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ELECTRICALLY DRIVEN THERMOACOUSTIC HEAT PUMP

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Abstract

Significant energy saving is expected by using innovative heat pump concepts for removal and supply of heat from/to a separation process e.g. distillation systems. Conventional heat pumps provide limited temperature lift in an economical way. New heat pumps are required which can operate at the temperature levels of the distillation column and provide the desired temperature lift in one step. These heat pumps are presently not commercially available. At ECN a laboratory scale heat pump based on the thermoacoustic technology is developed. It matches the temperature conditions of a distillation column where the condenser temperature is in the range of 50-80°C with a temperature lift of 50°C. The heat pump is driven by a linear motor with an electrical power rating of 300 W. The experimental results of the heat pump will be presented.

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

1 INTRODUCTION

About 40% of the energy use in the (petro)chemical and refining industry is used for the separation of products (Spoelstra 2007). This results in an energy use of more than 100 PJ in the Netherlands, mostly in distillation. The distillation process is a very inefficient process from a thermodynamic point of view. Heat is supplied to boil a mixture of liquids while most of this heat is released at a lower temperature level during condensation. This heat of condensation can be used in the same column if the temperature level of the heat can be increased to the level of the reboiler. In some existing columns this is achieved by a compression heat pump. The rise in temperature level which can be obtained in an energetically favorite way however is limited to 10 to 20°C. This small temperature lift is not sufficient for most distillation columns. 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 thermoaocustic heat pumps for distillation which will also result in the reduction of CO_2 and NO_x 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:

- Environmentally friendly working medium (air, noble gases)
- No moving parts for the thermodynamic cycle, so very reliable and a long life span.
- Simple implementation and use of common materials, mainly tubes.

The main focus at ECN is the development of cost effective technological solutions to reuse part of the huge amount of waste heat momently released to the environment. The reuse of waste heat will result in large energy savings and reduce global-warming emissions. The thermoacoustic heat pump is a promising innovative heat pump with the advantages presented in the foregoing (Spoelstra et al. 2005).

The aim of this paper is to present the proof of principle of a thermoacoustic-Stirling heat pump operating between 50-80°C and 100-150°C corresponding with two representative distillation columns. 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 measurements procedure is explained. Section 5 presents the experimental results. In section 6 some conclusions are drawn.

2 WORKING PRINCIPLE

A thermoacoustic heat pump uses acoustic power to pump heat from a lower-temperature source to higher-temperature sink, generating cooling or heating. Figure 1 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_w. The acoustic power $\dot{W}$ necessary to the operation of the heat pump can be delivered by an acoustic driver like a linear motor (Fig.1a) or by a thermoacoustic engine which converts heat into acoustic energy (Fig.1b). More information on how thermoacoustic systems work can be found in reference (Backhaus et al. 1999).

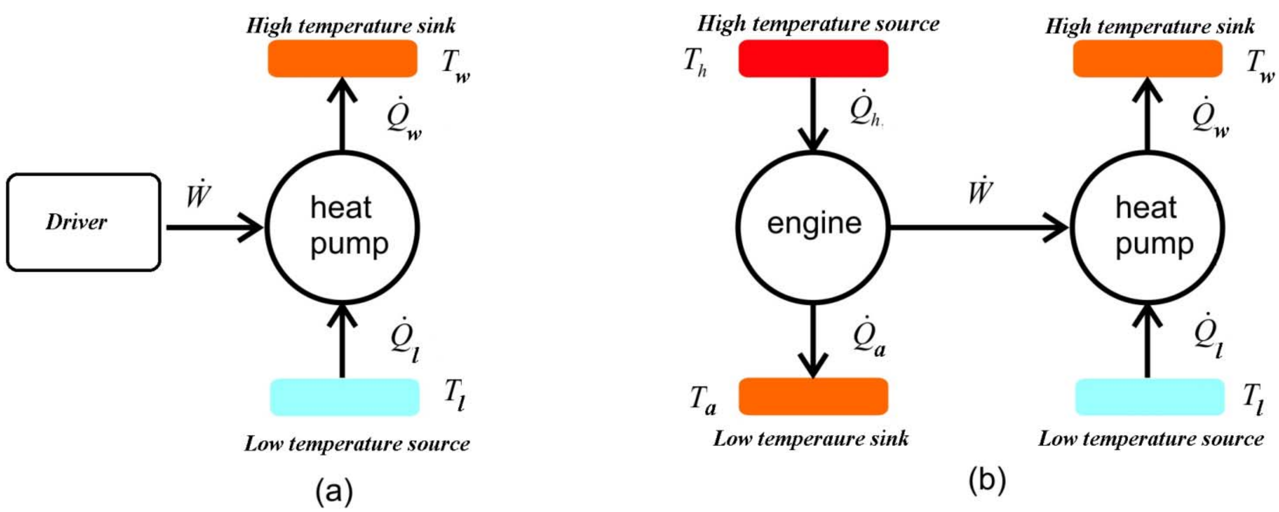


Figure 1 **Illustration of a heat pump driven by a driver (linear motor) (a) and a high temperature source such as a gas burner (b)**

Figure 1 shows a schematic illustration of the application of a thermoacoustic heat pump to a distillation column. Acoustic energy is produced by the electrically driven linear motor. The acoustic energy drives the heat pump which pumps heat from the condenser (top stream) to reboiler (bottom stream) of the column.

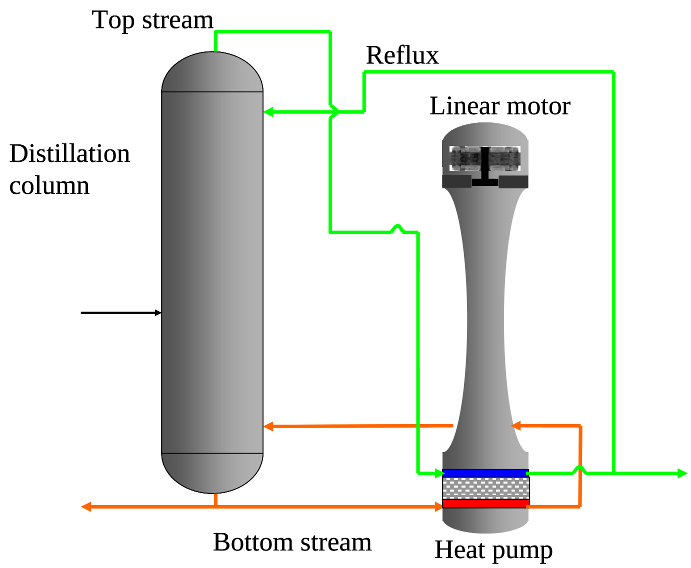


Figure 2 **Integration scheme for a linear motor driven thermoacoustic heat pump to a distillation column.**

Since Ceperley (Ceperley 1979, 1985) recognized that the time phasing between the pressure and velocity of the working gas in the regenerator of a Stirling system is the same as in a traveling acoustic wave, many attempt have been done to develop thermoacoustic-Stirling systems. A thermoacoustic-Stirling heat pump uses a traveling acoustic wave (acoustic power) to force the working medium in the regenerator to execute a thermodynamic cycle similar to the Stirling cycle and to pump heat from a low temperature heat source to a high temperature heat sink. This eliminates some of the moving parts present in conventional Stirling systems and related sealing problems. The travelling acoustic wave takes care of the compression, displacement, expansion, and the timing necessary for the Stirling cycle. The acoustic wave can be generated for example by an oscillating piston (linear motor).

Therefore, the working principle of a typical thermoacoustic-Stirling heat pump can be best understood by first explaining the classical Stirling cycle. The main components of a conventional Stirling heat pump consist of a regenerator, warm and cold heat exchanger, and a power and displacer piston as shown in Fig.3a. Ideally, the only thermal interaction of such a system occurs at the two heat exchangers. The power piston is the location where the acoustic power is delivered into the heat pump. The displacer is used to feedback mechanical power to the power piston and also to maintain a good phase relationship between oscillating pressure and flow in the regenerator. A regenerator bridges the gap between the two heat exchangers. The gas exchanges heat with the regenerator material during a part of the cycle and that heat is given back to the gas in a later part of the cycle. In order to have good heat transfer between the gas and the solid material, the surface area for heat transfer should be large which is accomplished with the use of a highly porous and small gas passages (hydraulic diameter) regenerator material. In a thermoacoustic heat pump the functionality of the displacer piston is replaced by a combination of an inertance (fluidic inertia) and a capacitance (buffer volume) as shown in Fig.3 (b). As in a mechanical Stirling heat pump, some of the acoustic power is feedback to the hot heat exchanger side of the regenerator via the feedback inertance. In contrast to the classical Stirling heat pump, thermoacoustic heat pump has fewer moving parts and hence is more reliable and cheaper to produce.

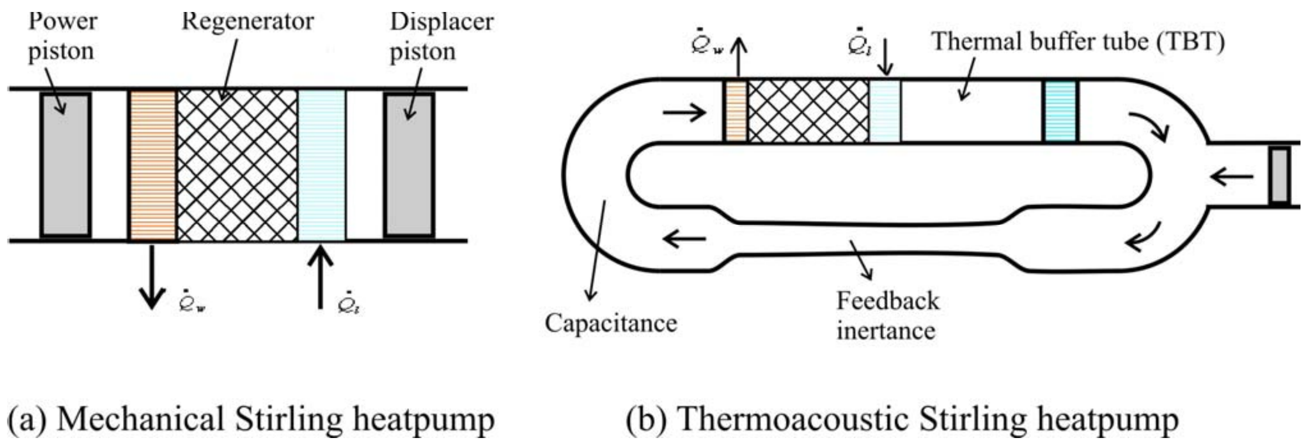


Figure 3. **Classical Stirling heat pump (a) with power and displacer pistons. The temperatures and the heat flows at the heat exchangers are also shown. Thermoacoustic (TA) Stirling heat pump uses fluidic ducts to replace the functionality of the displacer piston. TA heat pump shown in (b) has a torus configuration. The arrows point in the direction of the acoustic power flow.**

In thermoacoustic systems various performance parameters are expressed as a function of the drive ratio. The drive ratio P_1/P_m is the ratio of dynamic pressure amplitude at the piston and the average pressure in the system.

With reference to Fig.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 $\dot{Q}_w$ at the higher temperature T_w,

$$\dot{Q}_w = \dot{W} + \dot{Q}_l \qquad 1$$

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

$$COP = \frac{\dot{Q}_w}{\dot{W}} \qquad 2$$

The upper theoretical value of COP obtainable in a heat pump is the COP Carnot (*COPc)* and is given by,

$$COPc = \frac{T_w}{T_w - T_l} \qquad 3$$

The ratio between the two COP values is the exegetic efficiency of the heat pump or sometimes called the performance relative to Carnot value *COPr*.

3 DESCRIPTION OF THE HEAT PUMP

A CAD-illustration of the heat pump is given in Fig.4 and some pictures are given in Fig.5. The heat pump is designed to operate with helium gas at an average pressure of 30 bar and an operation frequency of 98 Hz. The acoustic network consisting of the resistance of the regenerator, the feedback inertance, and the compliance are designed to create the traveling-wave phasing necessary to operate in a Stirling cycle. The optimal design of the heat pump is done with the computer code DeltaE (Clark et al. 2007) It is worthwhile to note that the heat pump is originally designed to operate between 10 and 80°C for dwellings and offices applications (Vanappalli et al. 2010). However, because of the long time which may be involved with the development of a new heat pump, it decided to test the heat pump at higher temperatures and it is anticipated that the heat pump would not operate in an optimum way. A thermal bath with water is used to simulate a low temperature source at 50-80°C and a thermal bath using thermal oil is used to simulate a warm heat source at temperatures 100-150°C.

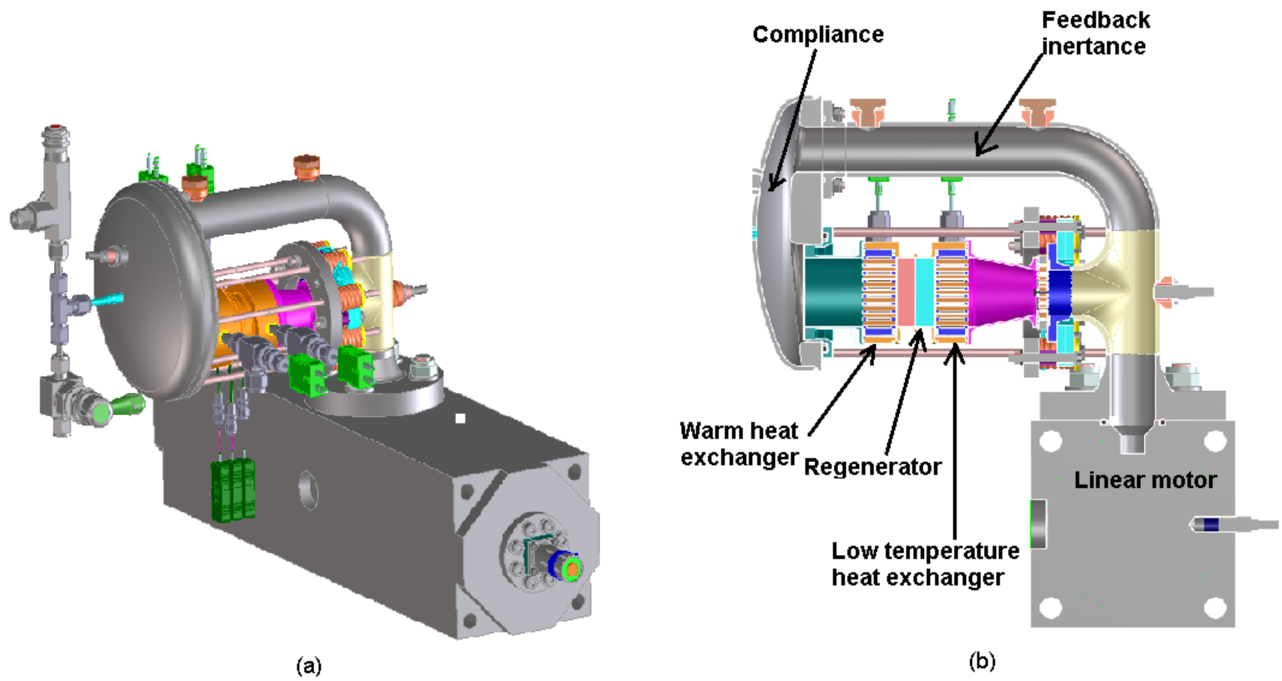
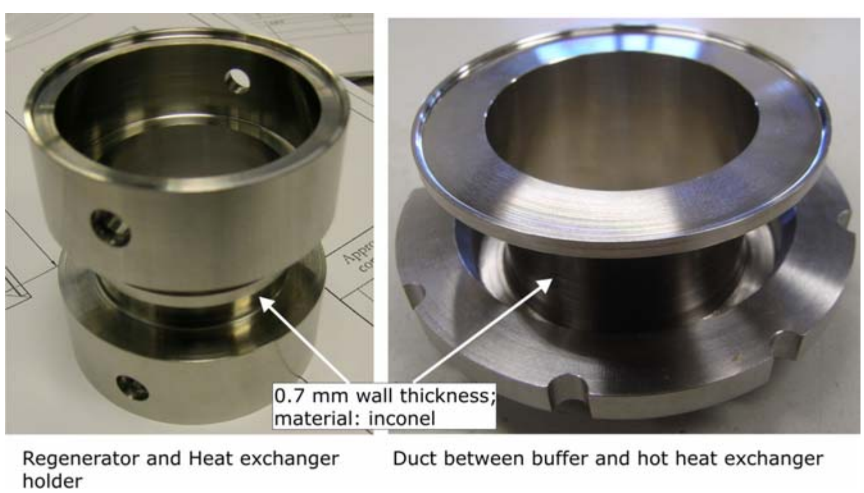
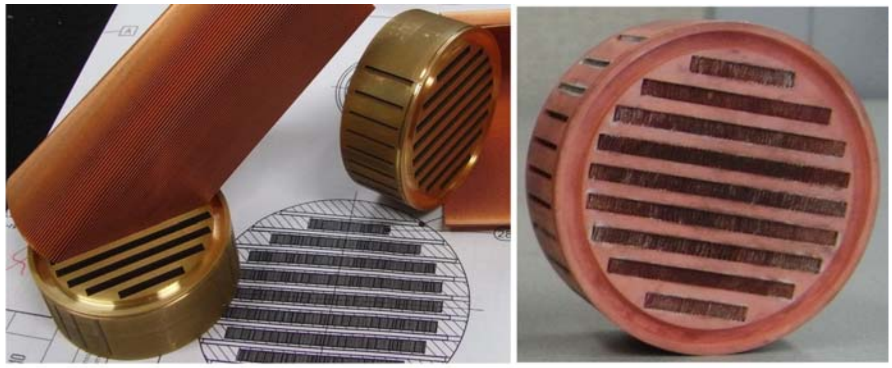


Figure 4. **CAD-illustration of the heat pump. (a) heat pump and (b) cross-section of the heat pump.**





Heat exchanger body before soldering fins

Heat exchanger body after soldering fins

Figure 5 **Pictures of the regenerator holder and duct between the compliance and the warm heat exchanger (top) and the heat exchangers (bottom).**

In the next section the different parts of heat pump will be described.

Linear motor

The linear motor is a twin-piston moving magnet electromotor. The rated electrical power consumption is 300 W. The piston diameter is about 70 mm and the maximum stroke is limited to 10 mm peak-to-peak. Provision is made in the moving mass of the motors to accommodate a displacer rod to measure the piston displacement. Dynamic pressure sensors are mounted on the front and back side of the piston.

Regenerator

The regenerator consists of a 25 mm thick stack of 180-mesh stainless-steel screen punched at a diameter of 42.5 mm. The diameter of the screen wire is 36 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 35 μm and the porosity is about 78 %.

Heat exchangers

The heat exchangers consist of a cylindrical brass block where passes are machined. Copper fins are brazed on the helium gas side to increase the heat transfer area. The diameter and length of the heat exchangers is 42.5 and 20 mm respectively.

Feedback inertance

The feedback inertance is made from a stainless tube of 28 mm inside diameter. The length of the feedback along the centerline from the T-junction to the buffer is 0.24 m.

Compliance

The compliance is an acoustic capacitance consisting of a buffer volume containing 0.5 liter of helium.

4 MEASUREMENTS PROCEDURE

Various sensors are placed through the system to measure the operating parameters of the heat pump. Thermocouples are positioned in the middle and at the ends of the regenerator to measure the temperature. Dynamic pressure sensors are located at the compliance, in the front and back of the pistons. LVDT's (Linear Variable Differential Transformers) mounted on the end caps of the PWG measure the displacement of the displacer rods connected to the piston. Water flow into the heat exchanger is measured with a turbine flow meter and the temperature of the water is measured with a thermocouple at the inlet and the outlet of the heat exchangers. The data is acquired using Labview. The detailed measurement procedure of the powers can be found in reference (Vanapalli et al. 2010).

Before starting a dynamic run (turning on the linear motor), the thermal baths are set to the desired temperatures. The system is allowed to attain a steady state which is monitored by the thermocouples that measure inlet and outlet temperature of the water and oil flow into the heat exchangers. In the Labview measurement program the outlet thermocouple temperature is corrected to read the same temperature as the inlet thermocouple. This will ensure that the duty of the heat exchanger is zero under static conditions. Once this is done, the linear motor is turned on and the data is acquired for the dynamic condition. This procedure is repeated for each different temperature run.

5 EXPERIMENTAL RESULTS

As mentioned in the introduction section, the heat pump is originally designed to operate between 10 and 80°C for households and offices applications (Vanapalli et al 2010). The thermoacoustic heat pump is applied for two low temperatures of 50 and 80°C and four warm temperatures ranging between 100-150°C.

The average pressure in the system is 3 MPa helium gas. The water flowing through the low temperature heat exchanger is maintained at 50°C or 80°C. The temperature of the oil thermal bath is maintained at temperatures 100-150°C. Figure 5 shows the *COPr* as function of the drive ratio for a low temperature of 50°C and three values of the high temperature. The drive ratio P_1/P_m is adjusted by regulating the electrical voltage to the linear motor. The *COPr* increases slightly as function of the drive ratio. The increase of the *COPr* as function of the warm temperature is due to an improvement of the phasing between the pressure and velocity in the regenerator as the temperature increases. A *COPr* of about 27 % is achieved at a high temperature of 120°C.

Figure 6 shows the *COPr* as function of the drive ratio for a low temperature of 80°C and three values of the high temperature. A slight increase as function of the drive ratio can be noted for all high temperatures. Again here the *COPr* increases with the high temperature and a highest value of about 26 % is achieved.

Although the heat pump is originally designed to operate between 10 and 80°C it still operate satisfactory at higher temperature range. A redesign of the heat pump for a given target temperature range will improve the performance of the heat pump.
The following additional improvement measures are suggested for the heat pump. The heat leak from the hot heat exchanger to the compliance is a major source of heat loss in the system. It is believed that this is mainly due to a dynamic leak caused by some non-linear phenomena in the tube between the hot heat exchanger and the capacitance (c.f.Fig.5). A more gradual thermal buffer tube of about 7° half angle can reduced acoustic losses due to cross-section change (Olson et al. 1997). The reduction of the acoustic losses in bends and T-branch will also lead to an improvement of the performance.

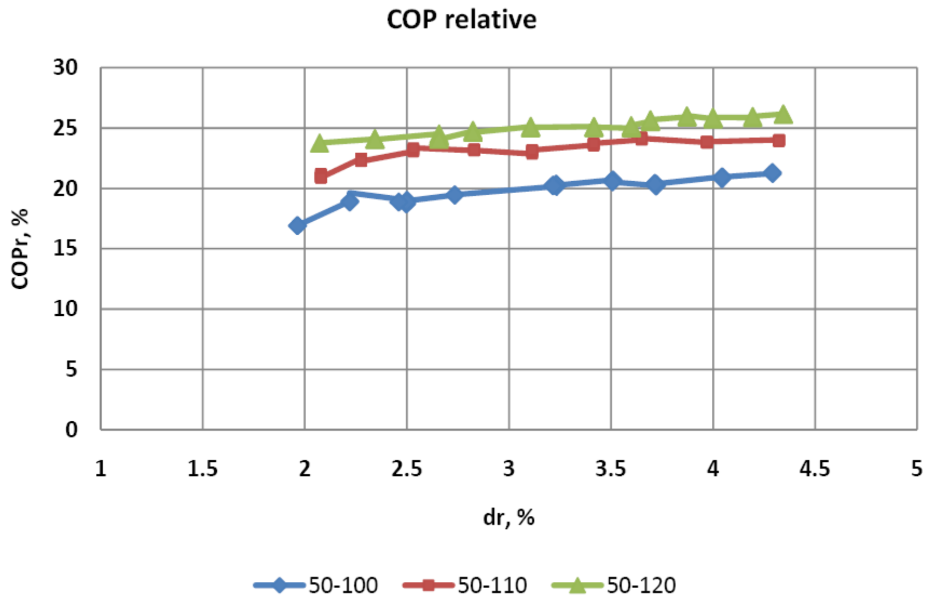


Figure 5 **COPr as function of the drive ratio for a low temperature of 50°C and three high temperatures. The experiments are performed at a frequency of 98 Hz and an average pressure of 3 MPa**.

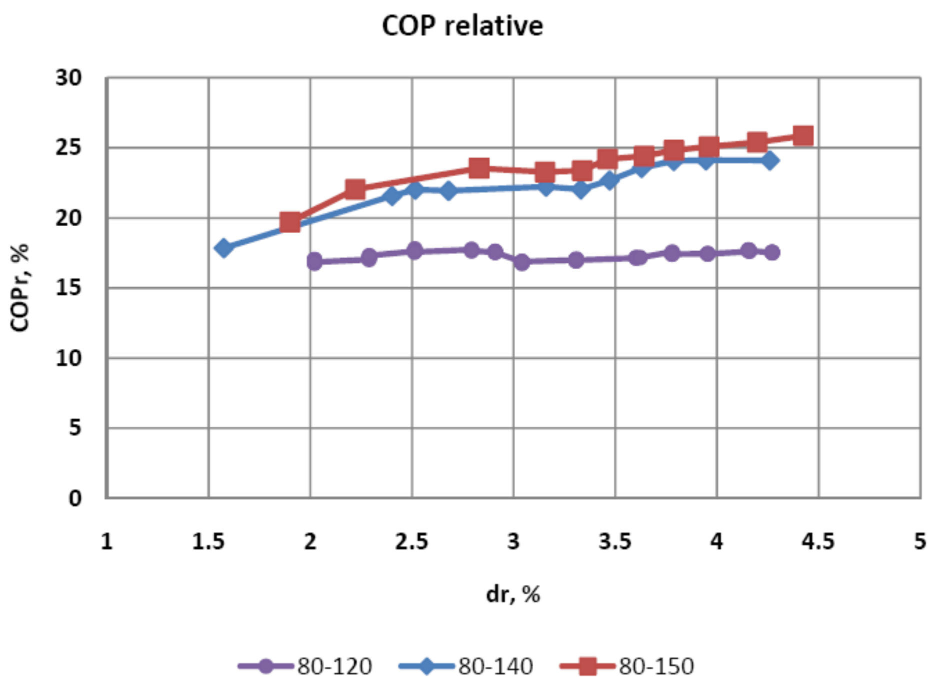


Figure 6 **COPr as function of the drive ratio for a low temperature of 80°C and three high temperatures. The experiments are performed at a frequency of 98 Hz and an average pressure of 3 MPa.**

6 CONCLUSION

A thermoacoustic heat pump is tested for conditions which simulate the application in a distillation column. Although the heat pump is originally designed to operate between 10°C and 80°C, it operates satisfactory in ranges between 50 and 150°C. A maximum COPr of 27 % is achieved by the heat pump for a temperature range between 50 and 120°C. An appropriate redesign of the heat pump for a given temperature range along with the reduction of the thermal and acoustic losses in the system will result in a further improvement of the performance.

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