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Energy harvesting from a convection-driven Rijke-Zhao thermoacoustic engine

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A convection-driven Rijke-Zhao thermoacoustic engine is developed. It can produce intensive oscillations at two different temperatures. Furthermore, it does not involve any heat exchanger and stack/regenerator, which play critical roles in conduction-driven standing- or travelling-wave engines. Thus, the Rijke-Zhao engine is much simpler in design and lower cost in fabrication. To demonstrate its potential of energy-harvesting, a design for the conversion of heat into electricity via sound is proposed by integrating Rijke-Zhao engine with a piezoelectric generator. The preliminary experimental results are presented. And it is found that 60% more power is generated than that from conduction-driven standing-wave thermoacoustic-piezoelectric resonator [Smoker *et al.*, J. Appl. Phys. **111**, 104901, (2012)]. In order to gain insights on the generation mechanism of the thermoacoustic oscillations in the present energy-harvesting system, 2D numerical simulations are conducted. Comparing the numerical results with the experimental one reveals that good quantitative agreement is obtained. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4767914>]

I. INTRODUCTION

Greenhouse gas emission and fossil fuel exhaustion are increasingly urgent issues. However, industry waste heat generated by burning fossil fuel is released to the atmosphere. This is not only harmful to the environment but also energy wasting. To recover waste heat, there is a need for energy conversion techniques to convert heat into electricity or mechanical work, especially for heat at low temperature. Thermoacoustic energy conversion technology¹ may be used to achieve this. Unsteady heat release is an efficient acoustic source,² and generates acoustic waves. These pressure waves propagate within a looped or straight tube and reflect back at the heating zone due to the changes of acoustic impedance, where they can cause more unsteady heat release. This feedback can result in the oscillation amplitudes successively increasing. Eventually, some nonlinearity in the system limits the amplitude of the oscillations. These self-sustained oscillations (also known as thermoacoustics) indicate an intensive energy conversion between heat and sound,^{2,3} which might be used for harvesting thermal energy.^{1,4}

Generally, thermoacoustic systems are associated with two distinct types of oscillations: (i) convection-driven or (ii) conduction-driven.⁵ Rijke tube is a laboratory-scale convection-driven thermoacoustic system. It is a simple open ended vertical tube with a confined heat source in its lower half. To generate self-sustained oscillations, the natural convection flow resulting from the heating is essential. Sondhauss tube is a classical device of producing conduction-driven oscillations.⁵ It is a pipe having one closed and one open end in the presence of mean temperature gradients. Unlike Rijke-tube, no mean flow is involved in Sondhauss.

To elucidate thermoacoustic energy conversion process, as occurred in Rijke- and Sondhauss-tube, considerable research has been carried out over the last decades. The first insight into thermoacoustic oscillations was provided by Rayleigh⁶ over a century ago. He stated that intensive thermoacoustic oscillations would occur when heat was added in phase with pressure, but would not occur if heat was added out of phase with pressure. Culick⁷ derived a general form of the Rayleigh's criterion, which is applicable to both linear and nonlinear thermoacoustic oscillations in any shaped chamber. He showed that an oscillating heat source functioned like an oscillating piston. The same conclusion was drawn by Rott.³

Besides offering insight into the energy exchange that gives rise to and limits the growth of intensive oscillations, Rayleigh criterion also suggests ways in which thermoacoustic oscillations can be maximized or minimized, depending on applications in practice. One application in aero-engines and gas turbines is to minimize convection-driven thermoacoustic oscillations to achieve safe operation.^{8–13} These have been well-reviewed by McManus *et al.*¹⁴ and Dowling and Morgans.² The other application is to maximize the thermoacoustic oscillations to enable it work as an engine. Thermoacoustic engines^{1,15} are generally associated with conduction-driven oscillations. Such engines consist of an acoustic resonator, a stack or regenerator, and heat exchangers.¹ And they can be divided into two varieties; one is standing-wave engine¹⁶ and the other is travelling-wave one.^{17,18} Both classes of engines are under vigorous development, after Ceperley¹⁵ realized that Stirling engines are of the travelling-wave class.

Thermoacoustic engines are more attractive than traditional Stirling engines involving pistons, due to the fact that they lack moving parts, require little maintenance and last a long time. However, these thermoacoustic engines^{19,20} provide lower efficiency, little reliability, or high fabrication

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cost. For example, the travelling-wave engines²⁰ have high efficiency and high reliability. However, the fabrication cost is high due to the proper design of regenerator and heat exchangers. The standing-wave engines^{1,4,16} are reliable and cost little to fabricate, but they are inefficient. Smoker *et al.*⁴ conducted an experimental investigation on a conduction-driven standing-wave engine for energy harvesting. A porous stack and two heat exchangers were used to generate a steep temperature gradient to produce self-sustained thermoacoustic oscillations. The resulting pressure fluctuations were then used to excite a piezoelectric diaphragm placed at the end of the resonator. The output power was found to be very low. However, they argued that the experimental setup is simple and involves no moving components, and so it is an invaluable tool in the design of thermo-acoustic-piezoelectric resonance system for harvesting thermal energy.

Much of the above work concluded that the majority of thermoacoustic engines has been designed based on the conduction-driven oscillations. However, convection-driven oscillations might be as intensive as the conduction-driven one.² However, very few designs and applications can be found in literature. In addition, the heat exchangers and stack (or regenerators) play important roles in conduction-driven thermoacoustic engines. However, they are costly and energy-consuming. Any means of eliminating these components would be highly beneficial in the design and manufacturing such thermoacoustic engines. This partially motivates present work.

In this work, a convection-driven Rijke-Zhao thermoacoustic engine coupled with a piezoelectric generator is designed and experimentally tested. This is described in Sec. II A. The Rijke-Zhao engine produces two different temperature thermoacoustic oscillations. One is “hot” and the other is close to ambient temperature, which enable the application of piezoelectric generator to convert heat into electricity via sound. The performance of the present energy-harvesting system is evaluated and compared with the conventional conduction-driven one.⁴ This is described in Sec. II B. In order to gain insight on the generation of dual-temperature thermoacoustic oscillations, two-dimensional numerical simulations are conducted, as described in Sec. III. Comparison is then made between numerical results and experimental ones. Good quantitative agreement is obtained in terms of the pressure spectrum generated by the unsteady heat release.

II. EXPERIMENTAL EVALUATION OF THE CONVECTION-DRIVEN ENERGY HARVESTER

A. Description of experiment

In order to explore an alternative system for harvesting thermal energy, a convection-driven Rijke-Zhao thermoacoustic engine is developed. The Rijke-Zhao prime mover as shown in Fig. 1 has a mother tube (bottom stem), which splits into two or more bifurcating daughter tubes (i.e., upper branches) with a diameter of 4.5 cm. The angles between the two branches are 30°. The lengths of the branches are 0.5 and 0.9 m, respectively. As a heat source (such as flame or solar heater *et al.*) is placed inside the mother tube, it provides a mechanism to produce convection-driven oscillations. However, unlike traditional Rijke-tubes, the unique

FIG. 1. Schematic of convection-driven Rijke-Zhao thermoacoustic-piezoelectric conversion system.

structures and geometric configuration of Rijke-Zhao tube with two bifurcating branches result in “cold” air being sucked in the upper short branch and joining the hot flow from the mother tube and finally blowing out through the upper longer branch.²⁴ Such heat-driven large-amplitude sound can be used for many purposes.¹ For convenience, however, the Rijke-Zhao prime mover is coupled with a piezoelectric generator to demonstrate harvesting thermal energy by converting it into electricity.

Fig. 1 illustrates the schematic of the convection-driven Rijke-Zhao prime mover. The piezoelectric generator is attached to one end of the bifurcating tube. A laminar pre-mixed flame anchored on the top of a Bunsen burner is placed at 11 cm away from the open end of the mother tube. T-shaped junctions protruding from both the upper branches are designed for placing sensors or transducers. To measure pressure fluctuations along the Rijke-Zhao prime mover, two arrays of B&K microphones (Type 4794) are implemented: one array consisting of 4 microphones is applied to the longer upper branch, the other 3 microphones attached to the shorter branch. The measurements are shown in Fig. 2.

FIG. 2. Measured pressure fluctuations and their pressure spectra of a Rijke-Zhao thermoacoustic system.

It can be seen that there are thermoacoustic oscillations in both bifurcating branches, and the maximum pressure oscillation can reach about 137 dB. The dominant mode in Rijke-Zhao tube is at around 176 Hz, and it has several harmonics. This frequency corresponds to the fundamental mode with a wavelength twice of the total length of the bottom stem and the upper longer branch. Furthermore, the “oscillating” nature of thermoacoustics in bifurcating tubes is confirmed via direct measurement by using a hot wire anemometer (HWA), as shown in Fig. 3. All these experimental measurements indicate that the Rijke-Zhao prime mover is a reliable system to produce self-sustained thermoacoustic oscillations, which can be used for energy harvesting.

The temperature distribution in upper bifurcating tubes is measured by using an infrared camera. It captures the quartz tube surface temperature spectrum. However, it can represent the “hot” status of the flow inside each branch. The camera is set to operating range of 0° to 500 °C. Fig. 4 shows the temperature measurements by using the infrared camera. It can be seen that the surface temperature of the short branch is around 25 °C, indicating that the air flow temperature inside the branch was very close to room temperature. To further validate the temperature measurement, two arrays of K-type thermocouples are placed side by side to the microphones. The measured gas temperatures in the bifurcating tubes are summarized in Table I. It can be seen that the self-sustained oscillations result in a “hot” pulsating flow in the longer upper branch, while the shorter one is at ambient temperature. And this finding is consistent with that from our infrared camera measurements.

B. Performance of the convection-driven thermoacoustic-piezoelectric system

The thermoacoustic oscillations at ambient temperature in the shorter branch enable a piezoelectric generator to be implemented to harvest thermal energy. In our experiment, a piezoelectric diaphragm (Piezo Systems Inc. T216-A4NO-573X) made of lead-zirconate-titanate is used. It has diameter of 63.5 mm, thickness 0.41 mm, and capacitance of 107 nF at rated frequency of 290 Hz. Before attaching the piezoelectric

FIG. 3. Velocity oscillation measurements at 2 cm to the exit of the upper short branch of the Rijke-Zhao thermoacoustic system by using a hot wire anemometer.

FIG. 4. Temperature measurement by using an infrared camera.

membrane²¹ to the end of the upper short branch as show in Fig. 1, it is tuned to maximize its electricity output by adding an aluminum disc-plate weighing 2.85 g at the center of the membrane. The performance of the convection-driven Rijke-Zhao thermo-acoustic engine coupled with the piezoelectric generator is shown in Figs. 5 and 6. Comparison is then made between our results and those from Smoker *et al.*⁴

It can be seen from Fig. 5 that tuning the resonant frequency of the piezo generator can significantly increase the electric power output. Fig. 6(a) shows that our present system generates 60% power more than the conduction-driven standing-wave engine with the same piezoelectric generator used. Fig. 6(b) shows the variation of the output power scaled with the cross-sectional area of the tube. The maximum output power per unit area is about 1277 mW/m², which is approximately 294% more than that from the convectional conduction-driven thermoacoustic system as reported by Smoker *et al.*⁴ Finally, the overall efficiency of converting input thermal power into output electrical power of conduction-driven system as designed by Smoker *et al.*⁴

TABLE I. Temperature measurement by using K-type thermocouples along Rijke-Zhao thermoacoustic system.

K-type thermoacouple	Temperature (K)
Sensor 1	434.25 ± 2.0
Sensor 2	442.75 ± 2.0
Sensor 3	453.25 ± 2.0
Sensor 4	463.45 ± 2.0
Sensor 5	300.85 ± 2.0
Sensor 6	300.85 ± 2.0
Sensor 7	301.65 ± 2.0

FIG. 5. Measured voltage from the piezoelectric membrane with varying resistance.

was shown to be about 0.00028%. In comparison with our present system, it is approximately 60% lower. However, the overall efficiency is much lower than the theoretical Carnot efficiency $\eta_c = 52.8\%$. It is calculated by using Bunsen burner temperature T_b and the environmental temperature T_a via $\eta_c = 1 - \frac{T_a}{T_b}$. The lower efficiency is most likely due to the hot flow and oscillations not being utilized.

III. NUMERICAL SIMULATION OF HEAT-DRIVEN THERMOACOUSTIC OSCILLATIONS

In order to simulate the experiments and to gain insight on the heat-driven acoustic characteristics in Rijke-Zhao engine, 2D numerical simulations by using ANSYS Fluent 13 are conducted. Since only natural convection is involved in our experiments, we set the boundary conditions of the

FIG. 6. Comparison of measured power output from the piezoelectric membrane with varying resistance.

experimental setup in the model to be acoustically open. The mesh of the Rijke-Zhao tube is generated by using Pointwise as shown in Fig. 7. For simplicity, the flame used as heat source in our experiment is replaced with an electrical heater consisting of 6 heating bands in our model.

The pressure of the gas mixtures in the system under consideration is always low enough to justify the assumption of the perfect gas laws. Thus, if $p = p_0 + p'$ the instantaneous pressure, T the temperature $\rho = \rho_0 + \rho'$ the density, M_w the molecular weight, and R the universal gas constant,

$$\frac{p}{\rho} = \frac{R}{M_w} T. \quad (1)$$

It is worth noting that the instantaneous parameters, such as pressure, density, acoustic velocity etc. consist of a mean and a fluctuation part, which are denoted by a subscript 0 and a prime, respectively.

The time-dependent evolution of the flow disturbances is modeled by solving the unsteady incompressible Navier-Stokes equations together with state equations for ideal gas and appropriate boundary conditions. The flow is assumed to be two-dimensional and laminar. The state-of-the-art CFD code employs a control volume based finite difference method to solve the unsteady conservation equations of mass, momentum, and energy as given as

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0, \quad (2a)$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}, \quad (2b)$$

$$c_p \frac{\partial(\rho T)}{\partial t} + c_p \frac{\partial(\rho u_i T)}{\partial x_i} - \frac{1}{\rho} \left(\frac{\partial(p\rho)}{\partial t} + \frac{\partial(\rho u_i \rho)}{\partial x_i} \right) = \frac{\partial}{\partial x_i} \left(\lambda \frac{\partial T}{\partial x_i} \right) + \tau_{ji} \frac{\partial u_j}{\partial x_i}, \quad (2c)$$

where

$$\tau_{ji} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2\mu}{3} \frac{\partial u_k}{\partial x_k} \delta_{ji}, \quad (3)$$

δ_{ij} is the Kronecker delta function. When $i = j$, $\delta_{ij} = 1$. Otherwise $\delta_{ij} = 0$. μ is the dynamic viscosity, and λ is the coefficient of heat addition to the fluid particle.

FIG. 7. Geometry and mesh grid for the Rijke-Zhao thermoacoustic engine.

The molecular weight M_w , the specific heat c_p , and viscosity η of the fluid are those of air at 290 K. The thermal conductivity is chosen to be $\lambda = 0.24$ W/mK to obtain a sufficient heat input from the heating element even though only six heating bands are used. This enables the use of a coarser computational grid and thus reduces the computational cost. The surface temperature of the heating bands is set and keeps constant at 1500 K. Under steady conditions, these assumptions lead to a temperature rise of the fluid from 290 to 1000 K. The total heat flux of the heating band is calculated as

$$\dot{Q} = \sum_{i=1}^N \dot{Q}_i, \quad (4)$$

where $\dot{Q}_i$ is the heat flux from the i th element of the heating band. And it can be determined by using

$$\dot{Q}_i = \lambda \frac{T_s - T_c}{\Delta d} A_s, \quad (5)$$

where T_s is the temperature of the heater surface, T_c is the local fluid temperature in the center of the fluid cell, A_s is the area of the contact surface, and Δd is the distance between the cell center and the hot surface.

A steady solution is first found as the initial condition for unsteady tests with a time step size 1.0×10^{-4} s, as shown in Fig. 8. The boundary conditions according to our experiments are: the open ends of the mother tube and long upper branch are set to pressure inlet and outlet, respectively. The short upper branch is set to be partially open. The gauge pressures at the mother tube and short branch end are set as 0.07 and 0.02 Pa, respectively. The resulting Reynolds number is less than 1200, which ensures that the flow in thermoacoustic system is laminar one. The tube wall is assumed to have a convection heat loss to the ambient with a heat transfer coefficient of 20 W/m²K. The air is considered to be

FIG. 8. Temperature contour (a) and velocity vector contour (b) in the Rijke-Zhao thermoacoustic system.

FIG. 9. (a) Heat-driven thermoacoustic oscillation, and (b) frequency spectrum of the limit cycle.

ideal gas with constant values for all air properties. A second-order implicit formulation in time integration is performed for unsteady simulation. In order to trigger thermoacoustic oscillations, small flow disturbances are initially introduced to the pressure outlet at the open end of the upper longer branch for 10 time steps and then set to 0 pa.

Fig. 9(a) shows time evolution of the thermoacoustic oscillations generated by the heating bands. The dominant mode is around 167 Hz, and the sound pressure level is approximately 133 dB, as shown in the frequency spectrum graph Fig. 9(b), which are in quantitatively good agreement with our experimental measurements. The discrepancy is most likely due to end correction effects.⁸

IV. DISCUSSION AND CONCLUSIONS

In summary, we demonstrate the feasibility of energy harvesting by using a Rijke-Zhao thermoacoustic engine, providing a simple but reliable system on which to produce self-sustained thermoacoustic oscillations at two different temperatures. However, our present system is a convection-driven one, which is different from the conventional conduction-driven standing- and travelling-wave systems.^{1,4,16} Furthermore, it does not involve using any heat exchanger and stack. Thus, our prime mover is much simpler in design and lower cost in fabrication. If the present system is used to drive a thermodynamic process via the produced large-amplitude sound waves instead of mechanical pistons, for example, for cooling purpose, then it involves no moving part. And there will be no structural fatigue problem, typically found in conventional Stirling engines.¹

For demonstration purpose, the present thermoacoustic system is coupled with a piezoelectric generator for energy harvesting. The preliminary experimental results show that the convection-driven system can generate 60% more power than the conventional conduction-driven standing-wave thermoacoustic system.⁴ When the output power is scaled with the cross-sectional area of the tube, the maximum power output per unit area from our present system is approximately 1277 mW/m², which is about 294% more than that

as reported by Smoker *et al.*⁴ These results confirm that the convection-driven Rijke-Zhao thermoacoustic system provides an alternative energy conversion approach to the conventional conduction-driven thermoacoustic engines.

The present system has the potential to be applied in drying industry, which is currently exploited.^{22,23} It is more energy-efficient than conventional thermal engine. This is due to both large-amplitude “hot” and “cold” pulsating flows dramatically enhance the heat transfer rates and so the drying rates. In order to gain insights on the generation mechanism of the thermoacoustic oscillations in the present energy-harvesting system, 2D numerical simulations are conducted. Comparing the numerical results with the experimental one reveals that good quantitative agreement is obtained.

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