International Journal of Heat and Mass Transfer 74 (2014) 228–237

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A fundamental study on characteristic of thermoacoustic engine with different tilt angles

Na Pan [a], Shuangfeng Wang [a,*], Chao Shen [b,*]

[a] The Key Lab of Enhanced Heat Transfer and Energy Conservation Ministry of Education, South China University of Technology, Guangzhou 510640, China
[b] School of Civil Engineering, Zhengzhou University, Zhengzhou 450001, China

ARTICLE INFO

Article history:
Received 25 April 2012
Received in revised form 16 January 2013
Accepted 8 March 2014

Keywords:
Thermoacoustic engine
Tilt angle
Thermal convection
PIV

ABSTRACT

Solar powered thermoacoustic engine is an attractive device for solar thermal utilization. Its performance is significantly affected by tilt angle when it rotates with the sun. In this study, the heat transfer and flow characteristics of thermoacoustic engine were investigated under five tilt angles including −45°, −90°, 0°, 45° and 90°. The temperature and velocity fields of thermoacoustic core were measured respectively by Thermal Infrared Imager and Particle Image Velocimetry (PIV). Experimental results show that acoustic oscillation has significant influence on the flow and heat transfer in thermoacoustic engine. This kind of influence is different when thermoacoustic engine works under different tilt angles. Five tilt angles were classified into three situations according to the relative position of two heat exchangers. And the interaction of thermal convection and acoustic oscillation was discussed in each situation.

1. Introduction

Thermoacoustic engine is a new type of device which can convert thermal into acoustic energy due to a thermal interaction between oscillatory compressible flow and solid structure such as thermoacoustic stacks. There has no moving components in thermoacoustic engine and the working gas is environmental friendly. In recent decades, much effort has been spent on the research of thermoacoustic effect. The linear theory of thermoacoustic oscillation has been developed by Rott [1–3], Wheatley [4] and Swift [5,6]. In addition, a great progress of nonlinear thermoacoustic theory has made by Karpov [7–9] and Hamilton [10,11]. Lu and Cheng [12–14] discussed the relationship between the mass streaming and the energy streaming in thermoacoustic oscillation. Shi et al. [15,16] paid much attention to investigate the complex flow patterns at the end of thermoacoustic stacks. Wang et al. [17] observed the effect of Gedeon streaming on the onset and damping process in thermoacoustic engine.

Since thermoacoustic engine can onset at a low temperature, it has remarkable advantage in the utilization of low grade thermal energy such as solar energy and waste heat in power plant. A project that is underway to recover 7 kW peak electrical power from the exhaust of an over-the-road heavy-duty diesel truck through thermoacoustic engine in Pennsylvania State University [18]. Solar powered thermoacoustic engine is heated by solar radiation, and the acoustic power can be used to pump heat from external load or to drive linear electric generator [19]. The first solar powered thermoacoustic engine was designed by Chen. It was used to drive thermoacoustic cooler which only achieved 1.8 °C temperature drop due to gas leakage and thermal loss [20]. A thermoacoustic refrigerator driven by solar powered thermoacoustic engine was built by Adeff and Hofler [21], which produced 2.5 W cooling power with the temperature span of 18 °C.

For solar powered thermoacoustic engine, a solar collector is generally needed to focus sunlight onto the hot heat exchanger. Tilt angle is one of the most important factors that affect the efficiency of solar collector. Tang did lots of research about the influence of tilt angle on the performance of solar collector [22,23]. It was found that the yearly optimal tilt-angle of solar tube collector should be lower than the site latitude for maximizing the annual energy collection. The optimal tilt angle of solar collector in different regions was also been discussed [24–26]. In order to better absorb the solar energy, solar powered thermoacoustic engine needs to rotate with the sun during a day. The tilt angle has significant influence on its performance. Shen [19] investigated the effect of tilted angles on the onset temperature, system pressure and resonance frequency of thermoacoustic engine. The results showed that onset temperature had big difference under different tilt angles. For low viscidity working gas, the difference can up to 52 °C due to the influence of thermal convection. The interaction of acoustic oscillation and thermal convection is the internal factor to influence the performance of thermoacoustic engine under different tilt angles. To the best of authors' knowledge, this fundamental interaction

* Corresponding authors. Tel.: +86 20 22236929.
E-mail addresses: sfwang@scut.edu.cn (S. Wang), shenchao@zzu.edu.cn (C. Shen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.019
0017-9310/

has not been adequately discussed so far which is very helpful to understand the complex energy transport in thermoacoustic oscillation.

The characteristic of solar power thermoacoustic engine has big difference when it works under different tilt angles. The previous work of the authors [27,28] studied the flow and heat transfer characteristic of thermoacoustic engine at horizontal situation (0°). Present paper is a substantial extension of previous work. Its main purpose is to systemically analyze the influence of tilt angle on characteristic of thermoacoustic engine. In this study, the temperature and velocity fields of thermoacoustic core at 45°, 90°, −45° and −90° were investigated and compared with the horizontal situation. The results of five tilt angles were classified into three situations to discuss the interaction of thermal convection and acoustic oscillation inside the thermoacoustic engine.

2. Experimental apparatus and measurement system

2.1. Thermoacoustic engine angle rotation installation

To study the effect of tilt angle on thermoacoustic engine, the experimental apparatus should be rotated to different tilt angles. In this experiment, the thermoacoustic engine was mounted on a rectangular shelf that made of angle steel. The shelf can rotate thermoacoustic engine to any tilt angle. The angle is defined as a positive value when the hot heat exchanger is above the cooling heat exchanger and defined as a negative value when the hot heat exchanger is below the cooling heat exchanger as shown in Fig. 1. The experiments were performed for every 45° from −90° to 90°. Therefore, five tilt angles including −45°, −90°, 0°, 45° and 90° have been tested in total. The thermoacoustic engine is composed of two heat exchangers, thermoacoustic core, resonance tube and loudspeaker. More details of the structure about thermoacoustic engine can be seen in previous study work [27]. The thermoacoustic core between two heat exchangers is the key component of thermoacoustic engine. The investigation of temperature and velocity distributions in this experiment was focusing on this part. To better visualization, thermoacoustic core was made into rectangular glass tube and no stack was fixed in it.

2.2. Experimental procedure

In the experiment, temperature and velocity fields in thermoacoustic engine were measured at different tilt angles. The experimental procedure was similar at each angle. The corresponding experimental set up is outlined below:

(1) The hot heat exchanger in thermoacoustic engine was made as an electric heater that twining resistance wire around a porous ceramic cylinder. A voltage regulator was used to control the heat power. It was heated to stabilize at 150 °C in this experiment. The cooling heat exchanger was cooled by circulating water with the temperature stabilized at 10 °C. Temperature of heat exchangers was monitored by K-type thermocouples which were equipped in them. The data were collected and recorded by Agilent (34970A).

(2) The acoustic oscillation in the resonance tube was provided by a loudspeaker. A 205 Hz sinusoidal signal was sent by a signal generator (RIGOL DG1022) to the power amplifier (BAudio 503-K). After adjusted the sound power, it was sent to the loudspeaker as shown in Fig. 2. To capture the whole cycle of acoustic oscillation, a phase locking technique was used in this experiment. As shown in Fig. 2 5 Hz TTL signal which synchronized with the sinusoidal signal was sent to the synchronizer to trigger the laser and camera.

(3) The velocity distribution within thermoacoustic core was measured by a TSI PIV as shown in Fig. 2. Two images were taken by the camera when the thermoacoustic core was illuminated by laser sheets. The velocity is calculated by the formula that the displacement of particles between two images divided by the time interval between the laser pulses. In this experiment, the time interval is set to 200 μs and the distance each pixel represented is calibrated by the calibration target. The uncertainty of this measurement system is 0.64% which has already considered the bias error of PIV and precision error that calculated through the standard deviation of samples [29].

(4) The temperature distribution was measured by a Thermal Infrared Imager (FLIR ThermerCAM SC3000) as shown is Fig. 2. The glass surface of thermoacoustic core was covered by thermal conductive adhesive to reduce the error induced by glass reflection. The emissivity of this adhesive was evaluated using the ThermaCAM research software by matching the measured temperature with a reliable value that synchronously measured by PT100 thermal resistance. In this work, the calibrated emissivity value was set to 0.576.

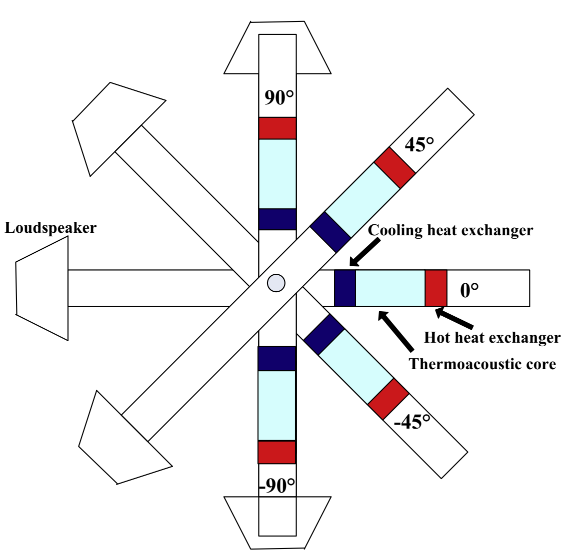

Fig. 1. Schematic of tilt angles of thermoacoustic engine.

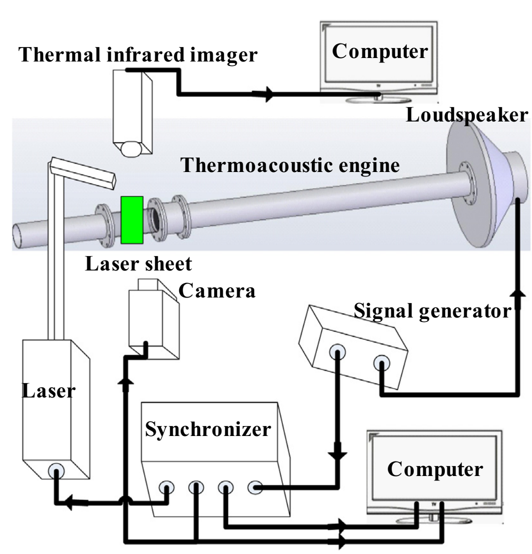

Fig. 2. Schematic diagram of measurement system.