Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 6, June 2021:197-209

Research Article

Experimental Analysis on Basic Combustion Instability using Rijke Tube

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Abstract

Thermoacoustic instability has been a significant design issue in liquid rocket engines and gas turbine engines, unsteady heat discharge sometimes gets in phase with pressure perturbations. It is essential to study and understand these instabilities so that they can be controlled or can be used to develop something that uses instability to its benefit. A Rijke Tube is a simple and inexpensive experimental setup, designed and developed for research and to study the fundamental mechanism of thermoacoustic instability. The Rijke tube represents resonating chamber with free airflow and a heat source just like a typical combustion chamber. At some higher gain value, a loud noise observed, representing thermoacoustic instability. This work focuses on designing and developing an experimental setup to perform experimental analysis by introducing a signal using a microphone and speaker. Different thicknesses of coils will be used to study how stabilization time and temperature vary. Each coil is positioned at two different positions to understand the variation in stabilization time. A comparison study is done to understand the variations stated above.

Keywords: *Combustion instability, Thermoacoustic instability, Rocket engines, Gas turbine engines, Resonating chamber, Combustion chamber, Signal, Stabilization time*

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Introduction

Since humankind has been developing propulsion systems, they are usually designed based on steady-state analysis rather than instability analysis. In most conditions, we end up designing an engine, where combustion can go unstable, i.e., engine develops significant levels of vibration and sound and creates many problems and may also lead to the destruction of the engine or sometimes failure of the whole mission. This instability is called combustion instability. Combustion instability is a consequence of interaction between flame, the flow, acoustics created, and the combustion chamber's oscillations.

It generally occurs in rocket engines and is rarely seen in gas turbine engines. It can most probably occur in ramjet and scramjet engines. It is so bad that even 1% or 2% oscillations result in about 1 bar loss in pressure. Combustion instability leads to severe vibration of the whole aircraft, cracks the fasteners that hold the engine, vibrations loosen the components. We can also see huge power loss, high unwanted heat transfer, thrust oscillations and thrust oscillations. In general or ideal condition, when compressed air exits the compressor and enters combustion chamber, fuel has to be sprayed equally at all points and is to be combusted at the same time at all the points. But this is not true in real conditions. In reality fuel is not sprayed equally at all the points. Some points in air might have more amount of fuel sprayed and some may have less quantity sprayed at them. Due to this, combustion too will happen rapidly and more vigorously at these points, causing heat and pressure differences in the combustion chamber.

The consequence of these differences is that a sequence of compression and expansion waves are formed. This is the definition of sound production. This sound travels all around the combustion chamber in longitudinal and transverse directions causing disturbances and hits the walls of combustion chamber.

Now, this disturbance happens continuously and causes changes the flame kinematics. Combustion starts getting more and more unstable. Combustion also adds energy to this acoustic field and gets in phase with pressure fluctuations. Heat is now added according to these fluctuations and the oscillations keep increasing. When these frequency levels of the sound produced comes in phase with natural frequency with combustion chamber, vibrations are formed. These vibrations increase at a nonlinear rate and lead to all the problems discussed above. It is a massive problem in aerospace industry and the best examples where this problem was experienced are The V2 Rocket and Rocketdyne F1 Engine in Saturn V.

1.1 Thermoacoustic Instability

Thermoacoustics is defined as the interaction between density of the fluid, temperature and pressure variations of acoustic waves. The instability caused to this interaction is known as thermoacoustic instability.

The sound wave that are formed (as discussed earlier) go and hit the walls, come back and starts to disturb the flame and also affect the flow of the air fuel mixture. This leads to nonlinear increase in instability. Combustion during such flow just adds energy to the fluctuations. Thermoacoustic oscillations have been observed from centuries. Glass blowers while working produced heat generated sound when blowing a hot bulb at the end of a cold narrow tube.

Thermoacoustic instabilities play a very important role in various technologies now a day. This is seen in the lean premix pre vaporize burners which is used in gas turbine engines to reduce NOx emissions. This would affect the flame propagation and tend to be unstable at the lean limit, and its coupling with combustor acoustics may give rise to combustion instability. This is a major problem and an active research topic in modern gas turbine industry. Rocket engines are mainly vulnerable to combustion instability particularly thermoacoustic instability. The pressure perturbations and flow oscillations inside the engine can lead to intolerable levels of vibration and enhanced heat transfer that would reduce propulsive efficiency, and damage or even destroy the system. This kind of instability causes huge amount of problems in terms of performance and safety of the mission.

P.L Rijke designed a simple experiment to study the thermoacoustic oscillations and since then many modificattions have been done to the original setup in order to study various factors using modern technology. Various researchers and scientists proposed many explanations and gave many theorems to explain the mechanism and the reason of occurrence.

1.2 Rijke Tube

Thermoacoustic instability is complicated phenomenon to study. Rijke tube is classic, simple and inexpensive (relatively to other models) to build and is a convenient system for studying thermoacoustic instabilities both experimentally and theoretically. It can also be used to study dynamic coupling between heat transfer and acoustics. This experiment provides a simple stage where we can inspect the countless issues related to thermoacoustic instabilities.

This setup was developed in 1859 by P.L Rijke a professor in physics from Leiden University, Netherlands discovered a way of using heat to sustain a sound in a cylindrical tube open at both ends. He used a glass tube with a length of 80 cm and of 3.5 cm diameter. At about 20cm from the bottom, he placed a wire gauge. By placing the tube in vertical direction and by heating the gauge red hot and moving it away a loud sound is produced until the gauge is cooled down. This is only observed when the tube is held vertical, if it is made horizontal, sound would disappear. Sound would also disappear if the tube is held vertically reverse. It was reported that sound created by the original setup was heard for several rooms. Later various scientists started testing various materials and methods to record the sound levels. Rijke proposed that the air expansion near the grid and contraction at upper cooler section of tube causes sound.

A vertical tube type is used for this project. In this type the tube is held vertically with respect to the ground with a gauge or heating coil placed at the lower position in the tube. There can be additional add ons like microphone, speaker etc to record and to change the air flow rate inside the tube with respect to acoustics produced inside the tube. The advantage of this type of setup is that it is simple in construction. The disadvantage of this type is that it doesn’t allow variable air flow rate and voltage. There is also a horizontal tube type and is more advantageous in studying various levels of temperature of coil, air flow rates and heating coil location. It is also possible to create frequencies close to natural frequency of the tube, which could be a crucial study. The main disadvantage is the complexity of the system. That is why a vertical tube setup is selected for this study.

The basic mechanism happening in a Rijke tube is related to fundamental frequency of open tube. The sound is obtained from a standing wave whose wavelength is about twice the tube's length. Lord Rayleigh gave an explanation for how sound is generated in 1877 as mentioned above. Let us consider a setup of Rijke tube and take the fundamental half wave form graph. Now let's divide this half wave form into initial and final stages. At the initial cycle air starts to enter the tube from the top and bottom ends and pressure at the center area of the tube is increased gradually. Note that the air entering from the bottom is hot as the gauze is hot and is transferring heat to its surrounding air and the air entering from the top is cold. Now, just before when pressure reaches maximum, some amount of air at the center portion will touch the gauze. This will create increase in pressure and starts the vibration in the tube along with a hum.

In the second cycle, there is a decrease in pressure due to the air above the gauze is pushed downwards past the gauze. Since the air is already hot enough, there would be no pressure change in the tube at the gauze, since there is no transfer of heat. That is why sound wave is strengthened once every half cycle, and it builds up quickly resulting in huge amount amplitude.

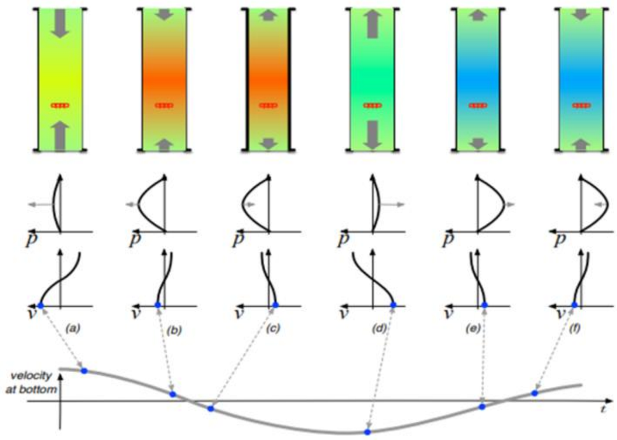

Figure.1 Fundamental Mode of Rijke Tube representing its half wave nature.

The first row depicts acoustic pressure is shown in color and the acoustic velocity (with directions) at the end of the tube is illustrated as arrow marks. The bottom row depicts one period of the temporal waveform of the velocity at the bottom of the tube. In the third row, at (a), the pressure just started increasing in the center of the tube due to the air rushing in from the top and bottom of the tube. (b) has led to the pressure achieving a maximum at the center, while simultaneously the velocity has been decreased by the resulting pressure gradient (shown parallel in row 2). In (c), the pressure gradient (shown parallel in row 2) has inverted the velocity, so that air now starts rushing out of the tube with (d) showing an increase velocity. Finally at (e) the pressure reaches a minimum in the center and the gradient leads to (f) air getting inside again, until (a) pressure moves towards its maximum again and the cycle keeps repeating.

That is the reason why there is no sound during the initial time where the gauze is gets heated. Initially all the air that is flowing through the tube is heated by the Bunsen burner, so when the air reaches the gauze, the gauze is already hot and no pressure increase takes place. When the gauze is placed at the upper half of the tube, there would be no sound. In this condition, the cool air entering in from the bottom end by the convection current comes in contact to the gauze at the end of the first half. Immediately before the pressure comes down to a minimum, there would be a sudden increase in pressure due to the heat transfer. This would negate the sound wave instead of strengthening it.

As long as the gauze is placed at the lower half of the tube, the position of the gauze doesn't matter much. To find a best position, there are two things that are to be considered. Most of the heat will be transferred to the air where the displacement of the wave is a maximum (at the end of the tube), but the effect of increasing the pressure is greatest where there is the greatest pressure variation (in the middle of the tube). Placing the gauze at one quarter of the length of the tube from the bottom is the easiest method to find the perfect position.

Design and Fabrication of Experimental Apparatus

A lot of attention was put into material and component selection to get the best component possible for the best performance of the model and cost-efficient. The learnings from the literature survey were helpful in getting the specifications for each and every component. An Extensive market study was done to obtain all the components in the desired specification range. The components were selected based on the ease of availability, cost, nature of workability and durability.

A mild steel stand with four legs, Breadth of 30.48 cm and height of 45.72 cm is cut and welded for the setup to hold its components. The reason to choose this material is because it has good strength, weldable and also cost effective. The borosilicate glass tube of height 34.8 cm and diameter of 5.7 cm is attached to the stand. A board is placed on the four legs to hold the electronic equipment that was to be used. A mesh board is drilled in the middle of the board to hold the ESP32 micro controller. It is done so because to avoid any touching of the pins to the board, with the mesh board placed in the middle the ESP is now good to function. A power supply module of 3V is also drilled to the board to avoid any surge in power when connected to the power source while on the right-side PAM 8403 pre amplifier is attached to the board to amplify the test signal that is recorded by the microphone.

An 8ohm speaker is placed at the bottom of the tube. It is kept in way that the centre of the speaker coincides with the centre of the tube so that audio from the speaker won't get much dispersed. A microphone MAX4466 is placed right at the top of the tube to record the sound waves that are travelling with air when the wire gets heated. The temperature of the coil is also recorded using MLX90614 IR sensor which captures the reading with the help of Arduino NANO. It gathers both object and ambient temperatures in Celsius and Fahrenheit. Finally, the Ni-Cr wire is held between the clips which holds the wire inside the tube and clips both red and black supply the current to the coil with the help of a 12V 7AH Battery.

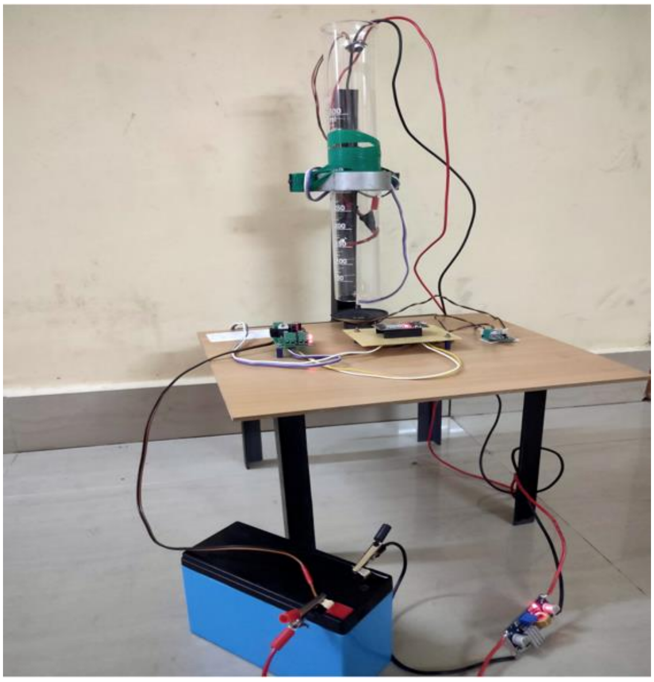

Figure.2 Experimental Apparatus

All the microcontrollers were programmed according to the experiement's requirement and the components are caliberated through a series of test runs in order to order to avoid any errors during experimentation.

3. Experimental Procedure

Before starting the experiment, make sure that the surrounding environment is as silent as possible. The experiment is first started by supplying power to the heating coil. At some time after supplying power to the heating coil, we start to hear a slight hum. This hum is recorded by the microphone. Now slowly amplify this signal with an amplifier and the amplified signal is transmitted back into the tube from the bottom through a speaker. Now we observe that the sound level of the hum is increasing. Keep on doing this until the peak frequency is reached. Once peak frequency is reached, how much ever amplification might be done, there will not be any increase in sound level. Record the findings obtained while experimenting.

Even though the setup and conducting the experiment might seem easy and straightforward, it contains a deep meaning and inference of the thermoacoustic phenomenon in the real world. The whole experimental setup can be parallel to a typical rocket or gas turbine engine where combustion instability, mainly thermos acoustics occurs.

First, the tube represents the combustion chamber. One can select a tube based on the aspect ratio of the combustion chamber of a real engine based on their liking. The heating coil and the air flowing through the coil and expands, represents the combustion process itself that takes place in the chamber and the hum represents the unsteady flow. Also, the advantage of using a heating coil is that we can assume that there is a steady combustion process and it would be easy for mathematical modelling

A microphone is used to detect the frequency of the sound (acoustic instability). This is recorded and then sent to a speaker via an amplifier. This shows air is being force induced into the tube. It also represents as more and more air is inducted into the tube or chamber, the instability increases. The amount of amplification can be seen as an increment of thrust that the aircraft requires. The same can be seen in the engines. The whole setup is a depiction of engine's combustion chamber in its simplest form.

3.1 Experimental Conditions

From the learnings taken from the literature survey, several conditions were considered depending on the output qualities of the constructed apparatus, as discussed earlier.

Present experiments are based on different thicknesses of coils being used to study how stabilization time and temperature vary. Each coil is positioned at two different positions to understand the variation in stabilization time. Three different thicknesses of coils as follows 0.34mm; 0.44mm; 0.68mm, all made from Ni-Cr material were used. All the coils were taken at a length of 34 cm. X/4 (8.7 cm) and X/2 (17.4 cm) positions from the bottom end of the tube were chosen to study the difference in stabilization time for each coil. The temperature coefficient of resistance of Ni-Cr is taken as 0.0004 K^{-1}. The room temperature while conducting the experiment varied from 35^0C to 36^0C (experimenting was done in multiple days). Resistance at room temperature for each coil is as follows:

THICKNESS	RESISTANCE AT ROOM TEMPERATURE
0.34	3.6
0.44	2.7
0.68	1.8

Table.1 Resistances at Room Temperature

A total of six cases/conditions are created to study the variations. A temperature sensor will be used to note the temperature of the coils in all six conditions. ESP 32 is not a data acquisition system, it is just data display system. All the frequency and time values have to be taken in somehow and have to be manually entered to get the required graphs. The frequency vs time graph have been plotted based on the data obtained by recording the serial monitor values shown in monitor option of Arduino IDE software. and comparative study is done.

Observations

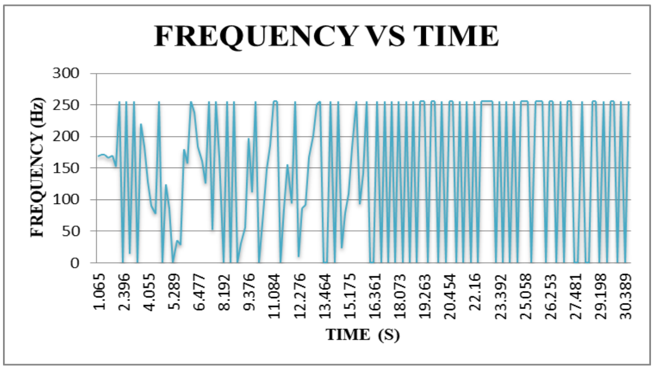

Figure.3 Thickness Of coil = 0.34 mm placed at X/4

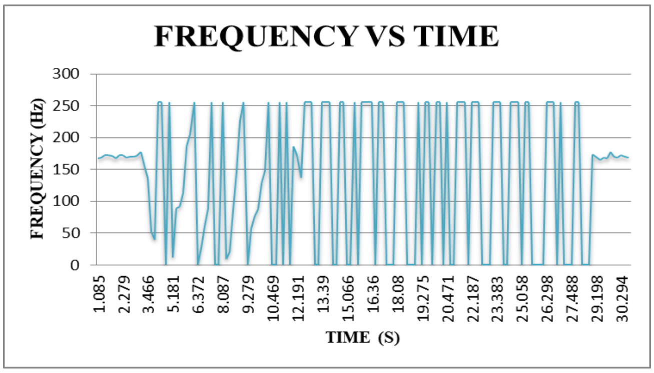

Figure.4 Thickness Of coil = 0.34 mm placed at X/2

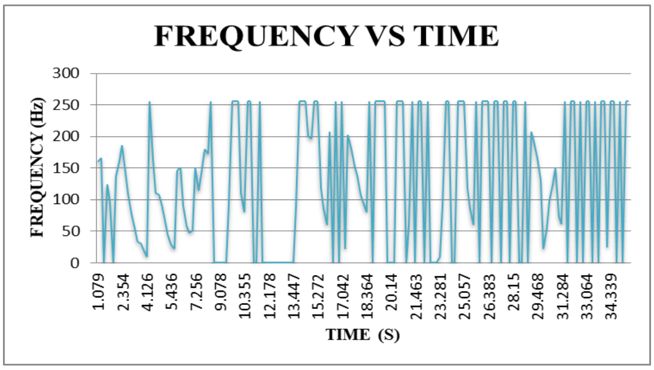

Figure.5 Thickness Of coil = 0.44 mm placed at X/4

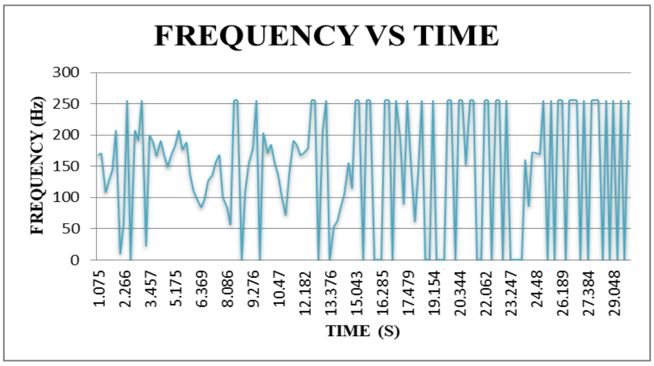

Figure.6 Thickness Of coil = 0.44 mm placed at X/2

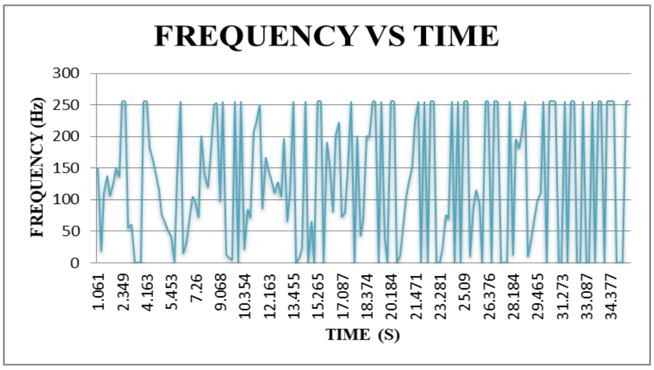

Figure.7 Thickness Of coil = 0.68 mm placed at X/4

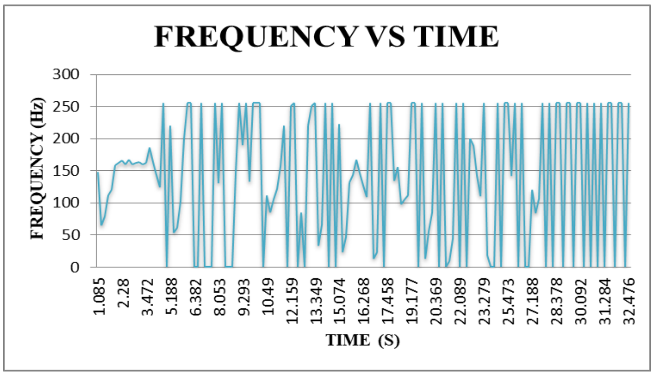

Figure.8 Thickness Of coil = 0.68 mm placed at X/2

4.1 Comparative Analysis

After experimenting with all the three thicknesses coils, a comparative study is required to understand the variations especially in stabilization time at each position with each coil and temperature changes with respect to each coil. Also change in resistance due to change in temperature is calculated for every coil. Change in resistance due change in temperature of coil is calculated by using the below stated formula:

$R = R_O (1 + \alpha (T - T_0))$

Where,

R is the Resistance of the coil at temperature T

R_O is the Resistance of the coil at room temperature T_O

α is the Temperature coefficient of resistance

T is the new temperature

T_O is room temperature

The change in resistance in coil after change in temperature is as follows:

THICKNESS	R_O	R
0.34	3.6	3.84
0.44	2.7	2.82
0.68	1.8	1.85

Table.2 Change in Resistance

The resistance increased in all three cases satisfying the relation resistance is directly proportional to temperature.

Coming to comparative study in terms of temperature, a graph is plotted with thicknesses taken in X axis and temperatures taken in Y axis.

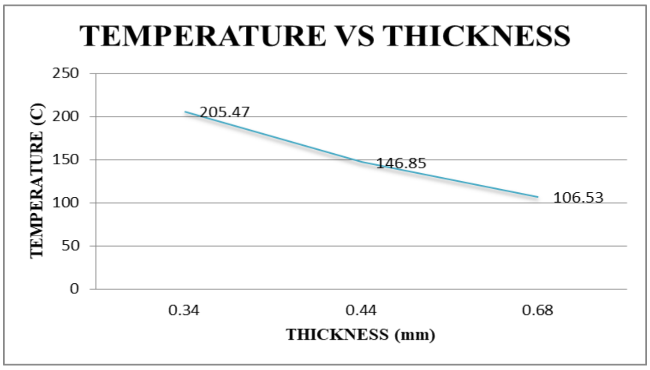

Figure.9 Temperature vs Thickness graph

From this graph it is clear that as thickness is inversely proportional to the thickness of the coil. This is because thicker wires need more time to heat and consume more power from the power source.

Comparative study to understand the effects of stabilization time is given by the graphs plotted with thicknesses taken in X axis and stabilization time taken in Y axis separately for experimentations done in X/4 and X/2 positions.

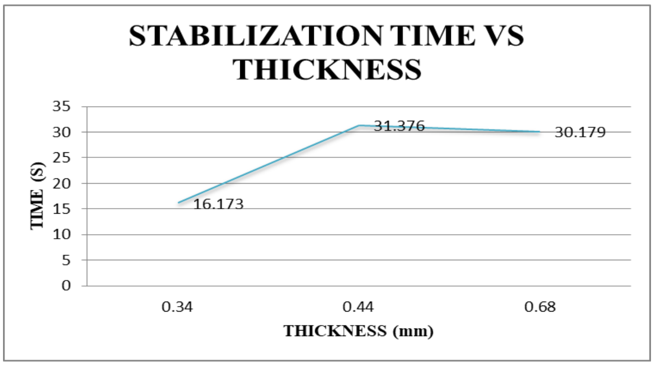

Figure.10 Stabilization time vs Thickness graph at X/4 position

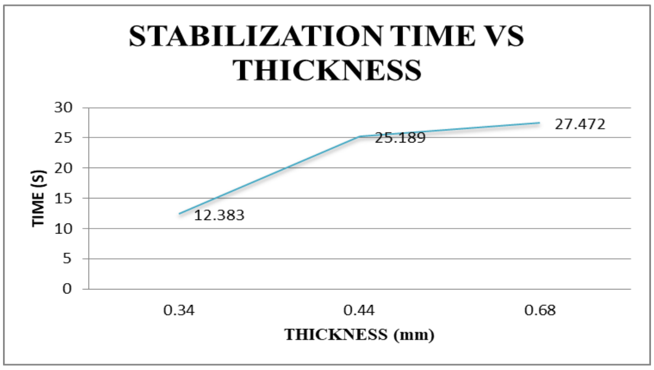

Figure.11 Stabilization time vs Thickness graph at X/2 position

From the graphs we understand that thicker the coil, more time it takes to get stable. This is because thicker coils take more time to get hot. During this process, some amount of heat gets dissipated into the air flow and causes hums. These hums have a very small amount of frequency and they take time to grow that is why there is the delay in stabilization time. It is also observed that stabilization time for coils at X/2 position is less than that of coils at X/4 position. This is because the coil is placed much closer to microphone.

4.2 Inference

For thicker coils, the time taken to reach maximum temperature is more. During this process some amount of heat gets dissipated into the air flow as unsteady heat release. If the amount of dissipated heat is high enough to expand the air, hum is heard at lower frequencies. In case of thinner coils, time taken to reach maximum temperature is less and can dissipate more amount of heat into the airflow at a faster and steady rate when compared to a thicker coil. That is why the instability for thinner coils occurs at much higher frequency. The time taken to stabilize the instability is more in thicker coil condition. This is mainly due to unsteady heat release in thicker coils. Coming to the positions of heating coils, it is observed that when coil is placed at X/2 position, stabilization of the flow was faster when compared to X/4 position.

Summary

The Rijke tube experiment was done based on the learnings taken from the literature survey. The apparatus was constructed based on the market study and specification range taken from the literature survey. Finally, all the experiments were done, graphs are plotted and a comparative study was done.

5.1 Limitations

The main limitation of this project is the ESP 32. It is used as a data acquisition device to get the data from the signal sensed by the microphone. The project required the controller to store the monitor data and the audio signal so that external noise can be removed from the audio file and the sound file can be studied, plotted and analyzed. The main disadvantage of using a microcontroller as a data acquisition device is that it does not store or record data. It can only monitor the data and show the continuous format of recognized data. That is why in this project, noise cancellation and clear projection of data were not possible to show. Better results would have been obtained if a DAQ board was used to record and store all the data required to produce better results. The data shown was a continuous screenshot of the monitor values and the graphs were plotted.

Another limitation of this project is the sensitivity of the microphone. The microphone was so sensitive that it reached peak value even for more minor noises. The sensitivity was reduced as much as possible during experimentations. All the electronics used in this project are sensitive to the high power supply. There was frequent shorting of components. A DAQ board is recommended to overcome this issue. The project’s overall complexity can be reduced by using a standard DAQ board and studying the signal received by the microphone, Real-time Simulink is recommended.

5.2 Future enchancements and Improvements

This project done so far is the construction of the Rijke tube experimental apparatus and basic experiments were performed to understand the apparatus’s basic properties and working nature. Several improvements can be done in this project. One improvement that can be done is to find a way to store and record audio files of the signal received from the microphone and refine the data for better results. Another improvement is to incorporate a DAQ board for ease of obtaining the data. Another interesting observation is to place the coil at different positions along the tube and study the tube's instability. Another observation can be made by studying how different lengths of tube affect instability.

Conclusion

Two observations were made with the results obtained. The first observation is that a thicker wire needs more time to get hot and transfer heat to the surrounding air and consume more power from the power source. Take the example of a 0.68 mm thickness coil. It can reach over 200^0C. However, the hum was recorded at 106.53^0C, which was not as loud as the hum that was produced by the 0.34 mm thickness coil. This is because as it was getting hot, at the 106.53^0C point, the coil started to dissipate very minimal amounts of heat to the air, thus creating a weak and slight hum. The coil eventually reached about 110^0C when the stabilization of instability was achieved. Note that the 0.34 mm coil took about 16 seconds to stabilize and the 0.68 mm coil took about 30 seconds.

This condition can be compared to the lean premixed pre-vapourize burners that were once developed to improve the fuel efficiency of gas turbine engines. Combustors equipped with LPPB had a significant combustion oscillation problem because LPPB releases very minimal amounts of fuel compared with its predecessor types. Due to the improper ignition happening in the chamber and improper convection, minor instability in the form of oscillations started accumulating and increased at a steady pace, resulting in unimaginative, uncontrollable and catastrophic failure to the entire system.

0.68 mm thickness coil experiment explains how less temperature can affect dissipation rate leading to unsteady heat release and create instability. It also explains how a good amount of dissipation is vital for a stable flow. 0.34mm thickness coil experiment shows how stable the flow is as it has more convection rate into the flow. That is why its stabilization time is almost 50 % less than that of 0.68 mm thickness coil.

Another observation done during the experiment was that stabilization time was less at the X/2 position when compared with the X/4 position. This is because the coil is placed closer to the microphone sensor. As a result of this setting, the microphone will absorb more amounts of disturbances quickly. That is why it feels like stabilization has occurred quickly. With noise cancellation, this could have been studied and observed better.

Acknowledgements

We would like to place on record our sincere thanks to all those who contributed to the successful completion of our final year project work. It's a matter of pride and privilege for us to express our deep gratitude to the management of Hindustan Institute of Technology and Science for providing us with the necessary facilities and support. We extend our sincere thanks to our Head of the Department Dr. R Asokan for inspiring and motivating us to complete this project. We would like to thank our guide, Dr. D. Raja Joseph, for continually guiding and actively participating in our project, giving valuable suggestions to complete the project work. We would also like to express our sincere gratitude to Dr. Purushothaman Nandagopalan for his continuous support, guidance, active participation and for his valuable suggestions to complete the project work. We would like to thank all the School of Aeronautical Science's technical and teaching staff, who extended direct or indirect support.

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