Process Modelling and Dynamic Simulations of CO_2 Cooling Systems

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PROJECT OVERVIEW

background & motivation

Tracker Cooling: The story so far

AMS Tracker	LHCb Velo	ATLAS IBL	CMS Pixel
• ~ 190 W	• ~ 1 kW	• 2 kW	• 2x 15 kW

Future systems

LHCb VELO+UT upgrade (2019)	CMS Tracker (2024)	ATLAS Tracker (2024)
• 2x 7 kW	• ~ 200 kW	• ~ 200 kW

Silicon cooling for the next decade will be accomplished using CO_2

Next generation system challenges

Problems

- Order of magnitude larger cooling loads (around 200 kW)
- Lower-than-ever evaporator temperatures (< -35°C)
- Many plants operating in parallel
- Shift to Microchannel evaporators (with many parallel channels)

Research Questions

- What to do about the accumulator?
- What about flow instabilities?
- How to move CO_2 quickly between the cavern and ground level
- How should these new plants be controlled?
- …what if something breaks/doesn't work?

Numerical Simulation

- Reality operates in real time but simulations are faster
- Building test setups is **necessary** but costs both time and money
- Simulations give insight into plant behavior
- Ability to study difficult-to-measure parameters
  - Vapour quality / void fraction
  - Two-phase fluid states
- Ability to study ‘what if’ scenarios; especially useful for controls
- Ultimately: Operator training and virtual commissioning

Research Objectives

- Develop tool for dynamic simulations of 2PACL based cooling systems
  - Scant prior art available performing thorough numerical modelling of such systems
  - No off-the-shelf solutions for 2PACL systems
- Use the tool to assist in design of next generation of plants
- Use the tool for investigating system control of new plants

This talk: progress made thus far in developing such a tool.

CO_2 RESEARCH APPARATUS (CORA)

test setup for this project

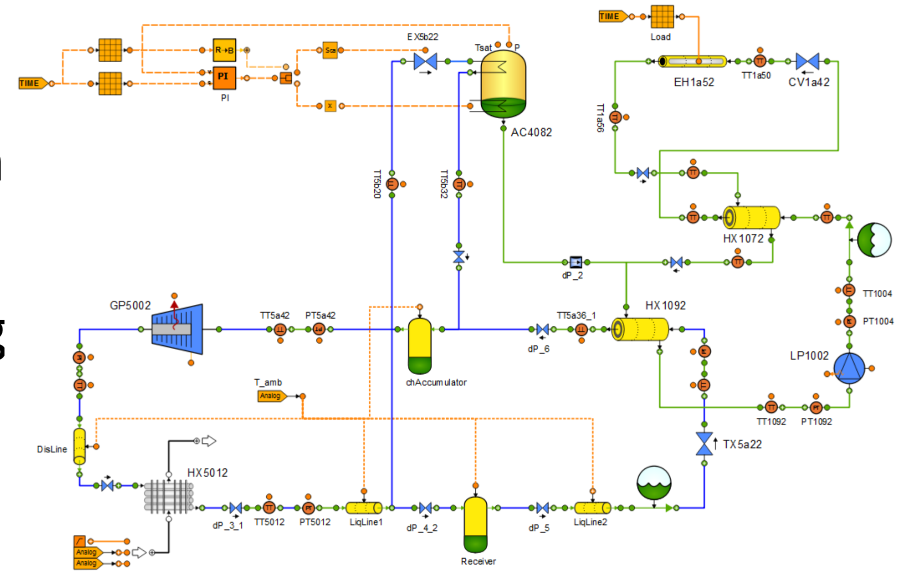
Overview

- **2 kW, -35°C, 2PACL plant**
- Repurposed for current project:
  - Upgraded with in-stream PT100 sensors in flow (instead of on tube)
  - Pressure and temperature measured at the inlet and outlet of each component
  - Plant located in an air-conditioned room
- Types of data collected:
  - Accumulator set-point step change
  - Evaporator load step change
  - Plant startup
  - Plant shutdown

LIBRARY ARCHITECTURE

Software: EcosimPro

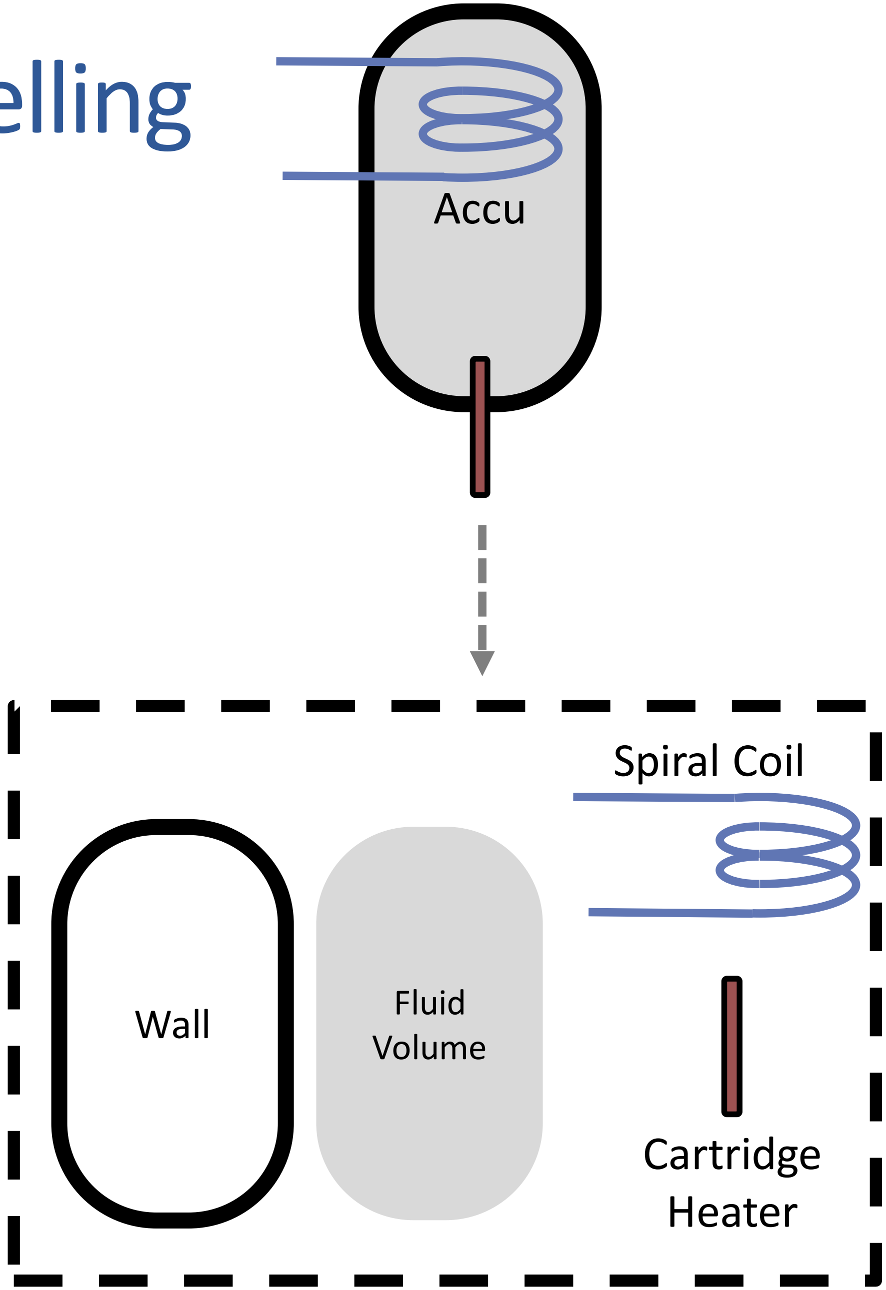
- Object-oriented modelling
- Acausal equations (w/ equation sorting algorithms)
- DAE solvers capable of handling stiff equations, sparse matrices
- Previous thermofluid code: Cryolib




```
// mass balance
geo[i].V*(drho_dP[i]*P_Pa[i]'+drho_dh[i]*h[i]') = m[i] - m[i+1]
// energy balance
geo[i].V*((h[i]*drho_dP[i]-1)*P_Pa[i]' + \
(h[i]*drho_dh[i]+rho[i])*h[i]') = mh[i]-mh[i+1] - Q[i]
```

Object-Oriented Modelling

- Very useful in physical modelling exercises
- Easy components reuse
- For example, an Accumulator contains:
  - Accumulator metal shell
  - Lumped refrigerant volume
  - Cooling spiral
  - Thermosyphon cartridge heater



Overview

- Pressure and enthalpy as state variables
- Finite volume method for discretization
- Staggered grid scheme for decoupling the momentum equation
- Quasi-steady state momentum equation
- Slip-ratio based correlations for two phase flow
- Upwind scheme method for dealing with reverse flow
- Port connectors for handling splitting and merging flows

Governing Equations (using P,h variables)

Mass and energy balance:

$$V_i\left[\left.\frac{\partial\rho}{\partial P}\right|_{h,i}\frac{dP}{dt}+\left.\frac{\partial\rho}{\partial h}\right|_{P,i}\frac{dh}{dt}\right]=\dot{m}_i-\dot{m}_{i-1}$$

$$V_i\left[\left(h_i\left.\frac{\partial\rho}{\partial P}\right|_{h,i}-1\right)\frac{dP}{dt}+\left(h_i\left.\frac{\partial\rho_i}{\partial h_i}\right|_{\mathrm{P},i}+\rho_i\right)\frac{dh_i}{dt}\right]=\dot{m}_{i-1}h_{i-1}-\dot{m}_i h_i-\dot{Q}_i$$

Momentum equation:

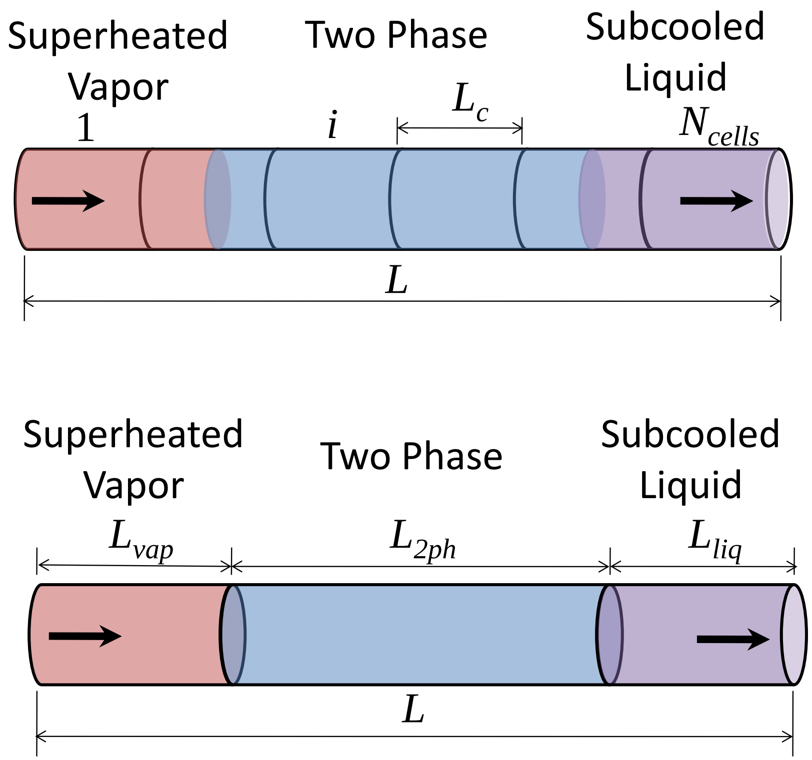
$$\dot{m}=\frac{\dot{m}_0}{\sqrt{dP_0}}\sqrt{\left|P-P_{out}\right|}.sign(P-P_{out})$$

Thermal components energy balance:

$$\frac{dT_w}{dt}=-\frac{\dot{Q}_{in}+\dot{Q}_{out}}{M_{wall}.c_{p,wall}}$$

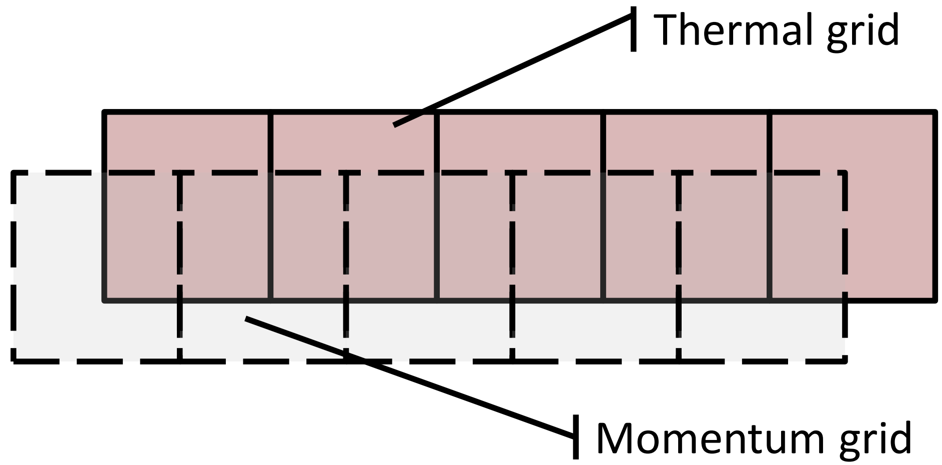
Finite Volume Method

- Discretize component into equal-sized control volumes
- Alternatives are: finite difference and finite element method
- Finite volumes easy to visualize
- Moving boundary method: good for control purposes



Staggered Grid Scheme

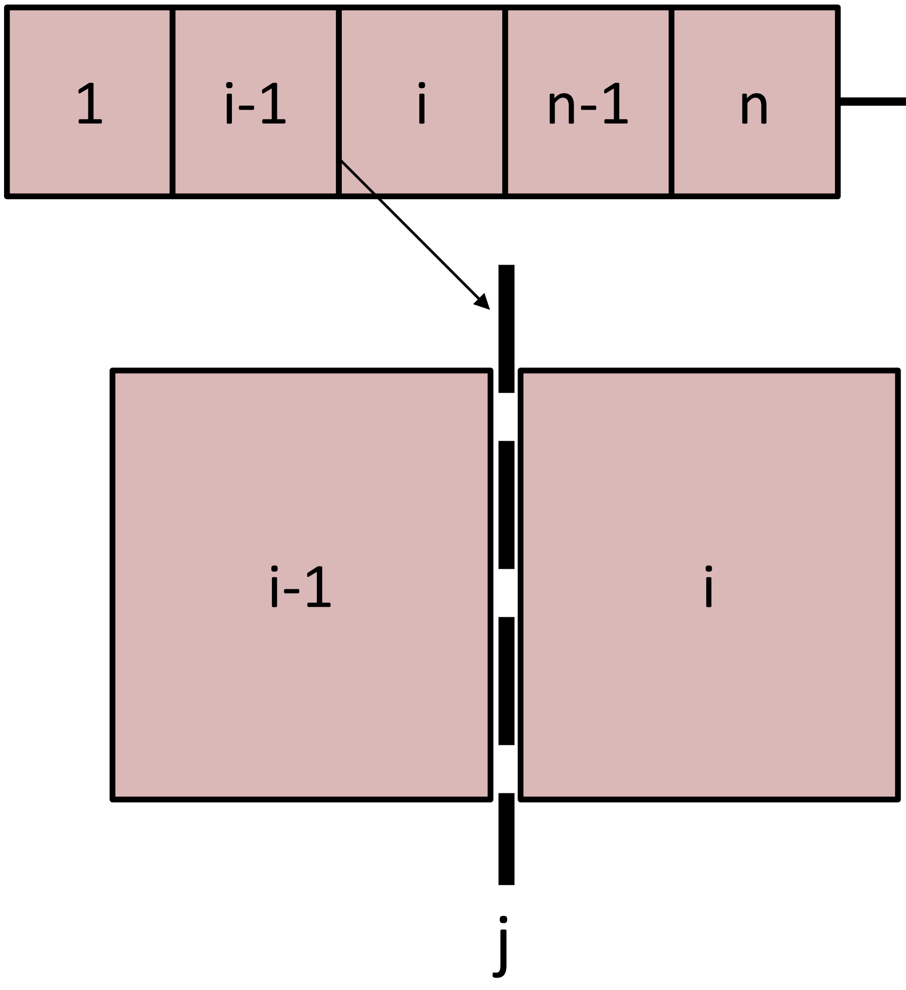
- Momentum grid offset from thermal grid by half cell width
- Mass and energy solved on thermal grid, momentum equation solved on momentum grid
- No averaging of properties needed
- Reduces coupling of equations
- Improves solver speed and robustness



$$V_i\left[\left.\frac{\partial \rho}{\partial P}\right|_{h,i}\frac{dP}{dt}+\left.\frac{\partial \rho}{\partial h}\right|_{P,i}\frac{dh}{dt}\right]=\dot{m}_i-\dot{m}_{i-1}$$

$$V_i\left[\left(h_i\left.\frac{\partial \rho}{\partial P}\right|_{h,i}-1\right)\frac{dP}{dt}+\left(h_i\left.\frac{\partial \rho_i}{\partial h_i}\right|_{P,i}+\rho_i\right)\frac{dh_i}{dt}\right]=\dot{m}_{i-1}h_{i-1}-\dot{m}_i h_i-\dot{Q}_i$$

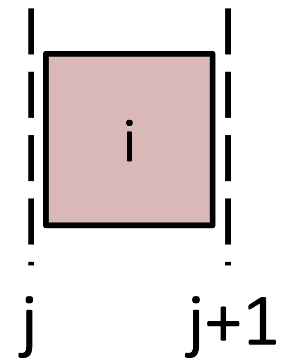
Upwind Scheme



$$H_j = \begin{cases} m_j h_{i-1} & m_j \geq 0 \\ m_j h_i & m_j < 0 \end{cases}$$

Two-phase flow modelling

- Three options
  - Ignore it (homogeneous flow)
  - Correct for it (slip ratio based models)
  - Model it thoroughly (Separated flow model)
- Slip-ratio based models adopted as first approximation
- Circumvents need for major modifications to governing equations
- Better (lower) prediction of void fraction: slower transients, more accurate charge prediction



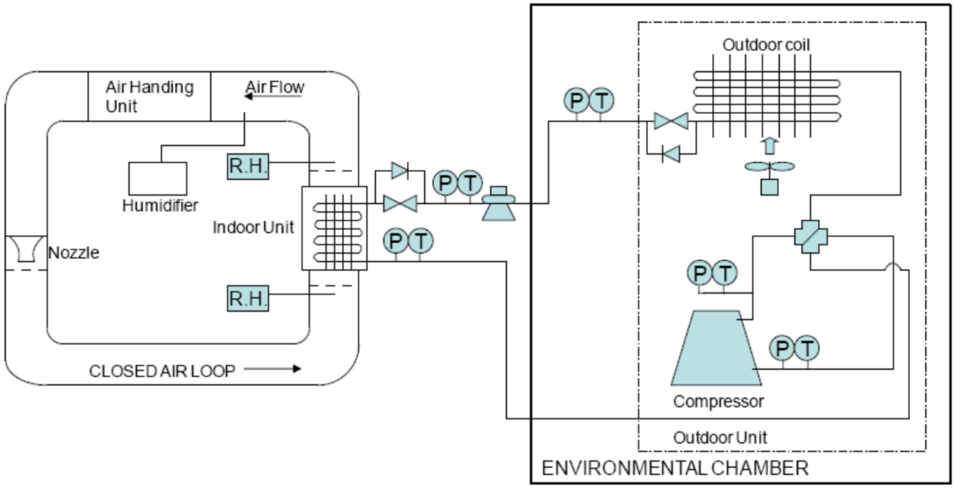
$$h_{j+1} = h_i + \Delta h_{c,i}$$

$$\gamma = \frac{x}{x + (1-x)\left(\frac{\rho_g}{\rho_f}\right) S}$$

VALIDATIONS OF MODEL OF RESIDENTIAL HEAT PUMP

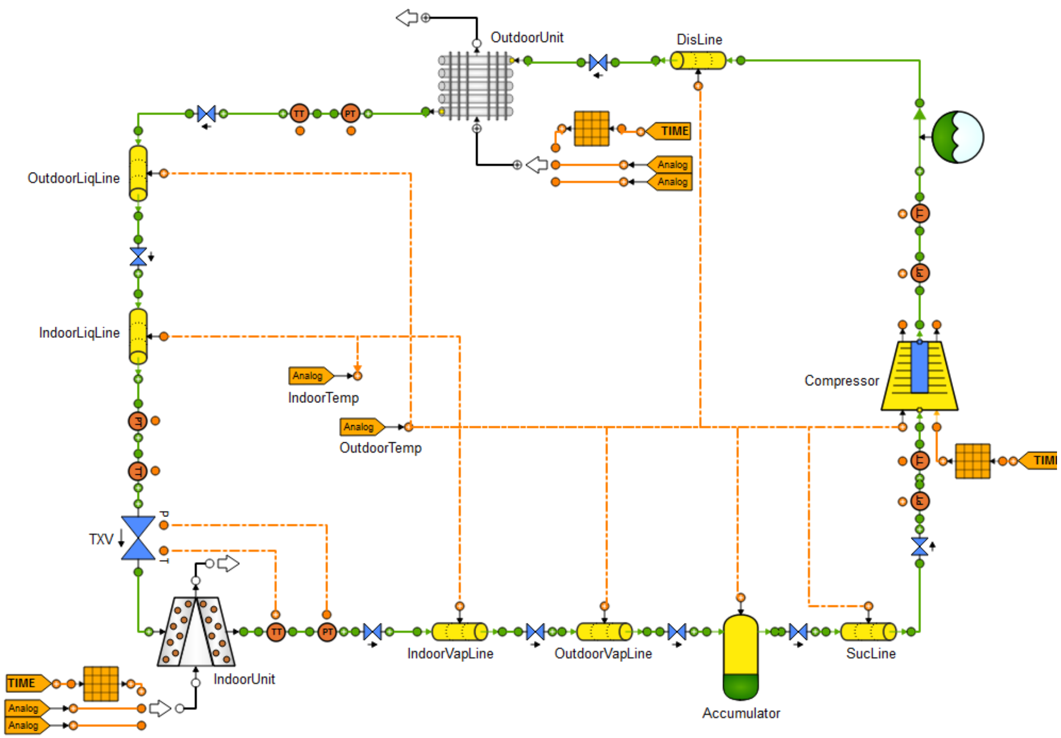
Heat pump validation

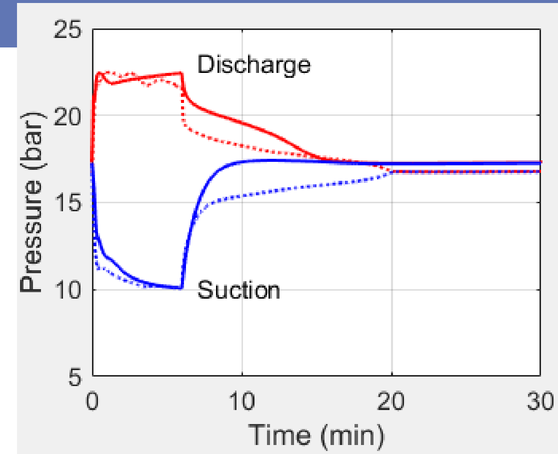
- Well-documented results
- Primary cooling in 2PACL is vapour-compression
- Relatively complex system:
  - Compressor
  - Valves
  - Heat Exchangers
- Simulation cycle: 6 min on, 24 min off

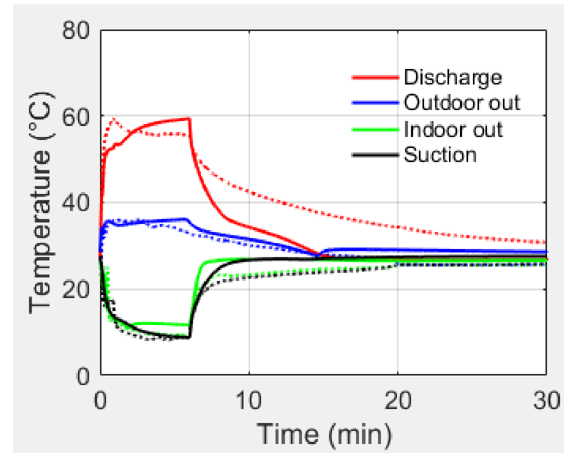


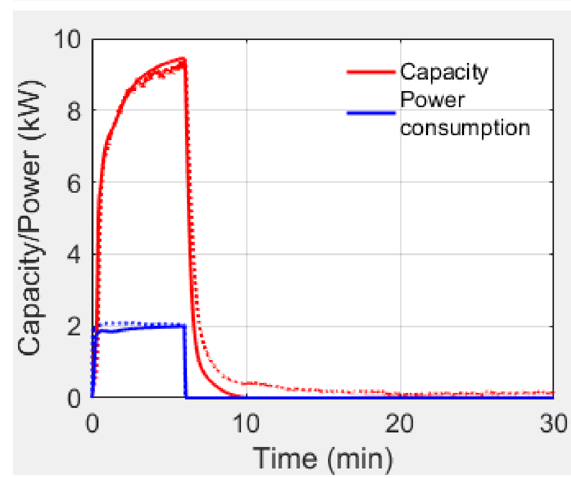
Test conditions	Indoor	Outdoor
D-test	26.7°C	27.1°C
High Temperature Cyclic	21.1°C	8.3°C

Cooling Mode









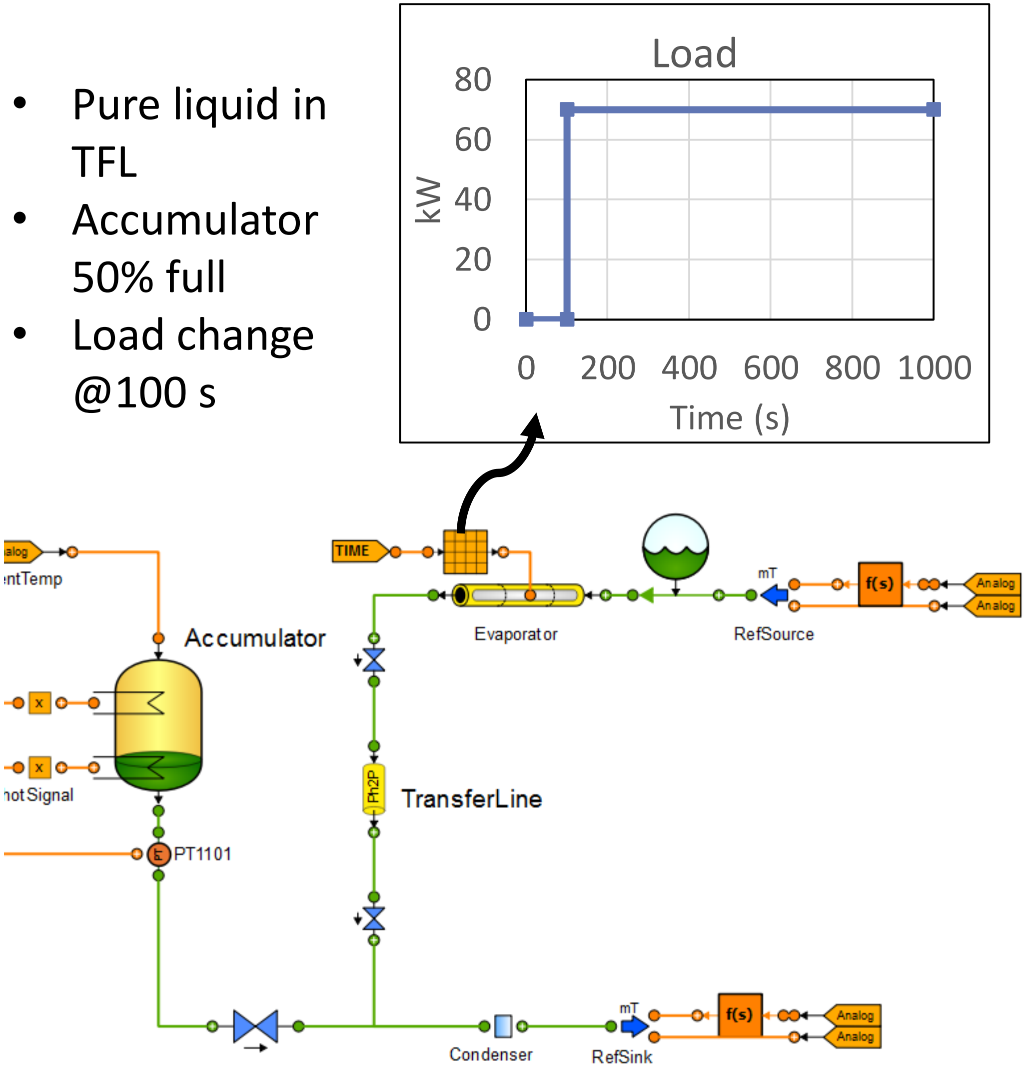
Reference: "**Comparison of Two Object-Oriented Modeling Environments for the Dynamic Simulations of a Residential Heat Pump**", Bhanot, V., Dhumane, R., Petagna, P., Cioncolini, A., Ling, J., Aute, V., Radermacher, R., 17th International Refrigeration and Air Conditioning Conference at Purdue, Purdue University, 2017

TRANSIENT SIMULATIONS OF 2PACL SYSTEMS

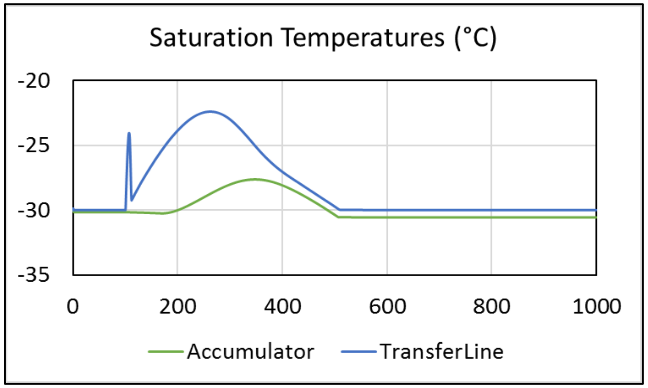
Accumulator sizing

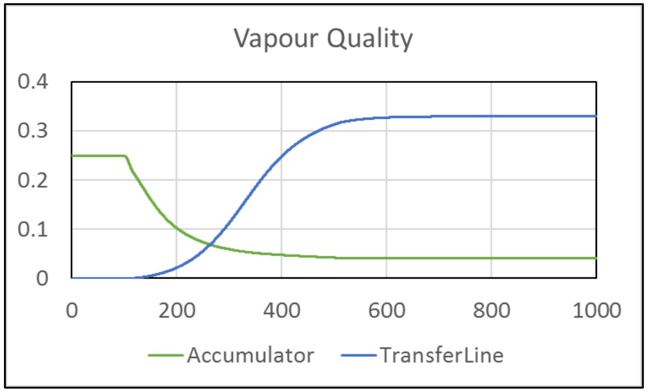
- One alternative : Tiny accumulator in the cavern, and most of the CO_2 storage on surface level
- Research Question: How tiny?
  - Accumulator might get overwhelmed and fill up completely
  - Will that be a safety concern or purely a performance concern?

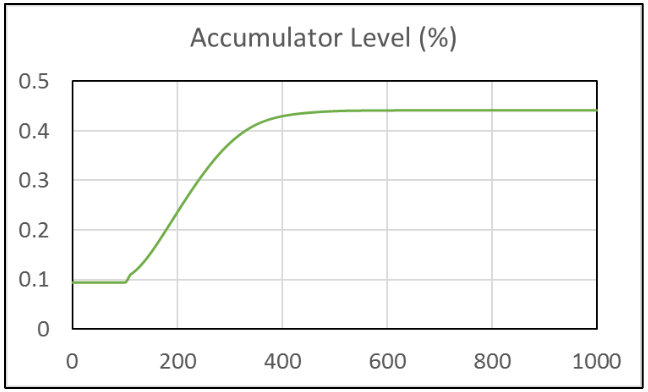
- Pure liquid in TFL
- Accumulator 50% full
- Load change @100 s



Results

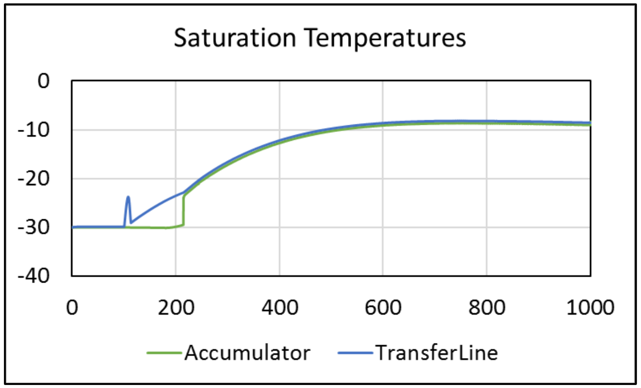


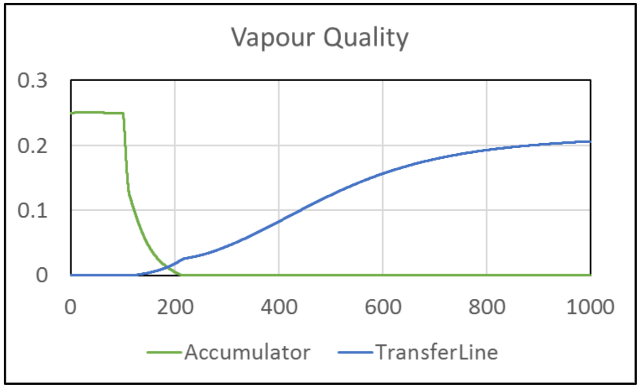


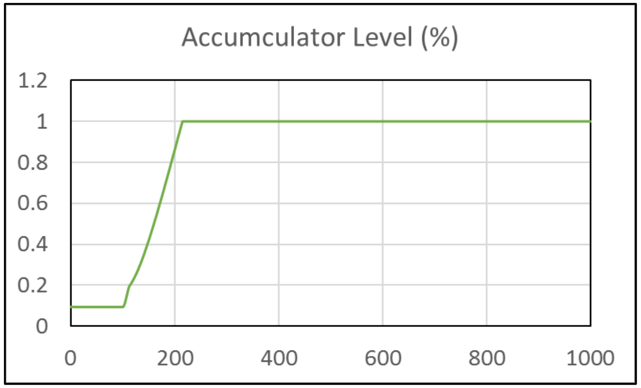


Accumulator 3x Volume of Transfer Line

Accumulator 0.5x Volume of Transfer Line

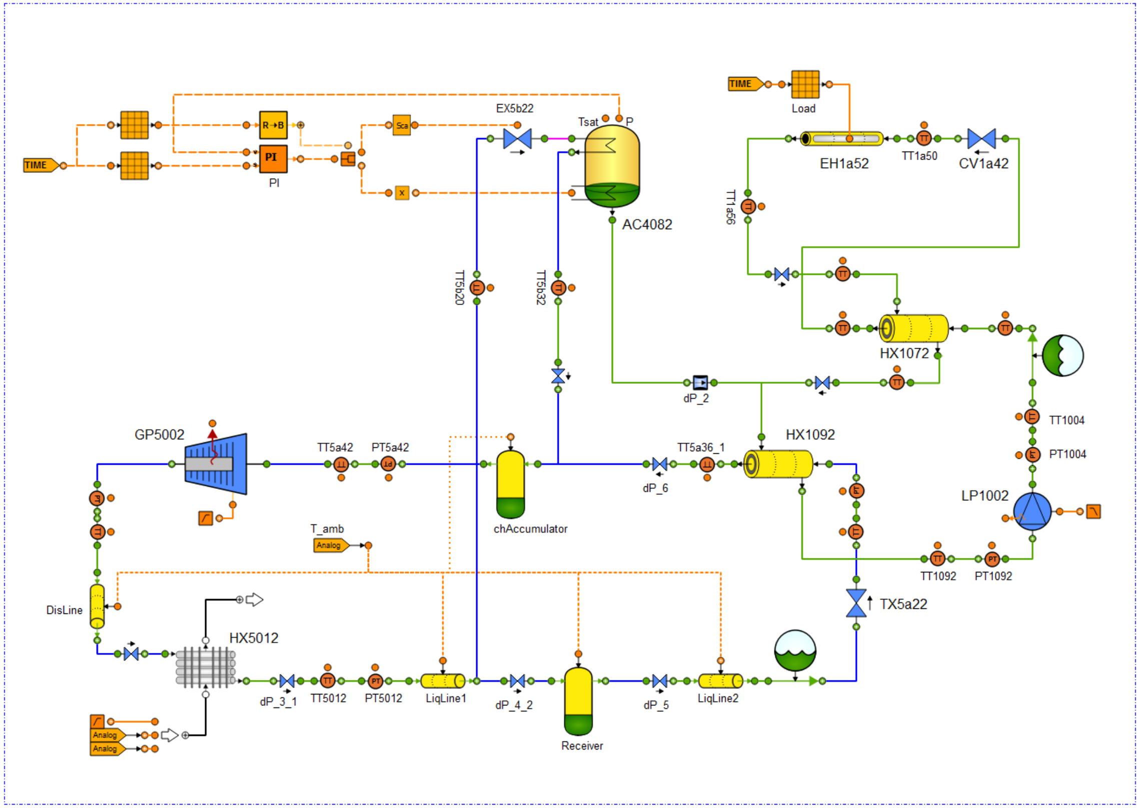




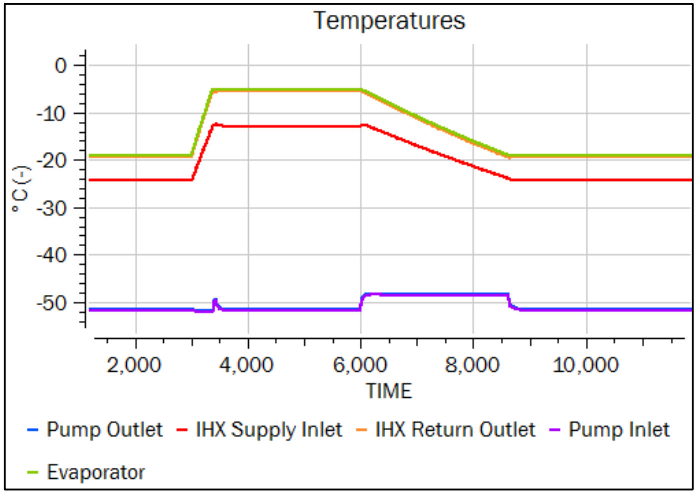


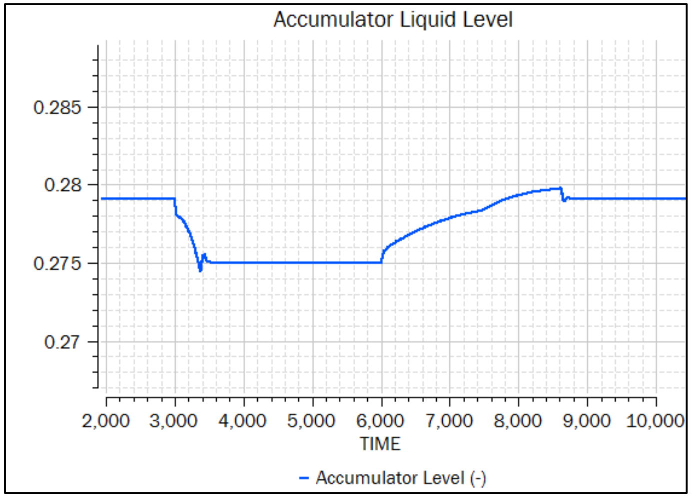
2. 2PACL Step Change Simulations

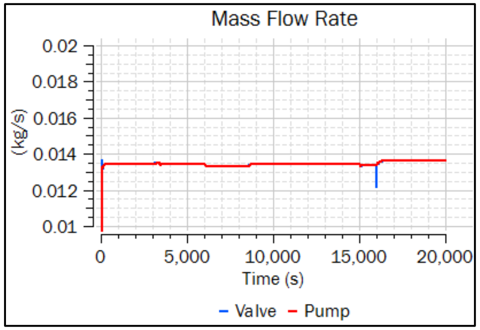
- Original 2PACL concept (chiller cools accumulator)
  - Complete chiller model
  - Constant HTC
- Accumulator set point from 20 bar, up to 30 bar and down to 20 bar again
- Evaporator load step change from 1.5 kW to 2 kW

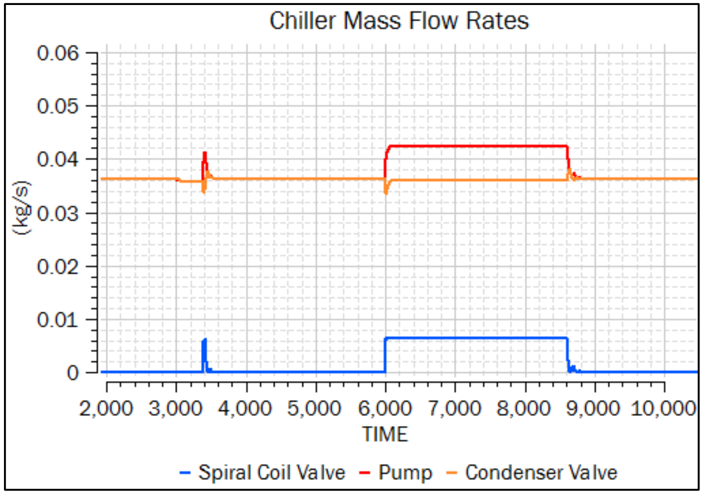


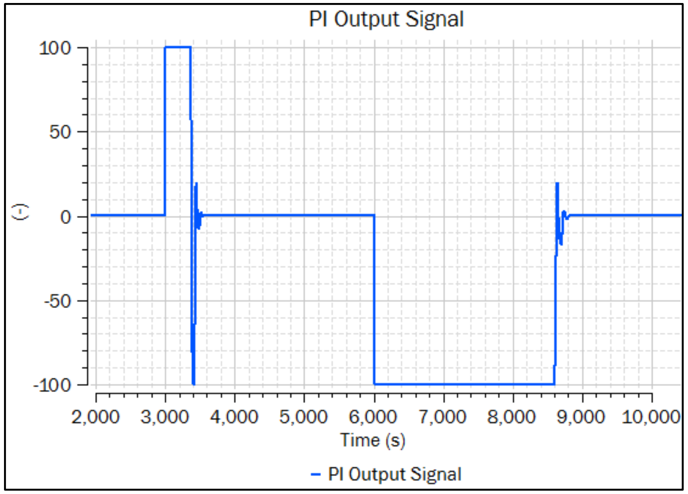
Results: Set point change



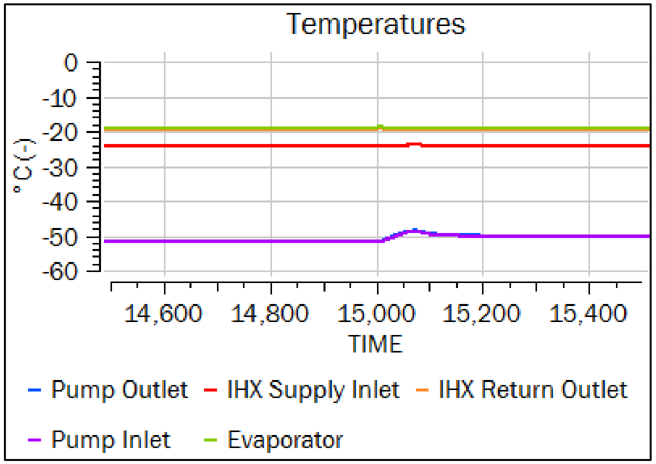


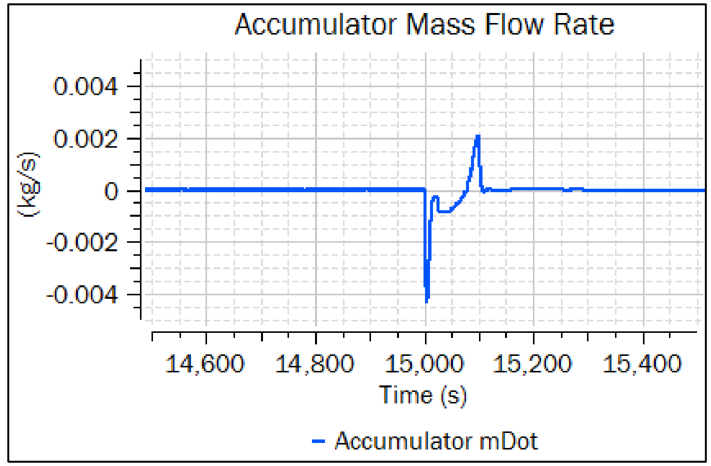


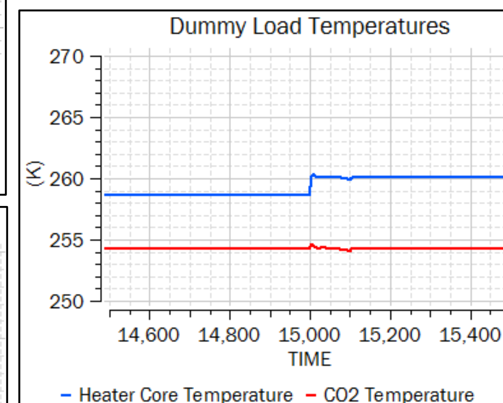


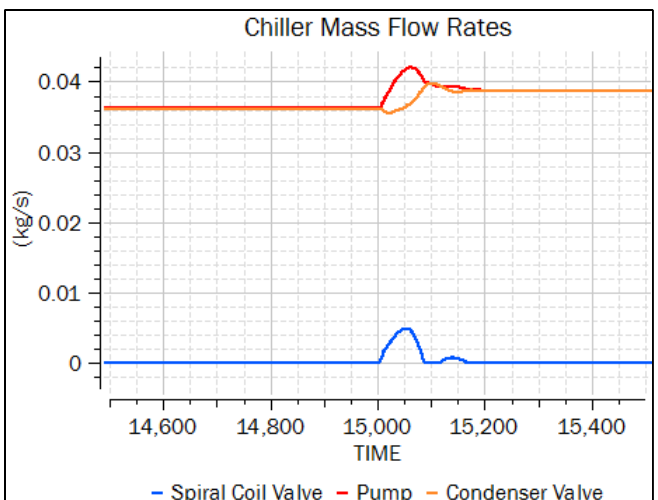


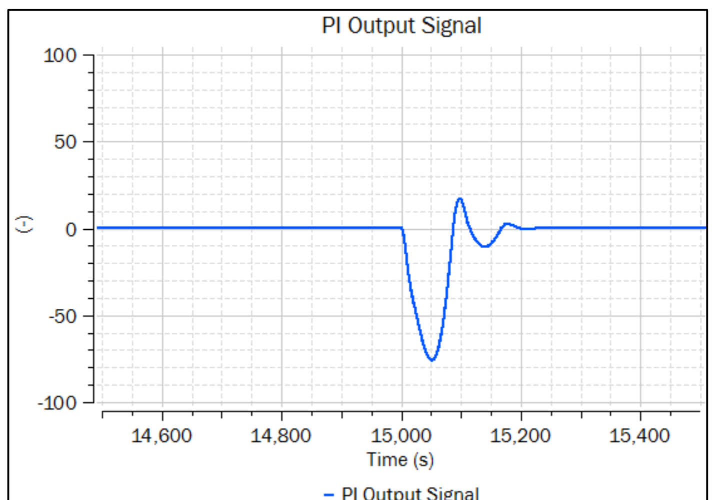
Results: Evaporator load change







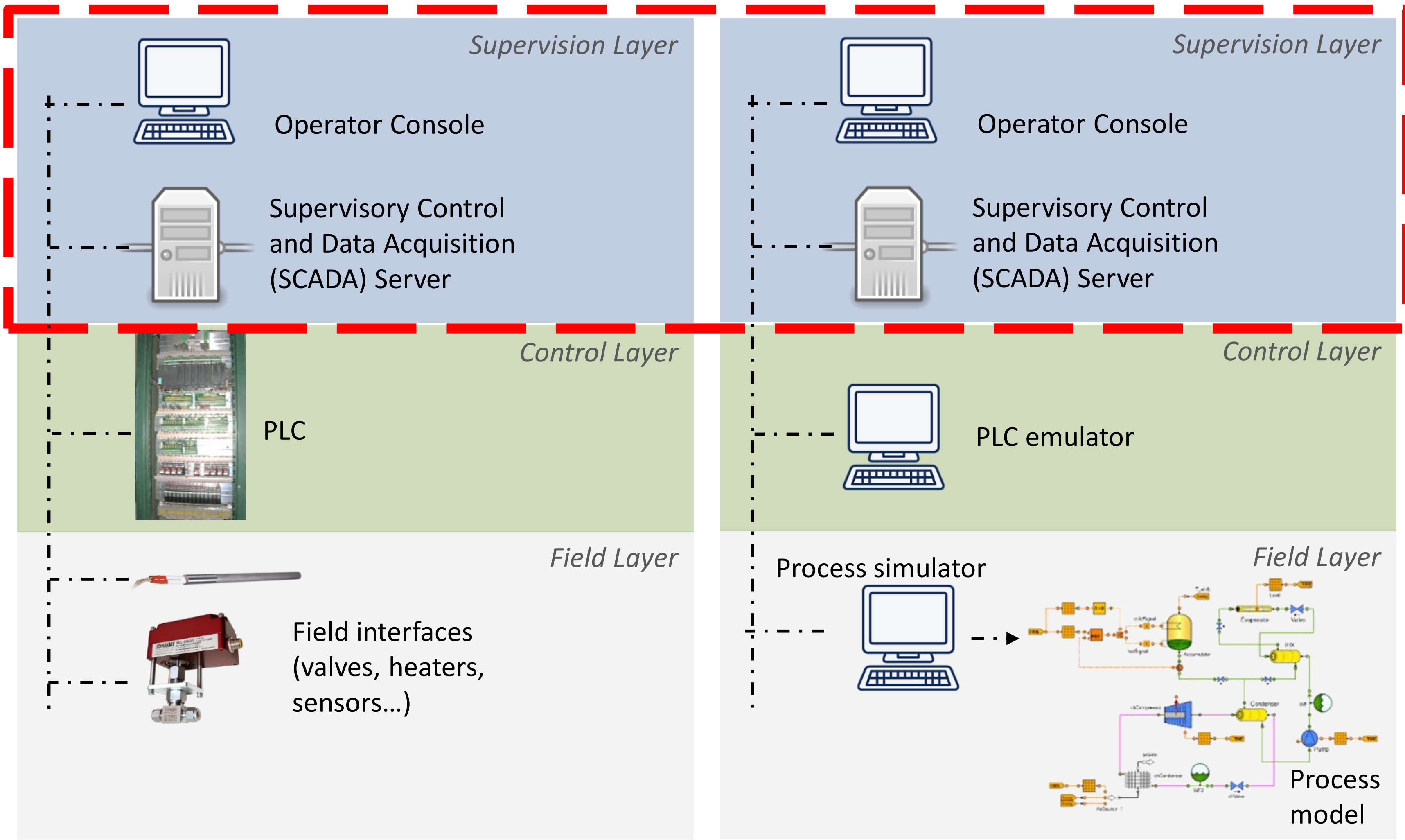




Future Work

- Model refinement
  - Good heat transfer coefficient values
  - Incorporate CO_2-side piping
  - Solver stability
- Validations against experimental data
- Incorporate PLC logic (PLC library based on UNICOS available within EcosimPro)
- Use library for component design and controller logic studies for DEMO and other upcoming plants
- Use library for safety and training related studies

Virtual Commissioning



Reference: Rogez E., Bradu B., Moreaux A., Pezzetti M., Gayet P., Coppier H. "A Simulation Study for the Virtual Commissioning of the CERN Central Helium Liquefier", in Proceedings of the twenty-second International Cryogenic Engineering Conference ICEC22, KIASC, pp. 249-253(2009).

Summary Slide

- Objectives of the current work:
  - tool for study of 2PACL systems
  - Optimal control design
  - Virtual commissioning and operator training
- Component library developed and behaves as expected
- Simulations are faster than real time (on the whole)
- Endless future work!
  - Validations against experimental data
  - Investigations into transients involving CO_2 flows in microchannels
  - DEMO project: Accumulator sizing,