

## BENCH SCALE ELECTRICALLY DRIVEN THERMOACOUSTIC HEAT PUMP M.E.H. Tijani, J.A. Lycklama à Nijeholt, S. Spoelstra

Energy research Centre of the Netherlands ( ECN)  
P.O. Box 1, 1755 ZG, Petten, The Netherlands, email: [tijani@ecn.nl](mailto:tijani@ecn.nl)

**Abstract:** Efficient use of energy and lower global warming emissions can be achieved by applying heat pumps in the industry. Heat pumps can be used to increase the temperature of industrial waste heat to useful temperature levels. This enables the reuse huge quantities of energy that would otherwise be rejected to the environment. However, widespread use of large scale heat pumps is not yet common due to the low operation temperatures and limited temperature lifts of conventional heat pumps. Innovative heat pump technologies are needed which can help to overcome these difficulties. One promising innovative heat pump technology is the thermoacoustic heat pump which uses acoustic power to increase the temperature of a waste-heat stream to a higher, useful temperature. Thermoacoustic heat pumps can be electrically or thermally driven and can operate over a large scale of (high) temperatures and can achieve large temperature lifts. This paper presents the design and construction of a bench-scale electrically driven thermoacoustic heat pump which is designed to deliver 10 kW of thermal power at 100 °C.

**Key Words:** Heat pump, thermoacoustic, Stirling, waste heat, distillation,

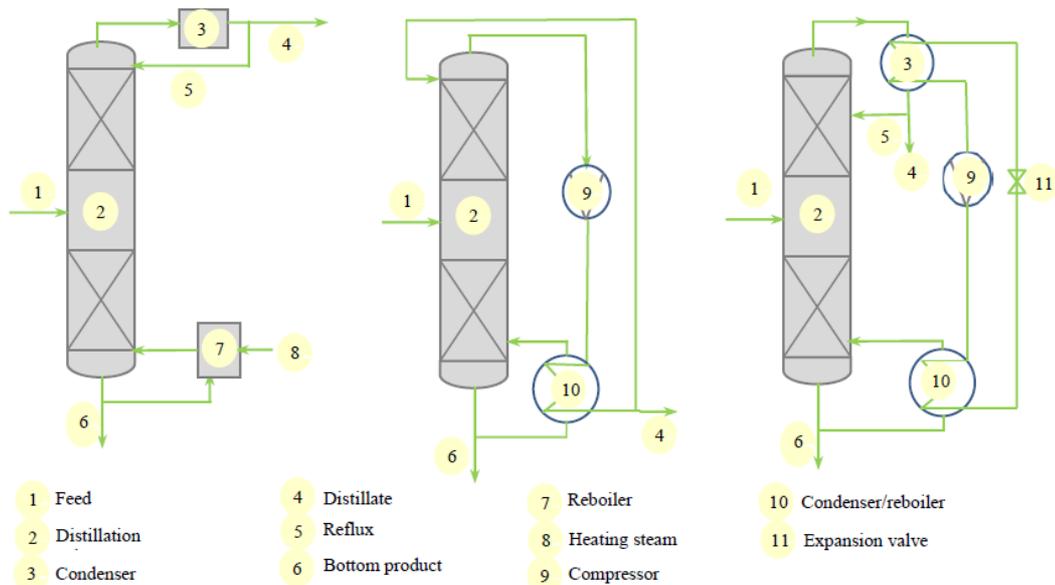
### 1 INTRODUCTION

The application of heat pumps in the industry is an important measure to achieve energy saving and lower global warming emissions (Spoelstra et al. 2005). A heat pump increases the temperature of a waste heat source to a high temperature so that the waste heat becomes useful. The reuse of the waste heat reduces the energy costs. The increase of the waste heat temperature requires mechanical or thermal input to the heat pump. The objective is to design a system in which the benefits of using a heat pump to upgrade the waste heat exceeds the cost of driving the heat pump. Several heat pump systems exist; some are electrically driven and some are thermally powered.

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One of the industrial applications where the application of a heat pump can be beneficial is the distillation process (Kiss 2012). Distillation is one of the largest energy consumers processes in refining and bulk chemical industries. It is estimated that distillation columns consume about 40% of the total energy used to operate plants in these sectors (Humphrey 1995, Dueck 1978). The distillation process is a very inefficient process as heat at high temperature is supplied to boil a mixture of liquids and most of this heat is released at a lower temperature level during condensation. Many methods have been introduced to improve the efficiency of distillation columns (Null, H.R.1976, Freshwater 1961, Soave 2002). However, the application of heat pumps to distillation columns has a significant energy saving potential and many other advantages. In a conventional distillation unit energy is supplied to the system via the reboiler to evaporate the feed

for the separation process. The vapors from the top of the column are liquefied in the (water) cooled condenser. About 95 % of the energy needed for the reboiler leaves the system as waste heat. In a heat pump assisted distillation column, the condenser is linked to the reboiler via the heat pump where the temperature of the vapor from the top of the column is increased and fed to the reboiler where it is condensed. In comparison to conventional distillation columns, this process requires only a fraction of the thermal energy. Furthermore, there is no need for any heating steam or large quantities of cooling water. Figure 1 shows a comparison of the conventional and heat pump assisted distillation columns. Additionally, the application of a heat pump has the advantage over other methods of not interfering with the distillation process.



**Figure 1 Conventional distillation column (left), a direct vapour recompression assisted distillation column (middle), and a heat pump with auxiliary circuit assisted distillation column (right).**

Some heat pump systems exist which are used for distillation columns like mechanical vapour compression heat pump (MCV) as shown in Figure 1. However, the temperature increase which can be obtained with such type of heat pumps in an economical beneficial way is usually limited to 10 to 20°C. This small temperature lift is not sufficient for most distillation columns. In contrast, a thermoacoustic heat pump is in principle able to achieve a sufficient high temperature lift up to 100°C in an efficient way. Large energy savings can be realized by the application of thermoacoustic heat pumps for distillation which will also result in the reduction of CO<sub>2</sub> and NO<sub>x</sub> emissions. In addition to their capability to operate at high temperature and to generate high temperature lift, thermoacoustic heat pumps have many other advantages like using only environmentally friendly working medium (air, noble gases), few moving parts, and can be made from commercially available materials.

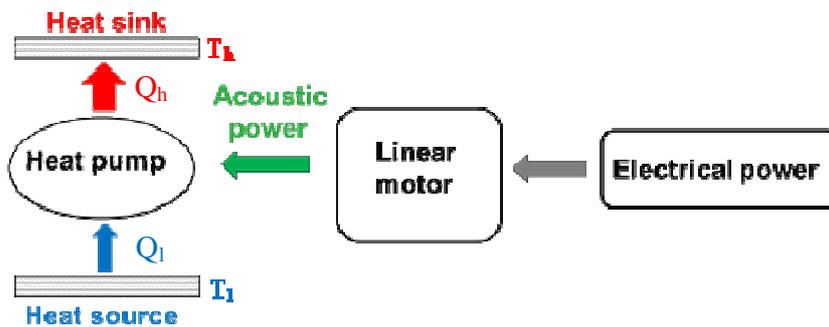
A recent study shows that the application of a thermoacoustic heat pump in distillation columns has a potential of primary energy savings estimated to 45 % of the total primary energy consumption in distillation processes.

This paper presents the study of a bench scale electrically driven thermoacoustic heat pump which is designed to deliver 10 kW of thermal power at 100 °C. The heat pump is powered by a linear motor. The design, development, and performance measurements of the heat pump will be presented.

The remaining of this paper is organized as follows: Section 2 is devoted to the working principle of a thermoacoustic-Stirling heat pump. Section 3 describes the heat pump. In section 4 the design and construction of the heat pump is explained. In section 5 some conclusions are drawn.

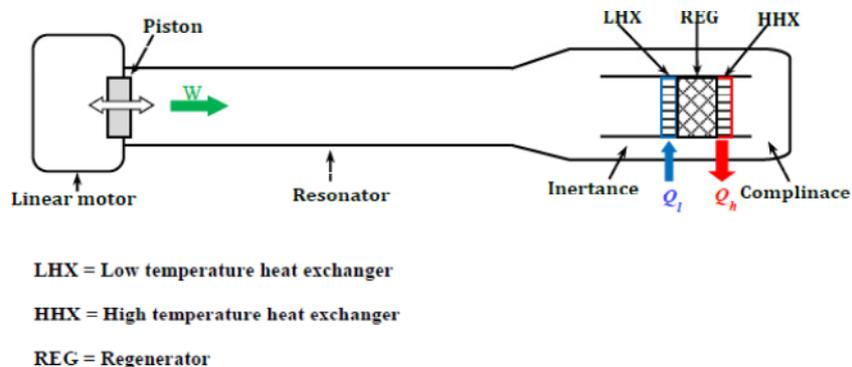
## 2 WORKING PRINCIPLE

The electrically driven thermoacoustic heat pump uses acoustic power to pump heat from a lower-temperature source to high-temperature sink. Figure 2 shows a schematic illustration of a thermoacoustic heat pump operating between a low temperature source at  $T_l$  and a high temperature sink at  $T_h$ . The acoustic power necessary to the operation of the heat pump is delivered by a linear motor which converts electrical power into acoustic power.

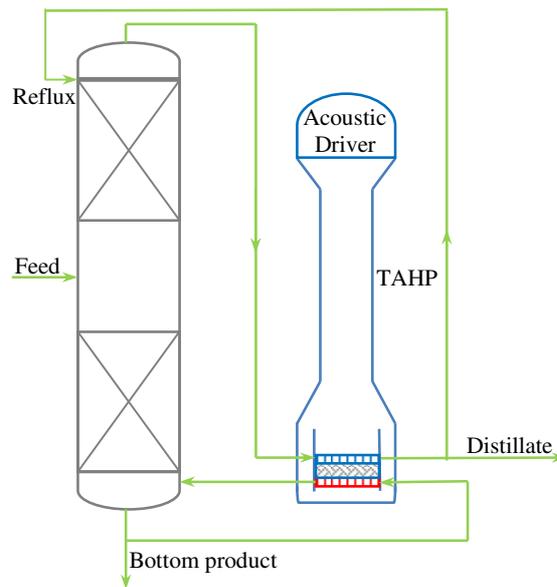


**Figure 2** Illustration of a heat pump driven by a driver (linear motor).

The working principle of a thermoacoustic heat pump is based on the Stirling cycle. However, in contrast to a conventional Stirling heat pump where a power piston and a displacer are used to force the working gas to execute the Stirling cycle, in a thermoacoustic heat pump a sound wave takes over the task of these mechanical parts (Ceperley 1979, Backhaus 2000). The acoustic wave takes care of the compression, displacement, expansion of the working gas and for the timing necessary for the Stirling cycle. Similar to a conventional Stirling heat pump, the core of a thermoacoustic heat pump consists of a regenerator placed between two heat exchangers. The core is placed in a gas filled acoustic resonator (tube). The acoustic wave is generated by an oscillating piston driven by an linear electrical motor as shown in Figure 3. Extended explanation of the working principle of thermoacoustic systems can be found in (Backhaus 2000) and references therein.



**Figure 3** schematic illustration of the electrically driven thermoacoustic heat pump



**Figure 4: a schematic illustration of the application of a thermoacoustic heat pump to a distillation column.**

A schematic illustration of a thermoacoustic assisted distillation column is shown in Figure 4. With reference to Figure 2, the first law of thermodynamics states that the sum of the work performed on the system  $\dot{W}$  and the heat extracted  $\dot{Q}_l$  from the low temperature reservoir at the low temperature  $T_l$  is equal to the heat delivered to the warm reservoir  $\dot{Q}_h$  at the higher temperature  $T_h$ ,

$$\dot{Q}_h = \dot{W} + \dot{Q}_l \quad 1$$

The measure of the heat pump performance is the coefficient of performance (*COP*). For heating applications this is the ratio of heat rejected at high temperature to the work input

$$COP = \frac{\dot{Q}_h}{\dot{W}} \quad 2$$

The upper theoretical value of COP obtainable in a heat pump is the COP Carnot (*COP<sub>c</sub>*) and is given by,

$$COP_c = \frac{T_h}{T_h - T_l} \quad 3$$

The ratio between the two COP values is the exegeric efficiency of the heat pump or sometimes called the performance relative to Carnot value *COP<sub>r</sub>*.

### 3 DESCRIPTION OF THE HEAT PUMP

A schematic illustration of the electrically driven thermoacoustic heat pump is given in Figure 5. The heat pump is designed to operate with helium gas at an average pressure of 50 bar and an operation frequency of 80 Hz. The acoustic network consisting of the resistance of the regenerator, the feedback inertance (fluidic inertia), and the compliance (volume of gas) are designed to create the traveling-wave phasing necessary to operate in a Stirling cycle. The resonator operates as a pressure vessel for the working gas and determines the operating resonance frequency of the system. The linear motor delivers the acoustic power needed by the heat pump. A thermal bench using thermal oil simulates the low temperature heat source (50-80°C) and the high temperature heat sink (100-150°C). A high temperature heat exchanger (HHX) and a low temperature heat exchanger (LHX) are used to connect the heat pump to the heat sink and heat source respectively.

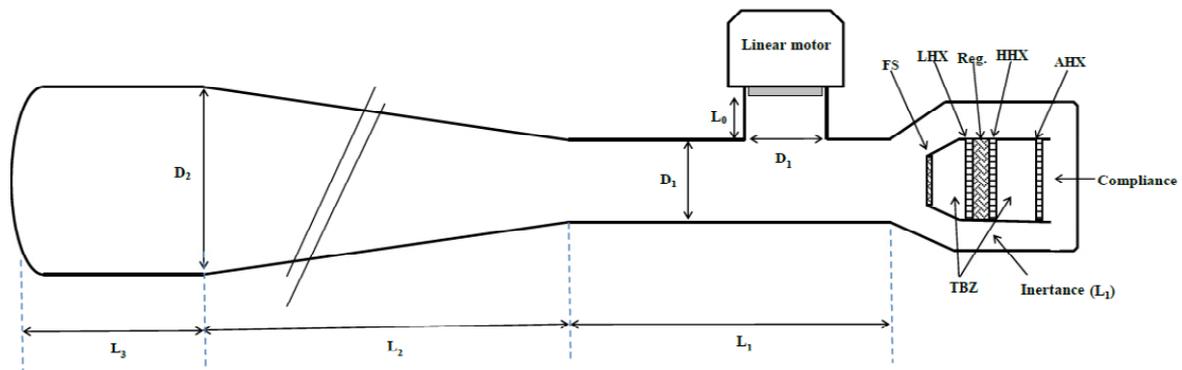


Figure 5: Schematic illustration of the heat pump

#### 4 DESIGN AND CONSTRUCTION OF THE HEAT PUMP

The optimal design of the thermoacoustic heat pump is done using the computer code DeltaEC (Clark et al. 2007). A DeltaEC-model of the system is build and simulation calculations are done to determine the optimal dimensions of the different components of the system. The different components of the system as incorporated in the DeltaEC model are indicated in Figure 5. The thermoacoustic heat pump is designed to deliver 10 kW of thermal power at 100 °C using 3.3 KW of acoustic power. The heat pump has thus a predicted coefficient of performance of 3.4. The resonator has an efficiency of about 88 %. This means that 88 % of the power produced by the linear motor is transmitted by the resonator to the heat pump.

A summary of the optimized dimensions of the different parts of the heat pump is given in Table 1.

Table 1: Simulation results for the high temperature thermoacoustic heat pump

Working gas	Helium
Average pressure	50 bar
Frequency	80 Hz
Drive ratio	5 %
High operation temperature	100 °C
High operation temperature	60 °C
Thermal power at 100 °C	10 kW
Thermal power at 50 °C	7.7 kW
Acoustic power input	3 kW
COP	3.34

A short description of the different components of the system will be given in the following.

#### *Linear motor*

The linear motor is a 1s297D STAR resonant linear alternator [Qdrive]. A piston is attached to the moving magnets of the alternator and it is placed in a cylinder with clearance fit. The rated electrical power consumption is 5 kW. The piston diameter is 22.3 cm and the maximum stroke is limited to 29 mm peak-to-peak. A displacement sensor is placed on the motor to measure displacement of the piston. A dynamic pressure sensor is mounted on the front side of the piston to measure the acoustic pressure at the piston location. The displacement and the acoustic pressure at the piston are used to determine the acoustic power input delivered by the linear motor to the heat pump. The linear motor is placed in a pressure vessel which is designed to withstand 50 bar. A cooling water copper spiral is wound around the vessel to remove the heat dissipated by the linear motor as shown in Figure 7.

#### *Regenerator*

The regenerator consists of a 30 mm thick stack of 140-mesh stainless-steel screen punched at a diameter of 26 cm. The diameter of the screen wire is 56  $\mu\text{m}$ . The stack is placed in a thin-wall tube. The regenerator is designed so that the hydraulic radius is small compared to the thermal penetration depth which is necessary for a good thermal contact of the gas with the regenerator matrix. The hydraulic radius of the screen is 44  $\mu\text{m}$  and the volume porosity is about 76 %. A picture of the regenerator is shown in Figure 7.

#### *Heat exchangers*

The heat exchangers consist of a cylindrical steel block where passes are machined. Copper fins with a density of 86 fins/in are brazed on the helium gas side to increase the heat transfer area. On the thermal oil side fins with a density of 50 fins/in are used. The diameter of the three heat exchangers is 26 cm and the length is 3 cm for LHX and HHX and 1 cm for AHX. The volume porosity of the heat exchangers at the helium side is 20 %.

#### *Resonator*

The resonator consists of two straight tubes connected by a cone. The first straight tube has an inner diameter of 22.3 cm and length of 82 cm, the conical tube has a start inner diameter of 22.3 cm, a length of 462 cm, and a final inner diameter of 48.4 cm. The last tube has an inner diameter of 48.4 cm and a length of 55 cm.

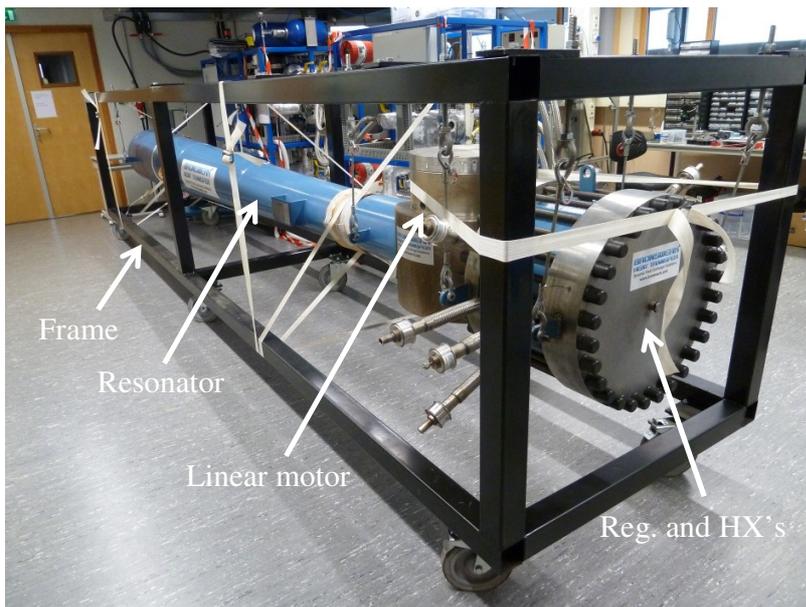


Figure 6: Picture of the thermoacoustic heat pump

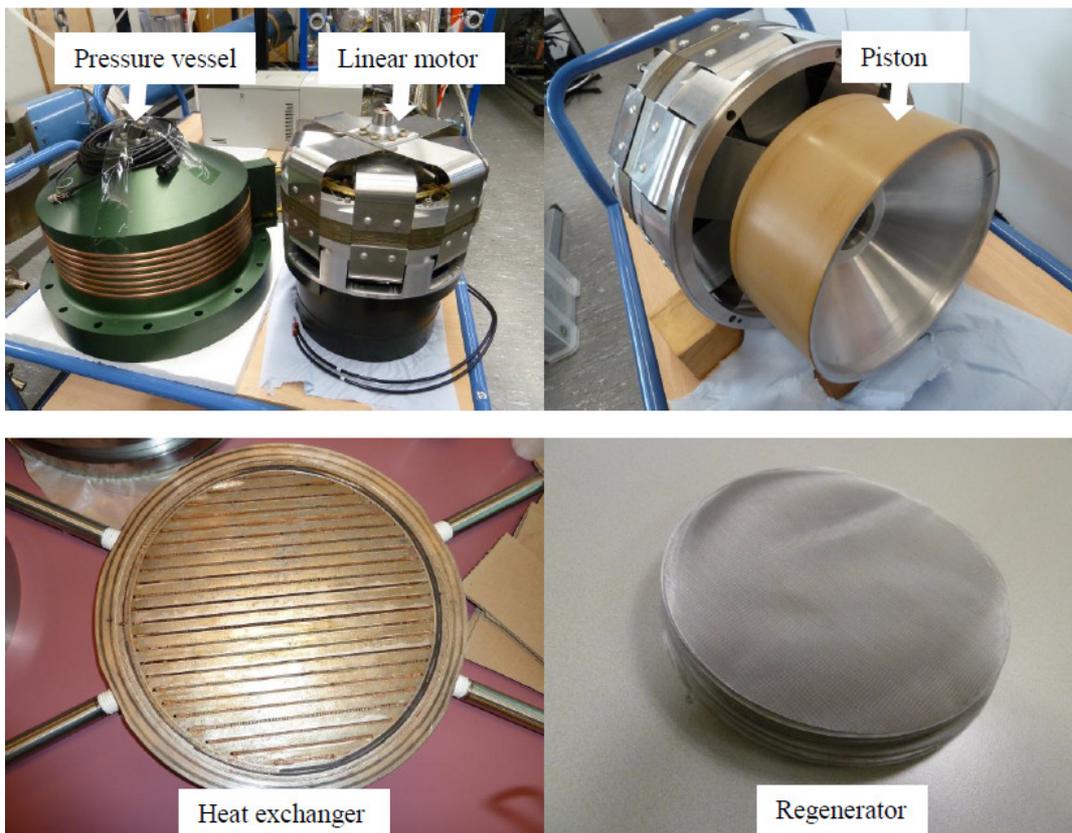


Figure 7: Pictures of pressure vessel, the linear motor, the heat exchanger, and the regenerator

## 5 CONCLUSION

An electrically driven thermoacoustic heat pump is designed and built. The optimal design of the heat pump using the thermoacoustic computer code DeltaEC show that heat pump can deliver 10

kW of thermal power at 100 °C with a coefficient of performance (COP) of 3.4. The design procedure is presented and the construction and assembly of the heat pump is discussed. The next step is to test the system.

### **ACKNOWLEDGEMENTS**

This work is funded in the scope of an ISPT(=Institute for Sustainable Process Technology) project.

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