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DEPARTMENT OF PHYSICS

TOPIC: **LASERS**

BY

M PAVAN KALYANI – III MPE
D DHANUNJAY– III MPC (TM)
K SANGEETHA – III MPCs
MD.K.RASHEEDUNNISHA – III MPC (EM)

Under the guidance of :

Mr. J RAMA MOHAN
Dr. L MALLESWARA RAO
Mr. P RAMAKRISHNA RAO

Lasers

A **laser** is a device that emits light (electromagnetic radiation) through a process called *stimulated emission*. The term *laser* is an acronym for ***light amplification by stimulated emission of radiation***. Laser light is usually spatially coherent, which means that the light either is emitted in a narrow, low-divergence beam, or can be converted into one with the help of optical components such as lenses. Typically, **lasers** are thought of as emitting light with a narrow wavelength spectrum ("monochromatic" light). This is not true of all **lasers**, however: some emit light with a broad spectrum, while others emit light at multiple distinct wavelengths simultaneously. The coherence of typical laser emission is distinctive. Most other light sources emit *incoherent* light, which has a phase that varies randomly with time and position.

Terminology:

From left to right: gamma rays, X-rays, ultraviolet rays, visible spectrum, infrared, microwaves, radio waves.

The word *laser* originated as an acronym for *light amplification by stimulated emission of radiation*. The word *light* in this phrase is used in the broader sense, referring to electromagnetic radiation of any frequency, not just that in the visible spectrum. Hence there are *infrared* ***lasers***, *ultraviolet* ***lasers***, *X-ray* ***lasers***, etc. Because the microwave equivalent of the laser, the *maser*, was developed first, devices that emit microwave and radio frequencies are usually called *masers*. In early literature, particularly from researchers at Bell Telephone Laboratories, the laser was often called the *optical maser*. This usage has since become uncommon, and as of 1998 even Bell Labs uses the term *laser*.

The back-formed verb *to lase* means "to produce laser light" or "to apply laser light to".The word "laser" is sometimes used to describe other non-light technologies. For example, a source of atoms in a coherent state is called an "atom laser".

Design:

Principal components:
1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler
5. Laser beam

A laser consists of a gain medium inside a highly reflective optical cavity, as well as a means to supply energy to the gain medium. The gain medium is a material with properties that allow it to amplify light by stimulated emission. In its simplest form, a cavity consists of two mirrors arranged such that light bounces back and forth, each time passing through the gain medium. Typically one of the two mirrors, the output coupler, is partially transparent. The output laser beam is emitted through this mirror.

Light of a specific wavelength that passes through the gain medium is amplified (increases in power); the surrounding mirrors ensure that most of the light makes many passes through the gain medium, being amplified repeatedly. Part of the light that is between the mirrors (that is, within the cavity) passes through the partially transparent mirror and escapes as a beam of light.

The process of supplying the energy required for the amplification is called pumping. The energy is typically supplied as an electrical current or as light at a different wavelength. Such light may be provided by a flash lamp or perhaps another laser. Most practical **lasers** contain additional elements that affect properties such as the wavelength of the emitted light and the shape of the beam.

Laser physics:

A helium-neon laser demonstration at the Kastler-Brossel Laboratory at Univ. Paris 6. The glowing ray in the middle is an electric discharge producing light in much the same way as a neon light. It is the gain medium through which the laser passes, *not* the laser beam itself, which is visible there. The laser beam crosses the air and marks a red point on the screen to the right.

Spectrum of a helium neon laser showing the very high spectral purity intrinsic to nearly all **lasers**. Compare with the relatively broad spectral emittance of a light emitting diode.

The gain medium of a laser is a material of controlled purity, size, concentration, and shape, which amplifies the beam by the process of stimulated emission. It can be of any state: gas, liquid, solid or plasma. The gain medium absorbs pump energy, which raises some electrons into higher-energy ("excited") quantum states. Particles can interact with light both by absorbing photons or by emitting photons. Emission can be spontaneous or stimulated. In the latter case, the photon is emitted in the same direction as the light that is passing by. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved and the amount of stimulated emission due to light that passes through is larger than the amount of absorption. Hence, the light is amplified. By itself, this makes an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser.

The light generated by stimulated emission is very similar to the input signal in terms of wavelength, phase, and polarization. This gives laser light its characteristic coherence, and allows it to maintain the uniform polarization and often monochromaticity established by the optical cavity design.

The optical cavity, a type of cavity resonator, contains a coherent beam of light between reflective surfaces so that the light passes through the gain medium more than once before it is emitted from the output aperture or lost to diffraction or absorption. As light circulates through the cavity, passing through the gain medium, if the gain (amplification) in the medium is stronger than the resonator losses, the power of the circulating light can rise exponentially. But each stimulated emission event returns a particle from its excited state to the ground state, reducing the capacity of the gain medium for further amplification. When this effect becomes strong, the gain is said to be *saturated.* The balance of pump power against gain saturation and cavity losses produces an equilibrium value of the laser power inside the cavity; this equilibrium determines the operating point of the laser. If the chosen pump power is too small, the gain is not sufficient to overcome the resonator losses, and the laser will emit only very small light powers. The minimum pump power needed to begin laser action is called the *lasing threshold*. The gain medium will amplify any photons passing through it, regardless of direction; but only the photons aligned with the cavity manage to pass more than once through the medium and so have significant amplification.

The beam in the cavity and the output beam of the laser, if they occur in free space rather than waveguides (as in an optical fiber laser), are, at best, low order Gaussian beams. However this is rarely the case with powerful **lasers**. If the beam is not a low-order Gaussian shape, the transverse modes of the beam can be described as a superposition of Hermite-Gaussian or Laguerre-Gaussian beams (for stable-cavity **lasers**). Unstable laser resonators on the other hand, have been shown to produce fractal shaped beams. The beam may be highly *collimated*, that is being parallel without diverging. However, a perfectly collimated beam cannot be created, due to diffraction. The beam remains collimated over a distance which varies with the square of the beam diameter, and eventually diverges at an angle which varies inversely with the beam diameter. Thus, a beam generated by a small laboratory laser such as a helium-neon laser spreads to about 1.6 kilometers (1 mile) diameter if shone from the Earth to the Moon. By comparison, the output of a typical semiconductor laser, due to its small diameter, diverges almost as soon as it leaves the aperture, at an angle of anything up to 50°. However, such a divergent beam can be transformed into a collimated beam by means of a lens. In contrast, the light from non-laser light sources cannot be collimated by optics as well.

Although the laser phenomenon was discovered with the help of quantum physics, it is not essentially more quantum mechanical than other light sources. The operation of a free electron laser can be explained without reference to quantum mechanics.

Modes of operation:

The output of a laser may be a continuous constant-amplitude output (known as *CW* or *continuous wave*); or pulsed, by using the techniques of Q-switching, modelocking, or gain-switching. In pulsed operation, much higher peak powers can be achieved.

Some types of **lasers**, such as *dye* ***lasers*** and *vibronic solid-state* ***lasers*** can produce light over a broad range of wavelengths; this property makes them suitable for generating extremely short pulses of light, on the order of a few femtoseconds (10^{-15} s).

Continuous wave operation:

In the continuous wave (CW) mode of operation, the output of a laser is relatively constant with respect to time. The population inversion required for lasing is continually maintained by a steady pump source.

Pulsed operation:

In the pulsed mode of operation, the output of a laser varies with respect to time, typically taking the form of alternating 'on' and 'off' periods. In many applications one aims to deposit as much energy as possible at a given place in as short time as possible. In laser ablation for example, a small volume of material at the surface of a work piece might evaporate if it gets the energy required to heat it up far enough in very short time. If, however, the same energy is spread over a longer time, the heat may have time to disperse into the bulk of the piece, and less material evaporates. There are a number of methods to achieve this.

Q-switching:

In a Q-switched laser, the population inversion (usually produced in the same way as CW operation) is allowed to build up by making the cavity conditions (the 'Q') unfavorable for lasing. Then, when the pump energy stored in the laser medium is at the desired level, the 'Q' is adjusted (electro- or acousto-optically) to favourable conditions, releasing the pulse. This results in high peak powers as the average power of the laser (were it running in CW mode) is packed into a shorter time frame.

Modelocking:

A modelocked laser emits extremely short pulses on the order of tens of picoseconds down to less than 10 femtoseconds. These pulses are typically separated by the time that a pulse takes to complete one round trip in the resonator cavity. Due to the Fourier limit (also known as energy-time uncertainty), a pulse of such short temporal length has a spectrum which contains a wide range of wavelengths. Because of this, the laser medium must have a broad enough gain profile to amplify them all. An example of a suitable material is titanium-doped, artificially grown sapphire (Ti:sapphire).

The modelocked laser is a most versatile tool for researching processes happening at extremely fast time scales also known as femtosecond physics, femtosecond chemistry and ultrafast science, for maximizing the effect of nonlinearity in optical materials (e.g. in second-harmonic generation, parametric down-conversion, optical parametric oscillators and the like), and in ablation applications. Again, because of the short timescales involved, these **lasers** can achieve extremely high powers.

Pulsed pumping:

Another method of achieving pulsed laser operation is to pump the laser material with a source that is itself pulsed, either through electronic charging in the case of flashlamps, or another laser which is already pulsed. Pulsed pumping was historically used with dye **lasers** where the inverted population lifetime of a dye molecule was so short that a high energy, fast pump was needed. The way to overcome this problem was to charge up large capacitors which are then switched to discharge through flashlamps, producing a broad spectrum pump flash. Pulsed pumping is also required for **lasers** which disrupt the gain medium so much during the laser process that lasing has to cease for a short period. These **lasers**, such as the excimer laser and the copper vapour laser, can never be operated in CW mode.

Laser:

In 1957, Charles Hard Townes and Arthur Leonard Schawlow, then at Bell Labs, began a serious study of the infrared laser. As ideas were developed, infrared frequencies were abandoned with focus on visible light instead. The concept was originally known as an "optical maser". Bell Labs filed a patent application for their proposed optical maser a year later.

At the same time Gordon Gould, a graduate student at Columbia University, was working on a doctoral thesis on the energy levels of excited thallium. Gould and Townes met and had conversations on the general subject of radiation emission. Afterwards Gould made notes about his ideas for a "laser" in November 1957, including suggesting using an open resonator, which became an important ingredient of future **lasers**.

In 1958, Prokhorov independently proposed using an open resonator, the first published appearance of this idea. Schawlow and Townes also settled on an open resonator design, apparently unaware of both the published work of Prokhorov and the unpublished work of Gould.

The term "laser" was first introduced to the public in Gould's 1959 conference paper "The LASER, Light Amplification by Stimulated Emission of Radiation". Gould intended "-aser" to be a suffix, to be used with an appropriate prefix for the spectrum of light emitted by the device (x-rays: *xaser*, ultraviolet: *uvaser*, etc.). None of the other terms became popular, although "raser" was used for a short time to describe radio-frequency emitting devices.

Gould's notes included possible applications for a laser, such as spectrometry, interferometry, radar, and nuclear fusion. He continued working on his idea and filed a patent application in April 1959. The U.S. Patent Office denied his application and awarded a patent to Bell Labs in 1960. This sparked a legal battle that ran 28 years, with scientific prestige and much money at stake. Gould won his first minor patent in 1977, but it was not until 1987 that he could claim his first significant patent victory when a

Federal judge ordered the government to issue patents to him for the optically pumped laser and the gas discharge laser.

The first working laser was made by Theodore H. Maiman in 1960 at Hughes Research Laboratories in Malibu, California, beating several research teams including those of Townes at Columbia University, Arthur Schawlow at Bell Labs, and Gould at a company called TRG (Technical Research Group). Maiman used a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light at 694 nanometres wavelength. Maiman's laser, however, was only capable of pulsed operation due to its three-level pumping scheme.

Later in 1960 the Iranian physicist Ali Javan, working with William R. Bennett and Donald Herriot, made the first gas laser using helium and neon. Javan later received the Albert Einstein Award in 1993.

The concept of the semiconductor laser diode was proposed by Basov and Javan. The first *laser diode* was demonstrated by Robert N. Hall in 1962. Hall's device was made of gallium arsenide and emitted at 850 nm in the near-infrared region of the spectrum. The first semiconductor laser with visible emission was demonstrated later the same year by Nick Holonyak, Jr. As with the first gas **lasers**, these early semiconductor **lasers** could be used only in pulsed operation, and indeed only when cooled to liquid nitrogen temperatures (77 K).

In 1970, Zhores Alferov in the Soviet Union and Izuo Hayashi and Morton Panish of Bell Telephone Laboratories independently developed laser diodes continuously operating at room temperature, using the heterojunction structure.

Recent innovations:

Graph showing the history of maximum laser pulse intensity throughout the past 40 years.

Since the early period of laser history, laser research has produced a variety of improved and specialized laser types, optimized for different performance goals, including:

- new wavelength bands
- maximum average output power
- maximum peak output power
- minimum output pulse duration
- maximum power efficiency
- maximum charging
- maximum firing
- minimum cost

and this research continues to this day.

Lasing without maintaining the medium excited into a population inversion was discovered in 1992 in sodium gas and again in 1995 in rubidium gas by various international teams. This was accomplished by using an external maser to induce "optical transparency" in the medium by introducing and destructively interfering the ground electron transitions between two paths, so that the likelihood for the ground electrons to absorb any energy has been cancelled.

Types and operating principles:

Gas lasers:

Gas lasers using many gases have been built and used for many purposes.

The helium-neon laser (HeNe) emits at a variety of wavelengths and units operating at 633 nm are very common in education because of its low cost.

Carbon dioxide lasers can emit hundreds of kilowatts at 9.6 µm and 10.6 µm, and are often used in industry for cutting and welding. The efficiency of a CO_2 laser is over 10%.

Argon-ion lasers emit light in the range 351-528.7 nm. Depending on the optics and the laser tube a different number of lines is usable but the most commonly used lines are 458 nm, 488 nm and 514.5 nm.

A nitrogen transverse electrical discharge in gas at atmospheric pressure (TEA) laser is an inexpensive gas laser producing UV Light at 337.1 nm.[1]

Metal ion lasers are gas lasers that generate deep ultraviolet wavelengths. Helium-silver (HeAg) 224 nm and neon-copper (NeCu) 248 nm are two examples. These lasers have particularly narrow oscillation linewidths of less than 3 GHz (0.5 picometers), making them candidates for use in fluorescence suppressed Raman spectroscopy.

Chemical lasers:

Chemical lasers are powered by a chemical reaction, and can achieve high powers in continuous operation. For example, in the Hydrogen fluoride laser (2700-2900 nm) and the Deuterium fluoride laser (3800 nm) the reaction is the combination of hydrogen or deuterium gas with combustion products of ethylene in nitrogen trifluoride. They were invented by George C. Pimentel.

Excimer lasers:

Excimer lasers are powered by a chemical reaction involving an *excited dimer*, or *excimer*, which is a short-lived dimeric or heterodimeric molecule formed from two species (atoms), at least one of which is in an excited electronic state. They typically produce ultraviolet light, and are used in semiconductor photolithography and in LASIK eye surgery. Commonly used excimer molecules include F_2 (fluorine, emitting at

157 nm), and noble gas compounds (ArF [193 nm], KrCl [222 nm], KrF [248 nm], XeCl [308 nm], and XeF [351 nm]).

Solid-state lasers:

Solid-state laser materials are commonly made by "doping" a crystalline solid host with ions that provide the required energy states. For example, the first working laser was a ruby laser, made from ruby (chromium-doped corundum). The population inversion is actually maintained in the "dopant", such as chromium or neodymium. Formally, the class of solid-state **lasers** includes also fiber laser, as the active medium (fiber) is in the solid state. Practically, in the scientific literature, solid-state laser usually means a laser with bulk active medium, while wave-guide **lasers** are caller fiber **lasers**.

"Semiconductor **lasers**" are also solid-state **lasers**, but in the customary laser terminology, "solid-state laser" excludes semiconductor **lasers**, which have their own name.

Titanium-doped sapphire (Ti:sapphire) produces a highly tunable infrared laser, commonly used for spectroscopy as well as the most common ultrashort pulse laser.

Thermal limitations in solid-state **lasers** arise from unconverted pump power that manifests itself as heat and phonon energy. This heat, when coupled with a high thermo-optic coefficient (d*n*/d*T*) can give rise to thermal lensing as well as reduced quantum efficiency. These types of issues can be overcome by another novel diode-pumped solid-state laser, the diode-pumped thin disk laser. The thermal limitations in this laser type are mitigated by using a laser medium geometry in which the thickness is much smaller than the diameter of the pump beam. This allows for a more even thermal gradient in the material. Thin disk **lasers** have been shown to produce up to kilowatt levels of power.

Fiber-hosted lasers:

Solid-state **lasers** where the light is guided due to the total internal reflection in an optical fiber are called fiber **lasers**. Guiding of light allows extremely long gain regions providing good cooling conditions; fibers have high surface area to volume ratio which allows efficient cooling. In addition, the fiber's wave guiding properties tend to reduce thermal distortion of the beam. Erbium and ytterbium ions are common active species in such **lasers**.

Quite often, the fiber laser is designed as a double-clad fiber. This type of fiber consists of a fiber core, an inner cladding and an outer cladding. The index of the three concentric layers is chosen so that the fiber core acts as a single-mode fiber for the laser emission while the outer cladding acts as a highly multimode core for the pump laser. This lets the pump propagate a large amount of power into and through the active inner core region, while still having a high numerical aperture (NA) to have easy launching conditions.

Pump light can be used more efficiently by creating a fiber disk laser, or a stack of such **lasers**.

Fiber **lasers** have a fundamental limit in that the intensity of the light in the fiber cannot be so high that optical nonlinearities induced by the local electric field strength can become dominant and prevent laser operation and/or lead to the material destruction of the fiber. This effect is called photodarkening. In bulk laser materials, the cooling is not so efficient, and it is difficult to separate the effects of photodarkening from the thermal effects, but the experiments in fibers show that the photodarkening can be attributed to the formation of long-living color centers.

Photonic crystal lasers:

Photonic crystal **lasers** are **lasers** based on nano-structures that provide the mode confinement and the density of optical states (DOS) structure required for the feedback to take place. They are typical micrometre-sized and tunable on the bands of the photonic crystals.

Semiconductor lasers:

Semiconductor **lasers** are also solid-state **lasers** but have a different mode of laser operation.

Commercial laser diodes emit at wavelengths from 375 nm to 1800 nm, and wavelengths of over 3 µm have been demonstrated. Low power laser diodes are used in laser printers and CD/DVD players. More powerful laser diodes are frequently used to optically pump other **lasers** with high efficiency. The highest power industrial laser diodes, with power up to 10 kW (70dBm), are used in industry for cutting and welding. External-cavity semiconductor **lasers** have a semiconductor active medium in a larger cavity. These devices can generate high power outputs with good beam quality, wavelength-tunable narrow-linewidth radiation, or ultrashort laser pulses.

Vertical cavity surface-emitting **lasers** (VCSELs) are semiconductor **lasers** whose emission direction is perpendicular to the surface of the wafer. VCSEL devices typically have a more circular output beam than conventional laser diodes, and potentially could be much cheaper to manufacture. As of 2005, only 850 nm VCSELs are widely available, with 1300 nm VCSELs beginning to be commercialized,[19] and 1550 nm devices an area of research. VECSELs are external-cavity VCSELs. Quantum cascade **lasers** are semiconductor **lasers** that have an active transition between energy *sub-bands* of an electron in a structure containing several quantum wells.

The development of a silicon laser is important in the field of optical computing, since it means that if silicon, the chief ingredient of computer chips, were able to produce **lasers**, it would allow the light to be manipulated like electrons are in normal integrated circuits. Thus, photons would replace electrons in the circuits, which dramatically increases the speed of the computer. Unfortunately, silicon is a difficult lasing material to deal with, since it has certain properties which block lasing. However, recently teams have produced silicon **lasers** through methods such as fabricating the lasing material from silicon and other semiconductor materials, such as indium(III) phosphide or gallium(III) arsenide, materials which allow coherent light to be produced from silicon. These are called hybrid silicon laser. Another type is a Raman laser, which takes advantage of Raman scattering to produce a laser from materials such as silicon.

Dye lasers:

Dye **lasers** use an organic dye as the gain medium. The wide gain spectrum of available dyes allows these **lasers** to be highly tunable, or to produce very short-duration pulses (on the order of a few femtoseconds)

Free electron lasers

Free electron **lasers**, or FELs, generate coherent, high power radiation, that is widely tunable, currently ranging in wavelength from microwaves, through terahertz radiation and infrared, to the visible spectrum, to soft X-rays. They have the widest frequency range of any laser type. While FEL beams share the same optical traits as other **lasers**, such as coherent radiation, FEL operation is quite different. Unlike gas, liquid, or solid-state **lasers**, which rely on bound atomic or molecular states, FELs use a relativistic electron beam as the lasing medium, hence the term *free electron*.

Exotic laser media:

In September 2007, the BBC News reported that there was speculation about the possibility of using positronium annihilation to drive a very powerful gamma ray laser. Dr. David Cassidy of the University of California, Riverside proposed that a single such laser could be used to ignite a nuclear fusion reaction, replacing the hundreds of **lasers** used in typical inertial confinement fusion experiments.

Space-based X-ray **lasers** pumped by a nuclear explosion have also been proposed as antimissile weapons. Such devices would be one-shot weapons.

Uses:

Lasers range in size from microscopic diode **lasers** (top) with numerous applications, to football field sized neodymium glass **lasers** (bottom) used for inertial confinement fusion, nuclear weapons research and other high energy density physics experiments.

When **lasers** were invented in 1960, they were called "a solution looking for a problem".[23] Since then, they have become ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, entertainment, and the military.

The first application of **lasers** visible in the daily lives of the general population was the supermarket barcode scanner, introduced in 1974. The laserdisc player, introduced in 1978, was the first successful consumer product to include a laser, but the compact disc player was the first laser-equipped device to become truly common in consumers' homes, beginning in 1982, followed shortly by laser printers.

Some of the other applications include:

- Medicine: Bloodless surgery, laser healing, surgical treatment, kidney stone treatment, eye treatment, dentistry
- Industry: Cutting, welding, material heat treatment, marking parts
- Defense: Marking targets, guiding munitions, missile defence, electro-optical countermeasures (EOCM), alternative to radar
- Research: Spectroscopy, laser ablation, Laser annealing, laser scattering, laser interferometry, LIDAR, Laser capture microdissection
- Product development/commercial: laser printers, CDs, barcode scanners, thermometers, laser pointers, holograms, bubblegrams.
- Laser lighting displays: Laser light shows
- Laser skin procedures such as acne treatment, cellulite reduction, and hair removal.

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TOPIC: **HIGH SPEED ULTRASONIC SYSTEM**

BY

K SAI RAKESH – III MPE
D DAIVA KRUPA– III MPC (TM)
K HEMA SRILATHA – III MPCs
A KEERTHI – III MPC (EM)

Under the guidance of :

Mr. J RAMA MOHAN
Dr. L MALLESWARA RAO
Mr. P RAMAKRISHNA RAO

HIGH SPEED ULTRASONIC SYSTEM TO MEASUREBUBBLES VELOCITIES IN A HORIZONTAL TWO-PHASE FLOW

1. INTRODUCTION

Two-phase flow is an important field of study, especially for power plants where the primary refrigeration circuit of nuclear reactors needs constant control of the gas-liquid two-phase flow parameters. The so-called LOCA's (Loss Of Coolant Accident) are examples of the importance of the measurement of interfacial parameters for the safe operation of a nuclear reactor. Among many intermittent horizontal two-phase flow parameters, the elongated bubble velocity (Taylor bubble velocity) and the liquid film thickness film under it are very important parameters to be measured. Many techniques have been developed to measure two-phase flow parameters and they can be classified into two types: intrusive and non-intrusive. For measurement using intrusive techniques, there are hot-film anemometers conductivity probe method. The spatial or temporal differential pressure is considered a semi-intrusive technique, it has been used the mean pressure drop to determine the liquid holdup. The disadvantage of using invasive or semi-invasive techniques in nuclear plants is the leakage risk. The main noninvasive techniques used to measure parameters of two-phase flow are the optical, radiation and ultrasonic techniques. The main optical techniques are laser Doppler anemometry (LDA) and particle image velocimetry (PIV). Although they are non-intrusive, they are restricted to transparent pipes. Ultrasonic techniques are non-intrusive. They do not need safety care to the operators, they can be used in high pressure and temperature flows and they can be used in opaque fluids and non transparent pipes. There are three ultrasonic methods for two-phase flow diagnostics, namely the pulse-echo,

transmission, and the Doppler shift methods. According to [7], the Doppler shift method has relative advantage when applied in low void fraction liquid flow velocity measurements and gas bubble velocity measurements. [8] and [9] applied the pulse-echo technique using a single transducer and the transmission technique using two transducers to determine flow regime and liquid level but they are limited to bubble velocity of up 0.7 cm/s and low gas entrainment. [10] presented a hybrid ultrasonic technique formed by a contra-propagating transmission ultrasonic flow-meter, pulse-echo transmission ultrasonic void meter and a FieldBus data acquisition system. This technique was used to determine the stratified and plug flow pattern in a horizontal air-water two-phase flow.

In this work a high speed ultrasonic multitransducer pulse-echo system was developed to characterize the shape of elongated bubble in a horizontal air-water intermittent flow.

2. EXPERIMENTAL SETUP

2.1. Two-Phase Flow Test Section

The experimental development was carried out in the Thermal-Hydraulic Laboratory of Nuclear Engineering Institute (IEN/CNEN). The two-phase test section consists of an air-water circulation system, a horizontal tube and an instrumentation system control, as shown in Fig. 1. The horizontal tube is made of a 5 m long stainless steel 316 pipe with an inner diameter of 51.2 mm, followed by a 0.6 m long transparent Plexiglas tube with the same inner diameter. The distilled water circulated axially through the venture mixer comes from an existing single-phase water loop which is equipped with a centrifugal pump a metering rig. Air is injected into the mixer by a compressor through a flow line equipped with an appropriated instrumentation. The air-water mixture goes out from the mixer and through the stainless steel tube along its length until the transparent Plexiglas tube where it can be observed visually. By means of a rotameter and a turbine flowmeter the air and water flows are measured in the single-phase lines, respectively.

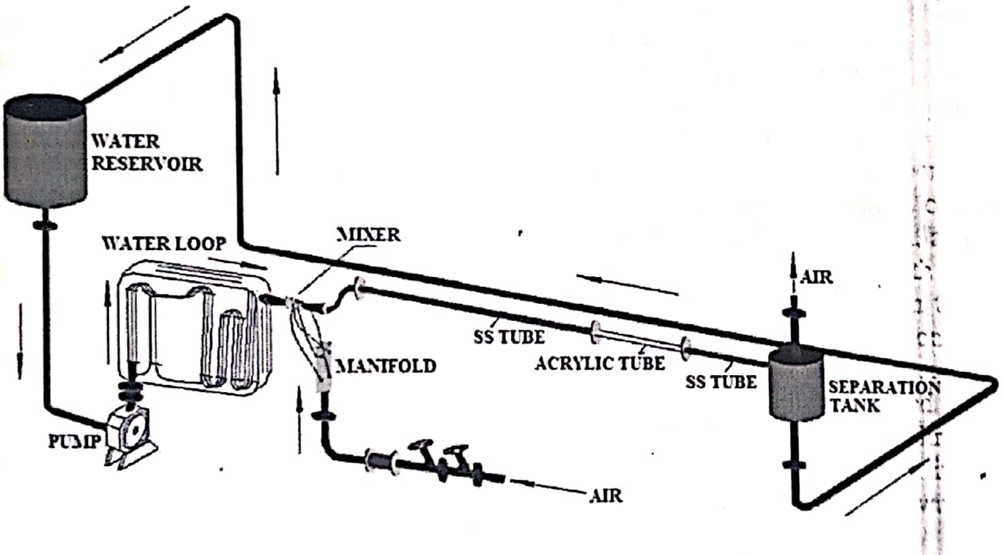


Figure 1. Schematic of two-phase test section

2.2. High Speed Ultrasonic System

The ultrasonic system was developed by the Instrumentation Department of Instituto de Engenharia Nuclear – IEN. This system consists of a computer (PC), a Ultrasonic Pulser/Receiver and 100MHz A/D Board for PCI Bus with up to four outputs multiplexer, and up to four ultrasonic transducers. In this work, two ultrasonic transducers are used. Figure 2 shows the assembly of the two ultrasonic transducers along the horizontal axis of the tube.

Specific software was developed for the acquisition of ultrasonic signals of which only the signals with time of flight smaller than the diameter of the tube are recorded. This procedure removes all unwanted signals, including the multiple reflections of the tube wall opposite the transducer. It is not necessary a filter to unwanted ultrasonic signals, so you do not need a high buffer capacity during the acquisition of signals.

The time interval elapsed between two echoes of ultrasonic signals is measured calculating the time elapsed between two reference points previously established in these signals. The maximum point of these echoes can be these reference points.

The computer used in the experiments has 1 GB of RAM and stores 8000 points, one point for each ultrasonic pulse. The sampling rate of the board is 100 MHz and thus the time between consecutive points is 10 nanoseconds. For greater accuracy of the profile curve (Volt x time), the software needs a routine of interpolation. The time interval of 10 ns is divided into 16 shares. It allows greater accuracy in measuring the heights of the liquid film, and thus greater accuracy of the longitudinal profile of the elongated bubbles.

The ultrasonic system is unable to effectively acquire signals from four transducers at the same time, because the card can only emit a pulse at a time per channel for each transducer. In each cycle, a set of 4 pulses is sent; the card sends a pulse for each transducer. The time between each pulse is about 200 us, sometimes with small variations. Between the first pulse of a cycle and the first of the next one, the time can be controlled in a range of from 187 Hz to 940 Hz, approximately. This time is between the first pulse of a cycle and the first of the next cycle. For each pulse sent, the card scans the returned signal at 100MHz (10ns) rate. The RAM memory of the PC stores up to 8000 of these frames, or 2000 of each transducer. The software lets you store all the frames and the results of the time of flight of each signal. The aim of the software is to process the data in a very short time interval, so that the result of the time of flight measurement of the ultrasonic wave is presented immediately after the acquisition.

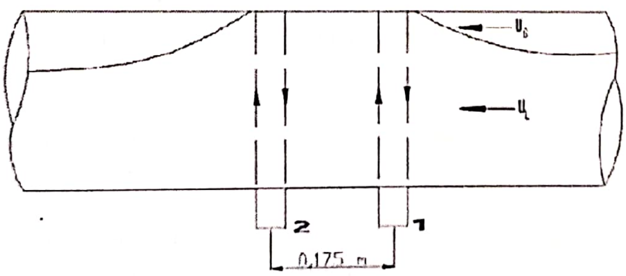


Figure 2. Schematic of the assembly showing the distance between the two transducers.

2.2. Visualization System

The visualization system can be seen in Fig. 3. They are formed by a monochrome digital high-speed camera with a CCD sensor (maximum resolution 480 x 420 pixels), zoom lenses, a PCI controller board of 12 bits, an image acquisition and analysis program and a computer. The frequency range of 250 frames per second was used to in this work. The sequence of images displayed on the computer monitor could be stored in a computer file, retrieved to analyze the flow motion sequence in detail.

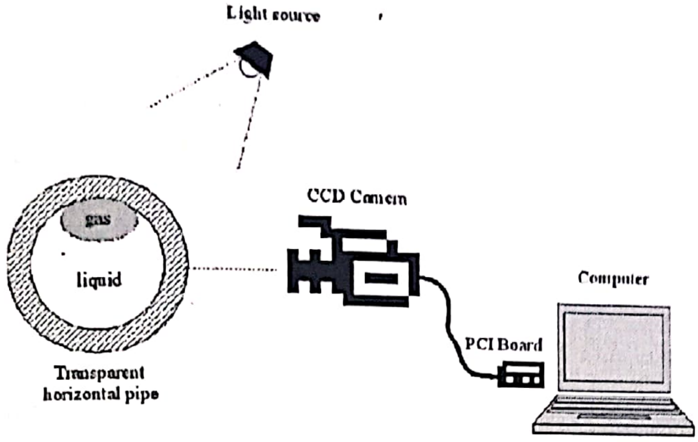


Figure 3. Schematic of the visualization system.

3. ELONGATED BUBBLE VELOCITY MEASUREMENT

A typical slug unit is characterized by the liquid slug that sometimes is very aerated, and an elongated gas bubble that is underlaid by a liquid film. If the flow regime is not in a stead state flow, the velocity of elongated gas bubble presents great variation from one after the other slug unit.

In this work, air volumetric flow of 8 m^3/h and water volumetric flow with the same value were used to measure the elongated gas bubble in intermittent flow pattern. The pressure operation was 10^5 Pa.

3.1. Velocity Measurement by Ultrasonic System

The elongated gas bubble can be detected by the transducers by reason of the change in ultrasonic wave time propagation, therefore the bubble velocity was determined by tracking one of the edges of the plug obtained by two transducers.

Figure 4 shows a typical ultrasonic waveform obtained by the ultrasonic system. The ultrasonic travel time Δt_Y corresponds to the total time of the ultrasonic wave traveling through the liquid film, reflect back from the air-water interface and returning to the ultrasonic transducer along the same way. The black line plot represents the ultrasonic signal of the ultrasonic transducer 1 and the blue line plot the ultrasonic transducer 2.

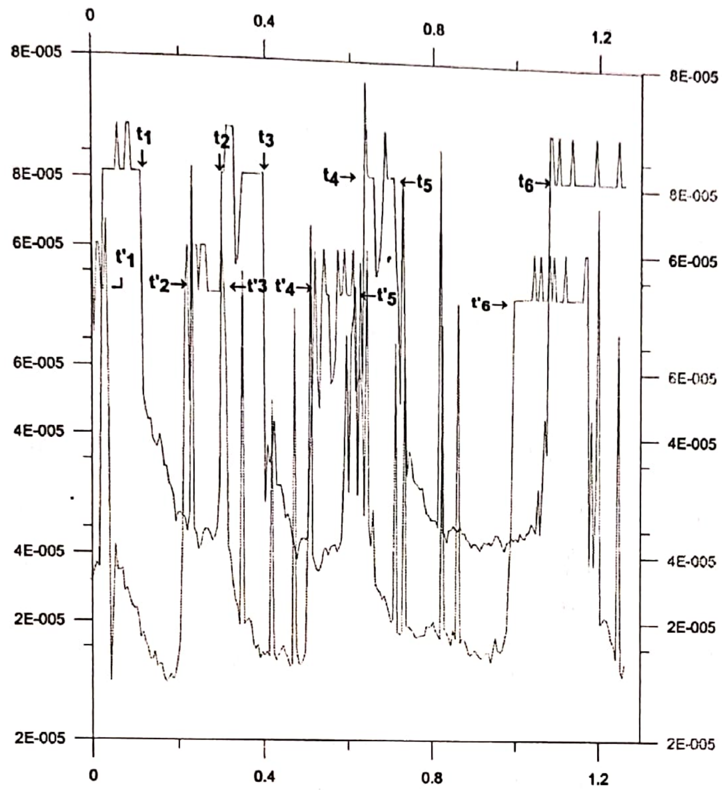


Figure 4. Typical ultrasonic wave form of the intermittent flow.

Initially the velocities of the bubble nose V_{NB} and bubble tail V_{TB} were obtained by the equations:

$$V_{NB} = \frac{\Delta Z}{\Delta T_N} = \frac{\Delta Z}{t_1 - t_1^{'}} \quad (1)$$

$$V_{TB} = \frac{\Delta Z}{\Delta T_T} = \frac{\Delta Z}{t_2 - t_2^{'}} \quad (2)$$

Where

ΔZ is the distance between the two transducers which, in this work, is 0,175 m.

ΔT_N is the time interval between the moments when the same edge of the bubble nose was detected by the transducers. In Fig. 4 it corresponds to the times t_1 (transducer 2) and t'_1 (transducer 1).

ΔT_T is the time interval between the moments when the same edge of the bubble tail was detected by the transducers. In Fig. 3 it corresponds to the times t_2 (transducer 2) and t'_2 (transducer 1).

In Tab. 1 it is shown the elongated bubble velocities V_B, calculated by the average of the bubble nose velocity V_{BN} and the bubble tail velocity V_{BT}, represented by

$$V_B = \frac{V_{NB} + V_{TB}}{2} \tag{3}$$

Table 1. Elongated gas bubble velocity measurement by ultrasonic system.

Interval Time	MEASUREMENT VELOCITY (m^3/h)		
	NOSE (V_{NB})	TAIL (V_{TB})	AVERAGE (V_B)
1 - 2	2.25	2.06	2.16
3 - 4	1.96	1.83	1.90
5 - 6	1.89	2.05	1.97
Average	2.03	1.98	2.01

3.2 Velocity Measurement by Visualization System

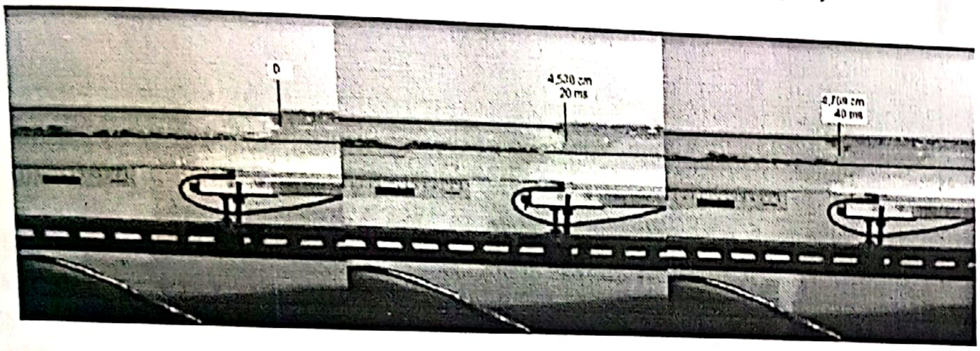
The observed frames bellow correspond to time intervals of 20 ms. In the first frame it was selected a reference point, and the distance of the bubble nose in relation to that reference point was measured in the following frames. The bubble nose velocity measurement in each of the two frames, corresponds to the ratio of bubble nose distance to time interval. It was used the same procedure to measure the bubble tail velocity.

Figure 5 shows some images of the elongated gas bubble motion in the Plexiglas tube with the bubble velocity corresponding to five frames.

The measurement of bubble tail velocity is more difficult to measure than the bubble nose velocity because of the large instability in the tail shape. Figure 6 show the shape modification of the bubble tail along the time.

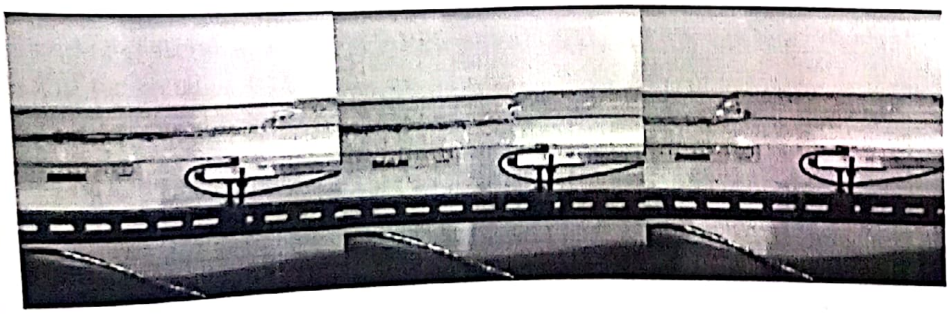
Table 2 shows the velocities of bubble's nose and tail correspondent to five frames.

(a.1) (a.2) (a.3)



(b.1) (b.2) (b.3)

Figure 5. Motion variation (Δs) and interval time (Δt) along the horizontal pipe
Bubble nose
(a.1) Reference point, (a.2) Δs = 4.5 cm, Δt = 20 ms, (a.3) Δs = 9.0 cm, Δt = 40 ms
Bubble tail
(b.1) Reference point, (b.2) Δs = 4.5 cm, Δt = 20 ms, (b.3) Δs = 8.8 cm, Δt = 40 ms



(a.1) (a.2) (a.3)

Figure 6. Shapes of the bubble tail along the time.
(a.1) initial time, (a.2) Δt = 36 ms, (a.3) Δt = 76 ms

Table 2. **Elongated gas bubble velocity measurement by visualization system.**

Elongated gas bubble	1ª		2ª		3ª	
Δt (ms)	V_{NB}	V_{TB}	V_{NB}	V_{TB}	V_{NB}	V_{TB}
20	2.19	2.89	2.19	2.50	2.19	2.27
40	2.23	2.96	2.10	2.81	2.08	2.15
60	2.12	2.69	2.15	2.85	2.23	1.96
80	2.23	2.81	2.20	2.50	2.04	2.31
Average	2.19	2.84	2.16	2.67	2.14	2.17
V_B	2.52		2.42		2.16	

4. CONCLUSIONS

In the present work a high speed ultrasonic system has been developed using ultrasonic pulse-echo signals from two transducers to detect the instantaneous elongated bubble velocity. Comparing the results given by the ultrasonic system with a visualization system measurement it was concluded that:

- The ultrasonic system measures bubble velocity by tracking one of the edges of the plug obtained by two transducers. The changes in the shape of bubble nose and tail do not affect the measure;
- The visualization system measures the bubble velocity tracking a reference point in the bubble nose and tail;
- The bubble tail presents changes in the shape along the time.

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