Final report

1. Project details

Project title	District Heating used for decentralized cooling
File no.	64019-612
Name of the funding scheme	EUDP
Project managing company / institution	STAC Technology ApS
CVR number (central business register)	37988952
Project partners	Brayton Energy LLC
Submission date	15 November 2022

Figure 1 - 250 kW cooling plant placed at Varde district heating

2. Summary

Through discussions with stakeholders in the district heating (DH) ecosystem, it was decided to apply for funds in the EUDP programme for the development of a novel chiller operated with low-temperature heat that uses only water-as-refrigerant. This project was completed in partnership with Brayton Energy, who specializes in gas-turbines and turbo-compressors, and the DH utility in Slagelse as the initial test site host.

The project has two primary technical objectives:

- Design and fabrication of a 250-kW turbo-compressor
- Implementation of a 250-kW cooling unit coupled to a DH network

The cooling plant has been assembled and completed in Esbjerg and tested at a DH plant in Varde. The results from that test are:

- A world first thermally driven water vapor turbo-compressor has been designed and fabricated.
- A water chiller has been installed at the DH plant in Varde, showing direct evaporation using the provided district heating water.
- Constant throughput flow of hot water in the chiller was achieved and generating steam to spin the turbine.
- The maximum achieved spin speed was 10.000 RPM, which is less than 1/3 of the design target, hence no usable compression for cooling was achieved.

From this work STAC Technology has secured valuable know-how in designing and producing the chiller and its subcomponents. The boundary conditions for completing the planned test were too narrow at the period of reaching testing capabilities.

Dansk Resume:

Gennem drøftelser med interessenter i fjernvarmeøkosystemet blev det besluttet at ansøge om midler i EUDP-programmet til udvikling af en ny kølemaskine drevet med lavtemperaturvarme, der kun bruger vand-som-kølemiddel. Dette projekt blev gennemført i samarbejde med Brayton Energy, som er specialiseret i gasturbiner og turbokompressorer, og fjernvarme forsyningen i Slagelse var tænkt som den første vært for test-sted.

Projektet har to primære tekniske mål:
- Design og fremstilling af en 250 kW turbokompressor
- Implementering af en 250 kW køleenhed koblet til et fjernvarmenetværk

Køleanlægget er blevet samlet og færdiggjort i Esbjerg og testet på et fjernvarme-anlæg i Varde. Resultaterne fra den test er:
- En termisk drevet vanddampturbokompressor er blevet designet og fremstillet.
- Der er installeret en vandkølingsanlæg på fjernvarme-værket i Varde, som viser direkte fordampning ved brug af det leverede fjernvarmevand.
- Konstant gennemstrømning af varmt vand i køle-enheden blev opnået og genererede damp til at rotere turbinen.
- Den maksimalt opnåede omdrejningshastighed var 10.000 RPM, hvilket er mindre end 1/3 af designmålet, og derfor blev der ikke opnået nogen brugbar kompression til køling.

Fra dette arbejde har STAC Technology sikret sig værdifuld knowhow inden for design og produktion af køleren og dens underkomponenter. Grænsebetingelserne for at gennemføre den planlagte test var for snævre i perioden for opnåelse af testkapaciteter.

3. Project objectives

In this project the main objective has been to demonstrate decentralized cooling of a 250-kW capacity by using district heating as a heat source. The project has had two major technical tasks:

- Design, develop and fabricate a 250-kW turbo-compressor combining both radial and axial turbine technology.
- Implement and demonstrate the 250-kW cooling unit coupled to an operational district heating network.

The STAC Technology cooling system utilizes low temperature thermal sources to generate steam. By having an internal vacuum, water evaporates much below 100 °C, which is possible when all air is removed from the system. The steam drives a turbine mechanically connected to a compressor. The compressor generates a vacuum evaporating water at the temperature desired for cooling. Water is used as refrigerant and driving media making the installation non-toxic and environmentally safe. The compressed steam (100+°C) transfers its surplus energy to the incoming hot water which reuses the energy to drive the expander, resulting in very high system efficiency. By transferring the excess heat to the evaporated steam, the temperature increases resulting in superheated steam, which ensures expansion process by dry steam only. By having superheated steam, the expansion process will not lead to condensation in the turbine. Otherwise, the turbine will be destroyed in a relatively short time.

From interviews with several district heating utility companies, it has been expressed that an alternative solution to district cooling or centralized cooling was desired, hence this solution enabling the use of already installed infrastructure was proposed as decentralized cooling aimed at buildings coupled to the district heating grid.

Expansion process:

The hot water from the district heating grid is ~~pumped~~/passed into an evaporator at low pressure (0,5 bar, absolute), where the low pressure makes the water boil. The generated steam is led into the turbine, but the steam is only so-called ‘wet steam’. The wet steam will condensate instantaneously and cavitate in the turbine when the pressure and temperature drop during the expansion. To avoid this occurring the system needs to run at temperatures above the boiling point, the generation of the superheated steam is provided from the compression process via heat exchange.

Compression process:

The steam is separated from the water in the evaporator that is returning from the cooling ventilation system. The water has absorbed energy from the warm air in the cooler. In the evaporator, steam is allowed to escape the water, which will boil at a low temperature made possible by very low pressure. The compressor removes the steam enabling a continuously running cooling process. The cooling process is similar to that of any traditional electrically powered air conditioning unit, but in contrast STAC Technology uses water in both the hot and cold thermal loops. When the generated steam exits the compressor, that compressed steam contains more energy and possesses a higher temperature. The excess energy and temperature are used to heat the steam in the expander turbine loop. Therefore, at steady state the heat exchange ensures a steady flow of only superheated steam, thereby enabling the turbine blades to have a long-expected lifetime. The two thermodynamic loops are separated with no material exchange. They are only exchanging energy as has been described in STAC’s patent application. The developed evaporation process and design has also been subject for an additional patent application.

Turbo-compressor design:

It was decided that the finished plant, hence outlining the specification envelope of the turbo-compressor, should be able to function all over the world. STAC's cooling plant takes into account future climate challenges, including in particular;

- rising ambient global temperatures driven by climate change
- relative energy intensity of conventional high-capacity cooling plants
- scarcity of renewably generated energy.

The plant was then specified to the following conditions:

1. Delivery of cold water to Air Conditioning at a temperature not exceeding 7 °C
2. Condensation should be able to take place under normally known and future temperatures
3. The energy consumption to operate the plant should be able to be obtained from either:
    I. From waste heat in the district heating network (surplus production in summer)
    II. From waste heat in industry
    III. From thermal energy obtained from the earth (geothermal)
    IV. From solar heating with regular non-focused thermal solar collectors.

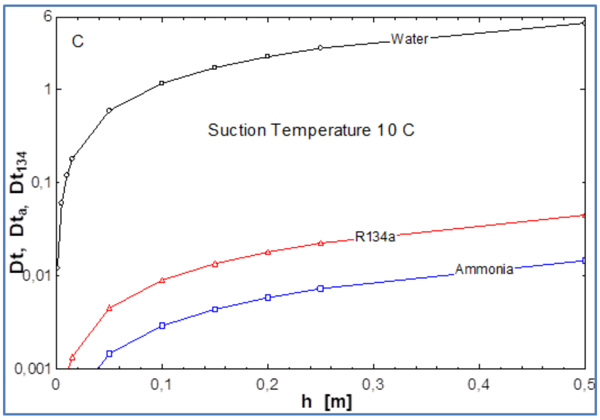
This led to the following conclusion and specification:

The compressor of the refrigeration system must necessarily be driven by an expander which can convert the energy content of hot water/steam into mechanical energy and rotate the compressor.

To reduce the mechanical losses, the expander and compressor are connected on the same shaft. Also known as a "Boot Strapped" connection.

Compressor		
Evaporation	7 °C	1,0 kPa
Condensation	45 °C	9,6 kPa
Cooling capacity	250 kW	
Pressure ratio	1:11,5	
Expander		
Minimum evaporation	67 °C	27,4 kPa
Minimum hot water source	72 °C	
Condensation	45 °C	9,6 kPa
Pressure ratio	1:2,85	

Furthermore, evaporators for both the hot and cold cycles had to be designed to match the above-mentioned criteria. The physical properties of water indicate that evaporation only takes place from the surface? of the water column, due to the poor thermal conductivity of water, this in turn means that no evaporation takes place below a certain depth. The evaporator must therefore be designed in such a way that the water column is only a few mm high and that the flow as far as possible becomes laminar, Re <2700. Or the evaporator is designed in such a way that a mechanical circulation of the water occurs.



Comparison between the three refrigerants Ammonia (NH_3), R134a and Water, the latter will evaporate, not boil.

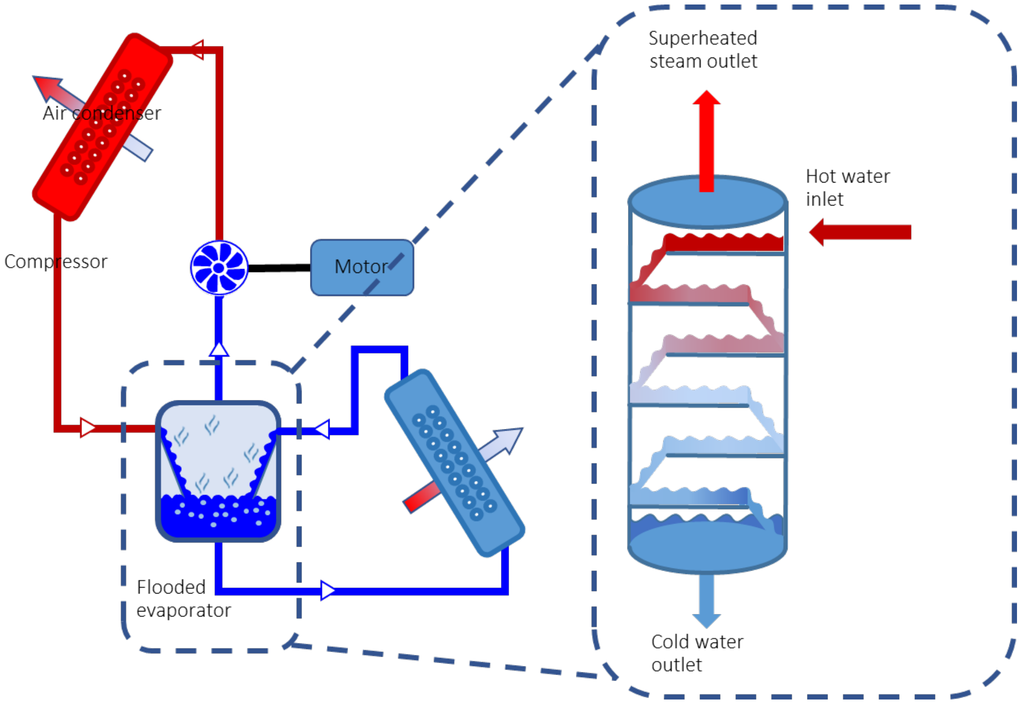


Figure 2 Example of flooded evaporation

4. Project implementation

The project started 1st January 2020 with a kick-off meeting at STAC Technology ApS, with project partner Brayton Energy participating online. As such the project was just gaining momentum when COVID-19 changed everyday life to a completely new paradigm and created a set of unforeseen obstacles and barriers. The progress of this project was indeed affected but the combined teams have persisted to produce a positive outcome.

Just prior to COVID-19, STAC Technology visited Brayton Energy to coordinate the planned work in WP2, as well as to resolve technical tasks already present. Teknologisk Institut was contacted to align expectations and conditions for a possible engagement as partner in this project. At the time it was thought that integrating a previously developed technology could help accelerate the program. This was shown though not to be an option. Both STAC Technology and Brayton Energy limited their in-person work for all employees during the pandemic and work-from-home arrangements and practices had to be established. This new paradigm for all parties led to some misinterpretations in the early part of this project. As new pandemic routines set in and we collectively gained experience with digital-only communication, STAC and Brayton established a virtual meeting cadence that ensured strong progress against identified project milestones.

The delivery of the turbo-compressor was delayed as both Brayton Energy and their subcontractors were limited by pandemic restrictions. Both financial and project planning issues were identified and mitigated. As quotes on subcontracting returns, we could accurately compare with the project budget.

It was decided that production of the turbo-compressor developed by STAC and Brayton should be transferred from the USA to Denmark, to give us greater 'hands-on' control of the supply chain. Simultaneously, we requested a reallocation of funds to the project to reflect the change in production and the progress of the project in regards to manhours and personnel. STAC Technology has been on a physical visit to Brayton Energy to discuss details of this process as it has proved to be troublesome to manage. Additional trips to Brayton Energy by STAC Technology have been required as the transfer of turbo-compressor manufacturing has been substantially more challenging than expected.

The pandemic amplified the impact of any delay, making even small issues sometimes very costly in terms of time and economic effect. The second-order pandemic related impact to supply chains across industry has also played a role in increasing the cost and lowering the availability of critical materials.

Subcontracting of the fabrication tasks has been completed through a selection process based on quotations and expected capacity. The manufacturing of the rotor parts of the turbomachinery was given to CS Techcom ApS in Hedensted, Denmark. The casting of the turbomachinery housing and volutes was given to Fonderia Augusta S.r.l. in Costa di Mezzate, Italy. Electronics and control system were acquired by EL:CON A/S in Hornslet, Denmark. Evaporators and condensation units have been produced by Eurotank A/S in Aarhus, Denmark.

Figure 3 Components for housing parts produced in Italy

The volutes of the turbo-compressor were casted in stainless steel. The housing was casted as well by Fonderia Augusta and STAC did perform inspection visits to ensure progress.

Prior to starting the project, a risk had been identified as the placement of test partner and site. In the original project proposal SK Varme in Slagelse had agreed to facilitate test of the chiller pilot. STAC Technology and

SK Varme have had successful testing of this technology prior to this project. As this project progressed and hit delays do to the above mentioned COVID-19 situation timing with SK Varme became mismatched. STAC immediately sought a new testing partner. Among others DIN Forsyning based in Esbjerg found the project interesting and offered their support.

Description of the test site: During the Fall of 2021 it was together with DIN Forsyning decided to establish a test side in connection with the district heating booster station at Brolæggervej 2 in Varde. The heating station has a capacity of 20 MW mainly provided by two natural gas boilers. The primary production of district heating for DIN Forsyning is delivered by Ørsted powerplant and Energnist waste incineration plant in Esbjerg and then distributed to Varde by DIN Forsyning. Two potential risks were identified and evaluated at the initial decision regarding placement. Firstly, as the return water is used for condensation in the power plant, there are strict regulation of the temperature of the returned water. DIN Forsyning would not accept to receive the not evaporated hot water, hence it was not possible to test or prove the full business potential of the proposed technology. The technical scope of the project was prioritized as proof of business could be derived indirectly afterwards. The second risk identified and evaluated was the site hot water capacity. It was found that dimension of the piping with corresponding water flow would just be sufficient with normal operation temperatures of 72 °C. As assembly and test was planned during normal heating season and operations, this risk was considered as a technical risk, that was acceptable even though it was vulnerable towards sever delays (more than 6 months).

As assembly of the pilot was commenced having all components present its progress was monitored and evaluated on a weekly basis. The chiller plant was connected during the end of August 2022 and district heating water was directly used for the first time ever in a chiller plant like this. One major discovery was the massive fluctuations in pressure/flow of the delivered hot water. Therefore, the entire chiller plant could be flooded in less than a minute and the response time from sensors and pumps just could not respond fast enough to avoid this. The piping of the water source had to be redesigned, reconstructed, and installed, including new valves, to delay the effect of sudden increase in water flow. Again, this caused further unforeseen delays. All the water pumps need to be driven by frequency converter.

The flow of water entering the chiller has been managed as to achieve constant levels and turbo-compressor has been spinning. The overall project delays have pushed the test period outside normal operational season of the district heating grid. The forward temperature of the water delivered to the booster station has lowered to below 55 °C and this is critical as the thermal power capacity is no longer enough to run the turbine at sufficient speeds. As the booster station is using natural gas it is not feasible with current energy pricing to increase to the water temperature merely for performing a test run. Neither STAC Technology or DIN Forsyning have had any chance to foresee these entangled consequences of energy prices dramatical increase, a warm Fall (extension of shut down period) and the amount of small setbacks.

5. Project results

The first main objective of this project was achieved, the development of a novel turbo-compressor to use for the demonstration of a 250-kW water-as-refrigerant cooling plant utilising district heat as the energy source. The thermal capacity available for demonstrating 250 kW of cooling capacity was not present. The chiller was installed and used all thermal energy available resulting in reaching below 1/3 of the needed spin speed, hence no meaningful vapor compression or cooling was achieved.

Turbo-compressor:

From the design envelope delivered by STAC Technology, the actual development was performed by Brayton Energy. The work included overall design considerations, aerodynamic flow and rotor analysis. Several material designs were considered. From the stress analysis aluminium was discarded resulting in the project focusing on the usage of stainless steel and titanium.

To complete the aerodynamic flow analysis Brayton Energy completed the final specification on the turbomachinery as shown in this table.

symbol	details	units	original inputs	Case 1	Case 2	Case 3
TDWH_in		˚C	**72,0**			
TDWC_in		˚C	**40,0**			
Tevap	Tevap = T1 = T7	˚C	**7,0**			
Tboiler	Tboiler = T9 = TDWH_out	˚C	**67,0**			
T_SC1	T_SC1 = TDWC_out,SC1	˚C	**45,0**			
T_SC2	T_SC2 =T5 =T6 = TDWC_out,SC2	˚C	**45,0**			
eff_poly_comp			**80,0%**			
eff_poly_turb			**80,0%**			
eff_HX	eff_HX = (T2 - T3) / (T2 - T9)		**90%**			
ΔT_{apprch}	ΔT_{apprch} = T4 - T_boiler	˚C	**4,0**			
Δp_{2_3}	$\Delta p_{2\_3} = (p_2 - p_3) / p_2$		**2,0%**			
Δp_{3_4}	$\Delta p_{3\_4} = (p_3 - p_4) / p_3$		**2,0%**			
Δp_{9_10}	$\Delta p_{9\_10} = (p_9 - p_{10}) / p_9$		**2,0%**			
W_{bngs}	fraction of turbine power		**2,0%**			
Q_{cool}		kW	**250**			

The compressor stages underwent considerable investigation to reach optimal performance with several iterations ranging from two radial stages, hybrids having both radial and axial stages even also considering an eight-stage axial solution.

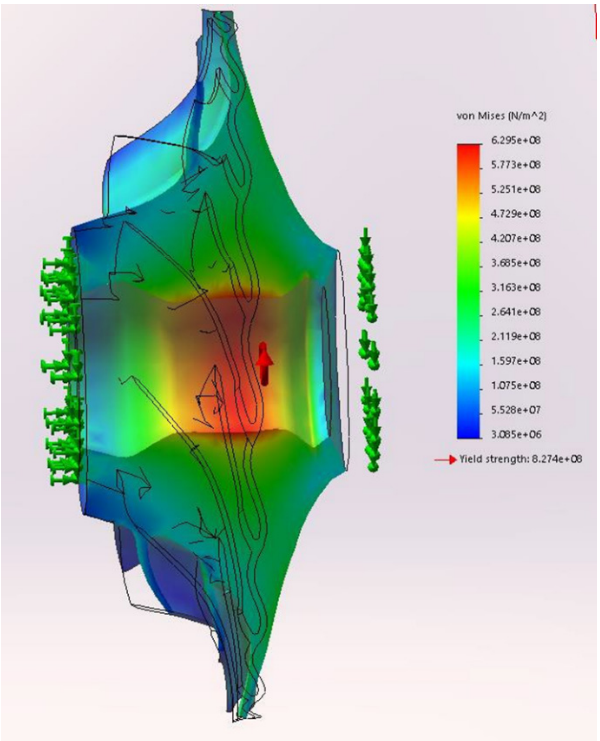


Figure 4 Stress analysis on radial compressor part

Stress analysis on a radial compressor stage with the following results:

- 32,000 RPM
- Ti-6AL-4V, 90mm bore
- Weight: 20kg
- Max stress: 630 MPa (74% yield)

Brayton Energy has performed a series of *in-silico* simulations to have the aerodynamics and the mechanics converge with the desired efficiency and performance. From Teknologisk Institut it is claimed to have an isentropic efficiency of more than 80%. Brayton has calculated 22 iterations achieving a minimum of 67% in efficiency. It is expected that the 13% difference in calculated efficiency may be explained in the compressor capacity of 2-MW and 250-kW, respectfully. Furthermore, the calculated 80% is only taking into account the first stage and not the entire unit.

The fabrication of the turbo-machinery was chosen to be done by CNC milling of the internals as being rotors and stators. The housing and volutes are being cast in stainless steel. Visits have been done to subcontractors to continuously adjusted to accommodate changes/ questions to the original construction drawings as well as regular physical inspections of the unit. This process has been performed jointly by Brayton and STAC.

The choice of stainless-steel grade for optimal compressor performance has also contributed to unexpected challenges during the production and milling process. Firstly, the raw material has been very difficult to source with longer delivery lead times as a result. Secondly, the mechanical properties of the material have made very rough on the tooling with machine tools abruptly splintering as a result (instead of foreseeable wear-and-tear that would be expected). As a result, the material choice will be reevaluated for future compressors.

The housing and volutes are cast in stainless steel which has also contributed to delays on account of material sourcing challenges. In addition, the housing experienced a significant setback when some parts cavitated during the casting process. Several parts have had to be further inspected for tolerance issues. Casted parts were delivered to CS Techcom for assembly of the turbo-compressor in early April 2022.


Figure 5 Expander / Compressor at mounting

On the left is shown a picture of the assembled turbo-compressor. The rotors and stators are placed inside after the final balacing.

A test bench had to be manufactored for assembly of the stages on a level axis. The balancing of the rotating elements were done prior to placement inside the turbo-machinery housing.

The housing was designed to enable top-down installation in contrast to end-to-end. Thereby the established balancing is readily transferred to the final assembly.

Each rotor wheel was milled in forged stainless-steel alloy at CS Techcom. Here, a finished rotor is inspected after milling.


Figure 6 Inspection on finished rotor part

Evaporator:

The task of designing the evaporator for the cooling cycle in the STAC system is firstly based on the mass and energy balances from the EES model describing the entire STAC coupled system. One major concern is the presence of droplets inside the compressor, that is water particles as liquids. If present, these water particles will:

- Lower the efficiency of the compressor
- Allow for cavitation on the compressor blades, resulting in blade surface rupture
- Carry solids or salts to the blade surface, resulting in an unbalanced disc and subsequent vibration

The design must lower the likelihood of droplets, contain enough flow of steam and water refrigerant and have minimal size. These considerations are backed by testing against multiple constraints from statistical physics.

Knudsen layer:

The Knudsen layer is the minimum thickness needed to perform evaporation. It is defined as the interface between water and steam, where the molecules co-exist in both states. The equation for this system is found to be:

$$L_K = \frac{k_B \cdot T}{d_m^2 \cdot p \cdot \pi},$$

L_k	Knudsen Length [m]	1.627e-05
k_B	Boltzmann constant [J/K]	1.380649e-23
T	Temperature [K]	280
d_m	Molecular diameter [m]	0.275e-9
p	Pressure [J/m^3]	1000

Resulting in a minimum layer thickness of 16 µm. This is not a practical thickness, but a lower limit. The energy needed for this evaporation must be delivered from the 1-dimensional water thickness below the Knudsen layer, which again is the minimum water height:

$$Q_{Heat-water} = Q_{Evap} \quad ,$$

$$m_1 \cdot C \cdot \Delta T = m_2 \cdot \Delta H_{Evap} \ \Rightarrow L_{water} = \frac{L_K \cdot \Delta H_{Evap}}{C \cdot \Delta T}$$

L_{water}	Minimum water layer [m]	0.0018 ~ 2mm
ΔT	Temperature diff. in water in-out [12-7 C]	5
C	Heat capacity at 7 C [J/kg K]	4194
ΔH_{Evap}	Enthalpy of evaporation [J/kg]	2328e3

To conclude, the minimum water layer thickness needed to supply energy enough to evaporate the Knudsen layer is approximately 2 mm.

Hertz-Knudsen speed:

From the Hertz-Knudsen relation it is possible to find the maximum evaporation flow. Firstly, we find the number of molecules escaping into the gas phase, then the evaporated mass:

$$J_{max} = \frac{p \cdot N_a}{\sqrt{2 \cdot \pi \cdot M \cdot R \cdot T}},$$

$$J_M = \frac{J_{max}}{N_a \cdot M},$$

J_{max}	Molecular flow [1/ (m^2 s)]	3.71e+25
M	Molecular weight [kg/mol]	0.018
R	Gas constant [m^3 Pa / K mol]	8.314
N_a	Avogadro's number [1/mol]	6.022e23
J_M	Mass flow [kg/s]	1.11

It was found that an upper limit of evaporation is 1.11 kg/s. From EES 0.106 kg/s is determined to be required for the cooling capacity needed, so we are well within range.

Droplet generation, formation and stability:

The formation of a droplet is defined by the Kelvin equation:

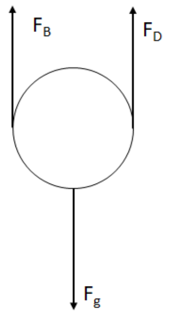
$$p_{in} = p_{out} + \frac{2\gamma}{r}$$

This equation may be rewritten as:

$$\Delta p = \frac{2\gamma}{r}$$

Δp	Pressure difference between the inside and outside of an interface [Pa]. P (7C) =1002, P (7.5C) =1037, P (12C) =1403, P(17C) =1938 and P(22C) =2645 Pa.	35 - 1643
γ	Surface tension [N/m]	$72.75 \cdot 10^{-3}$
r	Interface radius [m]	4.2 mm to 90 μm

When the hot refrigerant returns to the evaporator the water is not in equilibrium and will evaporate. This process may result in droplet formation and the radius of these droplets is governed by the ratio between the internal and external pressure (ΔP). Here it is assumed the pressure of saturation as being the pressure inside the droplet. The higher the inlet temperature of the water the smaller the droplets that are formed, as the droplet has more energy to form. In extreme circumstances, where inlet temperature ranges from 7.5 to 22°C. The latter is if we are having +5°C for a 17°C system. This results in droplet radii ranges from 4.2 mm to 90 μm. Smaller droplets are unstable and will aim to grow larger. If we assume a clean internal atmosphere no particles are present to become nuclei for the small droplets. Thereby formation and growth of small droplets are very unlikely.



In order for the generated droplet to escape the surface the particle has to be lifted by the compressor flow. It is a particle in a free flow situation and the working forces are drawn to the left. F_B is the buoyant force as some steam volume is occupied by the particle. F_g is the gravity force and F_D is the drag from the steam flow pulling the particle. From this an expression for the escape velocity is found:

$$v_e = \sqrt{\frac{4\,g \cdot (\rho_l - \rho_g) \cdot d}{3 \cdot C_D \cdot \rho_g}}$$

v_e	Escape velocity [m/s]	10.8-73.7
C_D	Drag coefficient [sphere]	0.47
ρ_g	Density of steam [kg/m^3]	0.042
ρ_l	Density of water [kg/m^3]	1000
g	Gravitation [m/s^2]	9.81
d	Droplet diameter [m]	180 - 8400 μm

With these calculations we may generate a scenario in which the likelihood of droplet generated from evaporation and then transferred to the compressor is minimized: From EES the steam flow is known, hence:

$$D_{min} = \sqrt{\frac{S_{com}}{v_e \cdot \frac{\pi}{4}}}$$

S_{com}	steam flow in compressor [m^3/s]	15.3458
D_{min}	Diameter of evaporator [m]	1.4 m

Graphically shown:

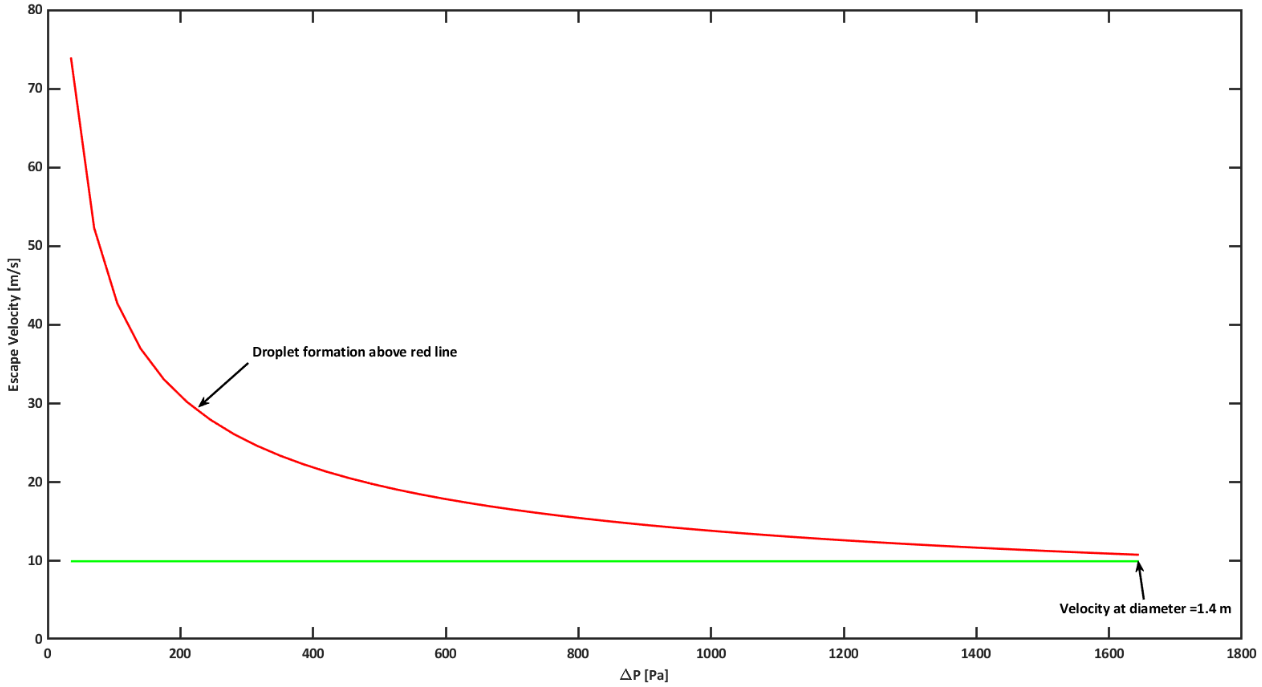


Figure 7 Calculation of dropless evaporation

So, by having the diameter of the evaporator at minimum 1.4 m, no potential particles will be able to escape the surface from which they have been generated.

Another way of generating droplets is from splashing water. The solution to minimize this effect is to maintain Laminar flow throughout the evaporator. From this the Reynold's number should be kept below 1.000.

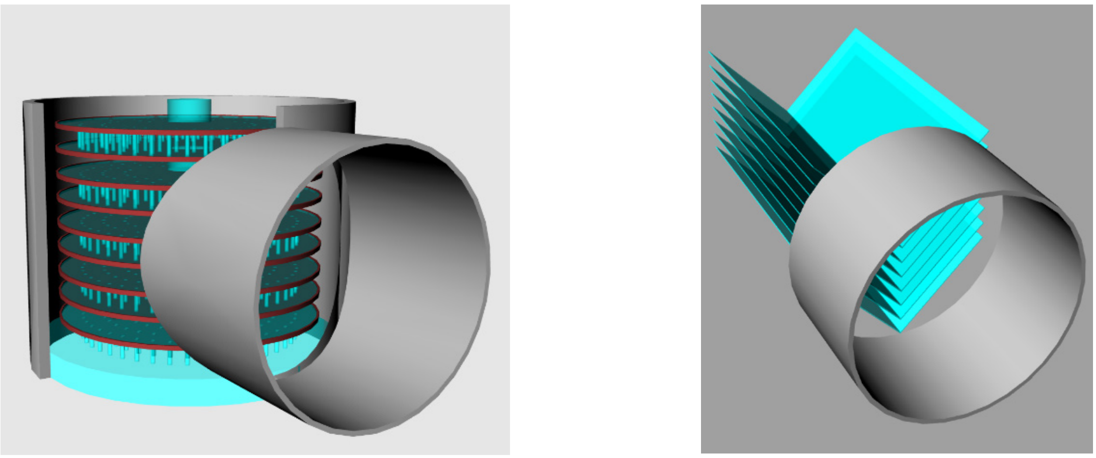


Figure 8 Design studies of evaporator. Several designs of the refrigerant flow were investigated. Laminar flow was the highest priority as the water was to slowly move along the plates for high surface area. From a combination of flow control and production readiness a version of two tilted plates was chosen.

Design:

From EES the waterflow through the evaporator is V_W=0.0122 m^3/s, with the optimal diameter for non-droplet generation leads to a water flow height, $h_w = \frac{V_w}{D^2_{min} \cdot \frac{\pi}{4}} = 7.9\ mm$. This is approximately 4 times the Knudsen water layer height. By installing 2 square plates for evaporation, the water height is set to 4 mm. The S_q ~1.25 m would be the side length of the plates. The minimum length from the Reynold's number is .11 m and calculating the Reynold's number with the chosen parameters equals:

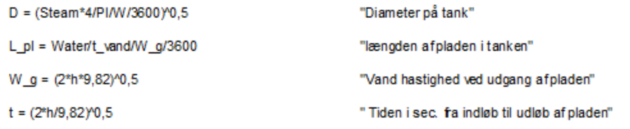
$$Re = \frac{V_w}{(S_q + h_w/2)} \cdot \frac{4}{\upsilon_w} = 94,$$

This number is well below the required 1.000 and ensures Laminar flow. By having two plates, the top plate may deliver its water in a manner to allow for having the 'hottest' water surface always being on top.

To further reduce the risk of droplets a knit mesh could be installed immediately after the evaporator. The piping connecting the evaporator and the compressor could be further heated by the steam exiting the super-heating procedure of the expander vapor. This would though allow for warmer steam to enter the compressor.

Suggested design: Main body is a pipe with a diameter of 1.4 m and with a length of 1.5 m allowing room for the knit mesh and two plates with side lengths of 1.25 m.

The actual final design of the hot and cold evaporators:



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D = (Steam*4/PI/W/3600)^0,5                "Diameter på tank"
L_pl = Water/t_vand/W_g/3600               "længden af pladen i tanken"
W_g = (2*h*9,82)^0,5                       "Vand hastighed ved udgang af pladen"
t = (2*h/9,82)^0,5                         " Tiden i sec. fra indløb til udløb af pladen"
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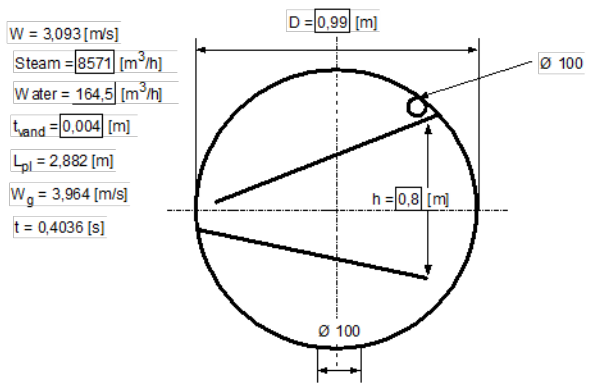
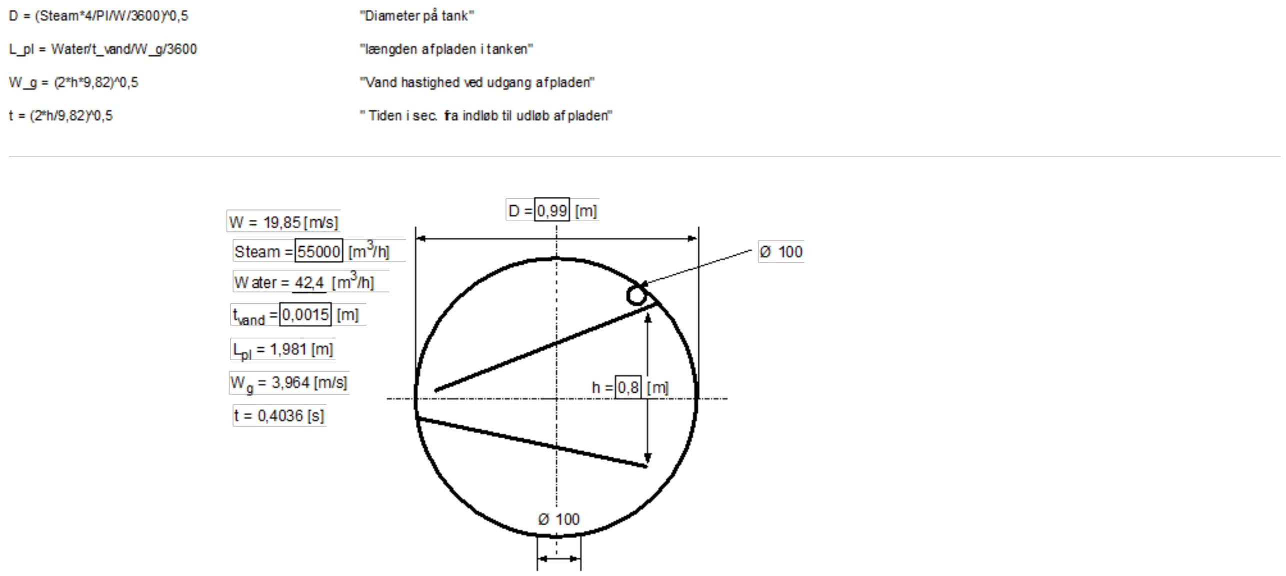


W = 3,093 [m/s]
Steam = 8571 [m^3/h]
Water = 164,5 [m^3/h]
t_{vand} = 0,004 [m]
L_{pl} = 2,882 [m]
W_g = 3,964 [m/s]
t = 0,4036 [s]
D = 0,99 [m]
h = 0,8 [m]



```
D = (Steam*4/PI/W/3600)^0,5                "Diameter på tank"
L_pl = Water/t_vand/W_g/3600               "længden afpladen i tanken"
W_g = (2*h*9,82)^0,5                       "Vand hastighed ved udgang afpladen"
t = (2*h/9,82)^0,5                         " Tiden i sec. fra indløb til udløb afpladen"
```

Figure 9 Actual and optimized evaporator design - dropless flow to expander / compressor

Condenser:

The condenser is designed as a spray condenser, where the cooling water is passed through a set of nozzles located at one end of a container, and the steam is conducted in counter current from the other end of the container.

Automation, controls, and plant regulation:

The controls have been developed to perform as follows:

a. Regulate the plant delivered capacity
b. Monitor compressor and expander to avoid critical failure

The plant has automated start-up procedures developed.

The input and output data are available on an installed touch screen, which also functions as regulation interface.

Prior to installation of the plant at DIN Forsyning test site, a thorough risk analysis according to ISO 12100-2010E has been performed.

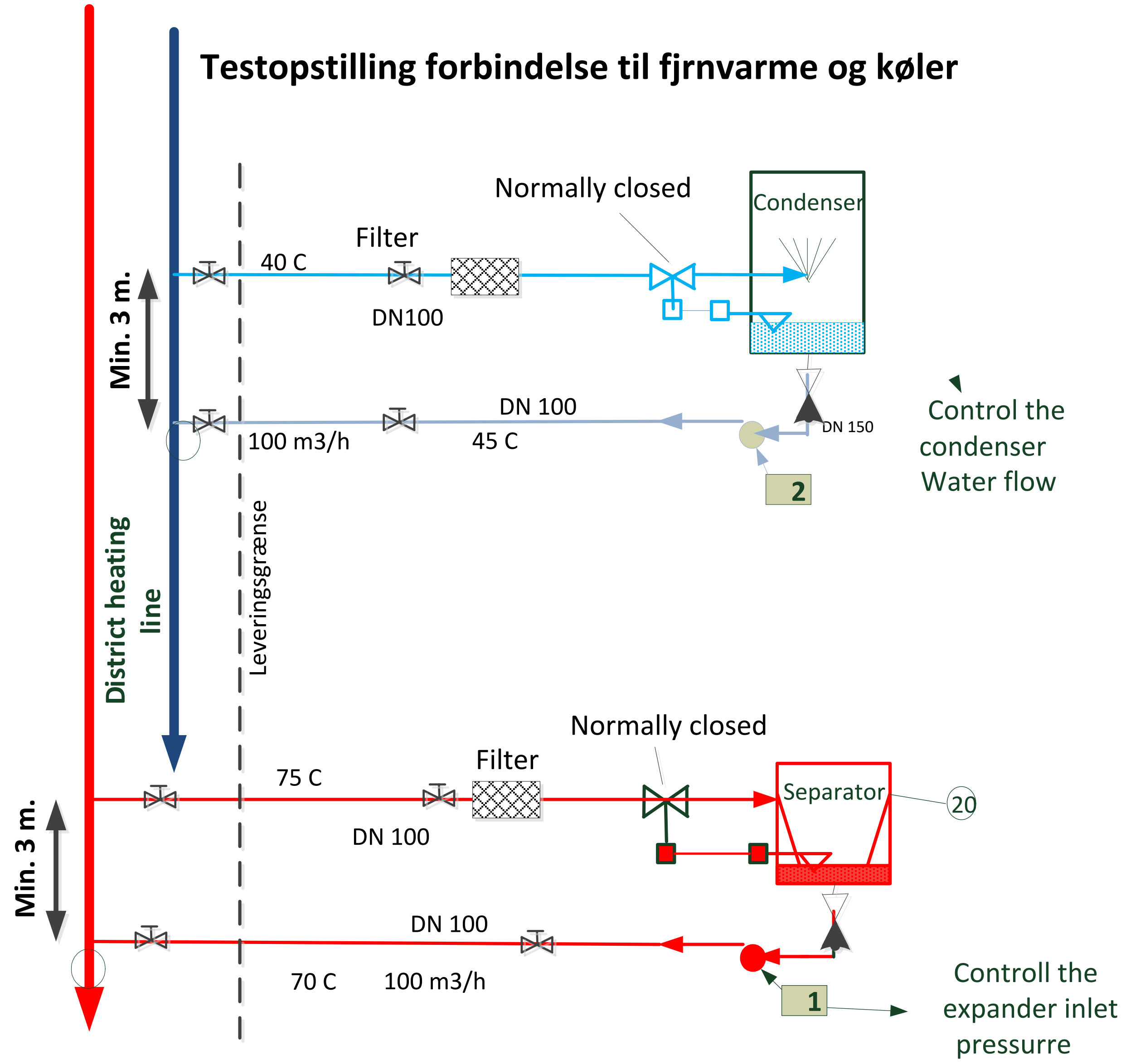


Figure 50 Connection of Unit at Varde district heating

In connection with the test itself, we utilize the produced cooling to condense the steam from the compressor, so as to ensure that the cold cycle is not coupled to district heating grid.

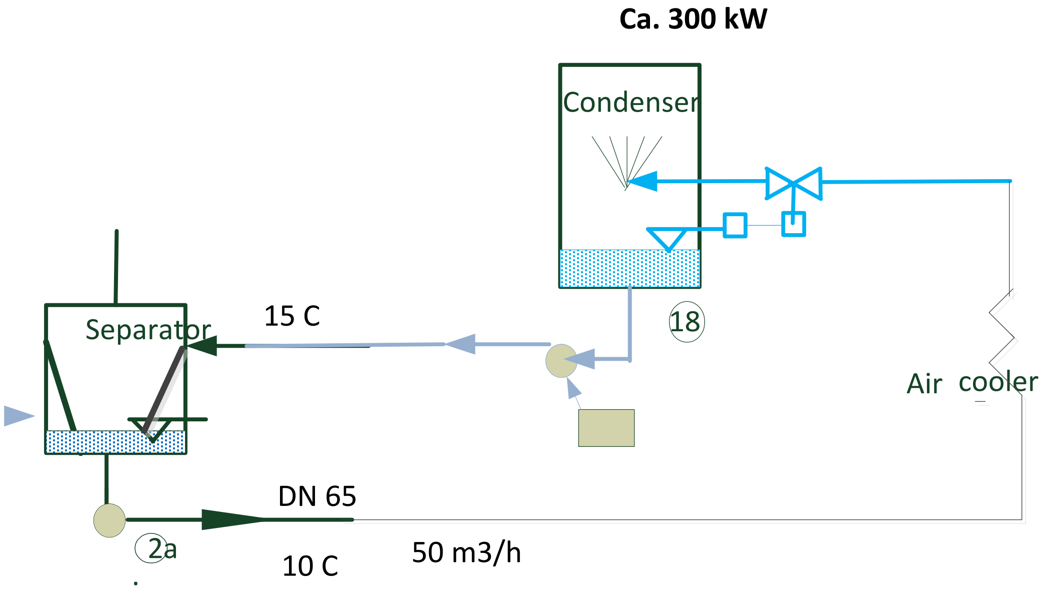


Figure 61 Actual connected test plant

General plant safety deliverables have been established to operate in compliance with customer requirements. These deliverables are outlined below:

- The system is dimensioned for external overpressure of 1 bar and internal overpressure of 10 bar. Except for an end bottom in the cooling circuit which is only laid out for 2.5 bar. An automatic non-return valve is fitted to the return flow, which secures against return to the tanks. Level meters are mounted on the tanks which control the flow of water from the district heating line to the tanks. Hand-operated shut-off valves and necessary filters are fitted between the district heating connection and the system.
- As extra safety, an extra level measurement is fitted approximately 200 mm higher than the first, which closes all valves, stops all pumps, and switches off the system. A valve opens and fills the system with air, after which the compressor automatically stops.

Initial components for regulation:

- Electricity consumption for the switchboard is approximately 10 Amp (3.8 kW)
- Internal water pumps approximately 5.2 kW
- Connection pumps for district heating 50 kW
- In total approximately 59 kW
- In total approximately 160 Amp. (3 x 380 V)

The system is delivered finished with the internal connections between evaporator and condenser on the compressor side (cooling side). Check valves are mounted on the 2 tanks connected to the district heating network, which prevent return to the (district heating) tanks during standstill.

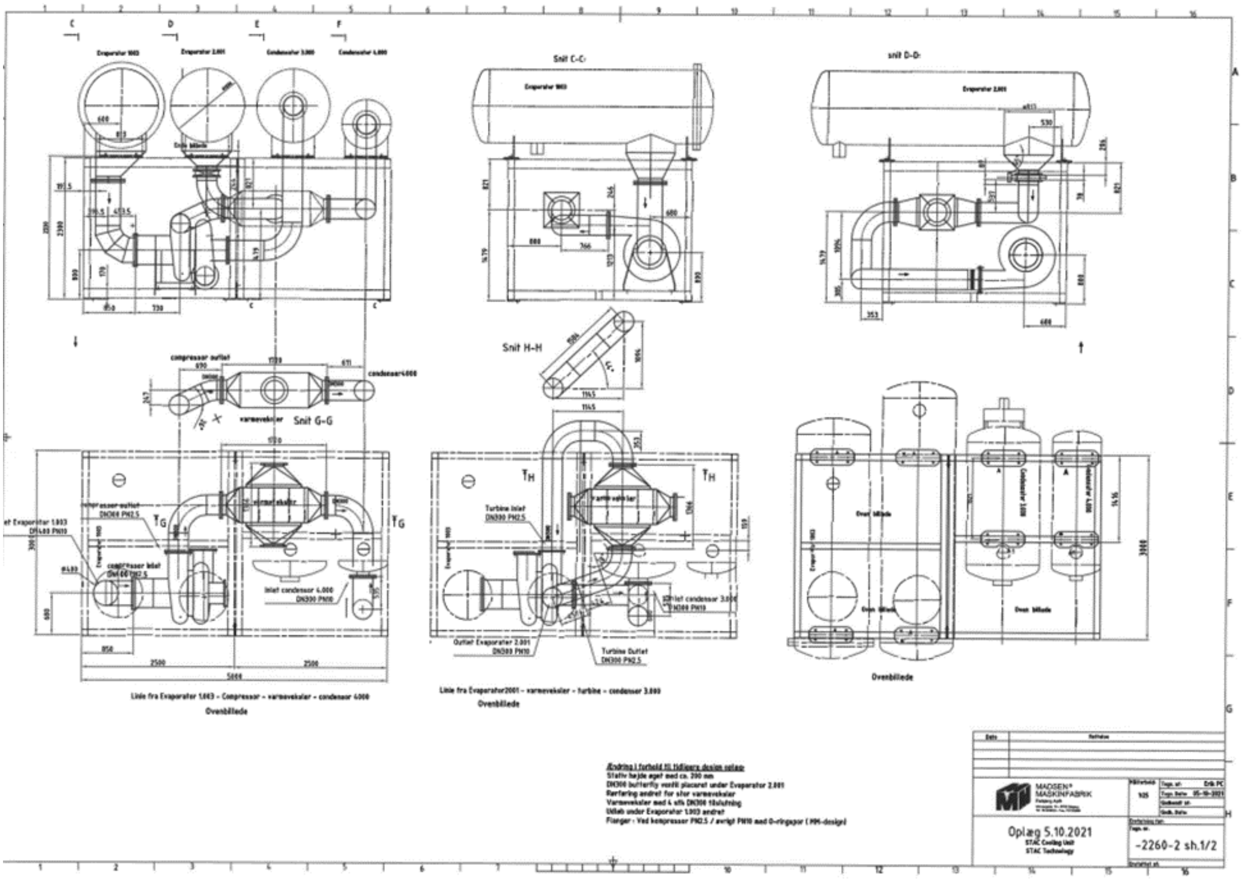


Figure 12 STAC Technology 250-kW cooling plant valid dimension sketch: Total weight approximately 9.000 kg. incl. water filling

Planned test envelope and obtained results:

a. After placing the system on site, all external pipes, pumps and electricity are connected between the system and the district heating network.

b. The pipe connections are checked for tightness with air at approximately 2 bar over pressure

c. The pipe network is checked for vacuum tightness at approximately 4mbar (abs).

d. The system is vacuumed for air to approximately 4 mbar (abs)

e. Flow to the mains is opened and it is checked that the water level in the connected containers can be kept constant during operation.

f. The condenser, evaporator and pipe network of the refrigeration compressor are filled with water and it is checked that the water flow works smoothly

g. Valve no. 19 is opened manually, and it is checked that the Turbo boiler runs flawlessly until RPM 32.000 is reached.

h. The system is restarted by the controller.

i. The necessary measurements for performance and safety are made

Figure 73 Preassembly of test plant

When all parts had reached Madsens Maskinfabrik, the first assembly could be initiated.

Connecting the major parts with pipes were completed and tested for leaks. Once achieved the entire setup was disassembled and underwent protective painting process prior to transfer to the test site.

In the picture on the right, the turbo-compressor is aligned to the connecting pipes when being installed. The developed and fabricated turbo-compressor is unique in its design and performance. Considering the steam throughput and the designed pressure lift it is compact. The yellow bench has been developed to both align and stabilize the turbo-compressor maintaining its position in the chiller frame.

Figure 84 Detail on test plant assembly

Figure 15 Detail on test plant

On the left is shown the installed turbo-compressor. The compressor part is facing forward.

On the right is shown the pneumatic reduction valve. This part has been installed to mitigate pressure/flow variations in the DH water supply. By adding this feature to the chiller it was possible to obtain and manage a constant level of water flow inside the chiller.

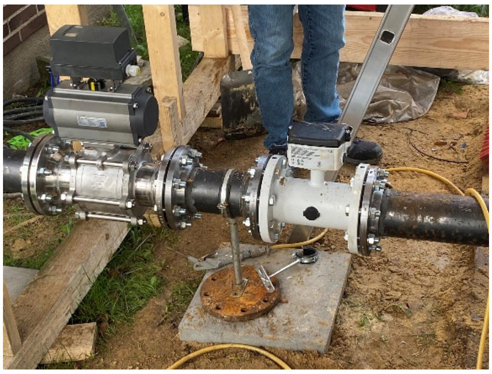


Figure 96 Installed Water controller

Figure 17 (same as figure 1): The STAC Technology chiller pilot has been assembled and installed at the test site. A constant water through put has been achieved. This has been accomplished using the automation setup developed to monitor and control the many valves and water pumps. The chiller has been pressure tested and the desired vacuum levels has been accomplished. Steam has been produced in the hot cycle to spin the turbine.

Figure 18 The chiller is fully automated and may be controlled by this touch screen interface. The outline of the sensors, actuators etc has been uniquely developed for this project.

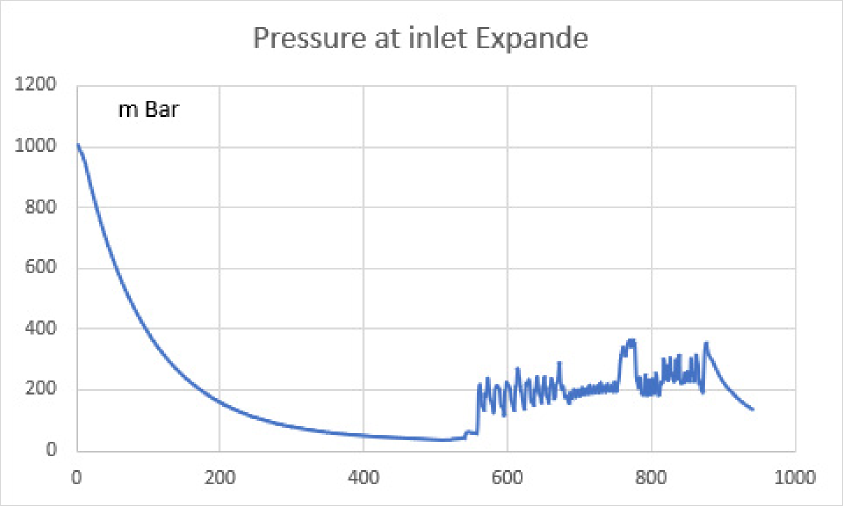


Figure 19 Pressure at evaporator for Expander

Above is data logged for the pressure measured just prior to the turbine inlet. The pressure has been kept around the 200 mbar level. This did result in the turbo-compressor spinning. The maximum achieved speed was 10.000 RPM. It is well above the critical frequency designed at 2000 RPM. The compressor was designed to perform at 32.000 RPM, which was not reachable. This is do to lack of thermal power available as the maximum temperature delivered to the chiller was below 55 °C. The corresponding pressure ratio from the compressor was just 1:1,2. The compressor and chiller are designed for a ratio of 1:11,5. Hence no usable data has been produced for the compressor.

Thermal power to run the turboexpander at Varde District heating plant:

Because of production problems with the turbo-compressor we were 8 months delayed for starting up the test plant. Therefore, the project test hit a time period where Varde District heating plant were running at verry low capacity and temperature. See figure 20.

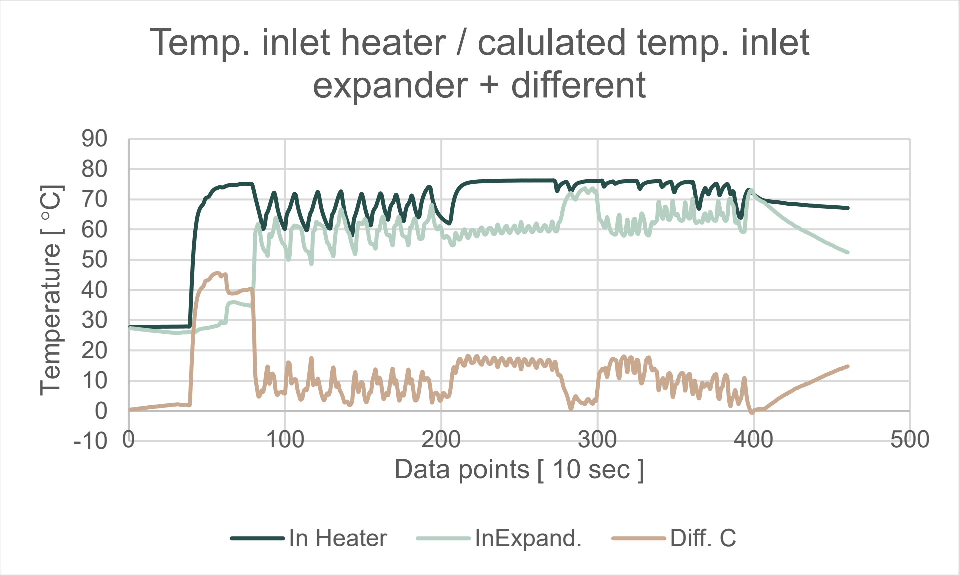


Figure 100 Actual Temperature in °C at inlet of the Expander

The temperatures for inlet expander are calculated from the measured pressure at inlet expander.

As shown in figure 20, it is not possible to maintain the temperature at 72 °C. Furthermore, the water flow was reduced to nearly the half of what is necessary.

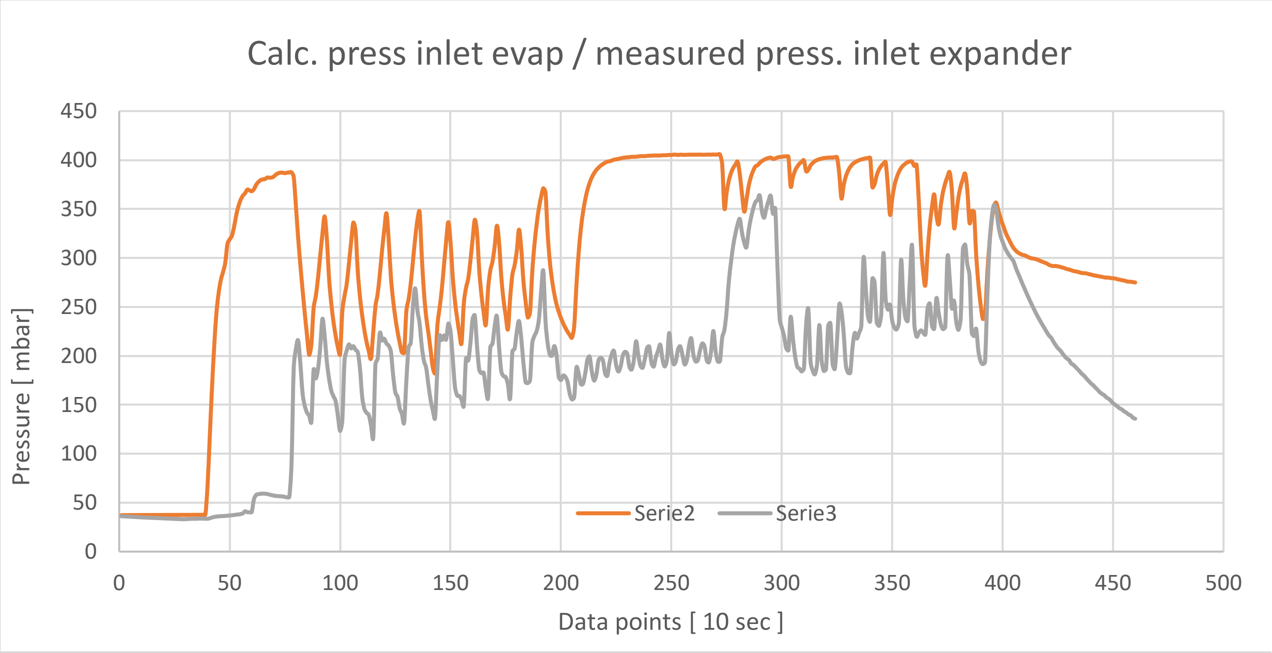


Figure 111 Actual pressure at inlet of the expander

The diagram as in figure 20 but shown data is expressed in pressure.

The capacity for the compressor is not calculated. Because of the low heat delivered to the expander, it is not possible to run the turbo expander with a higher rpm than 10.000 and this is only for a short time. The compressor is designed to produce a pressure ratio of 1:11,5 at 32000 rpm. At 10000 rpm the pressure ratio is calculated (11,5*(10000/32000)^2) to 1:1,123. Under the available circumstances the compressor would never be able to achieve any meaningful capacity.

The evaporator for the Expander

Based on the measurements recorded 28.10 2022 we are able to conclude that the evaporator who is generating steam to the expander is acceptable. To secure steam enough for the expander the control valve between the evaporator and expander was not fully open which results in pressure drop between evaporator and expander. The exact pressure drop is unknown. Between the evaporator and the expander is also a slight loss of heat even though insolation has been applied to the evaporator and the piping. In figure 20, the control valve was closed to 20% and the temperature did rise to the desired level. The difference between the inlet temperature and the evaporation temperature was reduced over time. But as is seen in figure 21 the delivered pressure was also reduced; hence the available thermal power could not sustain both a high enough temperature and pressure difference.

Dissemination:

The dissemination of the project has also been affected by the pandemic as lock-downs during the project period have hindered some physical meetings. Despite this challenge, the project has successfully been showcased to a broad array of stakeholders:

Figure 12 Test plant at Varde District heating

Physical visits have been held as the COVID-19 restriction allowed and significant step forward has been accomplished. The scale of the demonstration chiller is considerable considering the booster station in the background.

- **Conference and events:** STAC have furthermore been invited to present the technology at the GUSTAV LORENZ conference in Norway. In addition, STAC had a physical stand at the 2021 TechBBQ and again in 2022, where this project has been presented.

Figure 23 Physical stand at 2021 TechBBQ

Figure 24 Physical stand at 2022 TechBBQ

6. Utilisation of project results

The success of STAC Technology's decentralised cooling plant presents end-users with a compelling alternative to conventional solutions. Recorded technological results and data which validates the system's safety, performance and general operation will be utilised to refine the system for commercial release. End users of the results will include industrial, commercial and residential sites who are evaluating alternative cooling systems, academic institutions who are advancing research into novel cooling methods and engineering consultancies who are seeking novel advancements for inclusion into projects.

As regulations around the production and use of conventional refrigerants tighten as a result of signed legislation in countries across the world, we expect that increasing attention will be paid to cooling systems that employ natural refrigerants, especially water. With this regulated shift in technology, we anticipate a growing demand for access to our technological results from this operational test.

From the established technological results STAC Technology can refine our commercial models which will be used to inform ongoing and future sales campaigns. Data from the test will validate performance and operational claims that underpin the system's commercial results.

Commercial results will refine our existing catalogue of system payback and break-even models. These commercial models will be used by potential end-users who have a need for cooling, inclusive of:

- Industrial, commercial and residential site owners/ managers
- Engineering consultancies
- District heating network operators
- Original equipment manufacturers (OEMs)

Recent increases in the price of energy on account of macro-economic factors improve the commercial justification for STAC's cooling plant, on account of its lower comparative energy use and decreased operational cost profile. With the relative increase in the cost of electricity expected to continue over the coming decade we anticipate a growing demand for access to our commercial results from this operational test.

In Denmark alone it is calculated that only 10% of cooling need is currently being met. Similarly, across Europe and the rest-of-world, cooling demand generally exceeds existing supply by a wide margin. On account of this excess demand and forecast growth of over 300% in cooling need over the next 30 years (partially as a result of rising ambient temperatures) we expect that our commercial results will be disseminated widely to aid in the closure of next generation pilot sites for our novel technology.

There is a dense field of companies selling products across global cooling markets. This field of industry players encompasses a broad array of companies, ranging from established multi-nationals to nascent start-ups. STAC Technology differentiates itself from this field by being able to deliver a functional chiller that cools using only water-as-refrigerant in a decentralized manner to commercial, industrial and district scale markets. Our main competitors are those industry players who have the capability to deliver a decentralized solution to commercial, industrial and district cooling markets.

STAC Technology's advanced chiller plant helps in the effort to realise the objectives of current and future sustainability-oriented policy regulations. It does so by producing cooling at lower relative levels of energy consumption as well as eliminating the use of toxic and harmful refrigerants.

Most notably is that Denmark has a very strong position within District Heating (DH) with a deep knowledge base that has been further strengthened through the comprehensive conversion to very high dependence on non-fossil fuels, especially biomass. This strengthening of competences has been created through a close collaboration between heating plants, authorities, advisors and suppliers to the sector. The STAC project has the potential to further add to this competence base in a similar knowledge-building cooperation set-up, extending the build-up of knowledge into heat-driven decentralized cooling, which has huge potential for the future, both in Denmark and across major export markets in the EU and rest-of-world.

The principle of using existing DH infrastructure to provide decentralized cooling is well aligned with the overall Danish strategy of increasing energy efficiency and the circular economy. Estimations have been made on meeting the Danish cooling demand by laying a traditional district cooling grid buried alongside the existing heat network. By using existing DH infrastructure to deliver cooling in a decentralized manner, the single largest contributor to the budget for this project can be eliminated (accounting for roughly 50% of the total estimated cost), as seen in the 'K*øleplan for Danmark 2016*'. This similarly aligned with the EU policy on cooling strategy.

Additional EU-wide energy policy regulations and objectives impacted by our project are outlined below:

- **Heat Supply Act:** According to this act, measures must be promoted that 'promote the economy and result in the lowest possible heating prices'. The desire for cooling is also found in the Building Directive, VE- and EE directive, as well as the EU's heat - cooling strategy. The proposed project is fully aligned with providing funds for developing and demonstrating Danish technology for efficient use of the energy.
- **Regulation EU 2018/1999:** The Governance of the Energy Union and Climate Action, advocating for an integrated approach to tap all existing energy-saving potential to achieve an improvement in energy efficiency of at least 27% and a reduction of 40% in GHG emissions.
- **Directive 2009/28/EC:** The promotion of the use of energy from renewable sources, stating guidelines for the transition to a carbon-neutral economy based on diversification of the EU's renewable energy mix and prices.

- **Directive 2009/125/EC (the Ecodesign Directive) and the Commission Regulation (EU) 2016/2281:** Ecodesign requirements for air heating products, cooling products, high temperature process chillers and fan coil units, establishing a minimum efficiency performance to receive CE marking.
- **Directive 2010/31/EU:** Energy performance of buildings, aiming to promote the improvement of the energy performance of buildings.
- **2021 Energy Efficiency Directive (EED):** Under a proposed revision of the directive all municipalities above 50,000 inhabitants will be requested to prepare local heating and cooling plans. Those plans will be based on data provided in "a comprehensive heating and cooling assessment" prepared by each EU-country as part of their national energy and climate plans submitted to the European Commission every year.

7. Project conclusion and perspective

- *STAC Technology has together with partners successfully developed a turbo-compressor suitable for water-based cooling.*
- *A chiller plant designed to match the performance of the developed turbo-compressor has been installed at the district heating plant in Varde.*
- *The chiller has shown to be very vulnerable to the heating system it has been connected to. The combination of season period and test targets has prevented the expected success and outcome of this demonstration project.*
- *The project has been conducted in a time period with fundamental changes and major challenges to known development projects and way of life.*

- Our technology development roadmap for water-based turbo-compressors will initially focus on the refinement of our existing system to meet and exceed the specification of our customers in the district heating and cooling market. Adjacent application will then be pursued to cement our position as a leading developer of advanced turbo-compression systems that utilise water as the primary and secondary refrigerant media. This includes potential applications of a scaled common architecture across decentralised cooling applications (building and industrial) as well as ice-slurry production.

Technology	Application	Market Segment	Timeframe
Decentralised cooling	Generate cooling via established low-temperature heat source employing STAC's water-based turbo-compression system.	DH operators and end-users (scaled applications to MW scale) alongside pilot integration directly into solar, geothermal and industrial waste heat networks.	2023-2025
Ice-slurry	Continuous mass-production of pumpable ice slurry	DH, district cooling, thermal energy storage and agro-food	2024-2026

STAC's perspective on the project results is that validation of the system's safety and general operational performance has been a positive development in helping to advance its maturity.
Future development of this technology depends heavily on being able to continue testing the system in varying operational environments. The EUDP project has aided our ability to gain a foothold, through an initial in-service test of the technology and get us one step closer to commercial readiness. Ultimately, having confirmed results from this project will be critical towards:

- Confirming the system's general safety and robustness in-operation
- Refining the system design to improve the unit's interoperability and in-service performance
- Advancing elements of our intellectual property position
- Reinforcing customer-centric value models to aid in securing new pilot installations

STAC Technology has used learnings from this project to attract further funding. The technology will be further matured during the EIC Accelerator project DEOS, where the water vapor compressor will be powered by an electric motor, simplifying the energy supply needed to run the process.

Acknowledgement:

In this project STAC Technology has grown a strong partnership with Brayton Energy in developing this unique turbo-compressor. The collaboration has been challenged in this period and it is dearly appreciated by STAC Technology. New collaborations have been established as the project has evolved and STAC thanks CS Tech-com, Madsens Maskinfabrik, Eurotank, Fonderia Augusta and El:Con for their contributions and participation. DIN Forsyning has welcomed the project pilot to their heating plant in Varde and STAC appreciate their interest in the project.

This project was granted by the EUDP program and STAC Technology would like to acknowledge the agile project management and huge interest from Karsten Svoldgaard and his team. This support has been vital in developing this technology.