SUSHEAT

Smart Integration of Waste and Renewable Energy for Sustainable Heat Upgrade in the Industry

D3.3 Heat Pump Performance and COP

Document Summary Information

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Executive Summary

The SUSHEAT project's Task 3.3 focused on optimizing heat pump COP for the 200 kW HoegTemp heat pump. The work includes various types of simulations as well as extensive testing of industrial heat pumps in operation. The results from analyses and operational data have been compared.

A broad spectre of operational parameters has been tested. This includes tests with “normal” and increased compression ratio, a broad spectre of combinations of rotational speed and working medium charge pressure, different working mediums (helium, nitrogen and argon), different physical setup regarding heat losses on main components and operation at different combinations of sink- and source temperature.

This work establishes a better understanding of how to achieve optimal COP during operation of the stirling heat pump, contributing significantly to SUSHEAT's goals of sustainable heat upgrade solutions for the industry.

The updated and experimentally validated simulation model has been used to optimize the circuit performance, by varying the design parameters and operating parameters.

The simulations indicate that it will be possible to achieve the COP target of 2.8 at temperature ratio of 1.2, of KPI 1.

Revision history (quality control)

Version	Issue Date	% Complete	Changes	Contributor(s)
V1.0	2025-07-04	100%	First draft	Arne Høeg (ENER), Torgrim Aase (ENER), Tobias Dahl (ENER)
V1.0	2025-07-04	75%	Initial Deliverable Structure	Arne Høeg (ENER), Torgrim Aase (ENER), Tobias Dahl (ENER)

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Glossary of terms and abbreviations

Acronyms

COP	Coeficient Of Performance
DoA	Description of the action
GA	Grant Agreement
KPI	Key Performance Indicator
ODP	Ozone Depletion Potential

Symbols

Greek letters

Subscripts

1. Introduction

The 200 kW HoegTemp heat pump is a 3-cylinder 2-circuit Stirling-cycle heat pump.

D3.3 is the first deliverable towards KPI 1:

> *Heat upgrade from ambient, waste energy & RES, at the range of 0 – 100 ºC, up to 250 ºC. Stirling-based heat pump working with helium -non-toxic, inert, zero ozone depletion potential (ODP) and zero global warming potential- with a COP > 2.8 for a temperature ratio of 1.2. Long term production cost (2030) of 100 €/kW.*

A 1-dimensional finite element simulation model has been developed in the simulation software SAGE (of Athens), the best documented simulation software for stirling machines. The model includes both circuits, with all the volumes included.

Work has included performance mapping across the temperature range, testing across the range of temperature ratios, sensitivity analysis for different loss mechanisms, and optimization for higher efficiency and moving the Pareto front for capacity and efficiency.

The main objective of Task 3.3 has been to achieve a simulated performance of COP > 2.8 at a temperature ratio of 1.2 K/K, a 47% Carnot efficiency.

Table 1. Adherence to SUSHEAT's GA Deliverable & Tasks Descriptions. [1]

TASKS	
Task 3.3 COP Optimization	**Section Work Package 3, DoA (Part A)**
Any given Stirling machine is optimized to work at a given relation between source and sink temperatures. Consequently, as the working conditions change from the current to higher temperatures, an optimization COP must be performed. Optimization is done by state-of-the-art Stirling simulation software, where simulations and actual performance of the current heat pump design is used as reference. The optimization will lead to recommendations for change of heat pump parameters (typically compression ratio, heat exchanger length, gas path dimensions etc).	All sections below are reports of work that has gone into Task 3.3, which is the task required to complete Deliverable 3.3. - Section 1 defines the task scope and outlines the context for the COP optimization. - Section 2 supports material selection and sealing strategy by establishing boundary conditions. - Section 3 documents results from testing - Section 4 proposes improved sealing configurations and suggestions for test plans. - Section 5 synthesizes results and presents a recommended sealing setup for the upcoming SUSHEAT test rig.
DELIVERABLE	
D3.3 Heat Pump Performance and COP	**Section Work Package 3, DoA (Part A)**
Expected performance and COP across the case study temperature range. The simulation models and the results derived from them will be presented. (T3.3).	All sections below are reports of work that has gone into Task 3.3, which is the task required to complete Deliverable 3.3.

This report demonstrates adherence to the objectives by covering simulation, design, material selection, testing, and proposed improvements, supporting Deliverable D3.3 requirements.

1.1. Deliverable Overview and Structure

This deliverable documents the modelling of the Stirling circuit, the experimental validation of the simulation model, the sensitivity analysis for the most important loss mechanisms, and the parameter optimization towards the goals of KPI 1.

Process simulation analysis presents detailed Sage analysis results of the double-acting gamma configuration heat pump, establishing temperature profiles and operating conditions across the system. Sage of Athens is a simulation code especially suitable for Stirling-cycle machines. This work provided essential boundary conditions for subsequent analyses and material selection.

Laboratory and site testing with several different working media, at many combinations of operating conditions, through more than 11 000 hours.

This work directly addresses Task 3.3 requirements for performance and efficiency. The findings are supported by detailed technical data, simulations, and experimental results presented in subsequent sections.

2. Process simulation and analysis

The stirling cycle is not fully understood or documented in the scientific literature, however

Martin [2] gives a good overview of analytic methods. A more ambitious work on methodology and an attempt to develop a set of dimensionless parameters for stirling cycle design and optimization was done by Organ, and one of his most comprehensive overviews is given in [3]. Most of the available methods and relationships are developed for high-temperature stirling engines, while the first ground-breaking work on low-temperature stirling engines was performed by Kolin [4]. Høeg [5] laid out the groundwork for combining the above mentioned methods and applied them for medium-temperature stirling engines, while the optimization strategy has been described by [6].

Even though the above mentioned methods and optimization strategies are well-founded, an approach combining modelling and experimental validation of the simulation model was considered necessary to improve on documented earlier work such as [7].

The main goal of the simulation was to achieve a level of confidence required to be able to optimize the process parameters to achieve the project KPI regarding performance and efficiency.

2.1. Sage simulation model

The heat pump Stirling cycle has been simulated in detail using Sage [8]. The HoegTemp heat pump has two circuit pairs in the SUSHEAT version, in a double-acting gamma configuration, where one power piston separates two similar gamma circuits with a displacer piston and 2 sets of heat exchanger bundles, one on each side. The simulation model is described in Fig. 1 to 3.

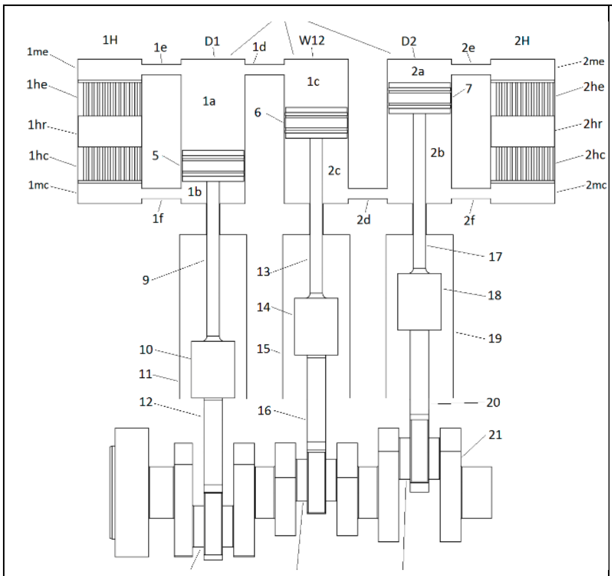

Fig. 1. A principal drawing of the circuit pair, showing the difference between the two circuits, where the power cylinder volumes are connected to the top volume in one circuit and the bottom volume in the other.

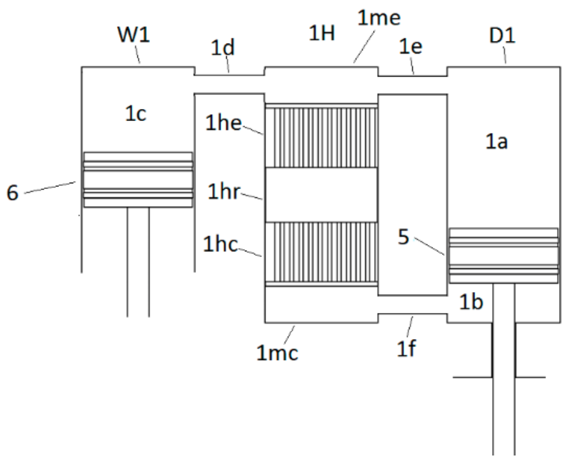

Fig. 2. Representation of the principal layout in one of the circuits in the circuit pair, with a common manifold. The two physical heat exchanger bundles are treated as one, with equivalent parameters.

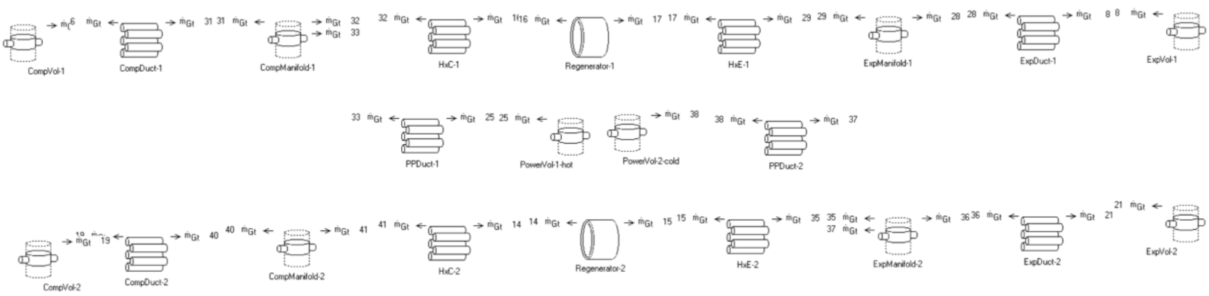

Fig. 3. Main elements of the gas circuit model.

The SAGE simulation model used in the work (internally named Gamma-V-2x49) represents the 2 circuits as

- One displacer cylinder, containing the hot cylinder volume CompVol-1 and cold cylinder volume ExpVol-1, separated by Displacer-1 (not shown in Fig.3.)
- The 3-way manifold CompManifold-1, connecting the hot cylinder volume CompVol-1 and the hot power cylinder volume PowerVol1hot via ducts
- The heat exchanger bundle of circuit 1: the heat exchangers Hxc-1, Regenerator-1 and Hxe-1, between the manifolds CompManifold-1 and ExpManifold-1
- One power cylinder, containing the Power piston separating the cylinder volumes PowerVol1hot and PowerVol2cold
- The 3-way manifold ExpManifold-2, connecting the cold cylinder volume ExpVol-2 and the cold power cylinder volume PowerVol2cold via ducts
- The heat exchanger bundle of circuit 2
- Leakage paths past the piston rings from CompVol-1 to ExpVol-1, from CompVol-2 to ExpVol-2, and from PowerVol1hot to PowerVol2cold.

The SAGE simulation software includes advanced models for each stirling machine component, including internal losses and heat transfer in each component. In addition, the following loss mechanisms have been modelled separately, as decoupled losses:

- Shuttle losses around the pistons, and conduction through the piston domes and cylinder walls
- Conduction through the heat exchanger housing walls
- Heat transfer to and from the surroundings
- Friction and drive losses (motor/VFD)

2.2. Relations and Sensitivity

The heating capacity of a Stirling-cycle heat pump is generally proportional to charge pressure, circuit swept volume, number of circuits and shaft speed. There is a trade-off between efficiency and heating capacity, as shown in Fig. 4.

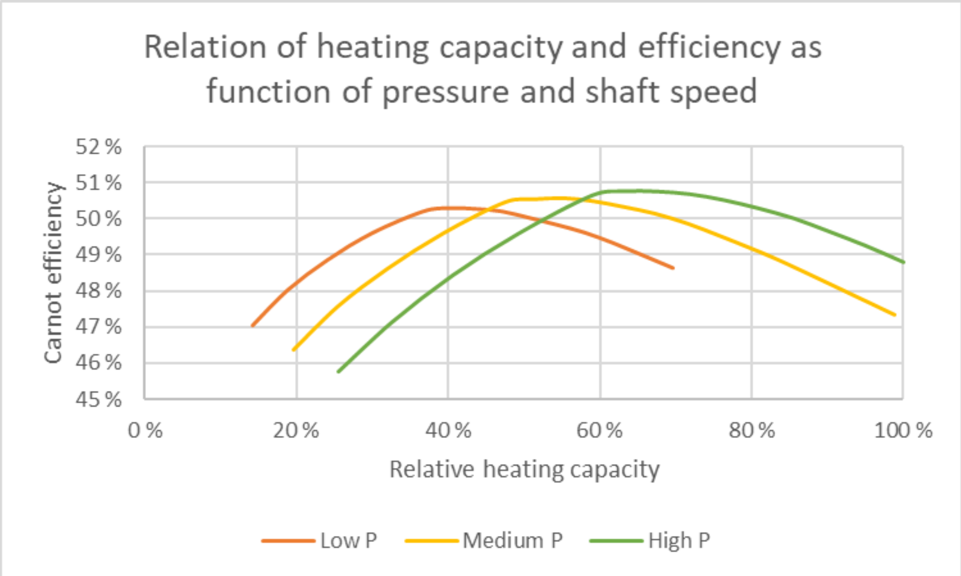

Fig. 4. Effect of charge pressure on performance

The heating capacity of a Stirling-cycle heat pump increases slightly with the temperature ratio, while the Carnot efficiency generally increases with temperature, as shown in Fig.5. Removing the electrical input would be the Carnot cooling efficiency, which shows a peak around 1.4 K/K and tapers off for lower and higher temperature ratios.

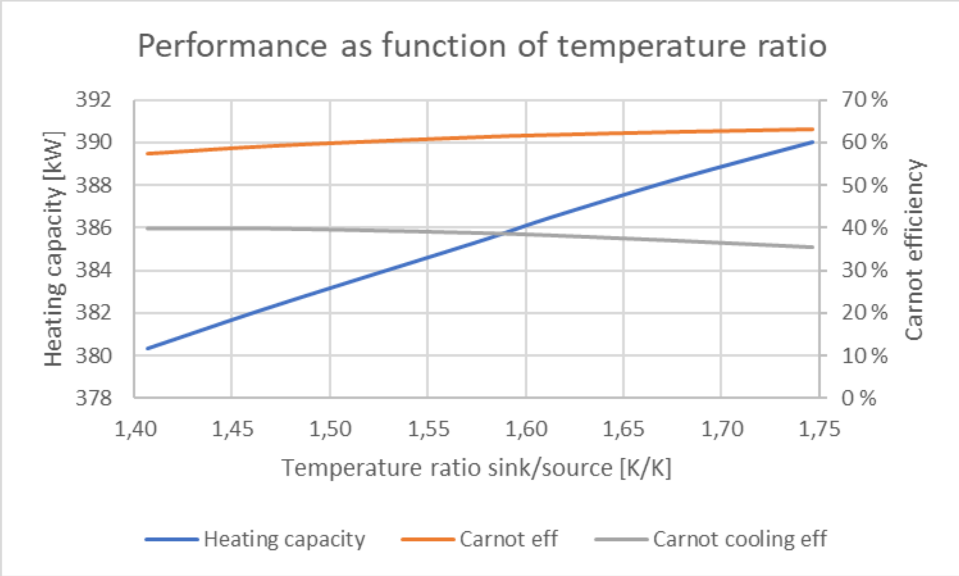

Fig. 5. Heating capacity and efficiency as a function of temperature ratio

The greatest challenge in modelling the Stirling cycle is getting the details of the loss mechanisms correct. Sensitivity analyses have been performed for the most important mechanisms.

Leakage past the power piston rings shows that increasing leakage increases the power consumption and the cold-side temperature significantly and reduces the heating capacity to a lesser extent. This is shown in Table.2.

Table 2. Sensitivity for power piston gas leakage

Model		Gamma-U-2x49			
Version		4	5	6	7
Piston ring gap	µm	10	25	50	100
Relative heating capacity	kW	100 %	100 %	99 %	95 %
Relative power consumption	kW	86 %	88 %	91 %	100 %
COP at 1.42 K/K		1,9	1,9	1,8	1,6
Carnot eff		57 %	55 %	53 %	47 %
Cold cyl temp	°C	7	15	28	72

Leakage past the displacer piston is less critical than past the power piston, as shown in Table 3.

Table 3. Sensitivity for displacer piston leakage

Model		Gamma-U-1x49			
Version		9	10	11	12
Displacer ring gap	µm	10	25	50	100
Relative heating capacity	kW	100 %	100 %	100 %	98 %
Relative power consumption	kW	100 %	100 %	100 %	100 %
COP at 1.42 K/K		1,9	1,9	1,9	1,8
Carnot eff		56 %	56 %	56 %	55 %
Cold cyl temp	°C	-3	-3	-2	7

The quality of heat exchanger flow patterns is important for efficiency as well. Table 4 shows the significance of the Bernoulli loss factor for the heat exchanger tubes.

Table 4. Sensitivity for pressure drop in heat exchangers

Model		Gamma-U-1x49	
Version		14	15
Bernoulli loss factor	K	1,5	15
Relative heating capacity	kW	98 %	100 %
Relative power consumption	kW	92 %	100 %
COP at 1.42 K/K		1,9	1,8
Carnot eff		55 %	52 %

3. Laboratory and site testing

More than 11 000 hours of testing have been logged in 3 operational heat pumps at 3 sites, including one belonging to SUSHEAT partner Pelagia. Source temperatures have varied from 14 to 44 °C, while sink temperatures have varied from 126 to 199 ºC. The tested operating points are summarized in Fig, 6.

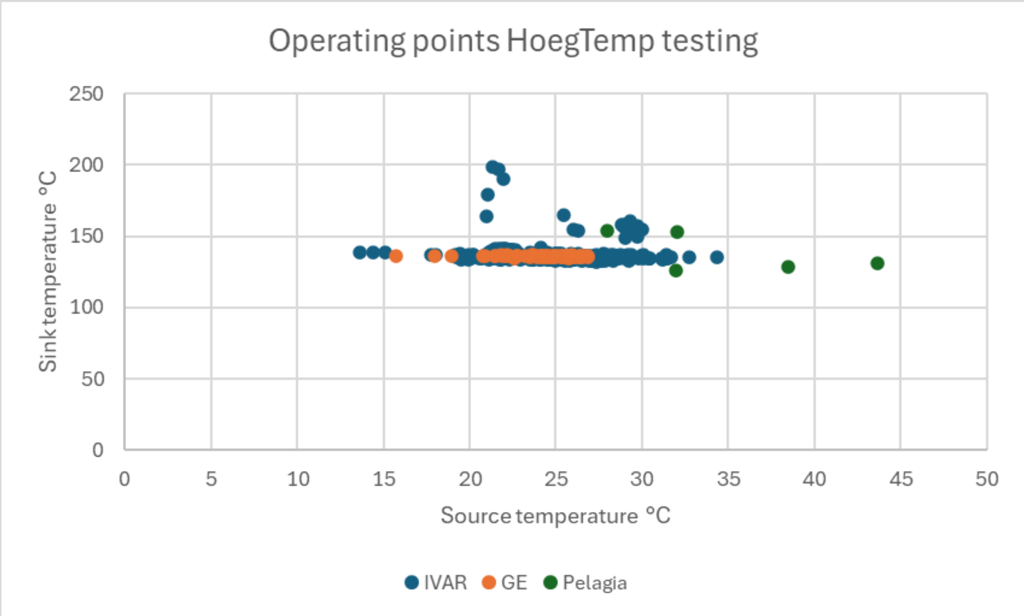

Fig. 6. Operating points tested

Simulations have shown that the COP of Stirling-cycle heat pumps is a function of the temperature ratio between the sink and the source temperatures (in Kelvin), and the temperature ratios during testing have ranged from 1.28 to 1.6 K/K. Achieved COP values are plotted against temperature ratio for the 3 operational heat pumps, in Fig. 7. Fig. 7 also shows a data point where a heat pump is tested with nitrogen instead of helium, a test performed for experimental validation of the simulation model.

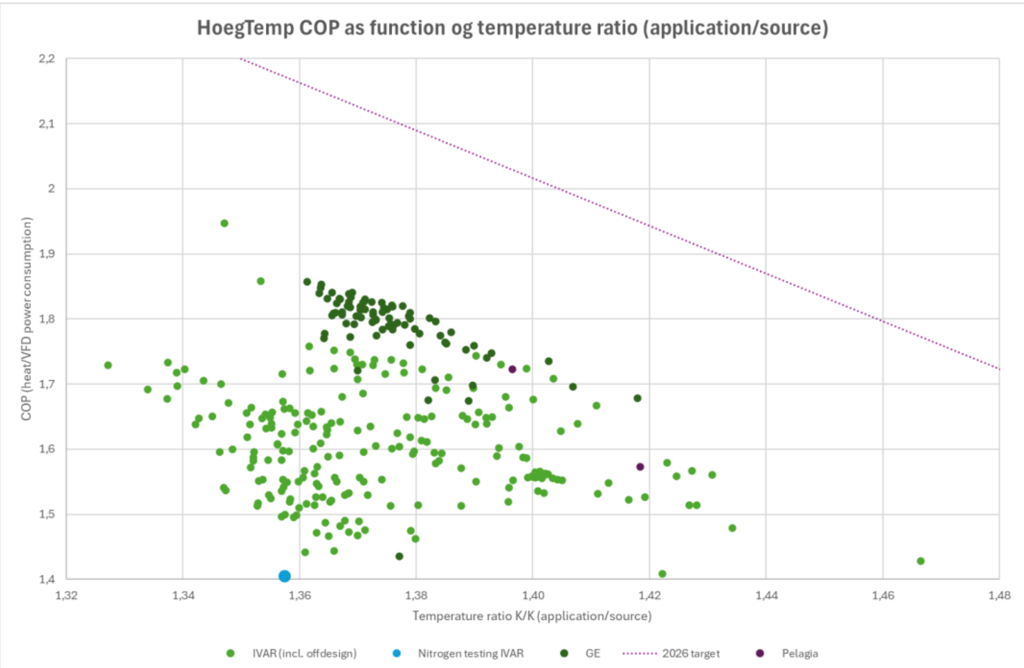

Fig. 7. Measured performance

KPI 1 sets a COP target of 2.8 at 1.2 K/K, and the operating range from 0°C to 250°C allows a temperature ratio of 1.2 K/K at two extreme temperature combinations. In addition to the COP target of KPI 1, we have set internal targets for the smallest and highest temperature lift to 250°C. The COP targets are summarized in Table 5, together with Carnot efficiencies for the same operating points.

Table 5. Defined operating points from KPI 1

		KPI 1a	Extr 1	KPI 1b	Extr 2
Source temperature	°C	0	0	100	100
Sink temperature	°C	55	250	175	250
Temperature ratio	K/K	1,2	1,9	1,2	1,4
COP target		2,8	1,2	2,8	1,7
Carnot efficiency		47 %	57 %	47 %	50 %

Fig. 8 shows the defined operating points together with achieved Carnot efficiencies for the tested operating points.

We see that heat pump at GE has shown performance close to the trend line between the targets, while the heat pump at IVAR generally has poorer performance, and the heat pump at SUSHEAT partner Pelagia shows lower performance at lower temperature ratios.

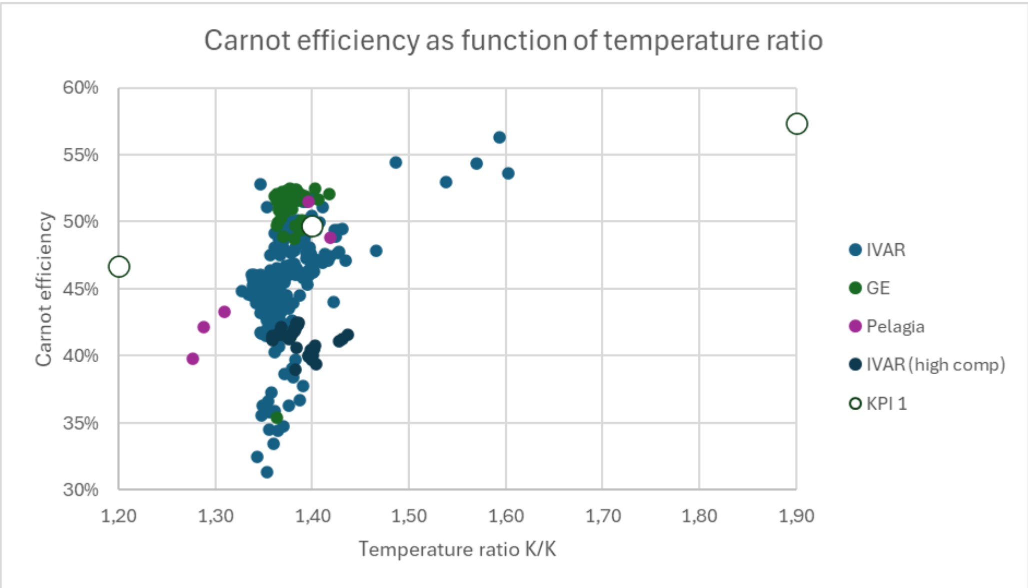

Fig. 8. Operating points from KPI 1 compared to test data

4. COP Optimization

The performance of the Stirling cycle is dependent on so many parameters that the optimization is generally considered in groups:

- Circuit swept volume, compression ratio, shaft speed and charge pressure, at a representative temperature ratio
- Manifolds and gas ducts contribute to pumping losses and introduce dead volumes that neither contribute to the heat exchange nor compression/expansion
- Heat exchangers

4.1. Swept volume, compression ratio, shaft speed and pressure

The main design parameters, swept volume, compression ratio, shaft speed and pressure, has been varied within the limitations of the design platform. Fig. 9 shows the performance curves for some important combinations of parameters. The simulations indicate the following effects:

- Increasing the shaft speed increases the heating capacity, while the efficiency is the highest at low to medium speeds
- Increasing the charge pressure increases the heating capacity, but with just a moderate increase in efficiency
- Increasing the swept volume and simultaneously, the compression ratio increases both the heating capacity and the efficiency. Increasing too much, however, is not helpful, as shown in the test results with a very high compression ratio (HC in the test results).

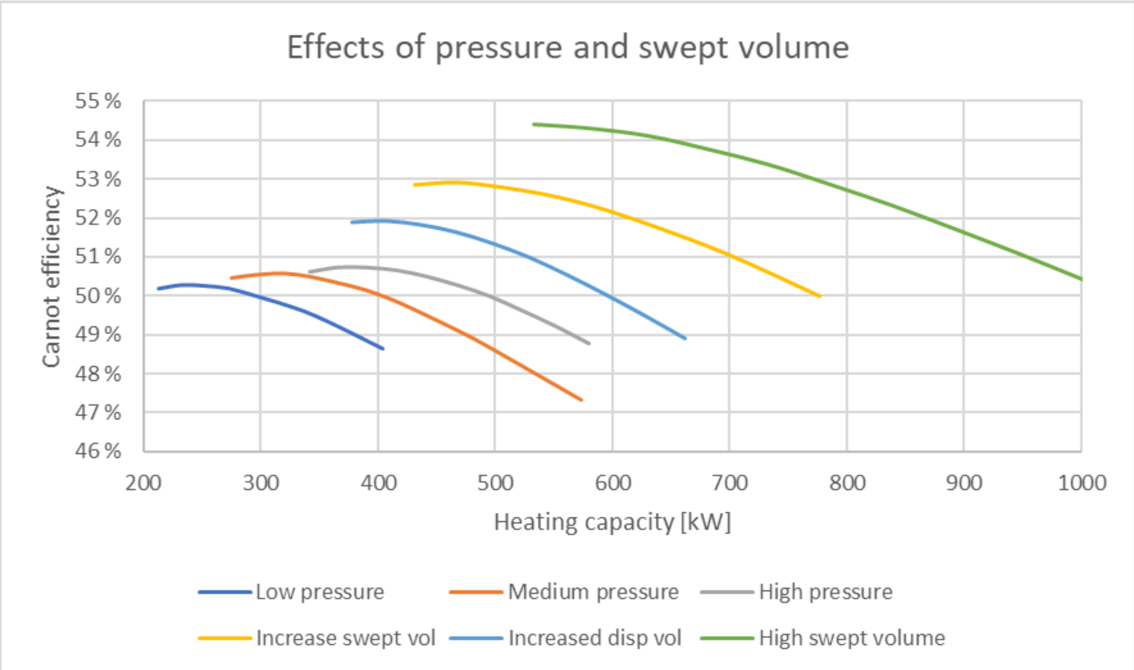

Fig. 9. Effects of pressure and swept volume

4.2. Manifolds and gas ducts

The dimensions of the internal gas ducts and manifolds have been varied within reasonable limits. If the manifolds and gas ducts are narrow and long, the performance suffers, as indicated in Fig. 10. The smooth gas flow (as represented with low k values for the Bernoulli losses) is more important than the dead volume (as represented by large volume L300 vs small volume L100).

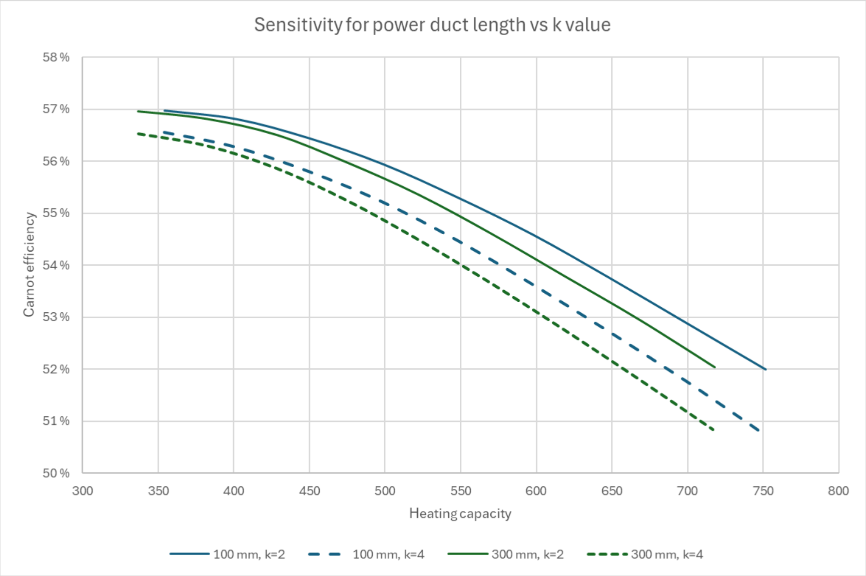

Fig. 10. Effect of duct shape

4.3. Heat exchangers

The heat exchangers are the most critical components in terms of optimizing the performance of a Stirling-cycle heat pump. A k^2 analysis has been performed for optimizing the complete set of heat exchangers (hot, cold and regenerative heat exchanger) in terms of number of tubes, tube dimensions and regenerator parameters.

One issue with the k^2 analysis is that the effects of tube inlets and exits, as well as the thermal effects of the header plates is not easy to model directly. We have found that:

- The total surface area and internal volume of the heat exchangers are more important than whether they are made with many short tubes or few long tubes, as shown in Fig. 11.
- The effective surface area of the heat exchanger tubes is more important than the total surface area of the heat exchanger tubes, as shown in Fig. 12. ShortTubes denotes the simulation with short wetted part of the tubes (thick header plates), and LongTubes denotes the simulation with long wetted part of the tubes (thin header plates).

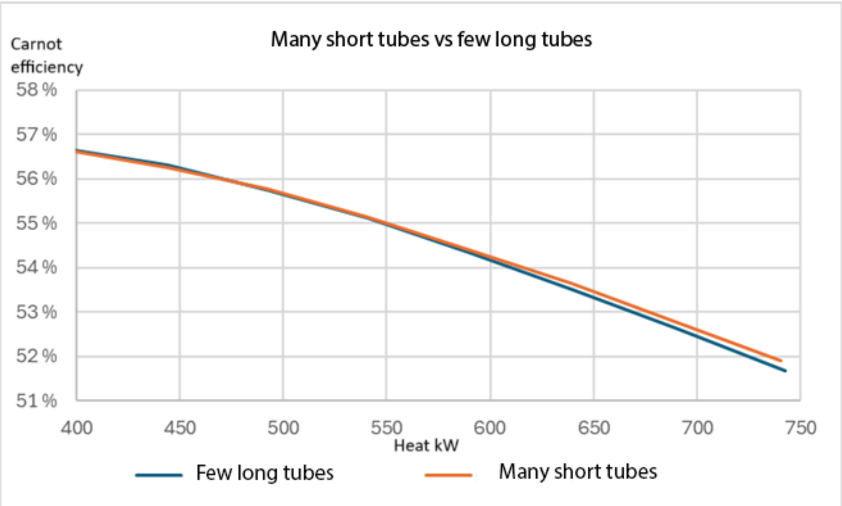

Fig. 11. Heat exchanger tubes: many short vs few long

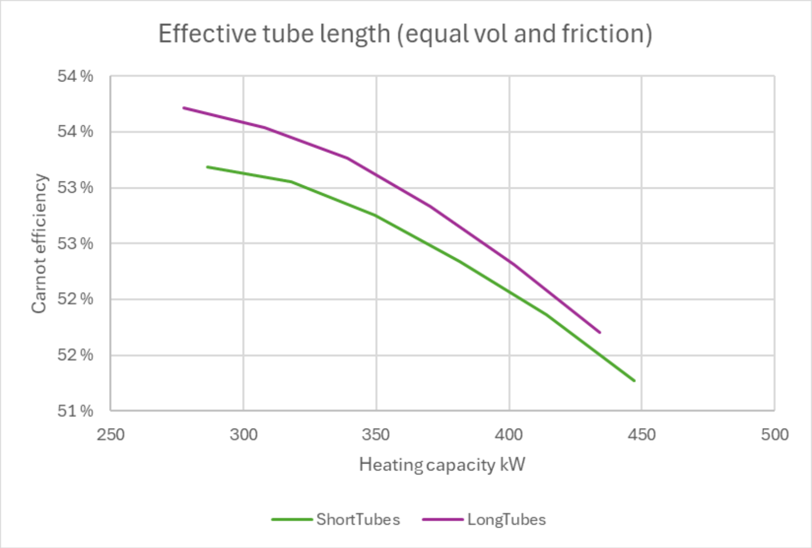

Fig. 12. Effect of header plate thickness

4.4. Results

After optimization of the Stirling cycle parameters, the simulations show that it should be possible to achieve the COP target of KPI 1 of 2.8 at 1.2 K/K (Fig. 13). This has been the most difficult target, as the stirling cycle is easier to optimize for higher temperature lifts. The internal targets of a COP of 1.7 at 1.4 K/K and a COP of 1.2 at 1.9 K/K will be easier to reach, as the simulations indicate COP values of 2.0 at 1.4 K/K and COP of 1.4 at 1.9 K/K.

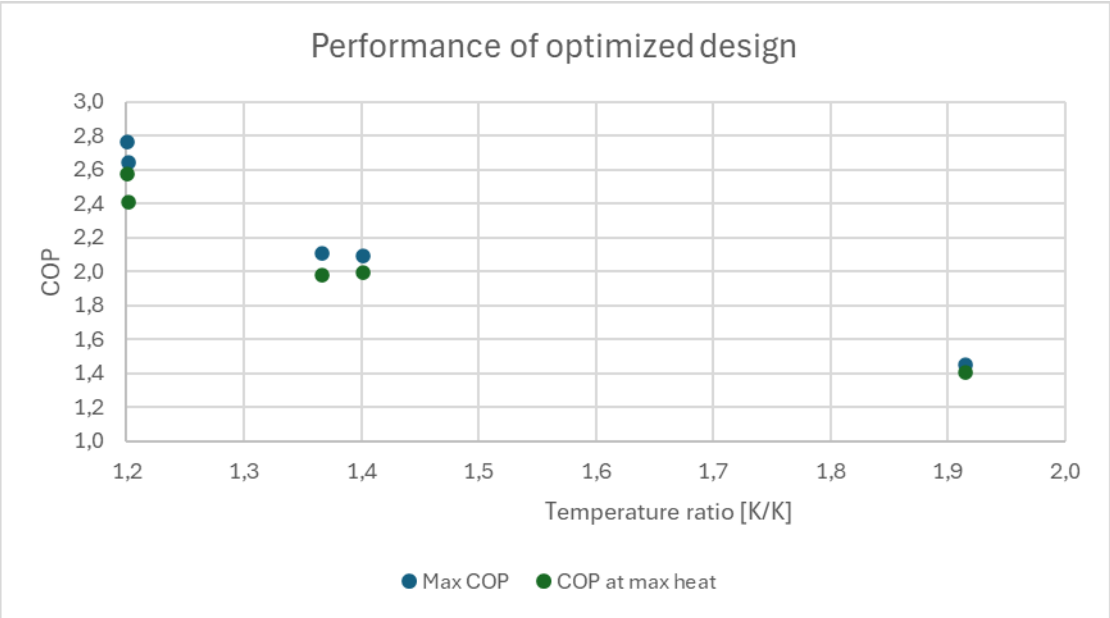

Fig. 13. COP values as function of temperature ratio between sink and source, for optimized heat pump

It should be possible to achieve Carnot efficiencies of up to 70% at high temperature lifts, as shown in Fig. 14.

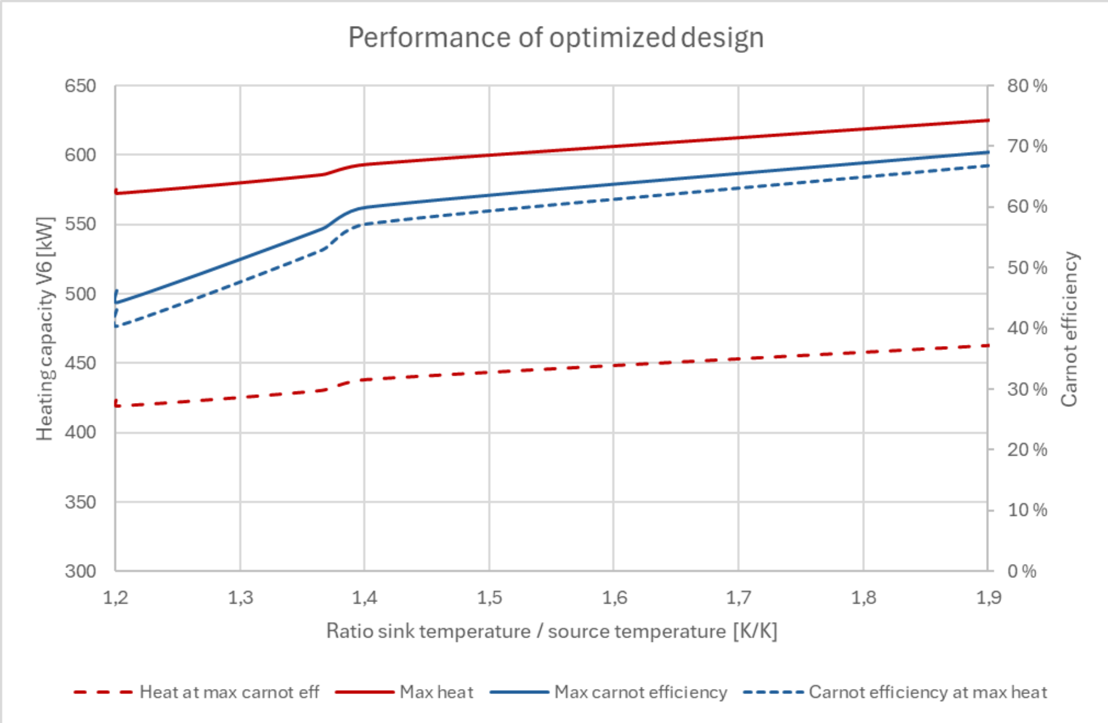

Fig. 14. Heating capacity and Carnot efficiency for optimized design, as function of temperature ratio sink/source.

5. Further work

From the experimental data, we see that there are several parameters that can be varied in the analysis, that is not straightforward to modify during the project. Careful investigation of the individual loss mechanisms may lead to a design in which the pistons have different bore/stroke ratios, the hot and cold heat exchangers have different parameters, and where especially the design of the pistons, the piston rings and the flow manifolds are fine-tuned for performance.

From the optimization work, we have also found that it would be possible to increase the performance even further by increasing the cylinder swept volume and charge pressure. This will increase the loads on the seals and the mechanical components, so it would be necessary to redesign several components. This may be worthwhile in a later generation of heat pumps, to increase the performance to weight ratio further, and hence move towards the second objective of KPI 1: to approach a specific cost of 100 €/kW.

A 50% increase in charge pressure combined with a 20% increase in swept volume would lead to a rated capacity of more than a MW per V6. The mass is around 6000 kg. With low-volume manufacturing, such as small-scale marine diesel engine production, the production cost is around 25 €/kg, while high-volume manufacturing, such as truck engines, is closer to 10 €/kg. That translates to production cost targets of 150 €/kW and then 60 €/kW in high volume.

6. Conclusions

Experiments have shown that cycle optimization is necessary to achieve the performance goals of KPI 1, while the experimentally validated simulation model indicates that an upgraded and optimized version of the heat pump will be able to achieve the COP goal of 2.8 at a temperature ratio 1.2 K/K.

The optimized design specification is being developed for production, and further simulations will be performed to ensure as good performance as possible in the final design.

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[1] European Commission. Grant Agreement Nº 101103552 – SUSHEAT “Smart Integration of Waste and Renewable Energy for Sustainable Heat Upgrade in the Industry”. European Climate, Infrastructure and Environment Executive Agency, Horizon Europe.

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