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abstract	

Investigation of a Free-piston Stirling Heat pump for water heating

Preparation

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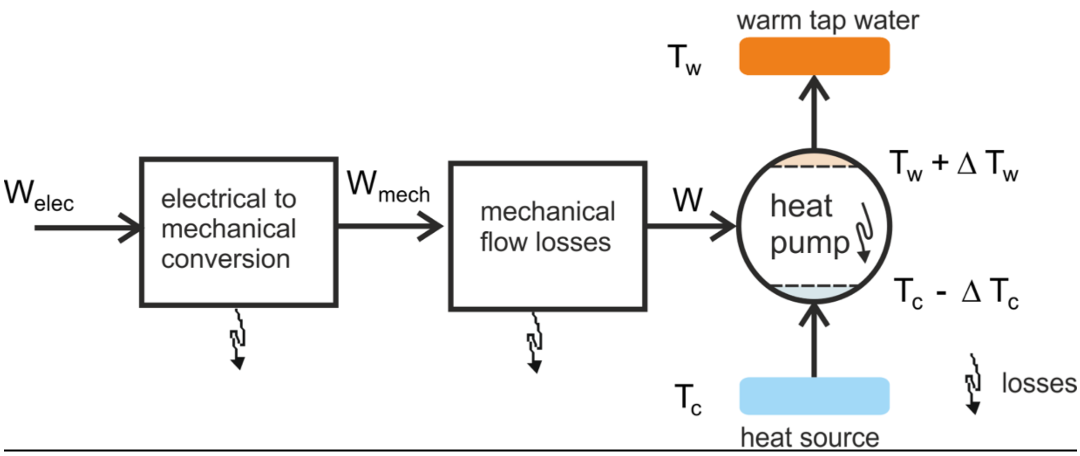
2 Introduction

In this project we explored the feasibility of reversing the operation of a commercially mature Stirling engine technology as a heat pump to produce tap water in a household. Stirling engine converts high temperature heat usually from combustion of natural gas to electricity. To accommodate relatively lower temperatures the heat exchangers are redesigned. A number of diagnostic instruments, such as pressure sensors and displacement sensors to measure movement of the piston and displacer were also mounted. The details of the system is shown in section 3.

First, let us take a look at the performance metric of this heat pump. The **COP** of the Stirling heat pump, which is the ratio of the heat output to the warm tap water to the electrical power input, is estimated by considering the following losses (these are shown systematically in the figure below); electrical to mechanical power conversion loss in the compressor, mechanical flow loss in the displacer and pressure drops in components, heat exchanger efficiency of at the source and the sink, regenerator heat losses. The table below shows the calculated values of COP for three cases; the baseline, pessimistic, and optimistic. The theoretical base line case COP is 4.3, where-as the measured value of the Stirling heat pump for the same conditions is about 2.4.



Tc = 20 °C, Tw = 60 °C			
Qw = 2000 W			
	Baseline	**Pessimistic**	**Optimistic**
ΔT_w (°C)	5	10	3
ΔT_c (°C)	5	10	3
Regenerator effectiveness	0.95	0.90	0.98
Compressor efficiency	0.90	0.85	0.95
Mechanical losses	0.1	0.2	0.05
Q_c (W)	1619	1485	1692
W (W)	381	515	308
W_{mech} (W)	423	644	325
W_{elec} (W)	470	757	342
COP=Qw/Welec	4.3	2.6	5.9

Although the measured COP value of this heat pump for a temperature lift of 40 °C is 2.4 and is close to the pessimistic estimation in the above table, it is must be noted that this heat pump is not yet optimized for performance. This is as far as our knowledge goes, a first such investigation. The commercial vapor compression booster heat pumps are currently quoting a COP of 2.0 for the same operating conditions. An important benefit of a Stirling heat pump as compared to a vapor compression cycle is that the hot and cold temperature can be a lot flexible. In this context, an important result from this project is the demonstration of a potential (almost mature) solution to the electrification of heating in households. We suggest TKI-UE to invest more resources in this promising technology.

The outline of this report is follows; in chapter 3 a short introduction to the Stirling engine and the hardware is given followed by definitions of metrics of a heat pump in chapter 4. Chapter 5 describes the test rig and chapter 6 concludes with results and discussion.

3 Stirling Engine

3.1 Introduction

Stirling engines use a temperature difference to generate mechanical or electrical power, and thus convert heat to power. Multiple types of Stirling engines exist. All consist of the same essential parts: A piston, a displacer, two heat exchangers, and a regenerator. In this research we are interested in the free piston Stirling engine (FPSE) (see figure 1).

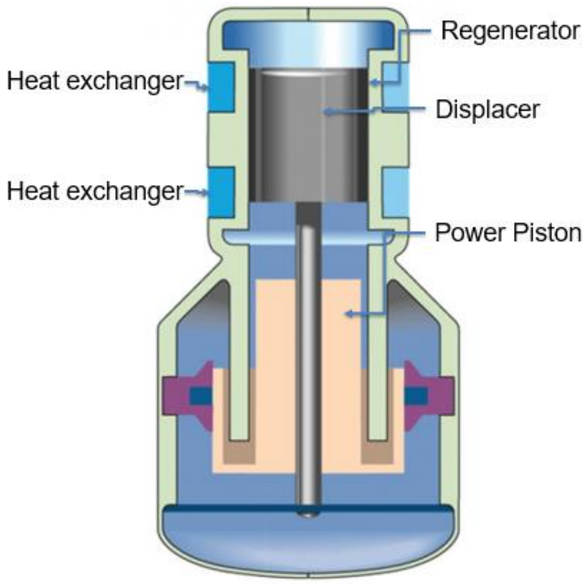


Figure 1: schematic drawing of a free piston Stirling engine

When heat is applied at the top heat exchanger, the working fluid expands causing the piston to move down. The displacer then moves this warm and expanded gas through a regenerator towards the bottom heat exchanger. The regenerator cools the gas as it moves through it. In the bottom heat exchanger the gas is cooled down, and thus contracting and forces the power piston upwards. The displacer then moves down to move the cold gas back through the regenerator to the top heat exchanger, taking up the heat it deposited earlier in the cycle. This results in the starting situation, with the gas ready to be expanded again, thus completing a cycle.

While the process described is sequential, in practice both the piston and displacer will move harmonically. Ideally, they are 90° out of phase, to emulate the sequential process as best as possible.

Microgen engine corporation produces such a FPSE. Aimed at generating electricity from heat (specifically a burner flame). Their design has the following specifications:

Table 1: specifications of the Microgen FPSE

Maximum (modulating) electrical output*	1050 W
Output voltage	nominal 230 V, min 186 V – max 264 V
Output frequency	50Hz, or 60Hz depending on model
Weight without burner	49 kg
Dimensions without burner	450mm high, 300mm diameter
Noise at 1m	52.5 dB without casing, 45 dB with casing
Engine efficiency	26%
Design life	50 000 hours
Internal pressure (20 °C)	24 bar (15-35 bar safe)
Internal working fluid	Helium

*the maximum electrical output is 1300 W at a higher operating temperature of 550-560 °C with an efficiency of 28 %. For the dutch market the system output is rated at 1050 W to suit the use of a single electricity group.

3.2 Free Piston Stirling Heat Pump

For our research, the application of the free piston Stirling engine is not to generate power, instead to generate a temperature difference. We are thus talking about a free piston Stirling heat pump (FPSHP). To achieve this, Microgen has customized a model for our needs. This means that the heat exchanger that is heated by the burner flame in the engine, is replaced by one that consists of fins and has two fluid connections for water flow. Additionally, our unit is fitted with a pressure sensor to monitor pressure inside the heat pump, to be able to measure the pressure swing in operation. The entire device is depicted in figure 2, with a cut open version showing the internal parts in figure 3.

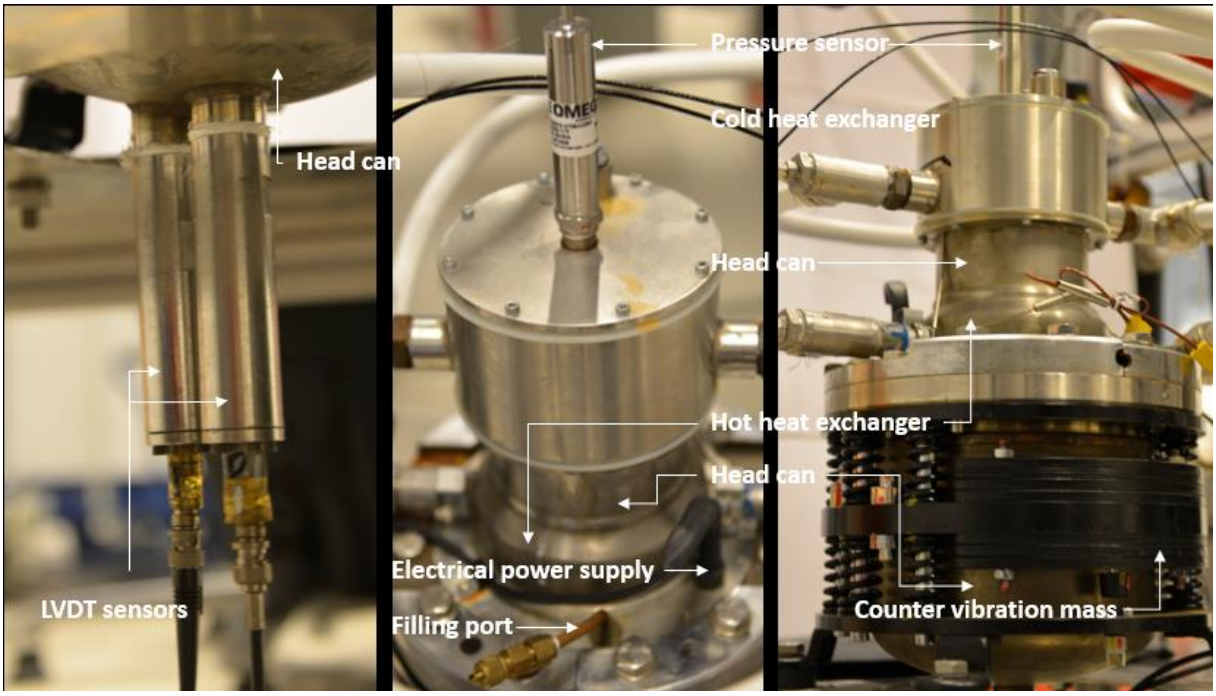


Figure 2: Photo of the FPSHP as modified by Microgen, enumerating the important parts

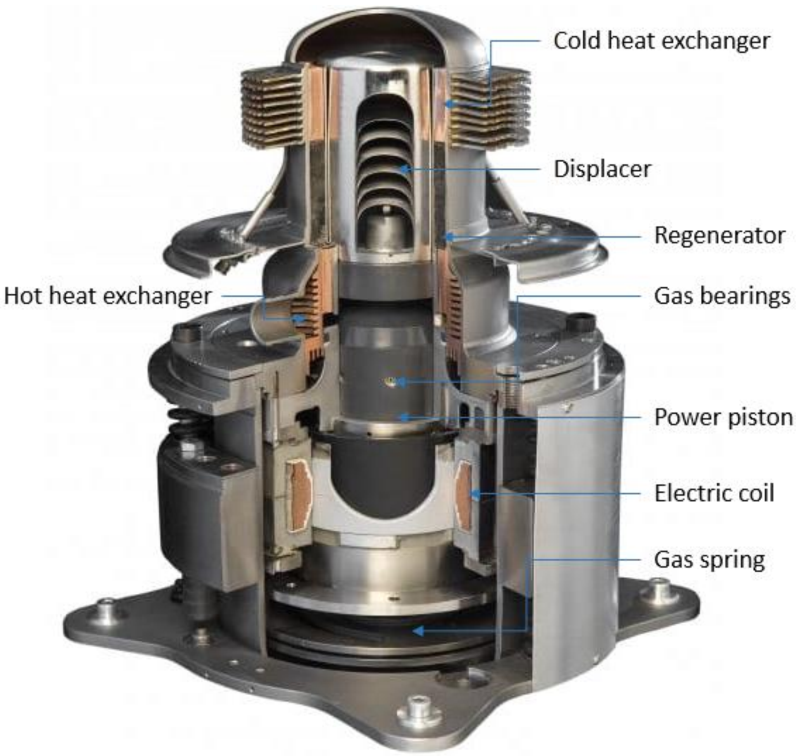


Figure 3: Cut open version of the FPSE, showing the internal parts of the heat pump

3.2.1 Head-can

The head-can is the pressure vessel of the system. It consists of a 2mm stainless steel container that encloses the components inside. The nominal filling pressure is 24 bar, though values of 15 to 35 bar should be safe.

3.2.2 Power piston

The power piston is powered by the electric coil, and by use of gas-bearings it is "free" floating. The piston is tuned by design in such a way that the volume below the piston, and the volume with reactionary load above the piston, make for a resonant system at 50 Hz. The resonance will depend on the pressure during operation, which depends on the filling pressure, and operational temperatures.

3.2.3 Displacer

The displacer is made of steel with a wall thickness less then 1.0 mm. , and a softer plastic in the bottom. To keep the mass low, and the resonance at 50Hz. The displacer is in open contact to the rest of the system via a pressure equalizer system . This reduces the pressure difference, and thus required wall thickness.

3.2.4 Hot heat exchanger

The hot heat exchanger is located half-way in the system, internally between the power piston and displacer and regenerator it consists of a copper block, where the copper separates the water from the helium gas. It is located entirely inside the head can, meaning that water flows through the head-can, into the heat exchanger and back out of the head-can. On the inside of the heat exchanger contact with the gas is realized by the use of a copper foil that fit concentrically in the heat exchanger.

To connect fittings to this heat exchanger a custom type of fitting is used, a rubber sealed fitting slides in to a larger pipe. This fitting is then secured with a clamping ring.

3.2.5 Cold heat exchanger

The cold heat exchanger is different in design from the hot one, in that it does not make contact with the cooling fluid inside the head can. Instead, the copper foil is concentrically mounted in the head-can, with copper fins mounted on the outside of the head-can. The reason for this difference comes from the original design, where this heat exchanger is used to receive a flame of about 600 °C.

To contain the water flowing past the fins on the outside of the head can, a cylindrical container is fixed to the outside of the head can. This container has three connections, two for the in- and outflow of water, and one on the top to be able to bleed the system. The flow connections are ¾ inch BSPP, and the bleeding port is ½ inch BSPP.

3.2.6 Regenerator

The regenerator is fitted between both of the heat exchangers. It consists of a steel mesh. This mesh is cut concentrically, as to fit around the displacer, and stacked to form the regenerator.

3.2.7 LVDT sensors

At the bottom there are the output of two linear variable displacement transducers (LVDT) sensors. These consist of a rod, which is connected to the displacer or power piston, that moves in or out of an electric coil, thus changing the inductance. This change in inductance can be measured and translated to displacement.

4 Heat pump

The main interest in investigating this heat pump is twofold. On the one side we want to investigate its efficiency and coefficient of performance (COP). On the other side we want to create a good physical understanding of the heat pump, to be the basis for modelling.

4.1 Operation

To operate the heat pump one must supply a 50 Hz AC voltage. This will run the heat pump, creating a temperature difference between the hot and cold side. At this temperature difference the heat exchangers need to extract heat from a medium at the cold side, and it should transfer to a medium at the hot side. This means a fluid (water for our temperature range) should run through both heat exchangers.

The heat pump is able to be operate in a variety of conditions.

- The temperature of the hot- and cold heat exchanger, can vary.
- The stroke of the piston, and thus input power, can be varied by applying a higher or lower AC voltage
- The internal filling pressure can be changed, and together with temperatures will be of influence to the mechanical resonance of the heat pump

Though not directly of influence on the heat pump itself, it should be noted that flow speed through the heat exchangers will also influence the performance indirectly, as behaviour of 50 °C water being heated to 70 °C will not necessarily be the same as heating of 65 °C to 70 °C.

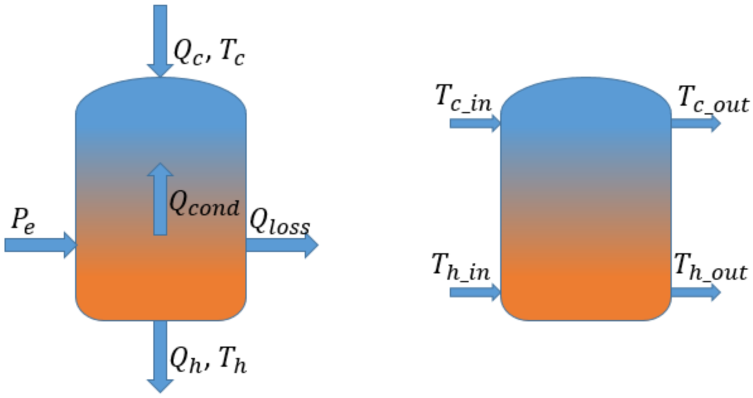


Figure 4: Diagram of the flow of powers into the heat pump, and corresponding temperatures

When investigating the heat pump, several different powers can be defined, as displayed in figure 4. Externally an electric power P_e is supplied to power the heat pump. At the cold side a thermal power Q_c is taken from the heat exchanger. Similarly, at the hot side thermal power Q_h is dumped at the heat exchanger. While the thermal powers at the hot and cold side are assumed with a corresponding temperature (T_h and T_c), in practice defining these temperatures is not as straight forward.

As a fluid flows through the heat exchangers, the inlet temperature of this fluid will not be equal to the outlet temperature. Thus, within a single heat exchanger a temperature gradient will exist. To define the COP's dependence on T_h and T_c, we take T_h to equal T_{h_out}, as this is the temperature at which the heat is used, and T_c to equal T_{c_in} as this is the required cold source temperature.

Aside from the usable powers, two types of losses can also be defined. The internal losses inside the heat pump (Q_{cond}). These losses occur due to the fact that the two heat exchangers are at different temperatures, the material connecting the two will thus conduct heat from the hot to the cold side. As this term exists entirely within the heat pump, it should not contribute to the energy balance of the system.

A loss term that will contribute to the energy balance of the system is Q_{loss}. This term can be summarized as conduction and radiation from the outer surface of the heat pump, to the air surrounding it.

4.2 COP

The COP is defined as:

$$COP = \frac{Q_h}{P_e} \quad (1)$$

The COP will differ depending on the operating conditions, which is what we want to investigate. The measured COP can also be compared to Carnot's COP, the theoretically highest achievable COP for a heat pump at given temperatures

$$COP_{carnot} = \frac{T_h}{T_h - T_c} \quad (2)$$

T_h and T_c both expressed in Kelvin.

We aim to determine the COP by measuring thermal and electrical powers. Technically speaking we only need to know the thermal power at the high temperature side. Though for completeness we will also measure it at the low temperature side.

The thermal power can be determined by the energy increase/decrease in the heating/cooling -fluids flowing through the heat exchangers.

$$Q_{h/c} = \dot{m}c_v(\mathrm{T}_{h/c\_out} - T_{h/c\_in}) \quad (3)$$

To determine the electrical power, we measure the voltage and current, and phase angle between the two, as the motor load is not fully resistive:

$$P_e = U_{rms}I_{rms}\cos(\theta) \quad (4)$$

U_{rms} being the rms value of the voltage, I_{rms} being the rms value of the current, and θ being the phase angle between the two.

Since we expect to measure both power and current with a data acquisition device, we will not measure rms values and phase directly. We can however do a Fourier analyses on the data points to attain the peak value of both the voltage and current, and the phase angle, such that the power becomes:

$$P_e = \frac{1}{2}U_{peak}I_{peak}\cos(\theta) \quad (5)$$

Using a Fourier analyses over a sum over all time steps has the advantage of accounting for truncated harmonics due to measurement frequency.

4.3 Acoustic power

Another important power to note is the mechanical power inside the heat pump, in other words the acoustic power inside the helium. This acoustic power $\dot{W}$ is given by:

$$\dot{W} = \frac{1}{2}P_1\dot{V}_1\cos(\phi) \quad (6)$$

P_1 being the amplitude of the sinusoidal pressure oscillation, $\dot{V}_1$ the amplitude of the volume flow at the piston, and ϕ the angle between the volume flow and the pressure.
The pressure can be measured directly by the pressure sensor, the volume flow can be determined by use of the position of the piston in time, and its area. The angle between the two follows directly from the measurement of the two quantities.

5 Setup

To measure the thermal powers, we need to measure the temperatures before and after the heat exchangers, as well as the flow rate. We also need a system around the heat pump to be able to provide the flows through the heat exchangers at the right temperatures. For this a test rig has been made. The rig contains equipment to measure electric and thermal powers, control the temperatures of the heat exchangers. This rig is schematically displayed in figure 6, and photo is shown in figure 7.

5.1 Data acquisition card

To read the general sensors, and to be able to control the setup, a data acquisition card (DAQ) is used. Specifically, the NI-USB 6218. This card is able to read analog voltages, put out analog voltages, and read and write digital channels. It is set to read at 1000 Hz. Depending on set range, accuracy will lie between ±88µV at 200 mV range to ±2.7 mV at 10 V range.

The DAQ is connected via USB to a laptop, to time the measurements, the time from the laptop is used for the first data point. Consecutive data points are timed by the internal clock of the DAQ, that has a 50 ppm accuracy. The control and data acquisition happens with a LabVIEW program, explained more elaborately in

Appendix A.

5.2 Electric power measurement

To supply an AC voltage to the heat pump, a variable AC transformer is used that transforms the mains voltage, as displayed in figure 5a. This variac can transform from 0 to about 270Vrms, depending on the actual mains voltage.

This voltage is measured with a Yokogawa 700904 Voltage probe (figure 5b) which can be set in either 100:1 or 1000:1 attenuation, to reduce the voltage to one that is readable with a data acquisition card (DAQ). In the 1:100 mode voltages of up to up to 250 V_{rms} can be measured. Or up to 1000 V_{rms} in the 1000:1 mode. Up to 400V_{peak} the accuracy is 2%.

To measure the current, a zero-flux sensor is used (figure 5c). In this type of sensor, one of the current leads passes through magnetic ring, thus magnetizing the ring. Around this ring a coil is wound, in such a way that passing a current through the coil will counteract the magnetization caused by the current lead. The remainder of the field is measured with a flux sensor, and with a known amount of windings in the coil around the ring, the flux generated by the primary current is known, and thus the current itself.

As our sensor has a maximum measurement range of 300A, the current lead is looped eleven times though this zero flux sensor, to increase accuracy. Zero-flux sensors are typically accurate in the ppm range. As this is an older type, we expect it to be accurate around 0.1% of the full scale.

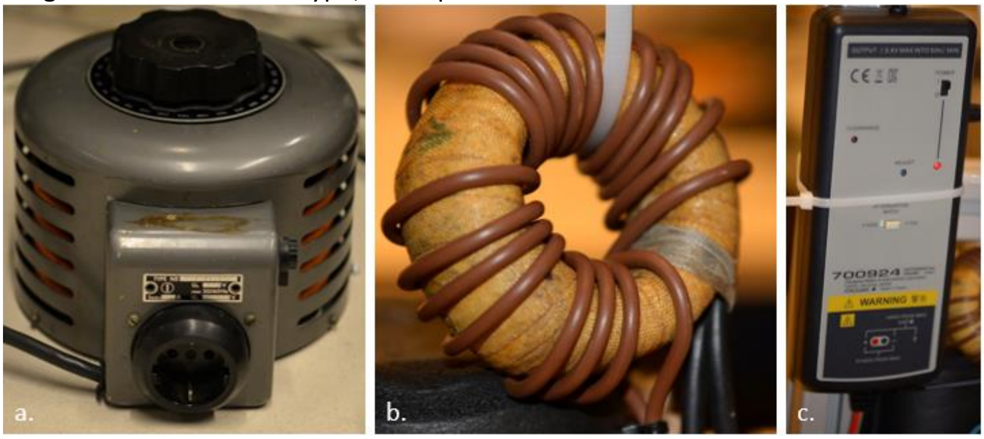


Figure 5: (a) showing the variac; (b) the measurement coil of the zero-flux sensor; (c) the voltage probe

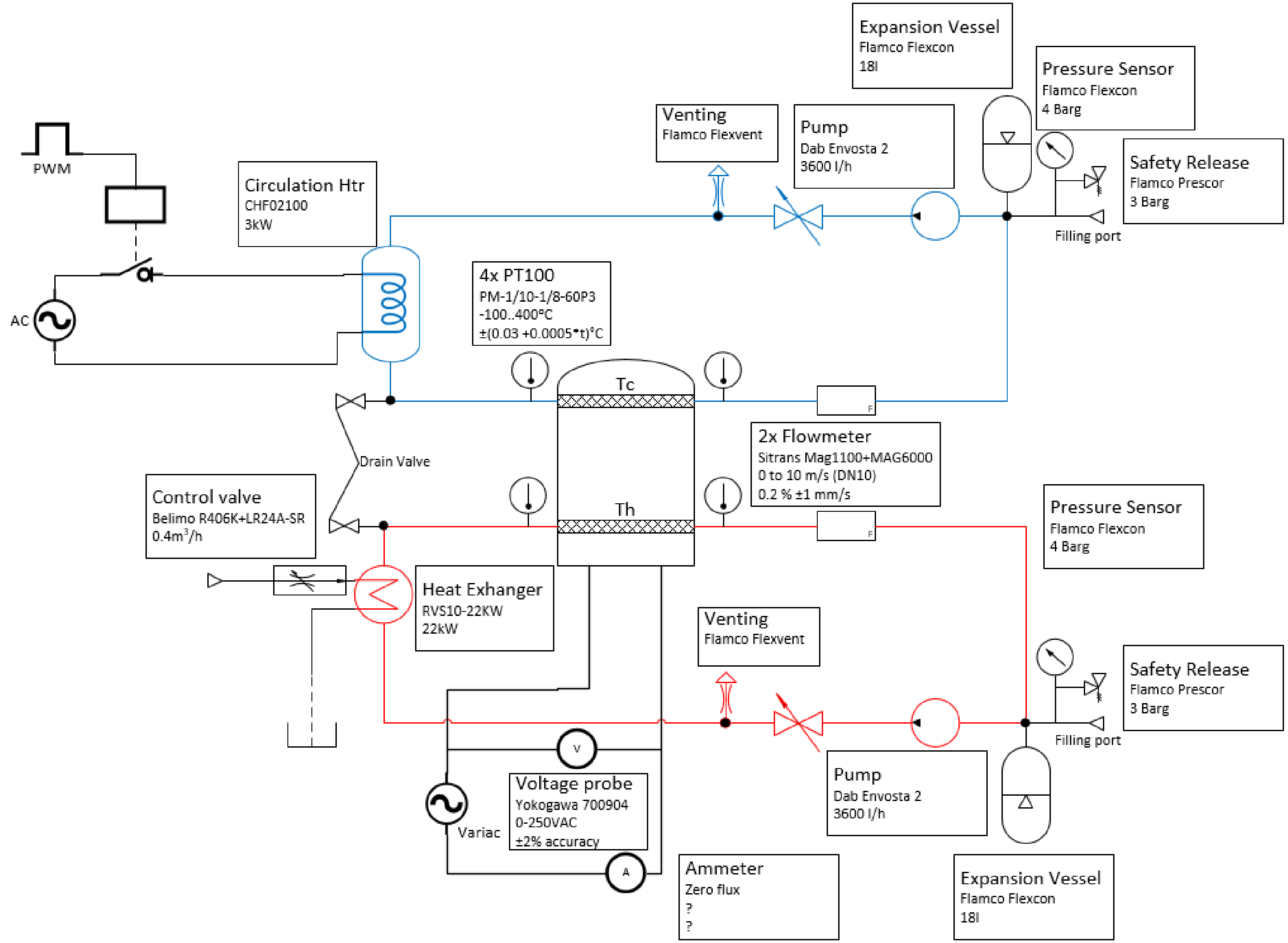


Figure 6: schematic of test rig of heat pump

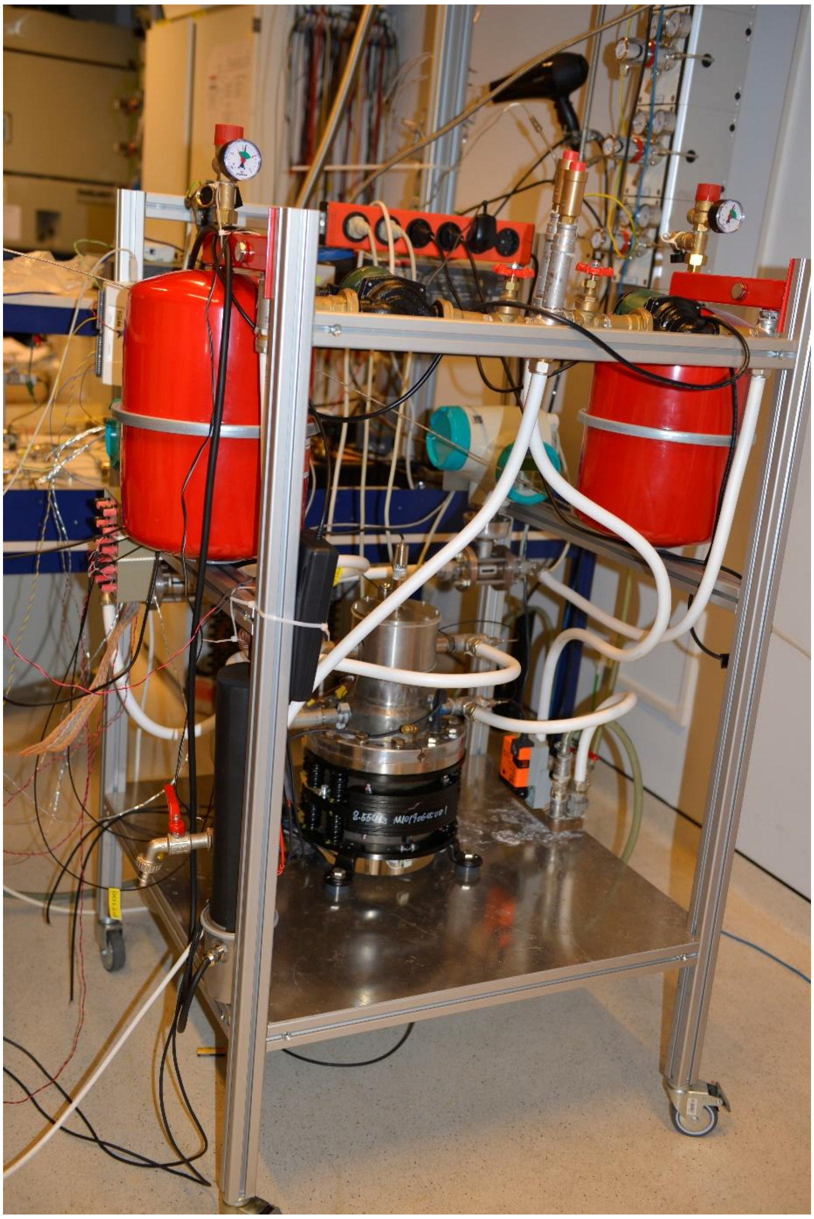


Figure 7: Photo of the test rig showing the heatpump, cooling and heating circuits, flow sensor and buffer vessels with filling ports.

5.3 Thermal power measurement

For the thermal power the temperature at the in- and outlet of both heat exchangers has to be measured, for this PT100 sensors are chosen, with a 1/10 DIN rating. This means they have an interchangeability of 0.03 °C at 0 °C, up to 0.08 °C at 100 °C.

These sensors are connected in series and powered by a Lakeshore 121 current source. That is set to supply 1mA at 0.1% accuracy.

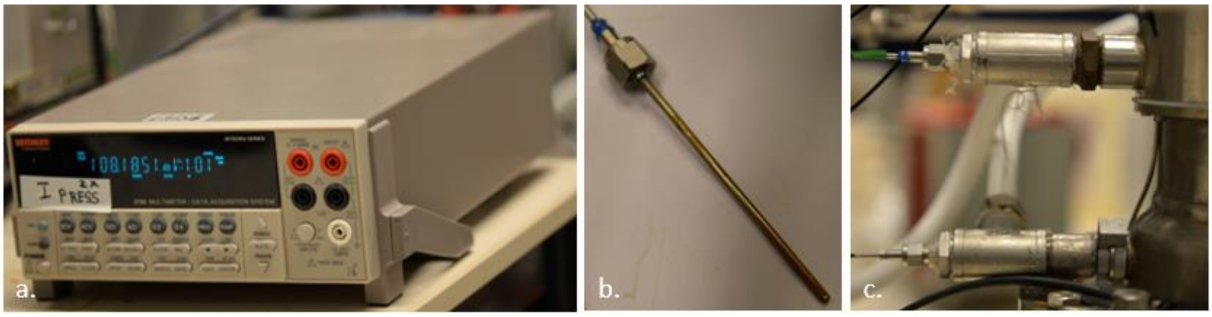


Figure 8: (a) shows the keithly multimiter; (b) one of the PT100's; (c) shows the PT100 mounted in the system, close to the heat pump

The voltage over these PT100's is then measured with a Keithley 2700 multi-meter with a 7706 scanner card that is connected to a laptop via GPIB. Timing wise the multi-meter has an internal clock, that is used for timing of the measurements.

It is able to measure in the relevant voltage range (1V) at 0.003% ±7μV accuracy. When it comes to the accuracy of the temperature sensors there are two relevant accuracies. First of all the accuracy of the individual temperatures, to determine the COP at given high, and low temperature. But also the accuracy of the difference between the two. As the inaccuracy of the current-source affecting the PT100 at the inlet, will affect the PT100 at the outlet in the same direction.

To improve accuracy, and to reduce the effect of the interchangeability, the sensors are calibrated in a water bath. As can be seen in figure 9. Starting with a bath of ice-water the temperature is increased up to 100°C while stirring, using a magnetic stirring device. After that the water is cooled again back to room temperature. While this does not give an accurate absolute calibration, it is possible to compare the temperatures of the PT100's to each other. The results of this calibration are shown in figure 10.

Figure 9: Calibration of PT100's

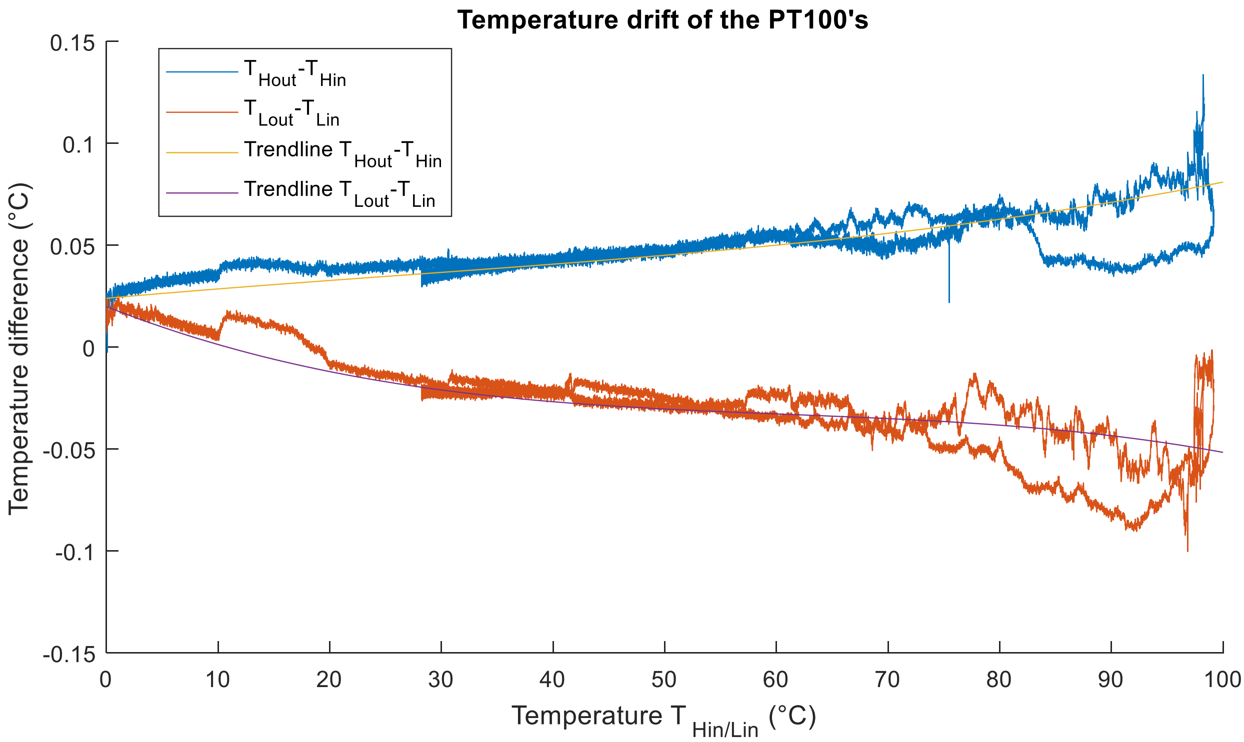


Figure 10: results of PT100 calibration, with fitted cubic trendlines. Sensor names refer to their normal locations.

For a given temperature of T_{Hin} or T_{Lin}, the expected offset of their outlet temperature is plotted. For analyses and correction of the data, a cubic trend line is chosen to approximate the datapoints. Measuring the flow is done with two Siemens Sitrans Mag1100+mag6000 flow sensors (figure 11), these measure flow velocity, and internally convert it to a volumetric flow rate based on flow diameter of the sensor (10mm). These sensors measure with an accuracy of 0.2% ±1mm/s.

Figure 11: Sitrans Mag1100+Mag6000 flow sensor

They work on the principle that moving an ionic fluid through a magnetic field that is perpendicular to the flow, produces a force on the ions. This force is positive one direction, and negative the other. Using electrodes to measure this voltage gives a measure for flow velocity.
The flow meters convert the measured velocity internally to a display value, but also to a 4-20mA analog output.

With the aim of reducing outside influences, the entire heat pump is insulated using foam and glass wool, as depicted in figure 12. Wall temperatures of the heat pump are measured using thermocouples placed inside the insulation materials. As well as a sensor on the outside of the foam.

Figure 12: Heat pump insulated with foam and glass wool

5.4 Flow loop

As measuring thermal power requires a flow through the heat exchangers, a pump is placed such that it circulates the heating/cooling fluid. The flow velocity can be tuned manually by opening or closing a valve placed in series with the pump.

Aside from the flow loop, the fluid has to be able to be filled, drained and bled. At the highest point an automatic vent is placed that lets air out, but keeps fluids in. At the lowest part of the loop, a tap is placed to be able to drain the loop of fluids. As the cold heat exchanger on the heat pump consists of a cylindrical housing, with an in and outlet lower than the top of the cylinder, a vent is also placed at the top of this housing, see figure 13. This time, a manual vent is chosen due to its smaller size.

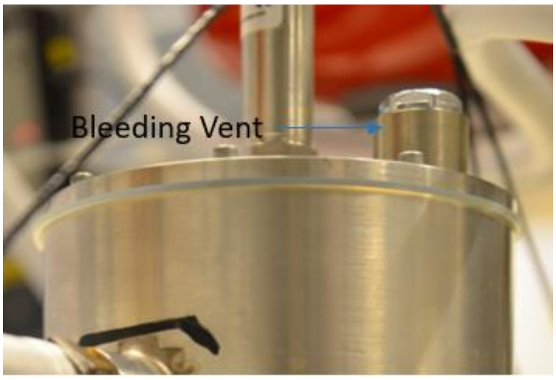


Figure 13:Bleeding vent on the heat pump

As the fluid in both of the loops will change their temperature, an expansion vessel is added in the loop to reduce pressure build up inside the loop. As a safety feature, both loops also have an automatic vent, that release the fluid if the pressure raises above 3 bar (gauge). To check the filling pressure a pressure indicator is included in the loop. When filling the fluid, the pressure in the loop is set to 2 bar (gauge).

5.5 Temperature control

At the hot side, the fluid has to be cooled. This is done by passing it through a plate heat exchanger, where it is cooled by tap water. To be able to control the temperature of the heat exchanger inlet on the heat pump, the amount of tap water that flows through the cooling heat exchanger is regulated. This regulation is done by an electric controllable valve. That is PID controlled by LabVIEW, using the inlet temperature, as a process variable.

At the cold circuit the fluid has to be heated. This heating is done by using a circulation heater. This circulation heater consists of a large cross sectional pipe, with an electric heating element inside. To be able to control the temperature at the inlet of the hot heat exchanger on the heat pump, we need to control the amount of heating done by the electric heating element.

To be able to use a PID control we generate a 10Hz PWM signal on a solid state relay, with the pulse width being controlled by the PID. This does however have some limitations. First one being that LabVIEW is not made for sub millisecond timing, thus the pulse width can only be changed in discrete millisecond values. Furthermore a property of the solid state relay is that it can only switch during a zero-crossing. The advantage is that there will be no sudden current surges. However this does mean that the PWM signal is further discretized by being dependant on a half sine wave (10ms at 50Hz).

5.6 Mechanical Power

To measure the mechanical power we want to determine the pressure swing, as well as the volumetric swing, and the phase between the two.

Our heat pump has an Omega PXM409-070BAUSBH pressure sensor. This sensor is able to measure up to 70 bar(a) with an absolute accuracy of ±0.35 bar (typical), and with a repeatability of 0.08%. The sensor is read out via USB, using the available software from Omega. A time stamp is added in this software, but as this is via USB, a delay will be expected, thus influencing the

The Sentech LVDT sensors for position of the piston, and displacer internally consist of a solenoid, where a rod connected to the piston/displacer moves a core in and out of this solenoid, changing its inductance. Externally they have a single coax connection and require an external unit to convert the inductance to position. For this the coax cable connects to a SCDR150 signal processor, that has a ±0.02% linearity. This signal processor outputs a 0-10V signal, this signal in turn is read by the DAQ. The phase between the pressure and volume oscillations is determined by the respective sensors. It should be noted that as the pressure sensor uses the computer's timing with a USB connection for all measurements. And the DAQ uses the computer's timing only for the first point, after which an internal sample clock takes over, some discrepancy in timing is to be expected. Where, as communication goes via USB, it is also hard to tell a discrepancy of the start time, as both devices use an internal buffer.

6 Measurement plan

In characterizing the heat pump we want to look for the dependence of the COP on several variables. With our test rig we are able to control the heat exchanger inlet temperatures at both high and low temperature side. As well as the voltage supplied to the heat pump, and the filling pressure inside the heat pump. We want to investigate the influence of these variables on the COP.

6.1 Measurement protocol

6.1.1 Pre heat pump operation

To be able to consistently measure a measurement protocol is devised. Before starting the heat pump, the water coolant in the loop is refreshed. As not all parts are non-corrosive, over time, we can expect iron, and other metallic particles to be mixed in the water. This means the heat capacity, c_p, may change over time.

To reduce this effect, before each run the existing water is drained. The loop is then flushed while opening and closing the valve that controls the flow speed, so both paths to the drain are flushed. When only visually clean water comes out of the drain, the drain is closed, and the loops are filled up to their required filling pressure of 2 bar (gauge). The automatic vents in the loop take care of most of the bleeding. The manual bleeding vent on the cold heat exchanger has to be bled manually. As some air will be left in the loop, after running the pumps for a while, the heat exchanger should be bled again. This often has to be repeated around an hour into the actual measurement.

As the head-can of the heat pump is not completely leak-tight, before a run, the pressure sensor is checked for the required filling pressure. If this does not match, helium is filled by flushing a filling tube, and connecting it to the filling port of the heat pump. The pressure is measured during filling. By manually tuning the pressure on the filling line, as well as tuning the inlet vent at the heat pump, the head-can is slowly filled. Making sure that filling speeds to not go over 1bar/min, the restriction by the displacer.

A measurement run is generally done at a constant voltage setting. The run is thus started by setting the variac to a certain setting, and measuring the voltage, powering the heat pump and starting its operation.

6.1.2 Measurement point

While during measurement continuous data acquisition is done, we are interested in the COP for given parameters, and thus require a stable measurement point. This single point is obtained by setting the low and high inlet temperatures to a given value. After the PID control in the LabVIEW program stabilizes both inlet temperatures, the temperature and flow values provide the thermal power measurement.

The flow is tuned in such a way that, generally speaking, the temperature difference between inlet and outlet is around 5°C.

6.1.3 Measurement run

A single measurement run consists of keeping the input voltage, filling pressure and low temperature inlet constant, and varying the hot temperature inlet. This means that after a single measurement point, the set hot inlet temperature is changed and the PID control stabilizes the inlet at its new set point.

As different temperatures will have different thermal powers, the temperature difference between in and outlet will also change. As the PID control is able to stabilize faster when only the set point is changed, the flow is only changed when the thermal powers cause too large or small a temperature difference.

A note should be placed on the PID control itself as well. As this is not intrinsically stable. At the low temperature side, the control signal is discretized, as described in Temperature control . At the high temperature side the control signal is analog, however the analog signal controls the opening and closing of a ball valve. The opening and closing of such a valve is not linear, and has a different response depending on the angle of opening. Opening from 0° to 1° will not cause any flow at all, from 10° to 11° will cause only a little flow increase, while from 40° to 41° causes the flow to increase more. This behavior translates to PID settings that easily become unstable.

An additional destabilizing effect is the interaction between the different temperature control loops. If the low temperature inlet increases, a normally stable high temperature inlet would also increase, causing the PID of the high temperature loop to react as well.

In the case of a settings where no completely stable situation can be found, despite changing PID settings, averaging over one or multiple oscillations in temperature will give an approximate result for the otherwise unstable settings.

7 Results

Stabilizing a single measurement point takes around 2-4 hours. The temperature sensors that are physically placed on the walls on or between the hot and cold heat exchangers react within minutes of a set point change. The temperature sensors on the passive side of the power piston react slower. This is due to the fact that this has to be heated or cooled due to conduction through the stainless steel head can, and ohmic heating of the coil. The different wall temperatures measured for a single point is displayed in figure 14.

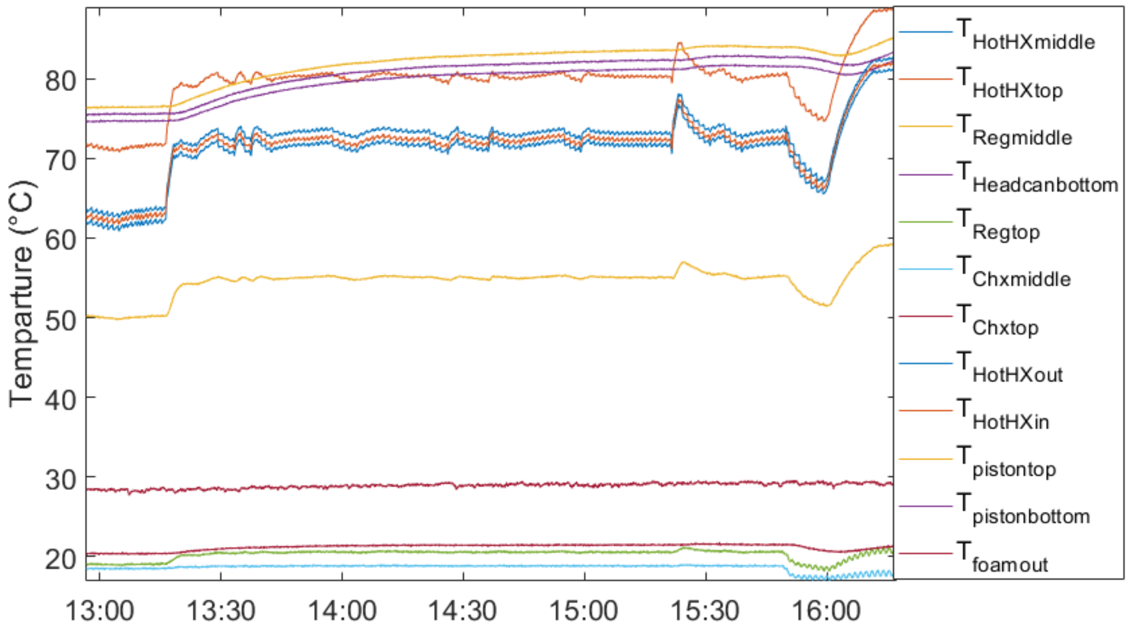


Figure 14: Different wall tempeartures during a single measruement point, $T_{pistonbottom}$, $T_{pistontop}$, and $T_{headcanbottom}$ show a slower behaviour than the other wall temperatures

Figure 15 displays the temperatures at the in and outlets of the heat exchangers, as well as the thermal powers output by those heat exchangers, and the electrical power. The variation in the temperatures is due to the control characteristics, and the tuning of this control. The flow rate has been tuned such that the temperature difference between in and outlet of a heat exchanger is around 5°C. A stable average is taken over the latter part of a measurement point, where the values are most stable.

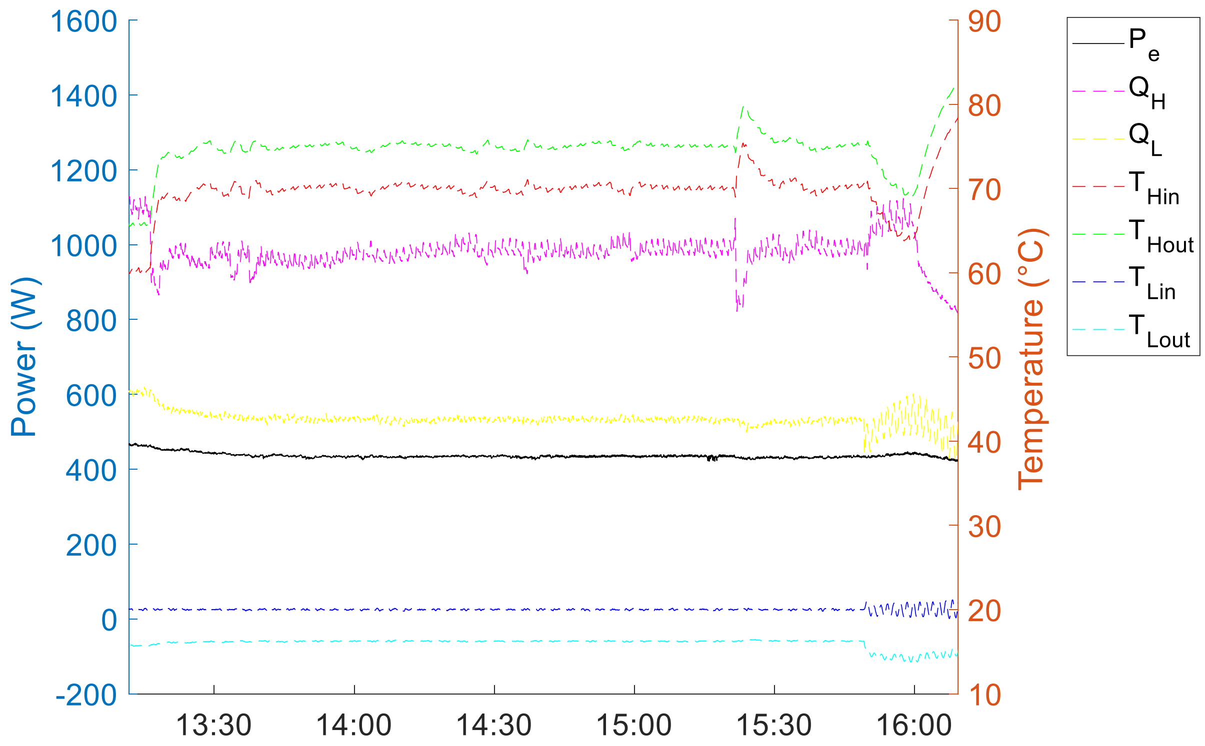


Figure 15: Thermal and electrical powers (left axis), and temperatures of the in and outlets of the heat exchangers (right axis)

Performance

With a constant cold inlet of 20 °C, measurement points have been taken for a varying hot inlet temperature from 20 to 80°C. The voltage is controlled at 4 different power levels, such that the voltage is set to 135, 190, 235 and 270V_{rms}, representing 25, 50, 75 and 100% of the power available in our setup. Note that as this represents electrical power, these are the percentages of the square of the voltage.

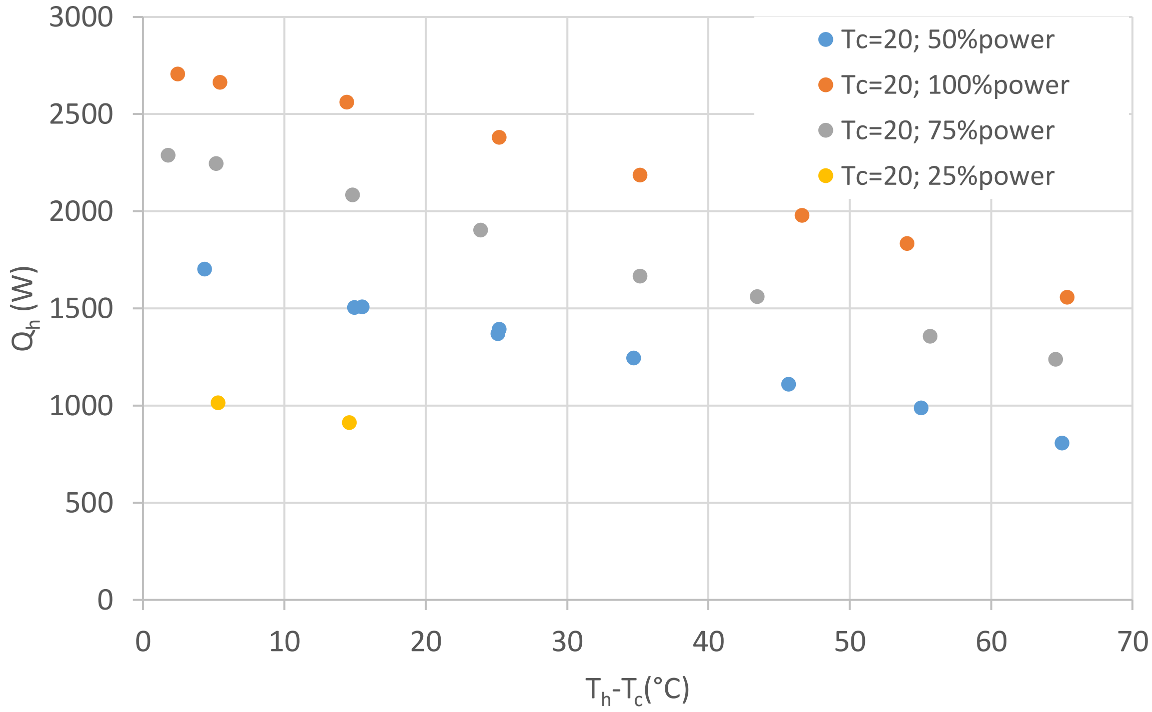


Figure 16. Heat out as a function of temperature for four compressor operating conditions

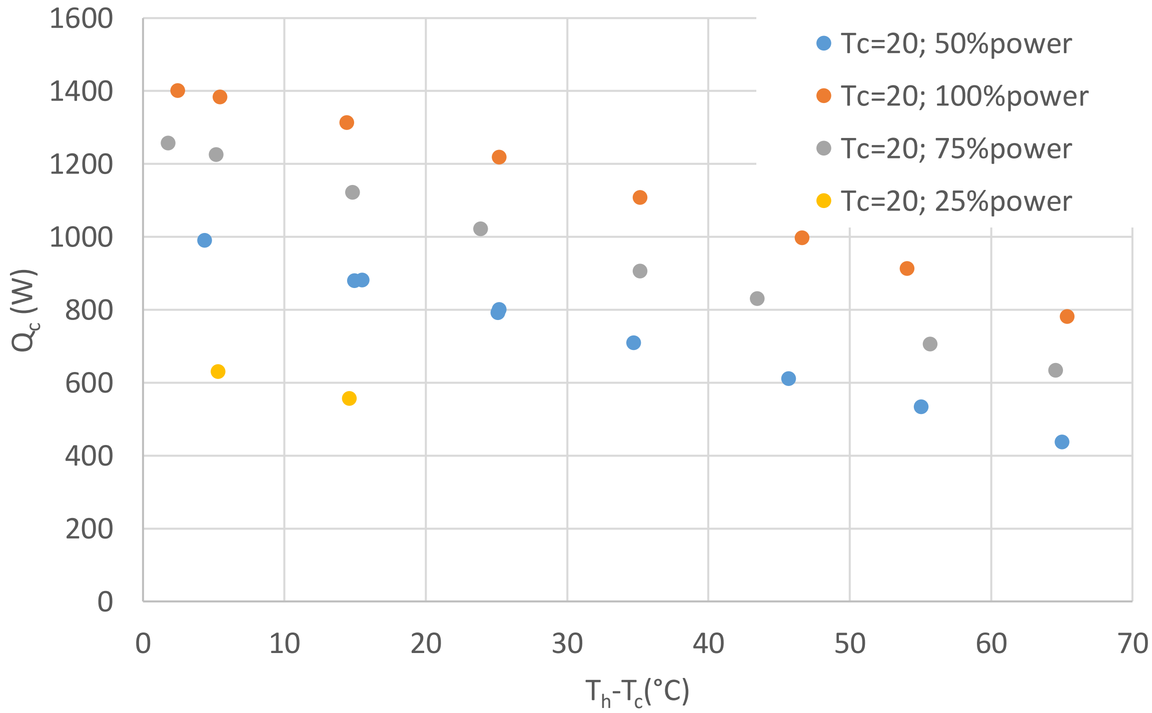


Figure 17. Heat in as a function of temperature for four compressor operating conditions

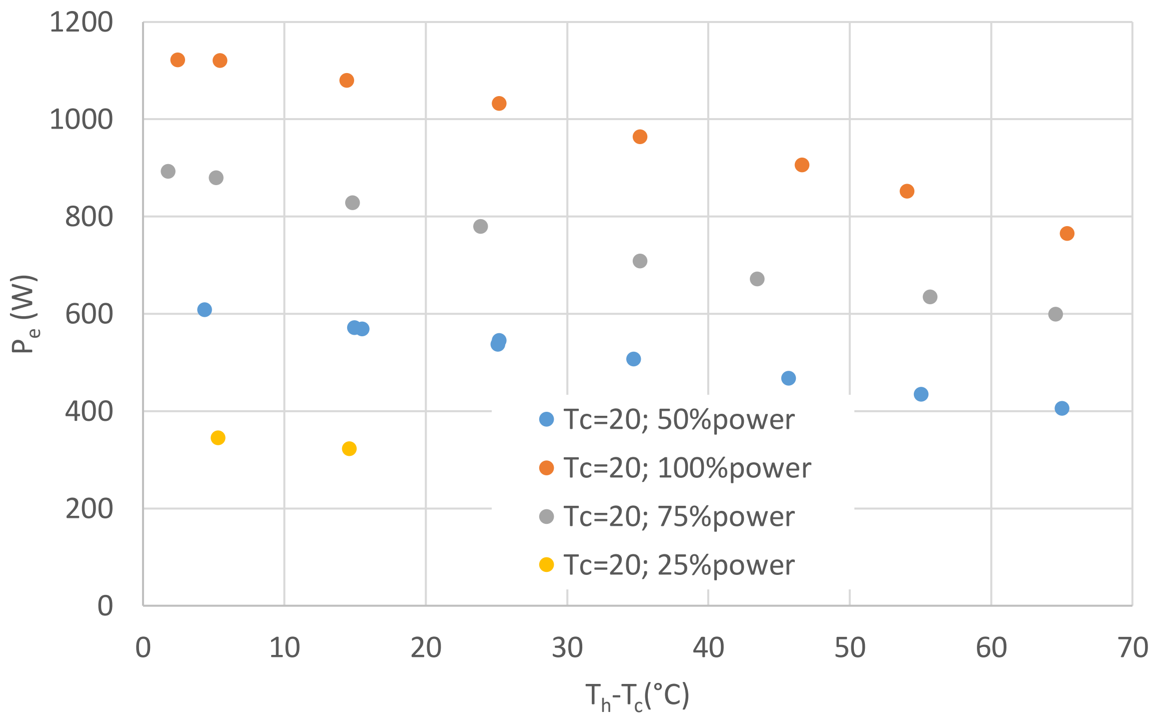
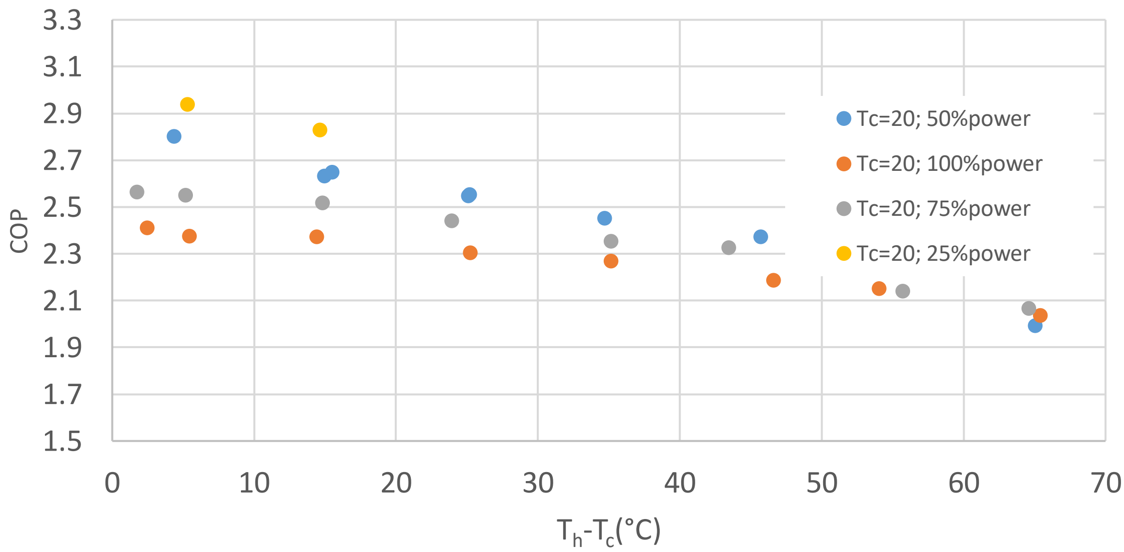


Figure 18. Electrical power



Discussion:
As discussed earlier we cannot device one particular temperature in the cold and hot circuits as the water is either heated or cooled by the heat pump. In the plots above we used an average temperature of the in and out flow in each circuit.

For a certain temperature lift the COP is lower as the powers increase. This is expected as a higher power will lead to an increase in piston stroke, therefore larger volume displacement, causing more flow losses in the ducts, heat exchangers and the regenerator.

This difference decreases at higher temperature differences indicating thermal losses are more dominant.

A DELTAEC model of the regenerator and heat exchanger is developed for this system. It is rather challenging to completely model this system using this tool. The primary reason being that this is a one-dimensional acoustic model, whereas in this heat pump due to flow loops and unconventional heat exchanger at the cold end three-dimensional flow effects are more dominant. The predicted performance is therefore is way off from the experimental values. A thorough CFD based numerical model (for example COMSOL) is therefore proposed as a follow up to this study.

In spite of a far from optimum cold heat exchanger design the measured COP values are for various hot temperatures look very satisfactory and are at or above par with vapor compression systems. In fact vapor compression systems cannot cover the range that this Stirling system can.

What next?

The main focus should be on improving the cold heat exchanger of this heat pump. Ideally, a copy of the design of the hot exchanger is sufficient.

A three-dimensional numerical model is necessary to capture the flow and heat transfer physics in this system.

Efforts must be made to reduce the cost of this system. Once again, the current design is for an engine with a hot temperature of 600 degree Celsius. Since the temperatures attainted in the heat pump is less lethal, the materials used to manufacture the displacer can be much cheaper.

Appendix A: LabVIEW program

Data acquisition and control of all but the pressure sensor, is done via LabVIEW. The pressure sensor has its own program. All other tasks are controlled by LabVIEW. As the other tasks are timing dependent and do not run at the same time, they are separated in different while loops, communicating via buffers and notifiers, so they can run asynchronous.

Reading of the Keithley multi-meter, is done on timing determined by the multi-meter, and scans all channels roughly once per second. The multi-meter stores the values in a buffer. This buffer is then read via a GPIB bus. It should be noted that the sampling rate of the multi-meter is not constant, for it depends on the voltages settling, and auto scaling. The buffer is read with a delay of 200ms, so that each read grabs a about a single measurement, minimizing the delay between measurement and the control loop being able to actuate.

The input channels of the DAQ measure at 1000 Hz, as to measure a 50Hz sine signal with decent accuracy. The DAQ is storing continuous samples to its buffer, and once 100 samples are available, the LabVIEW program requests them, and sends them to be read in the processing and storage loop. As temperature is controlled, no input signals from the DAQ are required in the control loop.

The control loop contains the control for the hot and cold inlet temperatures. It thus controls the valve for flow through the heat exchanger, using an analog output. And the circulation heater, using a 10Hz PWM signal. It starts off with a hard wired safety check. If the hot inlet, or outlet temperature is above 90°C, the control signal for the valve is set to fully open. Similarly, if the low temperature inlet or outlet is below 5°C, the circulation heater is set to fully on.

If the safety check is ok, the latest available temperature is passed to a PID controller, that outputs a voltage from 2-10V for the valve, and a value of 0-100 for the circulation heater, that represents the on time. The 0-100 value is rounded to a whole number of ms, as LabVIEW is not suitable for sub millisecond timing.

The processing loop has two functions, the storing of all the raw data, this happens in two different files. A LabVIEW measurement file (LVM) for storing the data from the DAQ. And a text file that stores the data from the multi-meter.

The other function is processing the data for display, so that during the measurement an estimation of powers and other variables can be seen. The powers are measured assuming a constant density and heat capacity of the water. Also no interpolation is used on the temperature data, instead the latest available value is used, meaning that for changing temperatures an error occurs in the ΔT. These things are taken into account during the post-processing of the data.