Final report

1. Project details

Project title	Energy Efficient Ventilation Heat Pump
File no.	64018-0524
Name of the funding scheme	EUDP Energy Efficiency
Project managing company / institution	Nilan A/S
CVR number (central business register)	11773397
Project partners	Danish Technological Institute, DTU MEK and Vonsild Consult
Submission date	12 September 2022

Content

2. Summary

In this project, a new concept for Nilan's ventilation heat pump has been developed and tested using R290 (propane) as refrigerant.

A prototype with R290 refrigerant was tested after EN16147 (the tap test of hot water), and an accredited test report was made. The result following the L tap profile was very good. The COP was measured to 3.75 which places the unit in Energy class A++. The similar result for the basic model was COP = 2.09 and energy class A. This test was conducted following the XL-tap program.

The result for tap water heat pump test is very satisfying.

The test result for the passive heat exchanger was also satisfying for the prototype. The efficiency for the internal (passive) heat exchanger is significantly better for the prototype compared to the basic model.

The test for the heat pump heating incoming air (from outside) after internal heat exchanging with exhaust air was not that satisfying, when the air was +7 C (simulating wintertime). The evaporator creates ice on the surface and frequent de-icing is necessary. It seems like the evaporator is too small. It should not be necessary to de-ice at an air temperature of +7 C. The evaporation temperature is too low.

Therefore, the efficiency of the heat pump in this situation is slightly lower compared to the basic model and prototype 1. This is a theme that Nilan will work further with during the commercialization of the R290 unit.

The use of flammable refrigerants (e.g. R290) requires safety issues, and this theme has been discussed continuously during the project. This theme also follows the international development of safety standards which are in continuously development during the project.

2.1 Dansk sammenfatning

Et nyt koncept for Nilans ventilationsvarmepumper med R290-kølemiddel er udviklet og testet.

En prototype med R290-kølemiddel er testet efter EN16147 (tappetest for varmt brugsvand), og der er udarbejdet akkrediteret testrapport. Resultatet ved test med "L"-tappeprofil er tilfredsstillende, idet COP blev målt til 3,75, svarende til energimærke A++.

Tilsvarende test for Nilans basismodel har givet en COP på 2,09, svarende til energimærke A. Denne test er foretaget i "XL"-tappeprofil.

Prototyperne er opbygget på en ny måde, som medfører forbedret luftflow igennem anlægget, og testresultat for den passive varmeveksler er også væsentlig bedre for prototypen.

Ved test af varmepumpen, når den leverer varme til indblæsningsluft, blev knap så god, når det sker i "vinterperiode" med +7 ^{0}C indblæsningsluft. Der sker tilrimning af fordamperen, hvilket viser, at fordampertemperaturen er for lav. Det burde ikke være nødvendigt at afrime fordamperen med indblæsningstemperatur på +7 ^{0}C. Derfor er effektiviteten af varmepumpen i denne tilstand lidt lavere end for basismodellen, og det er noget, som Nilan skal arbejde videre med under kommercialiseringen af produktet med R290-kølemiddel.

Brugen af brændbare kølemidler som R290 (propan) kræver at produktet er sikret mod, at der kan opstå brændbare blandinger af luft og kølemiddel i varmepumpen og i luftkanaler. Det er der arbejdet med i hele projektperioden, og det er sket parallelt med arbejdet i de internationale standardiseringskomiteer.

3. Project objectives

Nilan is the biggest Danish manufacturer of heat pumps. The production takes place in Hedensted, and the company has about 120 employees. Nilan also owns Vesttherm in Esbjerg. This daughter company manufactures tap water heat pumps and has about 30 employees.

Nilan's products are mainly connected to ventilation systems in houses, and most of the products are related to well insulated houses and other "low energy houses".

A process for changing to natural refrigerants has been underway in Denmark for many years, and in the refrigeration sector much new equipment uses natural refrigerants. This tendency has been delayed for heat pumps. In spite of several attempts to develop heat pumps for natural refrigerants, it has only recently succeeded to implement this in Denmark and in other European markets for heat pumps for residential buildings.

Heat pumps have so far been using HFC refrigerants with very high global warming impact. Caused by the new EU F-gas regulation and its "phase down scheme" and quote system, the prices have been increasing very fast, and this can be expected to continue for the next many years while the quotes are being smaller.

The big challenge of the project has been to develop and implement new technology that is using natural refrigerants and/or other low-GWP refrigerants in a way that is safe to use. The relevant new refrigerants are flammable, and this fact is a challenge when heat is transferred to the inlet air in the ventilation system in the houses. A new technology must be developed for this purpose since it is challenging to have direct heat transfer between a heat exchanger with flammable refrigerant inside and the inlet air.

Ventilation heat pumps are the object of the project, and a safe method to deploy propane (or other low-GWP refrigerant) in this heat pump must be developed, ensuring that the heat can be transferred to the inlet air. The system must also be designed to obtain the highest degree of energy efficiency.

Propane is a good refrigerant with splendid thermodynamic and thermophysical properties. Using this refrigerant and new components (like compressors for propane) would make it possible to enhance the efficiency of the heat pumps. The goal is a 10 % increase in efficiency (see later).

The present generation of Nilan's heat pumps is further described at www.nilan.dk.

The Technology Readiness Level (TRL) for this situation is 2 – 3, and during the project and the results from the project, this level has been raised to 7. After the project (and outside the budget of the project), Nilan will commercialize the technology, rising the TRL level to 8 – 9.

A PhD study at Technical University of Denmark (DTU) is connected to the project over three years, and this is partly funded by the EUDP project.

3.1 Aim of the project

There is a double aim of the project:

- To change to low-GWP refrigerants, including natural refrigerants
- To increase the energy efficiency.

This shall be done without compromising the safety of the products and by ensuring that the products are competitive on the global market.

The aim is to increase the efficiency of the exhaust air heat pump by 10 %. This would be tested for heating tap water, which is one of the tasks for this heat pump. This efficiency has been tested in an accredited lab at Danish Technological Institute (DTI) after EN 16147:2017.

The surplus heat will during normal duty be delivered into the inlet air, and the goal is to keep the energy efficiency at the same level or even better as today. This energy efficiency is measured after EN14511 and EN13141-7 ("the COP method").

3.2 Results of the project

The result will be a new technology for a new generation of efficient competitive heat pumps with natural refrigerants (or other low-GWP refrigerants). Nilan will after the project (and outside the budget of the project) commercialize the technology and the new generation of heat pumps.

3.3 Content of the project

The big challenge is to create a safe way for heat exchange to the inlet air when using flammable refrigerant(s). Most low-GWP refrigerants are flammable, and this is the reason why this challenge is the most important to solve.

It is important that this heat transfer is efficient, and that it does not reduce the energy efficiency of the products.

The content of the total project is divided into 6 work packages:

1) **Project management**. This WP contains the formal management of the project which includes the direct relations to EUDP, chairing project meetings, write the periodical reports to EUDP and develop periodic accounts etc. Nilan is responsible for this. Due to the solid experience that Danish Technological Institute (DTI) has with project management in technical R&D projects related to the heat pump businesses, DTI will help Nilan with the project management. DTU and Vonsild Consult participate in the project meetings and will give input to the periodic reporting.

2) **State-of-the-art** (studying literature, papers, etc., describing challenges and possibilities according to the EU F-gas regulation and the stage of the technological development). This WP will study the literature and contact key players in the research communities and in the branch for refrigeration and heat pump technology. DTI is responsible for this WP. DTU is participating as a major partner in this WP. Nilan will also play an important role in this WP due to the contacts to the component and refrigerant suppliers. The outcome will be a report with the status for using natural refrigerants and other low-GWP refrigerants in heat pumps and with some technical possibilities for new solutions. The results from this WP will be used in WP3 (simulation of different concepts) and in WP4 (development of actual concepts).

3) **Development of simulation program for analyzing different concepts for heat exchange to the inlet air in ventilation heat pumps**. The inputs for this are the results from WP2. DTU is responsible for this WP. The work will mainly be conducted by DTU in the PhD study. Nilan and DTI will also be involved in this WP with input to possible technical solutions and discussion of the results obtained along the study. Nilan will also contribute to the discussion of realistic technical solutions that can fit to the production line and be competitive to other solutions. This WP is very important and related to WP4 and WP5.

4) **Development of new concepts for exhaust air heat pumps**. Both propane, other hydrocarbons, and low-GWP HFCs ("HFOs") are flammable, and this needs special attention and precautions when the design for new products with new refrigerants is developed. Analyzing available components and "near available" components for exhaust air heat pumps, including compressors, expansion valves, evaporators, condensers, internal heat exchangers, fans, and heat pipes. Focus will be on the use of propane as refrigerant, but other low-GWP refrigerants will also be included. The big challenge is the heat exchange between refrigerant and the intake air (to the house) in the system. It is essential to prevent flammable mixtures of air and refrigerant in the incoming air. This WP will describe different concepts and choose the most realistic concept. Vonsild Consult is an expert in handling flammable refrigerants in systems and will be very active in this WP. One of the tasks in this WP is to minimize the volume and hence the refrigerant charge in the system. Nilan is responsible for this WP. DTI and Vonsild Consult are important partners in this WP. DTU is a discussion partner. This WP is essential for WP5.

5) **Building prototypes for test and analysis**. A first-generation prototype will be built and tested at Nilan and at DTI in Aarhus. The results will be analyzed and reported, and recommendations will be made for the design of a second-generation prototype which will be built and tested at Nilan and at DTI. The test at DTI will be an accredited test, and an accredited test report will be written. DTI is responsible for this WP. Nilan and DTI are the important partners in this WP, and DTU and Vonsild Consulting are discussion partners.

6) **Final report including analysis for energy efficiency, economy, and impact on climate change**. Papers for an international conference for refrigeration and heat pumps will be prepared and presented. Articles for Danish technical magazines will also be written. DTI is responsible for this WP. DTU and DTI will be the important partners in this WP.

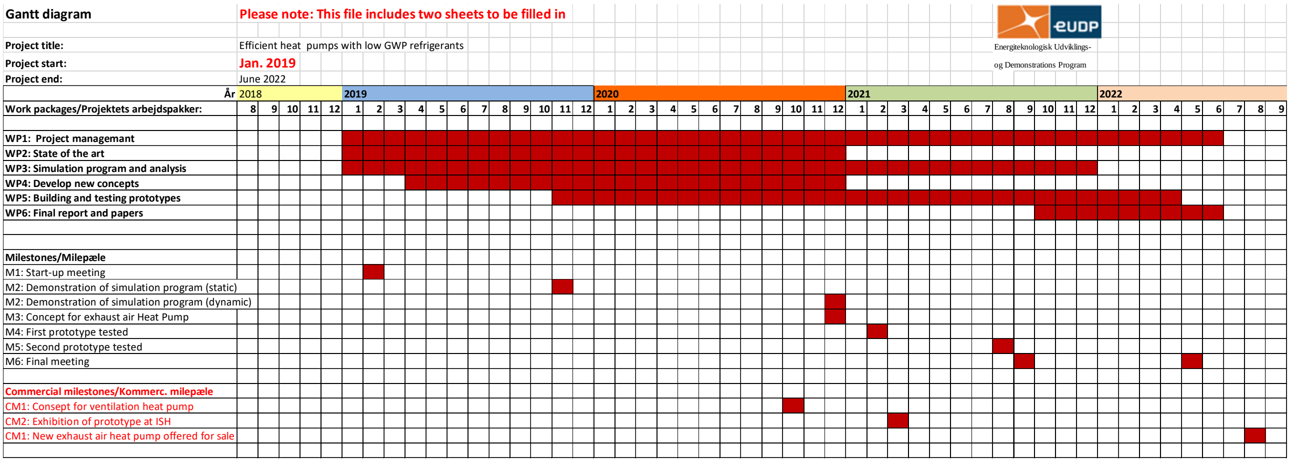

Figure 1: The Gantt diagram for the project.

During the project the following persons has been involved in the main the main part of the work:
Søren Skou Nørby, Nilan
Jens Frandsen, Nilan
Jesper Bude Christensen, Nilan
Lis Frandsen, Nilan
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Rossana Boccia, DTU MEK
Preben Eskerod, Danish Technological Institute
Kamalathasan Arumugam, Danish Technological Institute
Per Henrik Pedersen, Danish Technological Institute

4. Project implementation

A start-up meeting was held at Nilan on 5 February 2019 with participation from all partners and EUDP.

At the meeting, it was decided to test Nilan's existing ventilation heat pump at DTI in Aarhus as a part of WP2 ("state-of-the-art").

A series of project meetings and working meetings were held during the project. Due to the Covid pandemic, some of the meetings were web-based.

At a working meeting at Nilan in April 2019 (with the participation of DTI and Vonsild Consult), it was demonstrated how the existing ventilation heat pumps work, how the air channels are placed and how the refrigerant flow is in the unit. See the photo of the inside refrigeration system and the piping diagram below.

Figure 2: A look inside the existing Nilan ventilation heat pump.

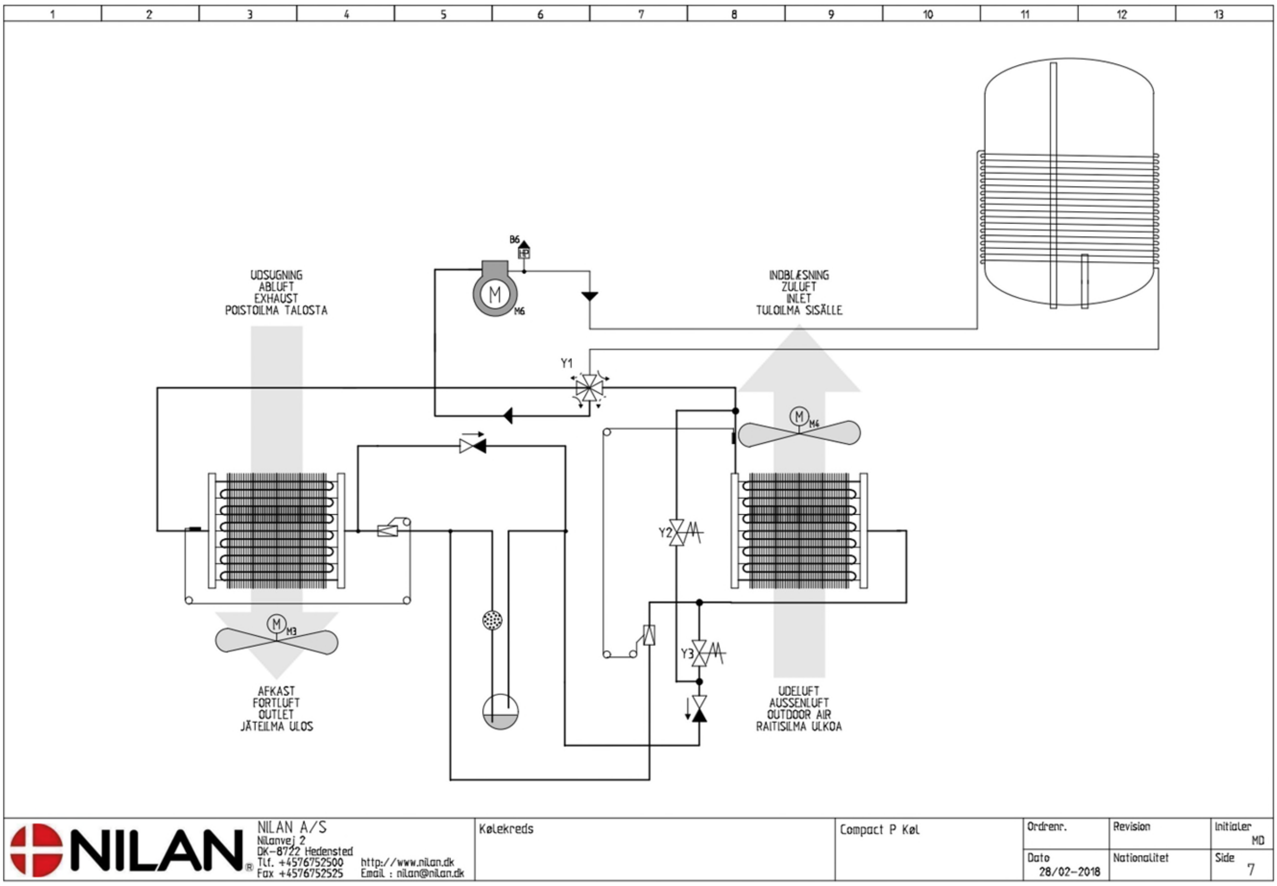

Figure 3: The piping diagram of the existing Nilan ventilation heat pump. During heating mode, the refrigerant flow through the condenser wrapped around the tap water tank (upper right) where it condenses and heats the tap water. When the water tank is full of hot water, the refrigerant will condense in the air condenser in the middle right and heat inlet air to the house. Hereafter, the liquid refrigerant will expand through the valve, and it is led into the evaporator (to the left) where it cools the exhaust air from the house.

At the working meeting, discussions about the new concept and the safety by using flammable refrigerants began, and this theme was a discussion point for the following meetings.

A unit of Nilan's existing ventilations heat pump was sent to DTI in Aarhus for instrumentation and test. The first test was the "tap test" after EN16147:2017. The tap test was conducted after the XL-tap program in the standard. This simulates the hot tap water consumption for a bigger family. The result is given in the table below (from the test report):

Results of domestic hot water test according to EN16147:2017

No		Symbol	Result	Unit
1)	Load profile	-	XL	-
2)	Settings of the control	-	50	-
3)	Heating up time	t_h	18207	[s]
4)	Heating up electrical energy consumption	W_{eh-HP}	1.99	[kWh]
5)	Stand-by power input	P_{es}	0.11	[kW]
6)	Total useful energy content during the load profile	Q_{LP}	19.20	[kWh]
7)	Total electrical energy consumption during load profile	W_{EL-LP}	9.17	[kWh]
8)	Daily electrical energy consumption	Q_{elec}	9.10	[kWh]
9)	Coefficient of Performance	COP_{DHW}	2.09	[-]
10)	Water heating energy consumption	η_{wh}	89.9%	[%]
11)	Annual electrical energy consumption	AEC	1864	[kWh/a]
12)	Reference hot water temperature	θ'_{WH}	46.8	[°C]
13)	Maximum volume of mixed water at 40°C	V_{40}	191	[L]
19)	Rated heat output	P_{rated}	1.32	[kW]
20)	Seasonal coefficient of performance	$SCOP_{DHW}$	2.09	[-]

Table 1: The outcome of accredited tap test. The XL-tap program was used, COP 2.09, and the Energy Class ended up being "A".

The test report is enclosed as an appendix to the present report.

Hereafter, the ventilation heat pump was moved to another climate chamber at DTI, and the ventilation tests were conducted with guidance from Nilan. The heat pump laboratory at DTI was not experienced with these tests, and the ventilation tests were not accredited tests.

The heat pump performance test was conducted with empty water tank, because it was impossible to achieve equilibrium with a full tank. The tests would take so long time that the refrigeration system for the climate chamber needed to defrost before a measurement could be made. Therefore, Nilan and DTI decided to conduct the test with empty tank. The test simulated the efficiency of the heat pump heating the intake air to the house, so it makes sense – also with an empty tank.

Målepunkt 20C - 7C		
Included corrections (Final result)		
Heating capacity	W	**1971,14**
COP	-	**6,13**
Power consumption	W	**321,40**
Measured		
Heating capacity	W	1975,75
COP	-	5,86
Power consumption	W	337,16
Calculation of fan corrections		
Indoor heat exchanger		
Air Flow (qv_22)	m^3/s	0,066
Measured: Static differential pressure, Fan	Pa	30
Global efficiency	η	0,30
Calculated Capacity correction	W	4,61
Calculated Power correction	W	6,59
Outdoor heat exchanger		
Air Flow (qv_11)	m^3/s	0,064
Measured: Static differential pressure, Fan	Pa	43
Calculated global efficiency	η	0,30
Calculated Power correction	W	9,18

Tabel 2: Performance test of the heat pump heating the inlet air to the house. Tested after EN13141-7 and EN14511.

Performance test passive recovery - 6 hours average													
	Målt [Pa]	Ps,ext,[Pa]	Qv11[m3/h]	Pe[W]	Fan,speed 11 [%]	T.tør.11.m [C]	T.våd.11 [C]	T.tør.12.m [C]	T.våd.12 [C]		P.amp[mbar]		**effektivitet_1[%]**
	43	NA	230	49	37	20,00	11,60	10,99	NA		997		**69**
	Målt [Pa]	Ps,ext,[Pa]	Qv21[m3/h]	Pe[W]	Fan,speed 21 [%]	T.tør.21.m [C]	T.våd.21 [C]	T.tør.22.m [C]	T.våd.22 [C]		P.amp[mbar]		**effektivitet_2[%]**
	30	NA	228	49	36	7,00	5,30	17,75	7,63		997		**83**

Tabel 3: performance test of the passive heat exchanger in the basis model.

4.1 Market for ventilation heat pumps in the EU

There are a number of manufacturers of ventilation heat pumps in Europe. This market is fast growing, especially for installations for newly built houses.

The market in Denmark is about 2.000 units per year according to the heat pump statistics from the Danish Energy Agency.

According to the ongoing EU review study for boilers (including heat pumps), the sales figure for 2014 was 270 for Denmark and 18.515 for the EU.

The sale has increased 7-fold since 2014. If we assume that this is also the case for the EU in total, this means that the sale in the EU now is in the order of 130.000 units per year. This figure is very uncertain.

In the table below, a number of products and manufacturers are listed. The table is from the "Passive House Institute", November 2021:

Component name	Manufacturer	Country	Type	Source	Sink	Climate zones
aerosmart m	Drexel und Weiss energieeffiziente Haustechniksysteme GmbH	AT	Compact heat pump unit	Air	Air	
Aquarea J series High Performance	Panasonic Espana Sucursal de Panasonic Marketing Europe GmbH	ES	Compact heat pump unit	Air	Water	Independent
CHM 200	zehnder (china) indoor climate Co. Ltd		Heat pump with ventilation	Air	Air	Cool, temperate
Combi 185L (Arbeistpunkt 150 m³/h)	Genvex A/S	DK	Compact heat pump unit	Air	Air	
Combi 185L (Arbeitspunkt 200 m³/h)	Genvex A/S	DK	Compact heat pump unit	Air	Air	
Compact P (Arbeitspunkt 172 m³/h)	Nilan A/S	DK	Compact heat pump unit	Air	Air	
Compact P (Arbeitspunkt 92 m³/h)	Nilan A/S	DK	Compact heat pump unit	Air	Air	
Dpurat DBDF-35B-15D-DH	Zhejiang Dpurat Environmental Equipment Co., Ltd.	CN	Compact heat pump unit	Air	Air	Independent
DR28WFJD7PA/ DR28GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent
DR35WFJD7PA/ DR35GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent
DR55WFJD7PA/ DR55GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent
DR63WFJD7PA/ DR63GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent
DR71WFJD7PA/ DR71GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent
DR78WFJD7PA/ DR78GFJDXPB	Lv Wu Environmental Technology (Taicang) Co.,Ltd.	CN	Heat pump with ventilation	Air	Air	Independent

Ethos 007 RS	Aernova Europe Srl.	IT	Heat pump with venti-lation	Air	Air	
LWZ 8 CS Pre-mium	Stiebel Eltron GmbH & Co. KG	DE	Compact heat pump unit	Air	Air	
PKOM4	J. PICHLER Gesellschaft m.b.H.	AT	Compact heat pump unit	Air	Air	
Proxon P1/ FWT1 (Heiz) +T300 (TWW)	ZIMMERMANN Lüftungs- und Wärmesysteme GmbH & Co. KG	DE	Compact heat pump unit	Air	Air	
recoCOMPACT 3kW VWL 39/5 230V	Vaillant GmbH	DE	Compact heat pump unit	Air	Air	
recoCOMPACT 5kW VWL 59/5 230V	Vaillant GmbH	DE	Compact heat pump unit	Air	Air	
recoCOMPACT 7kW VWL 79/5 230V	Vaillant GmbH	DE	Compact heat pump unit	Air	Air	
Stiebel Eltron LWZ 604	Stiebel Eltron GmbH & Co. KG	DE	Compact heat pump unit	Air	Air	Cool, tempe-rate
Tecalor TCO 2.5	tecalor GmbH	DE	Compact heat pump unit	Air	Air	Cool, tempe-rate
THZ 504	tecalor GmbH	DE	Compact heat pump unit	Air	Air	
XKD-51P-300H	Zhongshan Wonderful Ther-mal-Control Technology Co.,LTD	CN	Heat pump with venti-lation	Air	Air	
Systemair Genius	Systemair GmbH	DE	Compact heat pump unit	Air	Air	Cool, tempe-rate

Tabel 4: List of products and manufacturers of ventilation heat pumps (after the Passive House Institute)

The table can be found at this link:

https://database.passivehouse.com/en/components/list/heat_pump

As far as the project group knows, they all use HFC refrigerants in their products. Nilan has two products on the list.

4.2 Concept development

A study was conducted with the purpose of determining which new compressor should be used for the proto-type with R290.

The study was conducted in cooperation between Nilan, DTU MEK, and DTI. The results of calculation of performance were presented by DTU MEK at the project meeting on 17 June 2020. Three compressors for

R134a and three compressors for R290 were compared based on polynomials received from the manufacturers.

Compressors

R134a	
Secop	SC15GHH
Secop	SC10GHH
Highly	BDD102SX
R290	
Secop	NLU88DN
Highly	PDD084SV
Highly	WHP01500PSV_D3E

Comparison at:

- Evaporation temperature: varying
- Condensing temperature, Tc = 55 C and Tc = 45 C
- Superheat, ΔTsh = 10 K
- Subcooling, ΔTsc = 2 K

Table 5: The six compressors included in the study and comparison.

COP (heating)

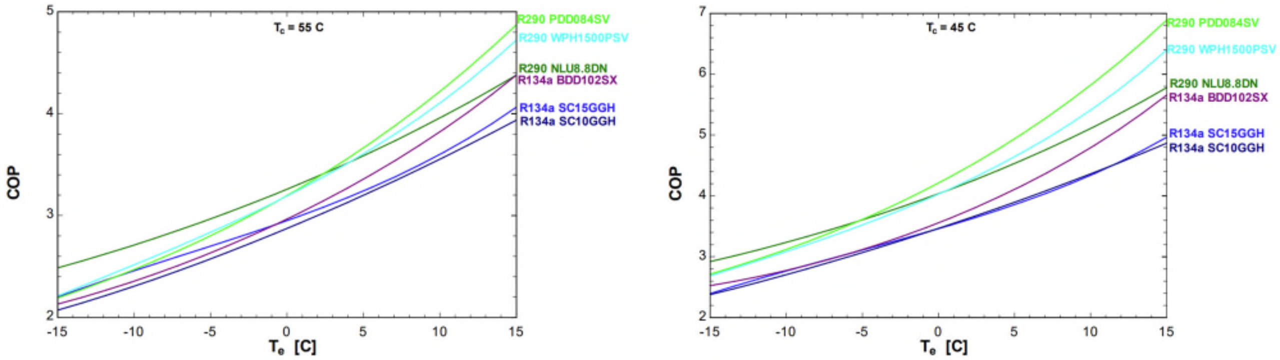

Figure 4: Comparison of energy efficiency of the six compressors at 45 °C and 55 °C condensing temperature.

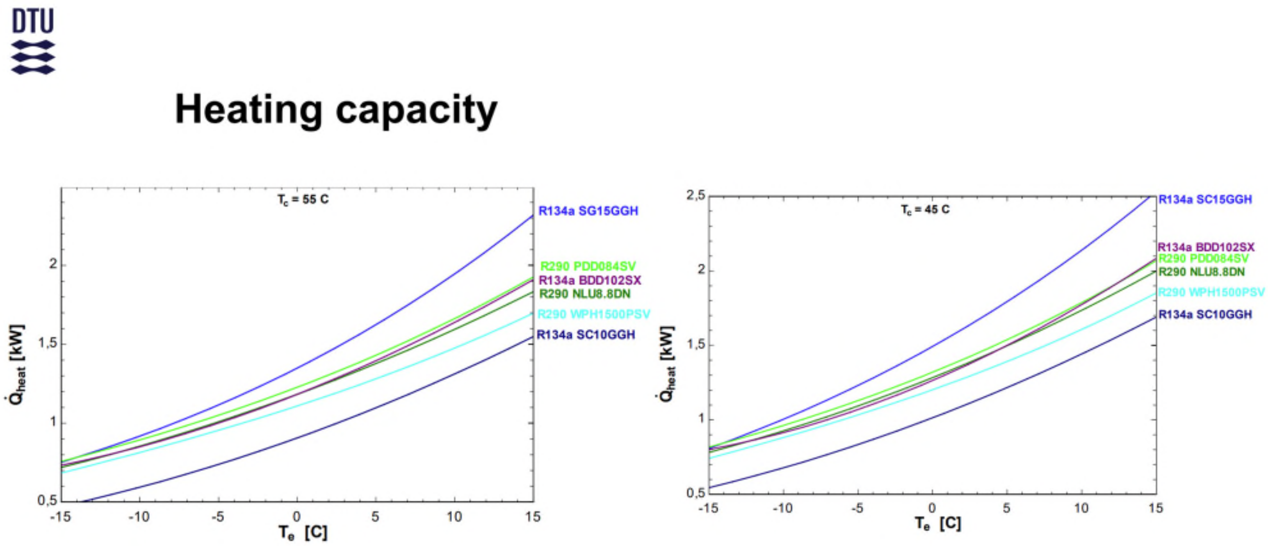

Figure 5: The heating capacity for the six compressors at 45 °C and 55 °C condensing temperature.

The analysis showed that the Highly PDD084SV has the highest energy efficiency at the relevant temperatures. The heating capacity is, however, a little lower compared to the SECOP SC15GGH compressor in the existing units.

Based on this analysis, it was decided to use the Highly PDD compressor type in the R290 prototype.

4.3 Use of flammable refrigerant

R290 (propane) is highly flammable, and it is important that no flammable mixture of refrigerant and air can occur anywhere inside the cabinet and the air channels.

One important parameter is the charge of refrigerant. The bigger charge, the bigger leakages can occur Therefore, it is an effort to minimize the charge of refrigerant.

The existing unit contains about 2 kg of R134a and this can be reduced by simple means to about 1 kg by ensuring that the no liquid refrigerant is placed in a condenser that is not in use.

Furthermore, the density of liquid R290 is much smaller compared to R134a. This will reduce the charge of R290 to about 0.5 kg with the simple means described for the R134a units.

Minimizing the volume of other components might reduce the necessary refrigerant charge further (see the discussion later on).

A leakage might occur in a connection of pipes or in a connection between components in the refrigeration system and pipes. This will take place in the "machine room" in the upper part of the cabinet.

One method to prevent flammable mixtures is the use of a gas detector. If the detector senses a gas leakage, it turns off the heat pump and ensures that the fans are running at highest capacity and leads the gas away (out of the house).

Figure 6: The use of flammable refrigerants is discussed at a technical meeting at Nilan, November 2021.

At the project meeting in June 2020, Vonsild Consulting concluded the following:

CONCEPT:

Maximum allowed charge: 988 g maximum.

Leak detection is applied, for instance:

- Gas detector
- Ultrasound detector
- Operational parameter leak detection
- When there is a leak, then the appliance sends the leak to the outdoors.

An estimate is made of how much leak can go indoors, and this amount is checked against the allowable limits in EN&IEC 60335-2-40.

4.4 Ultrasound detector

Asbjørn Vonsild, Vonsild Consulting, has developed an ultrasound detector prototype. This has been done based on a cooperation with Daniel Colbourne, UK, and a not yet published paper written by Colbourne and Vonsild (enclosed in appendix).

There are other detectors, especially gas detectors. The present generation of gas detectors has to be calibrated periodically, and this is costly.

Therefore, the ultrasonic detector technology would be interesting for smaller systems with flammable refrigerants like R290 propane. Detectors for ultrasonic noise are solid and will not change their sensitivity for a very long time (decades).

A small leakage of R290 will create ultrasonic noise.

Vonsild has built a prototype that works well, and the idea is that the concept will be free for all to implement. The prototype is built using standard components.

Investigation tells that normally there will be no other source of ultrasonic noise in a family house that can disturb the detector.

The idea is that the detector – if activated – will send a signal to the controller of the appliance, and then the controller will stop the heat pump and activate the fans, so the gas leakage is led outside the house.

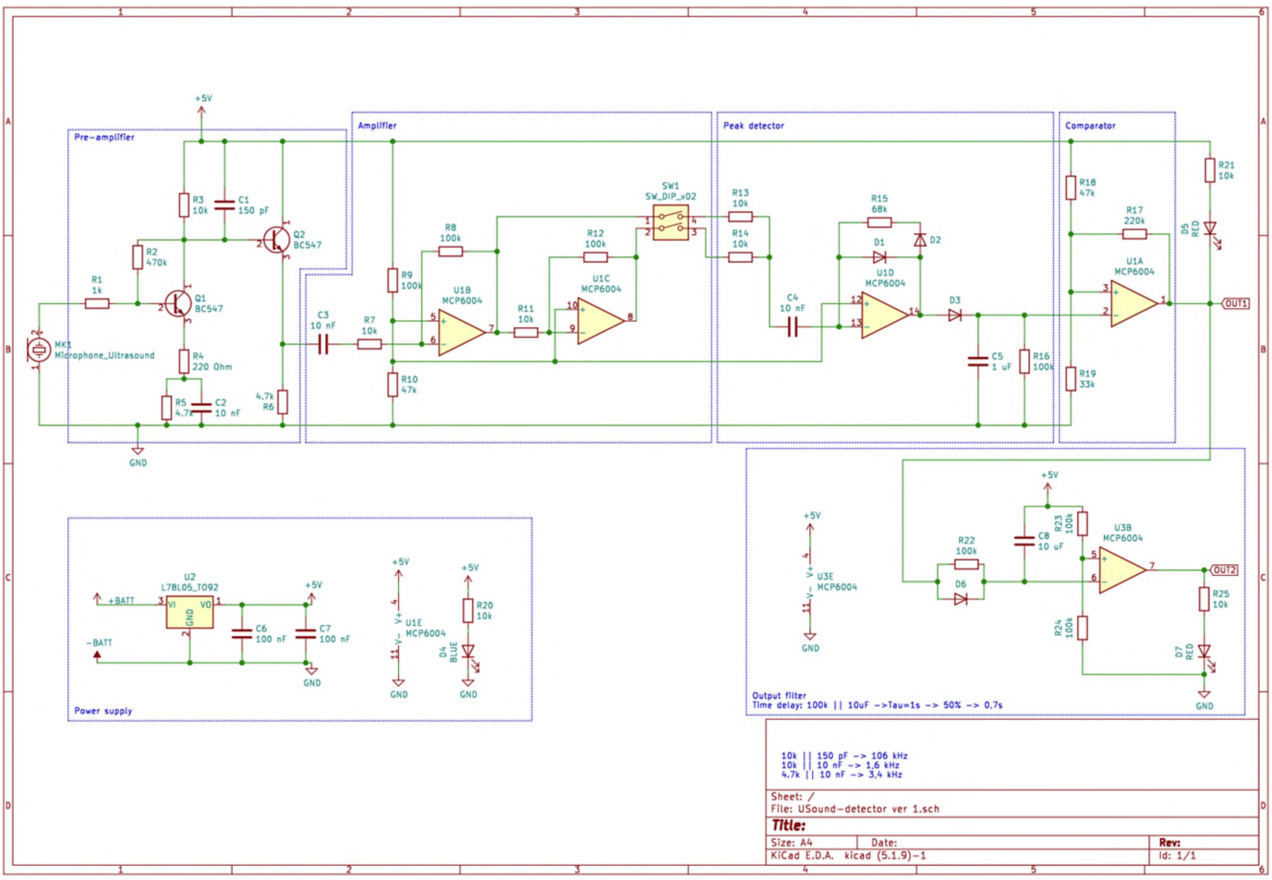

Figure 7: Vonsild's concept for ultrasonic detector.

Figure 8: Prototype of ultrasonic detector.

5. Project results

Nilan built a first prototype where the internal volume of the refrigeration system was reduced and hence the charge of refrigerant was reduced. This was done by changing the positions of the components. This also improved the efficiency of the internal passive heat exchanger due to a better air flow.

The first prototype was charged with R134a refrigerant.

The energy efficiency of the prototype during the tap test was measured to COP = 3.3, and the energy efficiency for the air heat pump was measured to COP = 6.3.

Satisfied with the good performance of the first prototype, the work of building the second prototype with R290 refrigerant (propane) was initiated.

5.1 Second prototype

Due to minimizing the charge of refrigerant, the system was constructed in a way so that either the tap water condenser or the air condenser is used (not both simultaneously). The condenser not in use will be drained for liquid refrigerant.

When using the air condenser, the system works fine with 220 g of R290, but when the tank condenser is in use, 420 g of refrigerant is needed. Therefore, the second prototype is charged with 420 g of R290.

In the future when new pipes from Hydro Aluminum will be commercially available (with reduced volume and fins to optimize the heat transfer to the tank), the charge for the system might be as low as 220 g of R290. At present, prototypes of the new pipes are under test at Vesttherm.

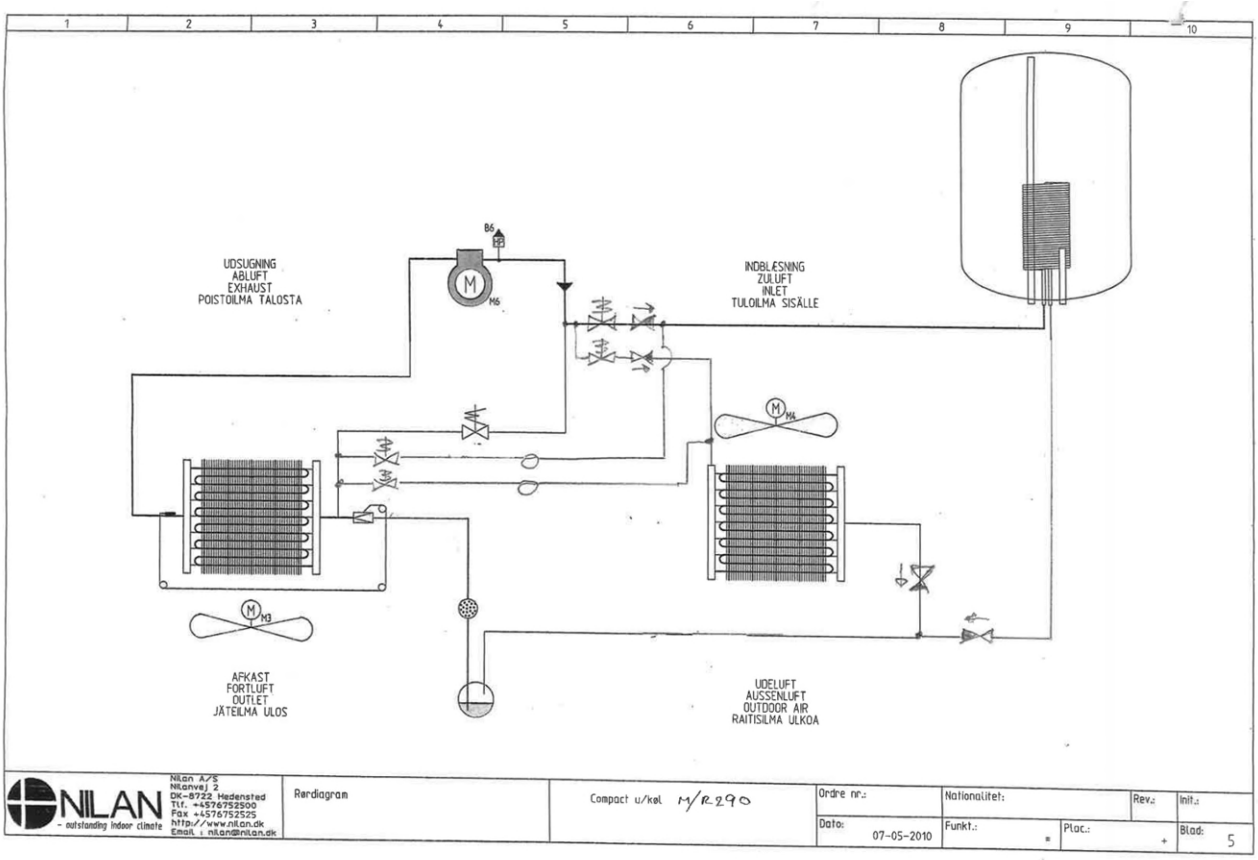

Figure 9: Piping diagram for the second prototype. The condenser at the water tank is wrapped around the tank – and not placed inside the tank as shown at the figure.

The main components in the second prototype are:

- 2x Delta Ø 190 85W fans
- Zern HU-EX366-450 counter current air heat exchanger
- Highly WHP01750PSV-H3BUN compressor.

Note that the compressor used in prototype 2 is a slightly bigger compressor of the same compressor type used in the analysis in chapter 4. The efficiency performance of the bigger compressor is expected to be similar to the one in the analysis.

In Table 11 (later in this chapter), more information about other components in prototype 2 is listed.

Figure 10: Prototype 2 without cover. The insulated water tank is placed in the lower part. The tank is equipped with a number of thermocouples inside the tank and at the condenser pipes wrapped around the tank as part of the DTU part of the project. The data logger for the DTU thermocouples is placed in the bottom of the cabinet, beside the water tank.

Figure 11: Prototype 2. The "refrigeration system" and the passive heat exchanger is placed in the upper part of the unit.

Prototype 2 was shipped to the heat pump lab at DTI in Aarhus for test.

The first test is again the tap test after the EN16147:2017 and after the XL-tap program. At the test of the standard unit, DTI used a method to compensate for hot water tap temperatures below 40 °C by adding electric heating up to 40 °C by calculation (with COP = 1), and the results were influenced by this.

In 2019, the EU Commission decided that this correction can no more be valid. The tap temperature must be at least 40 °C at the end of the tap.

This results in a situation where it is not possible to conduct an accredited test after the XL-program.

However, in the figure below, the results of this first tap test according to the XL-program are shown:

No		Symbol	Result	Unit
1)	Load profile	-	XL	-
2)	Settings of the control	-	50	-
3)	Heating up time	t_h	22154	[s]
4)	Heating up electrical energy consumption	W_{eh-HP}	2,52	[kWh]
5)	Stand-by power input	P_{es}	0,10	[kW]
6)	Total useful energy content during the load profile	Q_{LP}	19,14	[kWh]
7)	Total electrical energy consumption during load profile	W_{EL-LP}	8,53	[kWh]
8)	Daily electrical energy consumption	Q_{elec}	8,49	[kWh]
9)	Coefficient of Performance	COP_{DHW}	2,25	[-]
10)	Water heating energy consumption	η_{wh}	96,2%	[%]
11)	Annual electrical energy consumption	AEC	1741	[kWh/a]
12)	Reference hot water temperature	θ'_{WH}	50,9	[°C]
13)	Maximum volume of mixed water at 40°C	V_{40}	223	[L]
19)	Rated heat output	P_{rated}	-	[kW]
20)	Seasonal coefficient of performance	$SCOP_{DHW}$	-	[-]

Table 6: The results of the first tap test (after the XL-tap r prototype 2). The measured COP value is compensated by adding electrical heat (with COP = 1.0) to compensate for tap temperatures below 40 ˚C.

The value of the COP is 7.7 % better than for the standard unit. But it is not fair to compare the figures because the “additional” electrical energy can be very different.

The test was conducted again with slightly different setting of temperature, but the results were similar to the first ones. The conclusion was that the water tank is not big enough for the XL-tap program.

It was decided to conduct a new test after the “L” tap program. Now, the result was much better. There were no problems with the hot water tap temperature. The size of the tank fits to the L-program. This program simulates the consumption of hot tap water by a normal family.

Test results of domestic hot water test according to EN16147:2017

Presentation of main results

No		Symbol	Result	Unit
1)	Load profile	-	L	-
2)	Settings of the control	-	53	-
3)	Heating up time	t_h	21273	[s]
4)	Heating up electrical energy consumption	$W_{eh\text{-}HP}$	2.06	[kWh]
5)	Stand-by power input	P_{es}	0.03	[kW]
6)	Total useful energy content during the load profile	Q_{LP}	11.80	[kWh]
7)	Total electrical energy consumption during load profile	$W_{EL\text{-}LP}$	3.15	[kWh]
8)	Daily electrical energy consumption	Q_{elec}	3.11	[kWh]
9)	Coefficient of Performance	COP_{DHW}	3.75	[-]
10)	Water heating energy consumption	η_{wh}	159.4%	[%]
11)	Annual electrical energy consumption	AEC	642	[kWh/a]
12)	Reference hot water temperature	θ'_{WH}	51.5	[°C]
13)	Maximum volume of mixed water at 40°C	V_{40}	209	[L]
19)	Rated heat output	P_{rated}	1.23	[kW]
20)	Seasonal coefficient of performance	$SCOP_{DHW}$	3.75	[-]

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Test Reg. nr. 300

Table 7: Result of the test of prototype 2 after EN16147:2017 and the L-tap program. The COP is measured to be 3.75, which is very good and approves the unit to be in the A++ energy label class after COMMISSION DELEGATED REGULATION (EU) No 812/2013 of 18 February 2013. The test is an accredited test, and the test report is enclosed as an appendix.

Performance test passive recovery - 6 hours average

Målt [Pa]	Ps,ext,[Pa]	Qv11[m3/h]	Pe[W]	Fan,speed 11 [%]	T.tør.11.m [C]	T.våd.11 [C]	T.tør.12.m [C]	T.våd.12 [C]		P.amp[mbar]		**effektivitet_1[%]**
48	NA	268	64	60	19,9	11,90	8,8	NA		1010		**87**
Målt [Pa]	Ps,ext,[Pa]	Qv21[m3/h]	Pe[W]	Fan,speed 21 [%]	T.tør.21.m [C]	T.våd.21 [C]	T.tør.22.m [C]	T.våd.22 [C]		P.amp[mbar]		**effektivitet_2[%]**
39	NA	268	64	60	7,2	6,8	18	11,2		1010		**85**

Tabel 8: The performance test of the passive heat exchanger is much better than for the reference model.

When conducting the heat pump test for heating the ventilation air at +7 °C air temperature (representing winthertime and cooling of the exhaust air after the passive heat exchanger), the situation is a little difficult because the evaporator creates ice on the surface, and frequent de-icing is necessary.

It seems like the evaporator is too small. It should not be necessary to de-ice at an air temperature of +7 °C. The evaporation temperature is too low.

Frequent de-icing and a low evaporator temperature reduce the energy efficiency of the heat pump in this situation.

Therefore, the efficiency of the heat pump in this situation is slightly lower compared to the basis model and prototype 1. This is a theme that Nilan will work further with during the commercialization of the R290 unit.

Målepunkt 20C - 7C		
Included corrections (Final result)		
Heating capacity	W	**2010,06**
COP	-	**5,64**
Power consumption	W	**356,24**
Measured		
Heating capacity	W	2016,28
COP	-	5,39
Power consumption	W	374,00
Calculation of fan corrections		
Indoor heat exchanger		
Air Flow (qv_22)	m^3/s	0,078
Measured: Static differential pressure, Fan	Pa	34
Global efficiency	η	0,30
Calculated Capacity correction	W	6,21
Calculated Power correction	W	8,88
Outdoor heat exchanger		
Air Flow (qv_11)	m^3/s	0,076
Measured: Static differential pressure, Fan	Pa	35
Calculated global efficiency	η	0,30
Calculated Power correction	W	8,88

Tabel 9: Performance test of the second prototype of the heat pump heating the intake air to the house.

Measuring point 20 °C – 7 °C				
Included corrections (Final result)		**Reference model**	**Propan model_Transinet test**	**Propan model_Steady state test**
Heating capacity	**W**	1971,14	1909,46	2010,06
COP	**-**	6,13	5,46	5,64
Power consumption_total	**W**	321,40	349,57	356,24
Power consumption_fan	**W**	52	66	66

Tabel 10: Comparison of the test results of the basic model and the second prototype of the heat pump heating the intake air to the house at the condition of +7 ^{0}C air intake. At this condition the second prototype had problems with ice buildup at the evaporator.

5.2 Research study on the ventilation exhaust air heat pump

The research part of the project included both a modelling study on the entire heat pump with water tank and an experimental investigation on the interaction between the heat pump condenser and water tank during heat up.

In the following, first a brief summary of the numerical model is presented. The numerical model was validated against measurement data from the first tests of the baseline heat pump. The test of the baseline heat pump did not include measurements on the water side (inside the tanks). Since the interaction between the heat pump condenser and the water tank is not well described in the literature, we decided to carry out an experimental study focusing on this during the test of the final prototype. The experimental investigation is reported in the second part of this chapter.

5.2.1 Summary on the numerical model

A dynamic model of an R134a-based exhaust air heat recovery ventilation heat pump (EAHRV-HP) operating in domestic hot water production mode was developed at DTU Mechanical Engineering, and the results of the simulation were compared against experimental data. The complete study is published in the paper Boccia et al. [1]. The paper is enclosed in appendix.

The dynamic model of the heat pump was developed in Dymola [2] using the Modelica language [3] using component models from the TIL Suite [4] and property data from TIL Media [5]. The model was based on dynamic energy and mass balances for the heat exchangers and the water tank and quasi- steady-state models of the compressor and expansion valve. The water tank was discretised in order to simulate the stratification in the tank as well as the interaction between the heat pump condenser and the water tank. A comparison between the numerical results and test data showed that the largest deviation between calculated and measured values was found for the condensation pressure. This is probably due to the assumptions made on the condenser tank contact resistance value, the condenser coil modelled as a long horizontal tube and to the uncertainties in the measuring devices used during the experimental campaign. The model was considered adequate to be used for further numerical studies and it was therefore used to assess the energy performance of the system in the tested conditions. The simulations showed a gradual decrease of the instantaneous COP with the increase of the water temperature. When the stored hot water was at 30 °C, the COP was 3.5, and it dropped to 2.7 when the water temperature set point of 50 °C was reached. The calculated average COP in relation to the whole warming-up process of 180 L water from 12 °C to 50 °C was 3.5. Despite the limitations, the model could predict the COP with a relative error of 6 %. The developed dynamic numerical model was able to show the refrigerant change inventory in water heating configuration. The system was filled with 2 kg of R134a, and the calculated total refrigerant mass was 1.28 kg. The deviation in the calculation of the total refrigerant charge is likely due to the use of the homogeneous model, which tends to overestimate the fraction of vapour in the two-phase regions and to the neglected pipes and connections. Regardless of the constraints, valuable inputs for future research paths can be extrapolated from the outcomes of this study. In fact, the component holding the largest amount of refrigerant is the condenser. This result agrees with findings reported in the literature and shows the potential for charge minimization by design optimization of the wrapped around condenser in future work.

5.2.2 Experimental investigation of water tank temperature development during heating and tapping

The objective was to carry out an experimental study on the exhaust air to water heat pump prototype in order to understand the interaction between the heat pump and the water storage.

5.2.3 System description (prototype)

The heat pump consists of an on/off rotary compressor, a condenser coil wrapped around a 180 L water storage tank, a liquid receiver for refrigerant storage, a thermostatic expansion valve, and a fin and tube evaporator. The thermostatic expansion valve controls the superheat at the evaporator outlet. The system works with R290 and its nominal heating capacity is of 1.5 kW. The detailed system components characteristics are shown in Tabel 11.

Evaporator and Condenser (refrigerant to air)	
Manufacturer	
Type	Finned tube
Width (mm)	400
Height (mm)	300
Depth (mm)	80
Diameter of inner tubes (mm)	7.2
Tube thickness (mm)	1
Number of rows	3
Number of circuits	2
Number of tubes per circuit	16
Tube spacing (mm)	25
Row spacing (mm)	21.65
Fin pitch (mm)	2.5
Condenser (refrigerant to water)	
Type	D-shaped
Number of coil rounds	38
Flat portion length (mm)	11.4
Curved portion height (mm)	7.5
Coil length (mm)	590
Cross section area (mm^2)	73.3
Cross section perimeter (mm)	33.1
Storage tank	
Inner tank volume (L)	180
Inner diameter of the tank (mm)	502
Inner height of the tank (mm)	980
Aspect ratio (H/D)	1.95
Tank wall thickness (mm)	45
Diffuser type	Baffle plate above the inlet pipe
Insulation thickness (mm)	50
Lower height of the condenser coil (mm)	140
Upper height of the condenser coil (m)	500
Compressor	
Type	Rotary
Manufacturer	Highly WHP01750PSV-H3BUN
Displacement (cm^3)	8.9
Speed (rpm)	2900
Oil (mL)	150±20
Expansion device	
Type	TXV

Manufacturer	Danfoss 068U2022
Receiver	
Volume (L)	0.88
Fan	
Manufacturer	EbmPapst – R3G190-RG19-33
Type	Backward curved – single intake
Speed (min^{-1})	3255
Power consumption (W)	85

Table 11: Data for the components in the second prototype.

5.2.4 Methods

The exhaust air heat pump was tested according to the EN16147. This type of test imposes an external instrumentation to the system without any modification of the system itself. However, a more detailed instrumentation was necessary in order to analyse the interaction between the heat pump and the water in the tank.

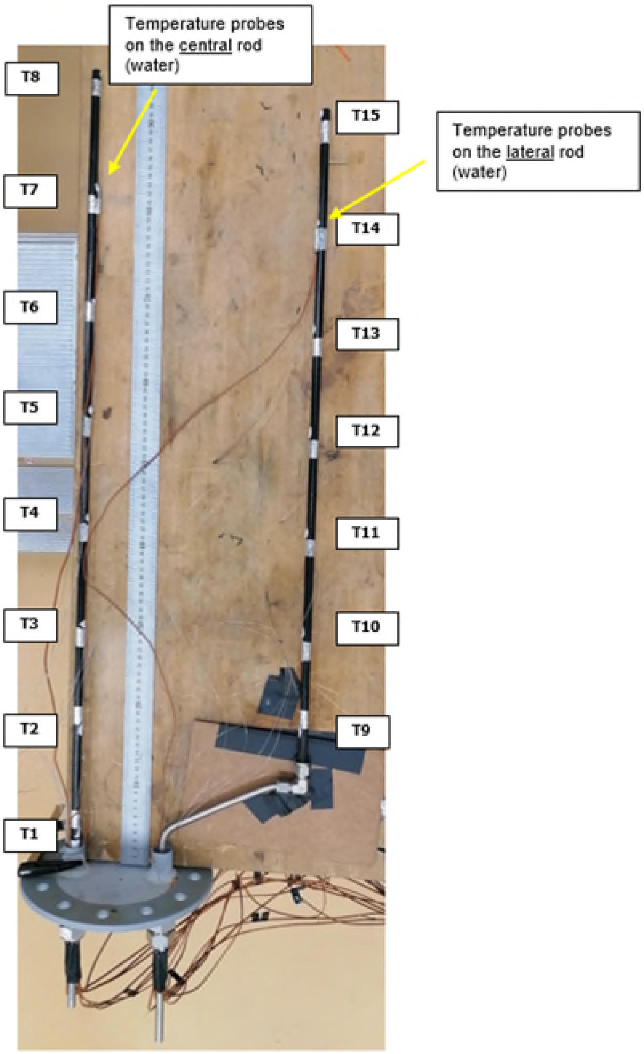
The test was carried out in climate chambers at Danish Technological Institute (DTI). A climatic cell makes it possible to recreate the heat source conditions specified by the normative. A DHW draw off bench was installed in order to carry out the required draw offs defined by the standard EN16147, and the power consumption was measured with a power analyzer ZES ZIMMER LMG450. A programmable control system governed the starting and stopping times of the heat pump, the DHW draw off timetables, regulation and control, etc. A computer-based data acquisition system was used to record the measurements at approximately 11 seconds interval during the test period.

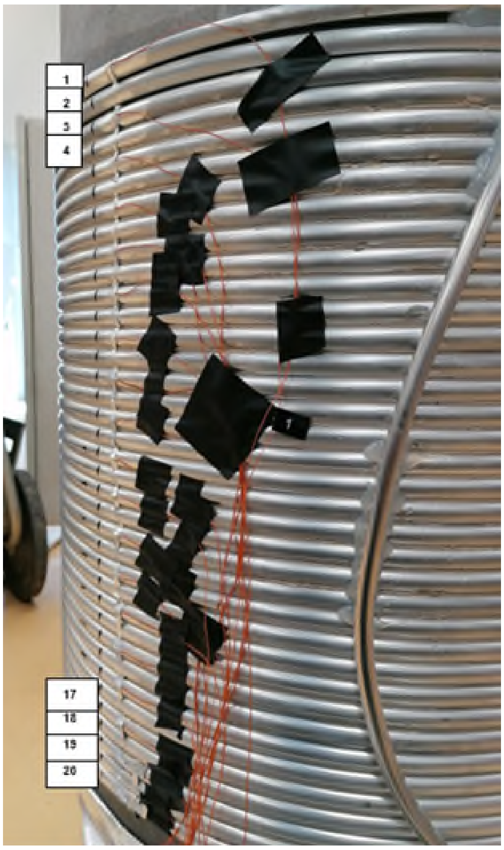
5.2.5 Instrumentation of water tank and condenser

Figure 12 shows a view of the tested storage tank with the wrapped around heat exchanger provided by Nilan A/S.

Figure 1: *Experimental set up of tested tank with wrapped around heat exchanger at DTU laboratory.*

The hot water storage is a key component of the heat pump, as its stratification determines the energy efficiency of the overall DHW production system. Thus, to characterize the stratification within the tank and the temperature variations during the charging and tapping processes, 16 PT-100 RTD temperature probes were installed in the storage tank. In particular, the probes installation aimed at analysing the vertical water temperature distribution at 0.125 m intervals close to the inner tank wall (7 probes on the lateral rod) and at 0.130 m intervals in the center of the storage (8 probes on the central rod). The vertical rods were inserted in the storage tank through the openings normally used for the recirculation pipes (Figure 13a) TC type thermocouples were used to measure the inlet and outlet water temperatures. The hot water storage was wrapped with an external condenser coil, and TC type sensors were used to analyse the vertical distribution of the outer surface temperature of the condenser coil wall in 20 points (Figure 13b). The insulation was set back once the sensors were placed in order to prevent heat losses. A Siemens MAG 1100 flow meter was used to measure the water flow rate during the tapping.





(a) (b)

Figure 2. (a)Temperature probes installed on the central and lateral rod measuring the temperature of the water stored in the tank. (b) Temperature probes installed on the condenser coil wall.

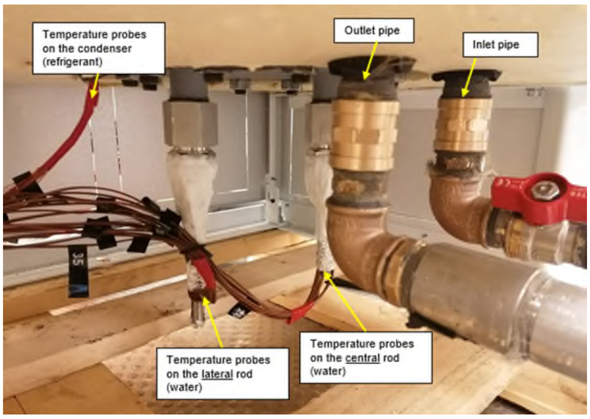


Figure 3. View of the inlet and outlet water pipes, of the vertical rods after the installation inside the storage tank, and of the temperature probes placed on the condenser coil wall.

The heat pump unit was equipped with temperature sensors (TC type) at the inlet and outlet of its components, and two Danfoss AKS33 pressure transmitters were placed at the inlet and outlet of the compressor. Dry and wet temperature of the air flowing through the evaporator, as well as the air volume flowrate, were also measured.

All the temperature probes were calibrated and determined to be precise to within 0.5 ºC.

Figure 15 shows the scheme of the tested exhaust air heat pump water heater and the position of the temperature and pressure sensors, and Figure 16 shows the test bench at the DTI Lab.

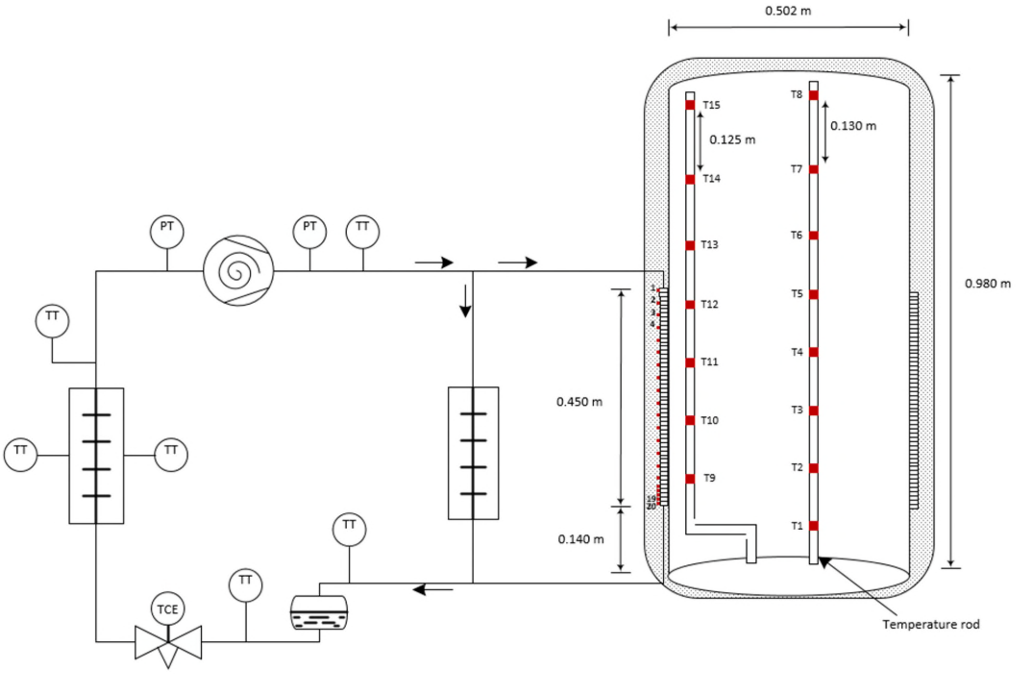


Figure15. Sketch of the tested storage tank with the position of the temperature sensors.

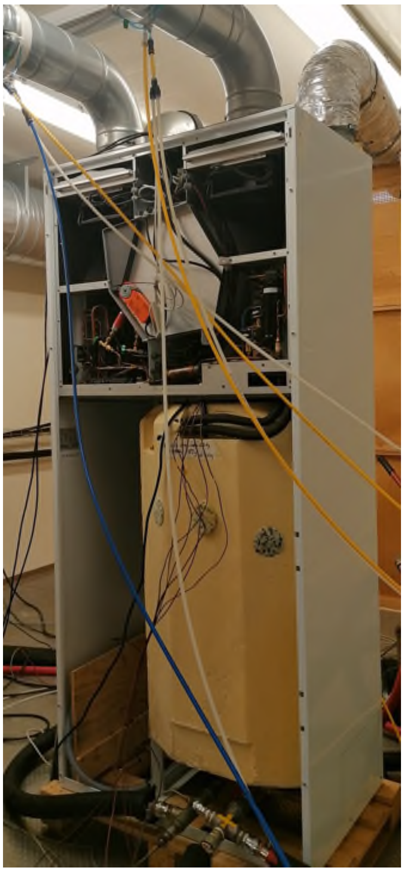


Figure 4. Experimental set up of the exhaust air heat pump at the DTI laboratory.

5.2.6 Normative test sequence

The experimental procedure followed the normative EN16147. The tank was initially filled with net water at the temperature of 10 ºC and perfectly mixed. At the instant time t = 0 s, the compressor was switched on, and the test started.

The operating conditions were:

- Exhaust air inlet-temperature (heat source): 21 ºC ± 2 ºC
- Exhaust air inlet-relative humidity (heat source): 60 %
- Exhaust air inlet-volume flowrate (heat source): 250 m^3/h ± 4 m^3/h
- Ambient temperature: 20 ºC
- Initial temperature of the water in the tank: 10 ºC
- Set point of the tank: 53 ºC ± 2 ºC
- Compressor speed: 50 Hz.

The test involved three phases which are presented in Figure 17.

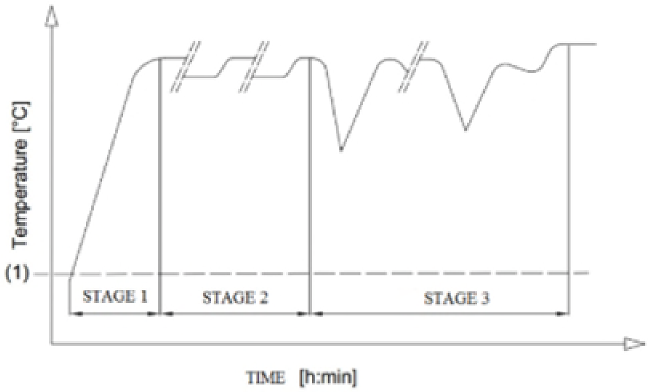


Figure 5. Phases of the EN16147 normative standard [1].

Phase 1 involved the process of heating water in the tank from an initial temperature (i.e., temperature of cold water) to a temperature that was demanded for the purposes of the cycle, i.e., in the range from 45-50 °C.

Phase 2 involved the determination of energy input by the heat pump in the conditions when it is in standby mode.

The final phase (phase 3) involved the determination of the energy use and coefficient of performance in the hot water production mode during the reference tapping cycle.

The duration of the measurements was 4 days from 26 November 2021 to 30 November 2021.

5.2.7 Correction for the pumps and fans

A further aspect to be considered when determining the COP is the power consumption of circulation pumps and fans. Some devices have hydraulic circulation pumps integrated into their design, whilst others are delivered without a pump. If these were disregarded, devices with integral pumps would be a disadvantage due to their higher consumption of electrical energy. In order to allow for this, the standard includes a correction for the pump. The correction is based on the measurement of the hydraulic capacity and on its conversion, using a virtual pump or fan efficiency factor, into an equivalent electrical input. This is then either added to the electrical energy consumption value or subtracted from it. Correction for the pump and fans affects the COP up to 0.3.

In the tested heat pump, the auxiliary devices are two fans of the type described in Table 11. It is to notice that the values presented in the result section regarding the electrical consumption of the heat pump during each different phase include electrical consumption of the fans.

5.2.8 Experimental results

In this section, the results of the different test phases are presented and discussed. Figure 18 shows the storage tank temperature measurements of the heating-up phase, and Figure 19 shows the measurement results of stage 2 (standby) and 3 (draw off). It may be seen that the water is heating up quite linearly interrupted by some disturbances, which intensify during the heating process. The gradients in these disturbances are extremely steep, and the measured temperature decreases so much in some parts, which would indicate an energy loss from the tank. It thus seems that the measurements have been affected by some kind of noise. Unfortunately, this was not discovered before the measurement campaign was over, and we did not have the possibility to repeat the tests. During the measurement campaign, a small leakage of water along one of the thermocouple threads was noticed. The water, unfortunately, collected in the Agilent data acquisition system. It might be that this was the reason for the noise.

In order to analyse the data, a data filtering of the measurements results on the storage tank side was carried out due to the measurements disturbances, mainly during the heating-up time. The data were filtered by means of the Hampel filter programmed in Python, which is an outlier detection algorithm. The Hampel filter is generally used to detect anomalies in data with a time series structure. It consists of a sliding window on the time series data, which has a parameterizable size. For each window, each observation is compared with the Median Absolute Deviation (MAD). In this study, the observation was considered an outlier in the case in which it exceeded the MAD by two times.

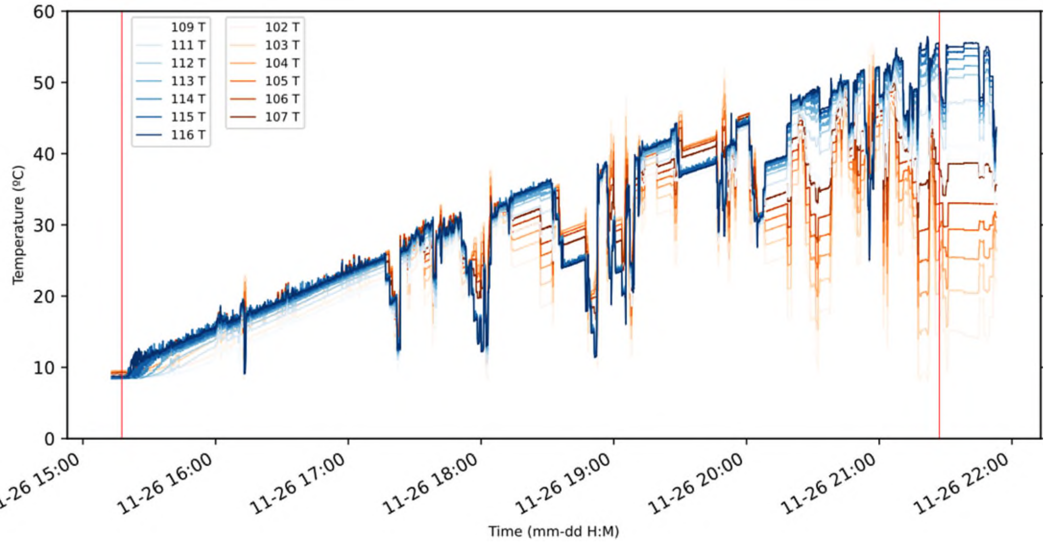


Figure 6. Measurement result of the heating-up phase (stage 1). Sensor 102T in the figure corresponds to the sensor named T2 elsewhere in this report. Sensor 103T corresponds to sensor T3 and so forth.

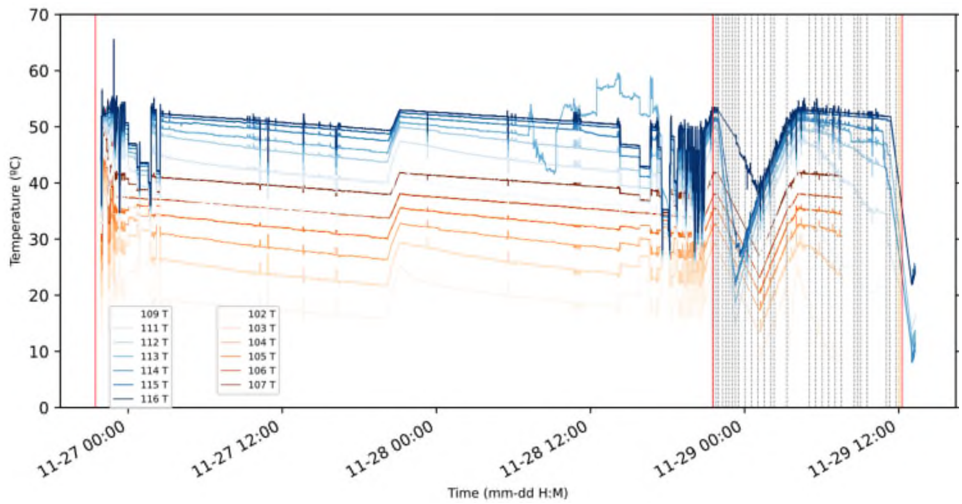


Figure 7. Measurement results of the standby (stage 2) and the draw off (stage 3) phases. The vertical dotted lines represent the time the draw offs were performed. Sensor 102T in the figure corresponds to the sensor named T2 elsewhere in this report. Sensor 103T corresponds to sensor T3 and so forth.

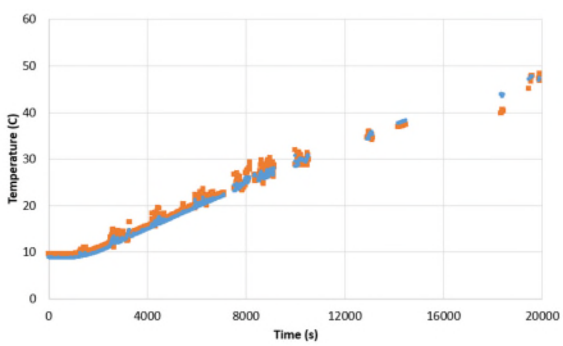
The measurement analysis showed that the thermocouple T1 was affected by measurement disturbances. This might be due to its location very close to the bottom flange of the tank (0.04 mm). This probe was therefore no longer considered in the analysis.

5.2.9 Heating-up time

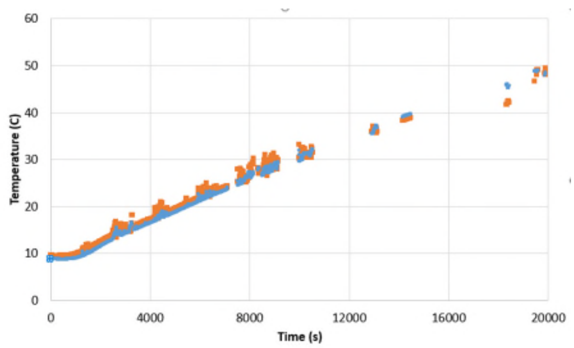
The heating-up time and the corresponding amount of electricity consumed were measured from the heat pump being switched on until it was turned off by the hot water thermostat, placed on the tank wall at 720 mm height from the tank bottom, when the temperature set point was reached. The tank set point was set at 53 ºC ± 2 ºC. During the test, the heat pump reached the set temperature of 6 h 10 min from the start of the heating process. The total electricity consumption (compressor, two fans, and controls) of the heat pump was at this time 2.52 kWh.

Figure 20 shows the evolution of the water temperature during the heating-up phase measured with the sensors installed on the central (blue) and lateral (blue) rod inside the storage tank. The central and lateral thermocouple placed at approximately the same height inside the storage tank are displayed in the same plot, i.e., T2&T9, T3&T10, T4&T11, T5&T12, T6&T13, T7&T14, T8&T15.

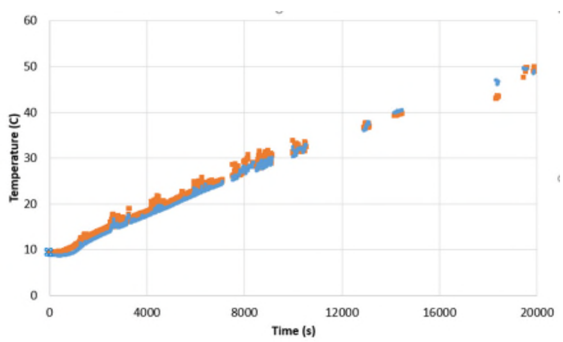
T9 T2



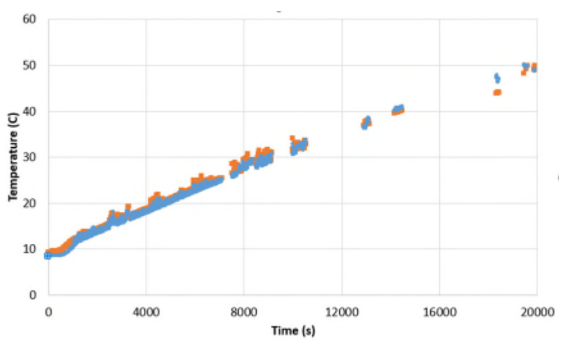
T10 T3



T11 T4

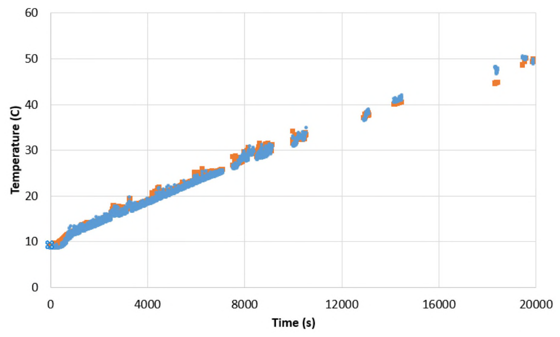


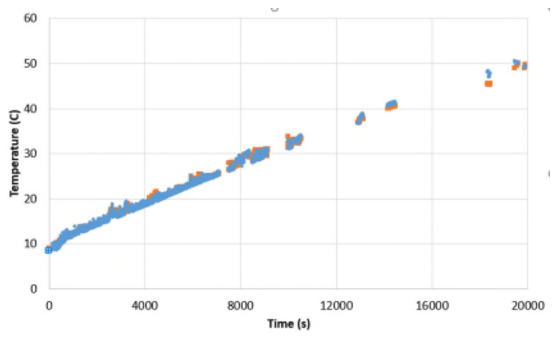
T12 T5



T13 T6

T14 T7





T15 T8

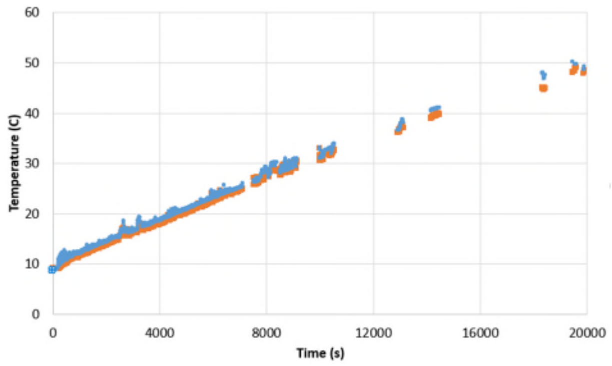
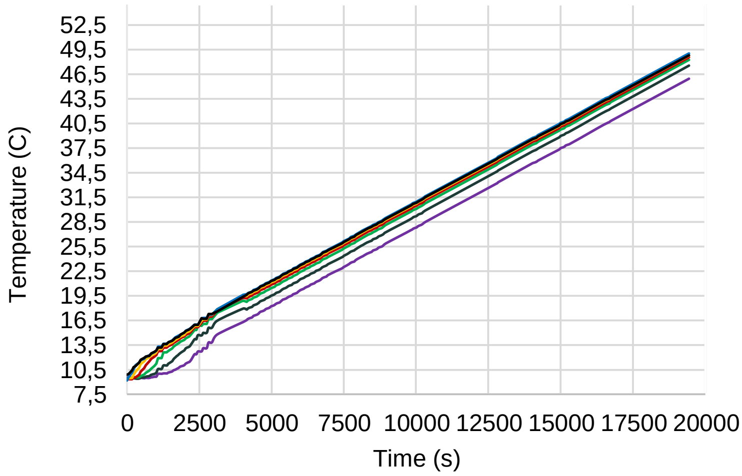


Figure 8. Temperature profile of each of the central (orange) and lateral (blue) sensors installed inside the storage tank.

The measurements show that the temperatures perceived by the sensors placed on the lateral rod from the bottommost to the one placed at approx. 800 mm were slightly lower than the temperatures measured by the corresponding sensors installed on the central rod. Instead, in the upper part of the tank, the water close to the inner tank wall is slightly warmer than that located in the center of the tank. This might be explained by the fact that the water starts being heated up in proximity of the tank wall, its density decreases, and convective movements bring it towards the upper part of the storage tank.

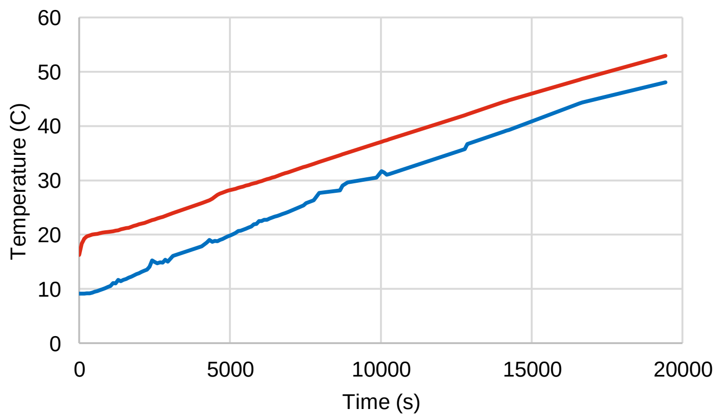
Figure 21 shows the temperature development of the water in the central part of the storage tank. In terms of temperature stratification, there is a difference between the bottom and the top of the tank of approximately 4 K during the first 40 minutes of the heating-up process. After this initial period, the temperature evolution of the water at different heights becomes almost linear, monotonically increasing curves that slightly tend to converge due to thermal diffusion. This transport phenomenon reduces the temperature gradient between the top and the bottom of the storage tank and promotes this convergence (Figure 21). The temperature difference between the bottom and top tank sides progressively reduces to approximately 2 K towards the end of the heating phase.



T8, T7, T6, T5, T4, T3, T2

Figure 9. Evolution of the water temperature in the central part of the tank, based on filtered data.

In Figure 22, the average condenser wall and the water temperatures are plotted during the heating-up phase. It can be seen that along the water heat up process, the condensing temperature increases. Furthermore, the temperature difference between the water and the condenser decreases during the heating-up process. This is most likely a result of the changing compressor capacity for changing condensing pressures as well as small changes in the heat transfer coefficients.



Average temperature of the condenser
Average temperature of the stored water

Figure 10. Evolution of the condenser temperature (red) and of the water temperature (blue) in the portion of the storage tank wrapped with the condenser coil.

In order to analyse the measurements in more detail, Figure 23 shows the temperature evolution at the surface of the condenser and the central storage tank water in the condenser area over the first 6 hours of heating. It can be observed that the condensing temperature rises with the increase in water temperature. From the stratification point of view, there is a slight difference from T5 to T2 in the storage: from approximately 3 K after 1 hour to 1.5 K at the end of the heating process. It can be observed that the pinch point of the condenser is located in the upper part of the condenser. This is one of the constraints to consider when positioning the condenser in order to optimize the heat transfer. Indeed, as [2] demonstrated, the condenser should be placed at the lowest part of the storage tank to improve the stratification, reduce the condensing pressure and optimize the system performance.

In terms of subcooling, the refrigerant exits the condenser with a subcooling of approximately 1 K during the heating process. It is to notice that the refrigerant circuit is provided with a liquid receiver, which guarantees the liquid state at the inlet of the expansion valve. The liquid receiver prevents the system from any significant subcooling being generated in the condenser as there will always be saturated conditions inside the receiver.

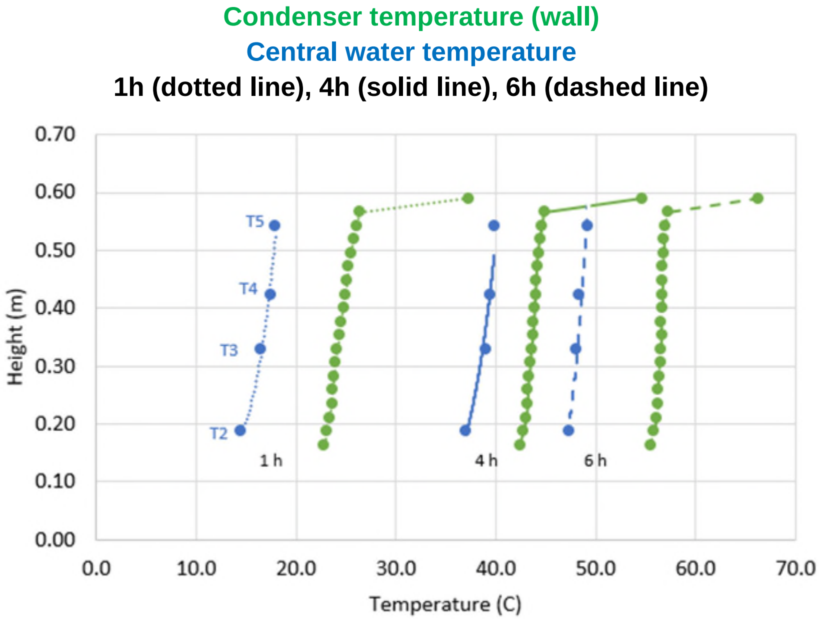


Figure 11. Temperature evolution of the central water in the storage tank and condenser surface temperature.

Figure 24 and Figure 25 display the suction and discharge pressures, and the condensation and the evaporation temperatures. It can be noticed, as on the condensation side, that the pressure and the temperature increase progressively during the heating process, while the evaporation temperature and pressure remain quite constant. During the operation of the heat pump, the condensation pressure was equal to approximately 20 bar at a maximum.

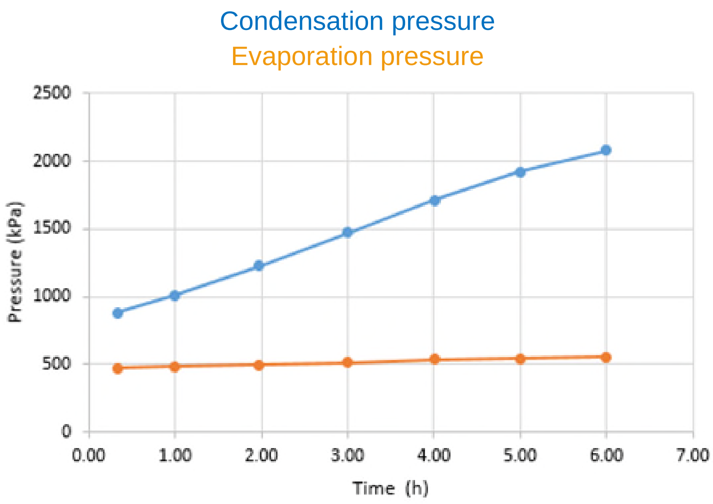


Figure 12. Condensation and evaporation pressures during the heating-up phase.

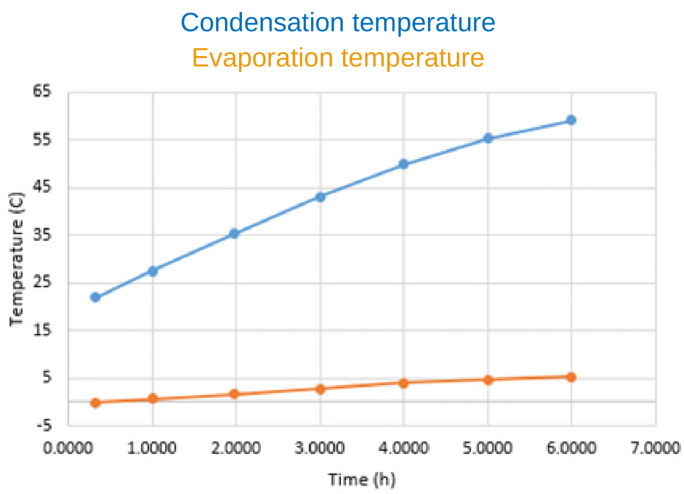


Figure 13. Condensation and evaporation temperatures during the heating-up phase.

The subsequent chart in Figure 26 presents the values of the temperatures measured after the compressor and at the outlet of the condenser. We can note that the discharge temperature increased to nearly 71 ºC, and the heat delivered to the water in the tank led to the decrease of the temperature at the outlet of the condenser to a value in the range of 20-60 ºC.

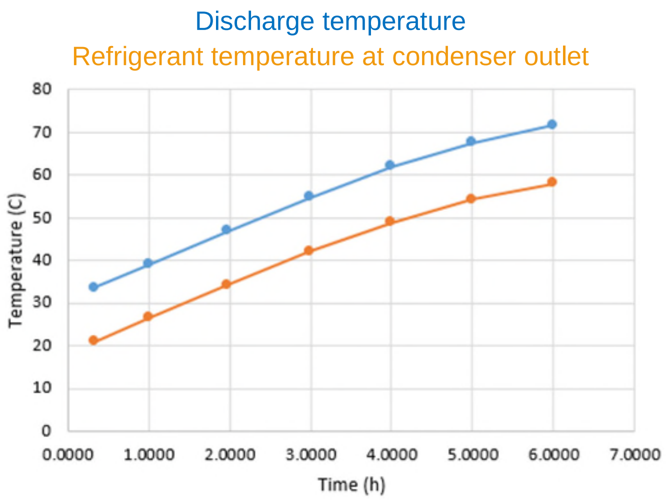


Figure 14 . Discharge temperature from the compressor and condenser outlet temperature during the heating-up time.

5.2.10 Standby

The heating-up phase was followed by a standby period, which is a stabilization period without water extraction from the tank.

The standard defines as outcome of this phase the total electrical consumption of the heat pump during the last on/off cycle ($W_{es,HP}$). The measurements showed a value of 2.5 kWh. The last on/off cycle lasted 24 h (t_{es}). Therefore, the standby power input (P_{es}) resulted to be 0.1 kW.

Figure 27 shows the average tank temperature during the standby period, which lasted 48h.

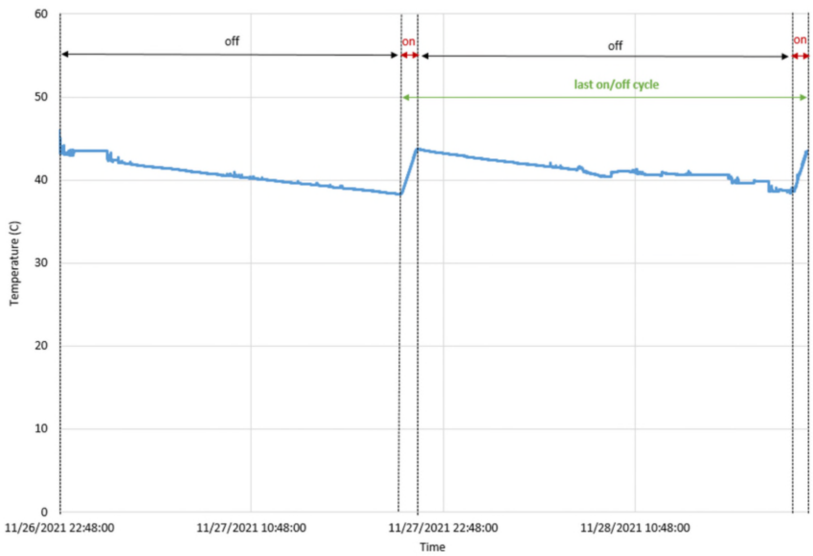


Figure 15. Average tank temperature during the standby phase.

It can be noticed that the control of the heat pump is such that when the tank set point sensor perceives a temperature of 52 ºC ± 2, the average tank temperature is allowed to vary in the range 39-45 ºC

5.2.11 Draw off

The standby period was followed by the water draw off phase, when a variable amount of energy was extracted from the storage tank, according to EN16147. The standard defines five water tapping cycles, ranging from S to XXL. These cycles vary in terms of the minimum volume of tap water use and daily profile of its tapping cycle.

The decision regarding the water tapping cycle applied in the test of a particular heat pump is made by the manufacturer of the equipment. The XL cycle was chosen for the test conducted in this study, and Figure 28 contains its detailed profile.

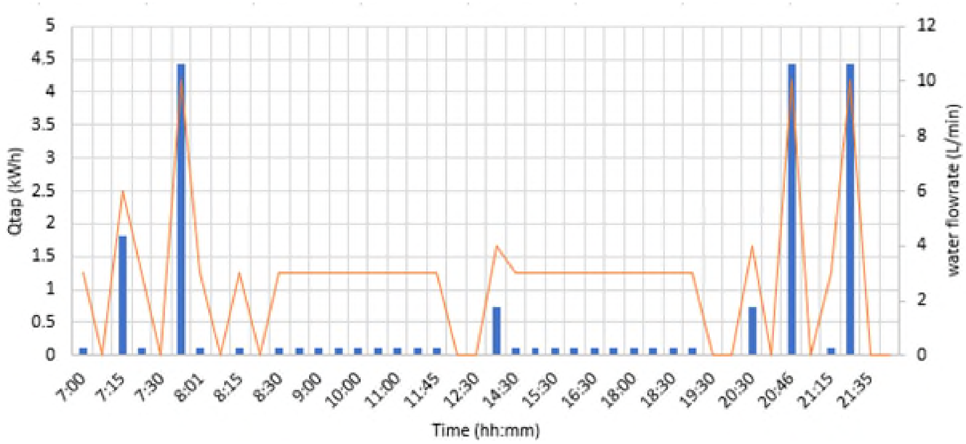
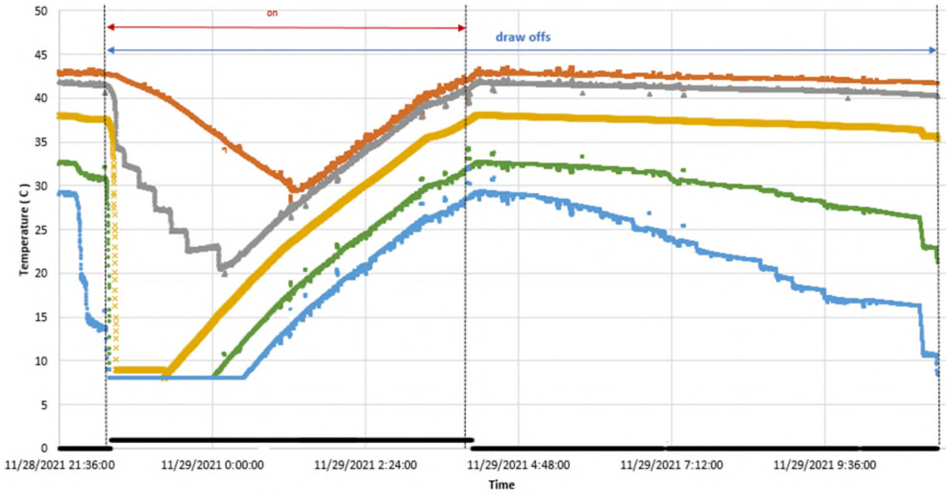


Figure 16. Tapping cycle profile XL.

Based on the analysis of the tapping profile shown above, it is to be noticed that the greatest hot water consumption happens between 7:15 and 8:00 and from 20:45 to 21:30. The XL profile results in a total thermal energy consumption of 19.07 kWh/day.

Figure 29 shows the experimental data obtained from the temperature measurements perceived by the sensors installed on the central rod during the draw off phase.

For some tapping, a water temperature of 45 K above cold-water temperature was required. However, the required temperature cannot always be achieved by the heat pump. In these cases, it was assumed for the calculations that an electrical resistance heater is used to provide the additional temperature increase. Consequently, the electrical consumption of this resistance was considered during the calculation of the final COP. According to the norm, only the DHW useful thermal energy must be used in the calculation, resulting in a COP of 2.25.



T3, T4, T6, T7, T8, **Compressor on** signal.

Figure 17. Temperature profile of the water in the tank (sensors T8, T7, T6, T4 and T3) during the draw off phase.

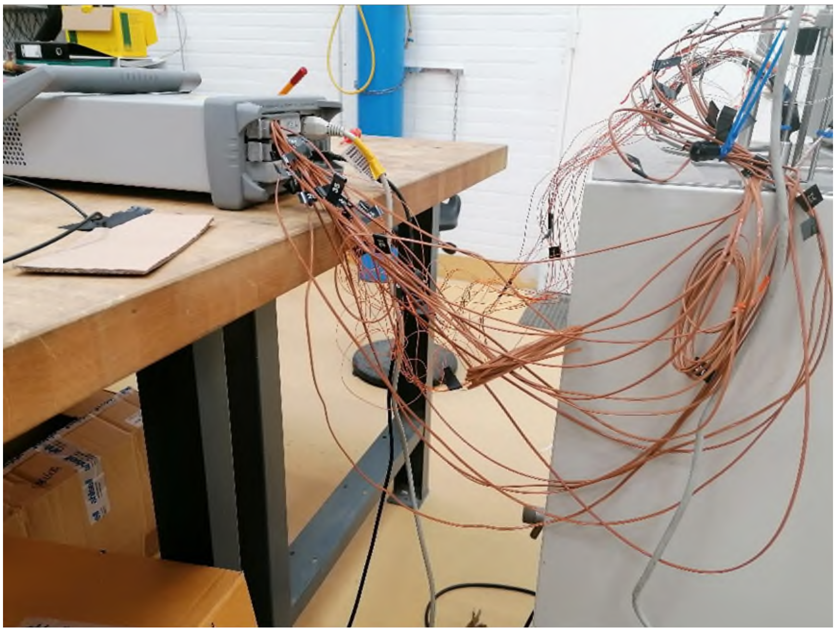


Figure 18. Calibration of thermocouples.

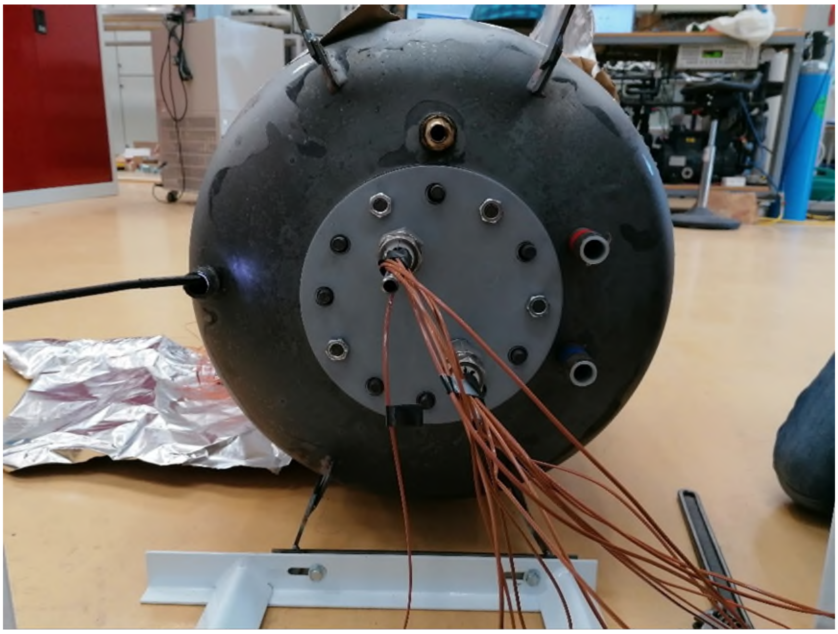


Figure 19. Bottom part of the tank. Investigation of the inside of the storage by means of a camera.

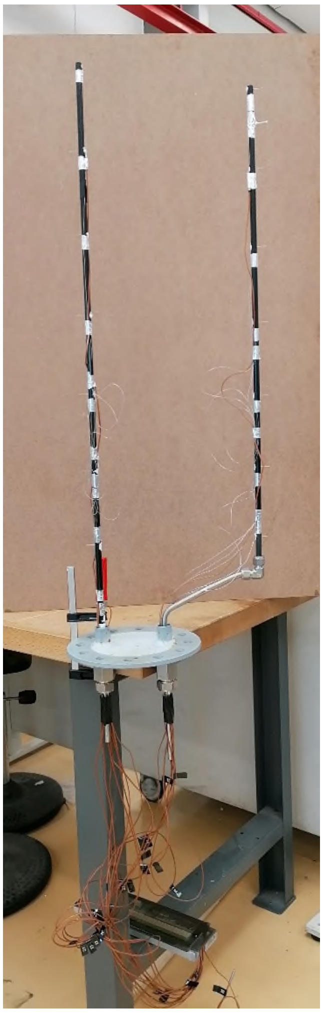


Figure 20. Lateral and central rods installed inside the tank, through the bottom flange.

5.2.12 Conclusions

An experimental study where a heat pump for domestic hot water production that uses exhaust ventilation air from buildings was carried out according to the EN16147. The results from the experimental work have been used to identify a value of the COP of the heat pump with the tapping cycle XL, whose value is 2.25.

The experimental set up also allowed the analysis of the water storage tank and its interaction with the heat pump. Unfortunately, the measurement data seem to have been affected by noise, which had to be removed through a filtering of the data for the analysis. The filtered data showed insights to the stratification in the tank during heating up, standby and tapping periods. The data will be valuable for further validation of a numerical model of a propane heat pump. However, in order to better understand the interaction between the condenser and the water in the tank, the measurements should be repeated in a new measurement campaign, taking into consideration all the learnings we got from the first measurement campaign.

5.2.13 References

[1] Boccia, R., Salgado Fuentes, V., Jensen, J. K., Pedersen, P. H., & Markussen, W. B. (2021). Dynamic modelling of performance and refrigerant charge distribution of an Exhaust Air Heat Recovery Ventilation Heat Pump. In *Proceedings of the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems 2021* (pp. 1553-1564). ECOS.

[2] "Dymola - Dassault Systèmes®," (2017).

[3] "Modelica Association," (2017). https://www.modelica.org.

[4] "TLK-Thermo GmbH," (2017). https://www.tlk-thermo.com.

[5] "TILMedia Suite," (2017). https://www.tlk-thermo.com.

[6] European Standard, "EN 16147 - Heat pumps with electrically driven compressors. Testing, performance rating and requirements for marking of domestic hot water units," (2017).

6. Utilisation of project results

The international regulation of F-gases in the EU and on global scale (the Kigali amendment to the Montreal Protocol) will force manufacturers of heat pumps to change to low-GWP refrigerants including R290 (propane) or other flammable refrigerants. Nilan is preparing to implement that change, and the results from this project will be a part of that change.

Heap pump manufacturers will, however, also prepare for the change at the production lines inside the production facility. This has to be done at the factory in Hedensted, where Nilan's heat pumps are manufactured. It is very important that the introduction of flammable refrigerants at the production lines will not compromise safety.

Nilan has developed a strategy for that change, and this strategy was presented at the final meeting in this project on 29 June 2022 in Hedensted. This presentation will be a confidential enclosure to this report.

6.1 Dissemination

The research carried out by the Ph.D. student in this project has been disseminated in papers and oral presentations at two international conferences. One paper was presented at the 14th IIR Gustav Lorentzen Conference on Natural Refrigerants, GL2020, and one paper was presented at the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS2021. Due to the pandemic, both conferences were held online. The presented papers are attached in Appendix.

Internally at DTU, the project was presented to students in the course "Refrigeration and Heat Pump Technology" in 2019 and 2020. Furthermore, the project provided the foundation for one special course entitled "Design of a ventilation air heat pump system for a single family house" carried out by M.Sc. student Matteo Daminato and one master's thesis entitled "Performance evaluation of ventilation exhaust air heat pumps with low GWP refrigerants" by Albert Frederik Bruun-Guassora. A link to the master's thesis is provided in Appendix.

Finally, the project opened a possibility for a new collaboration between a research group at UPV Universitat Politècnica de València and DTU Mechanical Engineering. The researchers at UPV are very experienced in the field of heat pumps with natural refrigerants, in particular propane, and charge minimization, and the PhD could benefit from this experience during her external stay at UPV.

7. Project conclusion and perspective

In this project, a new concept for Nilan's ventilation heat pump has been developed using R290 (propane) as refrigerant.

In the first part of the project, a standard version of Nilan's ventilation heat pump was tested at Danish Technological Institute in Aarhus.

The results were the basis for the further development work. The results were also used by DTU MEK to develop a calculation tool, and this was used in developing the concept for a prototype using R290 refrigerant.

The use of flammable refrigerants (e.g. R290) requires safety issues, and this theme has been discussed continuously during the project. This theme also follows the international development of safety standards which are in continuously development during the project.

A first prototype was constructed by Nilan with a new refrigeration system and alternative placement of components to ensure a smaller volume inside the refrigeration system and a better air flow through the appliance including the internal passive air-air heat exchanger. The first prototype still uses R134a refrigerant. The first prototype was tested at Nilan and showed a better performance compared to the standard unit.

This showed that the new concept for air flow, a smaller refrigerant charge and component placements were the right ways to go.

A second prototype was constructed by Nilan. Now the refrigerant was R290. Before the construction was started, the water tank was sent to DTU for installation of several thermocouples inside and outside the tank. The tank and data collecting equipment was returned to Nilan, and the tank was insulated and built in the second prototype.

The second prototype was tested after EN16147 (the tap test of hot water), and an accredited test report was made. The result following the L tap profile was very good. The COP was measured to 3.75 which places the unit in Energy class A++. The similar result for the basis model was COP = 2.09 and energy class A. This test was conducted following the XL-tap program.

The result for prototype 2 for tap water heat pump test is satisfying.

The test result for the passive heat exchanger was also satisfying for the prototype. The efficiency for the internal (passive) heat exchanger is significantly better for the prototype compared to the basis model.

The test for the heat pump heating incoming air (from outside) after internal heat exchanging with exhaust air was not that satisfying, when the air was +7 C (simulating wintertime). The evaporator creates ice on the surface and frequent de-icing is necessary. It seems like the evaporator is too small. It should not be necessary to de-ice at an air temperature of +7 C. The evaporation temperature is too low.

Therefore, the efficiency of the heat pump in this situation is slightly lower compared to the basis model and prototype 1. This is a theme that Nilan will work further with during the commercialization of the R290 unit.

The experimental set up in the second prototype connected to the PhD part of the project showed interesting results. It showed stratification in the hot water tank – both during the heating up and during the draw off phase during the tests. The stratification is important for the efficiency of the heat pump during water heating because it reduces the condenser temperature and hence increases the efficiency (the COP).

It also shows that the placement and the way the condenser pipe is wrapped around the lower part of the water tank works well and is the correct placement for the condenser.

There were some electrical noises during the heating-up phase of the test with the result that some of the data during this phase are not useful. It would be beneficial to make further tests with the prototype, and this time in the L tap profile which fits better to the appliance.

8. Appendices

Enclosed appendices:

Boccia, R., Salgado Fuentes, V., Jensen, J. K., Pedersen, P. H., & Markussen, W. B. (2021). Dynamic modelling of performance and refrigerant charge distribution of an Exhaust Air Heat Recovery Ventilation Heat Pump. In *Proceedings of the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems 2021* (pp. 1553-1564). ECOS.

Boccia, Rossana; Salgado Fuentes, Valentin; Jensen, Jonas Kjær; Markussen, Wiebke Brix. Heat Recovery Ventilation Heat Pump Water Heaters: Status of the Art and Transition to Propane. Published in: Proceedings of the14th IIR-Gustav Lorentzen Conference on Natural Refrigerants.

Dynamic modelling of R134a-based Exhaust Air Heat Recovery Ventilation Heat Pump. Boccia, Rossana; Markussen, Wiebke Brix. DTU MEK 2022.

Detection of R290 leaks in RACHP equipment using ultrasonic detection system. D. Colbourne, A. L. Vonsild, K. O. Suen. Not yet published.

Danish Technological Institute: Accredited Test report KLAB 300-19-007 Tap test of basic model. 2021.

Danish Technological Institute: Presentation of the results of tap test for prototype 2 in XL-tap profile.

Danish Technological Institute: Accredited test report KLAB 300-21-053. Tap test of prototype 2.