Development of a thermoacoustic heat pump for distillation column

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Abstract

A thermoacoustic heat pump is a promising innovative heat pump technology which can be applied in the industry to upgrade industrial waste heat. The thermoacoustic heat pump consists of a regenerator flanked by two heat exchangers and placed in a gas (helium) filled acoustic resonator. An acoustic wave is generated and sustained by an acoustic driver in the resonator. The acoustic wave forces the working gas in the regenerator to undergo a Stirling cycle and to pump heat from the low temperature heat exchanger to the high temperature heat exchanger. The advantage of the thermoacoustic heat pump is that it can operate over a large range of (high) temperatures and can achieve large temperature lifts. One of the industrial applications where the application of the thermoacoustic heat pump can be beneficial is the distillation process. Distillation is one of the largest energy consumers processes in refining and bulk chemical industries. In a thermoacoustic heat pump assisted distillation column, latent heat from the condenser in pumped to the reboiler. An energy saving potential of about 10-20 PJ/year is estimated for the Netherlands, 100-200 PJ/year for Europe, and 300-600 PJ/year for the world. This paper presents the design, construction, and test of a bench scale electrically driven thermoacoustic heat pump. A reciprocating piston compressor is tested as acoustic driver for the heat pump.

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***Keywords*: Heat pump, thermoacoustics, Stirling;**

1. Introduction

The application of heat pumps in the industry can lead to large energy savings and reduce global warming emissions. Heat pumps can be used to upgrade waste heat. This enables to reuse the huge quantities of energy that would otherwise be rejected to the environment. One of the industrial applications where the application of a heat pump can be beneficial is the distillation process [1-2]. 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 [3-4]. 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. In a conventional distillation column 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. For the Netherlands, the total energy saving potential is estimated to 10-20 PJ/year. The extrapolation to Europe and the world, based on production capacities, leads to more than 100-200 PJ/year for Europe and 300-600 PJ/year for the world.

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. Standard heat pumps can deliver heat at a maximal temperature of 90°C. This is due to the used refrigerants. However, most industrial processes require temperatures larger than 90 °C. Development of new refrigerants like DR-2 and SES 32 will probably make it possible in the future to reach higher temperatures with conventional heat pumps.

Innovative heat pump technologies 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 because they use mainly inert gas (helium) as working medium. They are environmentally friendly and reliable. Thermoacoustic heat pumps have also the advantage to be insensible to temperature fluctuation of the heat source.

An electrically driven thermoacoustic heat pump is driven by a reciprocating piston which compresses and expands the working gas. The piston can be powered by an electrical linear motor, an electrical rotary motor, an internal combustion engine, or a turbine. Small scale electrically driven thermoacoustic heat pumps usually use a linear electrical motor to drive the piston. The linear motor has the advantage that the piston is directly attached to the moving part of the linear motor. However, linear motors are not available at high power. The largest commercially available linear motor has a power of 10 kW. A reciprocating piston compressor (RPC) consisting of a rotary electrical motor which drives a piston using a crankshaft can be an alternative to drive an industrial thermoacoustic heat pump. RPC's are commercially available over a large power spectrum up to tens of megawatts. They are usually used in the industry to increase the pressure of gases but it is not known if they can be deployed to drive thermoacoustic heat pumps.

The objective of the study presented in this paper is to evaluate whether an RPC can be used as an acoustic driver for an electrically driven thermoacoustic heat pump (EDTAH). An existing bench scale EDTAH [5] which is driven by a linear motor is adapted to be driven by RPC. The specifications for the RPC are dictated by the requirements of the EDTAH.

The remaining of this paper is organized as follows: section 2 discusses the working principle of the thermoacoustic heat pump. Section 3 presents the thermoacoustic heat pump assisted distillation column. In section 4, the design and construction of the heat pump is discussed. Section 4 presents the experimental results. In section 5 conclusions are drawn.

2. Thermoacoustic heat pump

The electrically driven thermoacoustic heat pump uses acoustic power W to pump heat Q_l from a lower-temperature heat source and to deliver heat Q_h to a high-temperature heat sink. Figure 1 shows a thermodynamic 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 W necessary to the operation of the heat pump is delivered by a piston compressor which converts electrical power into acoustic power.

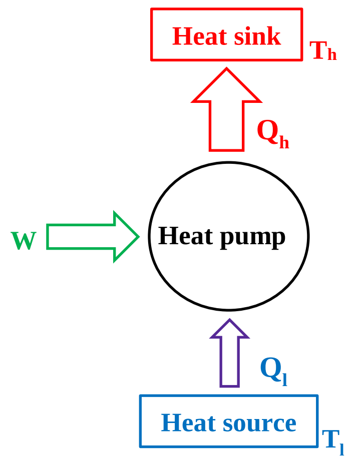

Figure 1 Thermodynamic illustration of a thermoacoustic heat pump

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 [6- 8]. 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 electrical motor as shown in Figure 2. A compact acoustic network creates the local traveling-wave phasing necessary for the Stirling cycle. The circuit consists of the resistance of the regenerator, a compliance, and a feedback inertance which are arranged in a loop configuration. The compliance consists of a volume of gas and is indicated by "C" in Figure 2 and the feedback inertance consists of a tube and is indicated by "L" in Figure 2. Extended explanation of the working principle of thermoacoustic systems can be found in [6-10] and references therein.

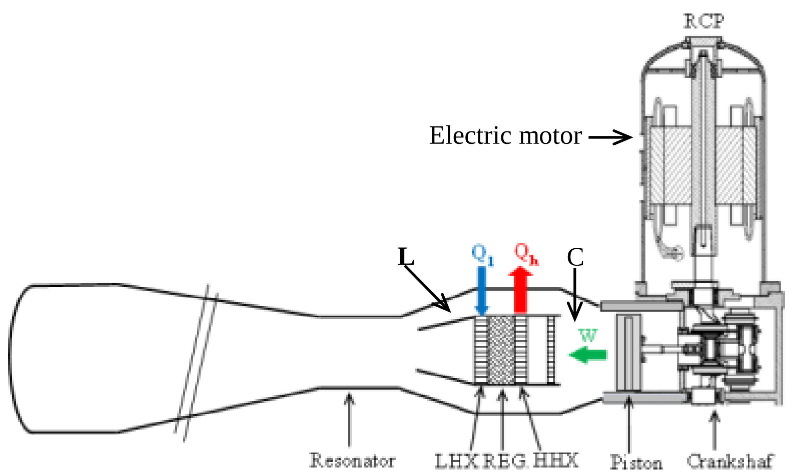

Figure 2 Thermoacoustic heat pump consist of a regenerator (REG), a hot heat exchanger (HHX), and a low temperature heat exchanger (LHX), placed in a resonator. A reciprocating compressor consisting of a piston driven by rotary electrical motor via a crankshaft is used as driver.

3. Thermoacoustic heat pump assisted distillation column

In a thermoacoustic heat pump assisted distillation column, the low temperature heat exchanger of the thermoacoustic heat pump is coupled to the condenser of the column and the hot heat exchanger to the reboiler.

In this way the heat released during condensation of vapors at the top of a column is upgraded by the thermoacoustic heat pump and delivered at high temperature to the reboiler of the column. The column stays adiabatically and changes are only made in the way heat is removed (condenser) or supplied (reboiler) to the process. This results in a reduction of both heating and cooling utility capacities. A schematic illustration of a thermoacoustic assisted distillation column is shown in Figure 3.

The most distillation processes operates in the temperature range of 100-200 °C [9] with capacities in the range 1- 10 MW. Thermoacoustic heat pumps can be developed to be applied to these processes. The upscaling of thermoacoustic heat pumps shows theoretically no limitations.

In the following section, the design of a bench-scale thermoacoustic heat pump is presented which can be applied for example to a methanol-water distillation column where the condenser temperature is 60 °C and the boiler temperature is 100 °C.

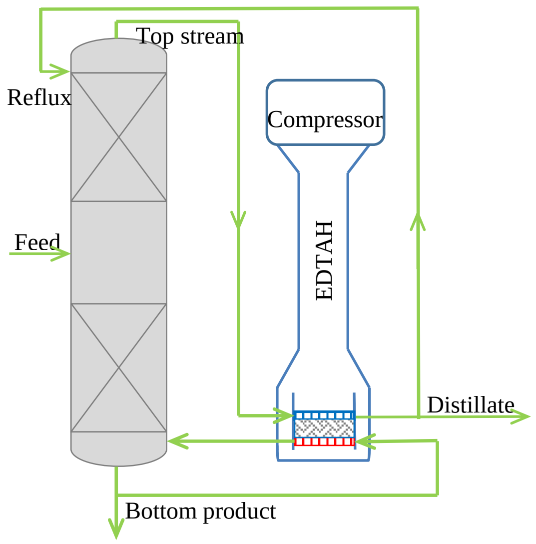

Figure 3 Schematic illustration of the application of a thermoacoustic heat pump to a distillation column.

4. Design and construction of the thermoacoustic heat pump

A schematic illustration of an EDTAH is shown in Figure 2. The heat pump is designed to operate between the condenser temperature and the boiler temperature of an industrial distillation column. The working medium is helium gas at an average pressure of 50 bar and the operation frequency is 80 Hz. A piston compressor delivers the acoustic power needed by the heat pump. The specifications of the thermoacoustic heat pump are summarized in Table 1. The temperatures

Table 1 Specifications of the thermoacoustic heat pump.

Working gas	Helium
Average pressure (bar)	50
Frequency (Hz)	80
High operation temperature (ºC)	100
Low operation temperature (ºC)	60
Thermal power at 100 ºC (kW)	10

The heat pump is designed and optimized using the thermoacoustic computer code DeltaEC [10]. A short description of the different components of the system will be given in the following.

Piston compressor

The objective is to evaluate whether a piston compressor can be used to drive the EDTHP. The compressor has to deliver the required acoustic power by the heat pump of about 3.5 kW. Because low power piston compressors are not commercially available, an outboard engine is adapted to function as a piston compressor. The engine is made oil free to avoid contamination of the heat exchangers and the regenerator. The engine is coupled to an electrical motor. The drive shaft of the electrical motor is attached to the crank shaft of the engine using a Bowex M28 consisting of two hubs and one M-sleeve. The electrical motor drives the piston of the engine via the crankshaft of the engine. The electrical motor and the engine are aligned and fixed in metallic frame. A picture of the compressor is shown in Figure 4.

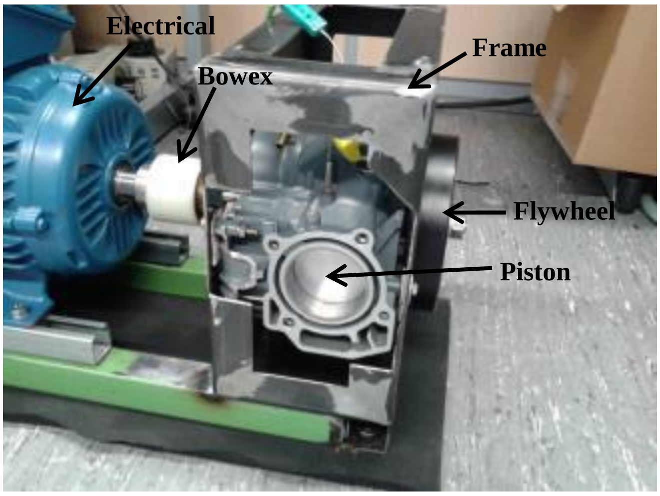

Figure 4 Picture of the reciprocating piston compressor

The specifications of the reciprocating compressor are summarized in Table 2 .

Table 2: Specifications for the piston compressor

Operation frequency (Hz)	80
Piston diameter (mm)	50
Swept volume (liter)	0.14
Acoustic power (kW)	4.5
Drive ratio (%)	5
Average pressure (bar)	50

The drive ratio is defined as the ratio of the dynamic pressure amplitude at the piston and the mean pressure of the gas. The compressor will be placed in a pressure vessel to operate at 50 bar as shown in Figure 5. The pressure vessel of the compressor has a flange which is used to couple it with the heat pump as shown on the right of Figure 5.

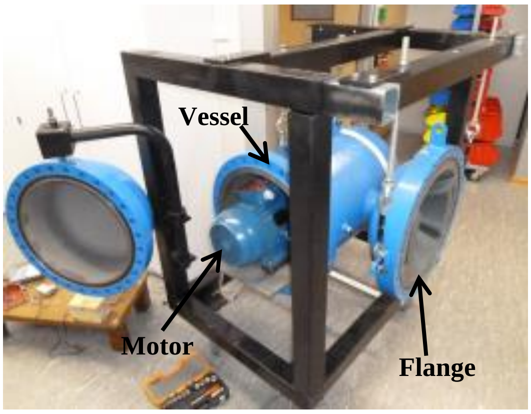

Figure 5 Picture of the compressor placed in a vessel pressure and to be coupled to the heat pump via the flange on the right of the picture.

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 μm. 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 μm and the volume porosity is about 76 %. A picture of the regenerator is shown in Figure 6.

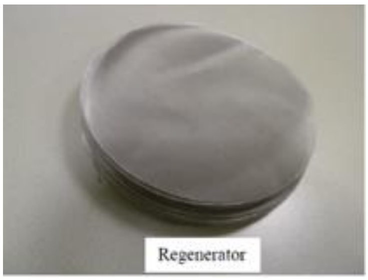

Figure 6 Picture of the regenerator

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 heat exchangers is 26 cm and the length is 3 cm for LHX and HHX. The volume porosity of the heat exchangers at the helium side is 20 %. A picture of the heat exchanger is shown in Figure 7.

Figure 7 Picture of the heat exchanger

Acoustic circuit
The feedback inertance, compliance, and regenerator acoustic resistance are designed to get the traveling-wave phasing in the regenerator and minimal viscous losses. The acoustic pressure and acoustic velocity have to be in phase at the regenerator midpoint. The inertance (L) consists of a tube with a diameter of 23 cm and a length of 40 cm. The compliance (C) has a volume of 10 liter.

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 8 shows a picture of the thermoacoustic heat pump.

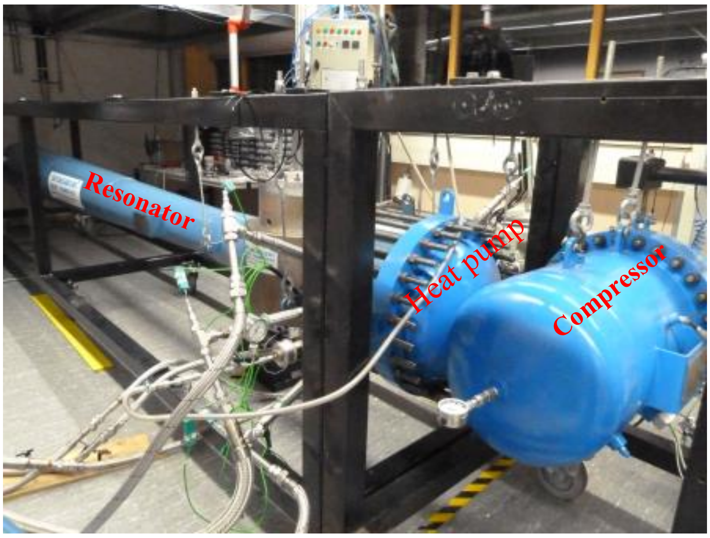

Figure 8 Picture of the thermoacoustic heat pump

5. Experimental results

A thermal bench using water and thermal oil simulates the low temperature heat source (20-80°C) and the high temperature heat sink (100-200°C). The high temperature heat exchanger (HHX) and the low temperature heat exchanger (LHX) are connected to the thermal bench using flexible tubing.

Various sensors are placed through the system to measure the operating parameters of the heat pump. The oil and water flow into the heat exchanger is measured with flow meters. The temperatures of the water and oil at the inlet and the outlet of the heat exchangers are measured with thermocouples. Several pressure sensors are placed throughout the system to measure the acoustic pressure at different locations in the system. The signals from the thermocouples are 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.

Acoustic measurements
The acoustic pressure generated by the compressor is measured as function of time using a Pico oscilloscope and the measurements are shown in Figure 9. The signals are measured at the piston location and in the inertance. The signal has a sinus shape which is required for the driving of the heat pump. The measurements show thus that the piston compressor can be used to generate and maintain an acoustic wave to drive the thermoacoustic heat pump.

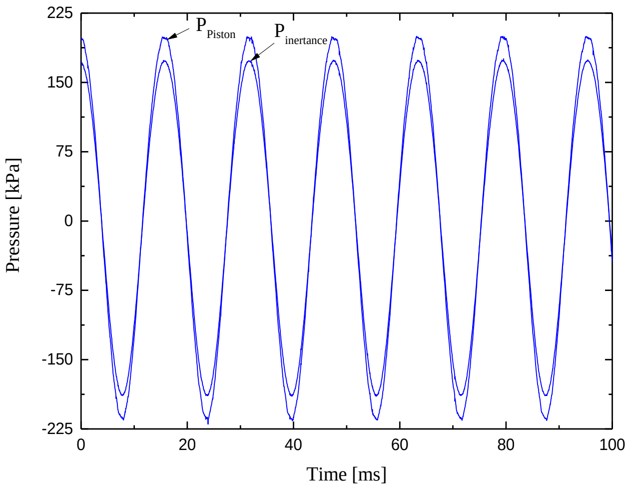

Figure 9 Acoustic pressure measured at the piston and in the inertance as function of time.

When the driving frequency of the compressor approaches the acoustic resonance of the heat pump, the electric power consumed by the electric motor of the compressor increases rapidly. This leads to an overheating of the motor which does not have a cooling system. The consumed electric power is proportional to the frequency. To avoid overheating of the compressor the operation frequency has to be decreased. The frequency can be decreased by using a gas mixture of helium and argon. A gas mixture consisting of 6 % argon and 94 % helium resulted in a decrease of the resonance frequency from 78 Hz to 63 Hz. Although the heat pump is designed for pure helium, the simulations show that the heat pump still perform well with 6 % argon in helium.

Performance measurements are conducted using a mixture of helium (94 %) and argon (6 %) and for a drive ratio (Dr) of 3.49 %. The drive ratio is defined as the ratio of the dynamic pressure amplitude at the piston and the mean pressure of the gas. The operation frequency is about 63 Hz. The measurements are summarized in Table 3. T_l and T_h are the low- and high-temperature of the heat pump, respectively. Q_l is the heat pumped at the low temperature and Q_h is the heat delivered by the heat pump at the high temperature. W is the acoustic power used by the heat pump and COP is the coefficient of performance of the heat pump (Q_h/W).

The acoustic power (W) used by the heat pump is deduced from the energy balance. The COP given in the Table 3 is internal and thus does not include the acoustic losses in the compressor and in the resonator. The measurements show that an internal COP of about 4.8 is achieved by the heat pump with a thermal power of about 3 kW at 109 ºC and a drive ratio of 3.49 %. It is expected that at the design drive ratio of 5 % the required 10 kW thermal power can be delivered by the heat pump. This is because the thermal power is a quadratic function of the drive ratio [11]. The drive ratio of 5 % can be achieved by the compressor if electric motor cooling is implemented.

In future measurements, the acoustic input power to the heat pump will be measured so that the external COP can be determined. The electrical motor will be provided with water cooling so that measurements can be done at resonance with pure helium and at drive ratio of 5 %.

Table 3 Performance measurements for the thermoacoustic heat pump

Dr (%)	3.49
T_l (°C)	40.80
T_h(°C)	109.02
T_{TBT}(°C)	22.63
Q_h (kW)	2880
Ql (kW)	2.519
W(kW)	0.498

COP	5.78

6. Conclusions

It can be concluded that reciprocating piston compressor can be used to drive a thermoacoustic heat pump, if it is designed to operate oil-free and to operate at 50 bar.

The RCP driven bench scale thermoacoustic heat pump delivers about 3 kW of thermal power at 109 ºC with an internal COP of 5.78. It is expected that at the design drive ratio of 5 % the required 10 kW thermal power can be delivered by the heat pump. This is because the thermal power is a quadratic function of the drive ratio. The drive ratio of 5 % can be achieved by the compressor if electric motor cooling is implemented.

In the near future, the piston compressor will be provided with water cooling so that the measurements can be done with pure helium and at a drive ratio of 5 %.

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