PRE-PILOT: ABSORPTION MACHINE WITH INTEGRATED ENERGY STORAGE

TERMISKA ENERGILAGER

Energiforsk

Pre-Pilot: Absorption Machine with Integrated Energy Storage

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Foreword

En kostnadseffektiv uppgradering av låggradig värme till höggradig värme eller kyla är attraktivt för flera energibolag och kommer bli allt viktigare i framtiden med lägre temperaturer i näten och större kylabehov. Att också kunna lagra energin för användning när behovet är som störst adderar ytterligare nyttor, exempelvis minskat behov av investeringar i distribution- och produktionsanläggningar. Detta projekt genomfördes för att undersöka om dessa behov kunde uppfyllas genom en absorptionsmaskin baserad på konventionell värmeväxlarteknik och SaltX saltlösning för energilagring.

Det här är slutrapportering av projektet *Demoanläggning – SaltX absorptionsmaskin med integrerat energilager* som har letts och genomförts av SaltX Technology genom Corey Blackman i samarbete med AlfaLaval.

Projektet har delfinansierats av, och ingår i, Energiforsks program Termiska Energilager. Ett forskning- och utvecklingsprogram vars långsiktiga mål är att visa hur, var och när termiska energilager kan utformas och användas och vilken ekonomisk och miljömässig nytta de kan ge. Programmet leds av en styrgrupp bestående av Henrik Lindståhl (ordförande) (Tekniska verken i Linköping AB), Lennart Hjalmarsson (Göteborg Energi AB), Per Haker (Hässleholm Miljö AB), Einar Port (Mälarenergi AB), Per Kallner (Vattenfall R&D AB), Mutaz Alkiswani (Öresundskraft Kraft & Värme AB), Joacim Cederwall, (Jönköping Energi AB), Morgan Romvall (Halmstad Energi och Miljö AB), Ted Edén (Norrenergi AB), Fredrik Martinsson, Markus Wråke och Julia Kuylenstierna (adjungerade Energiforsk). Suppleanter har bestått av Ulf Hagman (Göteborg Energi), Marianne Allmyr, (Mälarenergi AB), Mile Elez (Tekniska verken i Linköping AB), Jesper Baaring (Öresundskraft Kraft & Värme AB), Mats Svensson (Halmstad Energi och Miljö AB), Staffan Stymne (Norrenergi AB), Patric Jönnervik (Jönköping Energi AB) och Erik Holmén (ENA Energi).

För att kvalitetssäkra projektet har Lennart Hjalmarsson (Göteborg Energi AB) ingått i ett sekretessavtal med SaltX och kunnat följa utveckling.

Stockholm, mars 2020

Julia Kuylenstierna
Programansvarig Energiforsk

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

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Längre sammanfattning på svenska

SaltX inledde 2018 ett ambitiöst projekt för att designa, utveckla och utvärdera en flexibel absorptionsmaskin som skulle utnyttja lågtemperaturvärme och fungera som kylaggregat, värmepump samt ett integrerat energilager. Applikationen har en betydande potential att använda spillvärme för kylning samt lagring av spill och/eller överskottsenergi som sedan kan användas när behov uppstår.

På önskemål från ledande nordiska energiföretag har SaltX utvecklat en absorptionsmaskin baserad på konventionell värmeväxlarteknik där värme och kyla kan genereras samt energi lagras. Den centrala förutsättningen för att utveckla absorptionsmaskinen är att använda en kompakt "off-the-shelf" plattvärmeväxlare för att producera en mer kostnadseffektiv absorptionsmaskin än vad som för närvarande finns på marknaden.

SaltX patentansökta saltlösning har tidigare verifierats med en specialdesignad absorptionsmaskin där detta projekt ämnar till att verifiera samma funktionalitet med kompakt och kostnadseffektiv konventionell "off-the-shelf" värmeväxlarteknik.

Utvärderingar genomfördes inom projektet för att optimera SaltX saltlösning samt beräkningar och simuleringar som gjorts vid tidigare utveckling av applikationen. En första testrunda genomfördes vid Mariehamn Energys fabrik på Åland i samarbete med Alfa Laval. Resultaten av dessa första utvärderingar gav dålig drift av maskinen på grund av inläckage av luft i den valda plattvärmeväxlaren. Med tanke på att systemet kräver en hög nivå av vakuum för korrekt drift var det inte möjligt att uppnå kylning eller värmepumpningsfunktion av maskinen.

En förbättrad prototyp av en absorptionsmaskin konstruerades och utvecklades med större hänsyn till läckage och infiltration. En annan design på värmeväxlare valdes och integrerades och en ny omgång tester utfördes vid SaltX huvudkontors laboratorium. Resultaten av dessa tester visade att kylning och värmepumpningsfunktion skulle kunna uppnås med den förbättrade prototypen. Trots förbättringarna var prestanda i nämnda prototyp fortfarande relativt låg och uppnådde bara 50% av designade kylkapaciteten.

Projektets resultat visar på behovet av en mer integrerad strategi för utveckling av en kompakt plattvärmeväxlare för denna specifika applikation. I detta fall skulle frågan om enhetens vakuumtäthet övervägas i designstadiet och ge upphov till bättre passform för denna typ av absorptionsmaskiner som använder vatten som köldmedium.

PROJEKTETS MÅL

Huvudmål: att verifiera funktionalitet hos SaltX nya absorbtionsmaskin baserad på plattvärmeväxlare och SaltX patenterade saltmaterial. De 3 funktionerna värmepump, kylmaskin respektive energilager testas, utvärderas och verifieras. Underlaget används för design och projektering av fullskalig pilotanläggning som erbjuds deltagande bolag inom programmet Termiska Energilager för fullständigt pilotprojekt samt långtidsutvärdering. Anläggningen används för verifiering och referens inför uppförande av en fullskalig pilotanläggning.

Delmål 1: Baserat på plattvärmeväxlare och SaltX, erhålla funktionalitet såsom värmepump, kylmaskin samt förmåga att lagra och spara energi i koncentrerad saltlösning, med fjärrvärme om ca 70°C som drivenergi.

Delmål 2: Att som värmepump nå prestanda att höja temperatur från inkommande ca 70°C till ca 100°C.

Delmål 3: Att som kylmaskin nå prestanda att sänka temperatur till ca 7-8°C från inkommande ca 20°C.

Delmål 4: Att mäta maskinens prestanda vid olika temperatur samt flöde på fjärrvärmen.

Delmål 5: Att mäta maskinens förmåga och effektivitet att lagra upp och spara koncentrerad saltlösning, såsom ett högeffektivt energilager, för användning vid senare tidpunkt.

Delmål 6: Design och projektering av fullskalig pilotanläggning i MW-skala. Anläggningen specificeras utifrån ett konkret fall och behov hos någon av deltagarna i programmet Termiska Energilager, för ett fullständigt pilotprojekt med utvärdering över tid och med olika driftförhållanden.

MOTIVATION

Förmågan att utnyttja lågkvalitetsvärme och omvandla den till ett användbart termiskt flöde som kyla, eller högre kvalitetsvärme är av stort intresse. En anordning som man kan laddas i tider av överskott av lågkostnadsenergi som sedan kan laddas ur när det finns en efterfrågan på energi i kombination med höga energipriser är efterfrågat inom olika branscher, särskilt när det gäller värme- och kraftproduktion. En sådan absorptionsmaskin skulle kunna använda i fjärrvärmenät för att tillhandahålla decentraliserade fjärrkylcentraler, i processindustrier och även på fartyg som använder sig av spillvärme från stora marinmotorer.

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Sorptionsmaskiner är typiskt byggda med stora skrymmande och dyra värmeväxlare. Genom att använda "off-the-shelf" kompakt platta värmeväxlare kan det antas att en mer kostnadseffektiv absorptionsmaskin kan utvecklas. Projektet har utformats för att utveckla en sådan absorptionsmaskin med mål att utnyttja SaltX patentansökta saltlösning och integrerade termiska energilagringsmetod.

Om utvecklingen av en sådan absorptionsmaskin med flexibla driftlägen som kylning, värmepumpning och energilagring skulle lyckas skulle det ha en betydande potential på både nationella och internationella marknader. Flera energibolag i Sverige har stora överskott av värme under sommaren där stora ekonomiska och miljömässiga fördelar kan fås genom att omvandla denna spillvärme till nyttig distriktskylning. Ytterligare potential ligger i utnyttjande och lagring av förnybar energi som solenergi, geotermisk och bioenergi.

DISKUSSION

Det nuvarande projektet har utarbetats med en uppsättning mycket ambitiösa mål som under genomförandet inte var möjliga att uppnå. Målen för både sorptionsmediet, SaltX LMX samt den kompaktplatta värmeväxlaren är på gränsen till de termodynamiska möjligheter som tekniken erbjuder och skulle kräva en betydande nivå av optimering och integration av både medium och värmeväxlaren. Den mycket låga drivtemperaturen på 70 °C i kombination med det relativt låga kylvattentemperaturbehovet på 7°C kräver ett högt temperaturlyft av absorptionsmaskinen, hög energitäthet samt höga volymflöden av köldmediet vilket är en utmaning för den kompakta plattvärmeväxlaren. Maskinens lagringskapacitet och prestanda i värmepumpsläge undersöktes inte med tanke på maskinens dåliga prestanda. Följaktligen övervägdes ingen konstruktion för en uppskalning av applikationen.

Projektets resultat visar på behovet av en mer integrerad strategi för utvecklingen av en kompakt plattvärmeväxlare för denna specifika applikation. I detta fall skulle frågan om enhetens vakuumtäthet övervägas i designstadiet och ge upphov till bättre passform för denna typ av absorptionsmaskiner som använder vatten som köldmedium.

SLUTSATSER

Projektets ambitiösa mål uppnåddes tyvärr inte i enlighet med de testade prototypernas dåliga resultat. Man kan dra slutsatsen att de "off-the-shelf" värmeväxlarna som används som nyckelkomponenter, absorptionsmaskinens absorbator och desorber inte uppfyllde kraven för drift. Eftersom vatten används som köldmedium i absorptionsmaskinen måste höga vakuumnivåer uppnås vilket gör att vakuumtätheten blir avgörande för systemdriften. Nuvarande designer kan inte upprätthålla den nivå av lågt tryck och låg infiltration som krävs för det aktuella absorptionsmaskinkonceptet. En plattvärmeväxlare som är speciellt utformad för ändamålet skulle krävas.

Summary

SaltX embarked on an ambitious project to design, develop and evaluate a flexible absorption machine that could utilise low temperature heat and operate as a chiller, heat pump as well as an integrated energy store. Such a machine has significant potential to utilise waste heat for cooling purposes as well as storage waste and/or excess energy in times of plenty to be utilised in times of scarcity.

Based on the wishes of leading Nordic energy companies, SaltX has developed an absorption machine based on conventional heat exchanger technology. In this, heat and cooling can be generated as well as energy stored. The central premise of the absorption machine development is to use "off-the-shelf" compact plate heat exchanger components to produce a more cost-effective absorption machine than can currently be found on the market. SaltX's patent pending salt solution and integrated thermal energy storage method was verified with a specially built machine and the current project developed to verify the same functionality with compact and cost-effective conventional heat exchanger technology.

Evaluations were carried out within the project to optimise the SaltX salt solution and various calculations and simulations done in the design and development of the absorption machine prototype. A first round of tests was conducted at Mariehamn Energy's plant in Åland, in collaboration with Alfa Laval. The results of these first evaluations saw poor operation of the machine due to infiltration of air into the selected plate heat exchanger. Given that the system requires a high level of vacuum for proper operation it wasn't possible to achieve cooling or heat pumping functionality of the machine.

An improved absorption machine prototype was designed and development with greater consideration for leakage and infiltration. Another heat exchanger design was selected and integrated and a new round of tests carried out at the SaltX headquarters laboratory. The results of these tests showed that cooling and heat pumping functionality could be achieved with the improved prototype. However, the performance of said prototype was still relatively poor, only achieving 50% of the design cooling capacity.

Based on the outcomes of the project, a more integrated approach to the development of a compact plate heat exchanger for this specific application is required. In this case, the issue of vacuum tightness of the unit would be considered at the design stage giving rise to better fit for this type of absorption machines that employs water as refrigerant.

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1   Introduction

1.1   PROJECT OBJECTIVES

The main objective of the project is to verify the functionality of a novel absorption machine based on plate heat exchangers with SaltX's patented salt material. The machine is designed to perform 3 main operations; as a heat pump, a chiller and also as an energy store. The knowledge gained in the project would be design and development of a full-scale pilot plant that could be provided to participants of the Thermal Energy Storage programme for long term evaluation.

Within the current project specific targets were devised:

1. Based on the compact plate heat exchanger and sorption substance the unit should function as a heat pump, chiller and energy store with district heat around 70°C as driving temperature.
2. In heat pump mode the unit can increase incoming temperature from 70°C to 100°C.
3. In chiller mode the unit can reduce the incoming temperature of the heat transfer medium from 20°C to around 7°C to 8°C.
4. Accurate measurement of the absorption machine's performance via the various temperatures and flow of district heating.
5. Measurement of the machine's capacity to store concentrated solution as a highly effective energy storage for use at different times.
6. Design and planning of a full MW-scale pilot plant. The plant shall be developed based on a specific case and requirement of a participant in the Thermal Energy Storage programme. The plant would be developed for full long-term evaluation under different operating conditions.

1.2   MOTIVATION

The ability to utilise low quality heat and convert it to a useful thermal flow which could be cooling, or higher quality heat is of great interest. A device that one can charge during times of excess low-cost energy and discharge where there is an energy demand coupled with high energy prices is desired within various industries, especially in the case of heat and power production. Such an absorption machine could find use in district heating networks to provide decentralised district cooling centres, in process industries and even on ships making use of waste heat from large marine engines.

Typical sorption machines are built with large bulky and expensive heat exchanger components. By employing "off-the-shelf" compact plate heat exchanger components it is surmised that a more cost-effective absorption machine can be developed. Leveraging SaltX's patent pending salt solution and integrated thermal energy storage method the project has been devised to develop said absorption machine.

If successful such an absorption machine with flexible operational modes including; chilling, heat pumping and energy storage would have significant

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potential on both national and international markets. Several energy companies in Sweden have large excesses of heat during the summer where large financial and environmental benefits can be had by converting this waste heat to useful district cooling. Further potential lies also in the exploitation and storage of renewable energy such as solar, geothermal and bioenergy.

Sökord

Absorption, machine, district heating, waste heat, chiller, heat pump, salt solution, plate heat exchanger.

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2 Introduction Sorption Systems

2.1 GENERAL SORPTION PROCESS DEVELOPMENT

Absorption and adsorption cycles are the most popular and arguably the most efficient and cost-effective processes for using high temperature thermal energy to generate a cooling effect. The principle is based on the use of two species or substances with high chemical affinity for each other where one substance is typically a solid or liquid that combines with another substance which is in liquid or vapour form. If we consider two substances denoted A and B which combine to form substance C. The low energy and most stable form of the two substances is in their combined form (i.e. substance C). If it is desired to have two separate substances, then energy must be supplied in the form of heat to break them apart into their individual constituents (i.e. substance A and substance B). In this (high energy level) separated form, the two substances can be stored separately. However, upon recombination, energy must be released as heat as the low energy level substance C is reformed. This general principle may be referred to as a reversible sorption reaction or a sorption process.
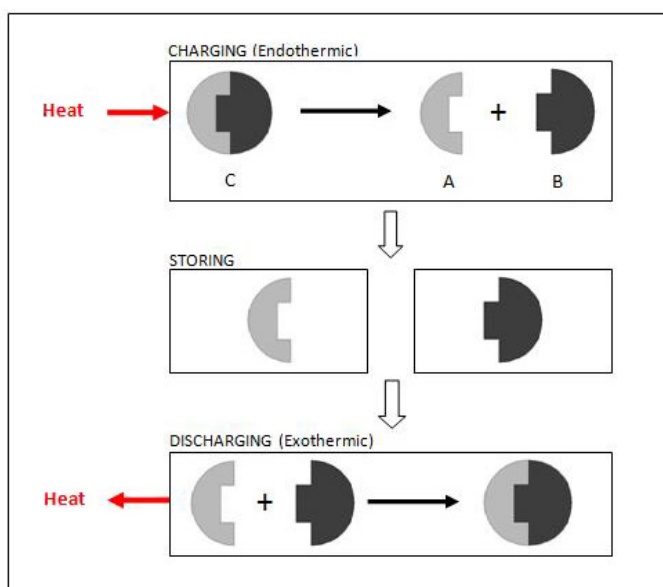

Figure 1 - Sorption process concept

There is a plethora of substances which undergo this reversible reaction or process however it occurs at different boundary conditions where reaction start and stop temperatures and heat evolution amounts are vastly different. Additionally, various other practical questions arise in terms of substance preparation, reaction stability, safety, and component costs when applying the process to a specific application. Over the years a database and knowledge set has been built up by SaltX on how to optimise various sorption substances for use in various applications via both theoretical and experimental studies, prototyping and component manufacture. This experience and knowledge include a range of

proprietary solutions and practices for various applications for cooling, heating, refrigeration and/or thermochemical energy storage.

2.1.1   Basic Sorption Process Principles

SaltX Sorption systems are based on a proprietary sorption technology. The basic principle is a chemical heat-pump technology with integrated energy storage in a dry salt. It is closely related to conventional absorption principles with the advantages that there are no crystallisation issues (unlike other absorption systems crystallisation is actually welcomed and not avoided), no need for precision control of temperatures and flow rates, and that it has integrated energy storage and no moving parts in the sorption core.

The Sorption systems are powered by heat which can be from various sources which include but are not limited to; waste heat from combustion engines, solar energy, waste heat from industrial processes, heat from a gas burner, etc. The heat source drives a chemical dissociation process. Two species, namely a specially prepared hygroscopic salt and a refrigerant (typically a natural inorganic compound such as water, methanol or ammonia), which at room temperature form a chemical complex and require a source of heat to elevate temperature levels (e.g. 150°C) to break them apart into separate salt and liquid refrigerant. The salt remains in one vessel called the Reactor while the refrigerant is kept in another vessel called the Condenser. When the temperature of the Reactor is reduced (to a low energy level) again the refrigerant can once again react with the salt to form a complex since the refrigerant has a high affinity for the salt as long as the salt is at medium temperature (e.g. 30°C). Once this medium temperature in the Reactor is reached the refrigerant can move merely due to its affinity for the salt, from a vessel called the Evaporator to the Reactor (i.e. no pump is required for this movement). This process causes an evaporation in the Evaporator and a chemical (reassociation) reaction to occur in the Reactor. This evaporation generates a cooling effect where temperatures can range from -10 to +10 °C depending on the refrigerant and salt combination employed. Thus, no compressor is required to run this cooling process only heat at the requisite temperature level for the salt and refrigerant employed in the system.

A typical SaltX sorption system consists of three key elements:

- A "Reactor" that houses the salt and is connected to the heat source during the chemical dissociation process also known as charge or desorption as well as the reassociation process known as absorption or discharge.
- A "Condenser" that condenses the refrigerant vapour leaving the Reactor during charge.
- An "Evaporator" that allows for the evaporation process to be carried out when the liquid refrigerant from the Condenser flows to the Evaporator (usually by gravity) where it evaporates and finds its way again to the Reactor when said Reactor is at medium temperature. This re-association process is also called discharge or absorption. The Evaporator can thus be connected to a hydronic chilling system to provide air conditioning.

The SaltX technology can conceptually be described as group of vacuum sealed vessels or chambers coupled together. Given the fact that the Sorption system works in a batch process similar to that of a battery with charge and subsequent discharge processes, it is possible for the Condenser and Evaporator to be one and the same vessel where is acts as a Condenser during the charge process and as an Evaporator during the discharge process. This unit can therefore be labelled as a combined Condenser/Evaporator. The figure below shows the process steps involved in a two vessel SaltX Sorption system with one Reactor Sub-component and one combined Condenser/Evaporator (C/E) Sub-component.
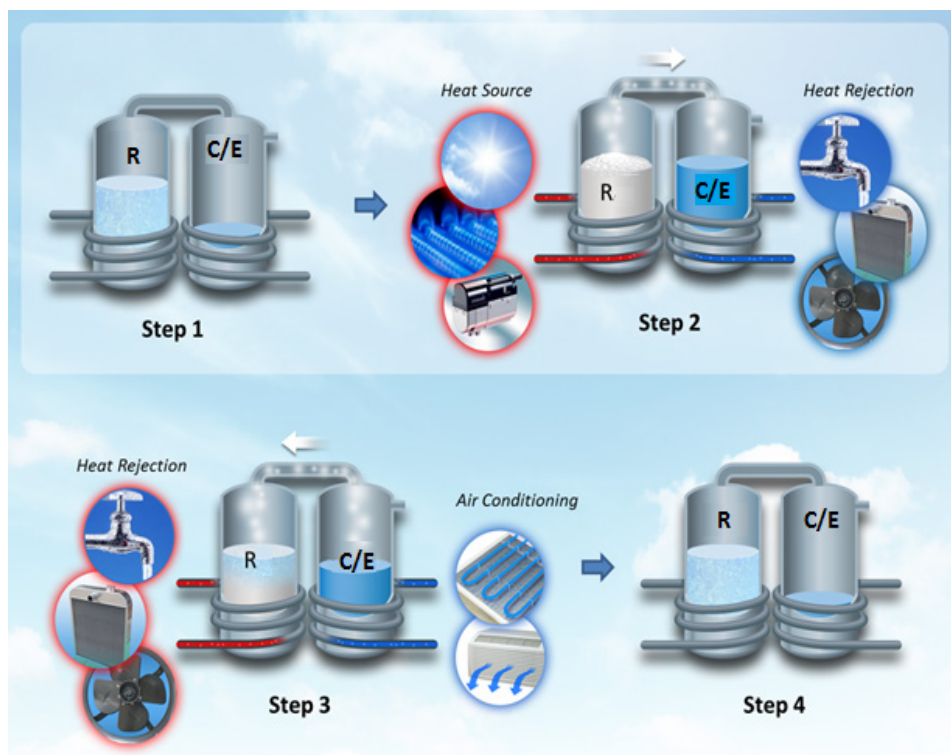

Figure 2 - Principle of the batch process of SaltX's Sorption system

Step 1 – Start

When the process starts the Reactor holds all refrigerant while Condenser/Evaporator is for the most part void of refrigerant.

Step 2 – Charge (or Desorption):

During desorption, a high temperature thermal energy source, is connected to the Reactor to concentrate the salt solution by dissociating the refrigerant. Heating continues until the desired amount of refrigerant has been desorbed from the salt and condensed in the Condenser/Evaporator. To carry out said condensation heat needs to be removed from the Condenser/Evaporator to allow the refrigerant to change from the vapour to liquid phase.

Step 3 – Discharge (or Absorption):

During discharge, the Condenser/Evaporator (now acting as the Evaporator) is connected to a low temperature heat source such as the return heat transfer fluid of an air conditioning system (typically water at 12°C). When the Reactor reaches its medium temperature (e.g. 30°C) refrigerant then starts to evaporate (from the Condenser/Evaporator), generating a cooling effect as it changes phase from liquid to vapour. The cooling effect generated by the refrigerant evaporation can thus harnessed to provide chilled fluid which can be supplied to an air conditioning system at a typical temperature level of 7°C. The vapour flowing from the Condenser/Evaporator to the Reactor is absorbed by the salt releasing chemical energy, similar to the condensation process, this chemical reaction heat needs to be removed by a heat rejection medium (which is typically at above ambient temperature).

Step 4 - End:

The absorption process ends when (most of) the refrigerant in the Condenser/Evaporator has been 'consumed' by the Reactor. The process can now restart from Step 1 when desired.

2.1.2 Summary of Sorption System Nomenclature

To describe the SaltX sorption system various sub-components are identified and specific nomenclature employed.

Table 1 - Main Sub-component description and general Component nomenclature

Sub-component /Nomenclature	Description
Reactor A	The reactor is a form of heat exchanger that facilitates the reaction of the salt with the refrigerant. This sub-component needs to be designed to allow for high temperature heating during charge and heat rejection during discharge processes. Thus, a single reactor could be used for both the absorption and desorption processes.
Absorber	The absorber is a type of reactor dedicated to facilitating the absorption of refrigerant into the salt solution. Concentrated salt solution flows into the absorber absorbing refrigerant vapour from the evaporator forming a dilute salt solution. During the absorption process heat is generated. As the temperature of the solution rises its ability to absorb water vapour rapidly diminishes, therefore the generated heat must be removed by a cooling medium which traverses the absorber to improve the absorption process and thus system performance.
Desorber (Generator)	The desorber also known as a generator is a form of reactor dedicated to the charging or 're-strengthening' of the diluted salt solution that leaves the absorber by facilitating the desorption of water from the salt solution. To carry out this operation heat must be supplied. Generated vapour passes to the condenser while the strong solution makes its way back to the absorber or solution storage tank.
Condenser	Dedicated Sub-component used for condensing of refrigerant vapour, that is, effectuating the refrigerant phase change from

Sub-component /Nomenclature	Description
	vapour to liquid. This Sub-component needs to only be designed for heat rejection.
Evaporator	Dedicated Sub-component used for evaporation of liquid refrigerant, that is, effectuating the refrigerant phase change from liquid to vapour. This Sub-component needs to only be designed for chilled fluid generation.
Condenser /Evaporator (C/E)	Single Sub-component that can perform both as a condenser or an evaporator. This is thus a combined utility Sub-Component which requires connections to allow for heat rejection during charge and the chilled fluid generation during discharge.
Salt	Is a hygroscopic substance, typically an alkali halides that reacts reversibly and spontaneously with a given inorganic compound. Special attention is paid to salt preparation methods.
Refrigerant (aka. "solvent" or "working fluid")	Inorganic compound that reacts with the salt in the SaltX Component. Special attention is given to ensure that this substance has minimal detrimental effects on the environment. Typical substances used are water, methanol and ammonia.
Working couple	The combination of salt and refrigerant.
Heat Transfer Fluid	The Heat Transfer Fluid (HTF) is used to transfer or 'carry' thermal energy to and from the Sub-components. The HTF travels in circuits (loops) that are physically separated (by a wall) from the internals of the sub-component that house the salt and/or refrigerant.
Heat Exchange Interface	The Heat Exchange Interface (HEI) is the physical surface or wall where the heat exchange to and from the Sub-components and the HTM takes place. It is designed for high thermal conductivity offering the least resistance possible to the transfer of heat into and away from a given Sub-component and thus into and out of the salt, matrix and/or refrigerant within the vessel.

2.2 SELECTION OF WORKING COUPLE

The first steps in SaltX sorption Component design is to select refrigerant, salt, and matrix. The selection of a suitable working couple is a critical step during the design of the Component that will have direct effects on the Component performance and cost. The salt, refrigerant and matrix are selected based on SaltX's knowledge acquired in the past years of research and on the application requirements of the project.

2.2.1 Selection Criteria

The selection criteria for sorption systems are determined by the application requirements and take into consideration:

- *Available Heat Source Temperature* – is the temperature at which the sorption-process-driving heat source is available. Applicable sources could be waste heat from engines, solar heat or any other form of free, low-cost or unused high exergy thermal energy.
- *Coefficient of Performance (COP)* – this is the ratio of heat energy input from the process-driving heat source to the amount of useful cooling or heating energy recovered during discharge.

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- *Chilled Water Temperature* – is the temperature of the fluid that is required to meet the cooling load.
- *Available Heat Rejection (or Cooling Medium) Temperature* – is the temperature of the heat rejection medium. This temperature is usually determined by ambient temperature for air cooled systems, sea water temperature for marine application or ground temperature for ground-source (borehole) heat rejection systems.
- *Process Temperature Lift (ΔTeq)* – is the temperature difference between the salt in the reactor and the refrigerant temperature in the C/E (basic sorption process). This has specific maxima dependent on the working couple employed.
- *Operational Temperature Lift (ΔT)* - is determined by the available re-cooling (heat rejection) temperature and the required chilled water temperature to the load. In general, higher lifts require higher desorption temperatures and cause lower cycle COP. The operational temperature lift is usually lower than the process temperature lift due to the required heat transfer driving temperature difference between the salt and/or refrigerant in the vessels and the HTF. The maximum value of this parameter is influenced both by *ΔTeq* and sub-component heat transfer design.
- *Energy Density* – refers to the useful cooling or heating energy delivered by the sorption device per unit volume during discharge. Higher energy density tends toward smaller unit size as well as higher coefficient of performance (COP).

3   LMX Solution Development

SaltX LMX (Liquid Matrix) solution is the name given to a proprietary blend of salts and water which is some cases might be enhanced with nanoparticles. The LMX solution is developed to be inexpensive with high energy density, suitable for use with carbon or stainless steel.

SaltX has a portfolio of sorption materials and solutions that work under a plethora of different temperature and pressure conditions. SaltX has selected a specific sorption solution blend based on the requirements and objectives for the project considering the aforementioned selection criteria. The solution was then subjected to application specific development evaluations in order to optimise its 'recipe'.

3.1   DENSITY TESTS

Density testing was required to understand the change in this physical property when the LMX solution is concentrated and diluted as it can have an impact on the pumping performance and wettability of the solution in the heat exchanger. SaltX carried out laboratory tests both at its headquarters laboratory as well as its laboratory in Åland using raw materials purchased from different sources.

3.2   CRYSTALLISATION TEST

The LMX solution was tested at different temperatures to study its crystallisation temperatures. Samples solutions at different concentration levels were stored in sealed test tubes and jars and put in a thermostatic water bath set at a certain temperature (above 0°C). For additional testing, in order to reach low temperatures (below 0°C), glycol was used instead of water. During testing, the temperature of the water bath was increased in stages with each temperature setpoint kept for a few hours. After the test at the maximum water bath temperature setpoint was completed the water bath temperatures were decreased in stages repeating each setpoint. Observations during the crystallisation tests indicated that the temperature that the LMX solution became a crystal and the temperature that the crystal melted were quite different. An understanding of these points was critical in the determination of the operating concentration range of the LMX solution in the process and system design.

3.3 PRESSURE TEST

This test was to characterise the vapour pressure of different concentrations of the solution at different temperature levels. The LMX solution has lower vapour pressure than pure water because the salt in the solution binds to the water, which gives an equilibrium point at a lower pressure than pure water at a given temperature. The higher the concentration of salt, that is, a concentrated solution, the lower the vapour pressure and the higher its capacity for water uptake. The pressure ranges are important inputs to the process and system design

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4   Sorption Process Simulations

During the first 3 months of the project, simulation exercises were carried out to evaluate a potential system setup, dimension heat exchange surface areas required as well as investigate the thermodynamic properties of the sorption solution. The simulations were aptly carried out based on the two main phases involved in the operation of the absorption machine; desorption and absorption.

4.1   ABSORPTION MACHINE: BASIC CONCEPT

The absorption machine concept for this project was based on a concept developed and implemented as a test rig at the SaltX facility in Åland.
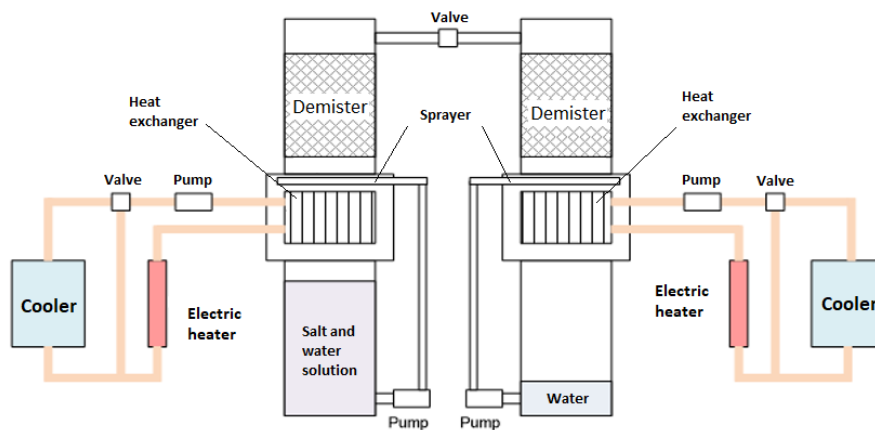

Figure 3 Sorption machine test rig

The test rig comprised two main vessels: a reactor and a condenser/evaporator (see Figure 3).

- The reactor was divided into three levels:
    - × The lowest level stored LMX solution.
    - × The heat exchange interface was located in the middle section
    - × The upper section housed a demister. The function of which was to remove any LMX solution entrained in the refrigerant vapour as it moved from the reactor to the Condenser/Evaporator.
- Similarly, the condenser/evaporator can be divided into three levels:
    - × The lowest level storing the refrigerant (water) in liquid form.
    - × The heat exchange interface in the middle section,
    - × The upper section also housing a demister which ensure no liquid refrigerant, only vapour refrigerant makes its way into the reactor during the discharging process.

The two heat exchangers transfer thermal energy from the working couple to the secondary fluid running in the external pipes. On the both sides, a cooler and an electric heater assist the charge and discharge process rejecting and providing thermal energy.

4.2   PROCESS DESCRIPTION

4.2.1   Charge

During charge thermal energy is transferred into the reactor (see Figure 4). The heat transfer medium, at high temperature, enters the heat exchanger inside the reactor vessel exchanging thermal energy with the dilute salt solution. The solution is pumped from the bottom of the vessel and sprayed over the heat exchanger to enhance the heat transfer.
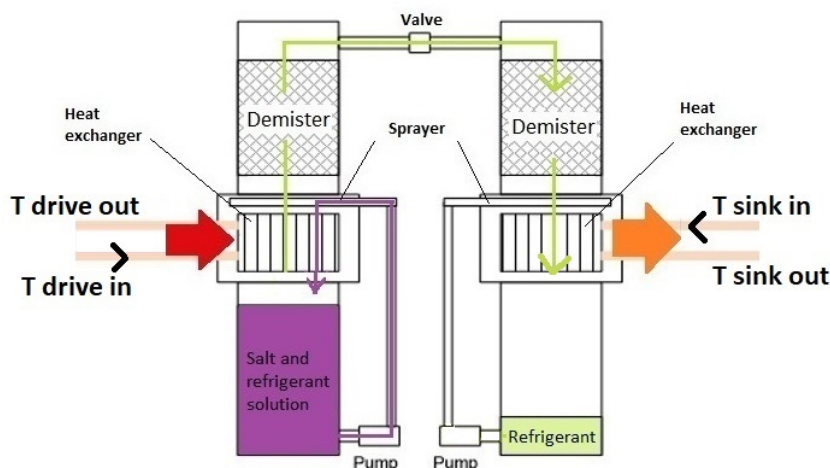

Figure 4 Charging process

Before falling to the bottom again, part of the refrigerant evaporates concentrating the LMX solution. The power and thus rate at which this concentration is affected by the speed of circulation of both the heat transfer medium on the inside and the

LMX solution on the outside of the heat exchanger as well as by the viscosity of the solution.

The vapour of refrigerant goes in the condenser vessel. Here it releases condensation energy to the heat exchanger located in the middle of the vessel and stored in liquid form in the lower part of the vessel.

The power on the reactor side is function of:

- Flow rate of fluids on both sides of the heat exchanger;
- temperature of the condenser.
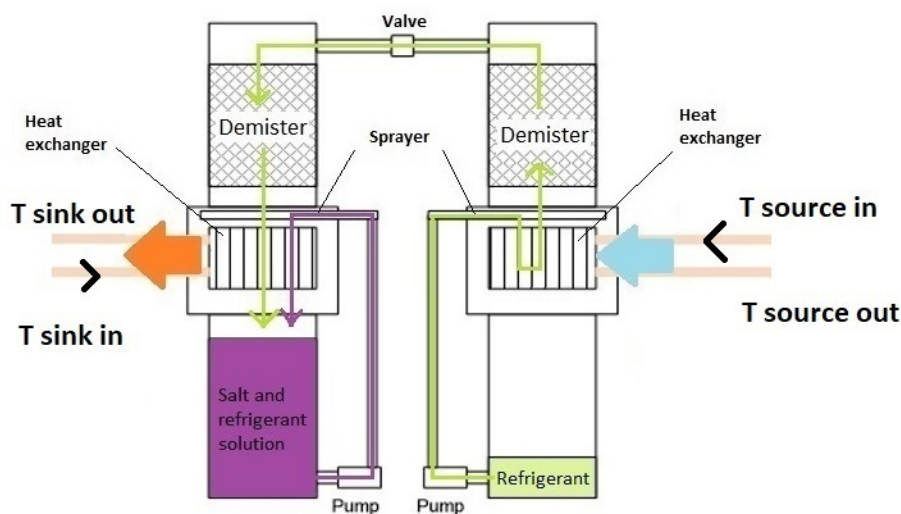
4.2.2 Discharge

Figure 5 Discharging process

During the discharge process the refrigerant evaporates from the evaporator creating a cooling effect. In order to create a better energy transfer, the refrigerant is constantly pumped and sprayed over the heat exchanger surface.

The refrigerant in a vapour phase will move to the reactor vessel. Here it will bind with the concentrated solution that is continuously sprayed over the heat exchanger. The recombination heat must be carried out via the heat transfer fluid. This is necessary, otherwise the reaction can't go further.

Even if the technology is based on a batch process, it is possible to obtain a continuous process coupling together two SaltX systems.

4.3 CHARGE PROCESS SIMULATION

The charge process involves the simultaneous removal of water (i.e. concentrating) of the LMX solution and the condensation and storage of said water. From a theoretical point of view, it is possible to estimate the energy fluxes involved in the desorption or charging process (Figure 6).
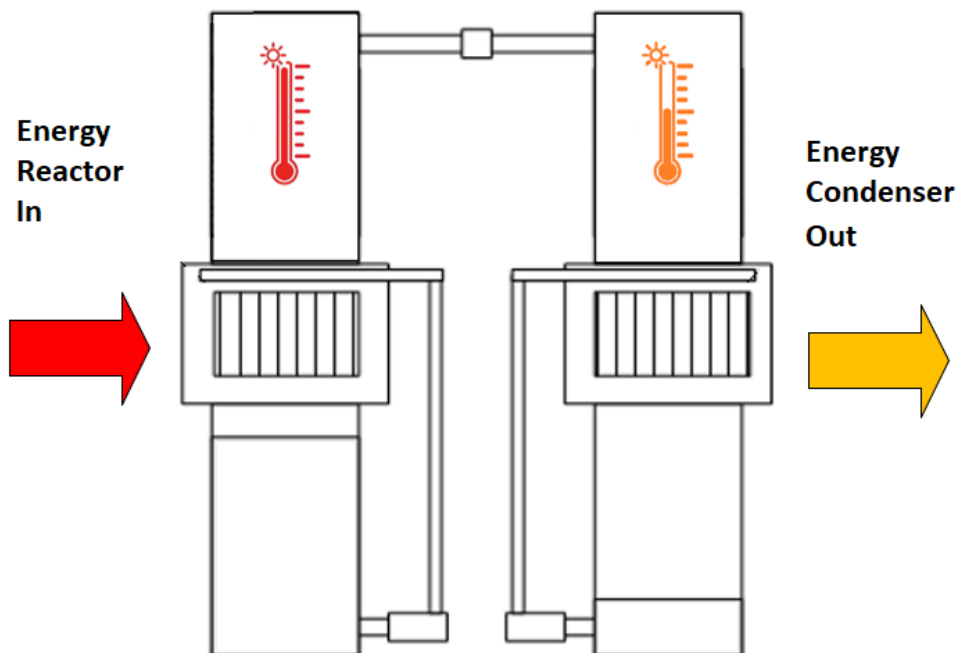
Figure 6 Charging process

These energy values are calculated under the following assumptions and simplifications:

- No thermodynamic irreversibilities are considered
- The temperatures used in the calculation refer to the chemical equilibrium
- The chemical energy has been assumed constant and it is based on experimental test conducted
- For 1 mole of salt, the process goes from 4 moles to 1.5 moles of water.
- The total charging process is carried out in discrete steps at the corresponding system pressure level (see Figure 7 and Figure 8)
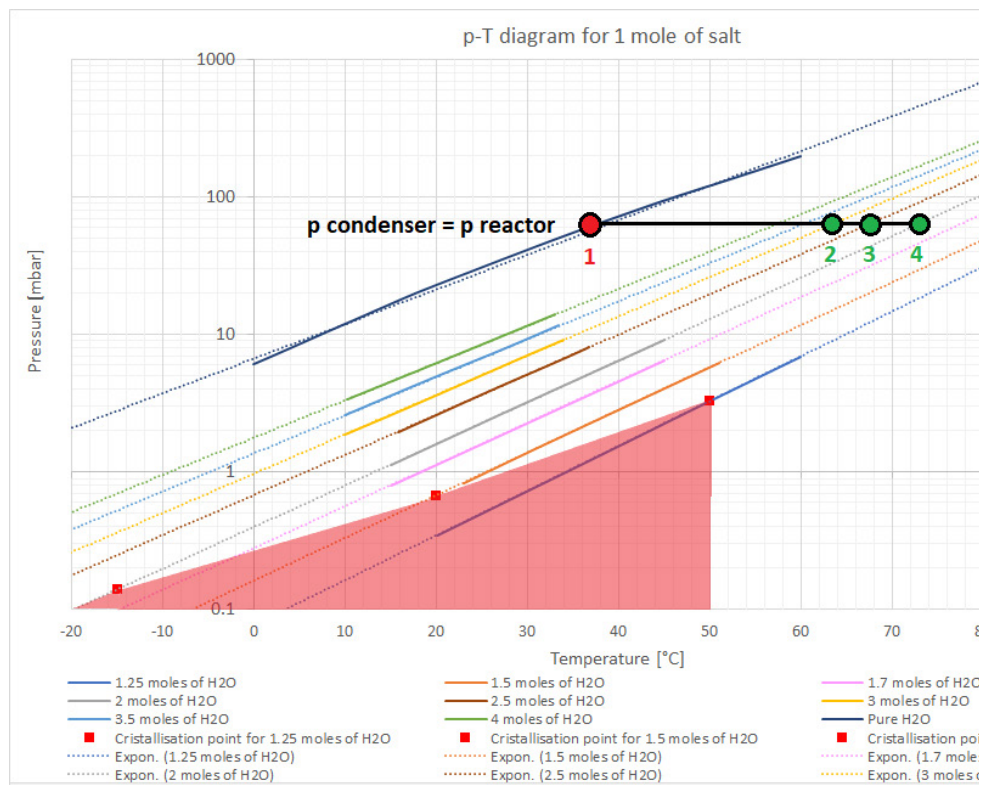
Figure 7 p-T diagram representation

Figure 8 Steps of the charge process on the p-T diagram

- The heat exchanger is large enough and the wetting is good enough to allow for full desorption to occur at a given step (e.g. from 2.5 to 2 moles)
- It is assumed that the solution is at the temperature required for desorption to occur
- Each step considers steady state conditions

4.4   DISCHARGE PROCESS SIMULATION

The absorption process involves the simultaneous evaporation of water from the evaporator and its absorption into the LMX solution causing it to become diluted. The energy fluxes involved in the absorption or discharge process are (Figure 9):
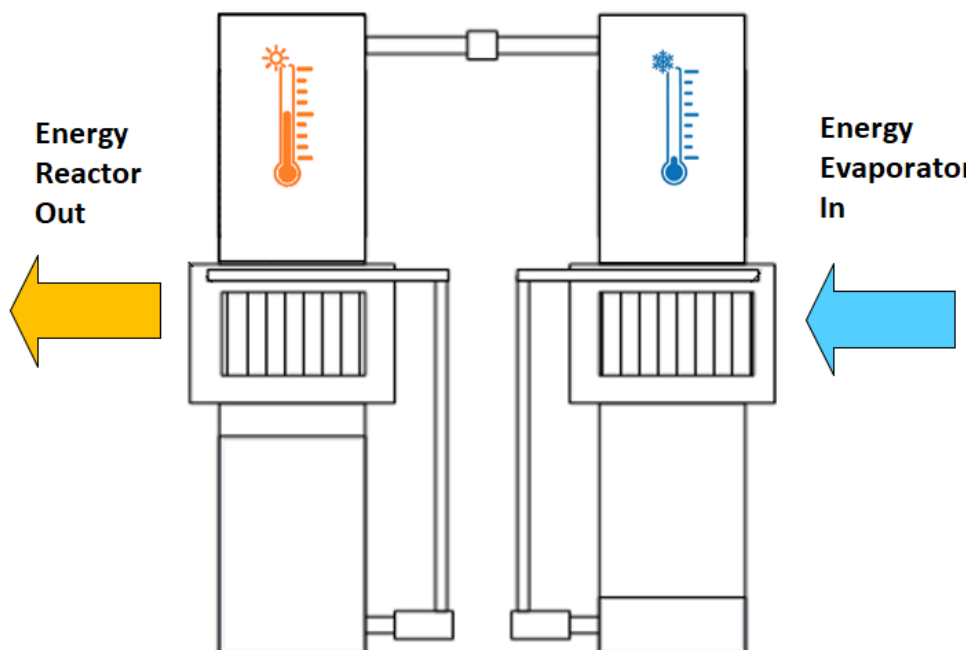

Figure 9 Discharging process

The energy values are calculated under these assumptions:

- No thermodynamic irreversibilities are considered
- The temperatures used in the calculation refer to the chemical equilibrium
- The chemical energy has been assumed constant and it is based on experimental test conducted
- The total absorption process considers discrete steps at the corresponding system pressure (see Figure 10 and Figure 11):
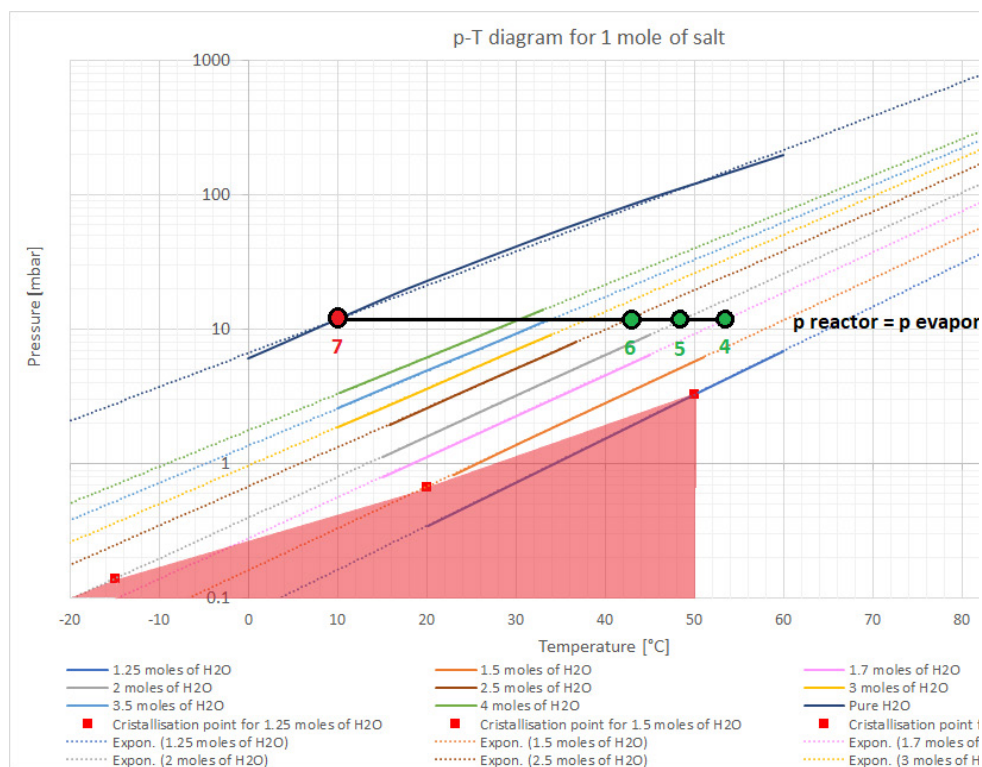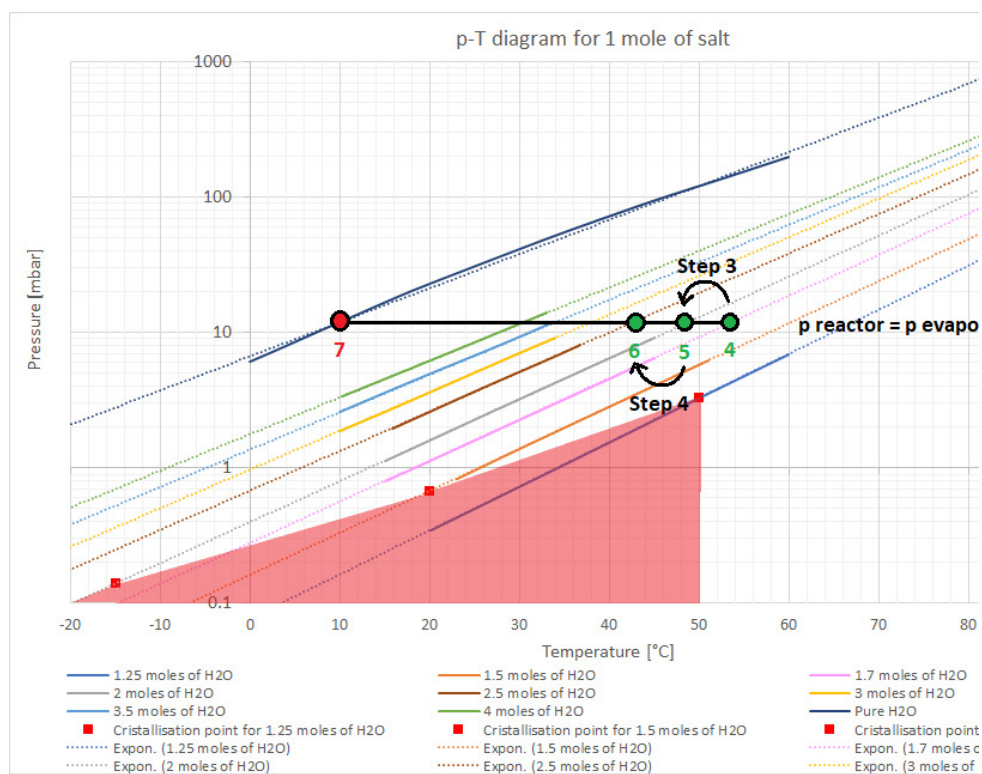
Figure 10 p-T diagram

Figure 11 Steps of the discharge process

- The heat exchanger is large enough and the wetting is good enough to allow for full desorption to occur at a given step
- It is assumed that the solution is at the temperature required for desorption to occur
- Each step considers steady state conditions.

4.5   PROCESS SIMULATION RESULTS

Process simulations were carried out using Microsoft Excel as well as Engineering Equation Solver (EES) (see Figure 12). Results from the simulations provided insight into the temperatures, flows, energies and heat transfer areas of the main components (i.e. condenser & evaporator) required for a 1 kW reactor design. The simulations were carried out for both the desorption (i.e. charge) and absorption (i.e. discharge) phases of the process. It was assumed that the results are linearly scalable for systems of larger capacities.

Figure 12 – Excerpt of Code for Engineering Equation Solver Simulations of Sorption Process

4.5.1   Overall process

For the overall process considering a (quasi) continuous operating process it can be seen that the process parameters considered would provide a coefficient of performance (COP) of 0.57 and 1.30 for the machine operating as a chiller and heat pump respectively. This COP could be improved with adequate heat recovery methods based on techno-economic system requirements.
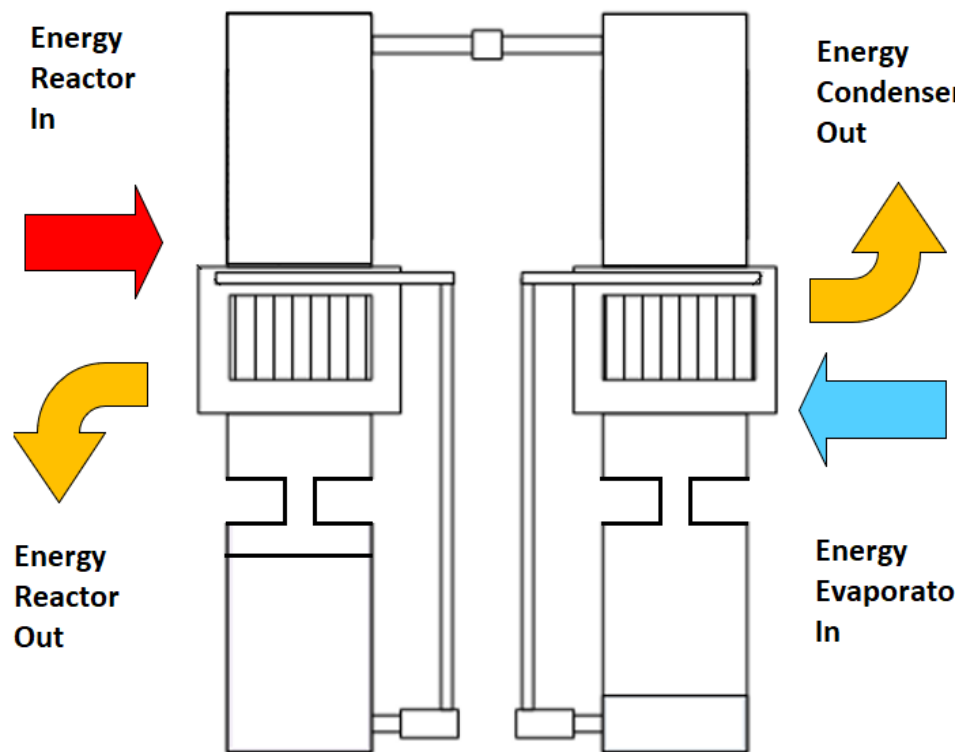
Figure 13 Overall energy balance

E warm up	0.02	kWh
E reactor in	0.29	kWh
E condenser out	-0.18	kWh
Total h	0.29	h
E cool down	-0.019	kWh
E evaporator in	0.18	kWh
E reactor out	-0.21	kWh
Total h	0.65	h
COP heating	1.30	-
COP cooling	0.57	-

5 Experimental Design

For the purposes of this investigative work test setups were designed and built to connect and measure fluid flows, temperatures and pressures of the various sorption system components. The main components included; reactor, condenser/evaporator and storage tanks. All the heat removal was done via heat exchangers with water as the cooling fluid, whilst inlet and outlet temperatures as well as flows were monitored.

Design Parameters	
Heat Source Temperature	70°C (Standard)
	100°C (Maximum)
Desired Coefficient of Performance (COP)	0.7
Chilled Water Temperature	7°C
Available Heat Rejection (or Cooling Medium) Temperature	30°C (Chiller mode)
	100°C (Heat pump mode)
Operational Temperature Lift (ΔT)	23°C

6   Experimental Setup 1

An experimental machine was designed and commissioned at the Mariehamn Energi plant in Åland. The experimental setup was based on the following main components:

- **Reactor:** based on the Aqua Blue Heat Exchanger developed by Alfa Laval. The unit comprises specific channel separations which allow for the desorption and condensation processes to occur simultaneously in a single channel. That is, a single compact Aqua Blue unit would be able to carry out the full charging process within its so-called process channels. The heat exchanger is such that plates can be added to the unit creating more parallel connected channels. This linearly increases the heat transfer area as per requirements of any given application. Conversely the channels of the Aqua Blue Heat Exchanger could also be employed to carry out the full discharging process, that is, absorption and evaporation processes within the heat exchanger channels. In experiments 10 plates were used corresponding to 5 process channels.
- **Storage tanks:** these were specifically made, vacuum tight tanks fused together. One tank housing the LMX solution and the other holding the refrigerant (water).
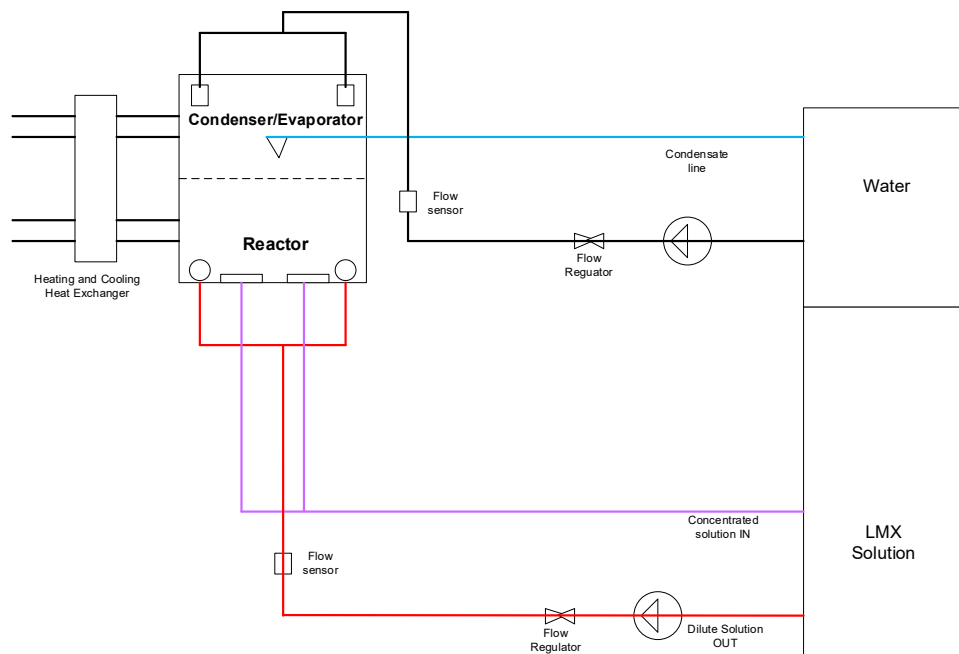

Figure 14 - Schematic illustration of Experimental Setup 1

6.1 TEST RESULTS

Tests were carried in the period from August 8, 2018 until August 30, 2018 with relatively poor results. During the test period a total 10 test days were achieved. Initial tests were carried out to verify the operation of the Aqua Blue unit based on its intended application for sea water desalination.

6.1.1 Desalination Tests

These tests were done with 70°C water to the unit with condensation temperature of 25°C this saw a desalination power of 25 kW at an operating pressure of 30 mbar (absolute).

6.1.2 Charge Tests

Employing a heat source temperature of 70°C and heat sink temperature of 25°C charging tests were carried out. This allowed for the LMX solution of be concentrated (i.e. charged) from 3 mol to approximated 2 mol water. Charging took approximately 10 hours over a period of 4 days with many starts and stops due to various control and system problems. A maximum charge power of 18.4 kW was achieved giving rise to heat rejection of 9.5 kW. This was significantly lower than expected charge power of 75 kW.

6.1.3 Discharge Tests

Experimental evaluations were carried out to evaluate the cooling capacity of the absorption machine when operating as a chiller. Tests were carried out at an absorber temperature of 30°C and a (desired) chilled water temperature of 7°C. Discharge tests were unsuccessful due to air infiltration into the Aqua Blue unit causing the process pressure to be too high to allow for adequate evaporation.

6.1.4 Discussion

The tests with the Aqua Blue unit as an off-the-shelf component provided by Alfa Laval showed that the unit was not sufficiently vacuum tight to achieve the high vacuum levels required for the evaporation of the refrigerant (i.e. water). For the evaporation of water to take place to provide the temperatures and chilling capacity desired for the absorption machine, a process pressure of less than 5 mbar is desired. This was however not possible to achieve in the tests at the Mariehamn facility.

Figure 15 - Photograph of experimental setup 1

7 Experimental Setup 2

Due to the poor results from the first experimental setup a revamp of the experimental unit was carried out. Considerations were made for the vacuum tightness of the Aqua Blue heat exchanger. Additionally recommended by Alfa Laval, the JWP Freshwater generator was used to carry out the discharge process which occurred at much lower process pressure than the charge process. The JWP deemed more vacuum tight, but less scalable in terms of thermal capacity compared to the Aqua Blue unit, was seen as a reasonable compromise.

The experimental set up basically consist of one charge loop and one discharge loop with common storage tanks for sorbent (i.e. LMX solution) and refrigerant. *Desorption processes* and *absorption processes* were performed separately in batches. A schematic illustration of the experimental set up is shown in Figure 14.
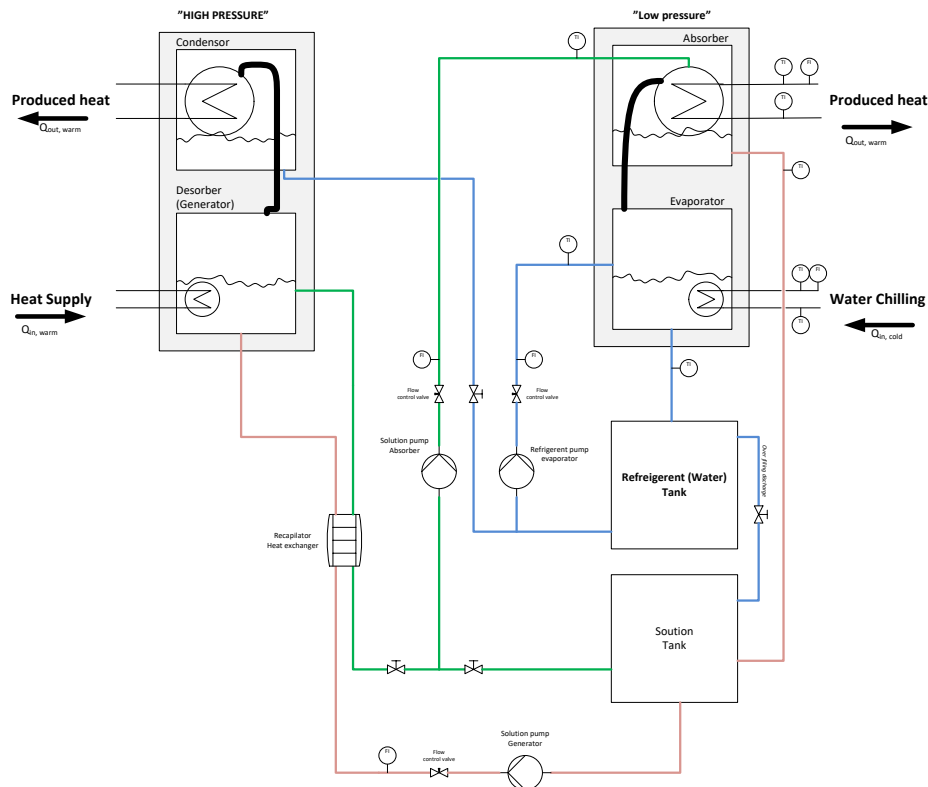

Figure 16   **Schematic illustration of experimental setup 2**

Figure 17 - Photograph of experimental setup 2

7.1 SUMMARY OF TEST RESULTS

The test performed has mainly been focused on the charge process where absorption and evaporation occur simultaneously.

7.1.1 Charge

Charging was carried out during early test rig conditions, and not all temperatures and flows were accurately measured. Given that previous tests discharging was the main challenge, due to time and resource constraint it was deemed necessary to focus on the discharge process. However, it was noted that approximately 30 liters of condensed water were produced during the charge process. The density of the LMX solution was measured correlating it to the molarity of 1.92 mol of water. With this molarity of the solution it was expected to produce about 37 liters of water. Various sources of error were considered and evaluated:

1. The final total volume of start solution (was less water added than stated in recipe?)
2. Measurement error of produced water volume due to poor calibration of the sight glass
3. Error in measured density
4. Error in density correlation

The test conditions of the first desorption run are summarized in Figure 14. A back calculation on water condensation enthalpy gives that the heating power in the desorbed was in the order of 1.7 kW (about 20.4 kWh of water was condensed during approximately 12 hours of operation).

It should be borne in mind that this first charge run was simply carried out to produce a "charged" LMX solution.
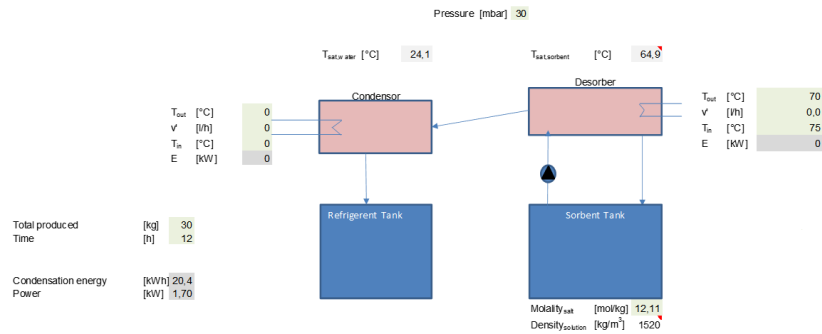
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Figure 18   **Summary of test conditions during first desorption run**

7.1.2   Discharge

Test was carried out during 2018-12-18. Before start, the JWP heat exchanger was evacuated from air and other incondensable gases to high vacuum pressure (about 10 mbar).

This first test performed was carried out as "quick and dirty" and the not in any case we can state that the system was in equilibrium.

Test 1

The conditions after about 30 minutes of operation are shown in Figure 16. About 0.7 kW chilling was produced at the same time as the refrigerant was cooled by about 0.2 kW. However, it should be noted that chilled water temperatures are higher than design/desired levels and heat rejection, that is, cooling water temperatures are lower than desired. Thus this case test case doesn't adequately fit the design conditions.
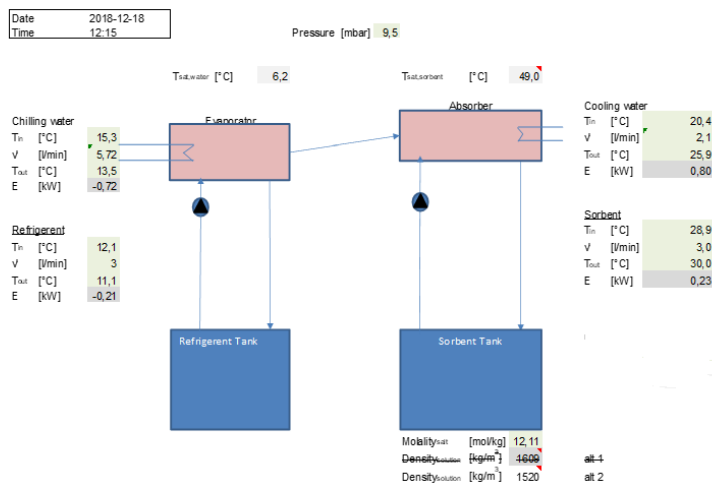

Figure 19   **Summary of results from first test 2018-12-18**

Test 2

Test set 2 showed after about 30 minutes of operation a chilling capacity of about 1.9 kW (see Figure 17). Chilling was produced at the same time as the refrigerant was cooled by about 0.1 kW. Again, this test case didn't adequately fit design conditions due to the high chilled water temperatures and low cooling water temperatures.
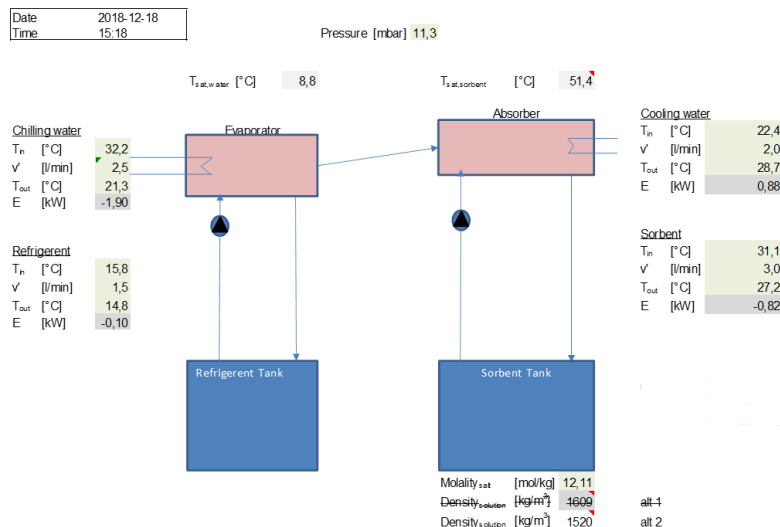

| Date | 2018-12-18 |
| Time | 15:18 |

Pressure [mbar] 11,3

$T_{sat,water}$ [°C] 8,8 $T_{sat,sorbent}$ [°C] 51,4

	Chilling water			Evaporator	Absorber		Cooling water		
T_{in}	[°C]	32,2				T_{in}	[°C]	22,4
$\dot{V}$	[l/min]	2,5				$\dot{V}$	[l/min]	2,0
T_{out}	[°C]	21,3				T_{out}	[°C]	28,7
E	[kW]	-1,90				E	[kW]	0,88

Refrigerent				Sorbent		
T_{in}	[°C]	15,8		T_{in}	[°C]	31,1
$\dot{V}$	[l/min]	1,5		$\dot{V}$	[l/min]	3,0
T_{out}	[°C]	14,8		T_{out}	[°C]	27,2
E	[kW]	-0,10		E	[kW]	-0,82

Refrigerent Tank   Sorbent Tank

Molality$_{sat}$	[mol/kg]	12,11	
Density$_{solution}$	[kg/m³]	1609	alt 1
Density$_{solution}$	[kg/m³]	1520	alt 2

Figure 20   Summary of results from second test 2018-12-18

Further Testing

Further testing was carried out between the period of December 18, 2018 and January 8, 2019 forcing the design condition temperatures by pre-cooling the chilled water loop. This still provided rather low cooling capacities of around 0.5 kW. This was significantly lower than the expected capacity of 1 kW at design conditions.

7.1.3   Discussion

In this round of experimental evaluations similar challenges to the first round were observed. Albeit, it was possible to discharge the absorption machine and produce a chilling effect. However, this chilling capacity was significantly lower than expected and was again shown to be due to inadequate vacuum tightness of the absorber and desorber components of the absorption machine. Other challenges with the distribution, flow and control of the LMX solution and heat transfer fluids were also observed. Although the JWP unit was found to be more vacuum tight and thus provide better performance than the Aqua Blue unit when employed as an absorber it was still not suitable to meet the requirements of the application at hand.

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8   Discussion

The current project has been devised with a set of highly ambitious targets which, during execution were not possible to achieve. The goals for both the sorption substance, the SaltX LMX as well as the compact plate heat exchanger are squarely on the limits of thermodynamic possibilities requiring a significant level of optimisation and integration of both. The very low design driving temperature of 70°C coupled with the relatively low chilled water temperature requirement of 7°C requires a large temperature lift of the absorption machine and high-power density with high refrigerant flow volumes which is a challenge for the compact plate heat exchanger. Storage capacity of the machine and well as performance in heat pump mode were not investigated given the poor performance of the machine. Consequently, no design for an upscaled unit was considered.

Based on the outcomes of the project, a more integrated approach to the development of a compact plate heat exchanger for this specific application is required. In this case, the issue of vacuum tightness of the unit would be considered at the design stage giving rise to better fit for absorption machines that employ water as refrigerant.

9   Conclusions

The ambitious goals of the project were unfortunately not achieved as manifested by the poor performance of the prototypes tested. It can be concluded that the 'off-the-shelf' heat exchangers employed as the key components, namely the absorber and desorber of the absorption machine do not meet the requirements for operation. Since water is used as the refrigerant in the absorption machine, high vacuum levels need to be achieved thus vacuum tightness is critical for system operations. These devices are not capable of maintaining the level of low pressure and low infiltration necessary for the current absorption machine concept. A plate heat exchanger specifically designed for this purpose would be required.

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PRE-PILOT: ABSORPTION MACHINE WITH INTEGRATED ENERGY STORAGE

Att kunna uppgradera låggradig värme till höggradig eller till kyla intresserar flera energibolag och förväntas bli allt viktigare i framtiden med lägre temperaturer i fjärrvärmenäten och en större efterfrågan på kyla.

Att också kunna lagra energin för att använda när behovet är som störst skulle adderar ytterligare nyttor, exempelvis ett minskat behov av investeringar i distribution- och produktionsanläggningar. En fungerande absorptionsmaskin skulle kunna användas i fjärrvärmenät för att erbjuda decentraliserade fjärrkylcentraler, i processindustrier och på fartyg som använder spillvärme från stora marinmotorer.

Här har man undersökt om en absorptionsmaskin baserad på konventionell värmeväxlarteknik och en saltlösning för energilagring kan fylla de här behoven.

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