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Performance analysis of the standing wave thermoacoustic refrigerator: A review

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A B S T R A C T

Concerns over environmental impacts of hazardous refrigerants have spurred much research into alternative technologies as well as more environmentally friendly refrigerants. A thermoacoustic refrigeration system uses no refrigerant but is currently not a feasible solution due to the still immature technology with much still unknown about the theories that explain the thermoacoustc cooling effects and the desired performance. This paper reviews past studies to achieve the desired outputs; lowest temperature, the highest temperature difference generated across the stack, the lowest acoustical work required for cooling, or/and the highest coefficient of performance (COP) of the standing wave thermoacoustic refrigerator and various attempts at optimization in terms of the many parameters that represent the outcomes. The review looked at methods employed to analyze the performance with discussions on the relevant parameters that must and have been be considered by past researchers. To date, most studies have been focused on the stack, the heart of the system. Optimization work has been performed parametrically, experimentally or/and numerically, where discrete variations of the parameters investigated are completed whilst others are held constant. Lately, genetic algorithm, a statistical approach, has been utilized in simultaneous optimization of the parameters of the desired outputs where conflicting objectives are possible. To date, thermoacoustic refrigerator remains an attractive alternative technology towards a global agenda of a more sustainable future.

Contents

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1. Introduction

The studies on thermoacoustics have continued for more than two hundred years, since that first observation of heat induced acoustic oscillations by Byron Higgins in 1777. Thermoacoustic phenomena, the solid–fluid interactions which involve heat pumping mechanism of the working fluid are capable of either generating acoustical work or inducing a cooling effect. However, the theoretical basis for thermoacoustic phenomena was only established in 1969 through 1980 in a series of papers presented by Rott and his co-researchers. The issues addressed included [1]:

- Thermoacoustic and its meaning.
- Categories of thermoacoustic devices.
- Attempts to calculate the effect of thermoacoustic streaming.
- Stability theory to define optimum effectiveness of the driving mechanism.
- The relationship between the heat flux, acoustic pressure and velocity of an isothermal and adiabatic tube.
- The theories of Kirchhoff and Kramers to develop a linearized thermoacoustic theory for cylindrical tubes.

The international attempts to conserve the earth's stratospheric protective ozone layer led in 1997 by the Montreal Protocol (MP) had prompted intensive research into alternative more environmentally friendly technology. In consequence of MP's regulations, the manufacture, import, export, use, transit shipment, sale and offer for sale of any Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs) or products that contain CFCs and HCFCs have been first prohibited and then banned in 2000 [2], except those that are already in use (in under-developed and developing countries). The CFCs have been used as refrigerants in conventional thermodynamics refrigeration, air conditioning systems and heat pumps. The banning of CFCs along with the awareness of their harmful destructive effects on the ozone depletion appeals the interest of researchers to find new environmentally benign technologies. Thermoacoustic refrigerating system could be a possible alternative to the conventional systems since it contains no refrigerant at all. The primary working fluid is inert whilst the secondary medium which transfers the heat between the cooling load and the environment via the heat exchangers is a solid of low conductivity.

Thermoacoustic refrigeration operates based on the fundamental thermodynamic heat pump where work is necessary – in this case acoustical work – to transfer heat from a low temperature reservoir to a high temperature reservoir. At resonant frequency, as the working fluid particles oscillate next to solid walls, significant cooling effects are induced as heat is moved from one end of the solid wall to the other. At high pressure and with appropriately designed solid structure called the stack, placed in the path of the oscillating working fluid particles, considerable amount of cooling could be harnessed, examples are works by Minner et al. [3], Reid and Swift [4], Tijani et al. [5], and Hariharan et al. [6] just to name a few. Two types of thermoacoustic refrigeration are possible, that based on the traveling wave which is generally a large system, and the standing wave type, a more compact system. Unfortunately, with the hype started over the environmentally friendly thermoacoustic refrigeration systems after the first cooler was developed by Hofler in his Ph.D. thesis [7], the thermoacoustic systems are generally characterized by their low performance and unknown technology. Most of the research is in the United States with others scattered among universities in Europe and China.

Optimization of energy-related system has never been more crucial today where energy sources are depleting and global concerns of degradation of our environment are of serious agenda. There is no review available on the analysis of the performance of the thermoacoustic refrigeration system, possibly due to the still much to be known about the theory explaining the phenomena itself as well as the small community of researchers involved. The lack of fundamental understanding in this "young" technology, the relatively low number of researchers involved, and the associated cost needed to be invested, should not discourage future researchers from venturing into this area. As much as possible should be done towards assisting the global need for alternative solutions for a sustainable future. Thus, this paper presents an overview of the studies completed to date on the standing wave thermoacoustic refrigeration systems, some focused on the stack which is the heart of the system, while others were on the whole system, as shown in Table 1. Unlike the conventional review done in the past i.e., each whole paragraph dedicated to explore a single study, this review is tabulated for an easier understanding of past work. The research method used, parameters addressed and outcomes achieved listed in the table will help future researchers to quickly identify areas that efforts can be better concentrated in certain aspects towards a comprehensive study of the performance of the thermoacoustic refrigeration system.

2. General review

When the first successful thermoacoustic refrigerator with a cooling power of 6 W was introduced by Hofler in 1986 [7], the cooling technology began to be considered as a potential alternative to the vapor compression system. The standing wave system operated at 10.2 bar with Helium gas as the working fluid. Thermoacoustic refrigeration involves no refrigerant which renders it an environmentally friendly system, an attractive technology in a global agenda towards a sustainable future. However, almost 30 years have passed and the closest a commercial thermoacoustic refrigerator that we could get was in 2004 when Poesse, Garret and Smith from the Pennsylvania State University, USA, collaborated with Ben & Jerry's ice-cream company to develop a system with a cooling power of 119 W using Helium at 10 atm pressure [70]. It took the team one year to complete the system with a million dollar sponsorship from Unilever Company [Garret, SL, personal communication, September, 2009].

The two main issues related to the commercialization of the thermoacoustic refrigerator are the technology and the associated cost, both being inter-related. The know-how of the development of a fully functioning system involves much time and diligence from participating researchers and institutions with consistently low performance output that is hardly encouraging for potential financial investors. Only a collectively small group of researchers have the staying power going by the repeated appearance of names in the citations of published work. No system parallel to the Ben & Jerry system has been reported since. Nevertheless, experimental and numerical research has continued towards the