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ACOUSTIC RESONATOR WITH NON-LINEAR STEADY STATE WAVES - ANALOGIES AND DIFFERENCES WITH OTHER SIMILAR DEVICES

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ABSTRACT

Present-day mechanical refrigerators and heat pumps that are used for near-room-temperature applications are based to a large degree on gas-cycle vapor-compression technology involving CFC refrigerants. These refrigerants are highly stable, unreactive, nontoxic; in addition, allow good values of efficiency. However, through various leakages during manufacture, normal operation, and decommissioning of the refrigeration equipment, CFCs are released into the atmosphere. It was claimed that they are responsible for the destruction of stratospheric ozone. Various alternatives have been proposed to vapor-compression cycles based on thermoelectric effect, on magnetocaloric effect and on thermoacoustic effect. Recently, new acoustic resonators have been developed. They allow us to reach so high pressures that they can be utilized as usual compressors of air and other gases or for reversed cycle plants.

1 - INTRODUCTION

The pulse-tube refrigerators were firstly described by Gifford and Longsworth in 1959. However, until recently they remained something of a curiosity. The great advantage of the pulse tube (operating at 1-60 Hz) is that it has no moving parts at low temperature [1-6].

Resonant, or thermoacoustic pulse tubes are partially similar to previous devices. However thermoacoustic pulse tubes operate at higher frequencies (100-1000 Hz) and are driven by an oscillating diaphragm. Thermoacoustical phenomena in pipes with a closed end and with both open ends were firstly examined by Sondhauss and Rijke, respectively, and after by other authors [7-9].

Wheatley and others examined various thermoacoustical systems both as heat engines and refrigerators [10-24]. These devices are intrinsically irreversible, since, in order to operate, the require, on principle, heat transfer with finite temperature difference,

2 - ACOUSTICAL RESONATORS OF LUCAS EMPLOYING NON-LINEAR STEADY STATE WAVES

Recently, some researchers have devised a new technology to use sound waves with a power remarkably higher than those previously realized. In this manner, they opened the way for simple acoustic compressors, speedy chemical-process reactors, and clean electric power generators [25-26].

Ever since electricity became a familiar part of everyday life, people have grown accustomed to the idea of getting the power for various mechanical tasks from unseen electromagnetic waves traveling through metal wires. Few, however, have witnessed the acoustic analogue of electromagnetism-sound waves, or pressure waves propagating through gas-filled chamber, doing useful work with a power acceptable for industrial applications

The situation may change as Lucas has developed a technique by which standing sound waves resonating in specially shaped closed cavities can be loaded with thousands of time more power than it was previously possible. Lucas's wave-shaping technology is known as "resonant macrosonic synthesis" (RMS). Lucas states (and his statement seems acceptable) that the inherent simplicity of this technology could result in increased reliability and durability. We, however, do not agree with the statements of Lucas on the possibility of obtaining high values of exergy efficiency. In these devices, indeed, there is the presence of ”constructive irreversibilities” that can not be reduced.

Finite-amplitude acoustic phenomena in resonant cavities have been of practical interest since the 1930s, when German researchers studied them in connection with the development of mufflers for tanks. Historically, researchers have believed that there is an intrinsic limit for sound waves in gases that would never allow high-power level to exist. Previous experimental work had shown that sound waves in a resonator would build up power to a certain level and no more. This acoustic saturation point occurs when shock waves start to form. Once a shock wave exists, any power added to the wave is wasted as thermal power. For resonant sound waves, Lucas discovered that the geometry of the resonator cavity through which the sound waves travel is the most important factor in determining the shape of the wave. In fact, many researchers in the pat had used cylindrical resonators. This configuration, however, is the most likely to produce shock waves. In 1990, Lucas found that he could create relatively large-amplitude, or macrosonic, sound waves up to a pressure of 4 bar by properly shaping the resonator. The next technical hurdle that researchers addressed was to figure out how to transfer a lot of power into a cavity. Lucas decided to shake the entire cavity with a linear motor, a vibrator that is nothing more than a glorified electromagnet. In that way, the whole inner surface of the resonator transferred power to the enclosed gas. Thus, the cavity acted like one large piston.

Lucas demonstrated his RMS technology using a resonator cavity shaped like an elongated pear. When this cavity is vibrated with a linear motor so that its walls move back and forth a distance of about 100 mm, it resonates with a smooth, shockless wave of high power.

The first major application of RMS technology was an acoustic compressor. Inside the cavity, dynamic gas-molecule displacement was about 5-6 cm, about one-third of the resonator length. Let us consider an acoustic compressor. The standing wave in the resonator causes the pressure to oscillate during one acoustic cycle of about 2 ms. When the pressure is low at the thinner end, the suction valve opens and low pressure gas flows in and enters the plenum. When the pressure is high at the thinner end, the discharge valve opens and high pressure gas flows from the resonator into the discharge plenum. High-pressure gas in the resonator holds the suction valve shut.

Lucas with his team has also designed a compressor that does not need valves. It is based on creating a static pressure distribution in which a high-pressure area is located at a port on one end of the resonator and a low-pressure area is placed near another port at the other end. This design generates a lower pressure head, but probably it can allow higher values of efficiency owing to lower ”essential” irreversibilities.

According to Lucas, the new RMS concepts will make previously unattainable physical effects possible. Such effects could be used in a range of new industrial devices and processes with cavities shaped specifically for each application. For example, specialized non-contaminating acoustic compressors and pumps for commercial gases, ultrapure fluids, and hazardous fluids are a possibility. These devices are important for the pharmaceutical and semiconductor industries.

RMS technology could be used to drive and control thermal and kinetic chemical reactions by producing localized heating with rapid pressure changes.

Acoustic chambers could be used for separation, agglomeration, mixing and pulverization of materials. For example, improved acoustic agglomeration of particulate contaminants, causing them to stick together, could lead to improved gas scrubbers for power-plant flue gases by allowing smaller units to operate at higher flow rates.

Electric-power generation using pulse combustion of hydrocarbon fuels [27] could also be realized through this technology.

It is to be remarked that acoustic compressors emit nearly pure tone that is sufficiently loud to require sound-deadening enclosure.

3 - SIMILARITIES AND DIFFERENCES AMONG SEVERAL SYSTEMS

As done in previous papers (e.g., [17]), also in this paper a table (Table 1) with similarities and differences among several systems, including the new RMS, is reported.

	Systems with ”essential” irreversibilities	*Systems without ”essential” irreversibilities*
Systems without a valuable mass transfer and (100 − 1000 Hz)	Standing wave thermoacoustic devices (Sondhauss and Rijke tubes within these)	Traveling wave thermoacoustic devices − Magneto-acoustic hydrodynamic transducers
Systems with a valuable mass transfer and (1-60 Hz)	Gifford-Longsworth pulse-tube refrigerators -	Classical Stirling engines
	Arkharov et al. Wave cryogenerator -	
	Stirling engines in which the velocity wave leads the pressure wave by a small phase angle	
Systems with a valuable mass transfer and (500-600 Hz)	Acoustic resonators of Lucas with non-linear steady state waves (RMS)	

Table 1: Similarities and differences among several systems.

The following distinguishing criteria have been assumed: (i) the presence or absence of constructive irreversibilities, (ii) the presence or absence of a valuable mass transfer and then of a valuable power, (iii) the range of the employed frequencies.

The systems characterized by irreversibilities having a ”constructive” role present low exergy efficiency, and for these the reference to reversibility is devoid of any meaning. In these cases, indeed, useful effect tends to zero as an infinitesimal of higher order than entropy production rate [28]. On the contrary, when irreversibilities have not a ”constructive” role, even if they are always present, the efficiency values can be higher, but only with an expedient choice of the various parameters.

REFERENCES

1. **Gifford W.E., Longsworth R.C.**, Pulse tube refrigeration, *Trans. ASME, J. Eng. Ind*, Vol. 86, pp. 264-268, 1964
2. **Gifford W.E., Longsworth R.C**, Pulse tube refrigeration progress, In *Int. Advances in Cryogenic Engineering, K.D. Timmerhaus, Ed*, pp. 69-79, 1965
3. **Gifford W.E., Longsworth R.C.**, Surface heat pumping, In *Advances in Cryogenic Engineering, K.D. Timmerhaus, Ed.*, pp. 171-179, 1966
4. **Mikulin E.I., Tarasov A.A., Shkrebyonock M.P.**, Low-temperature expansion pulse tubes, In *Advances in Cryogenic Engineering, R.W. Fast, Ed.*, pp. 629-637, 1984
5. **Richardson R.N., Evans B.E.**, A review of pulse tube refrigeration, *Int. J. Refrigeration*, Vol. 20, pp. 367-373, 1997
6. **Zhu S., Wu P., Chen Z.**, Double inlet pulse tube refrigerator: an important improvement, *Cryogenics*, Vol. 30, pp. 514-520, 1990
7. **Feldman K.T., Jr.**, Review of the literature on Sondhauss thermoacoustic phenomena, *J. Sound Vibration*, Vol. 7, pp. 71-82, 1968
8. **Feldman K.T., Jr.**, Review of the literature on the Rijke thermoacoustic phenomena, *J. Sound Vibration*, Vol. 7, pp. 83-89, 1968
9. **Bisio G., Rubatto G.**, Sondhauss and Rijke oscillations - thermodynamic analysis, possible applications and analogies, *Energy - The International Journal*, Vol. 24, pp. 117-131, 1999
10. **Wheatley J., Hofler T., Swift G.W., Migliori A.**, An intrinsically irreversible thermoacoustic heat engine, *J. Acoust. Soc. Am.*, Vol. 74, pp. 153-170, 1983
11. **Wheatley J., Hofler T., Swift G.W., Migliori A.**, Experiments with an intrinsically irreversible thermoacoustic heat engine, *Phys. Rev. Lett.*, Vol. 50, pp. 499-502, 1983

12. **Wheatley J., Hofler T., Swift G.W., Migliori A.**, Understanding some simple phenomena in thermoacoustics with applications to acoustical heat engines, *Am. J. Phys.*, Vol. 53, pp. 147-162, 1985
13. **Swift G.W., Migliori A., Hofler T., Wheatley J.**, Theory and calculations for an intrinsically irreversible acoustic prime mover using liquid sodium as primary working fluid, *J. Acoust. Soc. Am.*, Vol. 78, pp. 767-781, 1985
14. **Wheatley J., Buchanan D.S., Swift G.W., Migliori A.**, Non-linear natural engine: Model for thermodynamic processes in mesoscale systems, *Proc. Natl. Acad. Sci. USA*, Vol. 82, pp. 7805-7809, 1985
15. **Wheatley J.**, Intrinsically irreversible or natural engines, In *Frontiers in Physical Acoustics, North-Holland Phys. Publ., Amsterdam*, pp. 395-475, 1986
16. **Swift G.W.**, Thermoacoustic engines, *J. Acoust. Soc. Am.*, Vol. 84, pp. 1145-1180, 1988
17. **Benvenuto G., Bisio G.**, Thermoacoustic systems, Stirling engines and pulse-tube refrigerators - Analogies and differences in the light of generalized thermodynamics, In *Proceedings of 24th IECEC, W.D. Jackson, D.A. Hull, Eds., IEEE, New York*, pp. 2413-2418, 1989
18. **Swift G.W, Keolian R.M.**, Thermoacoustics in pin-array stacks, *J. Acoust. Soc. Am.*, Vol. 94, pp. 941-943, 1993
19. **Olson J.R., Swift G.W.**, Similitude in thermoacoustics, *J. Acoust. Soc. Am.*, Vol. 95, pp. 1405-1412, 1994
20. **Cao N., Olson J.R., Swift G.W., Chen, S.**, Energy flux density in a thermocouple, *J. Acoust. Soc. Am.*, Vol. 99, pp. 3456-3464, 1996
21. **Wetzel M., Herman C.**, Design optimization of Thermoacoustic refrigerators, *Int. J. Refrigeration*, Vol. 20, pp. 3-21, 1997
22. **Mozurkewich G.**, Time-average temperature distribution in a thermoacoustic stack, *J. Acoust. Soc. Am.*, Vol. 103, pp. 380-386, 1998
23. **Gopinath A., Tait N.L., Garret S.L.**, Thermoacoustic streaming in a resonant channel: The time-averaged temperature distribution, *J. Acoust. Soc. Am.*, Vol. 103, pp. 1388-1405, 1998
24. **Adeff J.A., Hofler T.J., Atchley A.A., Moss W.C.**, Measurements with reticulated vitreous carbon stacks in thermoacoustic prime movers and refrigerators, *J. Acoust. Soc. Am.*, Vol. 104, pp. 32-38, 1998
25. **Lawrenson C.C., Lipkens B., Lucas T.S., Perkins D.K., Van Doren T.W.**, Measurements of macrosonic standing waves in oscillating closed cavities, *J. Acoust. Soc. Am.*, Vol. 104, pp. 623-636, 1998
26. **Ilinskii Y.A., Lipkens B., Lucas T.S., Van Doren T.W., Zabolotskaya E.A.**, Nonlinear standing waves in an acoustical resonator, *J. Acoust. Soc. Am.*, Vol. 104, pp. 2664-2674, 1998
27. **Bisio G., Rubatto G.**, Sondhauss and Rijke oscillations - Thermodynamic analysis; possible applications and analogies, *Energy - The International Journal*, Vol. 24, pp. 117-131, 1999
28. **Bisio G.**, On the suitability of reversibility hypothesis, *Proceedings of FLOWERS '97, Florence, July 30 - August 1, SGE, Padova*, pp. 1143-1155, 1997