Thermoacoustic heat pumps for energy savings

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Abstract

Within the Netherlands' process industry large quantities of waste heat are released to the environment that cannot be reused, mostly because the temperature level is too low. It is estimated that the size of this industrial waste heat in the temperature interval between 50-500ºC amounts to approximately 250 PJ per year. In order to reuse part of this waste heat, a heat pump is necessary that can provide a temperature lift of 50-100ºC at the required temperature levels. A thermoacoustic (TA) system is theoretically able to do so. Since 2001 ECN develops, together with partners from business and universities, a travelling-wave thermoacoustic system to upgrade waste heat to either process heat or to generate cooling. The objective is to develop systems that lead to energy and cost savings. Although the proof-of-principle has been achieved in the laboratory, the most important challenge at the moment is to achieve the required conversion efficiency from thermal to acoustic power and vice versa.

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1. Introduction

In the 1990's, the government policy in the Netherlands with respect to energy saving has been formulated with the objective of achieving an improvement of 33% in energy efficiency in the period from 1990 till 2020. The energy savings resulting from this should make an important contribution to the fulfilment of the Kyoto-protocol, as agreed upon in 1997. In order to reach this objective, an important contribution is expected from the energy intensive industry that is responsible for about one third of the total energy use in the Netherlands. Figure 1.1 depicts the industrial energy use from energy carrier to energy function. This has to be compared with the total energy use in the Netherlands of about 3000 PJ per year.

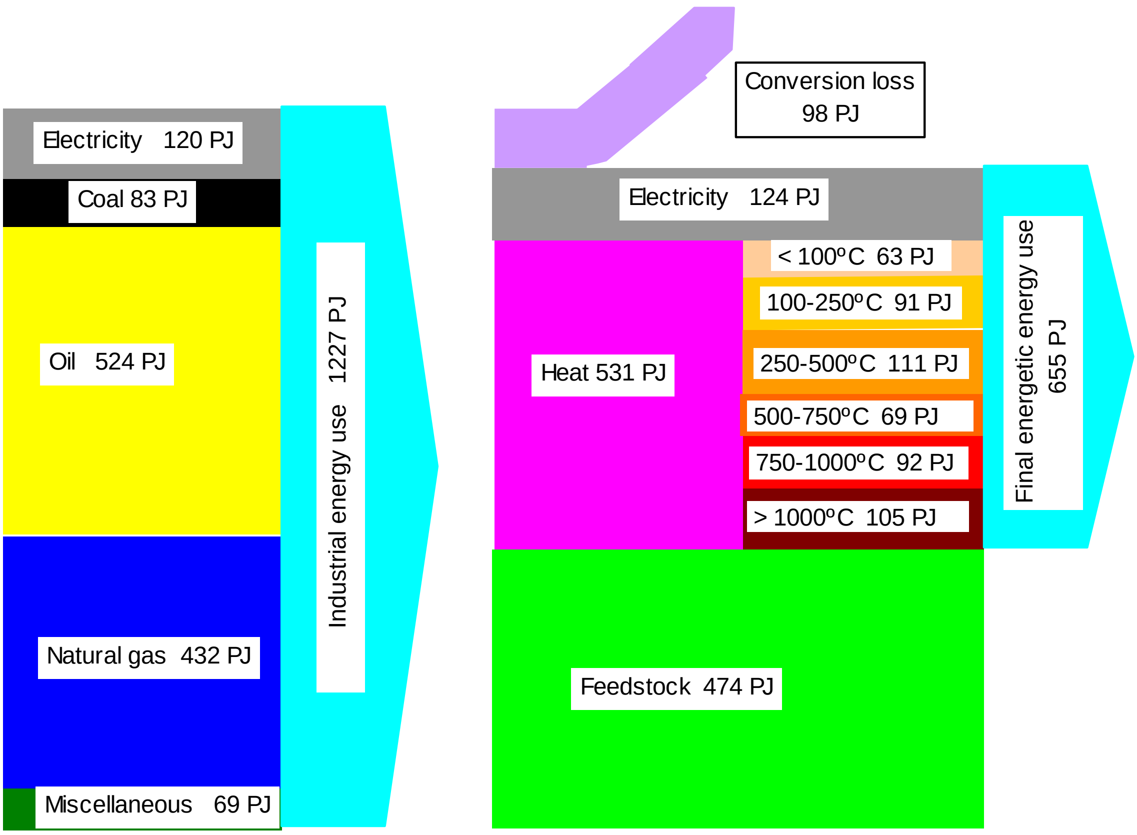

Figure 1.1 *Industrial energy use in the Netherlands allocated to energy function*

More than 80% of the total energy use within the Dutch industry consists of the need of heat in the form of steam at different pressure levels and for firing furnaces. Most of this heat is eventually released to the ambient atmosphere through cooling water, cooling towers, flue gasses, and other heat losses. We call this heat loss 'Industrial waste heat'. A detailed study of the magnitude of this waste heat within the Dutch chemical and refining industry revealed the picture below. Yearly, more than 250 PJ of heat above 50ºC is released to the environment within these industrial sectors.

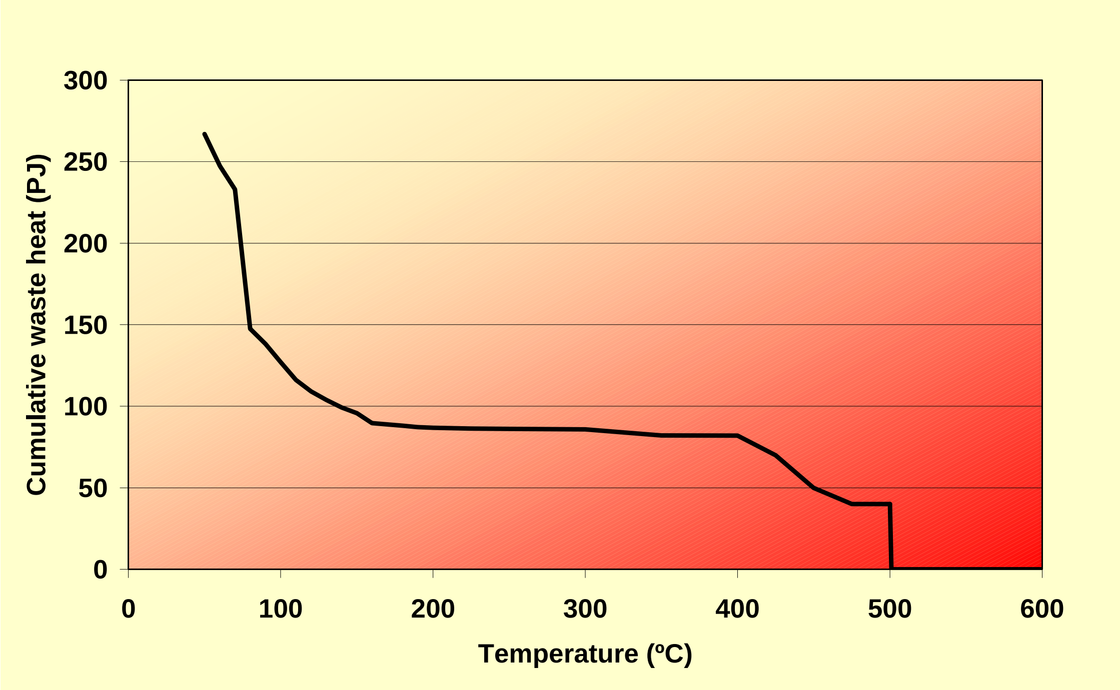

Figure 1.2 *Estimated cumulative industrial waste heat in the Netherlands*

A first, most logical, solution to this waste heat problem is to reuse the heat within the same process or at the same site. This kind of heat integration has already been applied to a great extent within the Dutch industry and offers no solution for the waste heat still remaining. The problem with the remaining waste heat is, beside the fact that there are many single sources:

- The temperature level of the waste heat is too low to be reused again at the same site.
- The waste heat is released at a different time than heat is needed.
- The distance between the location of the waste heat and the need of heat are too far apart.

ECN's main focus is to develop cost effective technological solutions for the first problem mentioned above. If one can upgrade the waste heat that is released to the environment to usable process heat or cold at the same location, energy can be saved. To this end, a heat pump is necessary that can operate at the temperature levels of the waste heat and the process heat. In addition, the heat pump has to deliver the required temperature lift. The heat pump that meets these requirements has to operate in a wide temperature window and have a temperature lift in the order of 50-100ºC. The heat pumps that are available nowadays are not able to fulfill both requirements. ECN is working on two innovative heat pump concepts that are in principle able to deliver the performance in the wanted temperature range.

The subject of this paper is the development of thermoacoustic heat pumps at ECN. Chapter 2 describes the thermoacoustic effect in a qualitative way and how this effect can be used to construct heat pumps. Some applications, presently under development at ECN, are presented in Chapter 3. This paper ends with some conclusions in Chapter 4.

2. Thermoacoustic systems

Thermoacoustics relates to the physical phenomenon that a temperature difference can create and amplify a sound wave and vice versa that a sound wave is able to create a temperature difference. This phenomenon can be used for several applications.

As known, a sound wave is associated with changes in pressure, temperature and density of the medium through which the sound wave propagates. In addition, the medium itself is moved around an equilibrium position. These fluctuations are too small to be noticed in the sounds we hear everyday. However, the sound waves that are common in thermoacoustics are extreme in magnitude, resulting in noticeable fluctuations. Table 2.1 presents a comparison of parameters between a normal conversation and thermoacoustics. The difference is several orders of magnitude.

Table 2.1 *Comparison between normal and thermoacoustic sound levels*

	Normal conversation	Thermoacoustics
Sound level	60 dB	170 dB
Temperature fluctuation	0,00002ºC	10ºC
Gas displacement (100 Hz)	0,00001 cm	4 cm
Gas velocity	0,0001 m/s	35 m/s (130 km/h)

In thermoacoustics, an acoustic wave is brought into interaction with a porous structure with a much higher heat capacity compared to the medium through which the sound wave propagates. This porous structure acts as a kind of heat storage. Generally speaking, in thermoacoustics there are two kinds of systems. Most research has been done on so-called standing wave systems. This paper however deals only with travelling wave systems that have an inherent higher efficiency and receive the most attention in recent R&D work.

Within thermoacoustics a distinction is made between a thermoacoustic engine or prime mover (TA-engine) and a thermoacoustic heat pump (TA-heat pump). The first relates to a device creating an acoustic wave by a temperature difference while in the second an acoustic wave is used to create a temperature difference. These two components are discussed first before going to the total system.

TA-engine

A temperature gradient is imposed across a regenerator by for example a cold and a hot heat exchanger. During a period of the acoustic wave, the following happens with a parcel of gas when a travelling acoustic wave passes by from the cold side. At the beginning of the cycle, the acoustic wave compresses the parcel of gas (compression). Successively the gas parcel is moved to a hotter part of the regenerator. Since the temperature over there is higher than the gas parcel, the gas is heated (heating). Then the gas parcel is expanded by the pressure wave (expansion). Finally, the gas parcel is moved back to its original position. The parcel of gas is still hotter than the structure (regenerator) resulting in heat transfer from the gas to the structure (Cooling). This process is depicted on the left hand side in Figure 2.1. The right hand side presents the cycle the gas parcel is going through in a PV-diagram. During this cycle the gas is being compressed at low temperature, while expansion takes place at high temperature. This means that work is performed on the gas. The effect of this work is an amplification of the acoustic wave.

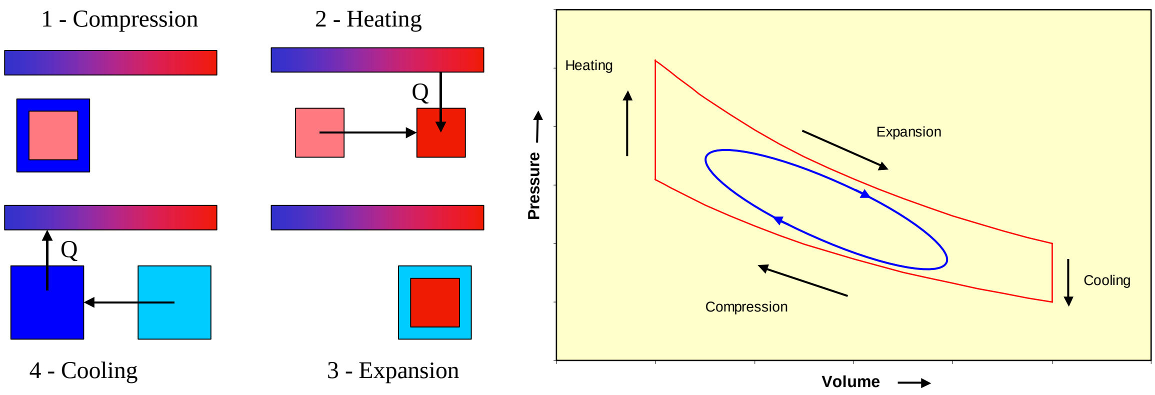

Figure 2.1 *Thermoacoustic thermodynamic cycle*

The thermodynamic cycle just described resembles the well-known Stirling cycle. The acoustic wave has the function of both the piston and displacer normally present in a Stirling engine. In this way it is possible to create and amplify a sound wave by a temperature difference. The thermal energy is converted into acoustic energy that can be regarded as mechanical energy.

TA-heat pump

The reverse process of what has been described above happens in a TA-heat pump. The thermodynamic cycle is run in the reverse direction, meaning that acoustic energy is use to pump heat. In this case heat is pumped from a low temperature source to a high temperature source. Since the medium that is used is a gas (air, noble gas) this kind of heat pump has virtually no limitations in its applications.

TA-system

The components just discussed are placed inside a resonator. This resonator is filled with the working medium (usually a noble gas) at the desired pressure. The dimensions of the resonator as well as the choice of working medium determine the working frequency of the system. The resonator also couples the separate components of the system and enables transport of acoustic energy.

The components, like the engine or the heat pump, have to be placed inside the resonator at locations of high impedance to avoid high viscous losses in the regenerator. This means that these components have to be placed near a velocity node of the resonator. There is however another requirement that has to be met. In order to achieve a high efficiency of conversion between thermal and acoustic power, use is made of travelling wave conditions where velocity and pressure amplitude are in phase. Use of for example a standard double Helmholtz resonator leads to standing wave conditions everywhere in the system. The acoustic configuration is changed at the regenerator location to circumvent this problem. When a feedback line, which acts as an acoustic inertance, is placed parallel to the regenerator one is able to create travelling wave conditions at the location of the regenerator. This enables the thermodynamic favourite Stirling cycle to be executed.

3. Applications

In principle there is a large variety of applications possible for both TA-engines as TA-heat pump and combinations thereof. Generally speaking, most applications involving heat, cold, or electricity production can be fulfilled with thermoacoustic systems. The specific situation however determines whether thermoacoustic systems have advantages over conventional systems. In a very generic way Figure 3.1 shows the combination of a TA-engine, operating between a temperature difference $T_{high,engine}$ and $T_{low,engine}$, and a TA-heat pump, operating between $T_{high,heat\ pump}$ and $T_{low,heat\ pump}$. These four temperature levels can, to some extent, be freely chosen to match the application.

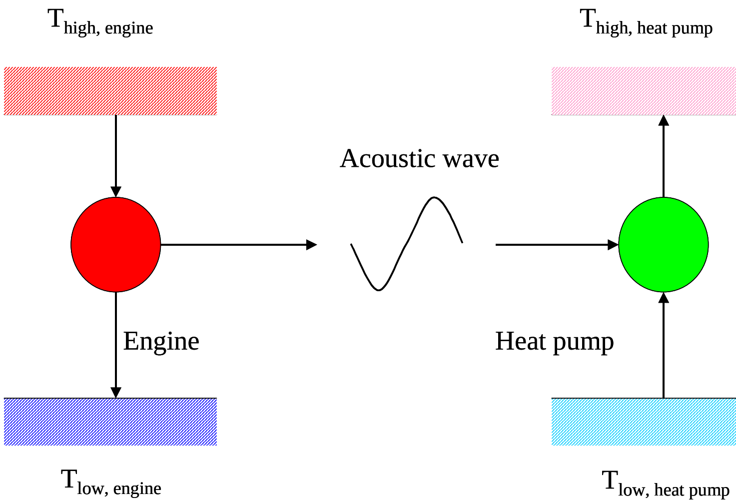

Figure 3.1 *Thermodynamic illustration of the combination of a TA-engine and TA-heat pump*

The activities within ECN are focused towards upgrading of industrial waste heat and production of cold. This results in the following R&D directions to be distinguished

- Upgrading of high-temperature waste heat. In this case the waste heat temperature is high enough to drive a TA-engine. The required temperature is at least 110ºC.
- Upgrading of low-temperature waste heat. The TA-engine is driven by a high temperature source like an electrical heater or a burner.
- Generation of cold. Using a linear motor as an acoustic source, very low temperatures can be reached.

Waste-heat driven engine

In this type of engine, the temperature difference between waste heat and the ambient atmosphere is used to generate a strong acoustic wave. ECN, together with partners, is developing a unique multiple regenerator system in which several regenerator units are applied within one TA-engine in order to generate sufficiency acoustic power from the relatively low waste heat temperatures. The picture below shows a TA-engine containing three regenerator units, which is already running at a waste heat temperature of 110ºC. This low starting temperature enables the application of waste heat for driving TA-engines.

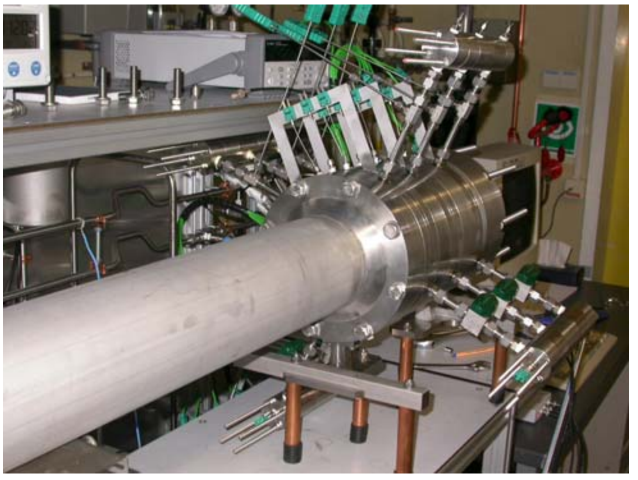

Figure 3.2 *Waste-heat driven TA-engine*

The acoustic energy is subsequently being used in a TA-heat pump to upgrade waste heat to usable process heat at the required temperature.

The picture below visualises the whole system. The TA-engine is located at the right side and generates acoustic power from a stream of waste heat stream at a temperature of 140ºC. The acoustic power flows through the resonator to the TA-heat pump. Waste heat of 140ºC is upgraded to 180ºC in this component. The total system can be generally applied into the existing utility system at an industrial site.

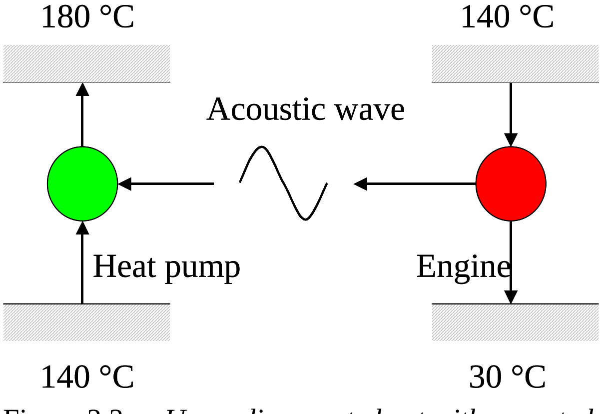

Figure 3.3 *Upgrading waste heat with a waste heat driven TA-engine*

Besides upgrading waste heat, the acoustic energy can also be used to provide cooling on the industrial site. The goal of the ECN activities is to develop this technology in order to upgrade industrial waste heat to usable process heat or cold in a cost effective way. The energy saving potential using this technology within the Netherlands amounts to about 16 PJ, which is comparable with the energy use of more than 150.000 households.

The present activities are carried out on a scale of 5 kW heat. The system has a waste heat driven multi-stage engine and is coupled with a heat pump in a double Helmholtz resonator. The working medium is nitrogen and the system can be pressurized up till 18 bar. The pressure amplitude in the systems depends on the loading conditions but varies between 4-7% of the average pressure. Although a first prototype of the application has been realised this way, the efficiencies are presently too low to enable a cost effective system. Much development work therefore lies ahead. In the longer term the expected size will be about 1 MW. The picture below gives an impression of such a system.

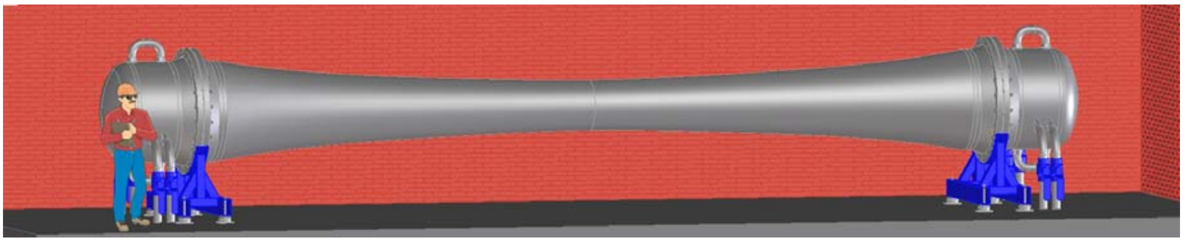

Figure 3.4 *Impression of a full scale 1 MW waste heat system*

Burner driven engine

An additional heat source is needed when waste heat temperatures are too low to drive a TA-engine. This can be a burner, an electrical heater, or another high temperature source. Applications are for example distillation columns, office buildings, and even residential dwellings. The process scheme for the application of a thermoacoustic heat pump for distillation columns is patented by ECN. In this scheme the heat that is released during condensation of vapours in the top of a column is used again to provide heat to the reboiler side of the column. Ambient heat is used as a waste heat source for the built environment.

Important part of the research in this area is the TA-engine driven by a burner. The photograph below shows a test installation of a TA-engine driven by a natural gas burner. This system has presently a thermal power of about 5 kW and is filled with Argon with 10 bar pressure. The pressure amplitude in this system is also about 4-7% of the average pressure. This system suffers from high heat losses due to the high temperature involved. However, it is one of the few systems in the world that runs on the heat input by a burner.

Figure 3.5 *Burner driven TA-engine*

The acoustic energy from the engine is used to pump up heat from the waste heat level to the desired temperature. The picture below visualises this for the application at a distillation column. The heat pump is being integrated with the existing column. In this example the temperature at the bottom of the column amounts 100ºC while the top temperature equals 50ºC. Energy savings are realised by reusing the heat of the condensing vapours at the top of the column.

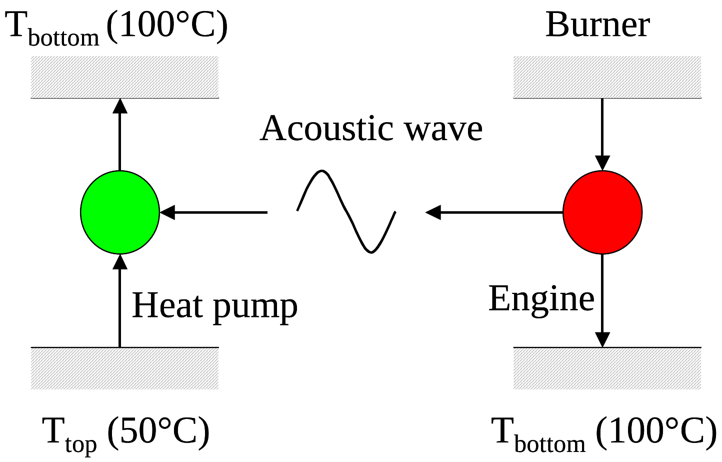

Figure 3.6 *Upgrading of waste heat by a burner driven TA-engine*

The goal of the ECN research is to achieve the most efficient conversion in both the engine and heat pump part of the system. The amount of energy that can be saved by this technology depends on the temperature level of both the waste heat and the required heat. An ECN study showed that application in the Dutch distillation market would save about 9 PJ per year, comparable to more than 90.000 households. An energy saving potential of 5 PJ per year in the Netherlands is realised by application in office buildings.

Thermoacoustic cooler driven by a linear motor

Instead of using a thermoacoustic engine for the production of acoustic power, a linear motor can be applied to this end. These motors are commercially available for producing acoustic power up tol power levels of 10 kW. The acoustic power is used to drive a heat pump or a cooler. A thermoacoustic cooler can provide high temperature lifts. Only a single stage is needed to reach low temperatures. This is beneficial in applications where multi-stage compression coolers are used nowadays. ECN is looking at coolers that can generate cooling at -100ºC. Figure 3.7 depicts the test installation used to investigate these coolers. The linear motor can generate up till 300 W of acoustic power.


Figure 3.7 *Linear motor driven thermoacoustic cooler*

4. Conclusions

Although the working principle of thermoacoustic technology is quite complex, the practical implementation is relative simple. This offers great advantages with respect to the economic feasibility of this technology. Other advantages are:

- No moving parts for the thermodynamic cycle, so very reliable and a long life span.
- Environmentally friendly working medium (air, noble gas).
- The use of air or noble gas as working medium offers a large window of applications because there are no phase transitions.
- Use of simple materials with no special requirements, which are commercially available in large quantities and therefore relatively cheap.
- On the same technology base a large variety of applications can be covered.

Thermoacoustics seems a promising technology for energy applications especially in those areas where conventional technologies offer no solutions. However, to come to practical, cost-effective, large-scale applications, much research and development still has to be done to reach the objectives. Research and development at ECN and partners is related to:

- *Acoustic configuration*
  This issue is related to enabling travelling wave conditions at the regenerator for optimising efficiency.
- *Regenerator material*
  The choice of regenerator material is dependent on working frequency, medium, and pressure. The optimal regenerator has a large heat transfer but low-pressure drop.
- *Heat exchangers*
  Heat exchangers play a crucial role in thermoacoustic systems. Especially for waste heat applications, the temperature loss by heat exchangers should be minimal.
- *Interaction multiple regenerator units*
  In case of multiple regenerator units, as has been applied in the waste heat driven TA-engine, it is not clear yet how the separate units interact which each other.
- *Non-linear effects and streaming*
  Most thermoacoustic devices are described by linear theory. This theory will deviate from reality as pressure amplitudes go higher. New effects come into play, which have a detrimental effect on the performance of the system.
- *Resonator losses*
  The function of the resonator is to act as pressure vessel, to determine working frequency, and to transport the acoustic power between components. Any losses associated with this transport function should obviously be minimized.
- *Heat losses*
  As indicated at the burner-driven engine, heat losses can be a very important factor for the efficiency of the system. This cannot always be resolved by a trivial solution as placing insulation.

Literature

The interested reader is referred to the following list of papers that provide more background information on thermo acoustics and its applications.

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Thermoacoustic heat pumps for energy savings

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Hassan Tijani

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- Industrial energy use and waste heat
- Thermoacoustics
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- Conclusions & Outlook

ECN

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- Turn over 55 M€
  - Governmental subsidy 23 M€
  - Contract research 32 M€

- Publications (/y)
  - Non-confidential 250
  - Confidential 116

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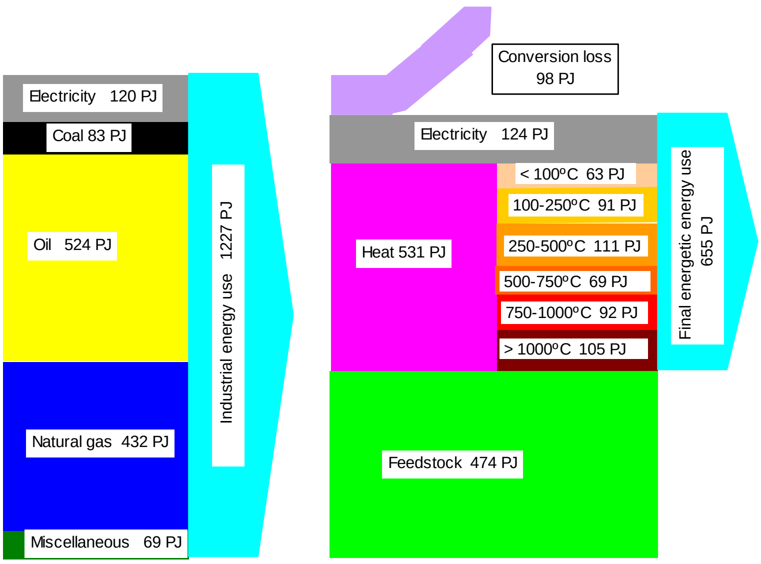
Industrial Energy use in the Netherlands

Total energy use in the Netherlands is approximately 3000 PJ per year



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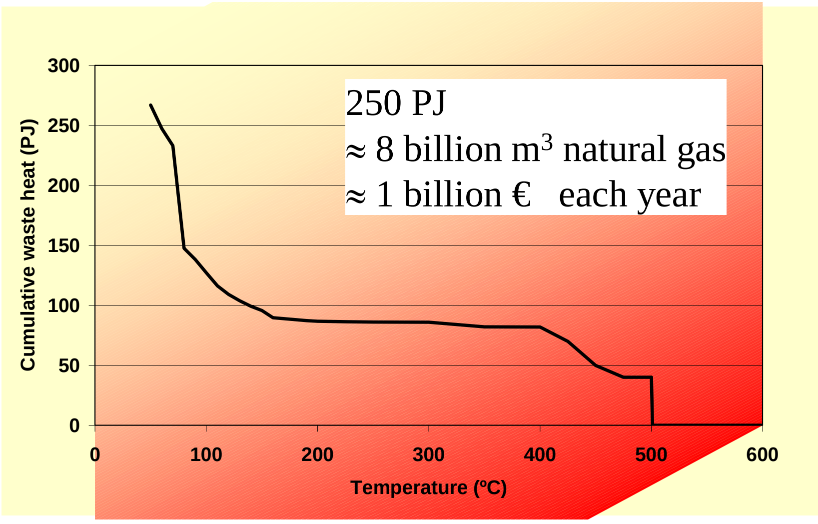
Industrial Waste Heat



Wrong temperature
Wrong time
Wrong place

ECN

Solutions for industrial waste heat

- Wrong temperature
  - Needed are heat pumps working at temperature levels >100°C with temperature lifts in the order of 50-100°C
- Wrong time
  - Needed are heat storage concepts with high storage density and low losses
- Wrong place
  - Needed are heat transport concepts with low losses

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Objective

Development of thermoacoustic systems that have sufficient conversion efficiency of thermal to acoustic power and vice versa in order to enable cost effective energy savings.

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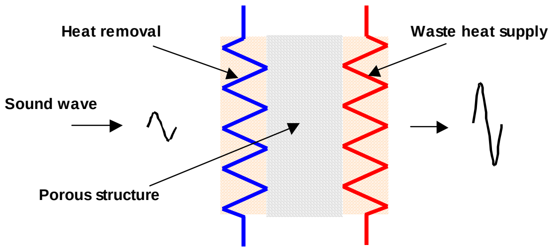
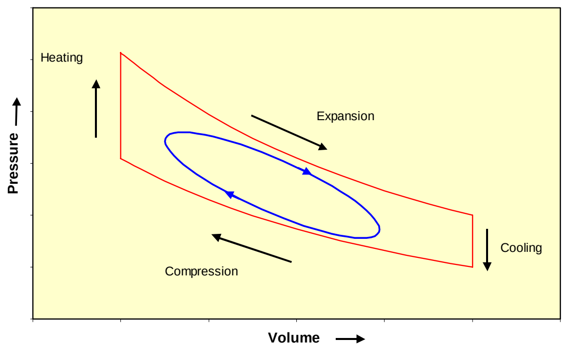
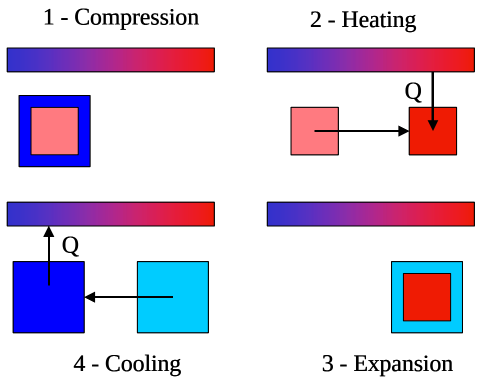
Thermoacoustics – working principle







Travelling wave TA-engine
=> Stirling cycle

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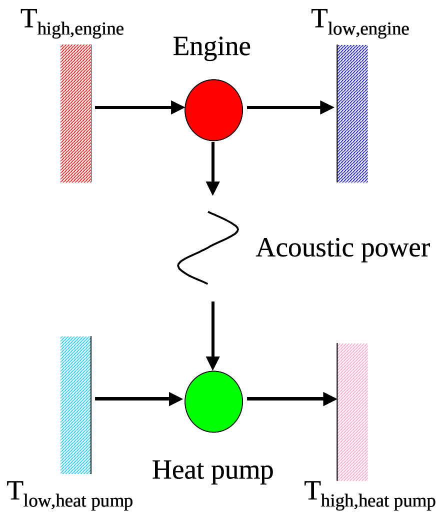
Thermoacoustic systems - characteristics



- Based on conversion of thermal power to acoustic power (engine) and vice versa (heat pump)
- High temperature lifts
- Working medium is noble gas
- No moving parts
- Stirling cycle (high efficiency)

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Thermoacoustic systems - applications

Drive	Load
Speaker	Elektricity
Piston	Heat
Temperature diff.	Cold
Other	

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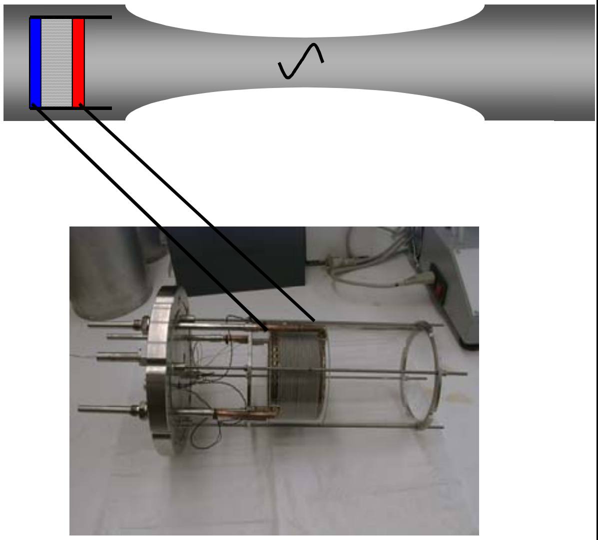
Travelling wave systems

- Conditions for regenerator
  - Pressure and gas velocity in phase to force a Stirling cycle
  - High pressure amplitude with low velocity amplitude (high impedance) to avoid large viscous losses.
- ☞ Standing wave resonator with local loop to enable local travelling wave conditions

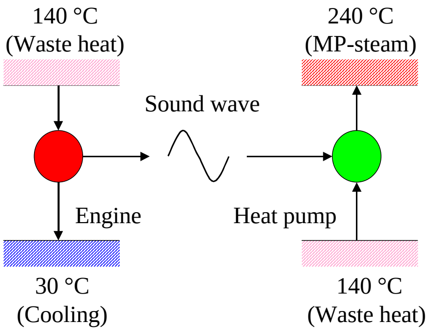


Activities on thermoacoustic systems

- TA-engines
  - Waste heat
  - Burner
  - Electrical heater
- TA-heat pumps
  - Upgrading waste heat
  - Production of cold
- Coupling of engine and heat pump

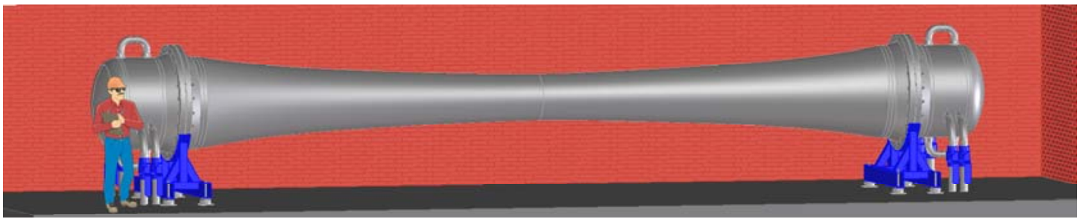
ECN

Applications (1)



- Upgrade high-temperature waste heat to process heat
- Potential energy savings in chemical and refining sector 16 PJ/year (≈ 65 M€ / year)

Full scale 1 MW waste heat system



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Upgrading high-temperature waste heat

- Multi-stage waste heat driven TA-engine
- Thermal power 5 kW
- Acoustic power 200 W
- Maximum working pressure 18 bar nitrogen
- Drive ratio 7%

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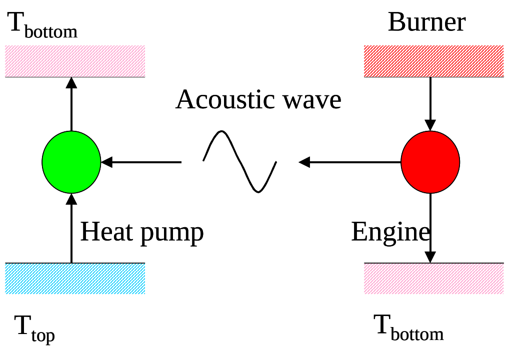
Applications (2)

- Upgrade low-temperature waste heat to process heat
- Potential energy savings
  in chemical sector and office buildings
  14 PJ/year (≈ 55 M€ / year)



ECN

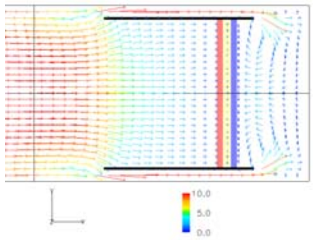
Upgrading low-temperature waste heat

- Burner driven TA-engine
- Thermal power
  5 kW
- Acoustic power
  200 W
- Maximum working pressure
  10 bar Argon
- Drive ratio
  7%

ECN

Thermoacoustic heat pumps – R&D issues

- Acoustic configuration
- Regenerator material
- Heat exchangers
- Interaction multiple regenerator units
- Non-linear effects
- Streaming
- Resonator losses
- Heat losses



ECN

Conclusions & Outlook

Conclusions

- Thermoacoustics is promising technology with some unique characteristics
- The principle is proven on reasonable scale
- Efficiency presently too low
- Early stage of development

Outlook

- Improve basic understanding and modelling
- Improve conversion efficiency
- Up scaling
- Cost reduction