HIGH TEMPERATURE THERMOACOUSTIC HEAT PUMP

M.E.H. Tijani

S.Spoelstra

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Hassan Tijani and Simon Spoelstra

Energy research Centre of the Netherlands 1755 ZG, Petten, The Netherlands,

email: tijani@ecn.nl

Thermoacoustic technology can provide new types of heat pumps that can be deployed in different applications. A thermoacoustic heat pumps can for example be applied in dwellings to generate cooling or heating. Typically, space and water heating makes up about 60 % of domestics and offices energy consumption. The application of heat pumps can contribute to achieve energy savings and environmental benefits by reducing CO_2 and NO_x emissions. This paper presents the study of a laboratory scale thermoacoustic-Stirling heat pump operating between 10°C and 80°C which can be applied in domestics and offices. The heat pump is driven by a thermoacoustic-Stirling engine. The experimental results show that the heat pump pumps 250 W of heat at 60 °C at a drive ratio of 3.6 % and 200 W at 80 °C at a drive ratio of 3.5 %. The performance for both cases is about 40 % of the Carnot performance. The design, construction, and performance measurements of the heat pump will be presented and discussed.

1. Introduction

The widespread application of high performance heat pumps in dwellings and industry can contribute to achieve energy savings and to reduce CO_2 and NO_x emissions. Most conventional heat pumps use working media which have ozone depleting and/or global warming potential. A thermoacoustic heat pump in contrast uses only environmentally friendly working media like air or noble gases. It has also other advantages like having no moving parts involved in the thermodynamic cycle which make it very reliable and having a long life span. Other advantages are simple implementation and use of common materials, mainly tubes. Thermoacoustic heat pumps are in principle able to achieve in one stage higher temperature lifts than conventional ones. Lifts up to 100°C can be achieved in an efficient way. All of these advantages make thermaocoustic heat pumps suitable for many domestic and industrial applications[1-3]. Thermoacoustic heat pumps can be electrically or thermally driven. This paper discusses a thermally driven thermoacoustic heat pump which might be applied in dwellings.

Thermally driven thermoacoustic heat pump systems use heat from a high-temperature source to upgrade an abundantly available heat source (air, water, geothermal, industrial waste heat). The heat pump system consists of a thermoacoustic heat pump driven by a thermoacoustic engine. The engine and heat pump are coupled by an acoustic resonator. The engine converts part of heat $Q_{h,e}$ from hot flue gases from a burner at $T_{h,e}$ into acoustic power W. The heat pump uses the acoustic power W_{hp} to pump heat $Q_{l,h}$ from a low temperature source at $T_{l,h}$ (10°C) to a high temperature sink at $T_{h,h}$ (80°C). A thermodynamic illustration of the system is shown in Figure 1. A part of the acoustic power produced by the engine is dissipated in the resonator (W_{hp}< W).

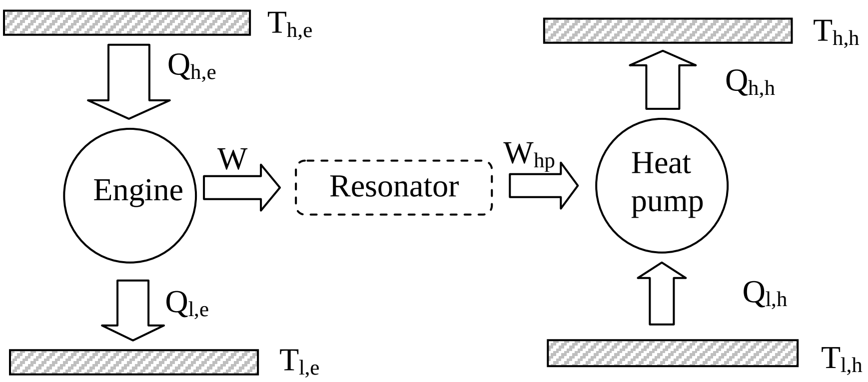

Figure 1. Thermodynamic illustration of the thermoacoustic system

The thermoacoustic engine and heat pump use a thermodynamic cycle similar to Stirling cycle[4,5]. This system is attractive since it uses a noble gas as working medium (helium) and has no moving mechanical parts or sliding seals. This paper deals mainly with the heat pump part.

The remaining of this paper is organized as follows: Section 2 is devoted to design and construction of the heat pump and its coupling to the engine. Section 3 presents the measurements procedure and performance indicators used to characterise the heat pump. Section 4 shows the measurement results. In the last section some conclusions are drawn.

2. Design and construction of the high temperature heat pump

A detailed discussion of the design, construction, and test of the engine can be found elsewhere[6]. The engine uses hot air, driven by a blower and heated by an electrical heater, to generate acoustic power. Hot air is used to simulate the flue gases of a gas burner. The low-temperature sink for the engine consists of cooling water chilled by a thermostat bath. This chapter presents predominately the design and construction of the heat pump along with its coupling to the engine.

2.1 Operation conditions

The heat pump is designed to be driven by an existing thermoacoustic-Stirling engine. The same operation conditions as the engine are considered. Helium gas at an average pressure of 40 bar is used as the working medium at the operation frequency of 110 Hz.

2.2 Design and construction of the heat pump

The thermoacoustic computer code DeltaEC[7] is used to design and optimize the integral system consisting of the engine and heat pump as illustrated in Figure 2.

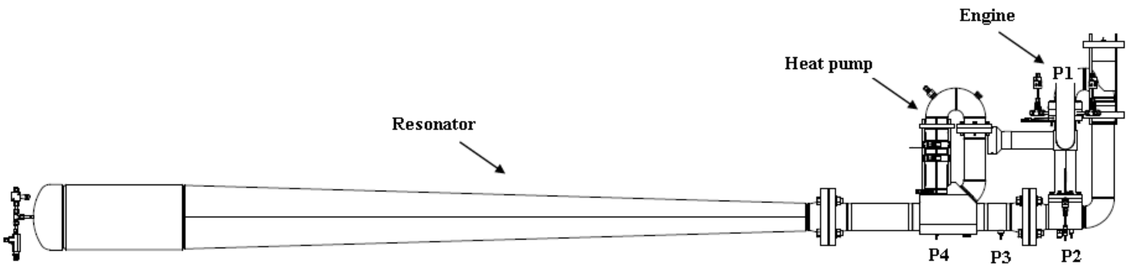

Figure 2. Schematic illustration of the heat pump attached to the engine and to the resonator

The heat pump consists mainly of a torus-shaped section attached to the straight part of the resonator. The torus-shaped section, contains a hot heat exchanger (HHX) to remove the useful pumped heat at 80°C, a regenerator (REG), a cold heat exchanger (CHX) to supply heat at 10°C, a thermal buffer tube (TBT), an ambient heat exchanger (AHX), and a feedback inertance as shown in Figure 3. The gas column in TBT provides thermal insulation between CHX and AHX.

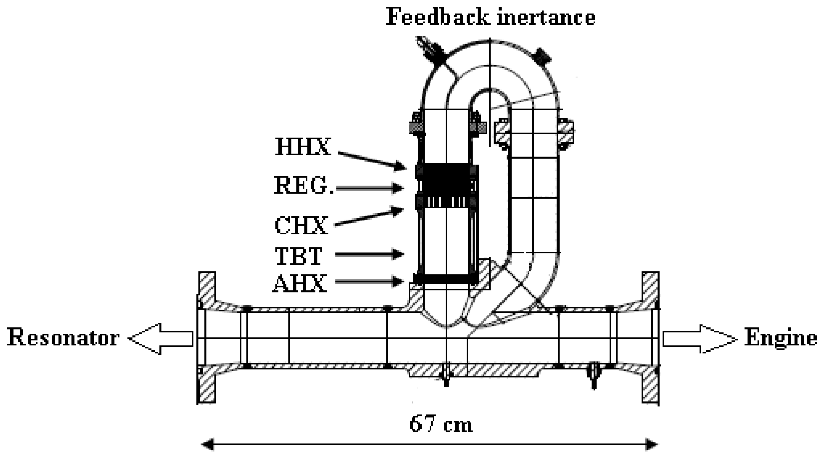

Figure 3. Schematic illustration of the heat pump. HHX = hot heat exchanger (80 °C), REG. = regenerator, CHX =cold heat exchanger (10 °C), TBT = thermal buffer tube, AHX = ambient heat exchanger.

The thermoacoustic heat pump functions like an acoustic attenuator. The acoustic power delivered by the engine is used to pump heat from CHX to HHX. The acoustic network formed by the elements in the torus section forces the acoustic wave generated by the thermoacoustic engine to propagate anti-clock wise entering the regenerator via the HHX, is partly used to pump heat against the temperature gradient along the regenerator, and the remaining power exits via the CHX to be added to the power delivered to the engine at the T-junction. The acoustic wave forces helium gas in the regenerator to execute a thermodynamic cycle similar to the Stirling cycle[4,5]. The acoustic wave takes care of the compression, displacement, expansion, and the timing necessary for the Stirling cycle. In the same way as do the piston and displacer in a classical Stirling system.

A DeltaEC-model of the integral system is built and simulation calculations are done to determine the dimensions of the different components of the heat pump. The different components of the heat pump as incorporated in the DeltaEC-model are indicated in Figure 3**.** The simulations show that the heat pump lifts 305 W of heat at 80°C using about 117 W of acoustic power with a coefficient of performance relative to Carnot of 50 % at a drive ratio of 5 % measured at the location of the pressure antinode of the engine (P1 in Figure 2). The drive ratio is the ratio of the dynamic pressure and the average pressure. A summary of the optimized dimensions of the different parts of the heat pump is given in Table 1. The length of the straight part of the resonator used to connect the heat pump to the engine and to the conical part of the resonator is 67 cm as indicated in Figure 3. A CAD-illustration and a picture of the heat pump are shown in Figure 4.

A CAD-drawing of the heat pump attached to the engine and resonator and suspended in the frame is shown in Figure 5. A short description of the different components of the heat pump is given in the following:

Hot heat exchanger (HHX) and Cold heat exchanger (CHX)

The Hot heat exchanger and cold heat exchanger are similar and they are of cross-flow type. They consist of a cylindrical brass block with a length of 2 cm and containing copper fins (86 fins/in) at the helium-side to increase the heat transfer area. The spacing between the fins is 0.295 mm, the fin height is 5.25 mm, and the thickness is 0.05 mm. The water-side consists of rectangular channels (slits) 1 mm high and 13 mm wide. Fins (86 fin/in) are soldered in the slits. Figure 6 shows an illustration of the heat exchanger.

Table 1. Dimensions of the heat pump

	Diameter (cm)	Length (cm)	Porosity (%)	Other properties
Regenerator (Reg.)	6.7	3.15	82.2	Mesh # 180, wire diameter = 32 µm, Hydraulic radius = 37 µm,
Hot heat exchanger (HHX)	6.7	1.5	50	Helium side: fin-spacing = 0.295 mm water-side: fin-spacing = 0.295 mm
Cold heat exchanger (CHX)	6.7	1.5	50	Helium side: fin-spacing = 0.295 mm water-side: fin-spacing = 0.295 mm
Ambient heat exchanger (AHX)	6.7	1.2	38	Shell-tube: tube-diameter = 1.5 mm
TBT	6.7	10	-	-
Feedback tube (L)	6.7	60	-	-

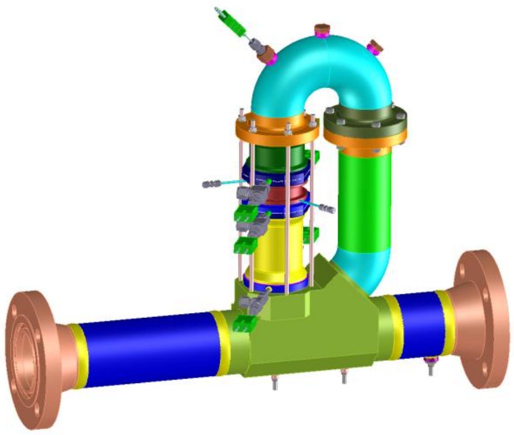

Figure 4. CAD-illustration of the heat pump

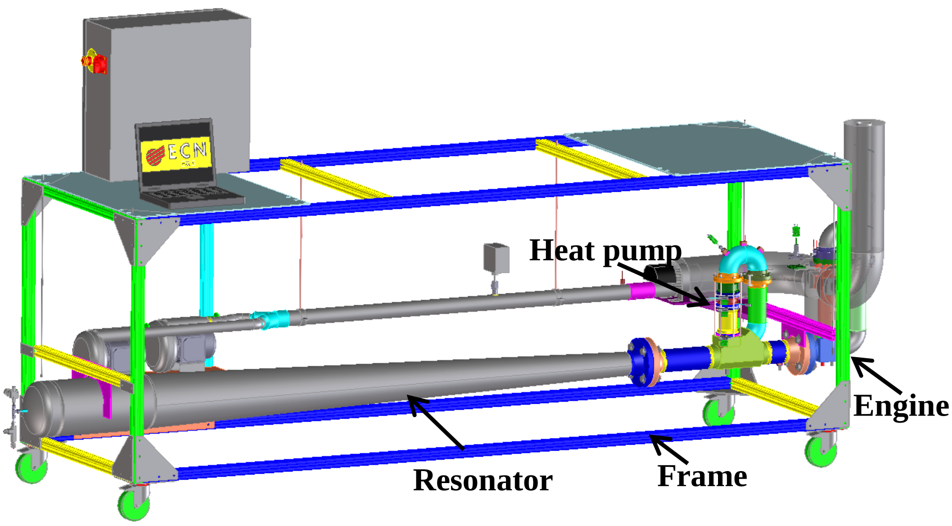

Figure 5. CAD-illustration of the heat pump attached to the engine and acoustic resonator and suspended in the frame.

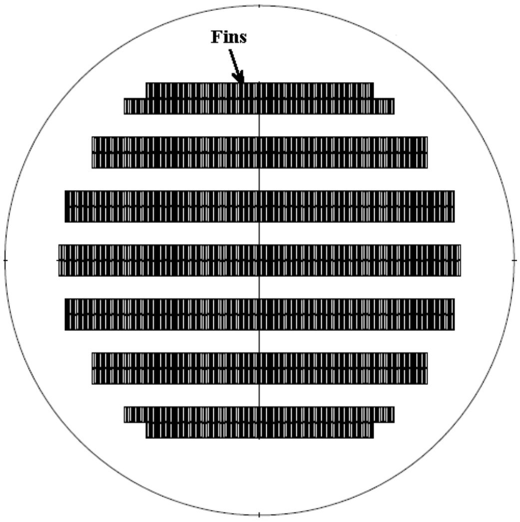

Figure 6. Schematic illustration of the heat exchanger

Regenerator (REG)

The regenerator consists of a 3.15 cm long stack of 180-mesh stainless steel screens with a diameter of 6.7 cm. The diameter of the screen wire is 32 μm. A volume porosity of 82% and a hydraulic radius of 37 μm are calculated using the mesh-number and wire diameter. The hydraulic radius of the regenerator should be smaller than the thermal penetration depth of the helium gas at the prevailing conditions, to ensure good thermal contact between helium gas and the regenerator material. The regenerator is housed in a thin-walled Inconel cylindrical holder.

Thermal buffer tube (TBT)

The thermal buffer tube consists of cylindrical tube with a diameter of 6.7 cm and a length of 10 cm made from Inconel.

Ambient heat exchanger (AHX)

The ambient heat exchanger consists of a cylindrical brass block containing 738 cylindrical holes with a diameter of 1.5 mm through which the helium gas oscillates. Water flows around the perimeter of this block to carry away the heat transferred by the gas.

Feedback inertance (L)

The feedback inertance consists of stainless steel cylindrical tube with a length of 60 cm and diameter of 6.7 cm.

Elastic membrane

An elastic membrane has been placed at the ambient heat exchanger to suppress Gedeon streaming[8].

3. Measurements procedure and performance indicators

The characterization of the performance of the heat pump requires the measurement of many quantities like temperatures, dynamic pressures at different locations of the system, heat powers at the heat exchangers, and acoustic power consumed by the heat pump. The system will be instrumented so that these different quantities can be measured.

Two thermal baths with circulating water are coupled to CHX and HHX. One functions as a heat source at 10°C and the other one as heat sink at 60°C or 80°C. Two 3 mm thick type-K thermocouples are used at each heat exchanger to measure the inlet and outlet temperatures of the water. Turbine flow meters are used to measure the water flow through the heat exchangers. Three 0.5

mm thick type-K thermocouples are used to measure the temperature profile through the regenerator. Several pressure sensors are placed throughout the system. They are indicated by "P" in Figure 2. The acoustic power, produced by the engine can be measured by the 2-microphone method[9] using the two pressure sensors P_3 and P_4. However, because of the short distance between the two-microphones it is difficult to measure the acoustic power. Instead, the measured signals are used in DeltaEC-model to determine the acoustic power. The pressure sensor P_1 is used to measure the drive ratio and P_2 is used to measure the average pressure in the system.

The signals from the thermocouples are directly read by a data logger and sent to a computer. The pressure signals (magnitude and phase) are first measured by lock-in amplifiers then read by the data logger and send to a computer. The signals are recorded and displayed using Labview.

3.1 Powers

The thermal power extracted from the source at 10°C or delivered to the sink at 80°C is measured using the following expression

$$\dot{Q}_a = \rho_w\, c_{pw} U_w (T_{out-w} - T_{in-w})\,. \qquad (1)$$

Here is ρ_w the density of water, c_{pw} is the specific heat, U is the volume flow rate of water, and T_{in} and T_{out} are the input and output temperatures of the water stream flowing through the heat exchanger. At CHX the temperature of the flowing water decreases as heat is extracted from it but at the HHX the temperature of water increases as it is heated by the heat extracted from the CHX.

The power, produced by the engine W_{out}, is the sum of the acoustic power, dissipated in the resonator W_{res} and the acoustic power used by the heat pump W_{hp}

$$\dot{W}_{out} = \dot{W}_{res} + \dot{W}_{hp}\,. \qquad (2)$$

The heat pump is thermally insulated by wrapping thermal insulation around the thermodynamic part.

3.2 Performance indicators

By reference to Figure 1, the performance of the heat pump also called the coefficient of performance is given by

$$COP = \frac{Q_{h,h}}{W_{hp}} \qquad (3)$$

Where $Q_{h,h}$ is the heat pumped by the heat pump at HHX and W_{hp} is the acoustic power used by the heat pump. The Carnot coefficient of performance is the maximal theoretical performance a heat pump can achieve and it is given by

$$COPC = \frac{T_{h,h}}{T_{h,h} - T_{l,h}} \qquad (4)$$

Where $T_{h,h}$ is the average of the inlet and outlet temperatures of water flowing through HHX and T_l is the average of the inlet and outlet temperatures of water flowing through CHX. The coefficient of performance relative to Carnot is defined as the ratio

$$COPR = \frac{COP}{COPC} \qquad (5)$$

The performance measurements are done at different drive ratio's. The drive ratio increases with the heat input to the engine.

4. Experimental results

The experiments consist of two series measurements at two high-temperatures 60°C and 80°C. The low temperature of the heat pump for both cases is fixed at 10°C. Figure 7 shows the heat pumped by the pump at HHX, acoustic power consumed by the heat pump W_{hp}, COP, and COPR plotted as function of the drive ratio. The heat pumped and the acoustic power increases with the drive ratio. At a given drive ratio the heat pumped at 60°C is higher than that pumped at 80°C.

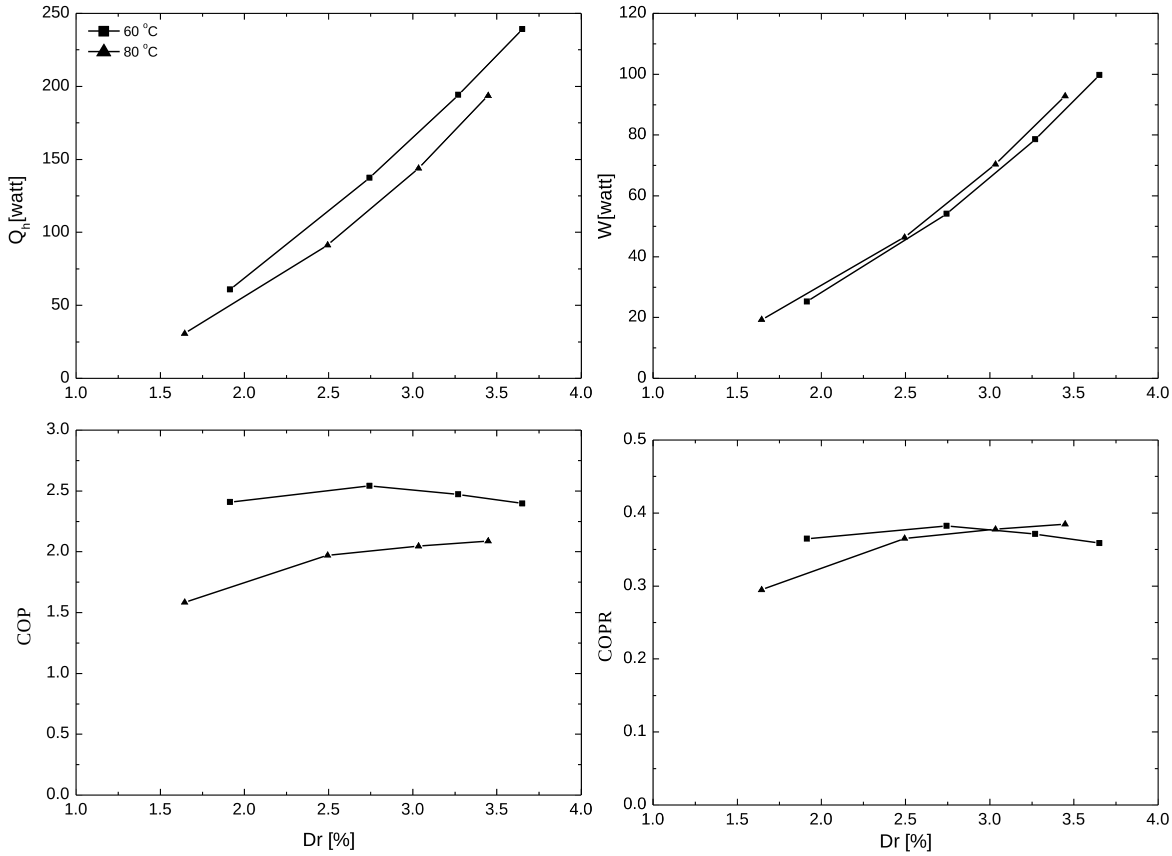

Figure 7. Heat pumped $Q_{h,h}$, acoustic power consumed by the heat pump W_{hp}, COP, and COPR of the heat pump operating at two high temperatures 60°C and 80°C as function of the drive ratio.

The acoustic power consumed by the heat pump for both high-temperatures is about the same. As a consequence the COP for 60°C at a given drive ratio is higher than that for 80°C. The COP and COPR for 60°C are slightly dependent on the drive ratio but they increases as function of the drive ratio for 80°C. About 250 W of thermal power is pumped at 60 °C at a drive ratio of 3.65 % and 200 W at 80 °C at a drive ratio of 3.5 %. The performance for both cases is about 40 % of the Carnot performance.

The measured performance for the laboratory scale is encouraging in considering the thermoacoustic heat pump as a potential candidate for applications in domestics and offices. However, further study is needed at real scale so that the real dimensions of the system can be determined and compared to conventional heat pump systems. The dimensions of the system are one of the important issues which have to be addressed. The acoustic resonator forms the largest part of the system while its function is limited to the determination of the resonance frequency for the system. Alternatives are under consideration like the use of a mechanical resonator[10]. This option makes the system more compact but introduces moving parts into the system.

5. Conclusions

A thermoacoustic-Stirling heat pump driven by a thermoacoustic-Stirling engine is designed, built, and tested. The experimental results show that the heat pump pumps 250 W at 60 °C at a drive ratio of 3.6 % and 200 W at 80 °C at a drive ratio of 3.5 %. The performance for both cases is about 40 % of the Carnot performance. These results are encouraging but further study at real scale is needed for a better comparison with conventional heat pumps. Issues like the dimensions of the system have to be addressed and ways to make the system compact have to be considered.

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