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Experimental investigation of thermal performance of random stack materials for use in standing wave thermoacoustic refrigerators

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ABSTRACT

In a standing wave thermoacoustic refrigerator, heat transport from the "cold" to the "ambient" end of a stack is achieved by means of an oscillatory motion of a compressible fluid undergoing cyclic compression and expansion. However, the stacks can be both costly and impractical to fabricate due to material and assembly costs, which limits the cost benefits of thermoacoustic systems. Some of these problems could be solved by the application of stacks that have irregular geometries, for instance stacks made of "random" materials from metal machining (swarf), which are often considered as waste. In this paper, the thermal performance of stacks made of a few selected materials is determined by carrying out experiments in a standing wave thermoacoustic refrigerator. The reported results will be beneficial for developing low-cost thermoacoustic refrigerators or heat pumps for both domestic and commercial applications.

Étude expérimentale de la performance thermique de stacks en matériaux aléatoires utilisés dans des réfrigérateurs thermoacoustiques à onde stationnaire

Mots clés : Réfrigérateurs thermoacoustiques ; Onde stationnaire ; Stacks thermoacoustiques ; Matériaux aléatoires ; Performance thermique

1. Introduction

Thermoacoustic refrigerators and engines are a group of systems that make use of "thermoacoustic effect" to achieve energy conversion between thermal and acoustic power. They rely on the interaction between the compressible fluid undergoing an acoustic oscillation and solid structures, such as stacks (the name "stack" being typically associated with standing wave systems) and regenerators (typically in travelling wave systems) that are placed in the resonator. In the last two decades, thermoacoustic devices have attracted a lot of attention because their only moving mechanical components are acoustic drivers (the oscillating working gas under

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Nomenclature

A	Cross sectional area
A_{spk}	Cross sectional area of diaphragm of a loudspeaker
A_{wet}	Total wetted area of a stack
c_p	Thermal capacity of fluid
f	Frequency
κ	Thermal conductivity
m_{solid}	Mass of solid material
p	Acoustic pressure amplitude
Q	Cooling load
r_h	Hydraulic radius
T_c	Temperature of the cold reservoir
T_h	Temperature of the hot reservoir
U	Volumetric velocity amplitude
V_{gas}	Volume of gas in a stack
V_{solid}	Volume of solid material in a stack
V_{tot}	Total volume of a stack, $=V_{gas} + V_{solid}$
W_{ac}	Acoustic power
δ_v	Viscous penetration depth
δ_κ	Thermal penetration depth
μ	Dynamic viscosity of fluid
ξ	Displacement amplitude
Π	Perimeter
ρ	Density of fluid
ρ_{solid}	Density of solid material
σ	Absolute uncertainty
Φ_{pU}	Phase difference between acoustic pressure and volumetric velocity
$\Phi_{p\xi}$	Phase difference between acoustic pressure and displacement
ω	Angular frequency
COP	Coefficient of performance
COPC	Carnot coefficient of performance
COPR	Relative coefficient of performance
PPI	Pores per inch

the acoustic excitation executing the thermodynamic process). The absence of mechanical moving parts and the associated dynamic seals and lubrication gives a great advantage to thermoacoustic devices over many other conventional energy conversion devices, especially in terms of high reliability and minimal maintenance. The working gas in thermoacoustic devices is usually one of the noble gases or their mixture, and sometimes air, making this technology also environmentally friendly.

However, achieving a high efficiency system remains one of the many challenges facing this relatively new technology before it can be applied more widely in industry. A systematic design and optimization algorithm was proposed for thermoacoustic refrigerators, based on the short stack boundary layer approximation (Wetzel and Herman, 1997). Simulations based on the same approximation indicate that refrigeration, including air conditioning and cryogenic cooling, is the best application of thermoacoustic cycles in terms of high efficiency (Paek et al., 2007). Several pieces of work were also devoted to a better understanding of how each of the essential components of the system performs, for example the stack (Tijani et al., 2002) or the regenerator (Backhaus and Swift, 2001). The impact of the operating frequency and temperature difference between the stack ends on the refrigeration power was studied using network and thermodynamic models, as well as experimental approaches (Jebali et al., 2004). Another important strand of research involves looking at the physics of the thermoacoustic effect, for example the experimental demonstration of the thermoacoustic effect (Biwa et al., 2004) and the nonlinear acoustic streaming that often takes place in such systems (Bailliet et al., 2001).

In parallel to the studies into the improvement of system efficiency by a careful design of all components, efforts are also made to develop systems that are low-cost but of an equivalent or marginally lower efficiency (Saechan et al., 2011). One component of particular concern is the stack/regenerator, because the fabrication of stacks, such as those made out of thin parallel sheets, is usually costly and impractical, while using pre-fabricated stacks, for example ceramic catalytic converter substrates used in the automobile industry, has high materials costs, which limits the cost advantages of thermoacoustic devices as well as pre-defined hydraulic radii, unsuitable for high pressure devices. Some of these problems could be avoided if irregular stack geometries made out of random (very often waste) materials could be used. There is a wide range of such candidate materials, including steel wool and waste material from metal machining (swarf, scourers) and others. However, the main difficulty is the lack of experimental data characterising the performance of such stacks at the design stage. The performance of some of these material used as regenerators in the travelling wave thermoacoustic devices has been recently studied by Abduljalil et al. (2011).

In many thermoacoustic engines, generators and refrigerators, noble gases and their binary mixtures are often used to meet the requirement for low Prandtl number, a high thermal conductivity, a high speed of sound and a large specific heat ratio. However, in view of the high costs of noble gases, air is considered a more economic and easily available alternative to be used as the working medium (Jaworski and Mao, 2013). Hence, air is used as the working gas in the work presented here. In this paper, a study of the performance of a standing wave thermoacoustic refrigerator with a stack made out of several types of random materials is reported. The results from this work are thought to be of particular benefit for the development of low-cost thermoacoustic coolers, heat pumps or prime movers for both domestic and commercial applications.

2. Experimental apparatus and instrumentation

The experimental apparatus consists of a straight square cross-sectional resonator, with one end attached to an acoustic driver (loudspeaker) via a transition section, and another end attached to a compliance “box” via a second transition section, as indicated by the photograph and schematic diagram of the experimental apparatus in Fig. 1. The resonator is a 1.82 m long duct of 76.2 mm × 76.2 mm in cross section. The acoustic driver is a subwoofer type loudspeaker (Precision Device Model 1850),