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PIV Investigation of the Velocity Field in the Thermoacoustics Device

Diplomová práce

Studijní program: N2301 – Mechanical Engineering
Studijní obor: 2302T010 – Machines and Equipment Design

Autor práce: **Suresh Ramarao**
Vedoucí práce: Ing. Petra Dančová, Ph.D.

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Master thesis

Study programme:	N2301 – Mechanical Engineering
Study branch:	2302T010 – Machines and Equipment Design
Author:	**Suresh Ramarao**
Supervisor:	Ing. Petra Dančová, Ph.D.

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Master Thesis Assignment Form

PIV Investigation of the Velocity Field in the Thermoacoustics Device

Name and Surname: **Suresh Ramarao**
Identification Number: S17000502
Study Programme: N2301 Mechanical Engineering
Specialisation: Machines and Equipment Design
Assigning Department: Department of Power Engineering Equipment
Academic Year: **2018/2019**

Rules for Elaboration:

This thesis deals with the experimental investigation of the velocity field created in the thermoacoustic device. The working fluid is gas. The PIV is used for the investigation.

1. Make the "state of art" of Thermoacoustics problem.
2. Make the state of art of possible experimental methods.
3. Perform the experiments on the existing device of the velocity fields using PIV method.
4. Analyze your data and do the comparison with the literature.
5. Suggest device improvements.

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Scope of Report:	up to 50 pages
Thesis Form:	printed
Thesis Language:	English

List of Specialised Literature:

[1] BACKHAUS, S. a G. W. SWIFT. A thermoacoustic-Stirling heat engine: Detailed study. *The Journal of the Acoustical Society of America* [online]. 2000, 107(6), 3148-3166. ISSN 0001-4966. Dostupné z: doi:10.1121/1.429343

[2] SWIFT, G. W. Thermoacoustic engines. *The Journal of the Acoustical Society of America.* [online]. 1988, 84(4), 1145-1180. ISSN 0001-4966. Dostupné z: doi:10.1121/1.396617

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3. 5. 2019

Suresh Ramarao

ACKNOWLEDGEMENT

I would like to take this opportunity to express my deep sense of gratitude to all those people without whom this project could have never been completed. First and foremost I would like to thank my **parents, sister and friends** for their inexhaustible source of inspiration.

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Their guidance and supervision was very helpful in bringing this work to conclusion.

ABSTRACT

In this thesis work we will see about the experimental investigation of the velocity field in the thermo-acoustic device with the help of particle image velocimetry which is commonly known as PIV method. The working fluid which is used in this process is gas. The main aim of the thesis is to obtain the velocity of the stack region and then the cooled region in the thermo-acoustic device and it is achieved by using the laser which is going through the required region which is filled with particles and is captured by the high range CCD cameras and from the image analysis have been done with PIV software and after the processing we will get the velocity field which is our main objective.

KEYWORDS

Thermo-acoustics, particle image velocimetry (PIV), velocity fields, sound waves, refrigeration.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SELECTED SYMBOLS

C	speed of sound	(m/s)
X	position	(m)
K	thermal diffusivity	(m^2/s)
∇	Laplace operator	no unit
ρ	Density	(kg/m^3)
µ	Velocity	(m/s)
λ	wavelength	(m)
f	frequency	(HZ)

ABBREVIATION

AWG	arbitrary waveform generator
CCD	charge coupled device
CMOS	complementary metal oxide semiconductors
CRT	cathode ray tubes
DDS	direct digital synthesis
DSO	digital storage oscilloscope
GPU	graphics processing unit
MS	microseconds
MOS	metal oxide semiconductors
MSO	mixed signal oscilloscope
PIV	particle image velocimetry
PS	picoseconds
PSU	power supply unit

1. INTRODUCTION

1.1 THERMODYNAMICS

It is one of the branches of physics which deals with temperature and heat and their relation to radiation, work, energy and properties of the bodies of the matter. It is generally maintained by the four laws of thermodynamics irrespective of the specific composition of material or system. Microscopic constituents by statistical mechanisms are used to explain about the laws of thermodynamics. Engineering and science are the basic topics in which thermodynamics is applied. By using different fundamental basics and experimental model it is classified into several branches such as statistical, classical, chemical, equilibrium and non equilibrium.[1]

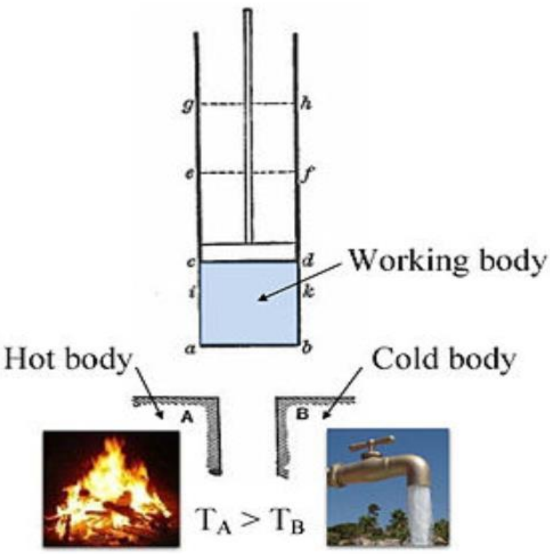


Figure 1 Basic thermodynamic system

1.1.1 ABOUT

Historically in order to increase the steam engines efficiency was developed by the thermodynamics through the physicist Nicolas Leonard Sadi Carnot (1824). The first one to formulate the definition for thermodynamics was Scots-Irish physicist lord Kelvin in 1854. He stated that it is the subject of relation to forces which acts between contiguous part of bodies and heat to the electrical agency. Chemical compounds and chemical reactions study extended early was the mechanical heat engines which is the initial application of thermodynamics. Study of the role of entropy in process of the chemical reactions is called as chemical thermodynamics. It provides more knowledge and lots of expansion in that field.

Whenever there is a description of any thermodynamic system they generally employ it with the four laws of thermodynamics. Energy can be exchanged between the heat and work systems are what the first law is about. The existence of quantity that is entropy explains about the direction where the system can evolve and measures the state of order of system used to quantify the work which is extracted from the system. Interactions between large objects are studied in thermodynamics. Main subject to this concepts are system which is composed of particles which also define its properties and its state of equation. Internal energy and thermodynamic properties are expressed so that properties can be combined and which is also used to determine the condition of equilibrium and spontaneous processes. With the help of these things it can be used to explain how the systems change their environment according to the changes they acquire during this. This can also be used in the black hole topic. Equilibrium and non equilibrium thermodynamics are the primarily study systems on classical thermodynamics and the one which brought so many advancement and betterment in the field is statistical thermodynamics.

1.1.2 HISTORY

The thermo-dynamical history started in the year 1650 by Otto von Guericke who is the first person in the world to design and built vacuum pump using the Magdeburg hemispheres. He made that only to disprove Aristotle's view about vacuum. By using this work Robert Boyle along with Robert Hooke built an air pump. They made a correlation between temperature, pressure and volume by that pump. This is how Boyle's law was formulated. It explains that pressure and volume are inversely proportional to each other. By the help of this works in 1679 a closed vessel with tight lid confined by steam until high pressure is given to it. Based on these innovations in 1697 the first ever engine was built by Thomas Savery. But they were inefficient and crude. Joseph Black developed the fundamental concepts of latent heat and heat capacity which were needed for the development of thermodynamics. Later James Watt was the one to express the idea of external condenser which resulted in the increase of steam engine efficiency. Reflections on the motive fire of power (1824) are the book which is written by Father of thermodynamics Sadi Carnot marked as the start of thermodynamics as a modern science. In that he explained a lot about motive power, Carnot cycle and Carnot engine. During 1873-76 Josiah Willard Gibbs published in a paper about with the help of studying temperature, volume, energy, pressure and entropy we can analyze the chemical reactions and thermodynamic processes graphically. And in the 20th century many chemists in order to analyze the chemical processes are applying mathematical methods of Gibbs.

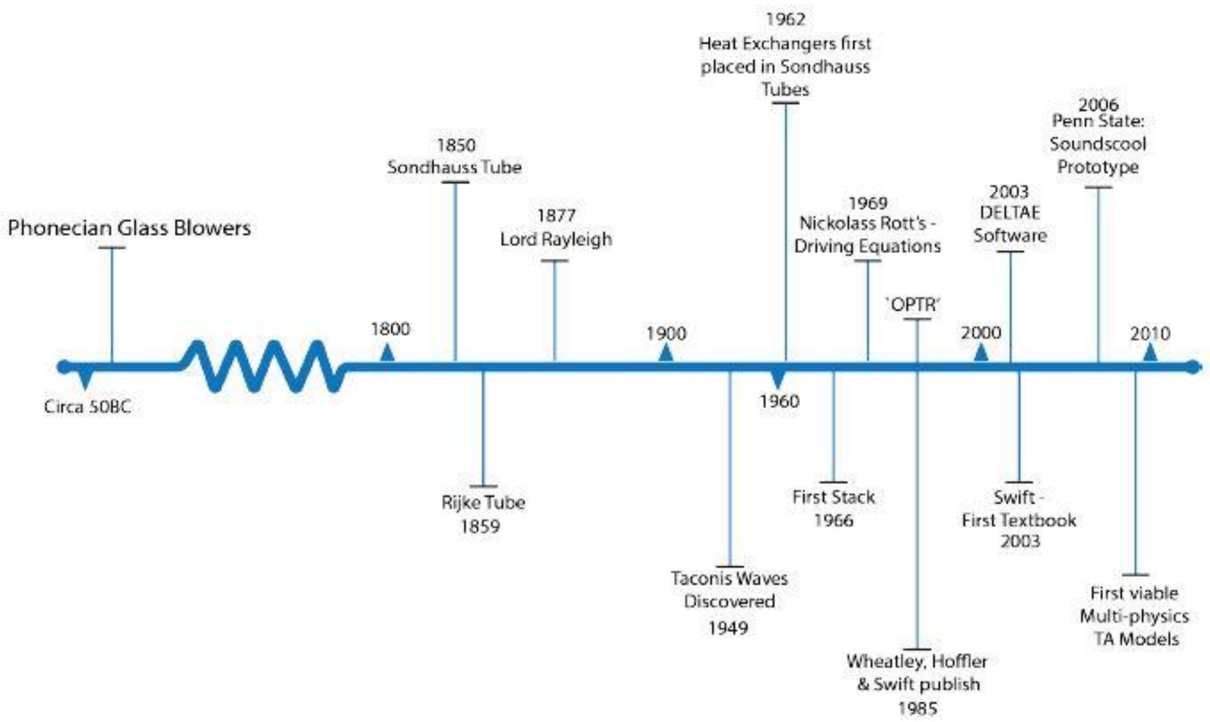


Figure 2 Time line in development of thermo-acoustics [2]

1.2 BRANCHES OF THERMODYNAMICS

By using various fundamental models as theoretical or experimental basis and also in applying principles to the different types of systems thermo-dynamical systems has developed into different branches. Let us see about the major and most important branches of thermodynamics.

1.2.1 STATISTICAL THERMODYNAMICS

These are the ones which emerged in the late 90s from the development of molecular and atomic theories. The interpretations of microscopic interactions between individual particles are also supplemented by classical thermodynamics. Individual atoms microscopic levels and bulk properties of materials through human scale can be observed with this field. So it is the way of getting natural result of statistics from explaining classical thermodynamics.

1.2.2 CLASSICAL THERMODYNAMICS

The thermodynamic system which uses measurable and macroscopic properties at near equilibrium is defined as statistical thermo-dynamics. Based on laws of thermodynamics exchanges of heat, work and energy are modeled by this. These explain the first level of understanding and later after some microscopic interpretations provided by the statistical mechanics development.

1.2.3 EQUILIBRIUM AND NON EQUILIBRIUM THERMODYNAMICS

Energy and transfer of matter in system while they shift from one state to another equilibrium state are systematically studied which is called as equilibrium thermodynamics. It is the indication of state of balance. Between macroscopic parts of system there will be no driving force and unbalanced potentials only in a equilibrium state. The main aim of this system is once we have good initial state, surroundings and consecutive walls to calculate it for the final equilibrium state of change in surroundings, walls for the thermodynamic operation. We can easily state this one because it is opposite to the above state. Systems which are not in thermodynamic equilibrium are called as non equilibrium thermodynamics. The most number of systems in the nature are non equilibrium because of continuous and discontinuous subject to flux of matter and energy and not in the stationary state to and from other systems. The macroscopic thermodynamic methods nowadays which are the natural systems beyond the scope are the natural systems.

1.3 LAWS OF THERMODYNAMICS

1.3.1 First law

Internal energy of isolated system is constant.

It is an expression of principle of conservation of energy and generally it states that energy cannot be created or destroyed but can be transformed. The formulation of first law states that the heat supplied to the system and work done by the system is equal to the closed thermodynamic system's change in internal energy. The one thing which we have to note is work and heat modifies the state of system whereas internal energy is a state of the system.

1.3.2 Second law

Heat cannot spontaneously flow from a colder to hotter location.

It is an expression of universal principle of observable decay in nature. In a physical system which is isolated from outside world the difference in temperature, pressure, chemical potential and time will tend to even out. To know about the progress of this system entropy is the measure. Maximum entropy production principle is one of the guiding systems which are far from equilibrium which is still one of the debatable topics. In order to maximize its entropy production non equilibrium system behaves as the way. This law is applicable to any system which involves in heat energy transfer in classical thermodynamics and as a consequence of randomness of molecular chaos which is assumed in the statistical thermodynamics.

1.3.3 Third law

As a system approaches absolute zero, all processes and entropy of system approaches a minimum value.

This law express about the impossibility of reaching absolute zero of temperature and statistical law of nature regarding entropy. Absolute reference point for the determination of entropy is provided by this law. The absolute entropy is the entropy determined relative to this point.

1.3.4 Zeroth law

If two thermodynamic systems are each in equilibrium with third one then all will be in thermal equilibrium.

It is not named as the law initially because its basis is implied in the other laws. Once importance of the definition of temperature is realized it was named as zeroth law. If the small random changes between the systems does not lead to change in internal energy then are in equilibrium. Definition of temperature and justification for the construction of practical thermometers are provided by this law. If two bodies are at same temperature then it is not necessary to bring them in contact and measure the changes of their properties in time.[1]

1.4 STATES AND PROCESSES

Under given sets of conditions when the system is at equilibrium then it is in definite thermodynamic state. Number of state quantities which describes the state of the system does not depend on the system from which the system arrived. Equations of state specify the relationship between the intensive and extensive variables are how which properties of system is described. The energetic evolution of thermodynamic system which proceeds from initial to final state is defined as thermodynamic processes. It can also be called as process quantities. From parameters such as temperature, pressure and volume thermodynamic process is distinguished form other processes.

- Adiabatic process – occurs without loss or gain of energy by the heat.
- Isenthalpic process – occurs at constant enthalpy.
- Isentropic process – occurs at constant entropy.
- Isobaric process – occurs at constant pressure.
- Isochoric process – occurs at constant volume.
- Isothermal process – occurs at constant temperature.
- Steady state process – occurs without a change in internal energy.

1.5 SYSTEM MODELS

The main concept of the thermodynamic system is everything in the universe except the system is called as surroundings. A system which is separated from the remaining universe by boundary defines a finite volume. Exchange of any source between the surroundings and the system will takes place along the boundary. Change in internal energy of that volume is the dotted lines of the volume. Energy balance equation is determined by the object which passes through the boundary that affects the change in internal energy of the system.

Generally fixed, movable, real and imaginary are the types of boundaries and the three classes of this system is given by open, closed and isolated.

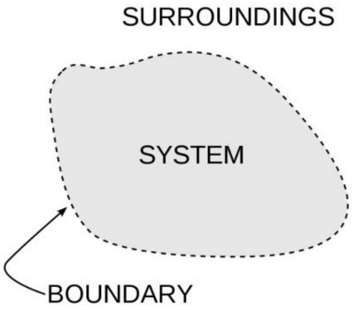


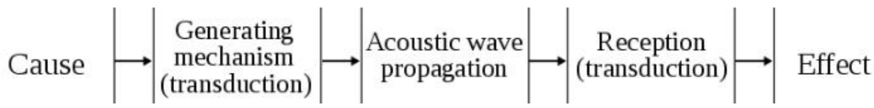
Figure 3 Generic Thermodynamic system

1.6 ACOUSTICS

It is one of the branches of physics generally deals with mechanical waves in all forms of states including the topics such as infrasound, vibration, ultrasound and sound. The main application for this field is that to reduce the sound and noise pollution in various types of industries.[3]

1.6.1 FUNDAMENTAL CONCEPTS

It is basically propagation, generation and reception of mechanical waves and vibrations are revolving around the acoustical studies.



Every acoustics work will go through the above steps but the situation will decide the process and the progress. The basic cause can be both natural and volitional. And there are so many types of transduction process available.

Acoustic wave equation is one of the basics which describe the sound wave propagation and this wave equation generally deals with the propagation of acoustic waves only through material medium. The wave equation expressing sound in one dimension is

$$\frac{\partial^2 p}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t} = 0, \qquad (1.1)$$

Where, p is the acoustic pressure (pa), c-speed of sound, x-position, t-time, µ-velocity(m/s)

That is also expressed in three dimensional as

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 \mu}{\partial t^2} = 0, \tag{1.2}$$

And for the vector field particle velocity the acoustic pressure is replaced by the velocity and it is given as

$$\nabla^2 \mu - \frac{1}{c^2}\frac{\partial^2 \mu}{\partial t^2} = 0, \tag{1.3}$$

∇ - Laplace operator

The middle stage is wave propagation and in fluids sound propagates as pressure wave. In solids mechanical waves can take different forms like longitudinal waves, surface waves and transverse waves. Acoustics give primary importance to pressure levels and frequency in the sound wave and also how it interacts with the surroundings. It can be described as diffraction, reflection and interference or the mixture of the all three.

1.6.2 TRANSDUCTION

It is basically a device which is used to convert one form of energy to the other and in this sound energy is converted into electrical energy. Loudspeakers, microphones, hydrophones and sonar projector will come under the electro acoustic transducers. Exactly sound pressure wave is converted to make an electric signal. Electromagnetism, electrostatics and piezo electricity are the transduction principles which were generally used.

Figure 4 Transducer [4]

1.7 THERMOACOUSTICS

Interaction between density, temperature and pressure variations of the acoustic waves is defined as thermo-acoustics.[5] It generally combines the branches such as acoustics and thermodynamics together in order to move the heat by using sound. The macroscopic effects of the sound transfer like motion oscillations and coupled pressure are the ones in which acoustics primary concern. Microscopic temperature oscillations that follow this change in pressure are generally focused by thermo-acoustics. By the help of these pressure oscillations to move the heat to a macroscopic level is an advantage to thermo-acoustics. And this will result in a large temperature difference between the cold and hot sides of the device and will cause refrigeration In this method heat engines are driven by using solar energy or unused heat. And for refrigeration it uses high intensity pressure waves in pressurized gas tube to pump heat from one place to other and this will produce the refrigeration effect. But, in this work we will see about the refrigeration effect only.[6]

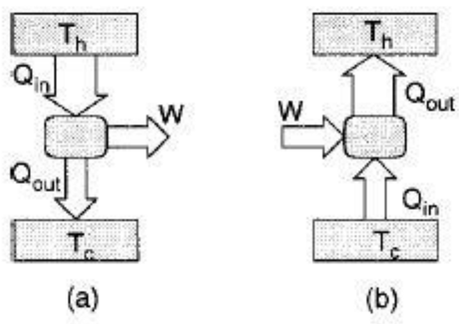


Figure 5 Basic action of (a) heat engine, (b) refrigerator

The components used in thermo-acoustic devices are simple when compared to the conventional engines. So, it can be controlled and maintained easily. We also have an technological advantage which is no moving parts makes it attractive for the various applications where key importance is reliability. Acoustic wave, pressure and density are not only dependent but also temperature and entropy. And the cycle of thermo-acoustic oscillation is the combination of pressure changes and the heat transfer in sinusoidal pattern.

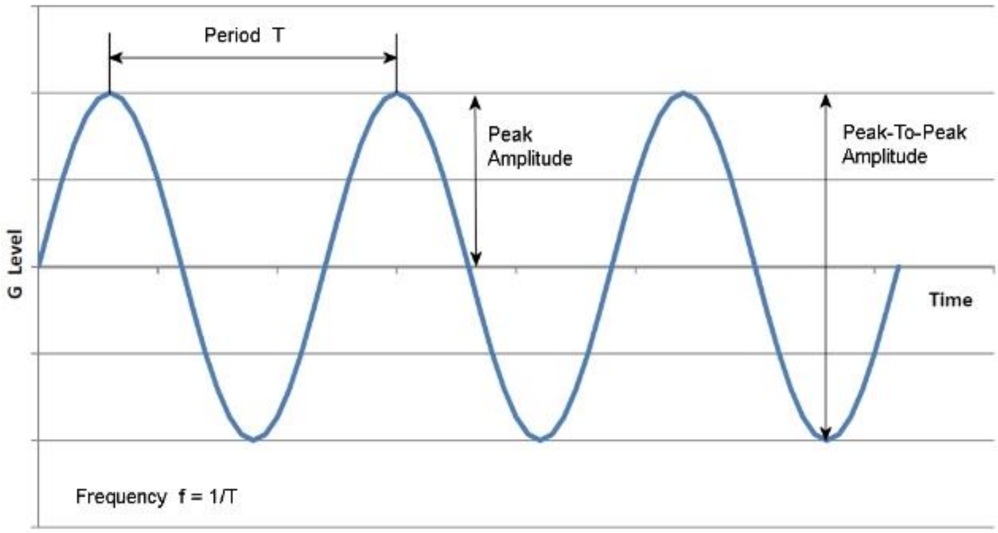


Figure 6 Sinusoidal wave patterns

1.7.1 PRINCIPAL CHARACTERISTICS

Basically there are four interesting characteristics which are interest in the field of energy harvesting.

(a) The working gas should be inert or noble.

(b) It is extremely versatile and capable of operating over wide range of temperatures because the process involves no phase change.

(c) Proportional control system is used rather than binary because it will allow the device to run at exact power output for a given load.

(d) There are very few inherently simple moving parts and therefore may be the possibility of being economic and reliable to produce.[2]

1.7.2 CLASSIFICATION OF THERMOACOUSTIC DEVICE

Thermo-acoustic device are generally classified into two types. They are given below

1. Refrigerator or heat pump
2. Engine or prime mover

(a) Standing wave device (b) Travelling wave device

REFRIGERATOR

These are the devices in which will utilize an acoustic pressure wave to generate a temperature differential across the stack.

ENGINE

And these are the devices in which exploit the temperature differential across the stack to amplify an acoustic pressure wave. [7]

STANDING WAVE DEVICE

These are the device which are specially designed to withstand the standing wave and has the advantage of phasing between the pressure amplitude and velocity which facilitates the thermo-acoustic effect.[8]

TRAVELLING WAVE DEVICE

These are the devices in which the acoustic wave transverses the device in the wave propagation direction

The figure explains the basic operation of heat engine and refrigerator.

(a) In heat engine heat is transferred from high temperature to low temperature reservoir by doing the work in the process.
(b) In refrigeration it is vice versa, that is from low temperature to high temperature from the externally applied work and that is supplied by standing wave in the resonator. [9]

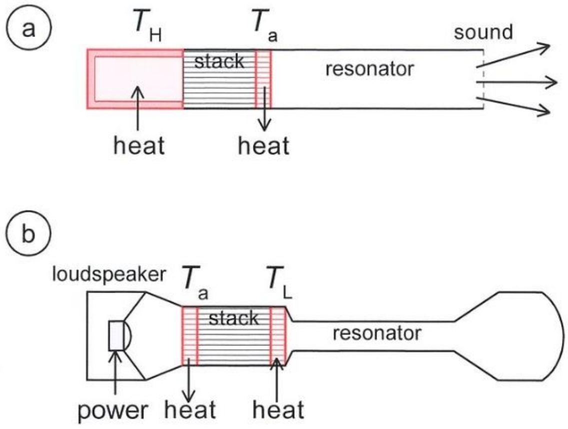


Figure 7 Schematic diagram of thermo-acoustic (a) mover, (b) refrigerator [7]

1.8 THERMOACOUSTIC REFRIGERATION

In order to create peaceful environment for both manufacturing field and humans, air conditioning is the must one but expensive. Still we have many improved technologies there is still lot of green house gas emission which leads to global warming. So, to reduce that thermo-acoustic refrigeration is a best alternative which is cheap and consumes lower energy. Basically refrigeration depends on two major thermodynamic principles.[10]

- Fluid's temperature will rise when it is compressed and temperature will reduce once it is expanded.
- When two substances are placed in contact with each other heat will always flow from hotter substance to the cooler substance. [10]

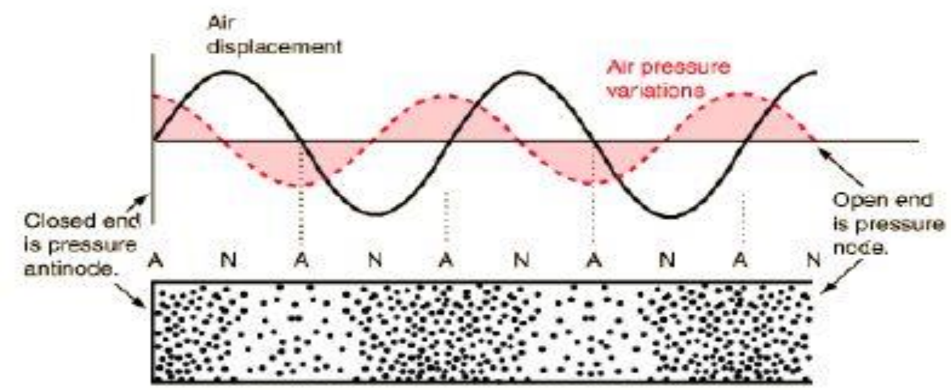


Figure 8 Relationship between phase of wave, pressure and actual arrangement of molecules [11]

The major highlight is that in normal refrigerators use the pump to transfer heat on a larger scale. But the thermo-acoustic refrigerators mainly rely on the sound to generate pressure waves which alternatively expand and compress the gas particles within the closed tube.[12]

1.9 STIRLING CYCLE

Refrigerator operates on the same principle of heat engine cycle but in reverse direction. In a heat pump it requires an input work to transfer heat from the cool container to the hot one. This heat pump cycle is the basic mechanism from which the refrigerator will work. In the Stirling cycle there will be an external heat source which transfers heat into the gas in the chambers. Heat in the expanded gas can go into cooler chamber by the metal fins of the heat sink from which the chamber into the gas expands. After this gas will compress and the piston will come to the rest position. This will be useful because we can power by any external power sources such as solar, nuclear and etc.

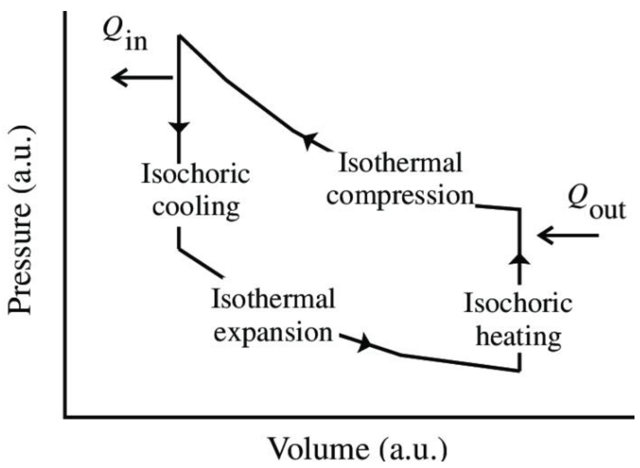


Figure 9 Ideal Stirling cycle [2]

In line with the second law of thermodynamics network input is necessary reversed Stirling cycle and also in any other refrigeration cycle. Temperature of system during compression is on average, higher than using expansion. And that is happened because of shutting of gas in system backwards and forward between hot end and cold end spaces.

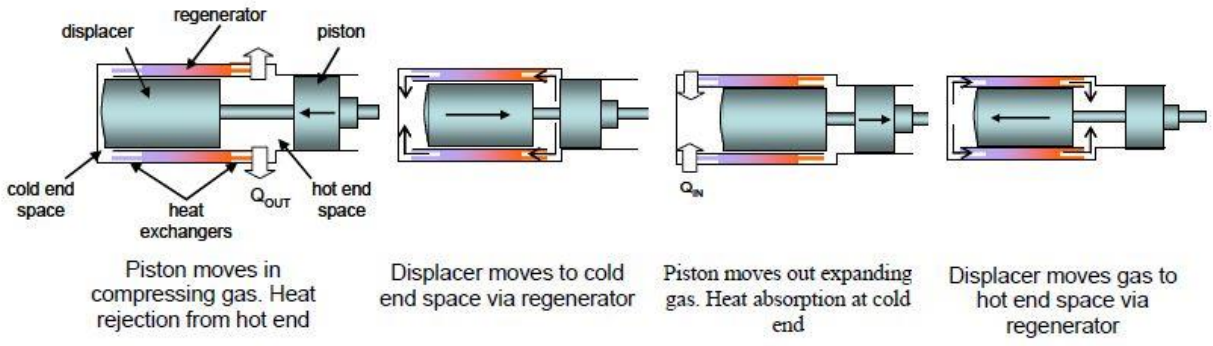


Figure 10 Piston and displacer movement during refrigeration cycle [13]

1.10 THERMOACOUSTIC CYCLE

The basic thermodynamic cycle principle is heat enters hot container, moving the piston (work comes out from the engine) and finally heat dissolute into cooler containers.

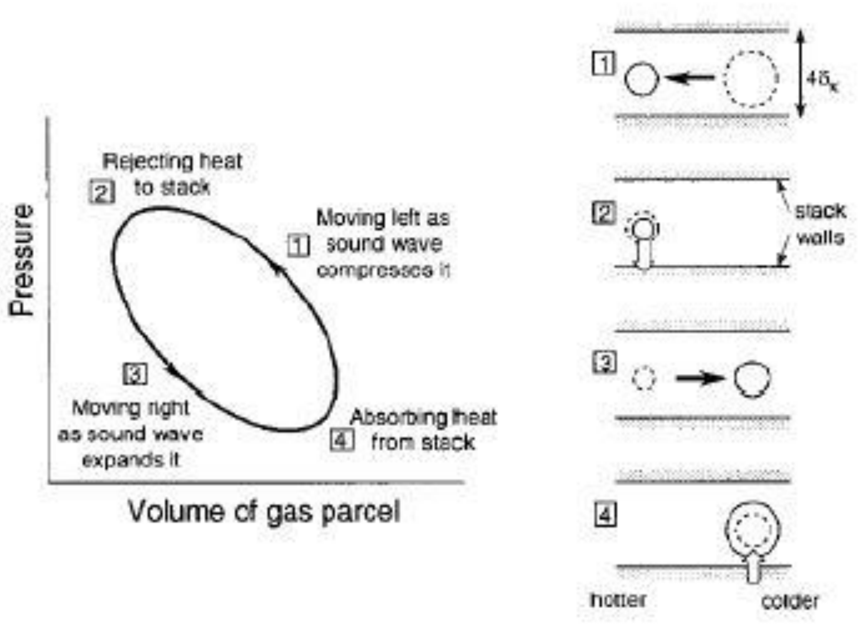


Figure 11 Stages of thermodynamic refrigerator cycle [14]

1.11 THERMOACOUSTIC EFFECT

It is the conversion of sound energy to heat energy or vice versa. By utilizing the thermo-acoustic effect both engine and refrigerators can be developed that will use heat as source of energy and having no moving part. In order to explain the thermo-acoustic effect consider by the help of loud speaker a sound wave is generated in a tube. We have stack of plates in the tube and one end should be hot and the other end is cool and put onto that tube. Then we are creating a high sound energy by external source in the tube and use that sound to cool another part of the tube by heating the other end by sound waves. It can also works in reverse.[15]

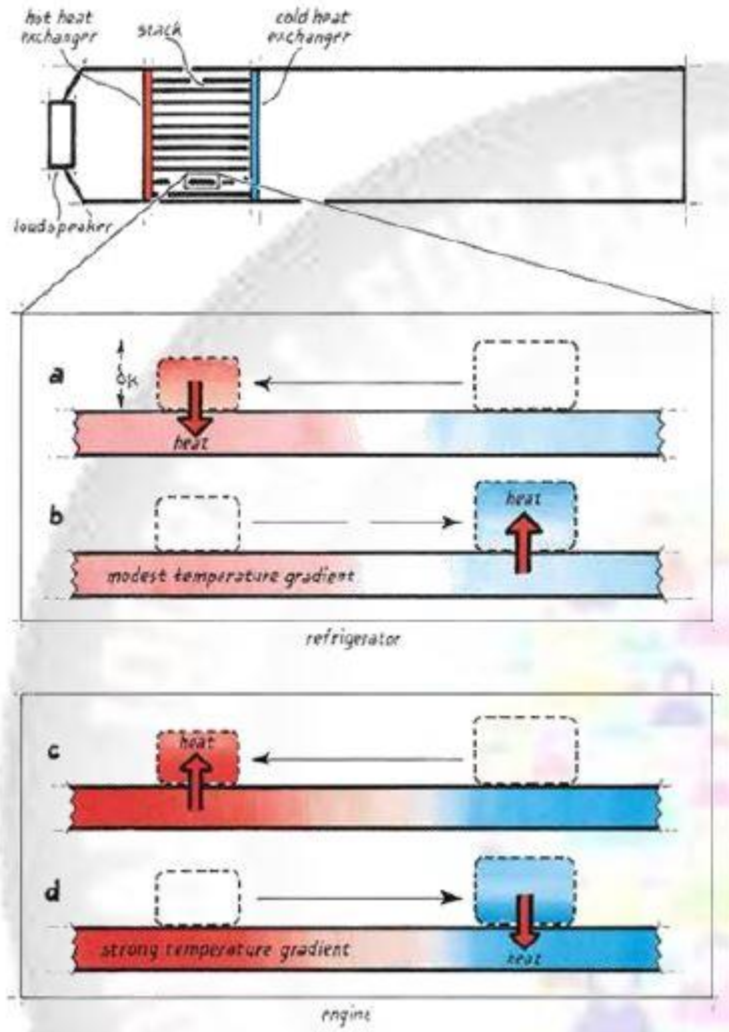


Figure 12 Transformation of heat energy into acoustic energy [15]

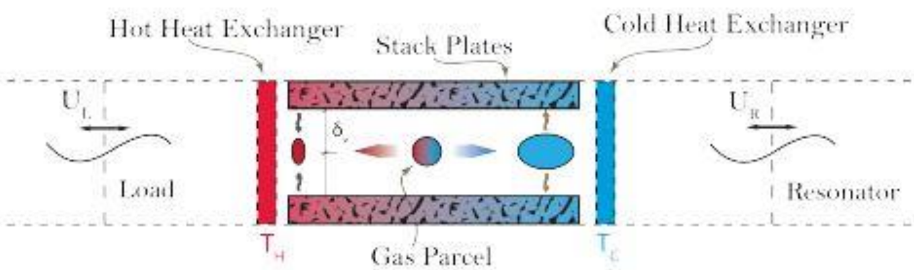


Figure 13 Heat transfer between plates in thermo-acoustic engine[2]

1.12 CRITICAL PARAMETERS

Critical parameters are associated with thermo-acoustic devices which are generally non linear and inter dependent. It is possible to evaluate each parameter independently. The coupled effects of every parameter make numerical modeling expensive.

1.12.1 STACK GEOMETRY

Stack is the most important component in the thermo-acoustic device. The stack consists of large number of closed spacing surfaces that are aligned parallel to the tube. The main purpose of stack is to create a medium for the heat transfer as the sound waves oscillates through the resonator tube. In general heat transfer occurs between the gas and the cylinder wall. Most of the stacks are honey combed model of plastic spacing which do not conduct the heat throughout the stack but absorb heat. By this property the stack can absorb heat by sound waves. The spacing design is very important because if holes are big it is difficult to fabricate and the viscous properties of air will make it difficult to transmit the sound through the stack. If walls are too far only less amount of air will be transfer heat to the walls which will result in lower efficiency.

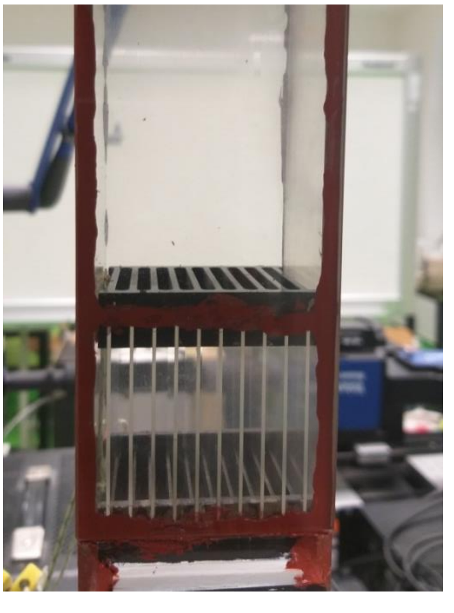


Figure 14 Stack region

1.12.2 PLATE SPACING

It is one of the basic methods to the way in which the device works. It is the function of viscous and thermal penetration depth of working fluid and ratio of square of these two values which is generally called as Prandtl number.

$$Pr = \frac{\mu\, c_p}{k}, \tag{1.4}$$

$c_p -$ *specific heat capacity at constant pressure*, $\mu -$ *dynamic viscosity*,

$k -$ *thermal diffusivity*

In the standing wave pressure and velocity are 90° out of phase. There are three different types of stack plate placing and they are given below

Figure 15 Types of plate spacing [2]

1.12.3 CRITICAL TEMPERATURE GRADIENT

It is generally described as the temperature gradient through length of stack plates in direction of wave propagation which match along with the temperature change in the working fluid. During compression, temperature gradient of plate and rarefaction the hysteresis loop is undergone by the gas. No acoustic work is done by the system under these conditions. Gas in contact with the each point in acoustic cycle is approached by temperature of the plate. Onset temperature gradient is one of the most useful parameter. It is defined as the gradient at which acoustic work is done can be made by two ways. Either pumping up or down the temperature gradient in figure 16(a) or through amplification in figure 16(b). Non isothermal process is assumed to be in the stack but acoustic attenuation which is not evaluated is influenced by conductivity of material through the length of the stack.

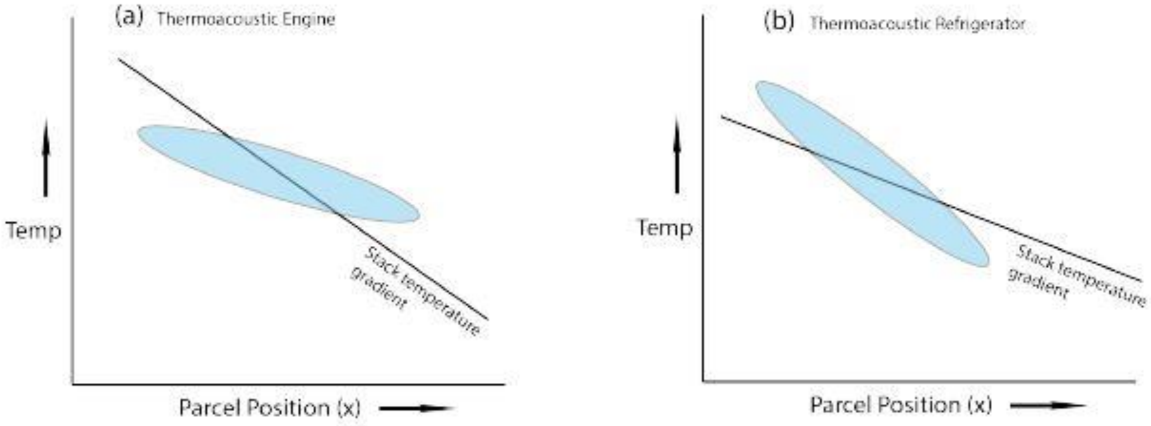


Figure 16 Onset temperature gradients [2]

1.12.4 WORKING FLUID

Efficiency of thermo-acoustic device and performance are having significant impact based on the working fluid. In the lightest gas like (He,Ne,H_2). Speed of sound is high and they are suited for low temperature only with application of heavy gases which condense, freeze and behave none ideally. This will leads to thermal penetration depths and in order to optimize the critical performance parameter range of predominantly binary mixtures have been used. The working fluid used in this experiment is gas. There are certain properties in which the working gas must confess.

They are given below,

(a) Ratio of specific heat capacities
(b) Viscosity
(c) Density
(d) Thermal conductivity
(e) Isothermal and adiabatic bulk modulus
(f) Environmental impact

2. DESCRIPTION OF THERMOACOUSTIC DEVICE

The thermo-acoustic device which is used is the standing wave model. It consists of a quarter wavelength resonator which is open in one end and closed in the end which has the loudspeaker. This the simplest way built and it has the least efficiency. It doesn't really matters because this device is specially designed to explain the action of an acoustic refrigerator. So this is the primary purpose and efficiency is the secondary thing. The resonator of this device is 0.5M length of acrylic tube with an inner diameter of 2.2 cm. always the resonance frequency of the system is defined by the length of the tube. In our case from the given parameters and the known properties and values we can find the frequency that have to be generated from the speaker. One end of the tube is connected to the speaker and the other end is open in order to pass the particles inside the stack region. In an acoustic refrigerator or either in the heat engine stack plays a very important role and also the very critical part of the system. In this device the stack is present in the inside diameter regions with the adjacent layers on both side surfaces. Both the top and bottom region of the stack is covered by the plastic layer. And at the end of the stack region both the heating and cooling coils are present in the opposite surfaces parallel to each other which is already connected to the thermocouples. Spacing between the stack is the most essential property in building the device. As we already know that if walls are too close sound cannot pass through the stack with more efficiency. And if the stack walls placed very far apart then the process does not occur because gas particles are very far away from the wall to effectively transfer the heat. Then the thermal penetration depth is the most important factor. It is basically defined as the distance heat can diffuse in a gas over a certain period of time. For example- if an Aluminium block is kept at constant low temperature and then instantly introduced to a very high temperature the distance that the heat will penetrate the block in one second is the heat penetration. [16]

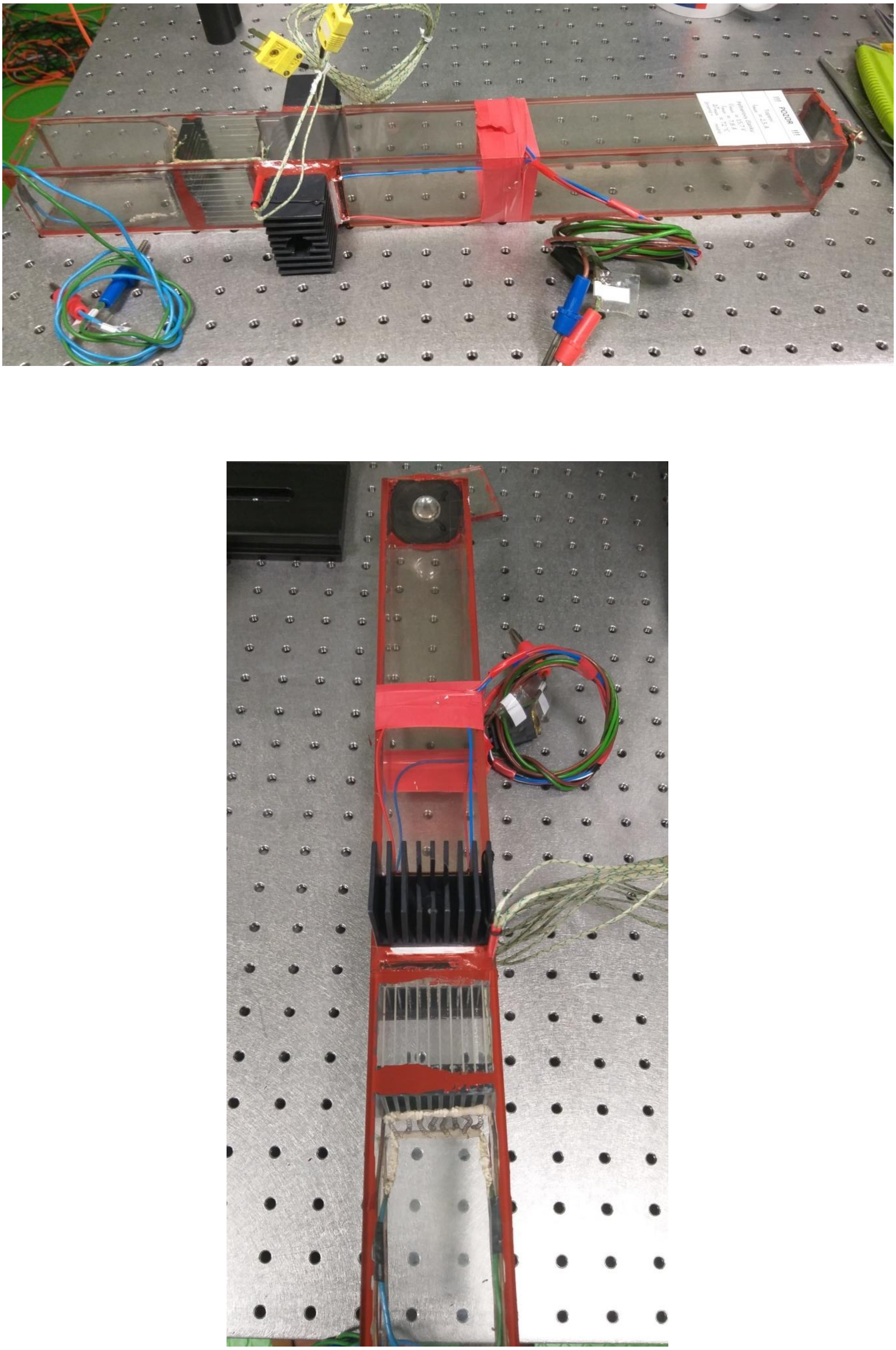


Figure 17 Thermo-acoustic devices

But since the sound waves are oscillating between the sources and sink the thermal penetration will be almost constant. The thermal penetration depth for an oscillating heat source is function of frequency of standing wave (f), density () and thermal conductivity (K). As well as the isobaric specific heat per unit mass of the gas is c_p. It is given by

$$\delta_k = \frac{\sqrt{K}}{\sqrt{f \times \rho \times c_p}} \tag{1.5}$$

Then the two thermocouples were made by constant wires together by soldering the copper. One is inserted to the outer winding to detect the temperature below the stack and the other one is fixed to control the temperature above the stack. Leads of both of them are passed through to the end of the tube. To measure the temperatures in the stack we are using digital multi meter.[17]

3. PARTICLE IMAGE VELOCIMETRY

3.1 INTRODUCTION

Particle image velocimetry (PIV) is an optical method of flow visualization which is mainly used in research and education. In order to get related properties in fluids and instantaneous velocity measurements this methods are used. In sufficiently smaller particles it is assumed to faithfully follow the flow dynamics, when the fluid is seeded with tracer particles. The particles are visible because the fluids with entrained particles are illuminated. Then the speed and direction of the velocity field of the flow is calculated by using the motion of the seeding particles. Hot wire anemometry and laser Doppler velocimetry are the other techniques used to measure the flow. Particle image velocimetry produces two dimensional or even three dimensional vector fields which is the main difference between PIV and other techniques because in those methods it will only measure the velocity at single point. The particle concentration is such that it is possible to find individual particles in a image but not the certainty to track it between the images. Particle tracking velocimetry is used when particle concentration is very low and in case of very high particle concentration laser speckle velocimetry is used to observe individual particles in an image. [18]

Normal PIV apparatus consists of a digital camera with CCD (charged coupled device) chip, a synchronizer which is the main control for the laser and camera, seeding particles and fluid under the investigation and a laser with an optical arrangement in order to limit the physical region. Fiber optic cable will connect to the lens setup from the laser. Post processing the optical images is done by the PIV software.

3.2 HISTORY

In the early 20th century Ludwig Prandtl was the first one to use particles to study the fluids in a systematic manner. To find the flow in a fluid by using the method of adding objects or particles have been used from long time through the ages and no sustained method of the application is known. For the widespread of research and industrial use laser Doppler velocimetry is used as the laser digital analysis. But from this method we can obtain only the two dimensional fluid velocity measurements. Later PIV found the laser speckle velocimetry and new technique experimenting in late 70s and came to field in the 80s with the advantage of particle concentration is decreased to certain levels. So that individual particles can be observed. And it is very easy to study the flow when they were split into many interrogation areas which can be analyzed separately by it to generate the velocity to each area. Analog cameras are used to record the images and also we need large amount of computing power for the analyzing process.

3.3 EQUIPMENTS

3.3.1 SEEDING PARTICLES

The critical component of the PIV system is seeding particles. Particles must match with the fluid properties well so the fluid has gone through some investigation. Because if not they will not follow the flow enough to make an accurate PIV analysis. Ideal particles will have some density as fluid system which is used and they are spherical. And the actual particle is independent of the fluid. In general for macro PIV investigations they are poly styrene, poly ethylene, Aluminium flaks and oil droplets but only if the investigation of fluid is a gas. Refractive index of seeding particle and fluid which they are seeding should be different in order that laser sheet incident on fluid will reflect of the particles and scatter towards the camera. Usually the diameter of particles is 10 to 100 micro meters. Just for sizing the particles should be small so the response time to particles to the motion of the fluid is very short. But large enough to scatter the significant amount of laser light. For some process which involves combustion it is just 1 micro meter to avoid the quenching effect which they have on flames. Stokes drag and settling dominate the particle motion due to its small size. Spherical modeled particles are having very low Reynolds number. The ability of particles to follow the fluid is inversely proportional to the square of their diameter and also inversely proportional to the difference in density between the particles and fluid. Then the size of the particle should get balanced in order to scatter enough light to visualize all particles within the laser sheet but very small enough to follow the flow. So it is designed to seed the flow to a significant angle without disturbing the flow.

3.3.2 CAMERA

Two exposures of laser light is required upon camera from the flow to perform PIV analysis on that. Camera has a disadvantage of capturing multiple frames at high speed. So both exposures are captured on the same frame and the same is used to determine the flow. Auto correlation is the process used for this analysis. But the direction of flow is not very clear in the Auto correlation result because the particle spots from first and second pulse are not clear. So, faster digital cameras with CCC or CMOS (complementary metal oxide semi conductor) chips are developed, but they are more expensive. It can capture two frames at high speed within a few 100 nanoseconds difference between the frames. This will allow each exposure to isolate on its own for more exact cross correlation analysis. Limited pair of shots can be transferred to computer before another pair can be taken. Normal cameras can take only up to few pair of shots that too in slower speed.[19]

3.3.4 LASER AND OPTICS

Because of the ability to produce high power light beams with short pulse durations lasers are pre dominant for the macro PIV set ups and this leads to short exposure time for each frame. Nd:yag lasers are generally used in PIV set ups. For safety reasons its band pass is filtered to 532 nm harmonics from its basic emission of 1064 nm wavelength and harmonics. In order to direct the laser light to the experimental set up a fiber optic cable is used. Both spherical and cylindrical lens combination are present in the optics. The work of cylindrical lens is it will expand the plane and the spherical will compress into thin sheet. PIV technique does not measure normal motion to the laser sheet because it is critical and eliminated ideally by maintaining two dimensional laser sheets. The ideal location to place the analysis area of experiment is minimum order wavelength of laser light occurs at a finite distance from the optical set up. In order to get the proper focus and visualization of particles in the investigation area contact lens for the camera should be selected.

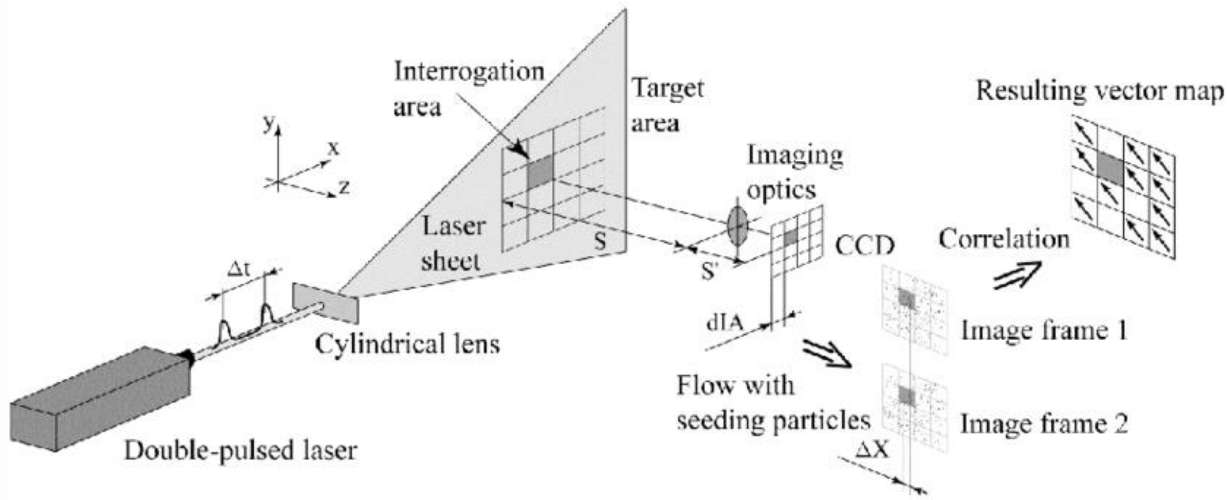


Figure 18 Working principle of PIV [19]

3.4 SYNCHRONIZER

The external trigger acts for both camera and the laser is called as a synchronizer. Instead of using light aperture and photo sensors in the past now we are using digital everywhere. Synchronizer will dictate the timing of each frame controlled by the computer of CCD camera sequence in coordination with the firing of laser with its precision. In reference to the timing of camera the time between each pulse of laser and the laser shot placement can be exactly controlled. In order to determine the velocity of fluid in the PIV analysis timing knowledge plays a crucial role. Generators as low as 250 PS to high MS stand alone electronic synchronizers are used which is called as digital delay generators.

3.5 ANALYSIS

Large numbers of windows or interrogation areas are splits from the frames. Displacement for each window can be calculated with the help of Auto correlation and signal processing techniques. Each pixel on the camera physical size and time between laser shots are converted in to the velocity by using the above. The number of interrogation window should be minimum 6 particles per window on average. Image pair acquired at various regions in the flow and the timing between image exposures can be controlled by using the synchronizer. Because it is the ideal region of the flow for an accurate PIV analysis which should have an average particle displacement of 8 pixels and this will make the particles further between the frames which results in harder to find interrogation window and the worst case in short time spacing as we cannot identify the displacement itself within the flow. 2 to 4 pixel across the image should be the scattered light from each particle of the region. Peak locking will occur once the large area is recorded and there is also some extra techniques to overcome the peak locking effect. Research grade PIV and custom PIV systems are also possible to build with high end camera specifications and high power lasers.

3.6 COMPLEX PIV SETUPS

There are many different types of complex PIV setups are available and are used in various fields and they are given below as,

(a) Stereo-scopic PIV
(b) Dual plane stereo-scopic PIV
(c) Multi plane stereo-scopic PIV
(d) Micro PIV
(e) Holographic PIV
(f) Scanning PIV
(g) Tomo-graphic PIV
(h) Thermo-graphic PIV

3.7 ADVANTAGES

- There will be distortion of the fluid flow because of the added tracers.
- Non intrusive methods are preferred for the larger angle.
- Measurement does not need any pitot tubes, hot wires and intrusive flow measuring probes.
- In this method we can measure totally two dimensional cross section of the field.
- Large number of image pairs can be generated because of high speed data processing.

3.8 DRAWBACKS

- It does not follow the motion of fluid due to high density.
- Fluid velocity or size of object will change because of the change in Reynolds number which is due to the density of fluid increase or decrease its temperature.
- Measuring components along the z axis is not possible in this method.
- It generally uses class Ⅳ lasers which is highly expensive and has some safety factors.

3.9 APPLICATIONS

Real time processing and application of PIV became possible because of the advanced digital technologies. GPUs can be used to level up Fourier transform based correlations of single interrogation windows. In order of multiple interrogation windows or the multiple images the beneficial one are multi- processing and multi- threading. It can be applied to wide range of problems which are varying flow over an aircraft wing in the wind tunnel. In order to analyze the jet and turbulent flow the 3D techniques are more often used. For the future use in active flow control along with the flow based feedback processing and PIV real time measurement are imposed. [19]

4 EXPERIMENTAL SETUP

The most crucial among all other thing is the experimental set up. Before explaining about that let us see the important components which are used. Thermo-acoustic device, laser, camera, signal oscilloscope, function generator, power amplifier and the particles. Each and every component is important because all are inter connected and reliable to each other.

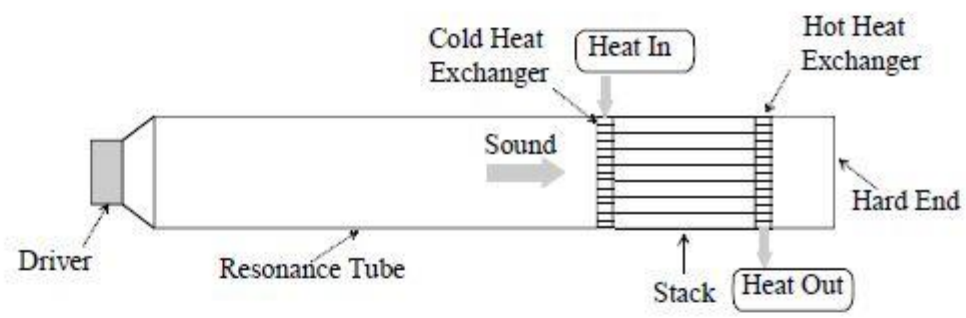


Figure 19 Illustration for thermo-acoustic refrigerator [17]

Experimental set up mainly has 3 major parts like instrument or device which is required for measurement, region of stack and the cooling region and finally the whole set up for the accurate acquisition for data. First and foremost is the mounting of the thermo-acoustic device in the space in which the camera will capture and should also within the range of laser. It doesn't have lot of difficulties in the case of laser because for the laser mounting with respect to the thermo-acoustic device there will be Guide lines. From the base of the table in which we are measuring a vertical rod is mounted and the laser is fixed on the top of the rod. Before the reading first the calibration should been done. So for the calibration instead of using the thermo-acoustic device the laser sheet is used.

4.1 CAMERA

First the camera CCD for digital imaging has become the major technology in the recent years. It works mainly on the principle that is signals between the stages within the devices are shifted one at a time. Charge between the capacitive bins is moved by the CCD's. Pixels are given as p-doped metal oxide semiconductors (MOS) capacitors in a CCD image sensor. When there is image acquisition which allows the conversion of electron charges from the incoming photons at the semiconductor interface. Though they are not the only technology for light detection but are widely used in medical and scientific applications. For the lesser quality demands Complementary metal oxide semiconductors (CMOS) are used and the advantage of using CCD was shortened over the years. Shift register is the main source for the built up of the transmission region and photoactive region. Each capacitor will accumulate an electric charge proportional to light intensity in that particular region caused by an image which is projected through a lens to the capacitor array. For line scan and single slice of an image one dimensional array is used and for videos two dimensional arrays is used respectively. Content of the capacitor is transferred to the neighbor who is caused by the control unit only when the array has been exposed to the image. Then last capacitor of the array deposits its charge to the charge amplifier which is used to convert the charge into a voltage. We can get the entire content of array in to charge by repeating the above process. In an analog device they are processed and given to other circuits for transmission and recording. But in the digital the voltages are digitized, sampled and stored in the memory. So in the CCD camera the external scope for the clear picture is removed because the object will be not very far from the focus and also for clear shot. Then it is attached to the stand which is separately there for the cameras according to the target which is the stack region in our case.[20]

4.2 POWER AMPLIFIER

Then the next important component is the power amplifier. An amplifier can be a electrical circuit within the another device or also can be a separate piece. It can be categorized in many ways such as audio amplifier which is used to amplify the audio signals with less than 20 kHz and also as server and instrumentation amplifiers which will reduce the frequencies to lower level down to the direct current. There are different types of amplifiers available according to the source and need. They are active devices, operational amplifiers, distributed amplifiers, switch mode amplifiers, negative resistance amplifier and finally the power amplifier which we are using in this experiment. It is an electronic device which gives ample of power to an output load to drive a speaker but only for very small range in order to match the input signal shape with larger amplitudes. It is designed basically to increase power available to the load and it mostly depends on source, voltage and gain. The power amplifier is an actual circuit in a single chain and is in the stage that requires attention to the power efficiency. Based on

Figure 20 Power amplifier

Biasing outputs transistors or the tubes there are various classes of power amplifiers which is taken into consideration for the efficiency. Basically taking the energy form the power supply and controlling the output are done by these power amplifiers. From the gain, ratio of output voltage to the input voltage is how the amount of amplification produced by the amplifier is measured. [21]

4.3 FUNCTION GENERATORS

Then let us see about the function generators. It is a software or small device over a wide range of frequencies it will generate different types of electrical waveforms. Sine wave, square wave, triangular wave and saw tooth shapes are the most common waveforms which are produced by these function generators.

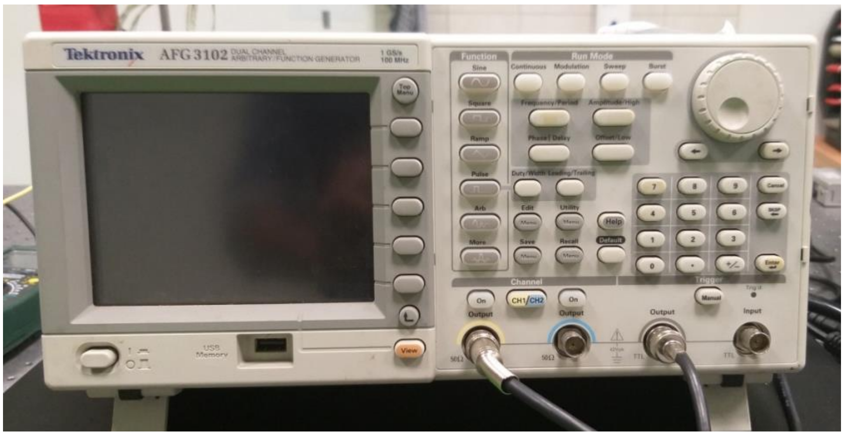


Figure 21 Function generator

They can be either single or multiple shots depending on the source and these waveforms are generated from the integrated circuits of function generator. They are not suitable for the stable or low distortion frequency signals but can be used to cover the audio and RF frequencies. So during these conditions the remaining signal generators are used. Sometimes they are phase locked to a function generator or external signal source. Working with analog circuits and related pulse generators are the primary function of the function generators. They usually generate triangular waveform on the basis for the outputs and can be continuously charging and discharging the capacitor from the stable current source. When there is change in upper and lower limits of output voltage it can be reversed by using a comparator. And the 50 percent of the cycle gets complete by the charging or discharging. Nowadays most of the function generators have the non- linear diode shaping circuit which converts these waves into sine wave by rounding of the corners. They also contain various modulating means, sweeping the frequency of output form between two operators and also an attenuator. This is the main factor which helps to get easy frequency response to the given electronic circuit. Arbitrary waveform generators (AWG) are the most advanced function generator. In order to generate any waveforms according to the given amplitudes they are using direct digital synthesis (DDS). [22]

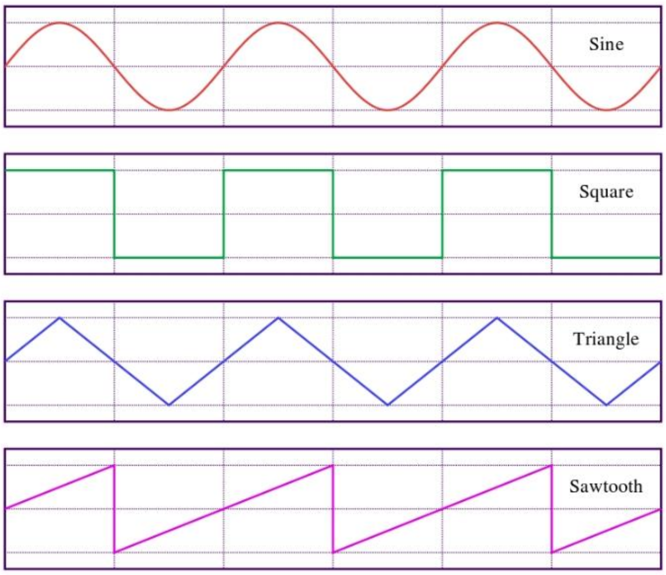


Figure 22 Types of waveforms [11]

4.4 SIGNAL OSCILLOSCOPE

And then now we are going to look after the device called as signal oscilloscope. It is generally used to analyze and display the electronic signals waveforms and because of this effect it will draw the graph for instant signal voltage as a function of time. Oscilloscope is an electronic instrument which displays signal voltages graphically as a two dimensional plot of one or more signal as a function of time. Remaining signals are displayed once they have been converted into voltages. It generally shows over time the change in electrical signal on a calibrated scale with time and voltage on x and y axis respectively. It can also be used to analyze the properties such as rise time, amplitude, frequency, time interval and distortion. They can be adjusted in order to observe the continuous shape on the screen. From the help of storage oscilloscope we can continuously display even the single shots. They are used in various fields such as medicine, engineering, automotive and telecommunications industry. The waveform of the heartbeat is displayed by the special type oscilloscopes which are called as electrocardiogram. Cathode ray tubes (CRT) are the early ones which is followed by the storage oscilloscopes later superseded by digital storage oscilloscopes (DSO) which are the fast processing from analog to the digital convertors. They are also available without the displays at low costs. Cathode ray oscilloscope, dual beam oscilloscope, analog storage, digital, mixed signal, mixed domain, handheld and pc based are the various types of oscilloscopes which are available and present. Signal oscilloscopes have large number of digital channels and two kinds of input. It has the ability to correlate the analog and digital channels of time. They are generally grouped and displayed with bus. Trigger can be set across on both the analog and digital channels on the most of the mixed signal oscilloscope (MSO).[23]

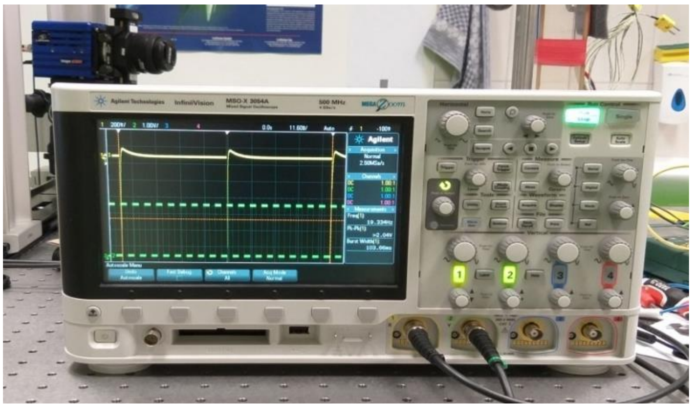


Figure 23 Signal oscilloscope

4.5 DC POWER SUPPLY

Then finally let us see about the power supply device which is also an important part of the set up. It is one of the electrical device which supplies electric power to an electric load. Its primary function is converting electric current to correct voltage, current and frequency to power the load. Basically there are three types of power supplies. They are given as linear regulated, switching and unregulated. Ripple regulated is the type which is the mixture of force and switching designs. Some of them are separate products which supplies power and some of them are built into a load that they have to power. There will be a power output which delivers current to the load and an input power connection receives energy from the source are the two which every power supplies will have. Electric outlet, energy storage devices such as fuel cells or batteries are the source from the electric power grid. The input and output are hardwired circuit connections and through some power they employ wireless energy transfer for the weird connections in order to power the load. And they will have inputs and outputs like monitoring and control for some of the power supplies. They are generally classified into functional, packaging and power conversion methods. There are so many types of power supplies are available even in the day to day life. They are switched mode power supply, DC power supply, linear regulators, AC power supplies and adapters, programmable power supply, uninterruptible power supply, Bipolar and high voltage power supply are the different types of power supplies. [24]

Figure 24 DC power supply device

There will be more heat generation from power supply of an electrical system. The more the heat is pulled away it will get more efficiency. For heating there are so many types but for cooling there are only two types which are very familiar to us conduction and convection. Natural and forced air flow and other liquid flow are the common convection methods for cooling. Followed by cold plates, heat sinks and thermal compounds are the common conduction cooling methods. For every device there should be some protection in order to the working safety and also to increase the device life time. So for that power supply device should have some protection like fuse, circuit breaker and PSUs. And other then this some supplies are using current limiting method. Basically they will choose one system according to the source and the situation they face and they have to react. They are commonly used in many fields such as computers, aircrafts, automation and medical.

4.6 WORKING

So we have seen about the devices which we are using in the experiment and the last one s which we have to discuss is about the particles. It is possible to use any gas for the flow inside the region and there is no restrictions except some rare gases which have some properties which changes continuously and the ones which are highly unstable. First the thermo-acoustic device is mounted parallel to the camera and the laser which are placed on the either sides of the device respectively. The three should be like the formation of triangle. The top side of the acoustic device is covered by the closed rectangular object. It is only used for the purpose of passing the particles in the stack region of the thermo-acoustic device. Then the loudspeaker is connected to the power amplifier I order maintain a certain frequency throughout the process because once it is supposed to change in any situation then we have again start the process and continue it to the place where we left it. So it is one of the most important parts. Then the power amplifier is connected to the function generator in order to know the waveform of the sustained work. And it will also control the system in various aspects. Next to that it is connected with the signal oscilloscope because we need to analyze the waveforms which we get through the function generators. Also the power supply device is connected to the source and the laser is calibrated according to our requirement. Once the set- up is done then the calibration is done with the laser sheet and once it is correct and gives the result which we need then we can precede to the main part.

This is the exact set up of the experiment which is explained as above. So once the set up is clear without any errors then there is very less possibility of mistakes and the better set up gives the better result.

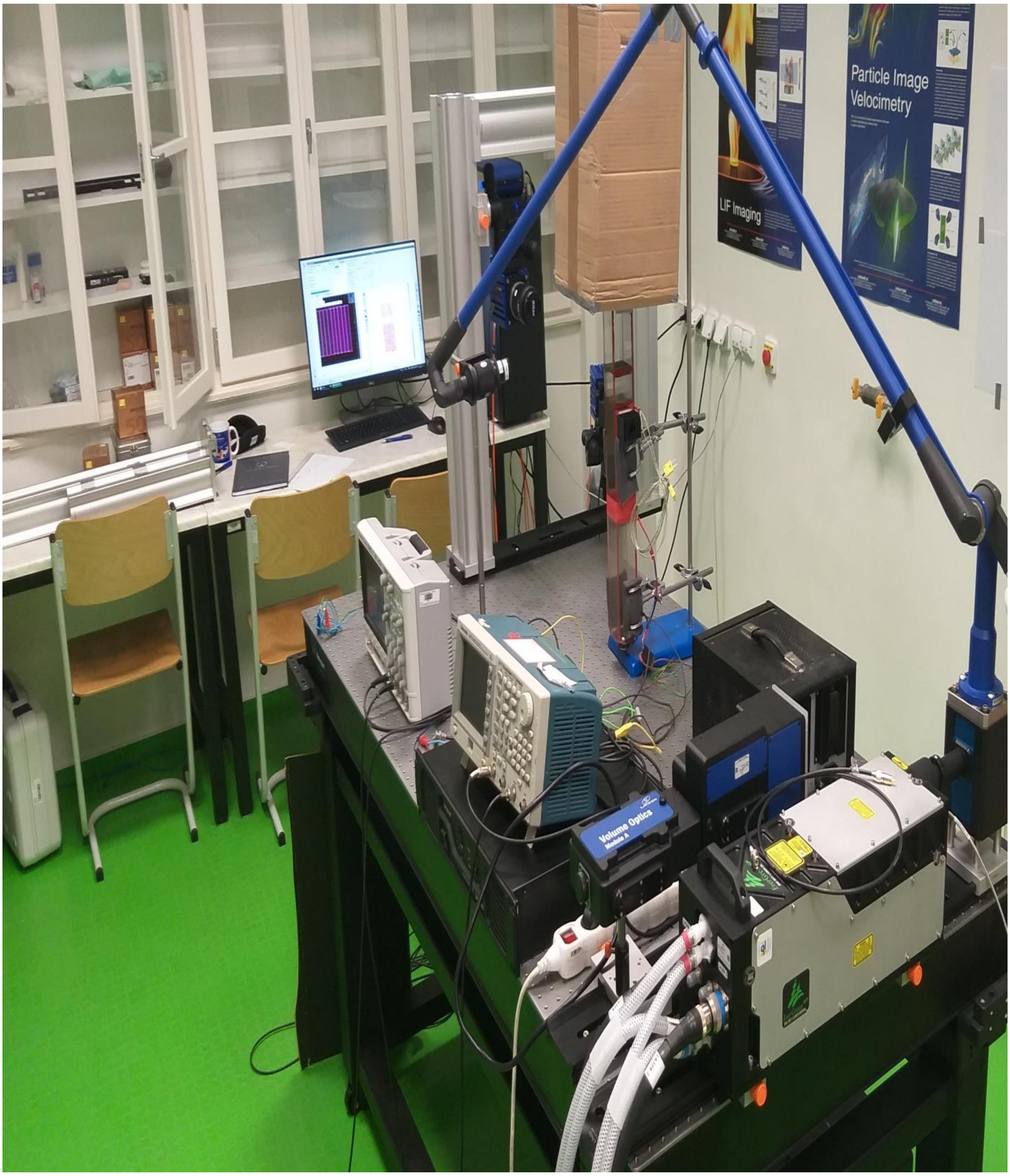


Figure 25 Experiment setup

4.7 SYNCHRONIZATION

It can be simply explained as managing of two or more things at the same time. So in the experiment while managing everything synchronization will play a very important role. In the electrical power system fields when multiple generators are connected to an electrical grid synchronization of alternator is required. Then here by finding the required frequency for the speaker by the velocity of sound to the total wavelength of the device. Once it is calculated then the system is synchronized for that frequency throughout the process. So it is like once the double beam laser is passed through the region and in the meanwhile by the help of power amplifier the frequency is made and the function generator is there to measure the waveform and in the stack region the particles are filled initially so once the laser is passed through that it is captured through the camera and also we can see the waveform type through the signal oscilloscope and the same process is done for different power supplies and once it is recorded then it has to be processed in the system with software related to this and after analysis we will get the velocity fields of the stack region. Other than this process cooling is also done. And for the cooling purpose the thermo-acoustic device is connected to the power supply and the outer region of cooling coil is generated some heat and the inner region is cooled. All the process which is done for the above normal method is applied to this and again the readings are taken. Once the measurement is done then again we have to process and after the analysis we can get the velocity fields for the cooled region.

4.8 CALCULATION

Known values

Length of the thermo-acoustic device = 0.5m

Total wavelength = 2m

Temperature of air = 25℃

Measured wavelength = $\frac{1}{4}$

Capacity of laser = 15 HZ

1. Velocity of sound a = $\sqrt{y \times r \times T}$ [25]

$$= \sqrt{1.4 \times 287.01 \times 298}$$

= 347 m/s

Where,

y – adiabatic constant, r – specific gas constant of dry air, T – absolute temperature

Wavelength of sound waves $\propto \frac{1}{\text{frequency}}$ [26]

W.K.T $\lambda = \frac{C}{\mathrm{F}}$

$$f = \frac{C}{\lambda}$$

$$= \frac{347}{2}$$

f = 173 HZ

Where,

λ - Total wavelength, f – frequency, c – velocity of sound in air

Note: if temperature is not given the velocity can be calculated by

C = $\sqrt{\frac{B}{\rho}}$

Where, B – bulk modulus of air [27], ρ - density

2. By another way we can get the frequency,

WKT, frequency of the wave travelling through a closed tube is given by,

f = $\frac{v}{4l}$

f = $\frac{347}{4 \times 0.5}$

f = 173 HZ

Where F = frequency, **ν** = velocity of sound wave, l = length of the tube.

5 RESULTS AND ANALYSIS

So let us see about the results for different variations along with different parameters. Figure 26 is about the measurement of velocity and figure 27 explains about the uncertainty and both are measured for 0.47w respectively.

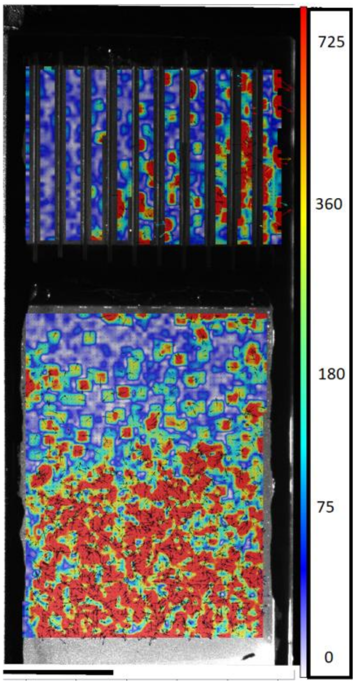


Figure 26 Velocity (m/s) at 0.47w

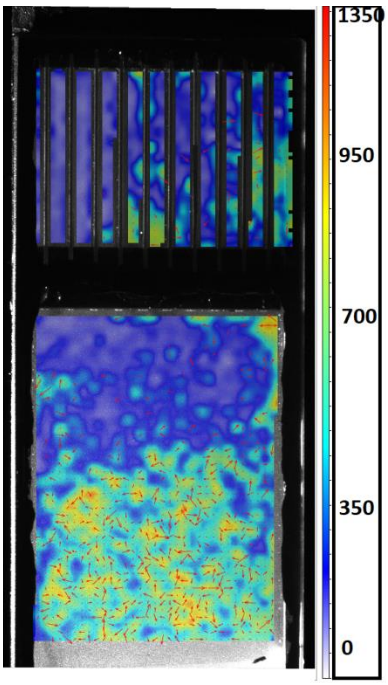


Figure 27 Uncertainty at 0.47w

Figure 28 is about the measurement of velocity and figure 29 explains about the uncertainty and both are measured for 0.5 w respectively at normal conditions.

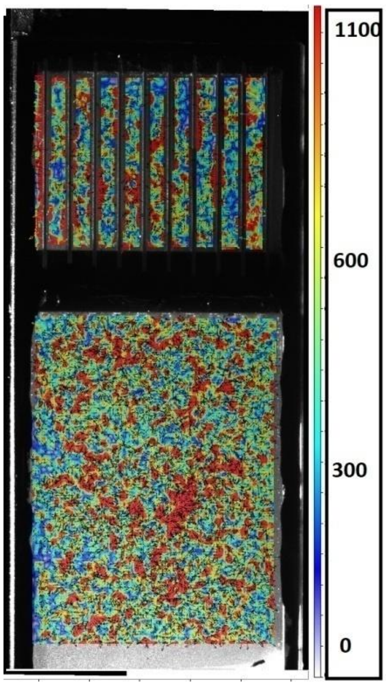


Figure28 Velocity (m/s) at 0.5w

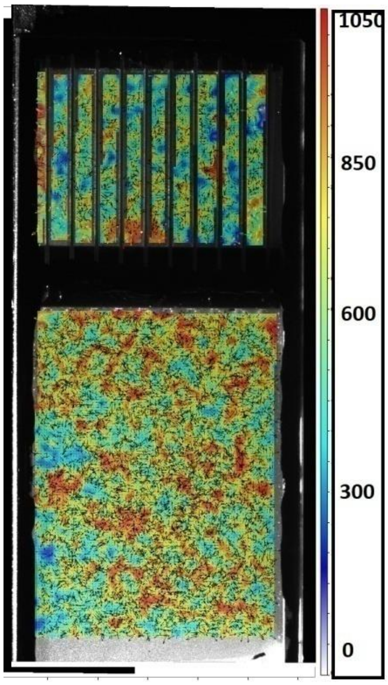


Figure 29 Uncertainty at 0.5w

Figure 30 is about the measurement of velocity and figure 31 explains about the uncertainty and both are measured for 1 w respectively at normal conditions.

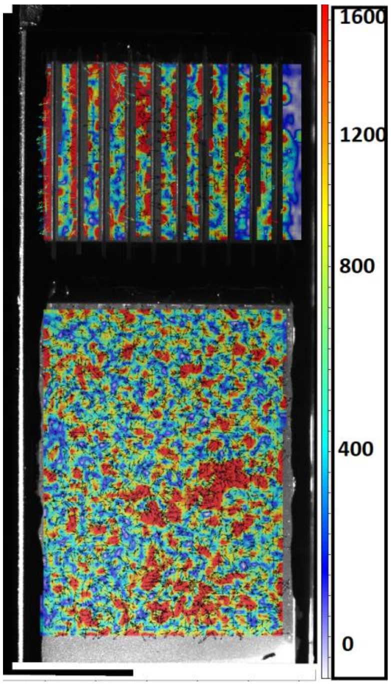


Figure 30 Velocity (m/s) at 1w

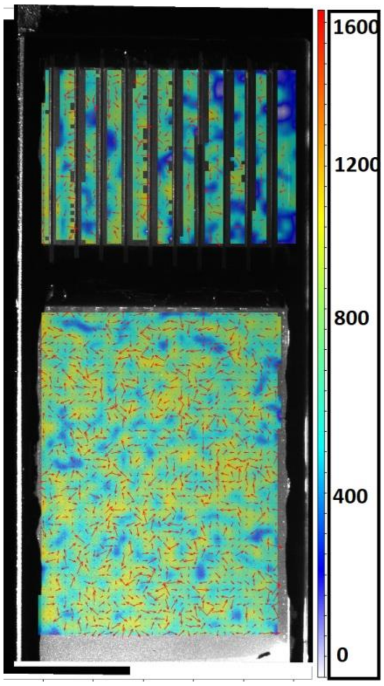


Figure 31 Uncertainty at 1w

Figure 32 is about the measurement of velocity and figure 33 explains about the uncertainty and both are measured for 0.3 w respectively at cooling condition.

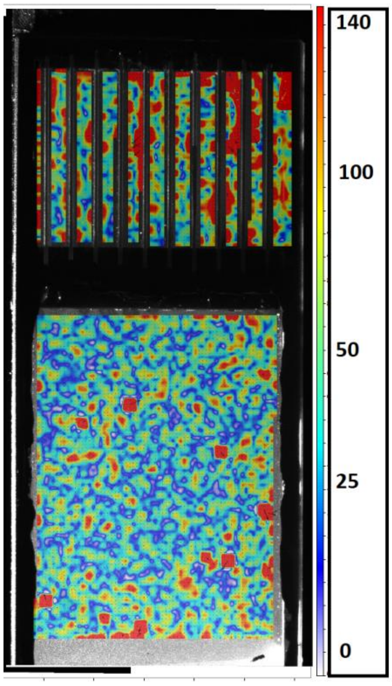


Figure 32 Velocity (m/s) at 0.3w

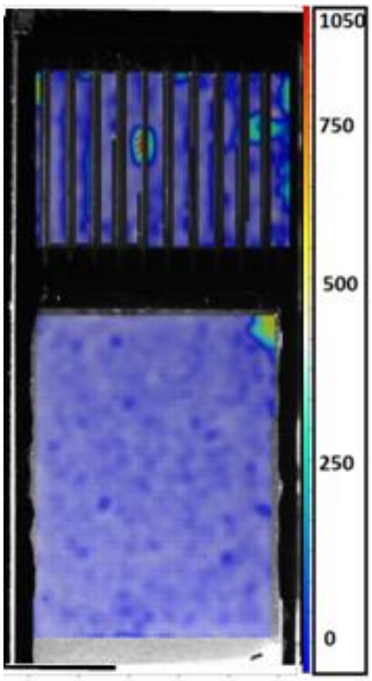


Figure 33 Uncertainty at 0.3w

Figure 34 is about the measurement of velocity and figure 35 explains about the uncertainty and both are measured for 0.47 w respectively at cooling condition.

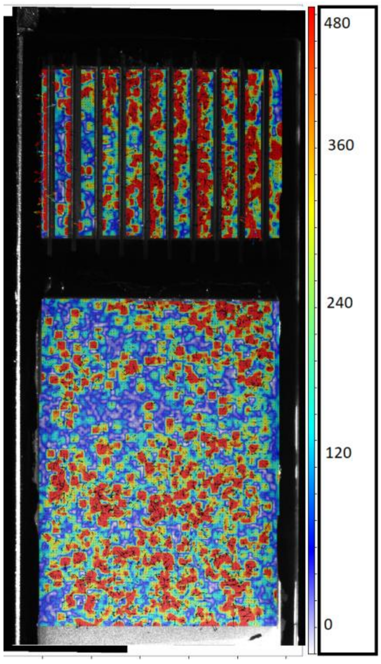


Figure 34 Velocity (m/s) at 0.47w

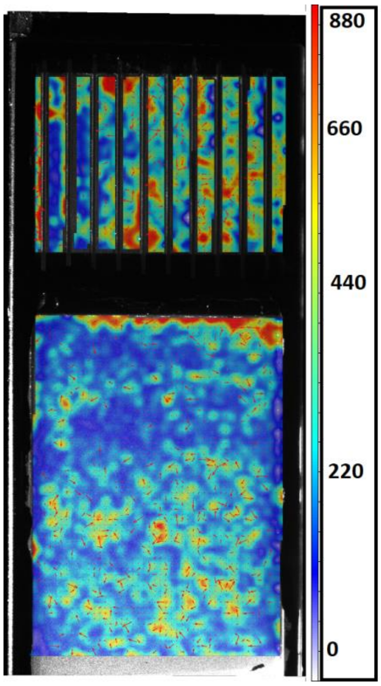


Figure 35 Uncertainty at 0.47w

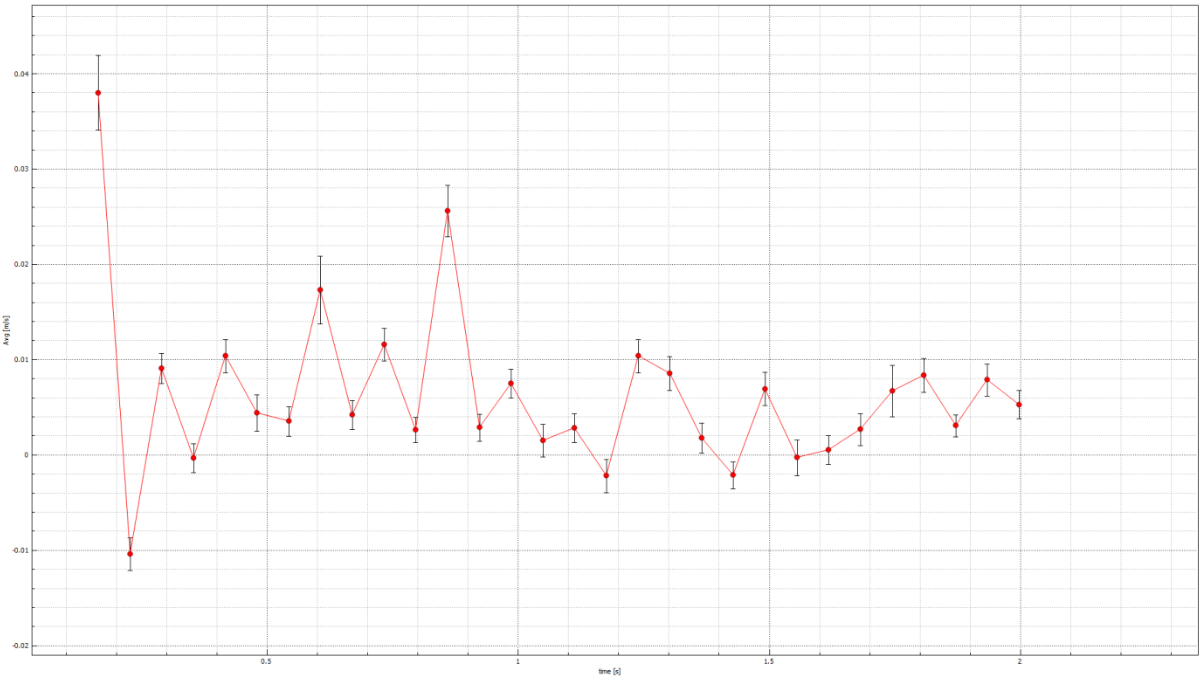


Figure 36 U component of velocity (m/s) vs. time (s) at 0.47w

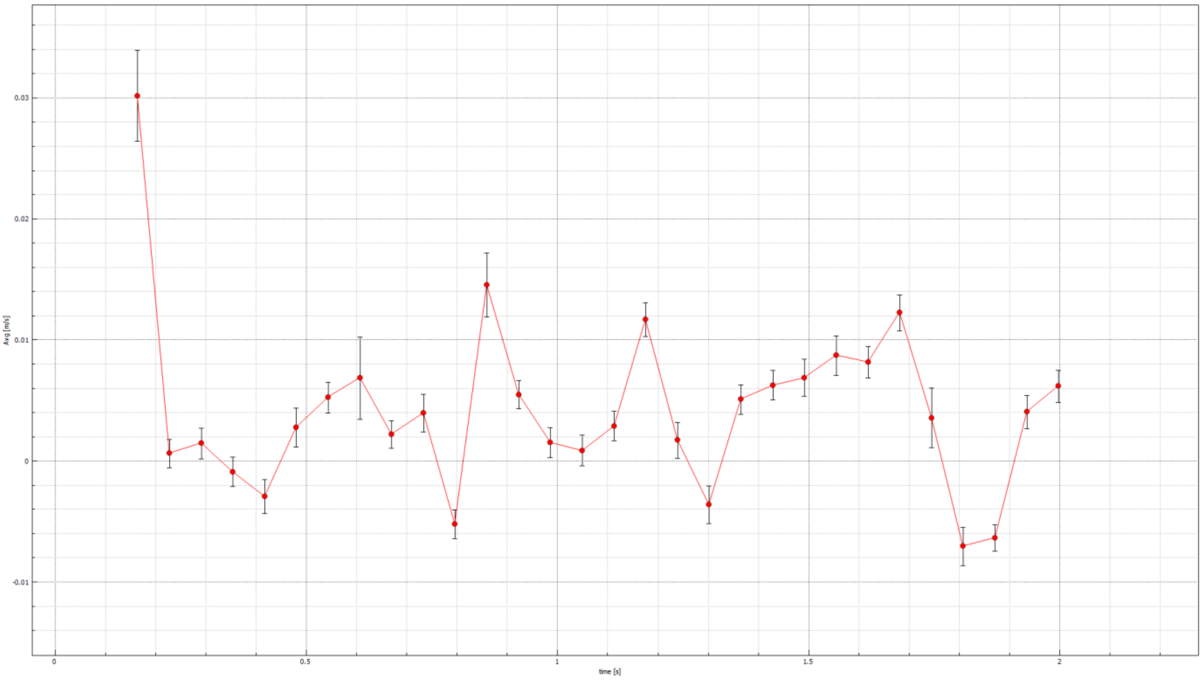


Figure 37 V component of velocity (m/s) vs. time (s) at 0.47w

The above two figures are the graphical representation of the u and v components of the velocity along with the time for 0.47w at normal conditions.

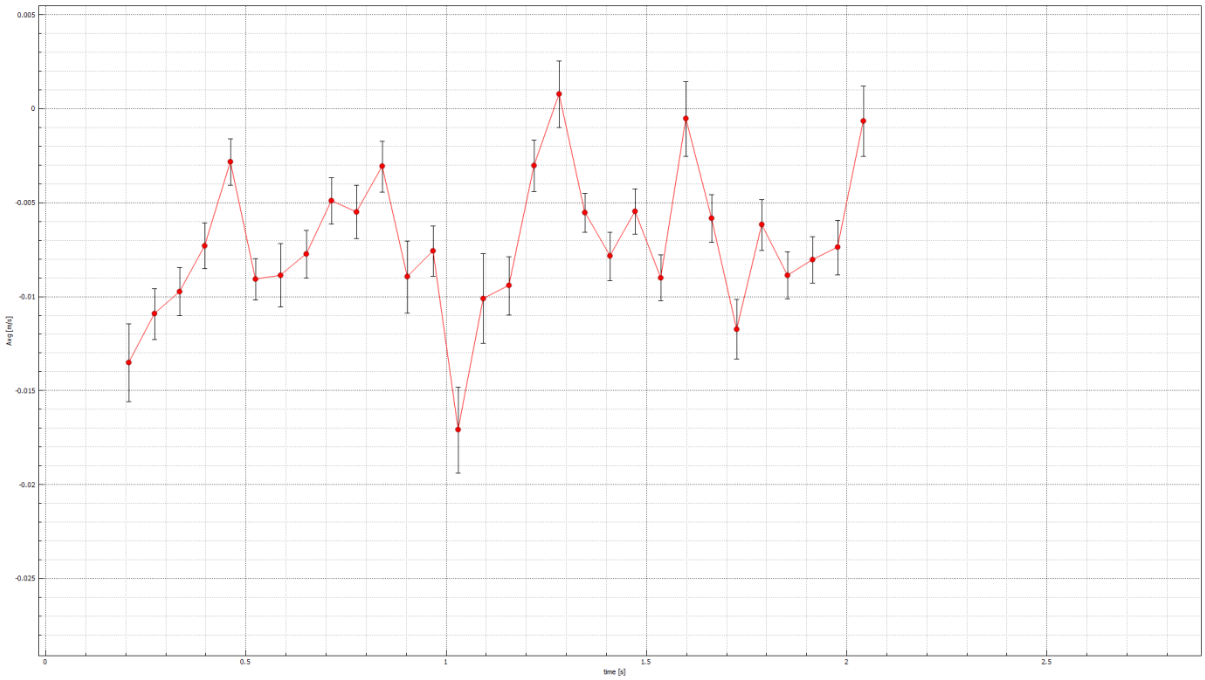


Figure 38 U component of velocity (m/s) vs. time (s) at 0.47w

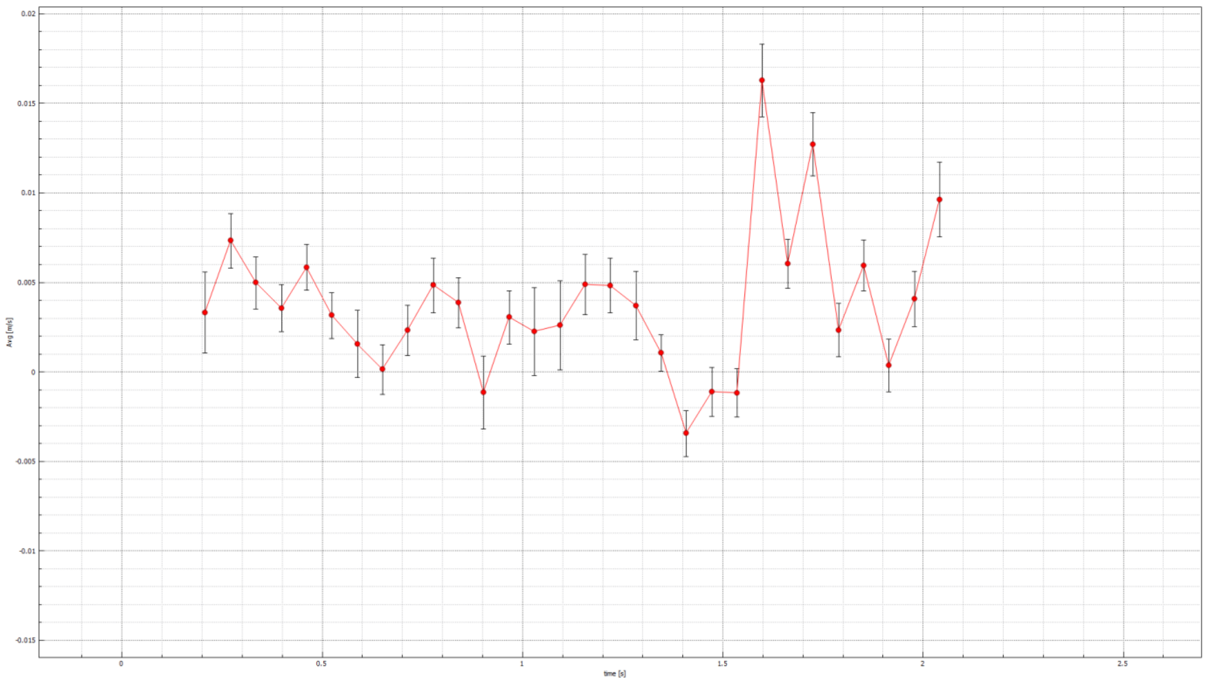


Figure 39 V component of velocity (m/s) vs time (s) at 0.47w

The above two figures are the graphical representation of the u and v components of the velocity along with the time for 0.47w at cooling conditions.

6 CONCLUSION

Thus from the above results and the analysis the primary goal of the task which is to find the velocity field in the stack region of the thermo-acoustic device is accomplished. In this experiment we calculate the frequency of the speaker for the device parameters and surroundings which is driving the device and with the help of basic refrigeration principle we are cooling the stack region. So the velocity field is measured at the stack and the region below that and for the investigation we are using the particle image velocimetry method (PIV).so once the image is captured it is processed to the required variations and the final result is produced. While doing this task the uncertainty of the flow is also calculated to make sure that the errors will be very less. Therefore the experiment and the results are successful.

After analyzing we got the clear idea that the during the normal conditions the velocity range is relatively when compared to the low range values for the velocity during the cooling and with the help of this we can easily distinguish between them.

7 FUTURE WORK

Even though the primary goal is achieved there is always a place for improvement in every aspect. So considering this work there are certain fields which we can improve and they are mentioned as below,

- Design of the thermo-acoustic device.

- Using different method of investigation for further improvement in the result.

- Instead of air different mediums can be also used.

- In this method refrigeration is made and we can also try it for both heating and cooling in the same process simultaneously.

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