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Exploring the Dynamics of Fire: A Comparative Study of Flame and Fire Behavior in Rubens Tube, Fire Swirl, and Rijke Tube Experiments

Gyan Ranjan
B-tech (Fire Engineering)
National Fire Service College Nagpur
Ministry of Home Affairs, Government of India.
Takli, Feeder Road, Rajnagar, Nagpur, Maharashtra 440013

Dharmendra Pal
M . tech (Indu. Safety Engg.)
Dept. of Fire technology and Safety Engg.
Shiv Kumar Singh Institute of Technology and Science,
Indore, Madhya Pradesh, India

Abstract **: Understanding the behavior of fire under different Conditions is crucial for various applications ranging From fire safety to combustion optimization. In this Research paper, we delve into the intricacies of fire dynamics by employing three distinct experimental Models: Rubens Tube, Fire Swirl, and Rijke Tube. The Rubens Tube model involves a Perforated pipe sealed at both ends, filled with a Flammable gas such as propane. By utilizing a suitable Constant frequency from a speaker or generator, a Standing wave is induced within the tube, causing the Gas to emit flames from the perforations. Through Meticulous experimentation, we explore the effects of Varying frequency, gas pressure, and tube length on Flame behavior and pattern formation. Fire Swirl phenomena occur when Intense rising heat and turbulent wind conditions Interact, resulting in the formation of whirling eddies of Air. This model mimics real-world scenarios such as Wildfires and building fires, where swirling patterns Significantly influence fire spread and behavior. By Studying the parameters influencing the formation and Stability of fire swirls, we aim to enhance predictive Capabilities and develop more effective firefighting Strategies . The Rijke Tube, a cylindrical apparatus with Open ends housing a heat source, demonstrates the Conversion of heat into sound through the creation of a Self-amplifying standing wave. By modulating the heat Input and tube dimensions, we investigate the influence of Acoustic perturbations on flame characteristics and Combustion stability. This model provides insights into Acoustic-driven flame behavior, with implications for Combustion control and suppression techniques. Through systematic experimentation and Analysis of the aforementioned models, this research Elucidates the complex interplay between fire, fluid Dynamics, and acoustics under diverse environmental Conditions. The findings contribute to advancing Fundamental understanding and practical applications in Fire science, ranging from fire prevention and mitigation Strategies to the optimization of combustion processes in Various industrial settings.**

Keywords : **Rubens Tube, Rikage Tube ,FIRE SWIRL, Standing Waves, Frequency generator, Heat source, Turbulent Wind, Firestorm, Sound pressure, Flame.**

1. INTRODUCTION

The goal of the experiment was to Understand the behavior of fire Under various conditions is crucial for enhancing fire safety Measures, optimizing combustion processes, and mitigating fire- Related risks. In this research paper, we delve into the intricate Dynamics of fire through the lens of three distinct models: the
Rubens Tube, Fire Swirl, and Rijke Tube. The Rubens Tube, first Introduced by Heinrich Rubens in the late 19th century, provides a Captivating demonstration of acoustics and fluid dynamics Intertwined with combustion. By employing a perforated pipe Sealed at both ends and filled with a flammable gas, this model Allows for the visualization of standing waves formed within the Tube when subjected to a suitable constant frequency. In contrast, the Fire Swirl phenomenon exemplifies the Spontaneous formation of whirling eddies of air within intense Rising heat and turbulent wind conditions. This swirling motion not Only influences the spread and behavior of fire but also presents Challenges for firefighting strategies and ventilation systems Lastly, The Rijke Tube offers a unique insight into the interaction Between heat, sound, and combustion. Consisting of a cylindrical Tube with open ends and a heat source placed inside, the Rijke Tube Generates self-amplifying standing waves that convert heat into Sound, providing a platform for investigating the intricate coupling Between thermal energy and acoustic phenomena.

Through an in-depth analysis of these models, this Paper aims to elucidate the multifaceted nature of fire behavior, Shedding light on the underlying principles governing Combustion processes in diverse environments. By synthesizing Theoretical frameworks with experimental observations, we Endeavor to contribute to the advancement of fire science and Engineering, fostering innovations in fire safety practices and combustion technologies.

2. MECHANISM

Fire is defined as steady state of exothermic, self- Catalyzed chemical reaction with the characteristic Ability to propagate through a combustible medium, Usually fuel and an oxidizer which is generally Atmospheric oxygen. An oxidizing agent, a Combustion material and an ignition source are Essential for fire or combustion. The combustible Material must be heated to its ignition temperature Before it will ignite or support flame spread.

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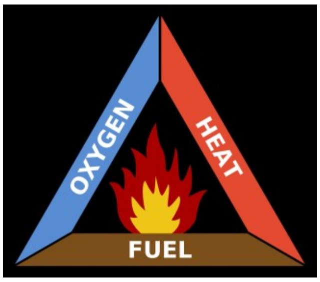

Figure 1. Fire Triangle

The Fire Triangle, or Combustion Triangle, is the three Components needed to ignite and sustain a fire. The Three ingredients of a fire triangle are Heat. Fuel and Oxygen. If just one of these components is removed, the Fire triangle will collapse and the fire will be extinguished

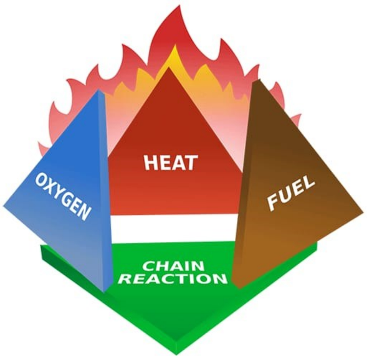

Figure 2. Fire Tetrahedron

The fire tetrahedron represents the addition of a Component in the chemical chain reaction, to the three Already present in the fire triangle. Once a fire has Started, the resulting exothermic chain reaction Sustains the fire and allows it to continue until or Unless at least one of the elements of the fire is Blocked.

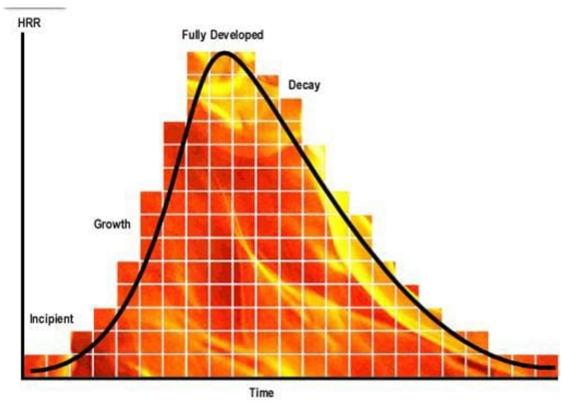

Figure 3. Heat Release Rate(HRR) And Fire Development

Incipient Phase: The material releases pyrolysis products, which Ignited through a variety of combustion processes such as Smoldering (non-flaming) or flaming.Growth Phase: With the initial flame a heat source, Additional fuel ignites. Convection and radiation Ignite more surfaces. The size of the fire increases And the plume reaches the ceiling. Hot gases Collecting at the ceiling transfer heat. Allowing all Fuels in a room to come closer to their ignition Temperature at the same time.

Fully developed Phase or Steady Phase:- Fire has Spread over much, if not all the available fuel; Temperatures reach their peak, resulting in heat Damage. Oxygen is consumed rapidly.
Decay (Burnout) Phase:- The fire consumes Available fuel, temperatures decrease, fire gets less Intense. Heat release rate rapidly decreases Despite the availability of sufficient quantity of air Which is basically due to less quantity of fuel. The Rare phenomena such as fire gas explosion or flash Fire also leads to decay with or without passing Through fire severity phase.

Figure 4. Ruben's Tube

3. MECHANISM OF RUBENS TUBE:

Rubens tube is an example of unsteady Combustion. The diffusion flames come out of the Large number of holes on the tube dance to the Acoustic modes generated by a speaker fed with Sound was supplied as fuel gas into the Tube. The standing pressure waves that Change With time in the tube lead to variation in flow Rates from the holes.
Sound propagates through air in the form of pressure Waves. However, it is difficult to watch a standing wave With the naked eye. Therefore, it can be visualized using The Ruben's Tube. By passing flammable gas through a Long metal tube with a small hole drilled in the top, it is Possible to create a line of individual flames. The height Of each flame is related to the gas flow rate through the Hole beneath it, which can be altered by modifying the Gas pressure inside the tube. If this is done by a suitable Choice of sound waves, standing waves can be Established inside the tube, resulting in a flame pattern. This can then be examined to establish relationships Between the sound waves and the gas in which they Travel. This Figure shows the experiment setup for Ruben's Tube.

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Figure 5.

Layouts:
Metal tube that has a row of holes lining it. The tube is Filled with gas that comes out through the small holes. One side of the tube is closed while the other is Connected to the gas cylinder. A loudspeaker is Directed towards the closed side of the tube so that The sound travels through the tube. For the experiment there are four main parts that we Had made :- The Metal Pipe , Diaphragm, Gas Input System, Stand.

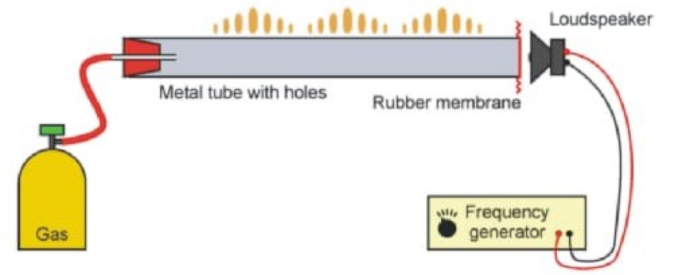

Figure 6

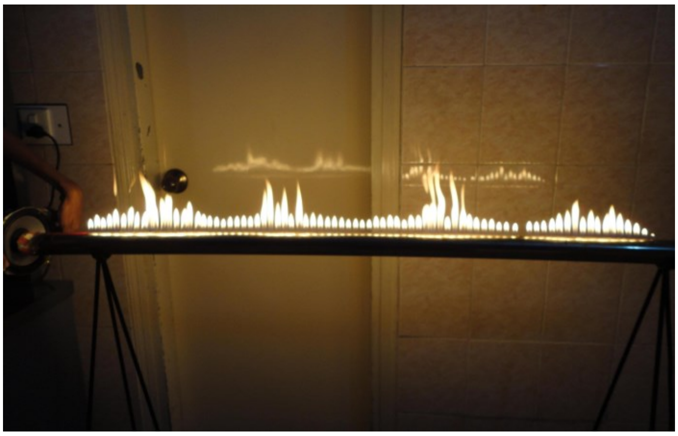

Figure 7

Mechanism behind it:

——1.Sound wave created by loudspeaker at the start.

2.Now there are two waves travelling in opposite Directions since the first wave hit the end of the tube and Is being reflected back.

3.The combination of the two waves creates a standing wave with the additional areas of oscillating pressure (antinodes) and constant pressure (nodes).

4. Short flames produced by areas of oscillating pressure and large flames produced by areas of constant pressure.

Theory:

When the gas is first lit the flames will be about the same Height due to the constant pressure, but once the sound Is transmitted through the tube the flames begin to vary In height because of the pressure change. The Rubens Tube illustrates a standing wave (wavelength) that Represents the sound that is being played. The highest flames would be represented in the areas of Condensation whereas the lowest flames would be found In areas of rarefactions. The Rubens Tube operates on the idea that the sound that is Being heard is the pressure waves that are travelling through The gas. "In some places the two waves add together forming extra Large changes in pressure (antinodes) and in other areas they Cancel each other out so the pressure is constant (nodes)." The two theories are approached differently because the High amplitude theory is still under further observation due To the lack of insight from Ruben himself. The low amplitude Theory explores the idea that when there is a quiet sound the Change in pressure in the tube is less than that of the Pressure of gas. Where there is oscillating pressure due to The sound waves, less gas leaves the perforations holes in The tube, and so the flames will be lower. At pressure nodes, Flames are higher.

Relation between gas flow, gas pressure and sound Pressure for a given sound frequency.

$$\sqrt{P_{gas} + P_{sound}\sin(\omega t)}$$

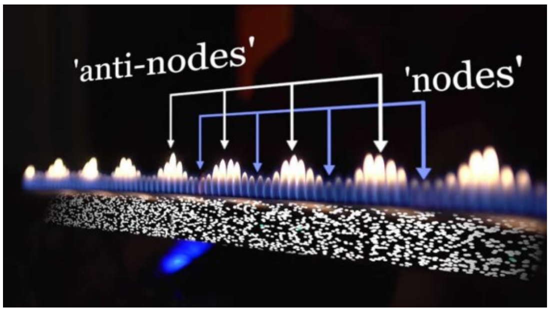

Figure 8

Functioning mechanism:

By applying Bernoulli's Principle to this experiment it Can be determined that the velocity of the gas that is Leaving the holes in the tube is related to the pressure That is pushing the gas through the small holes. The Flame height depends non-linearly on the local, time- Dependent pressure. The time average of the flow is Reduced at the points with oscillating pressure and Thus flames are lower.

The velocity of the gas that is attempting to leave Through the small holes is related to the pressure that Is forcing the gas

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outward. Where there is high Pressure, gas is found to travel through the hole at a Fast speed and that leads to the high flames. In areas Of lower pressure the flames are much shorter since The velocity of the escaping flames is reduced. The Sound waves are creating pattern of differing flame Heights because of the varying high and low pressures.

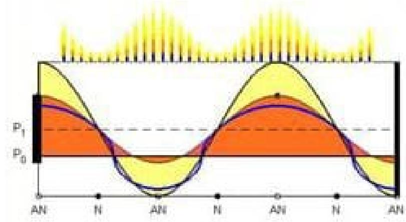

Figure 9. Pressure Wave

Conclusion *:*

Hence after Performing this Experiment we understood If we place a frequency generator or a speaker near the Diaphragm, we can see a change in pattern to the flame With the change in frequency. At the pressure nodes, The flames are higher and vice-versa. Also if you tap the Diaphragm with your finger you will Be able to see the same change instantly. Hence it is Confirmed that the standing wave will create points With oscillating (higher and lower) pressure and points With constant pressure (pressure nodes) along the tube. Thus we will see the formation of nodes and anti-nodes Among the flame. The result is in front of us now. At the pressure nodes, The flames are higher. At the end of the tube gas Molecule velocity is zero and oscillating pressure is Maximal, thus low flames are observed. It is possible to Determine the wavelength from the flame minimum and Maximum by simply measuring with a ruler.

4. MECHANISM OF RIJKE TUBE:

Rijke tube is a tube that converts heat applied in Specific location to sounds by creating a self amplified Standing wave The thermo-acoustic interaction is Governed by Rayleigh's criterion which states that the Energy introduced to the fluctuating pressure wave Must be broadly in phase for the oscillation to amplify In an experiment with a 50cm long Tube a few pieces of Charcoal are set on a wire gauze at About quarterly height of the tube. The charcoal was Heated till it was red hot with abunsen flame. When the Flame was withdrawn the tube started singing at a Frequency which can be calculated by the formula as Given below :

F experimental = 352.1 Hz

F =c/2L = 340 Hz

F: frequency (1st Mode)

C: speed of sound (340 m/s)

L: length of tube (50 cm)

F predicted = 340 Hz

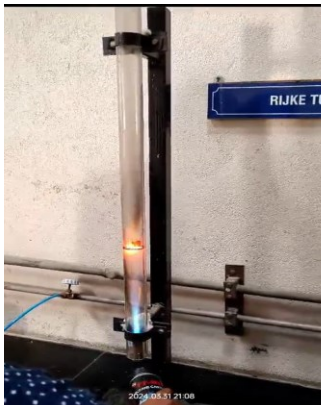

Figure 10. Rijke Tube

Thermo-acoustic instability appears inside Chambers with heat source and mean flow when Unsteady heat release is coupled in phase with Pressure fluctuations. Such instability gives rise to Excitation of acoustic modes resulting in noise. Typical examples include Rocket Motors, Pulsed Combustors, Noisy Industrial Burners and Heat Exchangers. Rijke tube is the simplest possible device that Demonstrates the thermo-acoustics instability. It is A vertical tube with open ends having its length to Diameter ratio of about 10. When a wire gauge Placed inside at about one fourth the tube length From its lower end is sufficiently heated with flame, A loud noise is produced. The reason for this noise is excitation of acoustic Mode due to the coupling between the unsteady Heat release and the pressure fluctuations that is Enabled by the low speed flow driven by the Convective currents.

Conclusion:

Hence after Performing Rijke tube experiment we Understand the phenomenon of thermoacoustic Instability, where the interaction between heat and Sound waves creates self-sustained oscillations in a Confined space. This experiment holds importance in Various fields, particularly in fire research, as it helps in Studying the dynamics of combustion and flame Behavior. By simulating combustion processes in Controlled environments, researchers can gain insights Into optimizing fire safety measures, improving Combustion efficiency, and developing cleaner burning Fuels. Thus, the Rijke tube experiment plays a crucial role In advancing our understanding of fire dynamics and Enhancing fire prevention and mitigation strategies. The Setup was capable of producing sound at a level of 53.1 dB. The experiment yielded that high heating and hence high temperature resulted in sound with more intensity. Hence we also have studied the effects of introduction Of stream wise vorticity and certain geometric Modifications including concentric tubes on thermo-Acoustic behavior of the Rijke tube.

5. MECHANISM OF FIRE WHIRL:

A fire whirl is a combination of concentrated heat Source coupled with an organised source of angular Momentum, either from wind shear or from the Fire's convection column, that must help create Larges wirl velocities as air is entrained in to the fire Plume.

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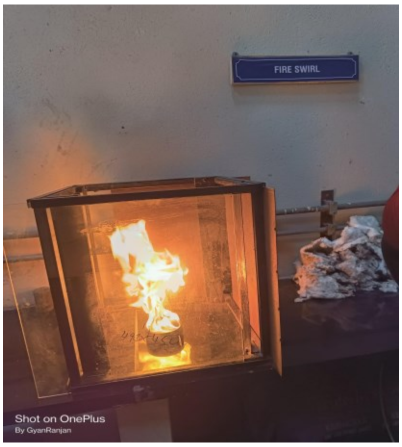

Figure 11

We have created a fire whirl, also referred to as a fire Devil. Fire whirls can occur naturally during forest Fires, and they allow the fire to reach the tree tops and Spread there. They are formed when hot air above a Fire rises and begins to rotate. When the air vortex Sucks in more air from the ground, the flames also Follow. Your fire whirl was created in the same way, Except that you needed to assist with the rotating air. You create the rotating air using the net in the trash Can. Without the trash can it will not work. The net Grabs the air molecules inside the trash can and Creates a spinning wind inside. Most fire whirls are less than 1 m (3 ft) in diameter and Short, but 15 m (49 ft) wide and over 100 m (328 ft) High ones have also been observed. A more extreme Version of the fire whirl is the fire tornado, which Originates from a thundercloud instead of from the Ground. The first documented fire tornado occurred in Canberra in 2003, where a severe forest fire resulted In the formation of a thunderstorm, which in turn Resulted in an approximately 500 m (1 640 ft) wide Fire tornado with wind speeds around 70 m/s (157Mph). This giant fire tornado was shrouded in smoke And clouds and there are no videos or photos of it (only tracks). Instead, this photo shows a vortex in a Forest fire in Oregon in July 2013.

Conclusion:

After performing a fire whirl experiment, We have Observe several phenomena, Formation of a Fire Whirl:- The experiment should Generate a swirling column of flame that resembles a Tornado or vortex.
Heat and Flames:- Depending on the scale and intensity Of the experiment, you'll see heat and flames rising from The fire whirl.
Air Movement:- Fire whirls are caused by the interaction Of air currents with the fire, so you may observe changes In air movement and temperature around the Experiment.
Combustion Patterns:- The experiment might reveal Interesting combustion patterns within the fire whirl, Showing how fuel is consumed and how air flow Influences the flames.
Potential for Spread:- Observing how the fire whirl Behaves could provide insights into its potential for Spreading fires in real-world scenarios.
Safety Precautions:- It's crucial to observe safety Precautions during the experiment, such as ensuring the Fire whirl remains contained and doesn't pose a risk of Spreading uncontrollably.

6. Out Comes of Study:

The outcome is a visible representation of sound waves Through the modulation of flames, providing a tangible Way to observe acoustic phenomena. Now we will see how does Wind Velocity affects the Fire Using FDS Now, Wind Effects :- Wind boundary was imposed on the Side facing wall A of the building. Free boundary Conditions were applied on the remaining parts between The computational domain and the external Environment. A typical atmospheric wind profile can be Described as:

$$u = u_0 (z / z_0)^p$$

Uo is the velocity at the Reference height Zo, z is the ground level, p is the Atmospheric profile exponent. In this case, the default Value of the reference height zo and the atmospheric Profile exponent p, 10 m and 0.3 are taken. Using the wind velocity uo as a Characteristic velocity, Froude number (Fr) can be Defined in terms of the fire width d and the gravitational Acceleration g as:

$$Fr = u_0^2 / gd$$

Five wind velocities have been tested are u0 0.5, 1.0, 1.5, 2.0 and 2.5 m/s.The corresponding values of the Froude Number are Fr = 0.127, 0.510, 1.148, 2.041 and 3.189. Now results, In addition to the no wind condition, six Simulations were conducted by FDS at varied wind Speeds 0.5, 1.0, 1.5, 2.0 and 2.5 m/s. All numerical Simulations were generated under the same heat release Rate 5 MW.

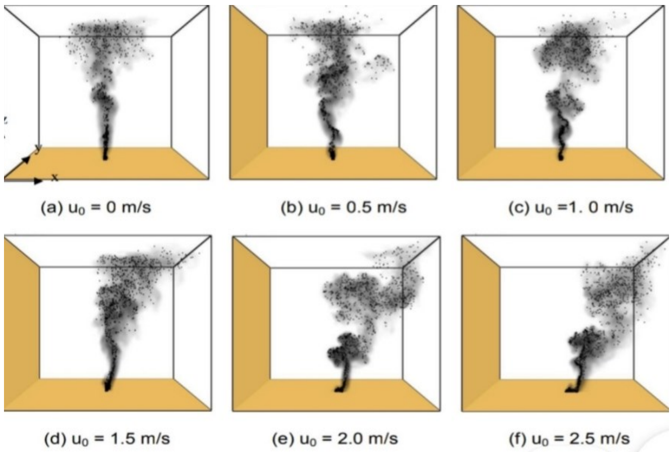

Figure 12. Smoke and particles distribution in between Leeward direction

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Table 1 The distance in x direction and y direction covered by the flame tip (Dx / Dy)

u_0 (m/s)	Z (m) / Dx / Dy (m)	2	4	6	8	10
0	Dx	1	1.3	2.4	2.2	1.3
	Dy	0.6	1.1	2.3	1.8	1.9
0.5	Dx	1.3	1.1	2.1	2.1	2.4
	Dy	1.1	1.3	1.7	2.4	1.5
1	Dx	1	1.5	2.9	1.8	2.6
	Dy	0.9	2.1	2	2.9	1.8
1.5	Dx	1.5	0.9	1.6	2.1	3.4
	Dy	1.3	1.8	1.8	2.9	2.9
2	Dx	1.5	2.2	3.3	N/A	N/A
	Dy	1.3	2.8	1.7	N/A	N/A
2.5	Dx	0.9	2.2	3	N/A	N/A
	Dy	1.2	2.9	2.4	N/A	N/A

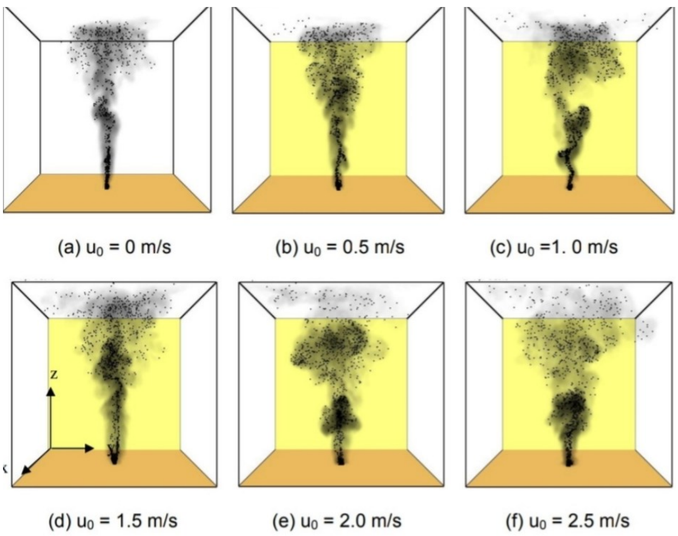

Figure 13. Smoke and particles distribution in cross-wind direction

Smoke and particles distribution in leeward direction (x Direction) are insensitive to wind velocity lower than 1.0 m/s, however, the distribution increases significantly when the wind velocity increases 0 to 1.0 m/s, as shown in Fig. 1. As in Fig. 2, in cross-wind direction (y direction), the distribution of smoke and particles indicates that the lateral spread of smoke increases with wind velocity. This relation may be prompted by the rise of turbulence level resulted from high wind velocity. Flame geometry and smoke movement induced By a fire under windy conditions were carried out By FDS. In addition to the significant flame and Smoke spread in the leeward direction, predicted Results showed that lateral spread of flame and Smoke are also directly proportional to wind Velocity in the cross-wind direction. These may Be due to the rise of turbulence level resulted From high wind velocity. As the wind velocity Increases, the plumes bent over further by the Approaching wind. This is different from the case When there is no wind. Smoke will spread radially From the central axis of the plume to higher Positions. Excessive wind-driven makeup air Would spread smoke at the lower level under Higher wind speed.

7. FUTURE SCOPE:-

We can also think how sound wave could be one of the Potential alternative in putting off flames. The acoustic Pressure and air velocity produced from a speaker is the Main theory used to explain how sound waves put off Flames and the Research aims study andanalyze the Effect of different frequency of sound wave on flames. A Simulation of sound wave should be carried out to study Behavior acoustic wave propagation in the collimator And surrounding environment. The combination of Varying high and low pressure and coupled with high Flow air velocity, which in then causes disturbances in Air-fuel ratio at the flame boundary (leading to thinning Of flame boundary), is one of the possible explanation Leading to flame extinction. Because till now we are using Fire Extinguishers to Extinguish the Fire which are trying to eradicate One of the elements in the pyramid (a flame Tetrahedron) in order to eliminate the flame. Firefighting in an enclosed space has always been A problem, other than the accessibility for the fire Fighter to access the place, accessing the water, Carbon dioxide (CO2) or other fire extinguisher Technology to the closed space is a major Challenge. A compact, independent and reliable fire Extinguisher is required in order to overcome this Problem. Space station and submarine are the main Examples of the application that highly required New fire extinguisher. Nevertheless, this sound wave based fire Extinguishing could be used to extinguish initial Stage fires. These Experiments can be used for Research Purposes in various fields, including Acoustic, Combustion, fluid dynamics, and even music :-

Acoustics Research:- Rubens Tube can be used to Visualize sound waves by producing standing waves Through the length of the tube. Researchers can Study the behavior of sound waves under different Frequencies and amplitudes. Combustion Studies:- Rubens Tube can be Employed to study the behavior of flames under Different conditions, such as varying gas Compositions, flow rates, and pressure. This can be Useful for optimizing combustion processes in Engines or industrial burners.

Fluid Dynamics:- Both Rubens Tube and Rijke Tube Experiments can be utilized to study fluid dynamics Phenomena, such as turbulence, flow patterns, and resonant Frequencies. Researchers can investigate how different Parameters affect fluid behavior within the tubes. Music and Education:- Rubens Tube can serve as a Captivating educational tool for demonstrating the Relationship between sound waves and standing waves. Researchers can explore how different musical notes or Frequencies produce distinct standing wave patterns, aiding In music education and outreach programs.

Sensor Development:- Researchers can develop sensors Based on the principles demonstrated by Rubens Tube and Rijke Tube experiments. For example, acoustic sensors can Be developed to detect changes in sound wave patterns, Which can have applications in various industries, including Aerospace and automotive.

Safety Testing:- Rubens Tube experiments can be used to Test the effectiveness of fire suppression systems or to Study flame

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behavior under controlled conditions, aiding in The development of safety protocols and devices.

Materials Testing:- Researchers can study the effects of Different materials on acoustic or combustion properties by Incorporating them into the tubes and observing how they Alter the phenomena being studied. Overall, These experiments offer versatile Platforms for conducting research across multiple Disciplines, providing valuable insights into various physical Phenomena and practical applications.

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