

Self-Excited Combustion Instability in Rijke-Zhao Tube with Bifurcating Branches

Zhiyuan Zhong and Dan Zhao

Abstract—Combustion instabilities are caused by a coupling between unsteady heat release and acoustic pressure waves, which is characterized by large amplitude pressure oscillations. In this work, combustion instability in a Rijke-Zhao tube is considered. It has a mother tube (bottom stem), which splits into two bifurcating daughter tubes (i.e. upper branches) with different lengths. As a premixed laminar flame is placed inside the mother tube, it provides a mechanism to produce self-excited combustion oscillations (also known as combustion instabilities). In order to investigate the Rijke-Zhao combustion instabilities, 2D numerical simulation of two different configurations of Rijke-Zhao tube by using Fluent 13.0 is conducted. Comparison is then made between numerical results and our experimental ones. Good agreement is observed.

Index Terms—Rijke-zhao tube, bifurcating branches, thermoacoustic oscillation, combustion instability.

I. INTRODUCTION

Combustion instabilities are caused by the interactions between unsteady heat release and acoustic waves [1-4]. For a given combustion system, when Rayleigh criterion is satisfied [1], unsteady heat release will amplify the pressure fluctuations which in turn increase the rate of the unsteady heat release. This feedback can result in the oscillation amplitude successively increasing, which is what is meant by a combustion instability. Eventually, some nonlinearity in the system will limit the amplitude of the oscillations. Whether or not an instability occurs depends on the nature of the coupling between the unsteady heat release and acoustic waves. A laboratory-scale setup used for demonstrating combustion instabilities is Rijke tube, in which a heat source is placed at bottom half. Due to its simple configuration, experimental and analytical studies are extensively carried out to understand the fundamental mechanism of Rijke-tube combustion instabilities[1-4].

Recent development of computational fluid dynamics (CFD) techniques promotes more and more numerical investigations conducted on self-excited combustion instabilities. Hantschk and Vortmeyer [5] used Fluent to study the non-linearity effect on combustion oscillations. The unsteady heat source is simulated by using heating bands. Thus an artificial temperature gradient is created in the tube. By imposing an initial pressure disturbance at the boundaries, self-excited combustion oscillations and higher harmonics are generated. It showed that both the predicted frequencies and mode shape agree with the experimental results well. Instead of using time-varying heat source or instability triggering method, Chatterjee et al [6] simulated the reacting

flow in Rijke tube and studied the spectral characteristics of the combustion instabilities. Validated by the experimental results, their numerical model is found to be able to capture the reacting flow physics and provide a tool to investigate the interaction between combustion and pressure oscillation. Similar CFD investigations of combustion instabilities can be found in the works [7-9].

In this work, self-excited combustion instability in Rijke-Zhao tube, which has a mother tube splitting into two bifurcating branches, is considered. Unlike the conventional straight Rijke tube, Rijke-Zhao tube is associated with dramatically different flow fields, and resulting combustion instabilities. Experiments are first conducted to examine the flow characteristics, and the amplitude and frequency of the combustion oscillations. This is described in Sect. 2. 2D numerical simulations are then conducted to simulate experiment by using ANSYS Fluent 13.0 [10]. This involves investigations of two configurations of Rijke-Zhao tubes, as described in Sect. 3.

II. EXPERIMENTS

A. Experimental Setup

The Rijke-Zhao tube made of quartz glass, as shown in Fig. 1, is designed and experimentally tested. It has a mother tube which splits into two bifurcating daughter tubes with different lengths. On each daughter tube, a T-shaped section connecting to the tube is designed for placing the microphone to measure the pressure. A Bunsen burner is placed in the mother tube with propane used as fuel. A metal gauze was anchored on the top of the flame-holder to increase the heat transfer. Therefore the thermal-diffusive instability defined by Chatterjee [6] is enhanced, moving the flame sheet forth and back from the gauze and resulting in a change of heat release rate which is used to trigger combustion instabilities.

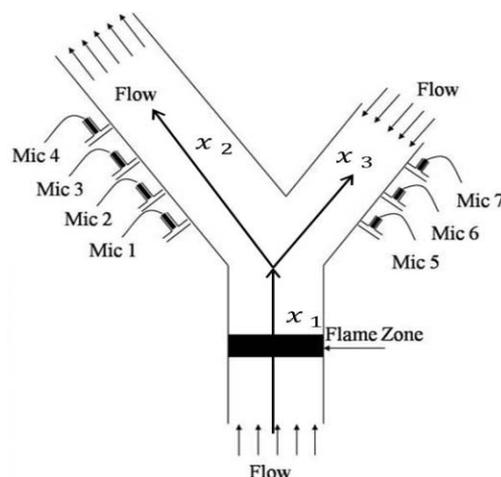


Fig. 1. Schematic of Rijke-Zhao tube.

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B. Flow Characteristics

Unlike conventional straight Rijke tube, where the flow direction is predictable, the structure of Rijke- Zhao tube with two bifurcating branches are associated with 3 different potential flow patents: (a) hot air flowing into both bifurcating branches, (b) cold air being sucked in the upper short branch and joining the hot flow from the mother tube and finally flowing out through the upper longer branch (c) cold air being sucked though the upper longer branch and joining the hot flow from the mother tube and finally flowing out through the upper shorter branch. It is worth noting that such flow patents determine the temperature distribution along the bifurcating branches. Fig. 2 is our experimental measurement of temperature along the bifurcating branches by using an infrared camera. It can be seen that the maximum temperature occurred in the mother tube near flame location. And the average temperature is about 60 °C along the upper longer branch, while the temperature is approximately 27 °C along the shorter branch. The experimental measurement means that only flow patent (b) is naturally selected, when combustion instability occurred in Rijke-Zhao tube. Detailed analysis can be found in the work [12].

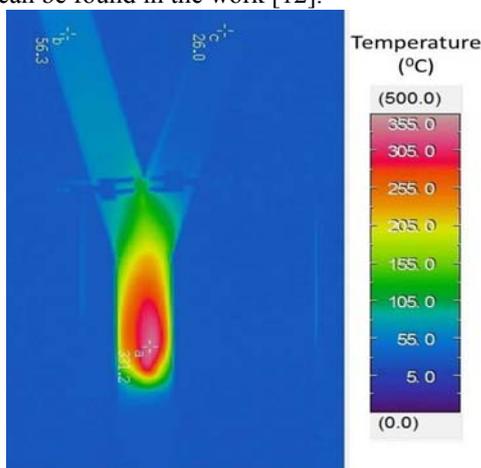


Fig. 2. Measured infrared image..

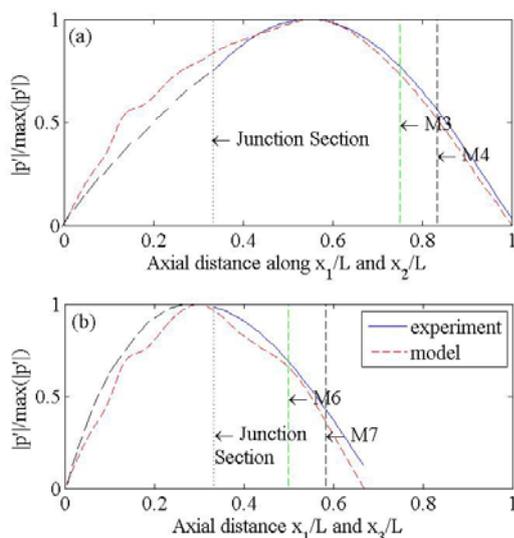


Fig. 3. Experimental measured mode shape along rijke-zhao tube.

C. Acoustic Characteristics

When combustion instabilities occurred in Rijke-Zhao tube, the frequency spectrum of the pressure measurement is measured, as shown in Fig. 5(b). It can be seen that the

fundamental mode is around 175 Hz and the maximum sound pressure level approximately 133 dB. Harmonic modes are also observed. In order to measure the mode shapes along the bifurcating branches, two-microphone technique [2] is applied, as shown in Fig. 3. Pressure nodes are found at the open ends of the bifurcating branches, as expected.

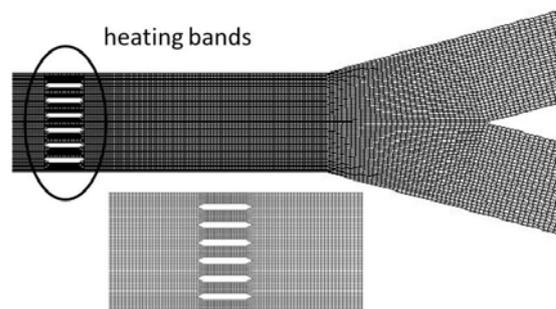


Fig. 4. Geometry and mesh grid for the rijke-zhao tube.

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III. 2D MODELING OF RIJKE-ZHAO TUBE COMBUSTION INSTABILITY

A. Configuration 1: Acoustically Open Inlets and Acoustically Open Outlet

In order to simulate the experiments and to gain insight on the flow and acoustic characteristics of Rijke-Zhao tube, 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 Rijke-Zhao tube in the model to be acoustically open. The mesh of the Rijke-Zhao tube is generated by using Pointwise as shown in Fig. 4. 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.

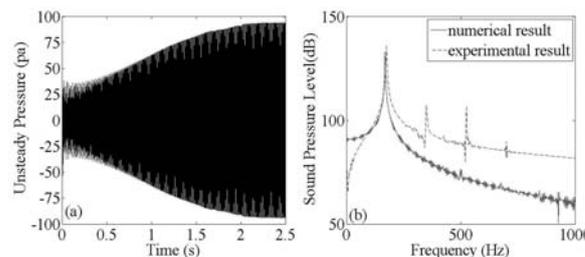


Fig. 5. (a) Unsteady pressure signal and (b) Frequency spectrum of limit-cycle.

A steady solution is first found as the initial condition for unsteady tests with a time step size 1e-4 s. The boundary conditions according to our experiments are: the open ends of the mother tube and short upper branch are set to pressure inlet and the long upper branch pressure outlet. The heating bands are assigned a surface temperature at 700 K which is closed to the temperature of the metal gauze in our experiments. The gauge pressure at mother tube and short branch end is set as 0.07 pa and 0.02 respectively. The resulting Reynolds number is less than 1200, which indicates the flow in Rijke-Zhao tube 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 assigned. The air is

considered to be ideal gas with constant values for all air properties.

A second-order implicit formulation in time integration is performed for unsteady simulation. A small initial disturbance $\Delta p = 100 \text{ pa}$ is initially assigned to the pressure outlet at the open end of the upper longer branch for 10 time steps and changes to 0 pa after that in order to trigger the combustion instabilities. Fig. 5(a) shows time evolution of the flow disturbances. The dominant mode is around 170 Hz and the sound pressure level is approximately 126 dB, as shown in the frequency spectrum graph Fig.5 (b), which are closed to our experimental measurements. The discrepancy is most likely due to end correction effects [2]. Fig. 3 shows the comparison between the predicted and measured mode shapes along the bifurcating branches [13]. Good agreement is observed.

B. Configuration 2: Acoustically Closed Inlets and Acoustically Open Outlet

The foregoing simulations is concerned with natural-convection-driven combustion instabilities in Rijke-Zhao tube. Now we consider another case. The mother tube and upper short branch ends are set to be velocity inlet at 0.1 m/s and 0.05 m/s respectively at a Reynolds Number smaller than 1000. This means that the boundary condictionation are acoustically closed. The upper long branch end is pressure outlet. The surface temperature for the heating bands is set as 1000 K. For steady calculation (see Fig. 6), the second order scheme for pressure interpolation and spacial discretization is chosen and PISO is used for pressure-velocity coupling. The thermal conductivity is chosen as 0.242 to use coarse mesh and reduce computational cost[5].

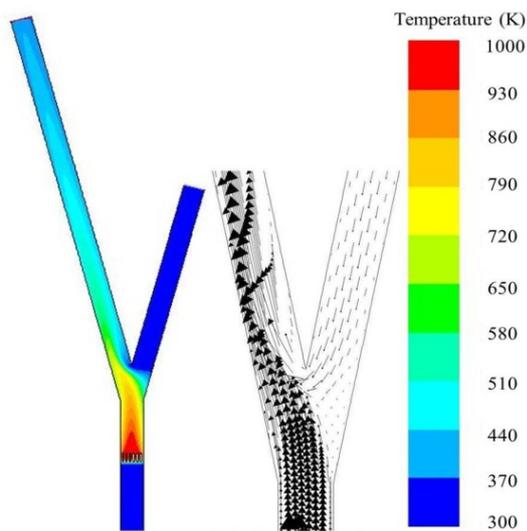


Fig. 6. Temperature contour and flow vector field.

Based on a steady solution, the unsteady simulation for this acoustically closed-inlets and open-outlet configuration is performed. The time step size is chosen as $2e-5$. Fig. 7 illustrates the time evolution of the flow disturbances and its frequency spectrum. It can be seen that a limit cycle with a frequency of 781 Hz and sound pressure level of 137 dB is generated.

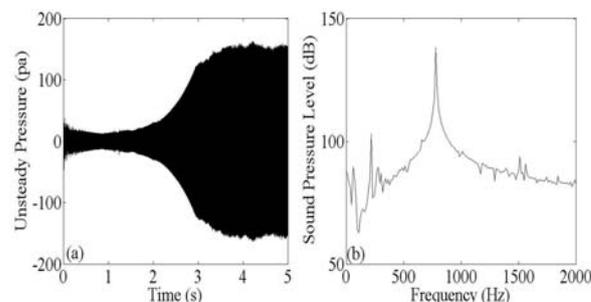


Fig. 7. (a) Predicted pressure fluctuation and (b) It's frequency spectrum.

Fig. 8 illustrates the mode shapes along the Rijke-Zhao tube. It is worth noting that the dominant mode is corresponding to the eight-quarter of the wavelength. Such high-frequency unstable mode is difficult to produce, due to the larger damping associated with the combustion instability. Comparing Fig. 8 and Fig. 3 reveals that self-excited combustion instabilities can be triggered in Rijke-Zhao tubes with different boundary conditions. However, such boundary conditions give rise to combustion stabilities with different characteristics, and different flow and temperature fields in the bifurcating branches.

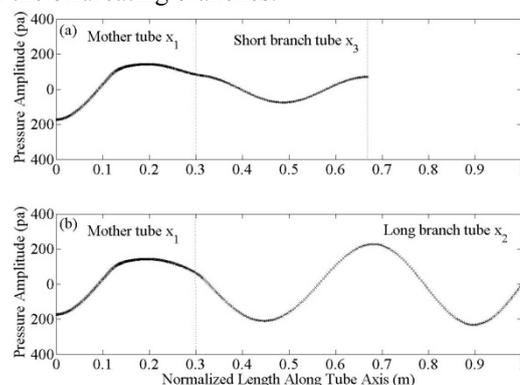


Fig. 8. Mode shapes along Rijke-Zhao tube bifurcating branches.

IV. CONCLUSIONS

The present work investigates self-excited combustion instabilities generated in a Rijke-Zhao tube with bifurcating branches. Unlike the conventional straight Rijke tube of which flow direction is predictable, this unique structure of Rijke-Zhao tube gives rise to three potential flow patents. However, our experimental measurement show that only one flow patent is naturally selected: ambient air being sucked in the upper short branch, joined the hot flow from mother tube and finally blew out through the upper longer branch. In order to simulate the experiments and to gain insight on the flow fields, 2D numerical simulations are conducted by using ANSYS fluent. Two configurations are considered. The first configuration follows our experimental setup. And the numerical results are found to agree with our experimental measurements well. Another configuration is chosen by setting the mother tube and the upper shorter branch ends to be acoustically closed, and the other one is acoustically open. Combustion instabilities at much higher frequency (781 Hz) is observed. This interesting result reveals that Rijke-Zhao tube can be used to trigger higher frequency modes, which is generally thought to be difficult to generate. Finally, this unique structure and the resulting flow characteristics in Rijke-Zhao tube has potential industrial applications.

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