Синхронізований акустичний холодильний і тепловий двигун (SARAH)

Аян Банерджі [1], Ґорав Наяк [2]

1. Кафедра механічної інженерії, Технологічний інститут Бірла, ІНДІЯ, Месра-835215, E-mail: arsenalite@gmail.com
2. Кафедра механічної інженерії, Технологічний інститут Бірла, ІНДІЯ, Месра-835215, E-mail: gnayak.bitp@gmail.com

У роботі запропоновано термо-акустичний (ТА) пристрій як нетрадиційне джерело енергії для мало- і великомасштабного економічно ефективного застосування. Функція пристрою полягає у перетворенні звукової енергії в тепло (охолоджувач і тепловий насос) і тепла у звукову енергію (двигун). Принцип роботи ТА заснований на здатності звуку реверсивно змінювати фізичні властивості (тиск, температуру) і викликати коливання молекул в холодильних та теплових агентах, у яких їхній рух передається у напрямі поширення звукових хвиль.

SARAH складається з двох систем – первинного збудника і холодильника або теплового насоса. Первинним збудником є, в основному, труба резонатора, з'єднана з одного боку з барабанною діафрагмою або мікрофоном, залежно від виду застосування. Холодильник має подібну конструкцію, невелика відмінність полягає у тому, що його відкритий кінець з'єднується з генератором акустичних хвиль, наприклад з гучномовцем. Обидва пристрої мають два теплообмінники – холодний і гарячий, з'єднані паралельною плиткою. Залежно від виду використання змінюється послідовність етапів роботи. Наш пристрій SARAH, який побудовано на основі експериментальної установки Арауджо, працюючи в режимі виготовлення електроенергії, виробляє 26.88 кВт. Див. рівн. (16). Цей вид двигуна є ідеальним для використання із сміттєспалювальними станціями, у поєднанні з автомобільними двигунами внутрішнього згоряння або будь-яким джерелом звуку і тепла. Пристрій може також використовуватися з протилежною метою, як холодильник, який отримує енергію від теплового двигуна, який у свою чергу живиться від зовнішнього джерела сонячної, геотермальної енергії, енергії спалювання сміття тощо. Найбільшою перевагою цього пристрою є відсутність рухомих частин, отже, тертя є невеликим, а разом з тим експлуатаційне зношення є мінімальним.

Переклад виконано в Агенції перекладів РІО
www.pereklad.lviv.ua

Synchronized Acoustic Refrigerator And Heat Engine (SARAH)

Aayan Banerjee [1], Gaurav Nayak [2]

[1.] Mechanical Engineering Department, Birla Institute of Technology, INDIA, Mesra-835215, E-mail: arsenalite@gmail.com
[2.] Mechanical Engineering Department, Birla Institute of Technology, INDIA, Mesra-835215, E-mail: gnayak.bitp@gmail.com

In light of the present global energy scenario, it is imperative to seek novel and efficient energy solutions to redress the situation. Solar energy, wind energy, geothermal energy, ocean thermoclines and waste heat recovery are the major players in the sustainable energy field. In this paper we propose a Synchronized Acoustic Refrigerator And Heat Engine (SARAH), a Thermoacoustic (TA) device capable of harnessing these untapped sources in a cost-effective and efficient way on both small and large scales. It is a coupled device which transforms acoustic power into heat (refrigerator or heat pump) and heat into acoustic power (engine or prime mover).

Keywords – Engine, Heat Exchanger, Refrigerator, Resonator Tube, Standing Wave, Thermoacoustics

I. Introduction

Thermoacoustics (TA) is the phenomenon which is responsible for the propagation of a sound wave due to a difference in temperature and the converse is also true. In the 1960s Nicolas Rott first theorized the thermoacoustic phenomenon by providing an explanation to the generation of a sound wave created by a temperature gradient within a resonator [3]. In the 1980s Weathley, at the Los Alamos National Laboratory, worked on the converse process i.e. creating a temperature gradient by the application of a sound wave thereby leading to a new type of heat pump. However, it was another scientist from the same research group as Weathley, Greg Swift who became a pioneer in this field and was responsible for many significant breakthroughs in TA [3].

A. TA Principle

The central idea of the principle behind TA is that sound is a disturbance which reversibly varies the physical properties (pressure, temperature) and causes oscillations of the molecules in the medium in which it propagates in the direction of propagation of the disturbance and thus sound is a longitudinal wave. The sound wave transports energy and not matter [6].

This idea is used to achieve local temperature gradients in the medium through which it propagates. For example, if a sound wave is propagated through a pressurized gas using a source such as a loudspeaker, it compresses and expands a small packet of gas molecules against another which in turn compresses and expands the subsequent packet and so on. Compression leads to an increase in temperature whilst expansion causes a decrease in temperature. *See Fig. 1.* This operates in half cycles and the gas oscillates about a mean value. Thus, in one half of the cycle the gas is on one side of the mean and is compressed and heated whilst in the next half, it is on the other side of the mean and is expanded and cooled.

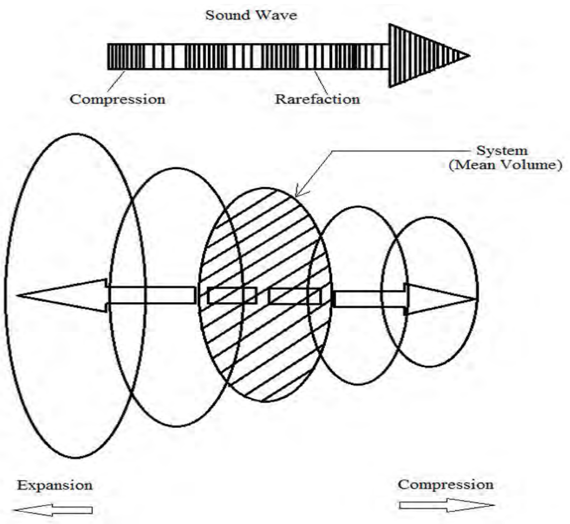

Fig. 1. Illustration of TA principle behind sound to heat conversion [3]

If a solid medium is now kept in contact with the gas it will absorb heat from the hot end of the gas and expel heat to the cold end. This creates a macroscopic temperature gradient in the solid medium. *See Fig. 2.* A heat exchanger can now be placed at either end of the solid medium either to remove the heat from the medium to cool it (refrigerator) or to provide heat to the medium to warm it (heat pump).

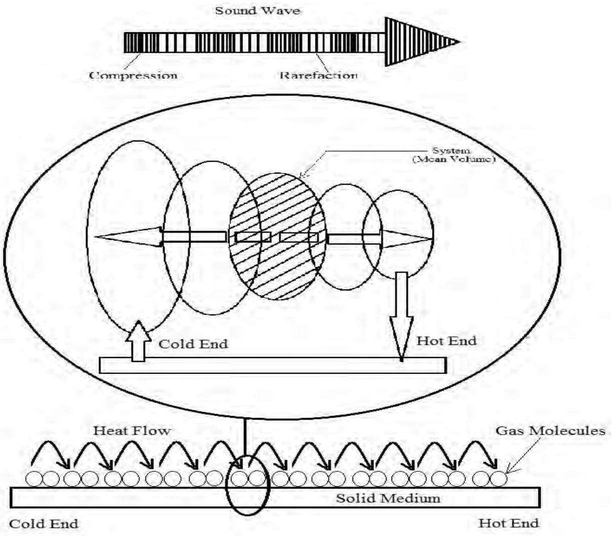

Fig. 2. Illustration of TA principle behind heat to sound conversion [3]

B. TA Prerequisites

According to Boyle's Law and Charles' Law, at constant volume, each degree rise in temperature leads to a 1/273rd rise in pressure of the gas [10]. Mathematically, if ΔT is the rise in temperature, P_i is the initial pressure and P_f is the final pressure,

$$P_f = \frac{\Delta T}{273} P_i + P_i \qquad (1)$$

For adiabatic processes,

$$\ln \frac{T_f}{T_i} = \frac{\gamma - 1}{\gamma} \ln \frac{P_f}{P_i} \qquad (2)$$

where, T_i is the initial temperature and T_f is the final temperature [5].

This shows a dynamic temperature rise causes a dynamic rise in pressure. To maximize the thermal energy transported, the surface area of contact between the solid medium and the gas must also be increased using parallel plate stacks, wire meshes, porous media, etc [1].

A matter of difficulty is an acoustic source capable of providing sound waves powerful enough to drive TA devices. Loudspeaker technology is still unable to efficiently meet the demands of TA. More intense wave generators are required such as piston motors. This causes further concern regarding contamination of the system by oil or the limitations imposed on the running speed due to mechanical inertia of the pistons [3]. However, TA dispels these concerns by providing an ingenious solution derived from the converse of its principle which states that a temperature difference can be used to generate a sound wave. Thus, a coupled device can be created which first creates a sound wave from a temperature difference and then uses that sound wave for heating or cooling. This is the working principle for our coupled device SARAH.

II. SARAH

Synchronized Acoustic Refrigerator And Heat Engine (SARAH) is a coupled device which consists of two stages- a prime mover and a refrigerator or heat pump. The prime mover is basically a resonator tube with one end closed and the other connected to a tympanic diaphragm or a microphone depending upon the type of application. The refrigerator has also similar construction with only difference being the open end is connected to an acoustic wave generator such as a loudspeaker. Both the devices have two heat exchangers- the hot heat exchanger (H_H) and the cold heat exchanger (H_C) connected by means of a parallel plate stack. Depending on the type of application, the sequence of the stages varies. For example, if electricity generation is the goal, then the first stage is the refrigerator which generates heat to be supplied to the heat engine. On the other hand, if the goal is refrigeration then the sound waves generated by the heat engine are supplied to the refrigerator. *See Fig. 3.*

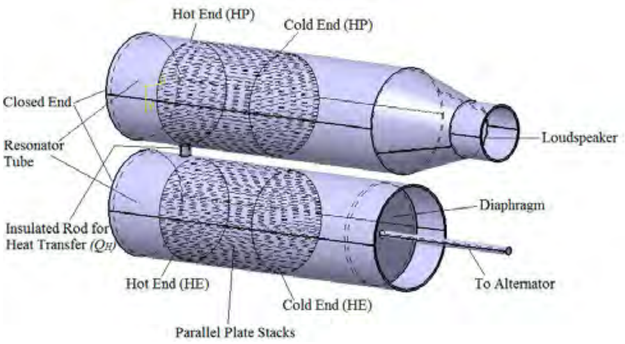

Fig. 3. Schematic design of SARAH when operating with the goal of power generation

C. Design Parameters

When designing a TA system various parameters affect the system's performance, which are discussed below –

1. *Stack Length*

As the stack length increases, the temperature gradient also increases linearly and thus the power generated also increases [1]. However, once a larger temperature gradient is developed, there will be greater thermal dissipation due to conduction and convection (which are undesirable). Also, viscous losses increase due to interaction with the stack plates. Therefore, the overall efficiency of the system decreases. Consequently, an optimization of the stack length is required.

2. *Stack Positioning*

Without a stack, the standing wave generated in the resonator tube would have its velocity nodes at the closed end and its pressure nodes at its open end [4]. Since acoustic power is a product of pressure and velocity, it can be inferred that the stack should be positioned somewhere between the velocity and pressure nodes.

3. *Resonator Tube Length*

Similar to stack length, a larger resonator tube leads to higher harmonics, thereby increasing power output [1]. However, it also leads to increased viscous losses, reducing the efficiency. So the length of the resonator tube must be optimized. The resonator must also be insulated so as to keep it at a constant temperature without heat leakage to the surroundings [9].

4. *Temperature Gradient Operator*

Temperature gradient operator I, is defined as the ratio of the mean temperature gradient to the critical temperature gradient.

$$I = \frac{\nabla T_{mean}}{\nabla T_{critical}} \qquad (3)$$

where,

$$\nabla T_{mean} = \frac{\Delta T_m}{L_s} \qquad (4)$$

ΔT_m – Temperature difference across the stack; L_s – Length of the stack; $\nabla T_{critical}$ depends on the frequency, cross-sectional area of the stack and gas properties.

If $I > 1$, the device works as a heat engine, and if $I < 1$, the device works as a heat pump or refrigerator.

The temperature gradient operator is directly proportional to the drive ratio [7].

Efficiency of TA engine,

$$\eta_{TA} = \frac{\eta_{carnot}}{I} \qquad (5)$$

COP of TA refrigerator,

$$COP_R = I \cdot COP_{carnot} - 1 \qquad (6)$$

From the equations (3), (4), (5) & (6), we infer that for a heat engine, I must be greater than 1 but should tend to 1 and similarly, for the refrigerator, I must be less than 1 but should tend to 1 [7].

5. *Working Fluid*

The most commonly used working fluids are gases like helium, argon and nitrogen. The working fluid should be thermally stable, chemically inert and its heat capacity must be necessarily lesser than that of the stack plates, so that the plate temperature can be considered to be in a steady state [1].

III. Calculations

To evaluate the performance of SARAH when it operates with the goal of power generation, the experimental setup specified by Araujo at Shell is followed which set the parameters (*listed in Table 1*) and yielded the following results –

Table 1

Parameters for the standing-wave heat pump and heat engine tested in [2]

Parameter	Symbol	Value	Unit
Speed of sound	c	375	m/s
Plate diameter	d_s	6×10^{-5}	m
Frequency	f	400	Hz
Stack Length	L_s	0.03	m
Distance between stack center and closed end	x_s	0.025	m
Thermal Conductivity of Air	K_a	0.0262	W/mK
Thermal Conductivity of Plate	K_s	2	W/mK
Isobaric specific heat	c_p	1000	J/kgK
Isochoric specific heat	c_v	714	J/kgK
Resonance tube diameter	D	0.073	m

Initially, air at 2 bar, 550 K and 5 bar, 310 K is pumped into the heat pump resonator tube and heat engine resonator tube, respectively.

I Stage – Heat Pump

P_{mean} = 2 bar

Under the specified experimental conditions,

Temperature at the cold heat exchanger, T_C = 450 K

Temperature at the hot heat exchanger, T_H = 850 K

Since the resonance tube is insulated and heat leakage is negligible, by adiabatic process,

$$\frac{P_{max}}{P_{mean}} - \left(\frac{T_H}{T_C}\right)^{\frac{\gamma}{\gamma-1}} \qquad (7)$$

For air, γ = 1.4

Therefore, P_{max} = 18.5 bar

Acoustic Power,

$$W_a = P_{mean} * c * \frac{\pi}{4} * D^2 =$$

$$2 * 10^5 * 375 * \frac{\pi}{4} * 0.073^2 = 314 \text{ kJ/kg} \qquad (8)$$

As SARAH operates in close approximation to the Brayton Cycle, therefore, heat extracted from the hot heat exchanger [8],

$$Q_H = c_p * (T_H \quad T_C) = 400 \text{ kJ/kg} \qquad (9)$$

Therefore,

$$COP_{HP} = \frac{Q_H}{W} = 1.27 \qquad (10)$$

$$COP_{carnot} = \frac{T_H}{T_H - T_C} = 2.125 \qquad (11)$$

Relative COP,

$$COP_R = \frac{COP_{HP}}{COP_{carnot}} = 0.6 \qquad (12)$$

II Stage – Heat Engine

Q_H along with heat from an additional heat source (solar, waste heat, etc.) is supplied to the hot heat exchanger of the engine [8].

Q_{in} = 500 kJ/kg
$T_{initial}$ = 310 K
P'_{mean} = 5 bar

If the temperature of the hot heat exchanger of the engine is T_{in}, then assuming no heat loss,

$$Q_{in} = c_p * (T_{in} - T_{initial}) \qquad (13)$$

Therefore, T_{in} = 810 K

If the cold end of the heat exchanger of the engine is maintained at room temperature, T_{room} (= 298 K) by use of extended surfaces (fins) and assuming no heat leakage, by adiabatic process,

$$\frac{P'_{max}}{P'_{mean}} = \left(\frac{T_{in}}{T_{room}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (14)$$

Therefore, P'_{max} = 165.5 bar

Now, dynamic pressure,

$$\Delta P = P'_{max} - P'_{mean} = 160.5 \text{ bar} \qquad (15)$$

Diameter of tympanic diaphragm = Diameter of tube
= 0.073 m

For a diaphragm displacement of 1 mm,
Engine Power = ΔP * Area of diaphragm * Diaphragm displacement * Frequency [10] (16)

$$= 160.5 * 10^5 * \frac{\pi}{4} * 0.073^2 * 0.001 * 400 = 26.88 \text{ kW}$$

$$\nabla T_{critical} = \frac{185}{0.03} = 6166.67 \text{ K/m}$$

$$\nabla T_{mean} = \frac{810 - 298}{0.03} = 17066.67 \text{ K/m}$$

Temperature gradient operator,

$$I = \frac{\nabla T_{mean}}{\nabla T_{critical}} = 2.77 \qquad (17)$$

$$\eta_{carnot} = 1 - \frac{T_{room}}{T_{in}} = 0.6321 \qquad (18)$$

Therefore, efficiency of heat engine,

$$\eta_{HE} = \frac{\eta_{carnot}}{I} = 0.2282 = 22.82\ \% \qquad (19)$$

Applications

SARAH can be used to generate power from any source – solar, geothermal, ocean thermoclines, waste heat etc. It can be used with trash incinerators, IC engines, turbines, boilers, blast furnaces i.e. any source capable of generating heat and sound. One of its possible usages may be in passenger air planes to convert body heat, engine heat and sound to air condition the aircraft. On a micro scale, it has limitless possibilities from charging a laptop or a cell phone using CPU heat to powering watches and pace-makers using body heat. Very soon, even Rock Concerts may be a source of power!

Conclusion

SARAH is a light-weight power house. With mere dimensions of 50 cm * 18 cm * 18 cm, it packs quite a punch generating 26.88 kW of power. Although its efficiency leaves a lot to be desired, the absence of moving parts and consequently, minimal wear and tear due to friction, goes a long way to offset this minor bump. It is cost-effective in construction, operation and maintenance, and is very simple to manufacture. Further developments in the micro scale of this device will significantly contribute in abating the energy crisis.

References

[1] in 't panhuis, Peter Hendrikus Maria Wilhelmus, May 2009, Standing-wave Devices, Mathematical Aspects of Thermoacoustics, pp.6-93 – 6-111, Technische Universiteit Eindhoven, Netherlands.

[2] Araujo, S. B., 2004, Downhole Electric Power Generation by Aeroacoustic Oscillations, Universiteitsdrukkerij Eindhoven, Eindhoven, Netherlands.

[3] Duthil, P.*, Thermeau, Jean-Pierre* & Le Polles, T.**, 2008/2009, Plein Sud, Special Recherche, *Institut de Physique Nucleaire d'Orsay, **Societe HEKYOM.

[4] Swift, G. W. & Keolian, R. M., 1993, Thermoacoustics in Pin-Array Stacks, Journal of Acoustical Society of America 94, pp. 941 – 943.

[5] Backhaus, S. & Swift, G. W., 2000, A Thermoacoustic Stirling Heat Engine: Detailed Study, Journal of Acoustical Society of America 107, pp. 3148 – 3166.

[6] Lord Reyleigh, 1945, Theory of Sound, Vol. II, Dover, New York.

[7] http://en.wikipedia.org/wiki/Thermoacoustic_hot_air_engine

[8] Chen, R. & Garrett, S. L., 2000, A Large Solar/Heat-Driven Thermoacoustic Cooler, Journal of Acoustical Society of America 108, pp. 2554.

[9] Chester, W., 1964, Resonant Oscillations in Closed Tubes, Journal of Fluid Mechanics 18, pp. 44 – 66.

[10] Oscar L. Fellows, 2009, Propulsion and Power for the Twenty-First Century, Fellows Research Group, Inc.

[11] http://www.io.com/~frg.