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Testing and Modeling of Subscale Ice-on-Coil Module as Low Temperature Reservoir for sCO₂ based Pumped Thermal Energy Storage Systems

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Abstract

Pumped Thermal Energy Storage (PTES) provides economic long-duration electrical energy storage free of geographical limitations. PTES uses a heat pump cycle with two thermal storage reservoirs at different temperatures to store excess electrical power during periods of high supply and low demand and return the electrical power to the grid at periods of low supply and high demand using a thermodynamic power cycle. Using their extensive experience in developing commercial sCO₂ power cycles, Echogen is developing a transcritical CO₂ PTES system that stores thermal energy at moderate temperatures (335°C and 0°C), with a competitive round-trip efficiency (RTE) and substantially lower cost than competing storage technologies.

A key component of this energy storage process is the low-temperature reservoir (LTR). For the CO₂ heat pump, the thermal energy transfer from the LTR occurs by evaporating liquid CO₂ at nearly constant temperature. By selecting the operating state of the heat pump cycle appropriately, this constant temperature can be maintained slightly below the freezing point of water. Since these two processes are both nearly isothermal, the exergy loss associated with the heat extraction from the LTR can be minimized, which improves the cycle RTE.

One of the LTR technologies being actively considered for PTES systems is called ice-on-coil (IOC). The IOC is a LTR technology which mainly consists of embedded tube banks in static bath of water. During the ice making or 'charging' process, cold saturated CO₂, at about -3°C to -5°C, flows through the embedded tubes causing the water to freeze on the outer surface of the tube transiently while vaporizing the CO₂. During ice melting or 'generating' process relatively warm CO₂ (about 20°C) flows through the tubes causing the ice on the outer surface of the tube to melt while the CO₂ is cooled to slightly sub-cooled or saturated liquid conditions.

Echogen tested approximately 10 kW_{th} subscale IOC system in their lab in Akron, OH for studying the feasibility, endurance and performance impact of the technology on PTES system. This paper discusses the test loop setup, testing and results from this sub-scale IOC testing. Along with testing, the project team also developed sub-scale IOC transient model. The paper discusses this transient model development and its validation against the test data.

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Nomenclature

COP	Coefficient of performance
EPS	Echogen Power Systems
IOC	Ice-on-Coil
LTR	Low temperature reservoir
LTX	Low temperature heat exchanger
PFD	Process flow diagram
PTES	Pumped Thermal Energy Storage
RTE	Round trip efficiency
SP	State point

1 Introduction

The ever increasing dependence of electrical grid on renewable energy sources (such as solar and wind) and decline in traditional energy sources (such as coal and natural gas) puts the grid reliability in cross-hairs due to intermittent availability of renewable sources. One way of solving this problem is to store the excess renewable energy when its available and use the stored energy later when demand increases. Echogen is developing one such energy storage technology called pumped thermal energy storage (PTES). During thermal energy storage, PTES system draws excess electricity from the grid and uses transcritical CO₂ heat pump cycle to transfer thermal energy from low-temperature reservoir to a higher-temperature reservoir. During electrical energy demand, this stored thermal energy is transferred back to low-temperature reservoir through sCO₂ power cycle, converting the temperature differential back to electrical energy.

Heat Pump Cycle (also called Charging cycle):In sCO₂ PTES system, during heat pump cycle (thermal energy storage cycle), electrical energy is drawn from the grid to run a compressor which in-turn compresses CO₂ to supercritical pressure and high-temperature. See figure 1A for reference. This high-temperature CO₂ transfers heat to high-temperature and medium-temperature reservoir fluids. The CO₂ exiting medium-temperature reservoir is at moderate temperatures but still at supercritical pressures, which is expanded across a turbine connected to generator. CO₂ exiting turbine is saturated or slightly subcooled liquid (low pressure and below 0°C). This sub-0°C CO₂ is evaporated in low-temperature reservoir while cooling the LTR fluid. This CO₂ from low-temperature reservoir serves as inlet to compressor and the cycle repeats.

Heat Engine Cycle (also called Generating cycle):Operation of sCO₂ power cycle (thermal energy discharge cycle) using high-temperature and low-temperature reservoirs as temperature differential is similar to the heat engine cycles explained in [1, 2, 3]. See figure 1B for reference. Subcooled CO₂ from lower-temperature reservoir is pumped to supercritical pressures. This high pressure CO₂ picks-up heat from medium- and high-temperature reservoir fluids. The high enthalpy sCO₂ runs the turbine, which in-turn spins the generator. The turbine exhaust CO₂ is condensed back to liquid using low temperature reservoir before returning to pump and the cycle repeats.

The main focus of this paper is testing a sub-scale ice-on-coil module a potential low temperature reservoir (LTR) in PTES systems, as its performance effects the low pressure of the system there-by

pressure ratio across turbomachinery and overall efficiency of the system. The paper also discuss the transient model development of sub-scale IOC and its validation against test data.

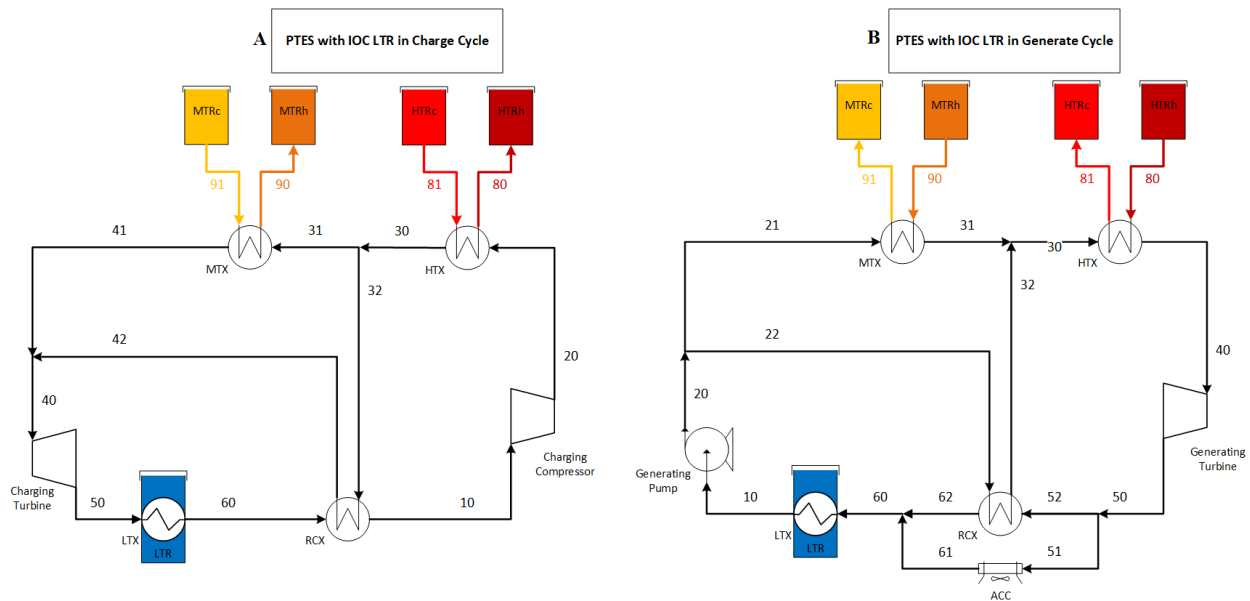


Figure 1: Representative PTES system process flow diagram for charge and generate cycles.

2 Ice-on-Coil Technology

The Ice-on-Coil (IOC) is a low temperature reservoir technology which mainly consists of embedded tube banks in static bath of water as shown in figure 2. IOC is a well known technology in refrigeration and HVAC industry [4, 5, 6], but application of that technology for CO₂ based PTES systems is an unexplored territory. Ice-on-Coil (IOC) as a low temperature reservoir (LTR) technology for PTES systems is being developed by Echogen. During the ice making or 'charging' process, cold saturated CO₂, at about -3°C to -5°C , flows through the embedded tubes causing the water to freeze on the outer surface of the tube transiently while vaporizing the CO₂. During ice melting or 'generating' process relatively warm CO₂ (about 20°C) flows through the tubes causing the ice on the outer surface of the tube to melt while the CO₂ is cooled to slightly sub-cooled or saturated liquid conditions.

2.1 IOC Lab Scale Test Loop Configuration and Operation

Figure 3 shows the as-built P&ID for closed loop lab scale IOC system with all the instrumentation labeled for data collection. During charging cycle (ice-making process), IOC was tested in two flow configurations with IOC bottom header as inlet in one and IOC top header as inlet is second charge test configuration. With bottom header as inlet during charging, CO₂ flow path in figure 3 will be 3-4-5-6-7-8-9-10 and during top header as charge cycle inlet the flow path being 3-7-6-5-8-9-10. The main reason for testing IOC in these inlet configurations during charging is being to measure the CO₂ liquid hold-up in IOC using difference in flow meter data (FT300 and FT438 in figure 3). CO₂ liquid hold-up in IOC during charge cycle has huge impact on overall PTES cycle inventory control and operation.

During generate cycle test (ice-melting process), IOC top header is always the inlet i.e. the CO₂ flow path for ice melting cycle is 3-7-6-5-8-9-10.

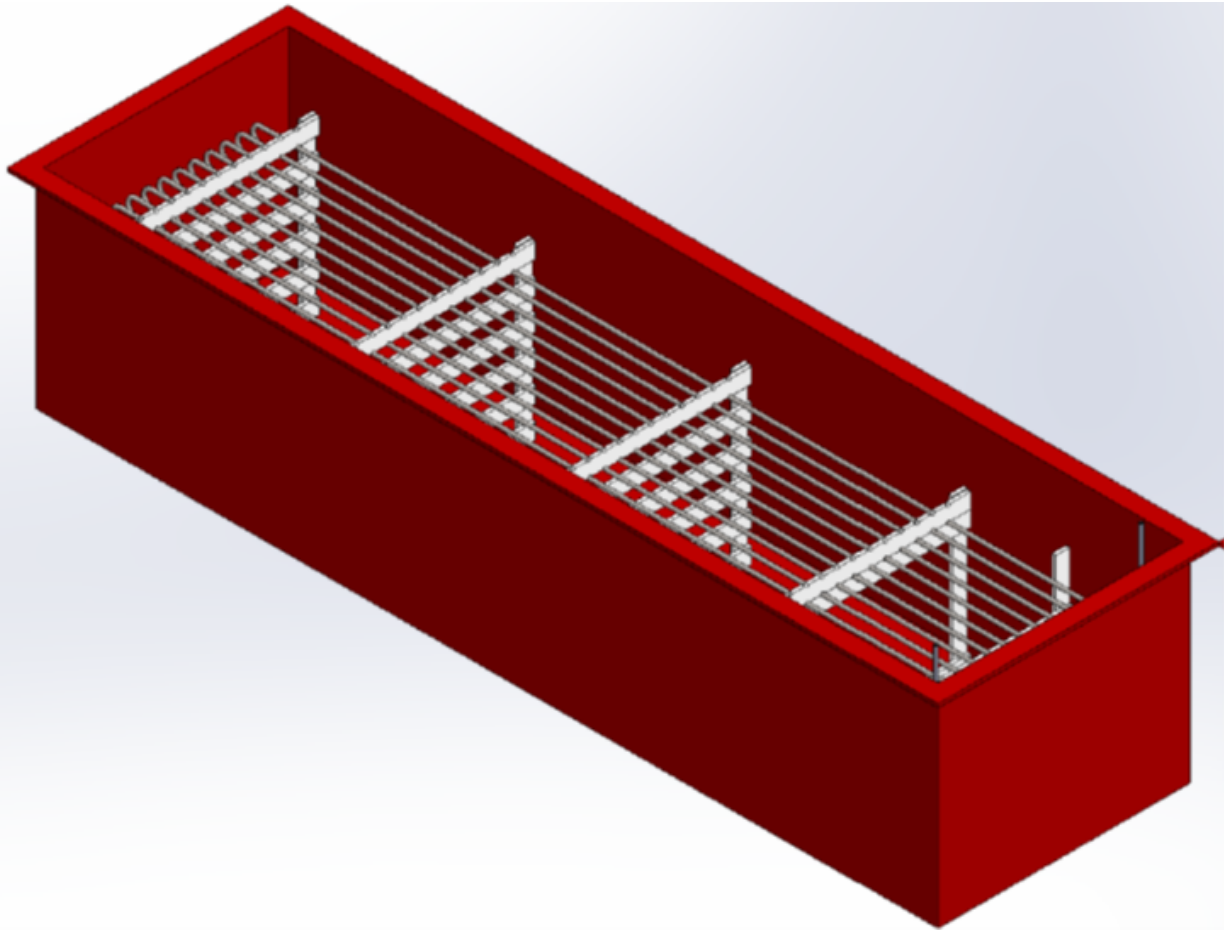
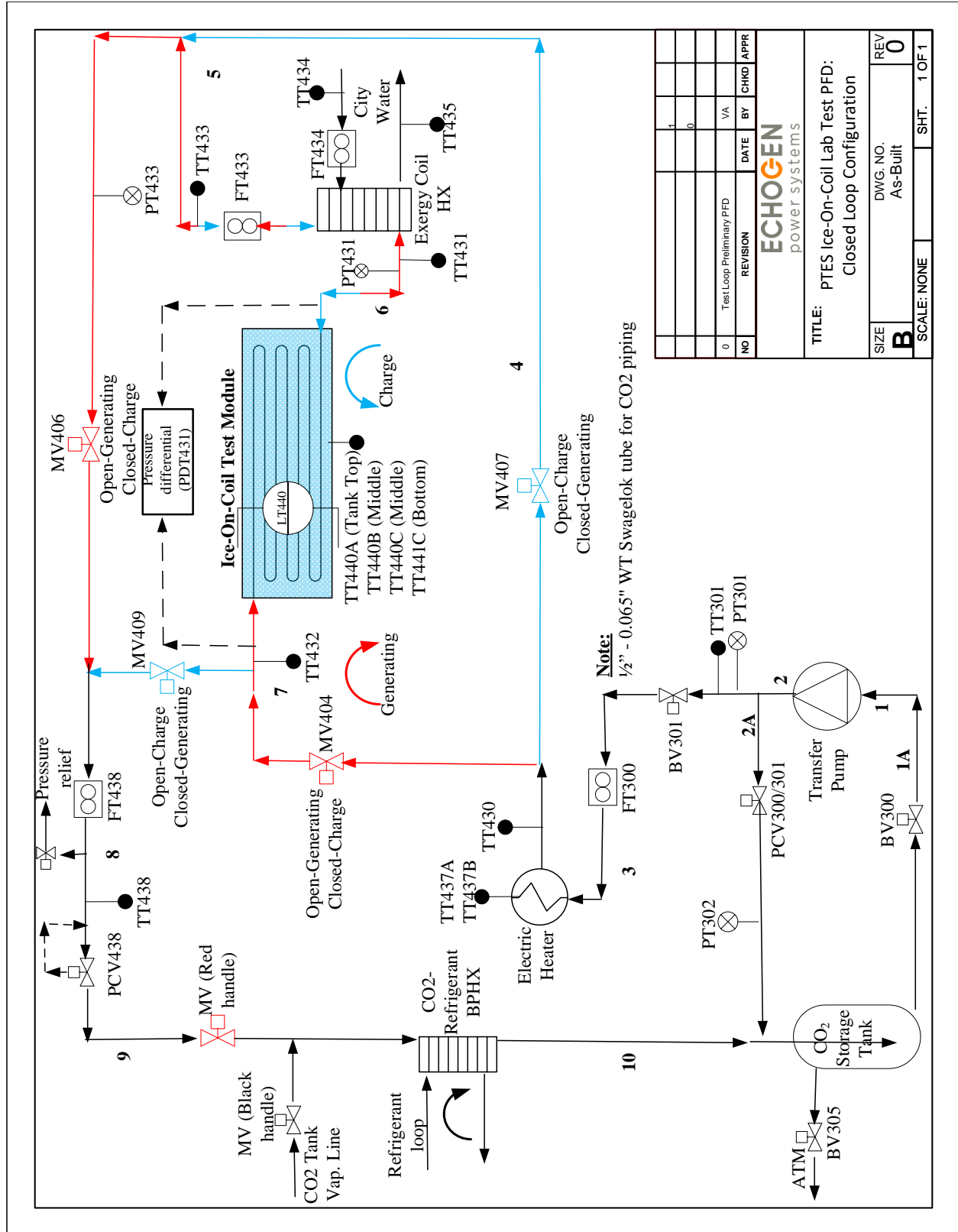


Figure 2: Subscale IOC test CAD rendering of coil and tank assembled configuration

Table 1 give the detailed instrument list. Manual valves (MV404, MV406, MV407, MV409) are used to switch between charge and generating cycles. CO₂ from the storage tank is much colder (around -20 °C) than the temperature needed for testing the IOC (see table 2). An electric heater (SP-3) is used to get the desired CO₂ temperature for charge and generate cycle conditions shown in table 2. During the test, CO₂ exiting the IOC is expected to be 2-phase during certain operating conditions. To determine the state of CO₂ quality exiting the IOC, a water-to-CO₂ heat exchanger ('Exergy Coil HX' on P&ID) is used to completely vaporise CO₂. This way by energy balance on the heat exchanger CO₂ quality exiting the IOC can be determined. CO₂ is completely cooled to liquid condition using a refrigerant loop before returning to storage tank (SP-10). An active pressure control valve (PCV438) is used to maintain CO₂ pressure in the loop at desired conditions of table 2 for charge and generate cycles. For this test CO₂ was supplied from a CO₂ inventory control system (storage tank) available on-site at Echogen facility.

Three main parameters, i.e. flow, temperature and pressure, are actively controlled during testing. CO₂ flow to IOC is maintained by controlling pump speed using a VFD, temperature inlet to IOC is controlled using electrical amperage on a heater and IOC pressure is maintained using back-pressure control valve (PCV438).

It is to be noted that the amount of ice in the tank at any given moment is estimated using the water level sensor (LT440 in table 1) taking advantage of difference in densities of water (1000 kg/m³) and



NO	REVISION	DATE	BY	CHKD	APPR
0	Test Loop Preliminary PFD		VA		

ECHOGEN
power systems

TITLE: PTES Ice-On-Coil Lab Test PFD:
Closed Loop Configuration

SIZE	DWG. NO.	REV
B	As-Built	0

SCALE: NONE SHT: 1 OF 1

Figure 3: Subscale IOC test process flow and instrumentation single line diagram

Table 1: List of instruments installed in IOC test for data collection

Instrument	Location	P&ID Tag
Pressure sensors	HTR1 inlet	PT301
	Charge inlet/Generate outlet	PT431
	Exergy coil CO ₂ outlet	PT433
RTD temperature sensors	HTR1 inlet	TT301
	HTR1 outlet	TT430
	Charge inlet/Generate outlet	TT431
	Charge outlet/Generate inlet	TT432
	Exergy coil CO ₂ inlet	TT436
	Exergy coil CO ₂ outlet	TT433
	Exergy coil water inlet	TT434
	Exergy coil water outlet	TT435
Thermocouple	Thermocouple in water-ice tank	TT440A, TT440B, TT440C, TT441C
Flow measurement	IOC inlet CO ₂ flow measurement	FT300
	IOC outlet CO ₂ flow measurement	FT433
	Water flow measurement	FT434
Pressure differential	IOC CO ₂ flow dP measurement	PDT431
Level sensor	Water level sensor	LT_440

Table 2: Subscale IOC planned test conditions for CO₂ during charge and generate cycles

State Point on P&ID	Description	Temp (C)	Pressure (MPa)	Flow (g/s)	Enthalpy (kJ/kg)	Quality (frac)
Charging Test						
8	IOC Charge Cycle Inlet -Cold	-5	3.21	33	187.92	Sub-cooled liquid
Generating Test						
5	IOC Generate Cycle Inlet -Hot	20	4.03	33	454.46	Super-heated vapor

ice (916 kg/m³). As ice forms on the tubes the bulk water density in the tank decreases which in-turn rises the water level and as ice melts bulk water density increases which accounts for decrease in tank water level.

Table 3 provide the physical dimensions of as-built sub-scale IOC tested at Echogen. Figure 4 and 5 are some pictures of the installed lab scale IOC system. Figure 6 shows the ice formation on the coil during one of the tests.



Figure 4: Installed coil and tank at Echogen lab facility

Table 3: As-built sub-scale IOC physical parameters

IOC Test Article Physical Dimensions)	
Number of tubes	12
Tube OD (mm)	12.7
Tube wall thickness (mm)	0.889
Length of tube (total) (m)	30.48
Length of tube single element (m)	0.924
Tube-to-tube distance (mm)	53.34

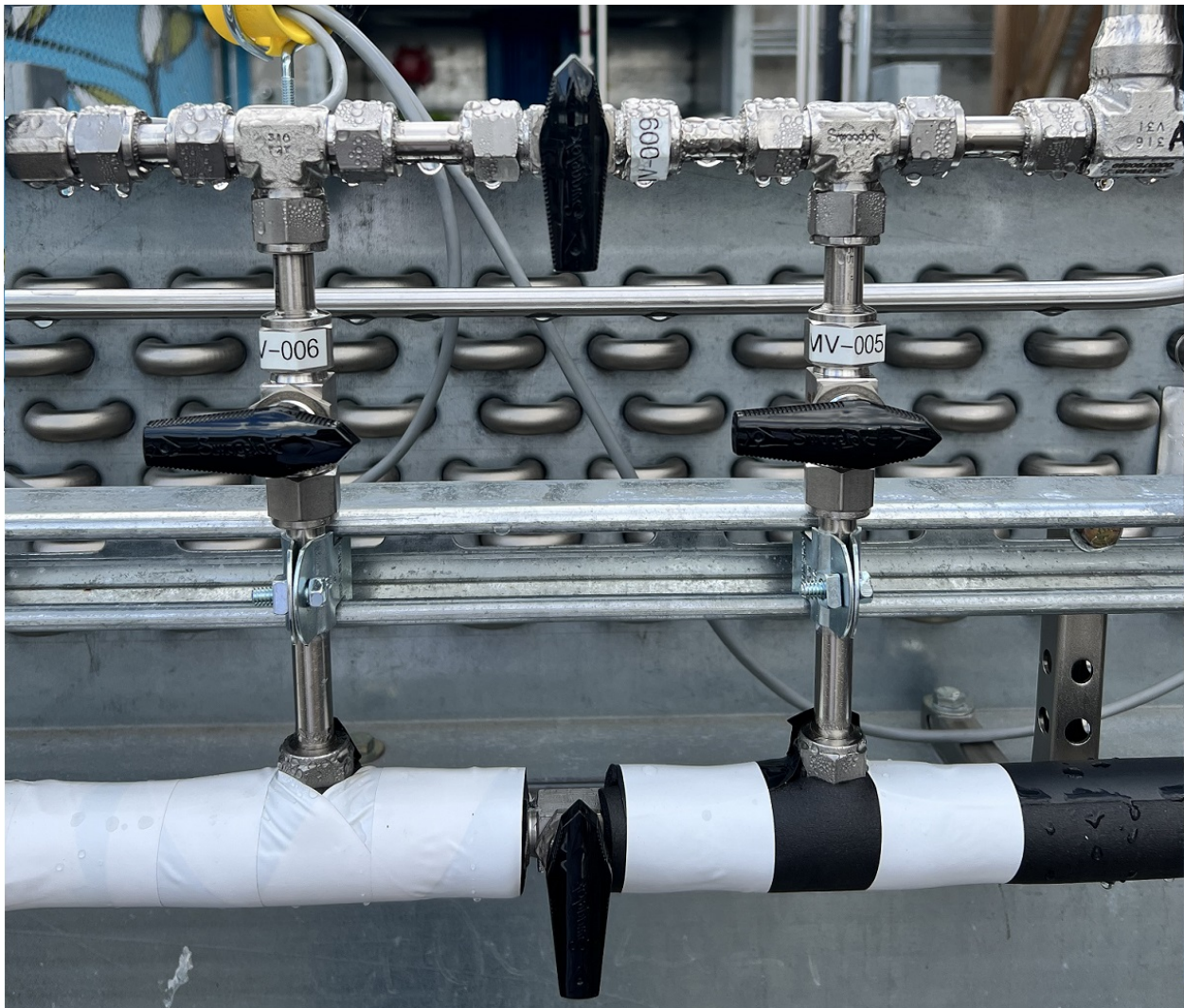


Figure 5: Installed manual valves to switch between charge and generate cycles



Figure 6: Ice formation on the IOC tubes during trail run of the installed system.

2.2 Lab Scale IOC Test Results and Discussion

The installed lab scale IOC was first commissioned which mainly involves (i) leak check by pressurizing the IOC loop with CO₂ and (ii) instrument and control check-out. Commissioning of the IOC test loop was smooth and was completed within a day. After commissioning the IOC was rigorously tested for both charge and generate cycles for more than 20 runs. Figure 7 to figure 14 are the representative plots from one of the IOC test. In all the plots, left side of the dotted line is charge test and right side of dotted line is generate test.

Figure 7, figure 8 are temperature plots for CO₂ and bulk water. The installed IOC was about 8.5kW_{th} capacity (figure 9). In IOC charge test (ice making test, left side of the dotted line in all plots), cold CO₂ enters IOC tubes and as it vaporizes, ice is formed on the outside of tube. Two major observations can be made from IOC charge test: (i) from figure 7 it can be inferred that when IOC is completely charged, the CO₂ temperature on the hot side (vapor end) drops to saturation temperature; (ii) for most of the charge test CO₂ temperature existing the IOC remains closer to 0 °C (freezing point of water) before dropping to saturation temperature.

In IOC generate cycle test (ice melting test, right side of the dotted line in all plots), warm CO₂ enters IOC tubes (through top header) and as it condenses, ice melts on the outside of tube. One major observation can be made from IOC generate test is that CO₂ condition on the cold end follows the saturation conditions which can be closely matched by bulk water temperature - i.e. CO₂ temperature on cold end in figure 7 match very closely with bulk water temperature in figure 8.

Figure 11, figure 12 and figure 13 are the plots for mass of ice formed/melted, thickness of ice and ice volume fraction respectively in the IOC tank during charge and generate test. About 80% ice volume fraction can be easily achieved in the IOC during charging test.

As commercial scale IOC in PTES applications is expected to have large number of tubes, knowing the CO₂ inventory requirements or swings during charge and generate test becomes crucial. IOC was installed on Load Cell to study the CO₂ inventory change during the entire test. Figure 14 show the plot from this measurement. As can be observed, during charge test the IOC is being filled with liquid CO₂ and when we transition into generate test, CO₂ mass in the IOC is depleted as generate (ice melt) cycle progresses.

2.3 IOC Transient Model Development and Validation against Test Data

Modeling IOC and validating the developed model against the test data is crucial in determining the size (number of tubes, tube length, tube-to-tube distance etc.) of IOC for commercial scale PTES systems. IOC model is inherently transient because as CO₂ vaporizes inside the tubes, ice is formed transiently on the tubes (or ice fraction in the tank increases) throughout the charge cycle.

The transient model for IOC was developed by Echogen in GT-SUITE [7] 1D system simulation software platform. In flow simulations (of present work), GT-SUITE solves 1D Navier-Stokes equations along flow components and solution convergence is checked using pressure, continuity and energy residuals. The models are built based on GT-SUITE supplied and/or user-defined component templates. Component templates can take manufacturer data and/or test data to size the component. Individual components can then be simulated using subsystem boundary conditions before being incorporated into full system model. These component templates are connected by piping components to build the full system model. GT-SUITE uses NIST REFPROP [8] for fluid thermal and transport properties.

Echogen has previously verified the GT-Suite transient model results against the test data from its commercially-available nominal 7.3 MWe (the EPS100) net power sCO₂ power cycle [9, 10].

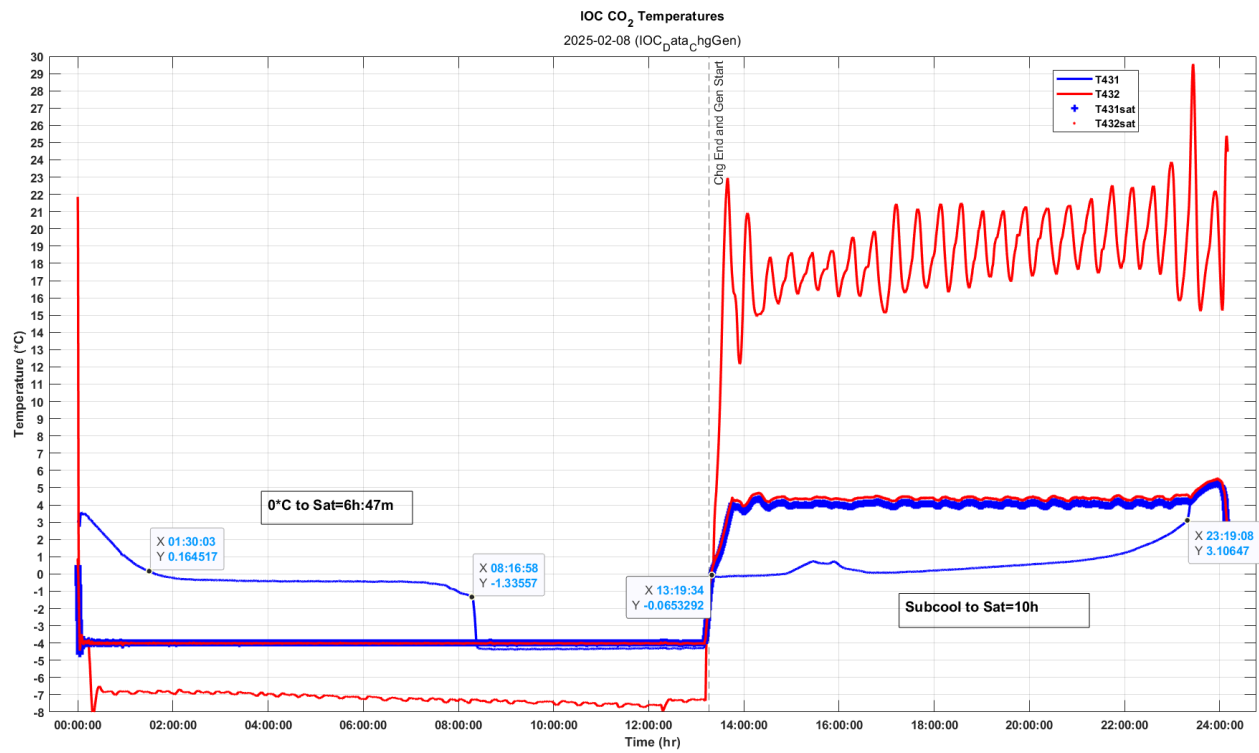


Figure 7: IOC CO₂ temperatures during charging (ice making) and generate (ice melting) tests. Left side of the dotted line is charge test and right side of dotted line is generate test. Red line is the CO₂ inlet temperature and blue line is the CO₂ outlet temperature during respective tests.

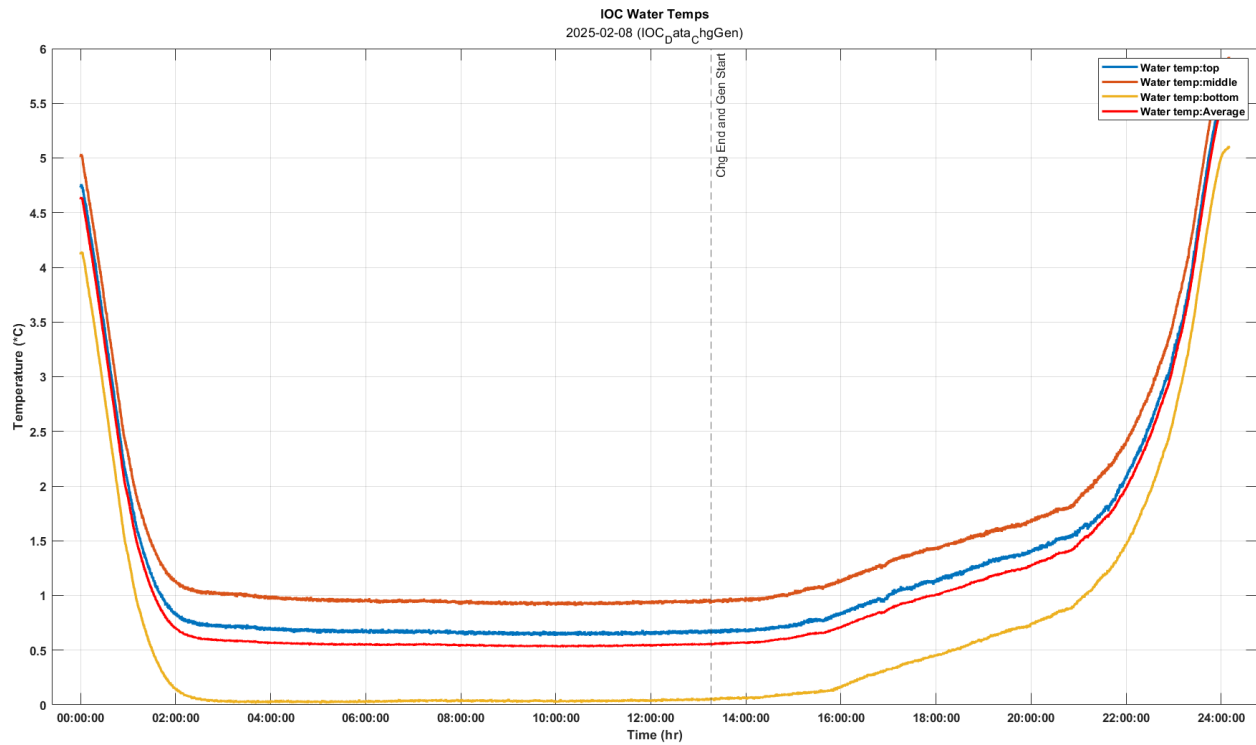


Figure 8: IOC bulk water temperature during charging (ice making) and generate (ice melting) tests. Left side of the dotted line is charge test and right side of dotted line is generate test.

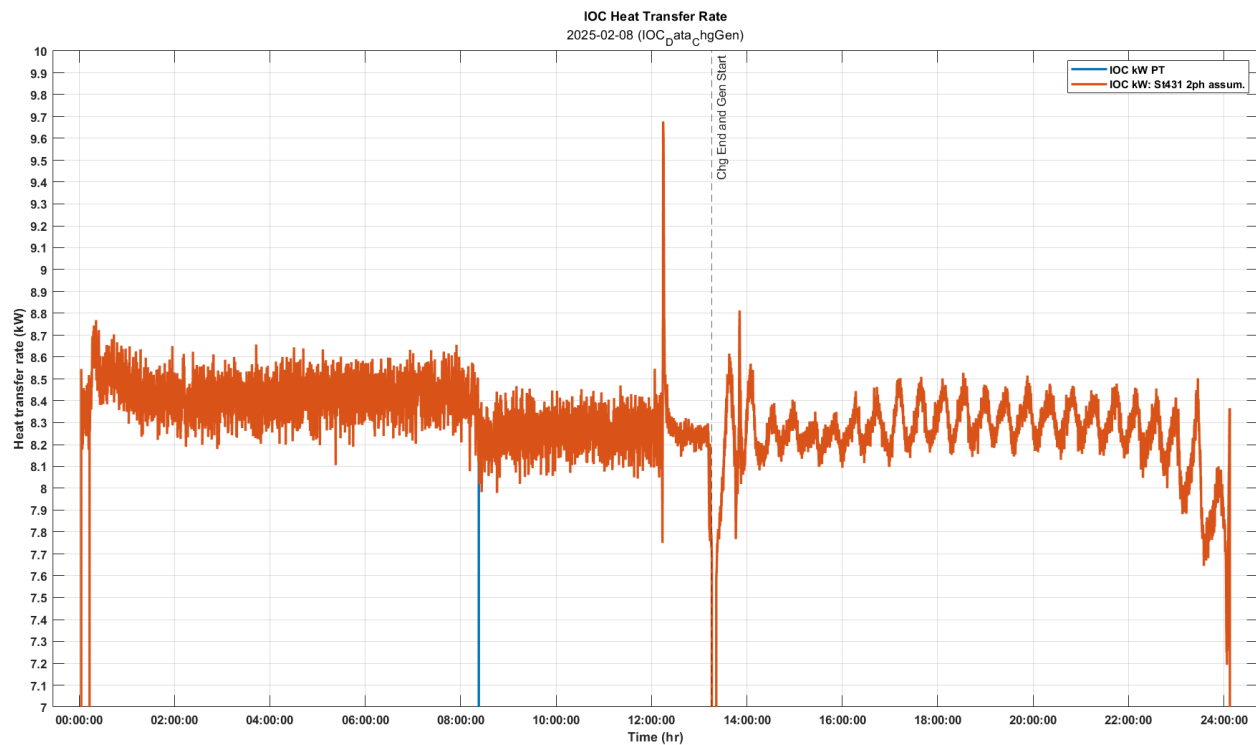


Figure 9: IOC heat transfer rate during charging (ice making) test and generate (ice melting) tests. The tested lab scale IOC was about 8.5kW_{th}. Left side of the dotted line is charge test and right side of dotted line is generate test.

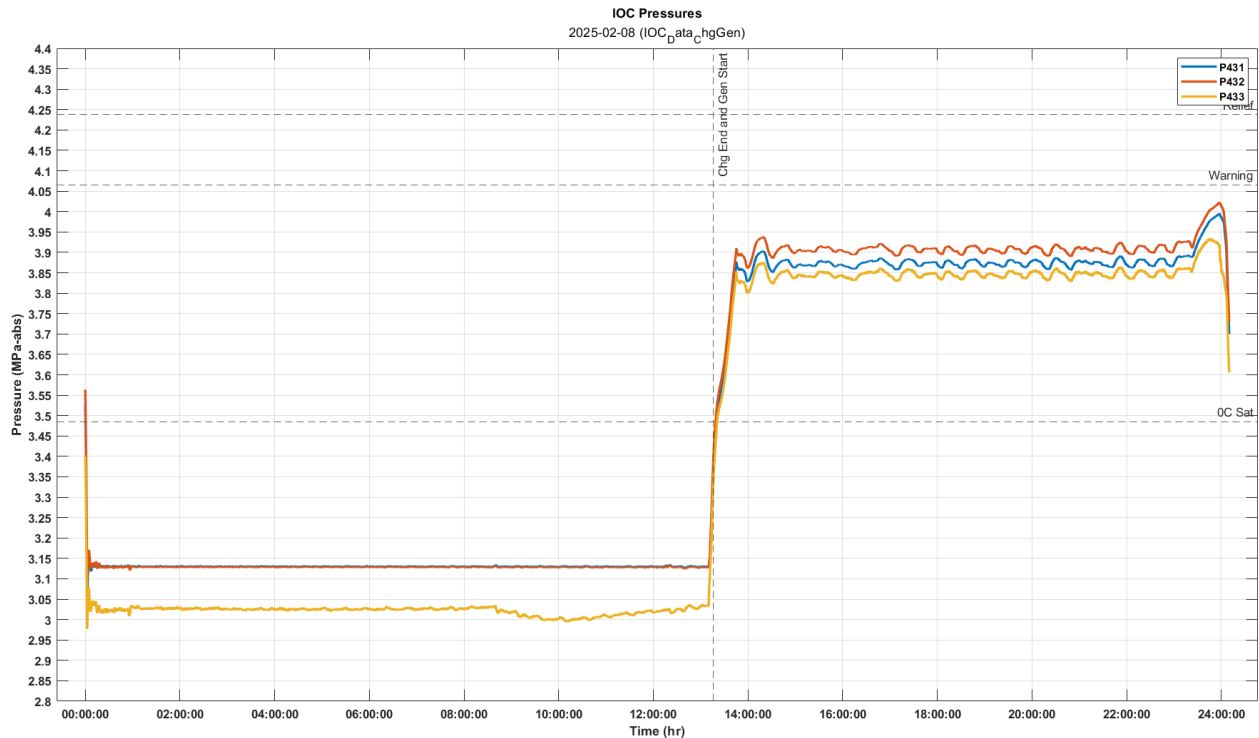


Figure 10: IOC CO₂ pressures during charging (ice making) and generate (ice melting) tests. Left side of the dotted line is charge test and right side of dotted line is generate test. The plot demonstrates the ability of control loops to maintain steady state conditions required for the test.

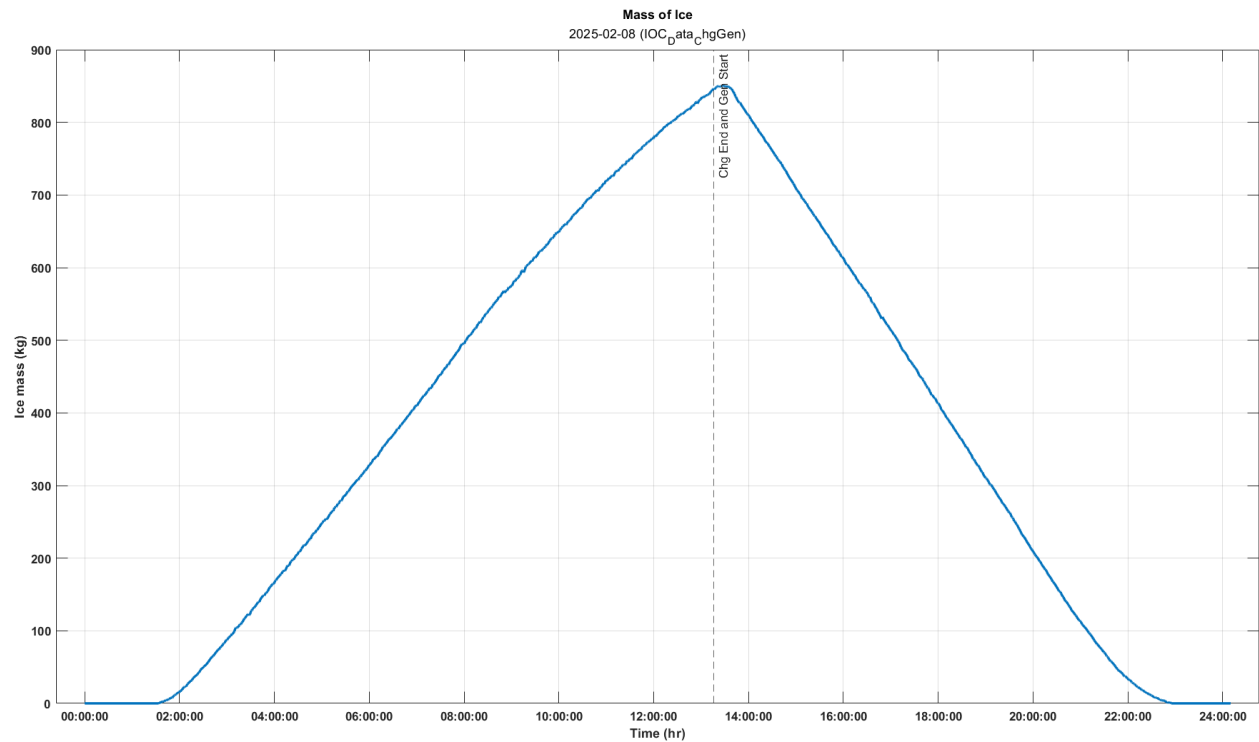


Figure 11: Growth of ice in the IOC tank during charge test (left side of dotted line) and melting of ice in the tank during generate test (right side of dotted line)

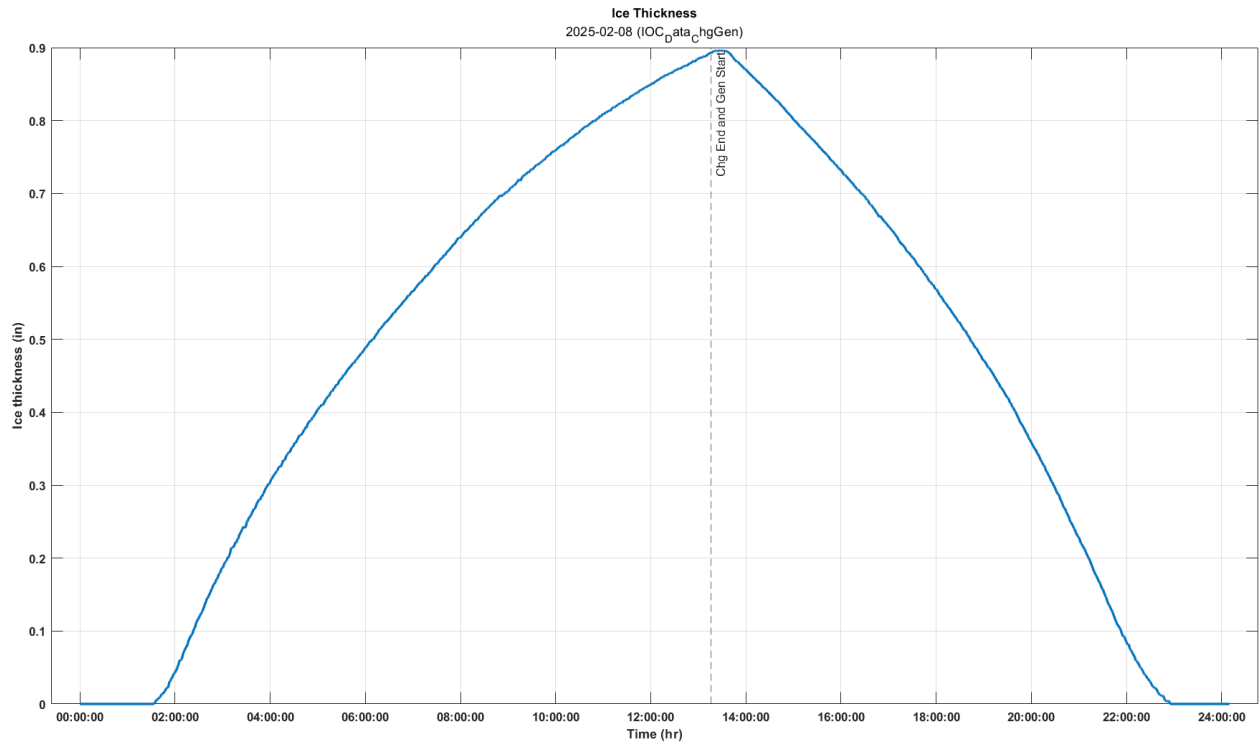


Figure 12: Growth of ice thickness on IOC tubes during charge test (left side of dotted line) and depreciation of ice thickness on IOC tubes during generate test (right side of dotted line)

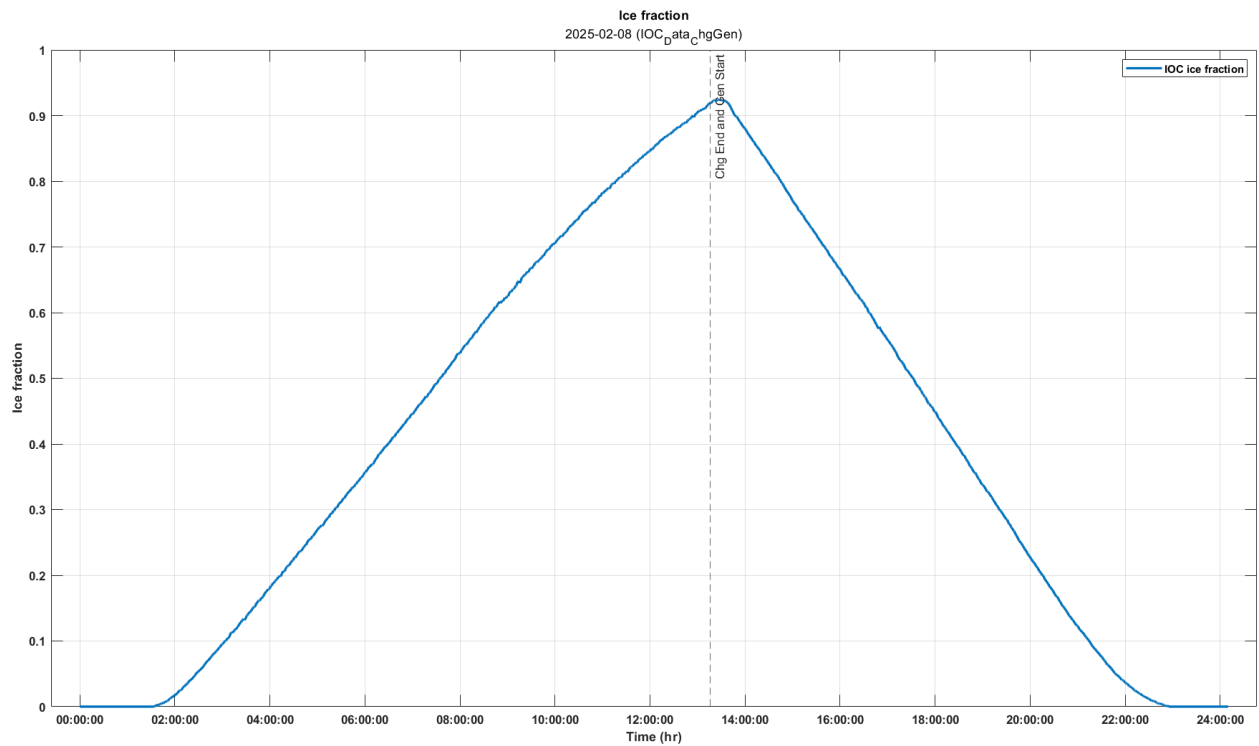


Figure 13: Increase of ice volume fraction in IOC tank during charge test (left side of dotted line) and depreciation of ice volume fraction in IOC tubes during generate test (right side of dotted line)

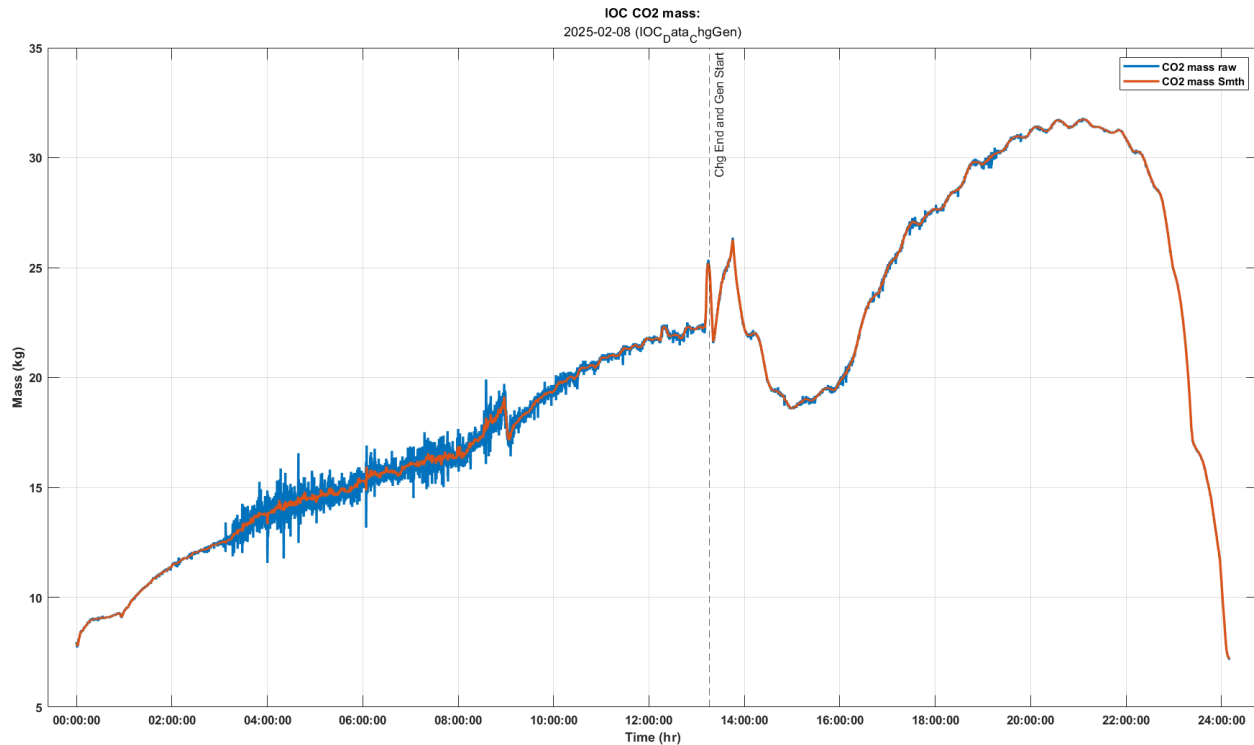


Figure 14: The entire IOC test setup was placed on Load Cells to investigate the amount of CO₂ changes in the IOC during charging and generate test.

Figure 15 shows the developed IOC transient model on GT-Suite platform. This model has two parts: (i) GT-Suite internal code was used to calculate CO₂ side heat transfer and pressure drop estimations and (ii) in-house (Echogen) built FORTRAN code was used for water/ice side heat transfer calculations. For CO₂ side heat transfer correlations GT-Suite uses standard Dittus-Boelter (for single-phase), Dobson (for condensation) [11] and Yoshida (for evaporation) [12] correlations. For water/ice side convection heat transfer around horizontal cylinder - Churchill and Chu [13] correlation was implemented in FORTRAN code.

The developed IOC transient model was verified/validated using the IOC lab test data. Model inputs are the IOC physical dimensions from the test IOC, provided in table 3.

Model boundary conditions are the CO₂ mass flow rate, CO₂ cold side temperature, IOC CO₂ pressure, water initial temperature and initial mass of water in the IOC. This information is provided to the model from one of the test runs. The simulation results are compared and verified with test data for CO₂ hot side temperature, mass of ice formed, heat transfer rate and average water temperature.

Figure 16 to figure 20 shows the comparison plots for test data versus simulation predictions for charge cycle. It is to be noted that for the model inputs values of initial water temperature and initial mass of water in IOC are 5 °C and 2067.5 kg respectively. From the comparison plots it can be inferred that the model predicts the IOC performance very well. With this validated transient model of IOC, the next step is to design an IOC system for commercial scale PTES system.

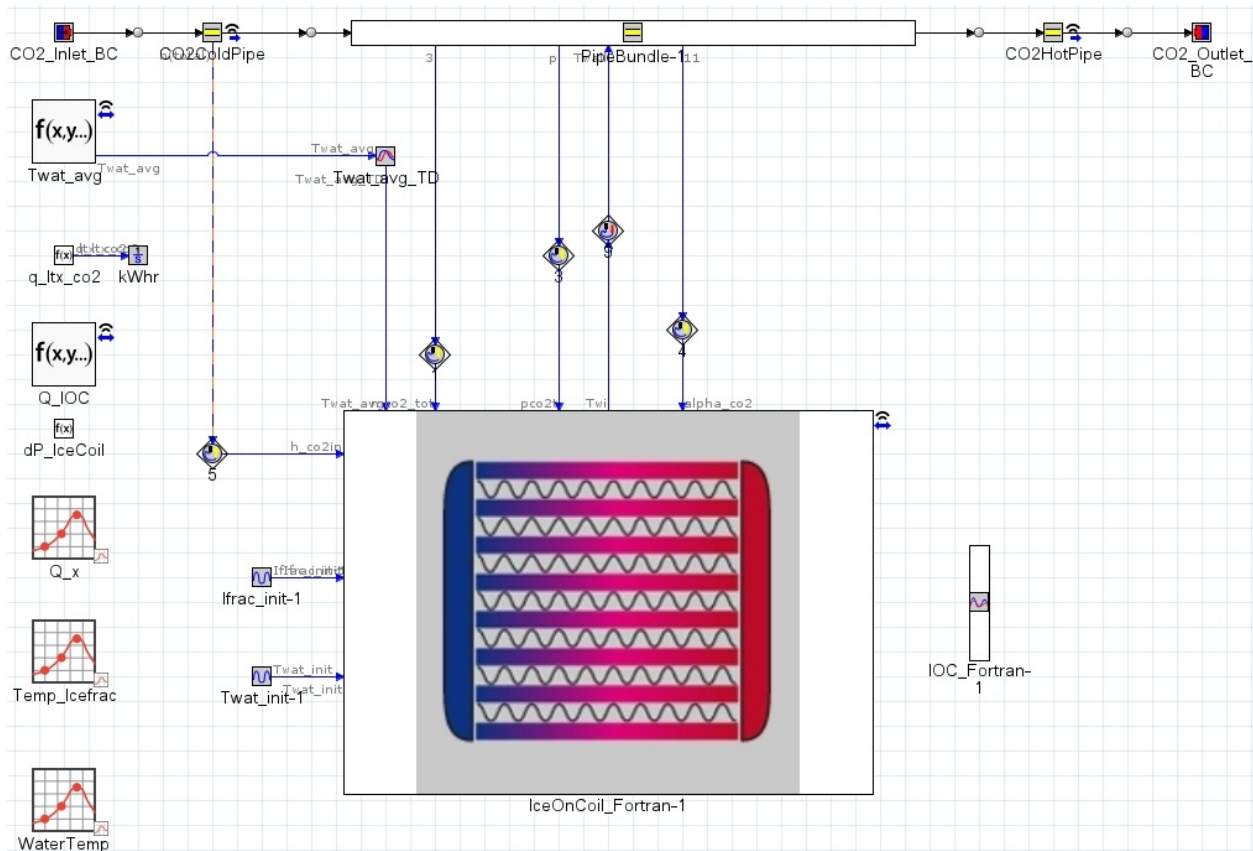


Figure 15: IOC transient model in GT-Suite system simulation software

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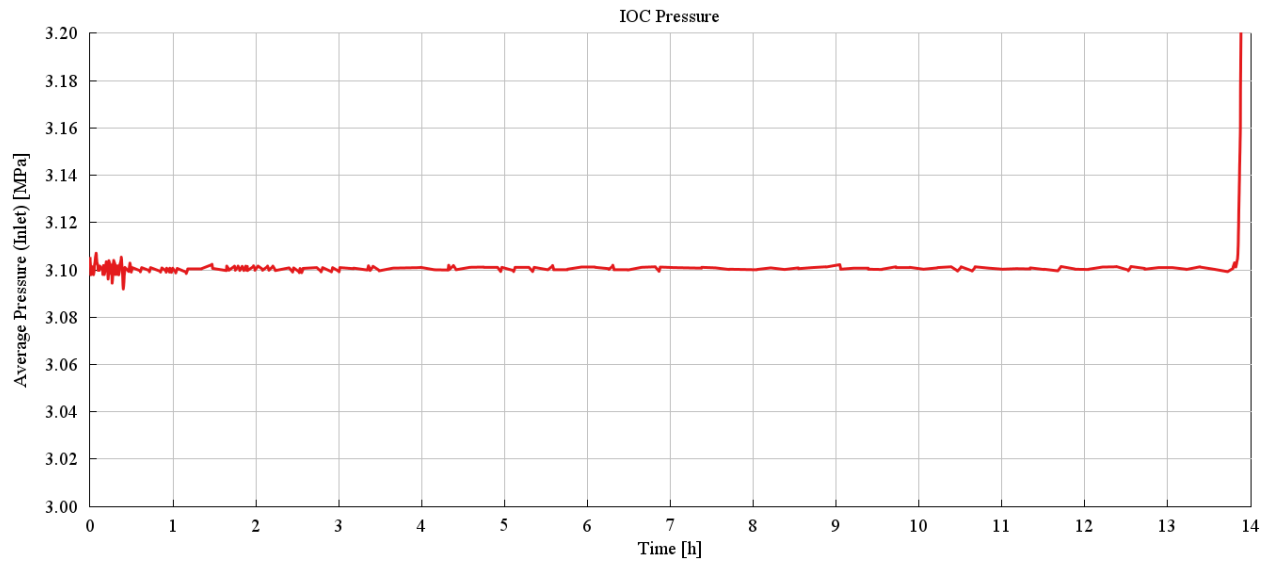


Figure 16: IOC charge cycle pressure which is input to model

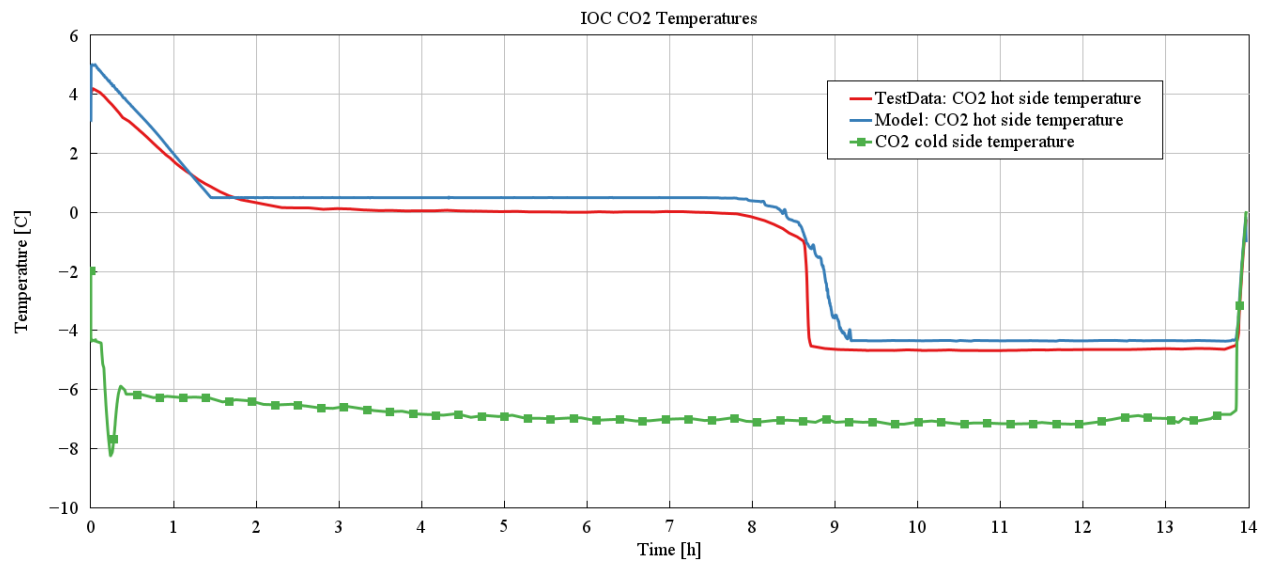


Figure 17: Model versus test data for IOC charge cycle temperatures on hot side while cold side is input to model

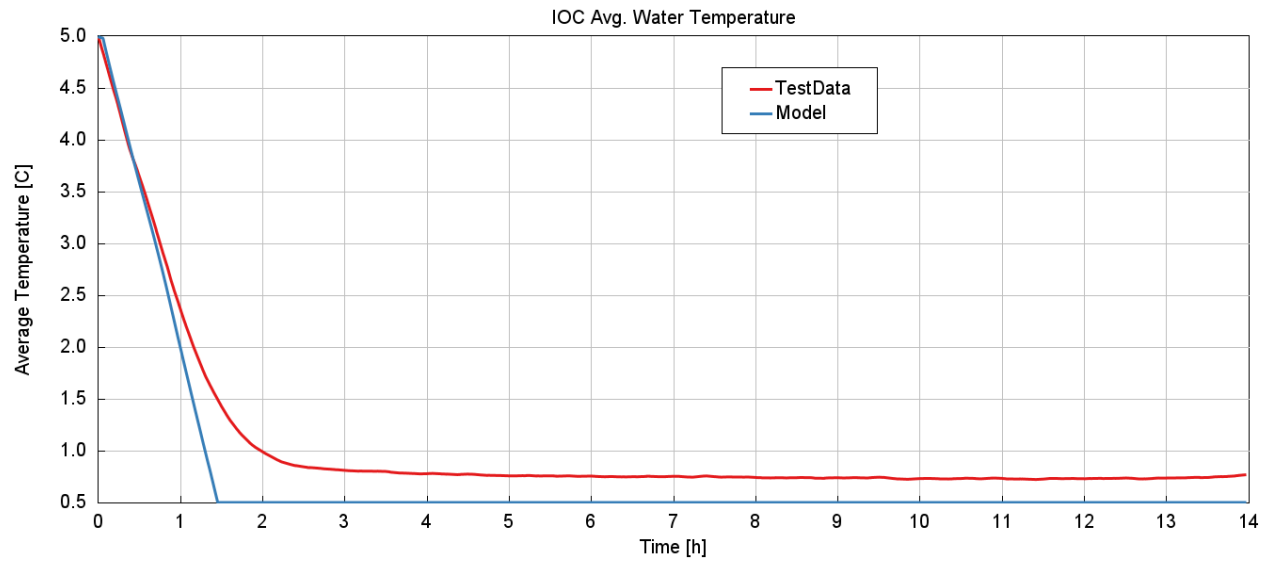


Figure 18: Model versus test data for IOC water average temperature during charge cycle

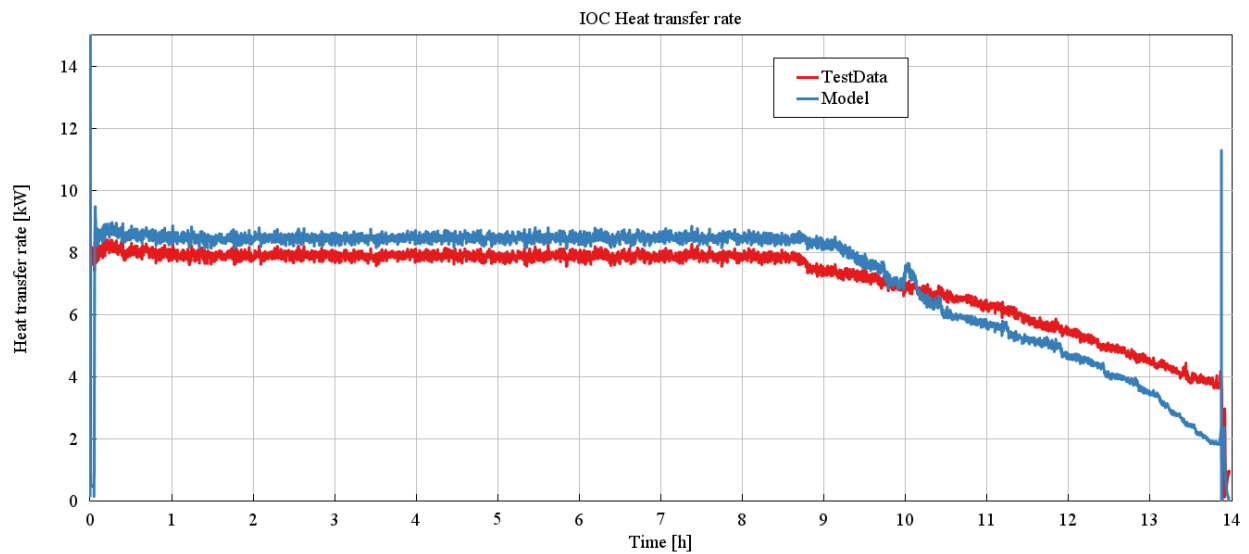


Figure 19: Model versus test data for IOC heat transfer rate between CO₂ and water during charge cycle

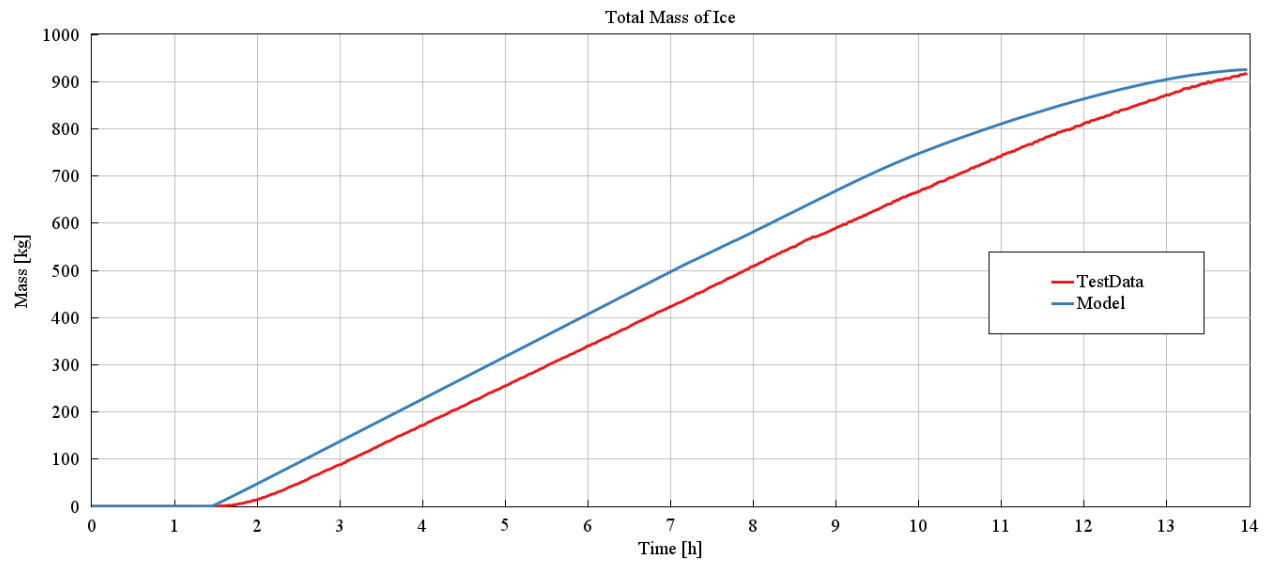


Figure 20: Model versus test data for mass of ice formed in IOC during charge cycle

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