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Study of thermoacoustic phenomenon in a rijke tube

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Abstract

Thermoacoustics is concerned with the interactions between heat (thermo) and pressure oscillations in gases (acoustics). A "Rijke Tube", named after its inventor, is a fundamental tool for studying thermoacoustic phenomenon. Rijke's tube turns heat into sound, by creating a self-amplifying standing wave. It is basically an open-ended tube with a properly placed heat source inside. To study the phenomenon a Rijke tube apparatus was designed and constructed with the facility to change the heat source position and the heat input of the source. Experiments were conducted by changing the heat input, the tube length and diameter. Effects of these parameters on the output sound level were studied. The heat source position was changed and the sound level was measured to estimate the optimal position of the heat source in Rijke tube and to compare it with Rayleigh's estimation. The input electrical power consumed by the heater and the output sound power was calculated. The conversion efficiency of sound power from heat input was calculated and found to be minimal. The focus of this paper is to quantitatively evaluate the performance of the apparatus designed and to explain the mechanism of thermoacoustic phenomenon in Rijke tube with the help of 'Rayleigh's criterion'.

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Keywords: Thermoacoustics; Rayleigh's Criterion; Rijke Tube; Pressure Oscillation; Sound Power (dB)

1. Introduction

Sound wave consists of compression (condensation) and expansion (rarefaction). At the area of compression a temperature rise occurs while at rarefaction occurs a temperature drop. These temperature oscillations accompany

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the pressure oscillations and they combine to produce “Thermo-acoustic Effect”. So thermoacoustic devices can convert temperature gradient to acoustic waves or convert acoustic waves to temperature gradient. When pressure waves are being created it is a thermoacoustic engine and when a temperature gradient is being created it is a thermoacoustic heat pump. Although in everyday life, the thermal effects of sound are too small, in a pressurized gas, these thermoacoustic effects can be used to create powerful heat engines and refrigerators.

The Rijke tube can be a very cheap and convenient system for studying resonance and thermoacoustic phenomenon. A Rijke tube usually consists of an open-ended tube with a heat source inside. The heat source may be a flame or an electrical heating element. Normally, the tube is positioned vertically and the heat source is introduced from below. Mean flow is caused either by natural convection (in vertical tubes) or by external means (in horizontal tubes). For certain positions of the heat source, the Rijke tube emits a loud sound. This phenomenon was discovered by Rijke around 1850 [1], and is therefore called the Rijke phenomenon. In 1896, Lord Rayleigh in his “The Theory of Sound” explained this thermoacoustic phenomenon which is called Rayleigh’s criterion [2]. Putnam and Dennis [3] derived a heat-driven wave equation and Rayleigh’s criterion was verified. Raun et al. [4] gave a review of thermoacoustic devices, especially Rijke tubes discussing the experimental and analytical work on the Rijke tube.

This paper discusses the typical structure of a Rijke tube and explain the thermoacoustic phenomenon behind it and the “Rayleigh’s criterion” with experimental results and discussions. This can lead to better understanding of thermoacostics which can lead to creation of better Thermoacoustic engines (TAEs) and refrigerators (TARs) which can be a great alternative to conventional systems. Study on Rijke tube and other thermoacoustic devices has already led to the invention of new kinds of thermoacoustic engines and refrigerators. Swift [5] implemented these studies to create practical thermoacoustic devices. Scott and Swift [6] discussed different types of thermoacoustic engines, Standing wave engine, travelling wave engine and cascaded standing and travelling wave engine. Rijke tube also provides a convenient system for studying ‘buzzing’ problems in jet and rocket engine combustors.

2. Experimental setup and procedures

A cheap and easy-to-build Rijke tube setup was built. In order to perform experiments some mechanisms were incorporated to vary various parameters such as position of the heater inside the tube, amount of current through the heater etc. The setup facilitated the possibility for precise control of the main system parameters in wide ranges, e.g. heater location and heating power released. The components are shown in the following figure:

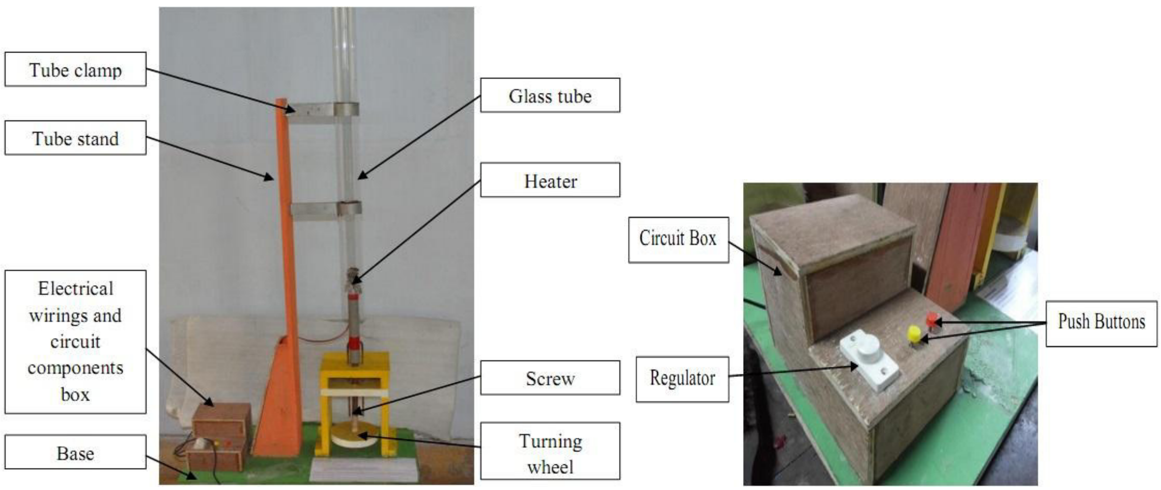

Fig. 1. Pictorial view of (a) the Rijke tube setup; (b) Electrical wirings and circuit component box.

The main components of the Rijke tube were as follows:

- Glass tube: Inside this tube the standing sound wave was generated.
- Heater: The heat source which initiates and reinforces sound, taken out from a cheap hair drier.
- Screw: Enabled up and down motion of the heater inside the tube.
- Turning wheel: Wooden structure that assisted in rotating the screw.
- Electrical wirings and circuit components box: This box contained the circuit and the wirings. The circuit contained a microcontroller to control the time of current input by means of two push buttons and a regulator to vary the current.

After the setup was built, the sound power, temperature of air and the heater was measured for different input current and thus different power. Then the sound power output was calculated by using the logarithmic rule and the power output was found to be very low compared to the heat input. This explained the low efficiencies of the thermoacoustic devices.

3. Rijke tube sounding mechanism and Rayleigh's criterion

Rijke explained [1] that the heat source transferred heat to the air in the tube, making the air to rise up, creating a upward flow. The rising hot air becomes dense by coming in contact with the cooler walls of the upper half of the tube. So in the lower half air always experienced expansion, while in the upper part air always experienced compression. But this explanation was not good enough for the full understanding of the phenomenon. Placing the heat source near the lower end of the tube leads to creation of a standing wave with nodes (N) and antinodes (A) as shown in Fig. 2 [7].

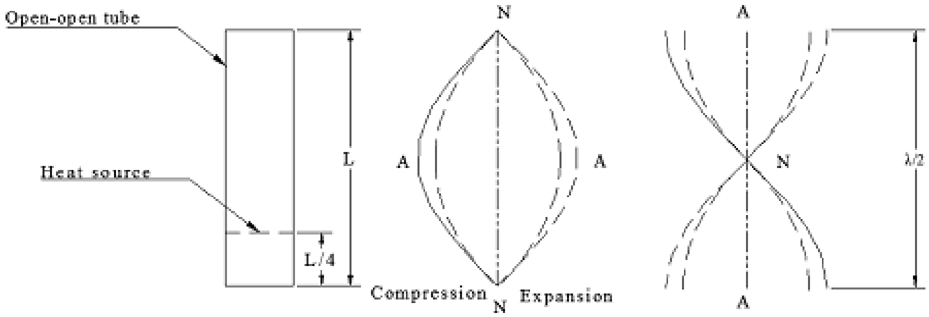

Fig. 2. Pressure oscillation and velocity (change of displacement) oscillations in Rijke tube [7].

So actually the air in the tube experience alternate compression and expansion. But without the energy source the acoustic waves will damp out. So, the energy source not only excites acoustic waves in the tube but also sustain the already excited acoustic waves (unlike Rijke's explanation). Lord Rayleigh explained how acoustic waves could be excited and sustained by heat addition in his "The Theory of Sound". He stated, "If heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged." [2] According to this the heat given to the wave over one part of the cycle is more than that over the other part of the cycle. So the net heat transfer from the source can be divided into two parts, mean heat transfer $\overline{q}$ and time-varying heat transfer q' as shown in Fig. 3 [7]. $\overline{q}$ creates the mean convective flow upwards while q' drives the acoustic wave. For half the cycle, the air flows into the tube from both ends until the pressure reaches a maximum and for the other half cycle, air flows outwards until the pressure is minimum. So for one half cycles the heat source comes in contact with fresh air, enhancing heat transfer. In the other half cycle, the heat source is surrounded by preheated air, which reduces the heat transfer in this half of the acoustic cycle. If the mean flow is stopped, heat transfer between the air particles and the source stops after a few oscillations. So if heat is added during the compression half cycle or removed during the expansion half cycle, then the acoustic waves is sustained.

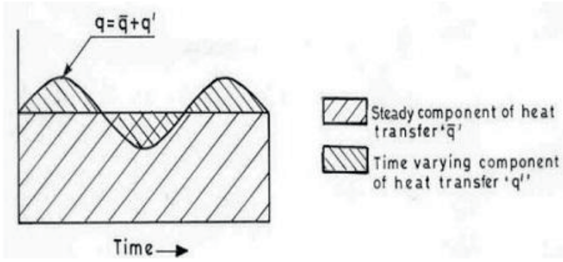

Fig. 3. Heat transferred to air flow past the heat source at various time [7]

Now when the source is in the upper half of the tube, the cool air coming by the convection current reaches the source immediately before the lowest pressure. So the increase in pressure due to the heat transfer tends to cancel out the sound wave instead of reinforcing it. Now as most of the heat is transferred to the air at the end of the tube but the effect of increasing the pressure is greatest in the middle of the tube, the source should be midway between these two positions for highest sound output (one quarter of the length from the bottom end).

4. Experimental results and discussion

Using the setup built some experiments were performed by varying a number of parameters to observe the change in the generated sound level. The experiment mainly dealt with measuring the sound level with some predetermined values of those parameters. For most of the experiment a glass tube of .71 meter length and .05 meter diameter was used and heating source was at the optimum position (one quarter of the length from the bottom end).

4.1. Variation of air temperature with current and sound level with current and heater temperature

From Fig. 4a it is observed that the air temperature has an increasing trend with the increase in current. From Fig.4b it is observed that the sound level also has a similar trend with current and heater temperature. This trend is as expected and conforms directly to the underlying mechanism since increasing current through the coil implies providing more heating to the system, more heat means greater reinforcement of the standing wave at every cycle. Greater energy input increases the intensity of the generated sound and this would result in greater sound level.

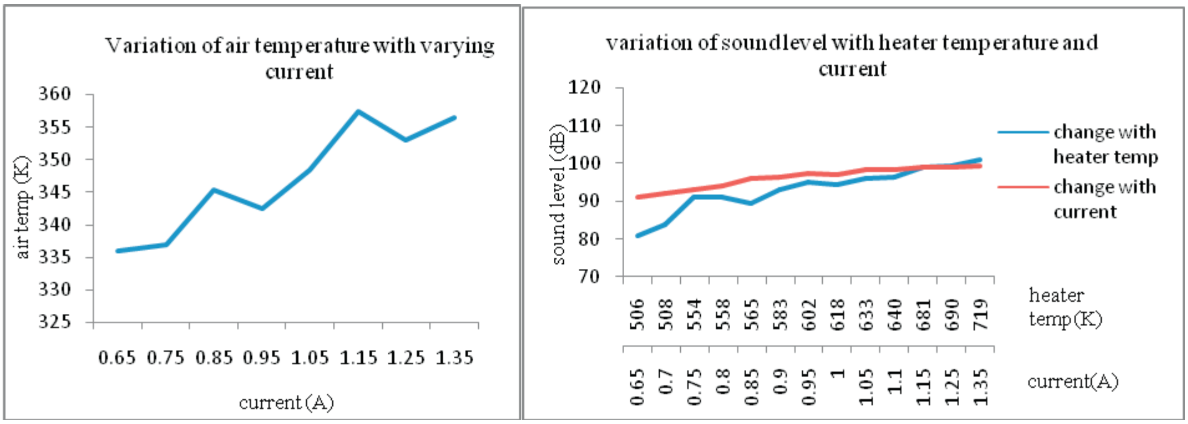

Fig. 4. (a) variation of air temp with varying current; (b) variation of sound level with varying heater temperature and current.

4.2. Variation of sound level with input power

From Fig. 5a and Fig. 5b it is observed that the sound level increases with the input current, as well as input power (because power increases as current increases). But it is also seen that for .55 Amp and 40.8 Watts there was no sound and in practice it is quite expected to have a threshold value for the generation of sound. Under this threshold value the heat is too inadequate to initiate enough variation in pressure inside the tube (initiate the sound wave) and reinforcing the pressure wave in every cycle. That is why figure 5(a) and 5(b) shows a sharp slope after this threshold value.

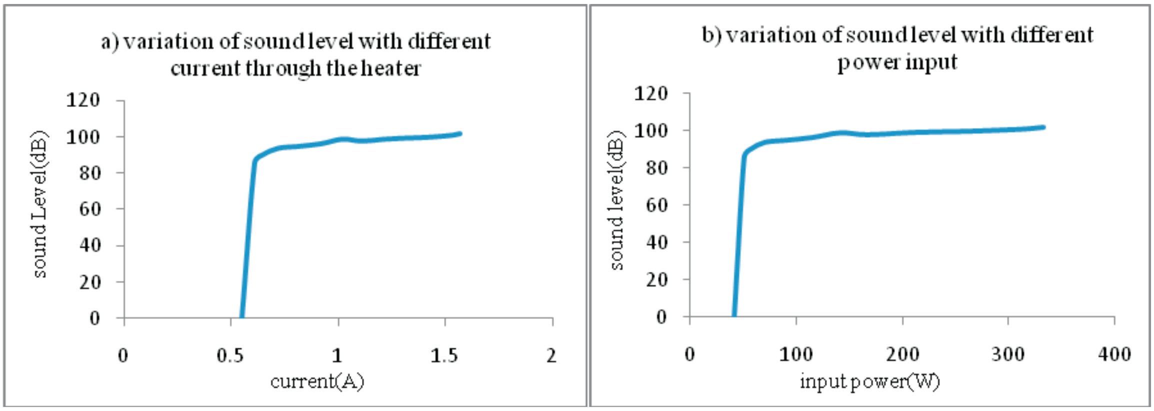

Fig. 5. variation of sound level with (a) different current through the heater; (b) different power input.

4.3. Experiment to find the optimum position of heater

From Fig. 6 it is observed that the sound level first increased with the heater being moved from the bottom end of the tube towards the upper region, until the heater was at a position where sound level was maximum, after that the sound level started to decrease. From the theory, for .71 meter tube, optimum position of the heater should be around .18 meter from the bottom end. Since the heater in this setup was almost .05 m in length, it can be assumed that its middle point was well within the .18 meter mark. So the experimental data supports the underlying theory.

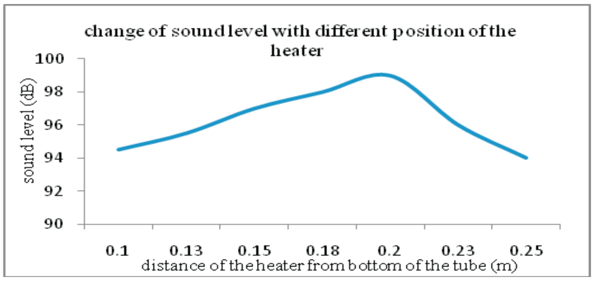

Fig. 6. change of sound level with different position of the heater inside the tube.

4.4. Variation of sound level with different tube length and diameter

The first experiment was done with a .056 meter diameter plastic tube. The plastic tube was used in this experiment so that it could be cut to change the length of the tube. If Fig. 7 is observed, it is seen that there lies an optimum length of the tube for which the sound generation will be maximum for a given setting of other parameters. Also the graph suggests that there is a minimum length for which the tube produces sound. Because when the length decreases the tube has less variation in temperature along its length. Since temperature gradient along the pipe length plays a pretty important role in generating the sound wave, with too much decreased length of the pipe the sound ceases. If the pipe length is decreased too much then the entire pipe will get hot and there will not be enough temperature gradient for the sound to generate.

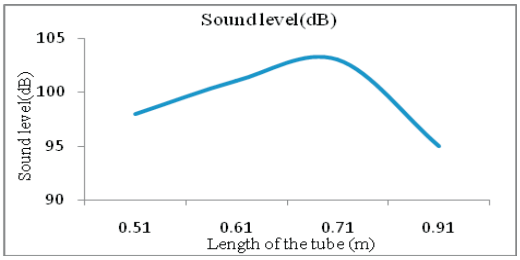

Fig. 7. sound level with tube length

The second experiment was done with a pipe of .084 meter diameter. As it can be seen from Table 1 that there is no sound when the pipe diameter is increased. Even changing the length of these tubes had no effect on this pipe. In this case the heating source might be too inadequate in terms of heating the bulk of air inside the tube in such a way as to produce a sound wave.

Table 1. Sound level for .084 diameter pipe.

Length of the pipe (m)	Sound level(dB)
.91	No sound
.71	No sound

5. Conclusion

The Rijke tube setup was built for controlling the main system parameters (e.g. heater location and heating power released) in wide ranges. The performance of the designed apparatus was evaluated and compared with the Rayleigh's estimation for a better understanding of the underlying thermoacoustic effect occurring within the Rijke tube setup. The setup was capable of producing sound at a level of 94-102 dB. The experiments yielded that high heating and hence high temperature resulted in sound with more intensity but this variation had a non linear approach.

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