REMOTE MEASUREMENT OF FLOW RATES OF POLLUTED WATER WITH DOPPLER VELOCIMETRY

M. A. Gondal[1], J. Mastromarino[1] and Uwe K. A. Klein[1,2]

1: Laser Research Section, Center for Applied Physical Sciences, The Research Institute, KFUPM
2: Chemistry Department, KFUPM, Dhahran 31261, Saudi-Arabia

Fax: +96638604281; e-mail: magondal@kfupm.edu.sa

ABSTRACT

A Doppler Velocimeter for monitoring the flow rates of liquid and gaseous pollutant discharges remotely has been developed. The system has been tested for the measurement of polluted water and gaseous discharges. It is calibrated with a rotating wheel at constant speed. The system has also been used to study gaseous discharges and to investigate turbulent flow profiles of water. The system is capable of measuring Doppler shifts as low as 0.25 MHz corresponding to 0.1 m/sec velocities of the fluids.

Keywords: *Doppler LIDAR, Doppler Velocimetry, Turbulent Flow Profiles, Lasers, Remote Doppler Instrument, Laser- Doppler Measurements*

الملخص

جهاز دبلير لقياس التدفق المستخدم لقياس معدل تدفق الغازات والسوائل الملوثة التي سيتم طردها بعيداً . لقـد تـم اختيار النظام بواسطة قياس المياه والغازات الملوثة التي يتم التخلص منها ، وتم معايرة الجهاز باستخدام بكـرة تـدور بسرعة ثابتة . وتم أيضاً استخدام الجهاز للتحقيق من سلوكيات التدفق المضطرب للماء . كما كان النظام أيضـاً قـادراً على قياس تغير دبيلر الحركي للسوائل إلى سرعة متدنية مقدارها (٠,١) متر/ ثانية (٢٥٠٠٠٠ هيتز).

1. INTRODUCTION

Doppler Velocimetry in conjunction with LIDAR (Light detection and ranging) technique has proven to be an excellent tool for remote measurements of gaseous and liquid pollutants by recording flow rates and making volume estimations of polluted water and gaseous discharges. This technique can also be employed in the industrial environment to monitor the amount of liquid pollutants dumped into a river or sea and also the volume of hazardous gases released from industrial exhausts. In addition to this environmental monitoring, Remote Doppler Velocimetry is used for the measurement of wind velocity, turbulent flow, cloud movement and other metrological parameters in the troposphere and stratosphere [Huffaker et al, 1996, Hausamann et. al, 1990, Killinger, 1986, Kobayashi, 1987, Measures, 1984a, Measures, 1984b, Drain,1980, Hall et. al,1984, Kane et. al, 1984, Post et. al, 1990, Rees et. al, 1990, Frehlich, 2000]. Most of the Doppler systems are for the measurements of velocities at supersonic speeds, however in the case of monitoring liquid and gaseous pollutants, the system should be of high resolution and capable of measuring fluids with very low flow rates. Although the concept of Doppler Velocimetry is relatively old and has been applied in various areas, recently it has gained real significance when coupled with LIDAR for remote measurements [Zanzottera , 1990, Vinogradov, 1987, Svanberg,1991, Grant et. al, 1983, Hinkley,1976, Sigrist, 1994].

During the past few years, efforts are concentrated on development of laser-based sensors for the measurement of concentration of different atmospheric pollutants for environmental protection [Gondal et. al, 2000, Gondal et. al, 1998, Gondal et. al, 1997, Gondal et. al, 2001]. Keeping the focus toward environmental application, an effort has been made to develop a Doppler Velocimeter for a unique application to monitor the liquid and gaseous pollutant discharges remotely. This application is very important for the estimation of volume of discharges (liquid as well gaseous) for the pollution control and modeling for the impacts on the environment. The system has been tested for measurement of polluted water and gaseous discharges. The turbulent flow profiles for the water were also investigated. The system has been calibrated with a rotating wheel at constant speed prior to these measurements.

2. TECHNICAL DETAILS OF THE SYSTEM

Fig.1 presents a block diagram of the high resolution Doppler velocimeter for remote measurement of liquid and gaseous discharges. An argon ion laser (Coherent, Model Innova 100) is used to excite an actively stabilized ring dye laser (Coherent, Model 699), which has been employed as the transmitter. With spectral line widths of less than 1 MHz, the ring laser becomes an excellent tool as a light source. The dye laser output is divided into two beam paths by a beam splitter. One beam which is 80% of the total incoming dye laser output is directed to the remote target (see Fig 1). The target could be a rotating wheel for the calibration purposes or flowing water or steam. In the case of a wheel, this beam is focused on the upper or lower side from the center of the wheel with the help of a focusing lens having long focal length (150 cm). The focal spot size at the target is about 50 μm and little larger than the Gaussian beam waist. Since the focal spot size is very small, therefore one can scan spatially the laser beam on small targets with better accuracy. This technique therefore could be applied to measure the flow rates of fluids in small Capilaries as well. The sampling

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volume in the case of a rotating wheel at the speed of 4.45 m/sec and for sampling time of 1 sec will be 0.35 $(mm)^3$.

The other beam which is 20 % of the dye laser output is employed as a reference local oscillator (LO), which is frequency shifted with respect to the transmitted beam by using an acousto-optic device (Bragg Cell). Using a single pass optical configuration through the Bragg Cell results in a diffracted LO beam frequency shifted by the acoustic frequency (300 MHz in this case). A Radio Frequency (RF) generator from Amplifier Research (Model 10W1000) capable of generating frequencies in the 1-1000 MHz range was applied to the acousto-optics device. In order to suppress the background noise, the RF generator was located in another room away from the detection system. In addition, narrow line-width optical and electronics band pass filters were also used to suppress the optical and electronic noise.

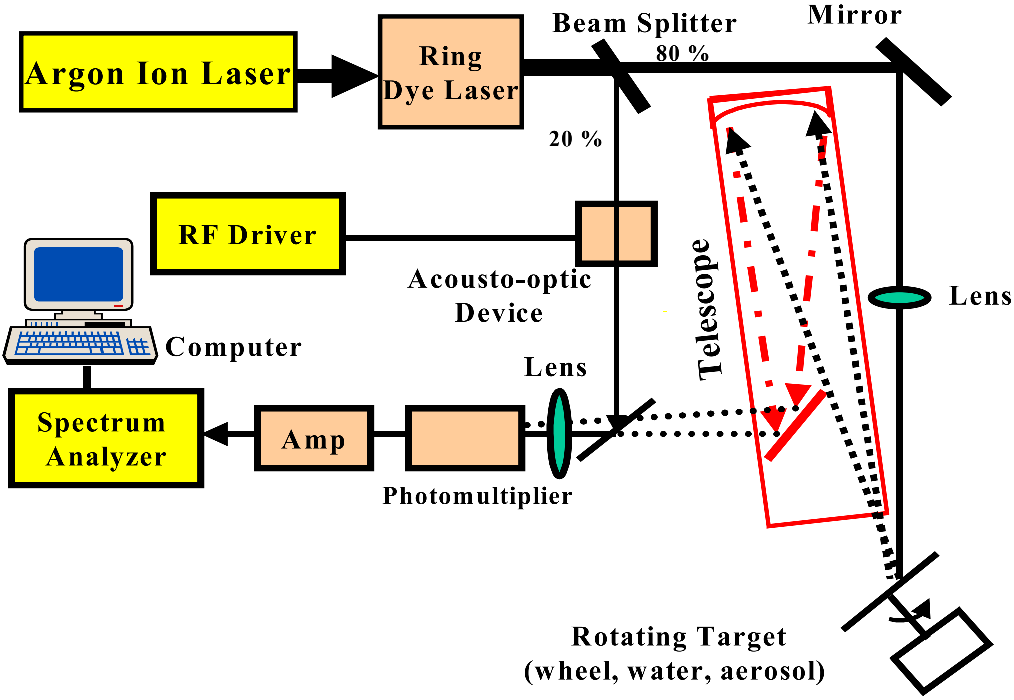

Figure: 1 Block diagram of the Doppler setup for the measurement of flow-rates and velocity profiles of gaseous and liquid discharges

A highly sensitive photomultiplier (PMT) from Hamamatsu (Model 2809U-07) with an excellent frequency response up to 1GHz is used for mixing of the reference LO beam and the collected backscattered signal. The time response of PMT is in the order of Picoseconds. The backscattered signal is collected by a self built telescope (Newtonian type, 8 inch diameter mirror) and spatially mixed with the LO reference beam onto the photomultiplier. The backscattered signal was corrected spatially with the help of a focusing lens and overlapped to the LO reference beam. A weak beat frequency signal corresponding to the frequency difference between the LO reference beam and the collected signal is amplified with a 30 dbm pre- amplifier. The amplified beat frequency signal is then displayed on a spectrum analyzer (Hewlett Packard, Model 8568 B). The spectrum analyzer has wide dynamic frequency response in the 100 Hz – 1.5 GHz range. The typical sampling period was 25 msec. The spectrum analyzer is interfaced with an on-line personnel computer for data transfer and further data analysis.

For the measurement of velocities of polluted water discharges, a closed cycle water flow system using a highly stabilized powered pumping unit was constructed. The water outlet where laser beam hits is a nozzle of brass. Two different diameters were used for the study of turbulent profiles. A calibrated flow meter was inserted in series for measurement of the flow rate of water. For the simulation of gaseous flows, steam was generated in a container having a specific nozzle shape outlet. For generation of acoustic vibrations, a loud speaker was used which was driven by a signal generator at 400 Hz.

3. RESULTS AND DISCUSSIONS

The system has been applied for the measurement of following parameters:

(a) Flow rates of polluted liquids

(b) Gaseous discharges,

(c) Turbulent velocity profiles

Prior to the employment of the Doppler system for the above mentioned applications, the system has been calibrated with a wheel rotating at a constant angular speed of 30 revolutions/ second. For angular speed of 30 rps, a Doppler shift (blue and red shift) of 11.0 MHz has been recorded by directing the laser beam at the upper and lower portion of wheel from the center. The linear speed ‘V’ of the wheel having a radius ‘r’ = 23.75 mm and rotating at frequency ‘f’ = 30 Hz is computed:

$$V = 2\pi rf = 4.476 \text{ m/sec.} \Rightarrow 11.0 \text{ MHz Doppler shift} \quad \therefore \; 1\text{m/sec} = 2.45 \text{ MHz}$$

The calibration factor of 2.45 MHz Doppler shift corresponds to 1 m/sec velocity with our system.

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The Doppler shift '$\Delta\nu$' of a light scattered from a moving object where the source (laser) and observer (detector) being stationary (as for our case) is given by equation:

$$\Delta\nu = (2\ V / \lambda) \cos\alpha \quad \text{----------------} \quad (1)$$

Where V = velocity of the moving object, λ = wavelength of laser light,
α = Angle of incidence.

For a Doppler shift of $\Delta\nu$ = 11.0 MHz, λ= 575 nm and $\alpha = 45^0$, the velocity computed through equation (1) will be

$$V = 4.473 \text{ m/sec}$$

Which is almost the same as the actual measured velocity of the rotating wheel.

3.1 Resolution of Our System

In order to determine the resolution (limit of detection) of our system, Doppler shifted backscatter signal was recorded by irradiating the wheel at different locations. Fig.2. depicts the typical signals recorded at various rotating speeds by irradiating the wheel at different locations. All possible precautions were taken during the measurements to keep all the other parameters same and also highly stabilized main supply voltage was provided to the rotating

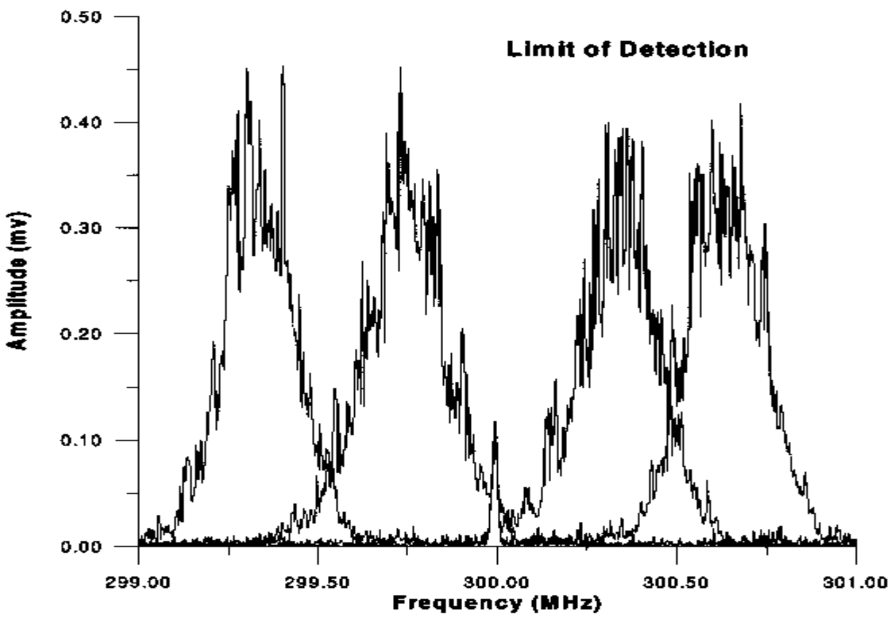

Figure: 2 Typical Doppler shifted signals indicating the resolution limit of our system.

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motor. The frequency response of the PMT and Spectrum analyzer have very wide range (1-1 GHz) so they have flat response over the measured frequency ranges.

The resolution (e.g. difference in frequency between two neighboring peaks) for the Doppler shift of our system is 0.25 MHz corresponding to 0.1 m/sec (see for example Fig. 2).

3.2 Measurements of Turbulent Flow Profiles

For the measurements of the flow rate of polluted water discharges, a closed cycle water flow system was built. The water pump was supplied with a highly stabilized power supply to avoid any current fluctuations, which could eventually cause velocity fluctuations due to different pump speeds. The water flow rate was measured using a calibrated flow meter constructed in series with the water flow line. For the study of turbulent flow profiles, the backscattered Doppler shifted signal was measured while translating the incident laser beam across the water flow profile from the hose. Fig. 3 shows the velocity profiles recorded at various positions such as 3, 2 and 1cm from the end of nozzle. These velocity profiles are calculated from the measurements of Doppler shifts using the spectrum analyzer at these positions and then converting them to velocity using the calibration factor (e. g 2.54 MHz = 1 m /sec) and counterchecking them by applying equation # 1. One can notice from the Fig. 3 that near the output of the hose (1cm), the fluctuations are less and velocity profile is almost

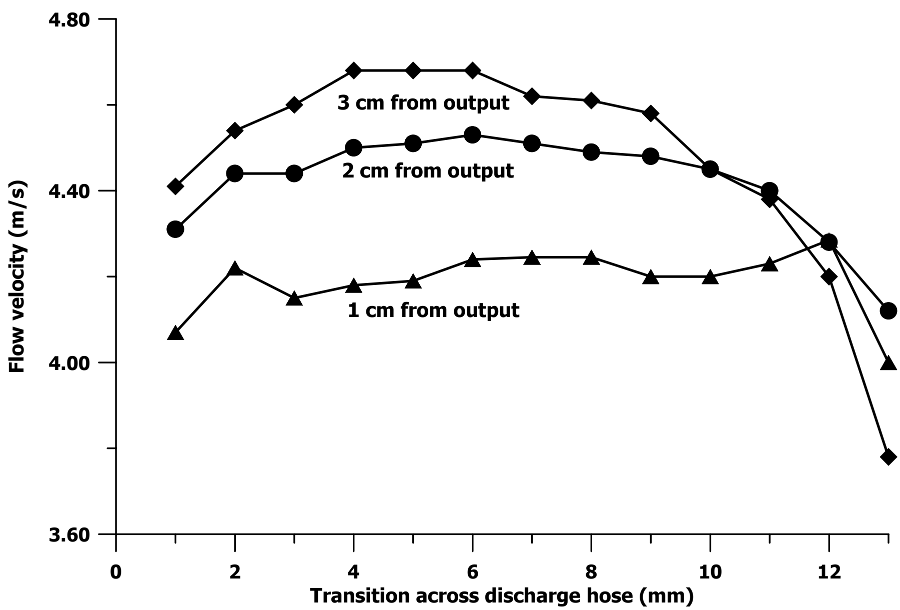

Figure: 3 The velocity profiles recorded at various positions such as 3, 2 and 1cm from the orifice.

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uniform over a wide cross section of the hose (≈10 mm) and as one measures away from the output (end of nozzle) of hose (3 cm), the velocity profile is only uniform for small cross section of the hose (≈3 mm). It is worth mentioning that this is a plot of the actual data points without any smoothing. As one can notice from the Fig. 3, there are some data points where anomalies (sharp changes in velocity) are obvious. These gradients are due to instabilities in water flow caused either by the water pump or by the inhomogeneous character of impurities in water. Also it is important to note that the velocity drops sharply at the edges of the water profile lateral position.

Using the measurement of flow rates to estimate the discharge per unit time, the average velocity of water was measured at different flow rates controlled by a valve and checked with a calibrated flow meter. The average velocity calculated from the measured Doppler shift and measured by flow meter are plotted in Fig. 4. A very good agreement has been found between the average velocity calculated from measured Doppler shift and from our flow meter. A linear dependence of velocity on the Doppler shift was found over a flow range of 8−40 liters/minutes. The system is thus capable of measuring polluted water remotely and other liquid discharges very accurately.

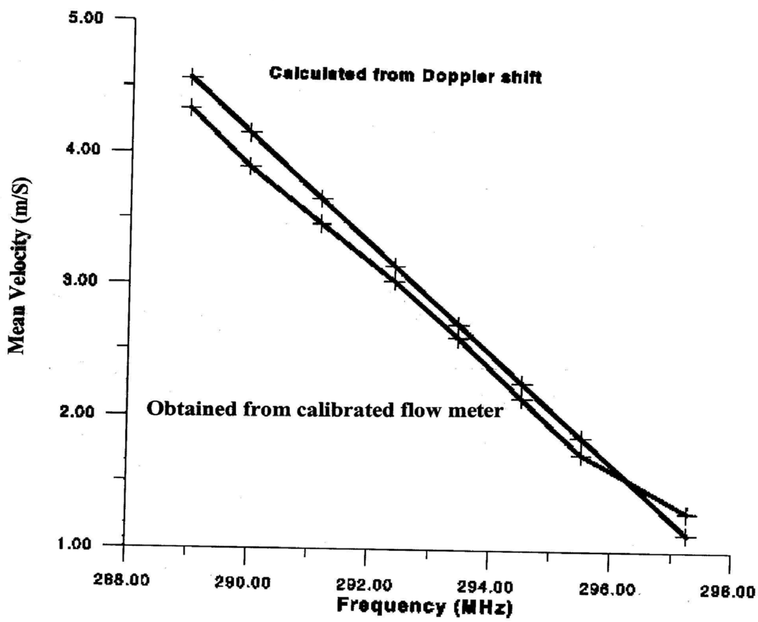

Fig. 4. Comparison between the velocities calculated from Doppler shift and actual flow rate measurements.

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3.3 Calculation Of Volume Flow Rate

Once the velocity of a toxic pollutant has been measured remotely using the Doppler velocimeter, the volume flow rate can be calculated by using the relation:

$$\text{Volume Flow Rate} = \int_0^R 2\pi r V(r)dr \quad \text{-------------} \qquad (2)$$

Here "R" is the radius of the hose (or pipe) through which the pollutant is flowing. Since the velocity variation is measured at discrete points across the hose cross-section, a simple mathematical relation (polynomial relation) between the velocity and r can be obtained. Consequently, equation 2 can be solved either numerically or analytically to obtain the value of flow rate.

3.4 Testing of the System for Gaseous Discharges

Another significant area for application of a Doppler LIDAR can be in the measurement of gaseous discharges from industrial exhausts used for atmospheric pollution modeling studies. We also tested our system for the measurement of flow rates of gaseous emissions. Laboratory simulation studies were carried out by measuring the backscattered signal from steam. A typical Doppler shifted signal recorded from steam with our set up is presented in Fig. 5. It is

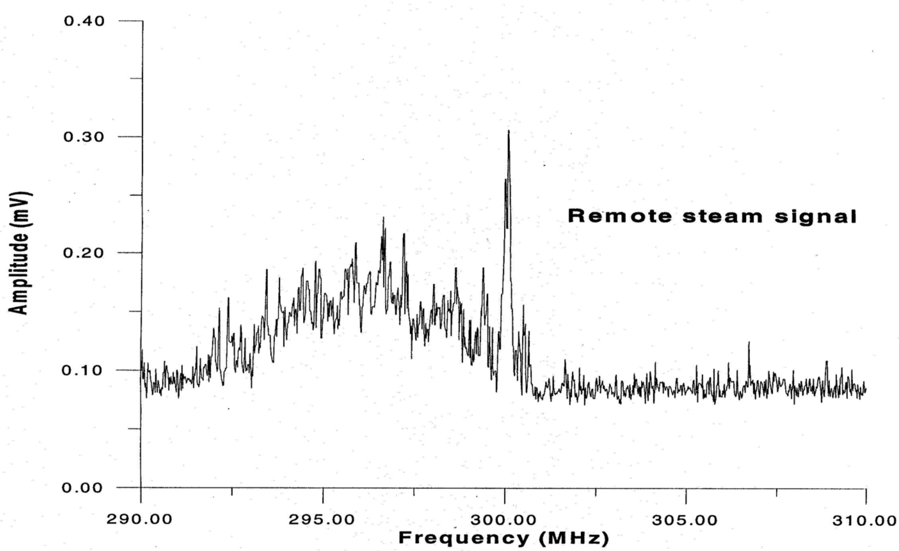

Figure: 5 Typical Doppler shifted signal recorded from steam.

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clear from the figure that Doppler shifted signal is quite broad and not a sharp peak as is case for water. The main reason for this broadness is the non-uniformity in the generation of steam process in our setup due to the heating of water under open environment. A shift of 3.8 MHz was estimated from the measured Doppler shift at the center of broad peak which correspond to the average velocity of 1.55 m/sec for the steam under our experimental conditions.

It is worth mentioning that the water used for the measurement of liquid and gaseous flow rates was not pure and clean. The suspended particles due to impurities in the water under investigation were responsible for the backscattering of the laser beam and therefore no extra seeding particles were required.

4. CONCLUSIONS

Doppler shifts as low as 0.25 MHz corresponding to 0.1 m/sec velocities has been measured with a highly stabilized ring dye laser. The system has been successfully applied to velocity measurements in the laboratory and can be used in several industrial applications. It is worth mentioning that our achieved sensitivity and simulation studies could be of great interest for the measurement of wind profiles, and turbulence of boundary atmospheric layers remotely. These parameters are important for various applications in different areas like meteorology, atmospheric physics, environmental protection, wind – energy utilization, and air traffic control.

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