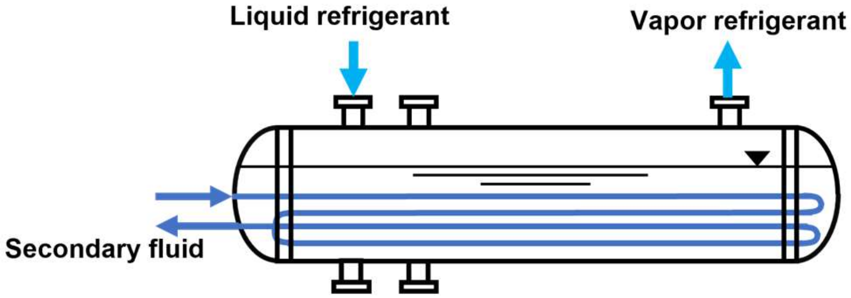
Flooded evaporator configurations

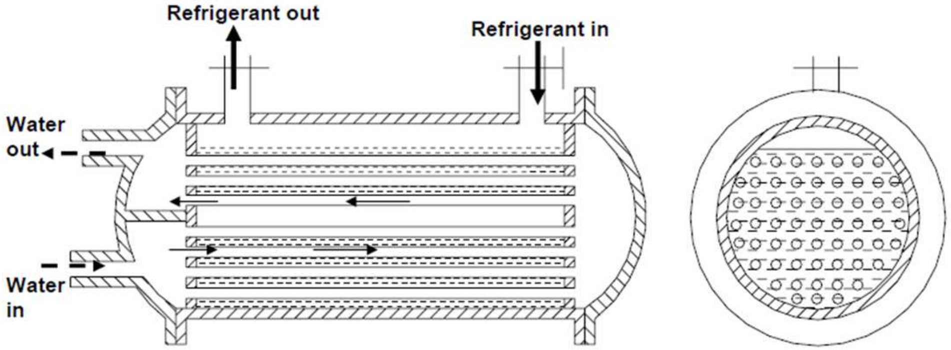
Can be classified into two broad categories:

➡ **Without liquid circulation**

- ❖ Shell and tube heat exchanger is used.
- ❖ Tubes are entirely submerged.

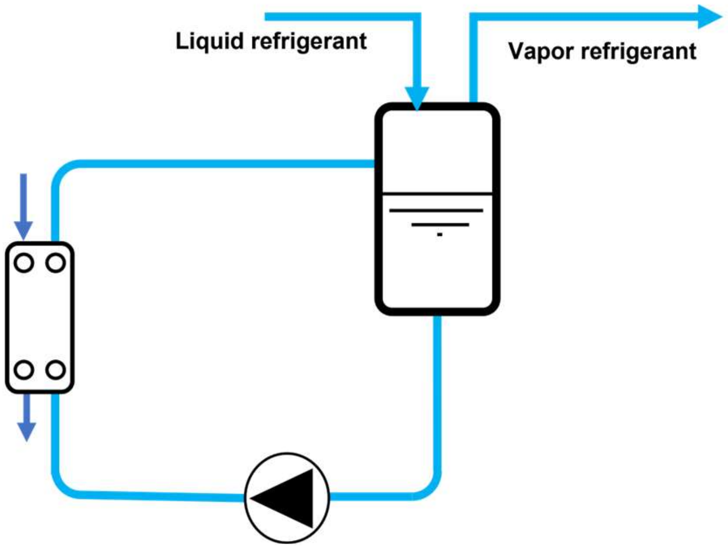
➡ **With liquid circulation**



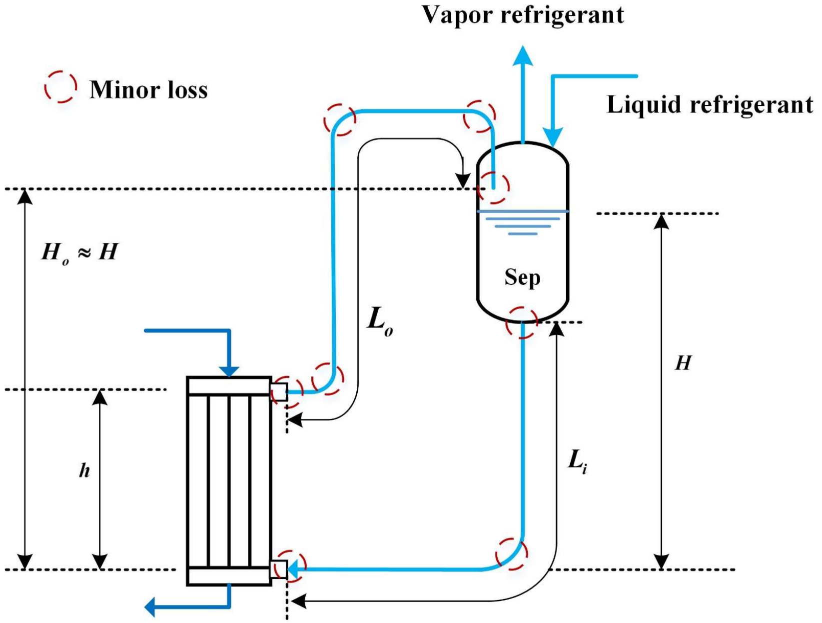


Introduction

Flooded evaporator with liquid circulation



Forced circulation with pump

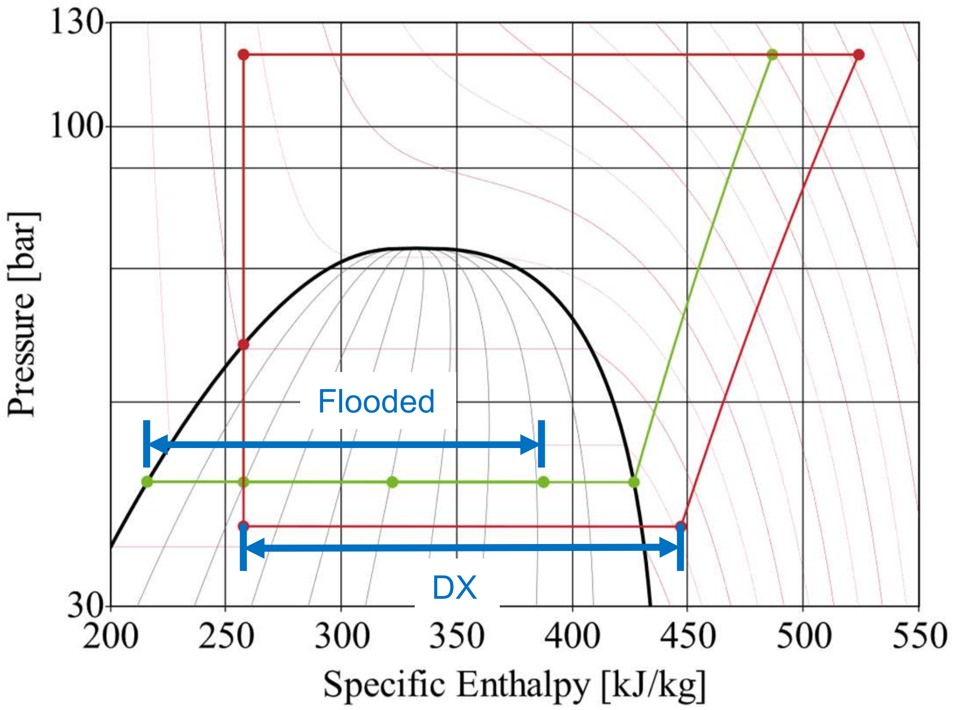


Gravity-fed evaporator loop

Introduction

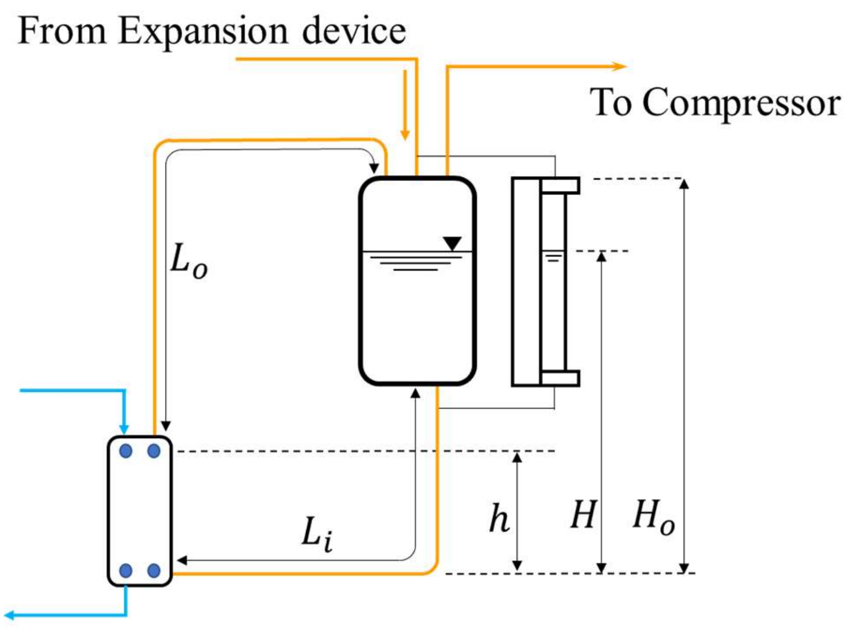
Benefits of the flooded evaporators

- Refrigerant is 100% liquid at entry
- Better distribution of liquid
- Higher heat transfer rate
- Lesser pressure drop
- All phase change latent energy available
- Operated at higher evaporation temperature

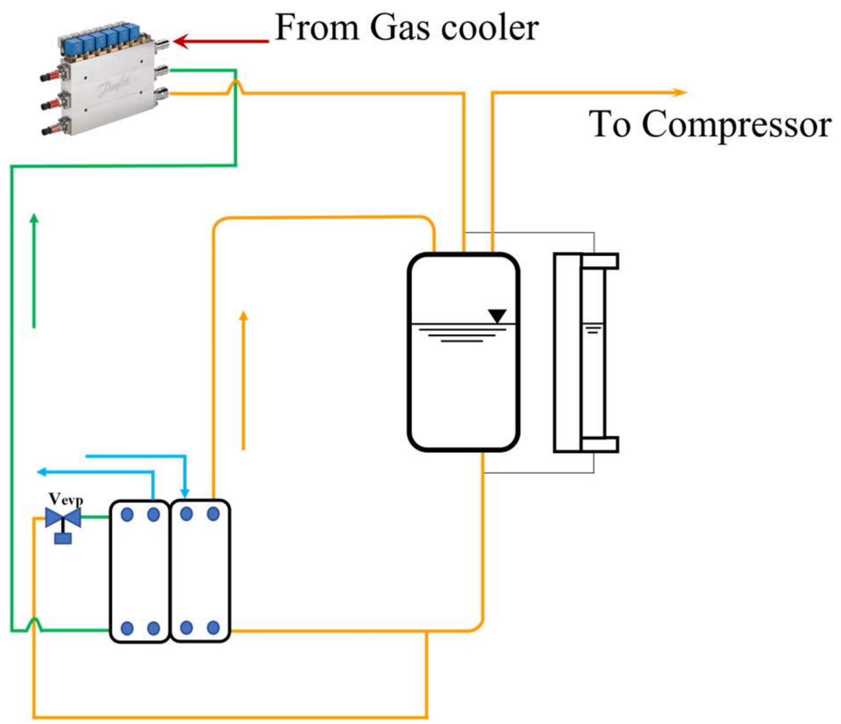


Goal: Design flooded evaporator configurations

Gravity-fed evaporator

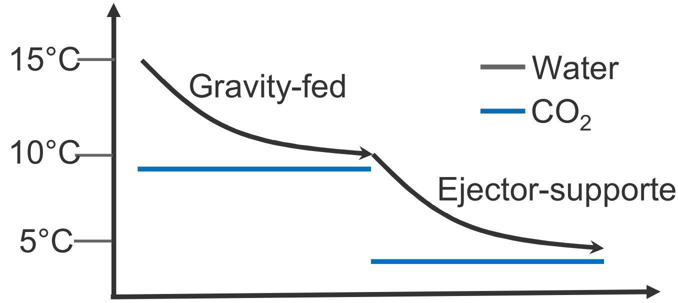


Two-stage evaporator



Working principle: Two-stage evap.

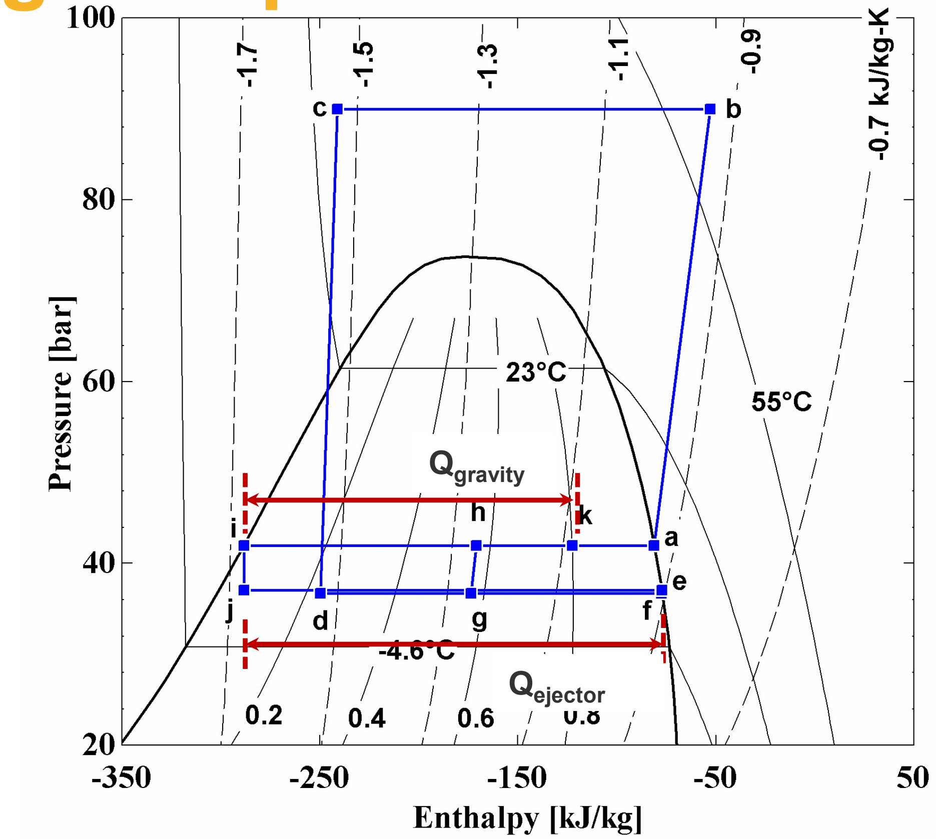
- Designed for large temperature glide
- Different evaporation temperatures



- Gravity-fed evaporator operates = Suction pressure of the compressor

  Ejector-supported evaporator operates = Suction pressure of ejector secondary nozzle

  Applications: Hotels, large kitchens, fishing vessels, etc.



Outline

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- Goal: to design flooded evaporator configurations
- Working principle: novel two-stage evaporator
- **Objective**
  - ➢ **Modeling of gravity-fed evaporator loop**
  - ➢ Modeling of two-stage evaporator loop
  - ➢ Test-rig with two-stage evaporator
  - ➢ Validation of numerical model
- Goals for further investigations
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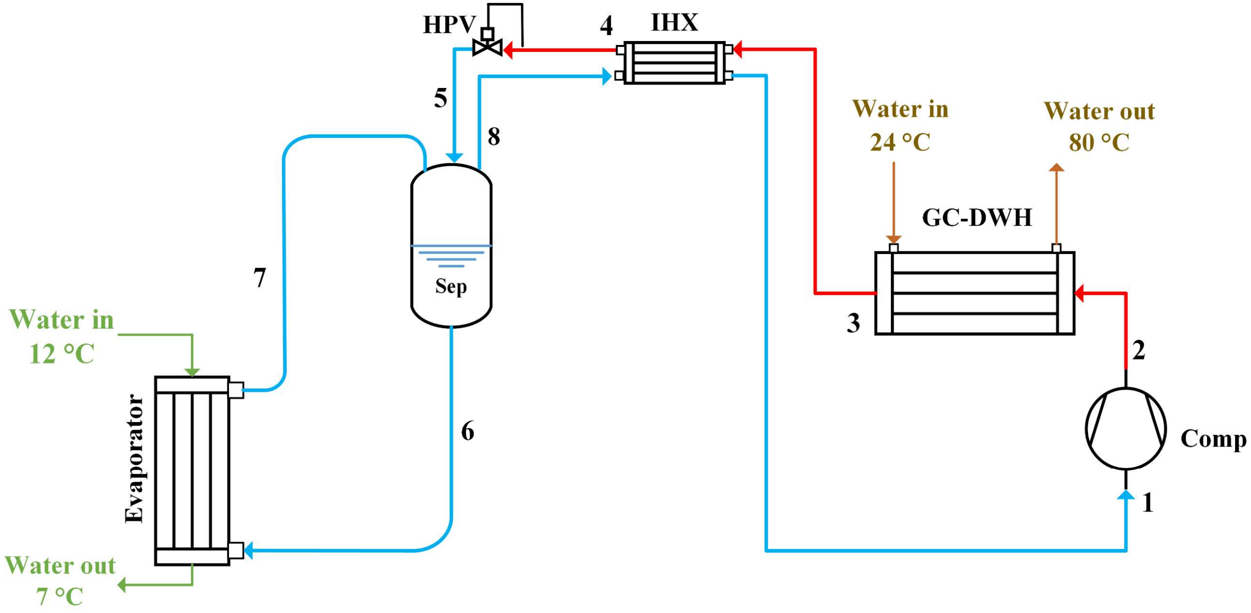
Modeling of gravity-fed evaporator loop

- Model is developed in Modelica
- Individual models are selected from TIL library (TLK-Thermo Gmbh)
- To model the gravity-fed loop
  - ➢ Appropriate equations are derived (minor loss, major loss, and gravity term)
  - ➢ TIL models are upgraded
- Dymola 2021 is the modeling environment



Governing Eqs.: Gravity-fed evaporator loop

$$H\rho_l g - h\rho_m g - (H-h)\rho_o g = \Delta p_i + \sum \Delta p_i + \Delta p_{ev} + \sum \Delta p_{ev} + \Delta p_o + \sum \Delta p_o$$

Frictional pressure drop in the riser

$$\Delta p_o = \beta_o \times \Delta p_g$$

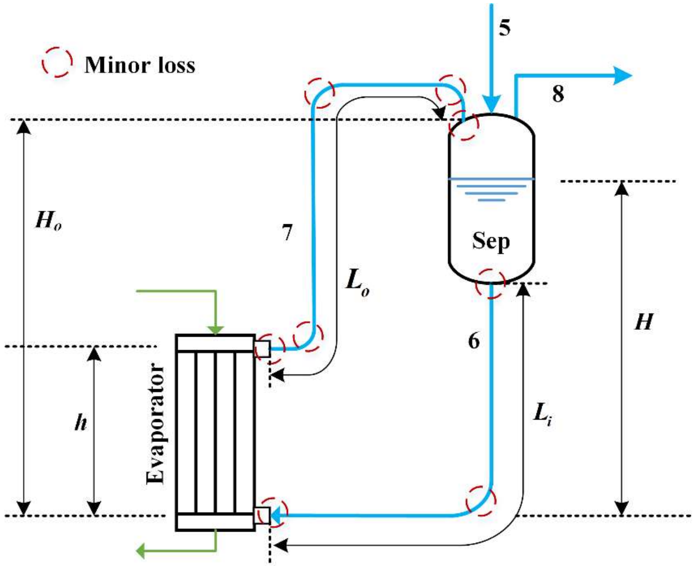
$$\Delta p_g = 0.241 \times \frac{{\mu_g}^{0.25}}{\rho_g} \times \dot{m}^{1.75} \times \frac{L_o}{{d_o}^{4.75}}$$

$$\beta_o = [\vartheta + 2(1-\vartheta) \times \dot{x}_o](1-\dot{x}_o)^{0.333} + {\dot{x}_o}^{2.276}$$

Pressure drop due to minor losses in the riser

$$\sum \Delta p_o = \frac{\dot{G}^2}{2\rho_g} \sum \xi_j \, \beta_{c,j}$$

$$\beta_c = [\vartheta + C(1-\vartheta) \times \dot{x}_o](1-\dot{x}_o)^{0.333} + {\dot{x}_o}^{2.276}$$



Frictional pressure drop in the downcomer

$$\Delta p_i = 0.241 \times \frac{{\mu_l}^{0.25}}{\rho_l} \times \dot{m}^{1.75} \times \frac{L_i}{{d_i}^{4.75}}$$

Pressure drop due to minor losses in the downcomer

$$\sum \Delta p_i = \frac{\dot{G}^2}{2\rho_l} \sum \xi_j$$

Pressure drop in the evaporator

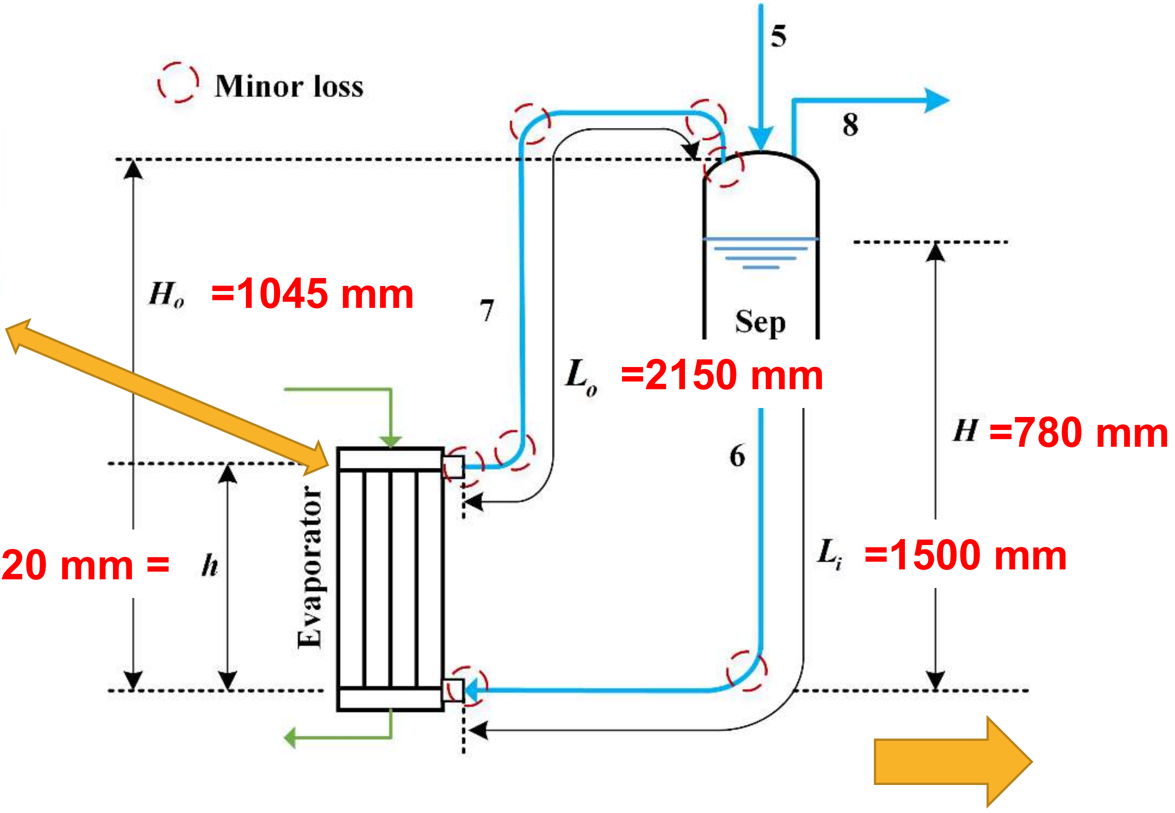
$$\Delta p_{ev} = b \times \dot{m}^2$$

$$b = \frac{\Delta p_n}{\dot{m}_n^2} \times \frac{l}{l_n}$$

- **TIL models are upgraded including these equations**

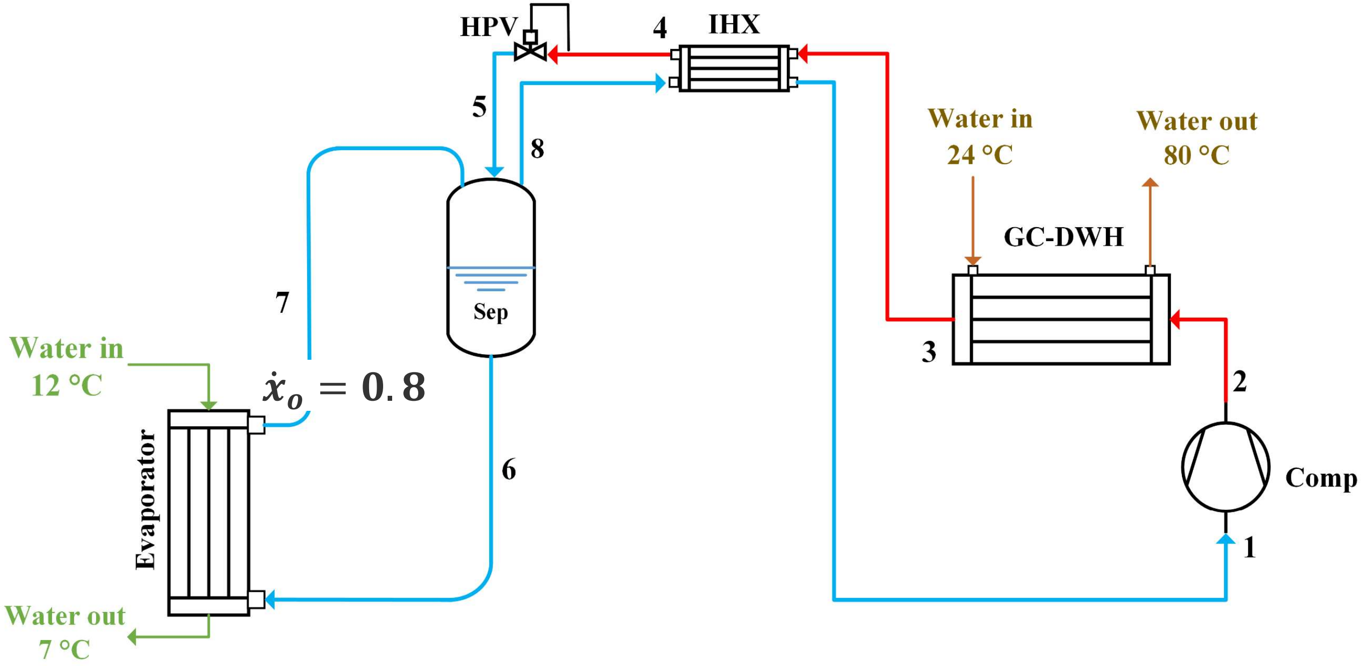
Dimensions of components

Evaporator (BPHX)	
Number of plates	40
Plate length (mm)	420
Plate width (mm)	155
Pattern angle (°)	22.5
Wall thickness (mm)	0.5
Pattern amplitude (mm)	2.9
Pattern wavelength (mm)	6



Simulation conditions

Simulation conditions	
Discharge pressure (bar)	120
Suction pressure (bar)	41
Cooling capacity (kW)	8.3
Cold water in (°C)	12
Cold water out (°C)	7
Hot water in (°C)	24
Hot water out (°C)	80
GC approach temperature (K)	3



Outline

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- Goal: to design flooded evaporator configurations
- Working principle: novel two-stage evaporator
- **Objective**
    - **Modeling of gravity-fed evaporator loop** → **Simulation results**
    - Modeling of two-stage evaporator loop
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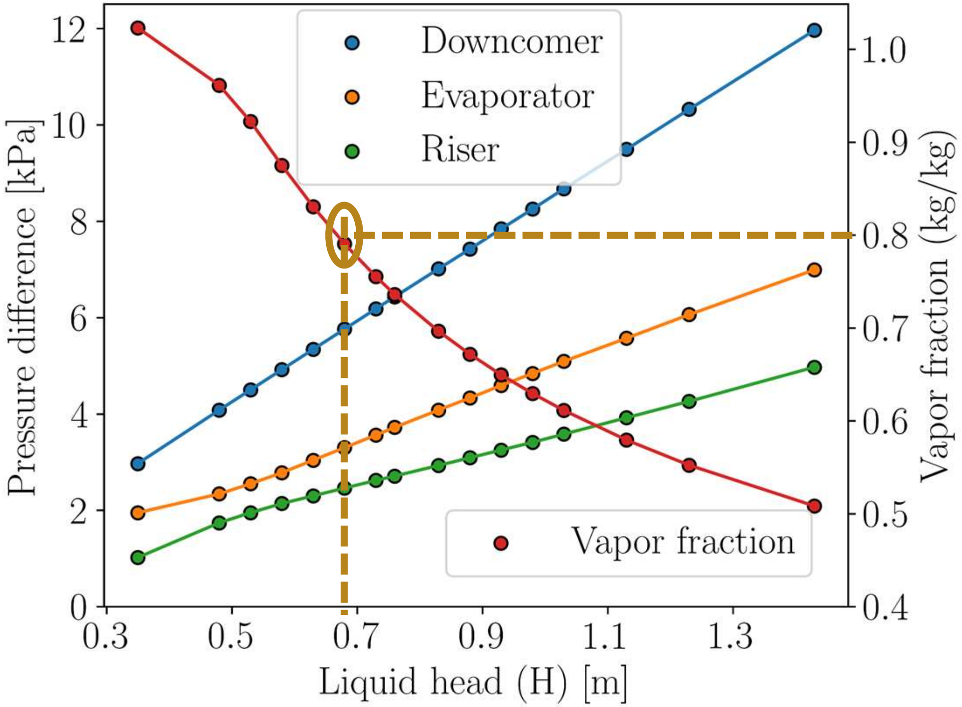
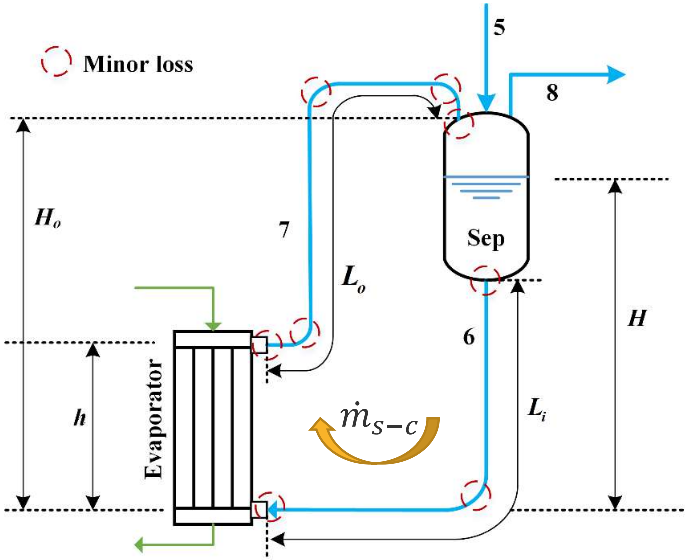
Results

Effect of liquid head 'H'





- Higher the liquid head 'H' ↑
  - ➢ Higher pressure gain in Downcomer ↑
  - ➢ Lower $\dot{x}_o$ ↓
- H=0.68 m, gives $\dot{x}_o = 0.8$

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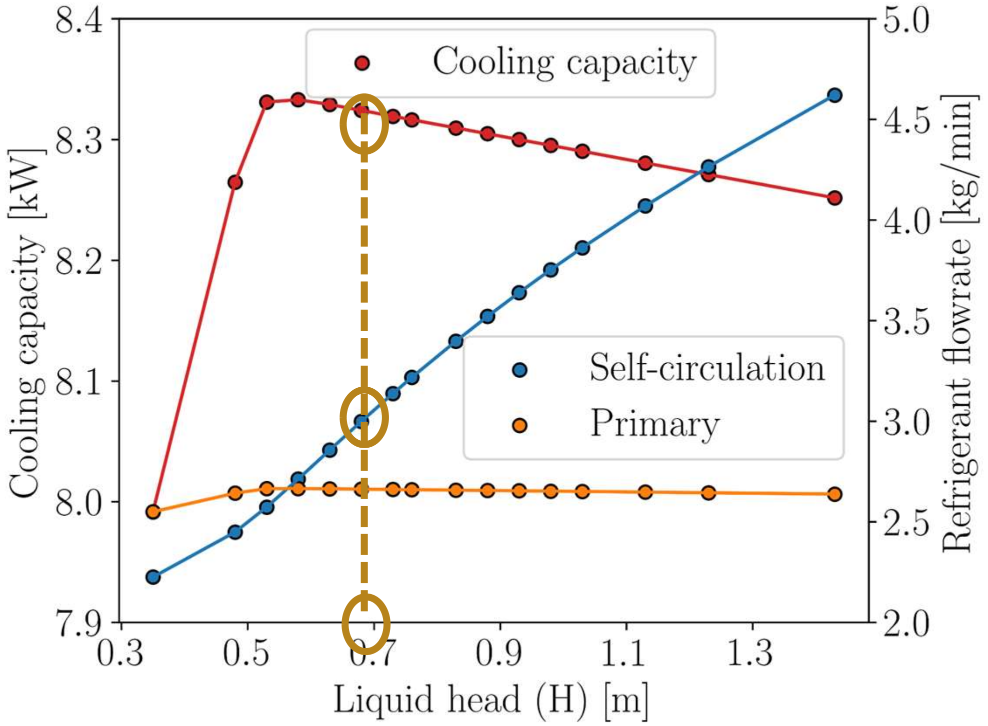
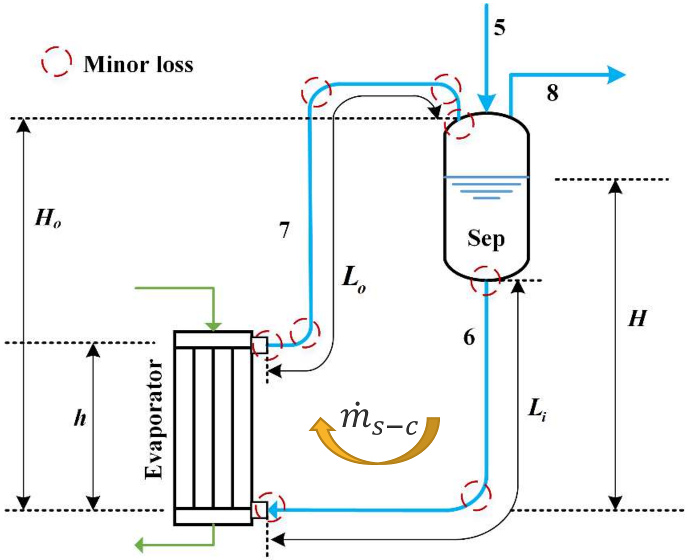
Results

Effect of liquid head ‘H’

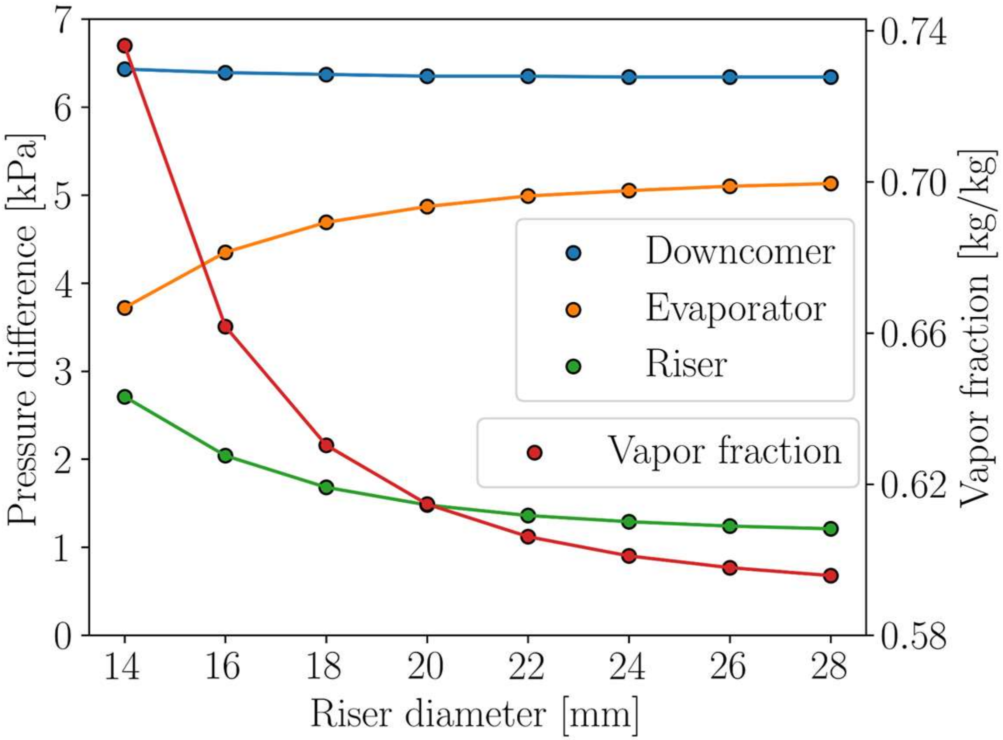


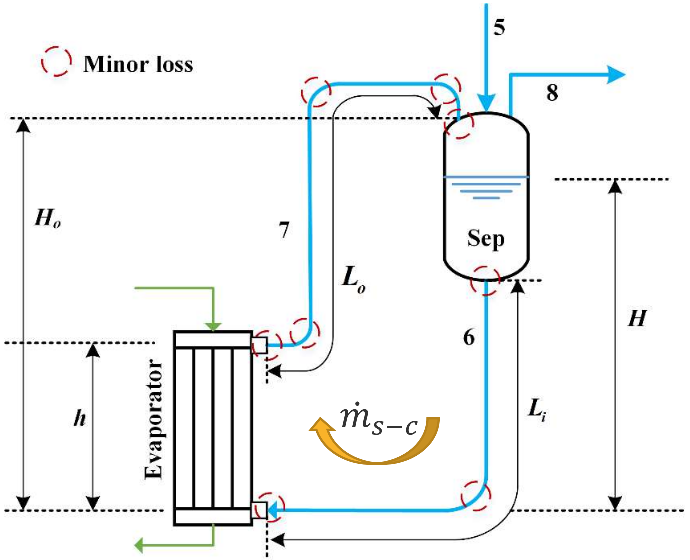


- ‘$\dot{Q}_{ev}$’ and ‘$\dot{m}_{s-c}$’ corresponding to H=0.68 m

Results

Effect of Riser diameter ‘d’

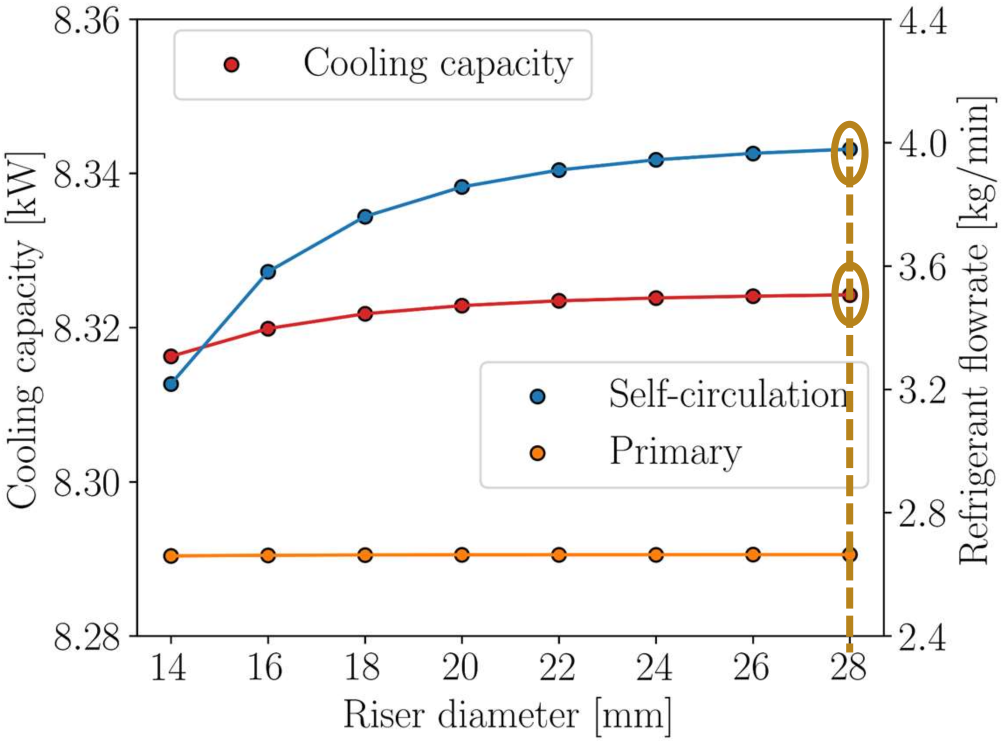


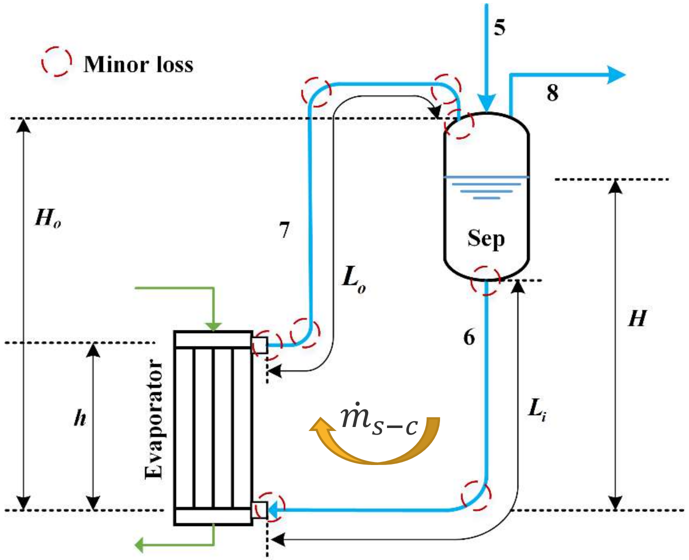


- Higher the Riser diameter ‘d’
  - Lower pressure drop in Riser
  - Lower $\dot{x}_o$
- No reduction in ΔP beyond d=28 mm

Results

Effect of Riser diameter ‘d’





- Riser diameter should be twice the size of Downcomer diameter

Simulation results summary

- Gravity-fed evaporator performs better as compared DX evaporator
- Gravity-fed evaporator performance
    - Liquid head ‘H’ and riser diameter ‘d’ are critical parameters
    - H=0.68 m, gives desired capacity with $\dot{x}_o = 0.8$
    - Riser diameter should be twice the size of downcomer diameter
- Gravity-fed evaporator: Simple and easy modification to enhance the performance

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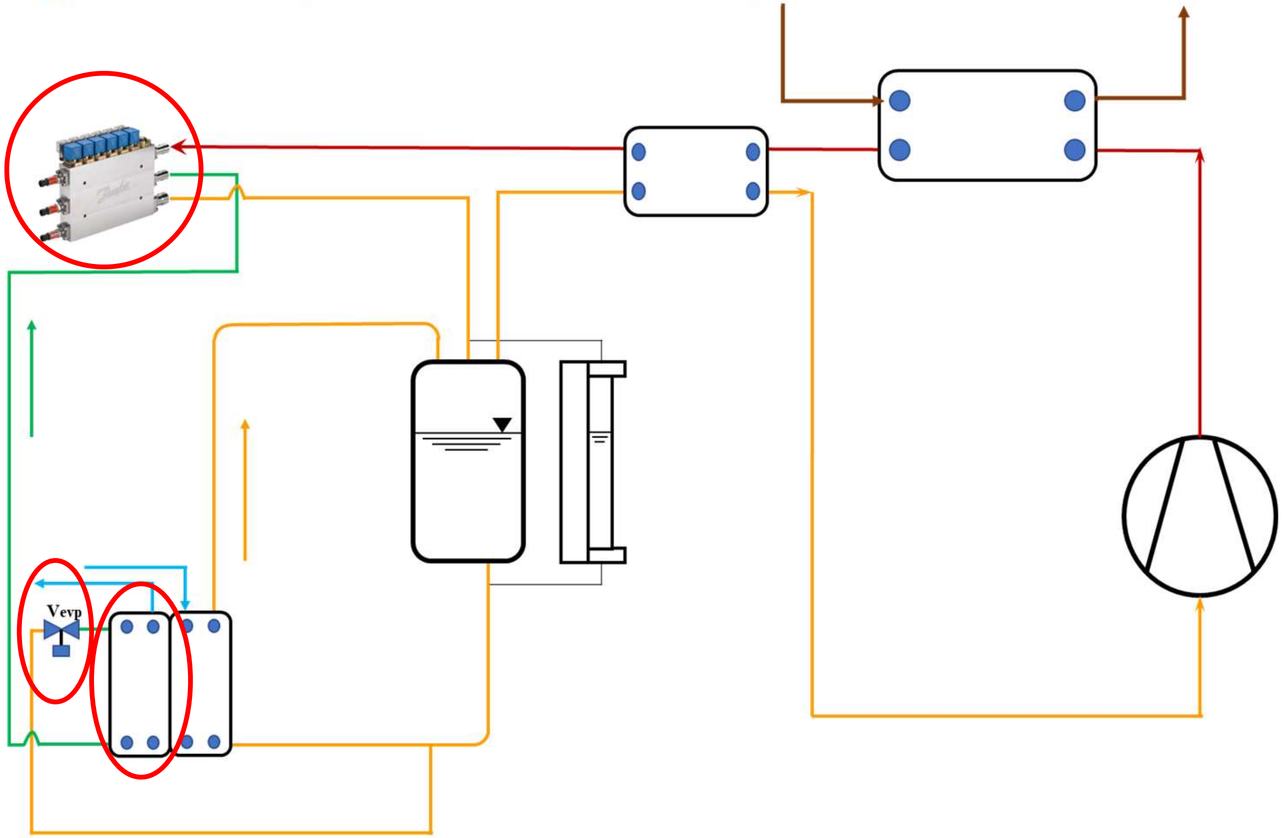
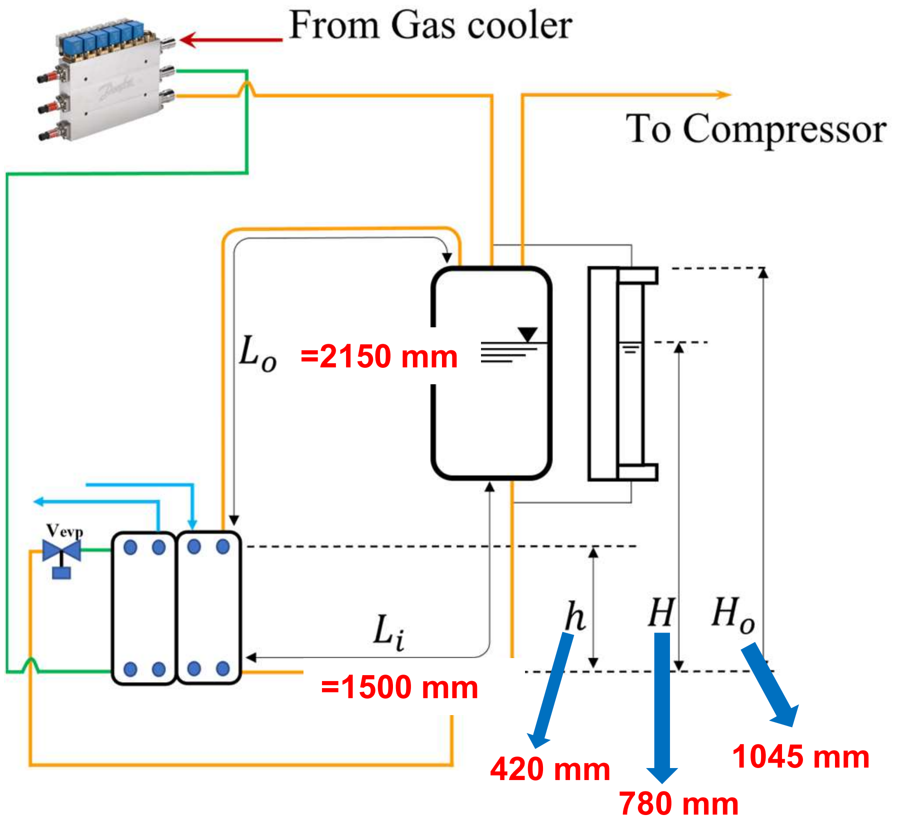
Modeling of two-stage evaporator loop

- Model is developed in Modelica
- Models are selected from TIL library (TLK-Thermo Gmbh)
- Model for gravity-fed loop is extended using
    - Ejector
    - BPHX as ejector-fed evap.
    - EXV to regulate the flow of ejector-fed evap.
- Dymola 2021 is the modeling environment



Two-stage evaporator loop dimensions

Two-stage evaporator (BPHX)	
Number of plates	40 (Gravity-fed) + 40 (Ejector-fed)
Plate length (mm)	420
Plate width (mm)	155
Pattern angle (°)	22.5
Wall thickness (mm)	0.5
Pattern amplitude (mm)	2.9
Pattern wavelength (mm)	6



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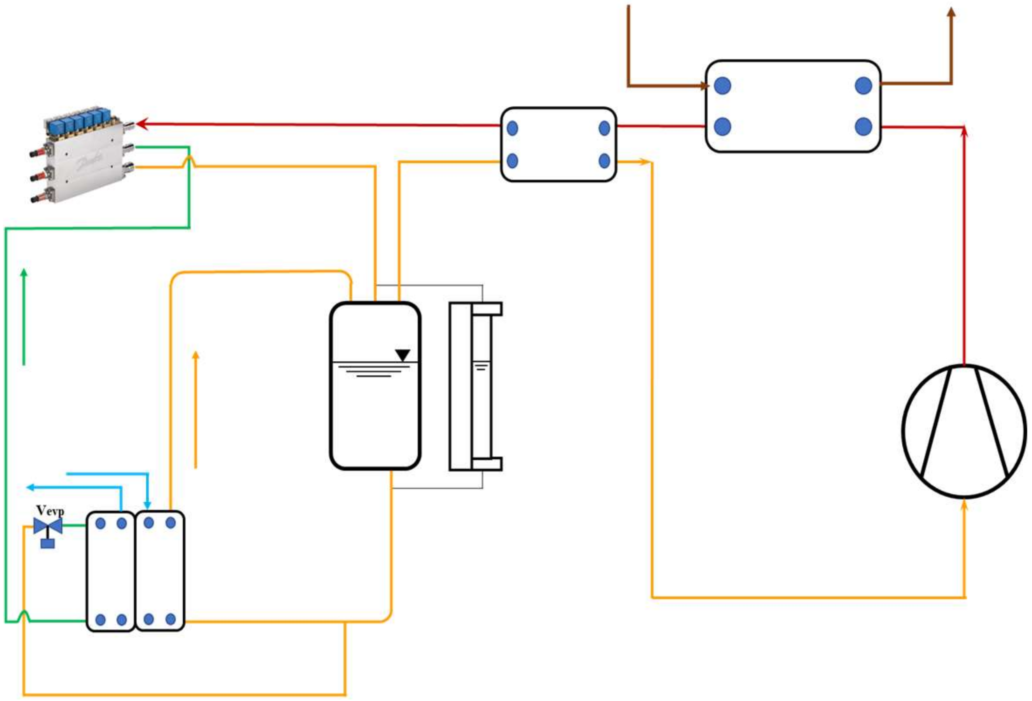
Boundary conditions and simulation results

Gas cooler		
High-side pressure (bar)	120.0	
Water temperature at inlet (°C)	24.0	
Water temperature at exit (°C)	88.5	
Heating capacity (kW)	17.9	
Approach temperature (K)	3	
Two-stage evaporator		
	Gravity-fed	Ejector-fed
Water temperature at inlet (°C)	12.0	8.18
Water temperature at exit (°C)	8.18	4.09
Water flowrate (kg min^{-1})	24	24
Evaporation pressure (bar)	42.3	38.0
Cooling capacity (kW)	6.42	6.86



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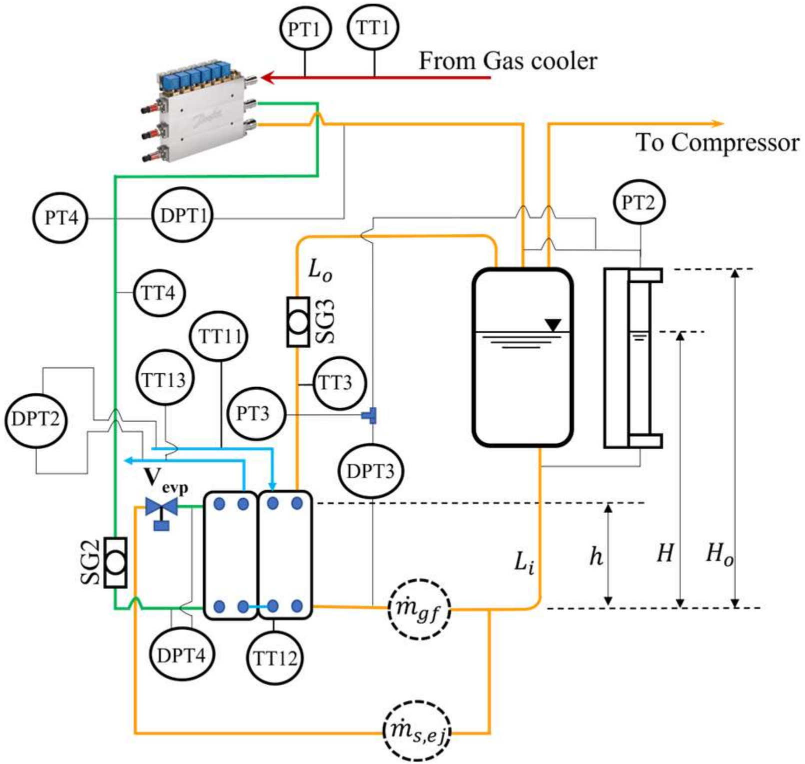
Test-rig with two-stage evaporator

Two-stage Evaporator (BPHX)		
Number of Plates	Plate length (mm)	Plate width (mm)
40 (Gravity-fed) + 40 (Ejector-supported)	420	155

Test-rig with two-stage evaporator

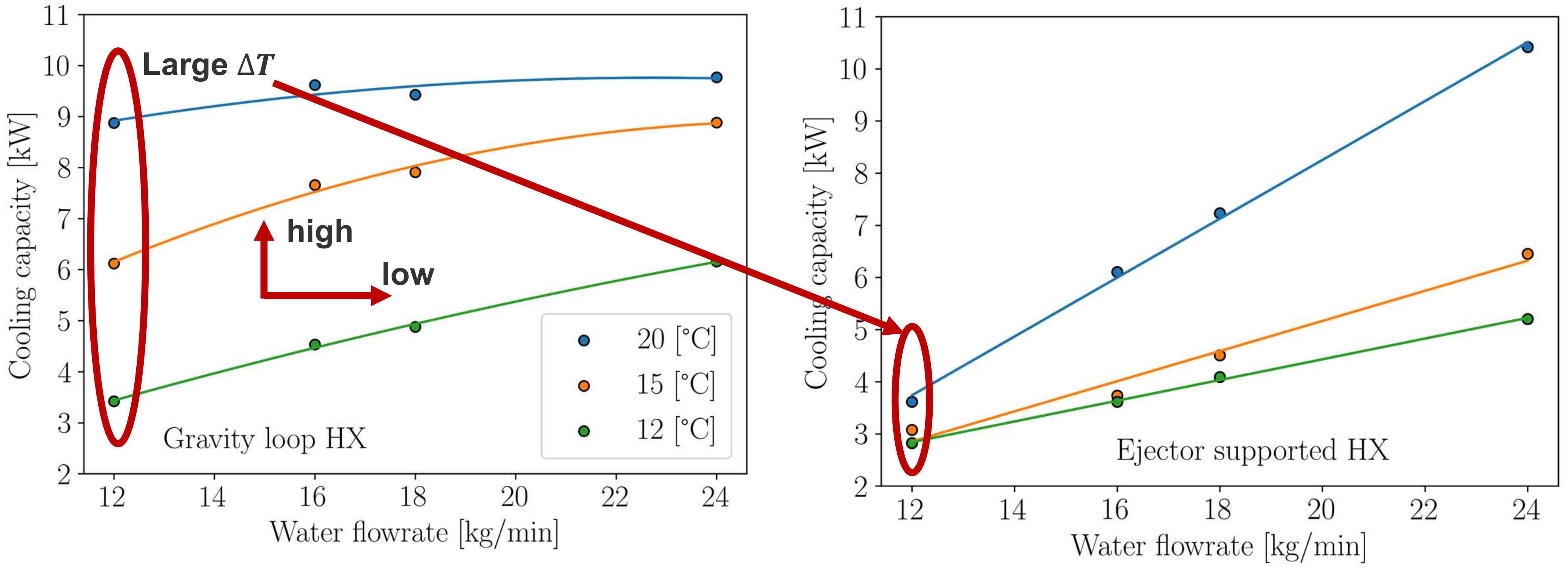
Location of different sensors



Test conditions			
Secondary fluid temperature (°C)	Secondary fluid flowrate (kg min^{-1})	Evaporation pressure (bar)	
		Gravity-fed	Ejector-supported
12 - 20	12 – 24	42 – 45	38 - 41

- Steady-state results obtained for these test conditions are presented here

Test results

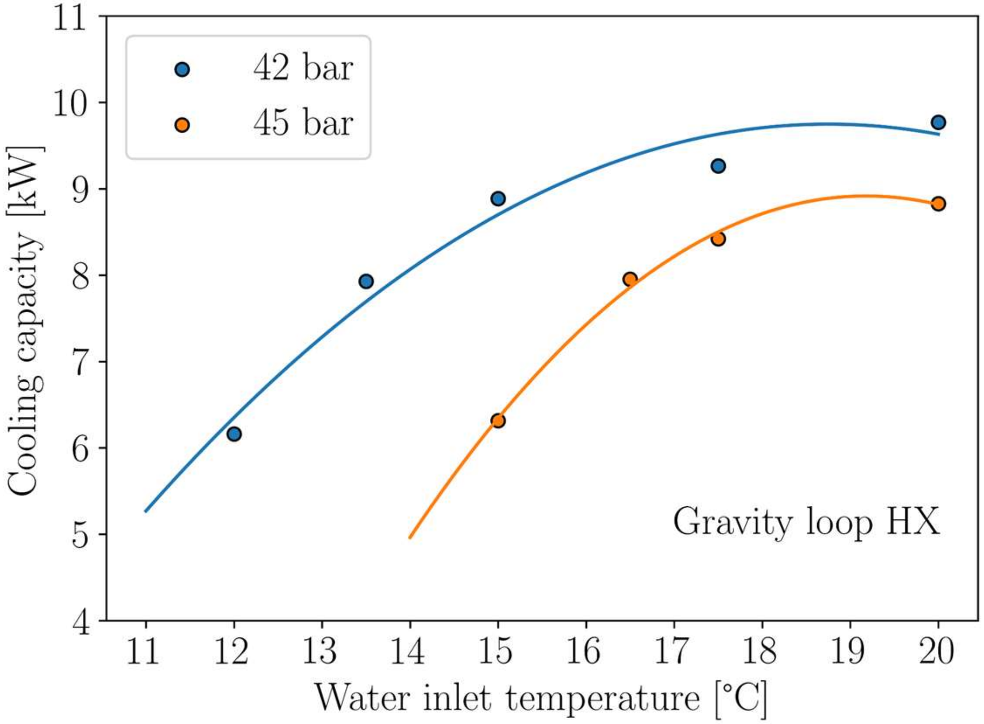


Cooling capacity of Gravity-fed evaporator

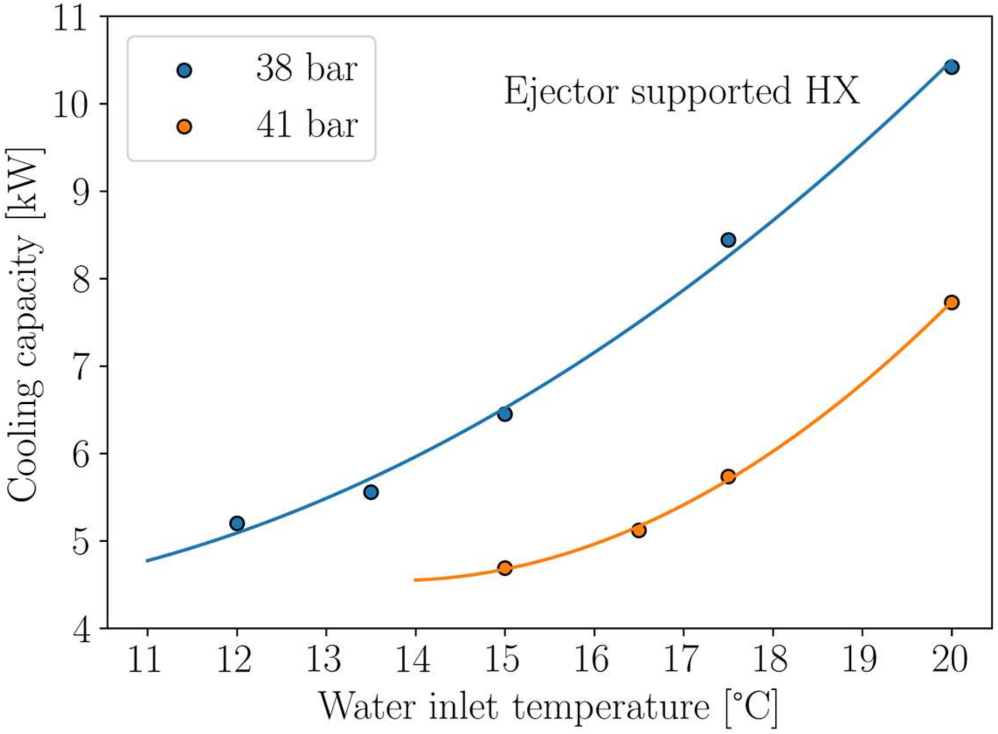
Cooling capacity of Ejector-supported evaporator

Test results

Cooling capacity of Gravity-fed evaporator



Cooling capacity of Ejector-supported evaporator



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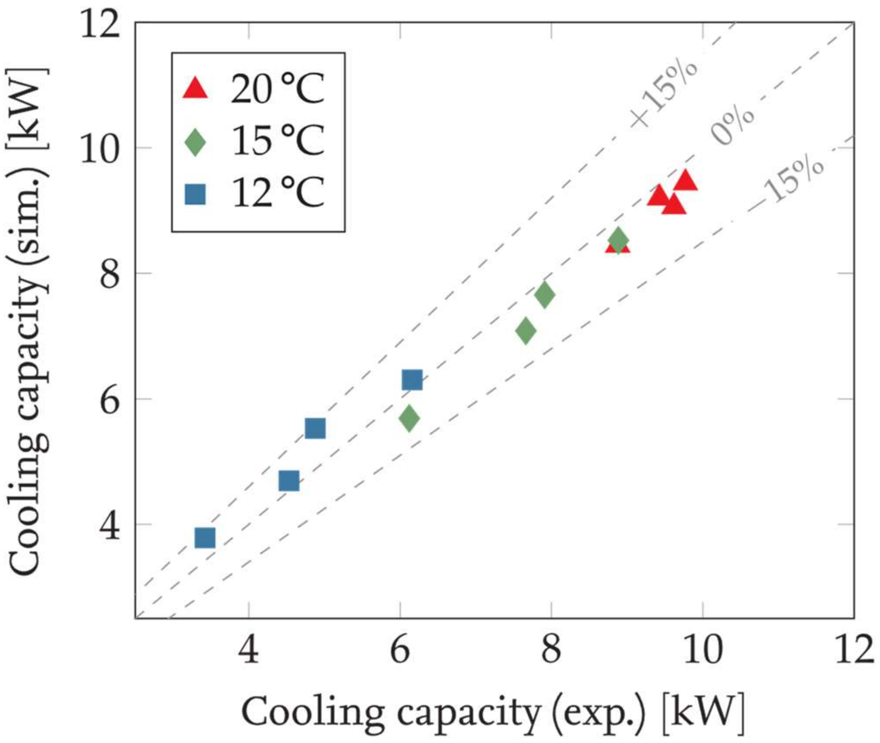
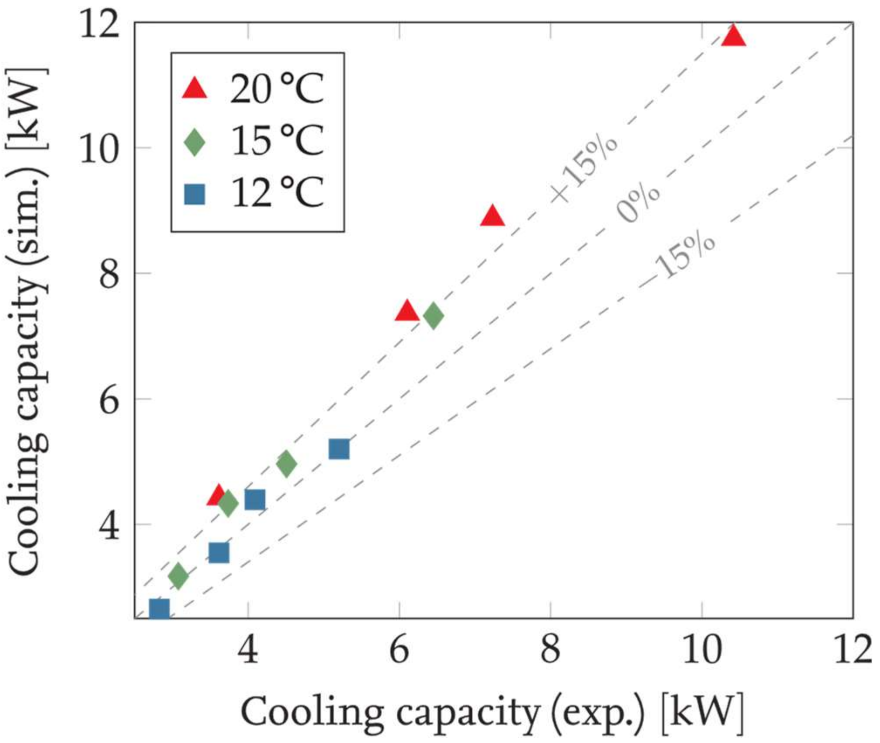
Validation of simulation results with test results

Gravity-fed evaporator



Ejector-supported evaporator



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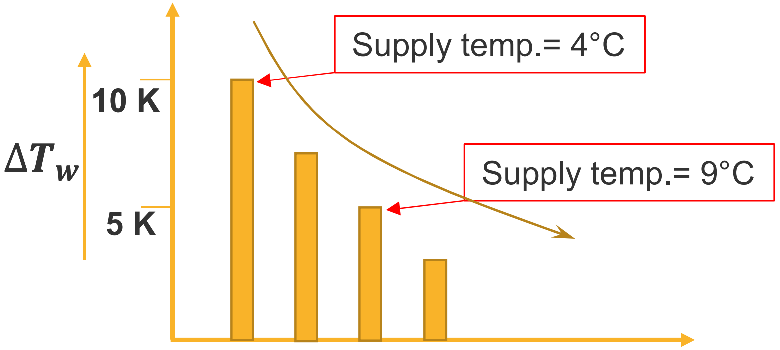
Goals for further investigations

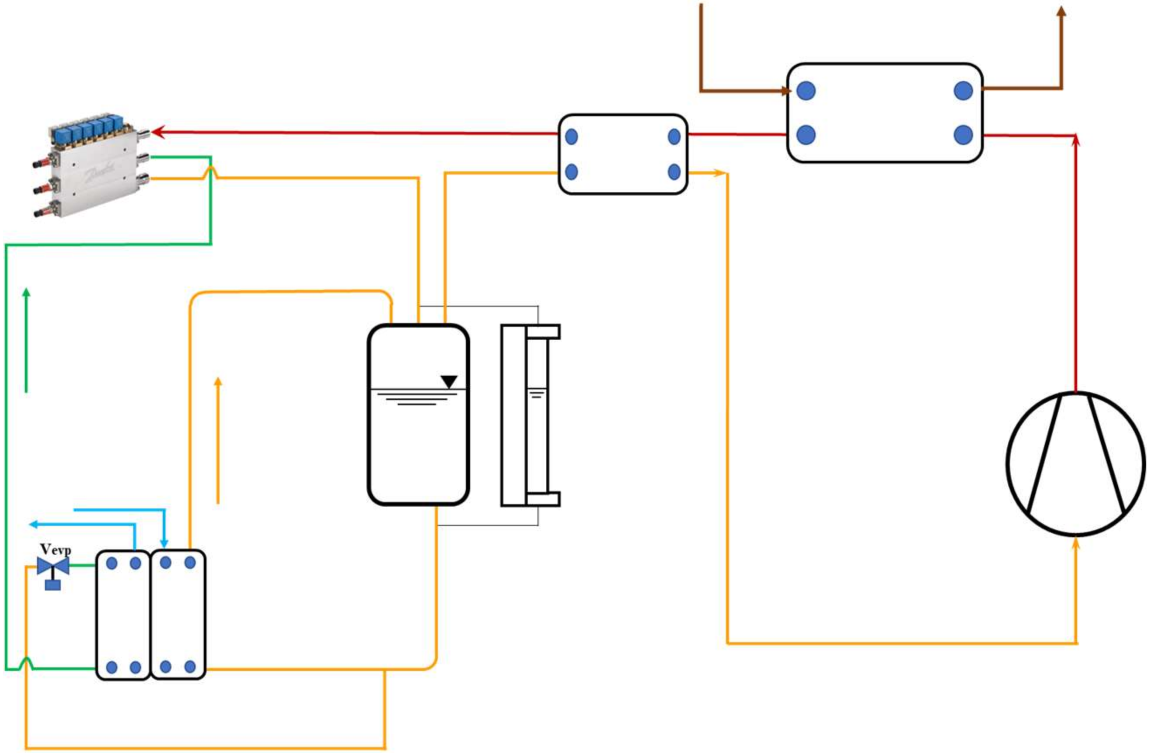
Model-based investigations

To investigate how to regulate the water temperature to match the load requirement:

Full load (10kW+10kW)=20kW → part load



Higher the supply temp., higher will be the P_{evp} and higher will be the load shared by ejector-fed evap.

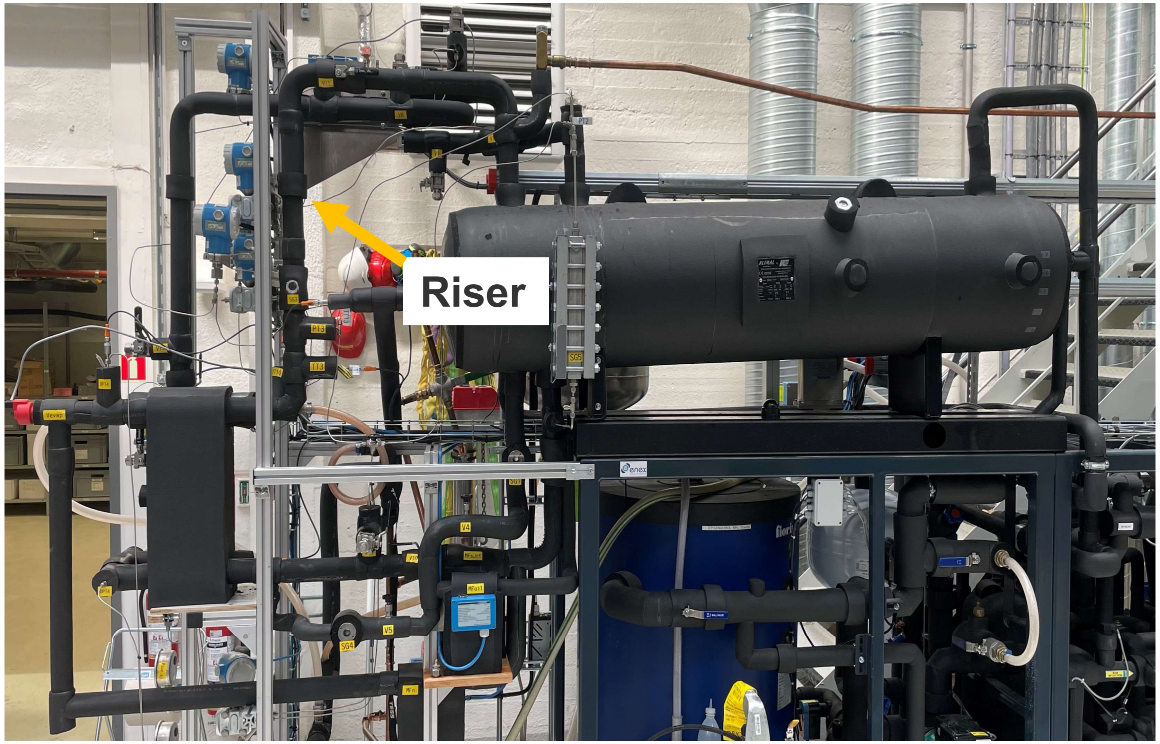


Goals for further investigations

Experiment: **To investigate the effect of static height on the performance of Gravity-fed loop**

Goals for further investigations

Experiment: To investigate the effect of riser dia. on the performance of Gravity-fed loop



Goals for further investigations

Experiment: **To compare the performance of top-fed and bottom-fed ejector-supported evaporator**

Summary

- Proposed novel two-stage evaporator
  - ➢ First stage: Gravity-fed mode; Second stage: Ejector-supported mode
- Large ΔT on water-side
- Higher heat transfer coefficient improves heat transfer rate (flooded HX)
- Overall performance improvement
  - ➢ Shared cooling capacity
  - ➢ Elevated suction pressure of the compressor

Reference

1. Cheng, L., Ribatski, G., Thome, J.R., New prediction methods for CO_2 evaporation inside tubes: Part II – An updated general flow boiling heat transfer model based on flow patterns, *Int J Heat Mass Transf.* (2008) 51, 125 – 135.

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Thank you

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