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Studies on water vapour droplets using a laser based air quality monitoring system

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Abstract : This paper is concerned with the design and fabrication of a laser based air quality monitoring system combining the design principle of the nephelometer, transmissiometer and a point visibility meter. The system is tested by investigations on water droplet formation in air having different concentration of different gases. As such the work involves the theory of extinction and scattering, especially Mie scattering. Essentially in the system light from a laser source passes through a simulation chamber and the extinction and angular scattering of the light is monitored by photo detector arrangement. The signals are digitized and interfaced with pc for data recording and processing. Finally a correlation is drawn between the experimental results and the theoretical work.

Keywords : Extinction coefficient σ, scattering coefficient β

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1. Introduction

Several aspects of environmental pollution are studied all over the world. Our main aim is to develop an air quality monitoring system. It is necessary to know the different components present in normal air. It is also necessary to find out whether polluting particles have entered the air; if so, it will be necessary to quantify the pollutants. So if a relation can be found between a certain gas present in air and its characteristic scattering at specified angles then it will be possible to infer about the components of gases and their quantity from the same measurement. The extinction coefficient σ and the scattering coefficient β are used as a critical parameter for air quality monitoring. By knowing σ the phenomenon of visibility can be studied because visibility is related to extinction. Also

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the instrument yields information about the scattering coefficient β as well as the size of water droplets [1,2,3,4,5,8] The techniques of measurement used are (i) to compare the transmitted intensity of light with the original intensity of light and compute the corresponding extinction coefficient and (ii) to compute the scattering coefficients by observing the scattered intensity from different angles These two are the basic parameters through which the monitoring of air quality is developed and specific observations of water vapour in air having varying levels of CO_2 are performed Data have been processed to find out specific behaviors of gases towards scattering and absorption with an aim to identify their presence Starting from Maxwell's equation and the poynting vector, leading to the theory for finding the amplitude scattering matrix and then the stokes parameter for finally developing the Mueller matrix for scattering by a particle, as the value of one of the elements of the matrix, the element s_{11} in the first row and first column is experimentally determined in our investigations on water droplet formation in air

The Muller matrix developed is given as

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{k^2r^2}\begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{matrix} I_i \\ Q_i \\ U_i \\ V \end{matrix} \qquad (1)$$

The 16 scattering matrix elements for a single particle are not all independent only seven of them can be independent corresponding to the four moduli $|S_j|$, (j = 1,2 3 4 and the three differences in phase between the S_j Thus there are nine independent relations among the S_{ij} The element S_{11} is related to the measurements made by the air quality monitoring system The matrix is the transformation of stokes parameters of the incident light to stokes parameters of the scattered light Next Mie theory [6,7] is taken up to explain the angular variations of the scattered light by water droplets in air, which is investigated by our system and is found to be as follows

$$\begin{matrix} I_s \\ Q_s \\ U_s \\ V_s \end{matrix} \quad \frac{1}{k^2r^2}\begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix}\begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix} \qquad (2)$$

For water droplet state we have $I_s=(1/k^2r^2)\, S_{11}\, I_i$ (3)

The system uses gamma distribution given by $N(a) = p\, a^{\gamma} e^{\eta a}$

where a is the radius of the particle and p, γ, η are parameters of the distribution related to the density of scattering particles N_{tot} by $N_{tot} = p\eta^{-(\gamma+1)}\Gamma(\gamma+1)$ Again γ and η are related to the particle radius a_c corresponding to the peak of the distribution, the so called modal radius, by $a_c = \gamma / \eta$ The use of size distribution then leads to the formation of the volume scattering coefficient $\beta(\theta)$ for light which is obtained by integrating S_{11} as given by 3 over the size distribution $N(a)$ and is given as,

$$\beta(\theta) = \frac{1}{k^3} \int^{\infty} N(a)\, S_{11}\,(\theta)\, da \tag{4}$$

where $\beta(\theta)$ is in units of per steradian per centimeter ($sr^{-1}cm^{-1}$) Thus it is evident from 3 and 4 that experimental measurements of I_s and I_t will yield experimental $\beta(\theta)$ values, which is used in the system This aspect of the theory is taken advantage of in developing a software to simulate, using dummy initial values, theoretical values of $\beta(\theta)$ over a wide range of size distributions $N(a)$ and over a range of angles θ which may be used in drawing a co-relation with the experimental values S_{11} obtained by investigation on water droplets in air [6,7]

2 System description

It consists of a He-Ne laser source, some detectors, namely the transmitted light detector, the scattered light detector, the reference light detector The scattered light detector detects light from seven different angles The light entering these detectors produces photo current that is fed through an amplifier to produce the signal carried through one of the three channels for input to the Data Acquisition System In the Data Acquisition System, the four analog signals are digitized by using ADC 0809 and fed to a pc unit The software developed for the pc unit scans the channels and continuously stores the data in the hard disc

3 Extinction coefficient, scattering coefficient, correlation of theory and experimental Results

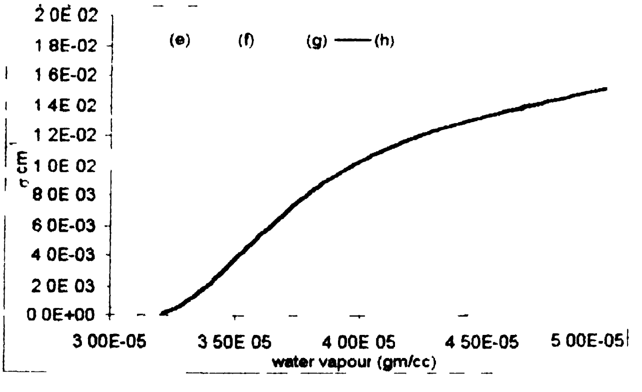

Figure 1. Extinction coefficient σ *versus* water vapour density of air for air having carbon dioxide densities of (e) CO_2 = 6 25x10^{7}gm/cc (CO_2 density of pure air), (f) CO_2 = 2 796x10^{6}gm/cc, (g) CO_2 = 4 97x10^{6}gm/cc and (h) CO_2 = 7 14x10^{6}gm/cc

4. Conclusions

The plots in Figure 1 and Figure 2 shows that there is considerable variation in the extinction coefficient as well as volume scattering coefficient of water vapour laden air where the CO_2 levels in air increases beyond the levels normally present in pure air This signifies that the trend in which the density of water vapor in the air increases is a function of the proportions in which the gaseous constituents of air are present. The plots in Figure 3 and Figure 4 represent the experimentally measured $\beta_{av}(\theta)$ and theoretical

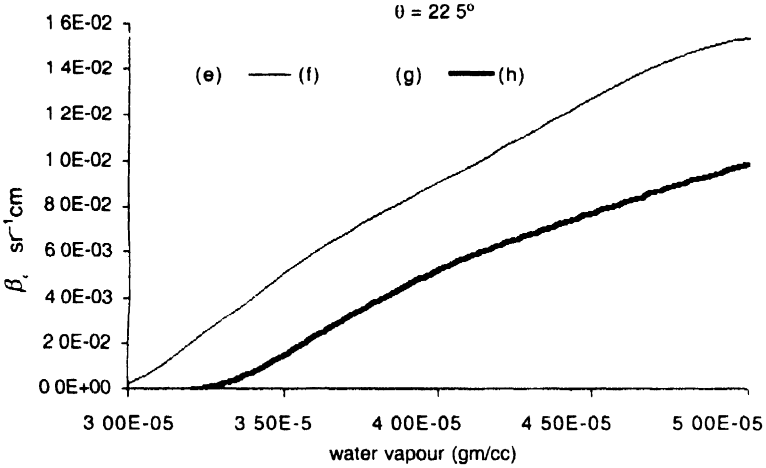

Figure 2. β_{av} (22 5°) *versus* water vapour density of air for air having carbon dioxide densities of (e) CO_2 = 6 25 x 10^{-7}gm/cc (CO_2 density of pure air), (f) CO_2 = 2 796 x 10^{-6}gm/cc, (g) CO_2 = 4 97x10 ' gm/cc and (h) CO_2 = 7 14 x 10^{-6}gm/cc

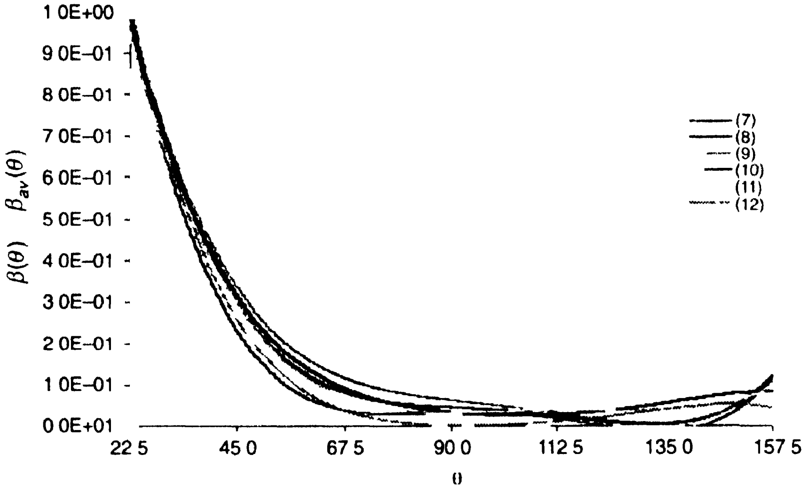

Figure 3. Experimentally measured $\beta_{av}(\theta)$ and theoretical $\beta(\theta)$ *versus* scattering angle θ Experimental $\beta_{av}(\theta)$ *vs* θ graphs are for air having CO_2 density of 6.25 x 10 ^{7}gm/cc (CO_2 density of pure air) and (7) water vapour density = 4 20 x 10^{-5} gm/cc, (8) water vapour density = 4 40 x 10^{-5} gm/cc and (9) water vapour density = 4 60 x 10^{-5}gm/cc Theoretical $\beta(\theta)$ *vs* θ graphs are for water vapour with a size distribution around (10) modal radius = 0 9μm and (11) modal radius = 1.0μm and (12) modal radius = 15 0μm

$\beta(\theta)$ *versus* scattering angle. The theoretical pattern corresponding to an aggregate of $S_{11}(\theta)$ values of water droplets having a particular size distribution *N(a)*, that is $\beta(\theta)$ for all angles θ. From Figure 3 it can be seen that when air has an CO_2 density of 6.25 x 10^{-7}gm/cc and water vapour density of 4.20 x 10^{-5}gm/cc, the experimental $\beta_{av}(\theta)$ vs θ plot (7) corresponds to the plot (12), which is the theoretical $\beta(\theta)$ *vs* θ plot for air having water droplets with model radius 15.0µm. When the water vapour density is 4.40 x 10^{-5}gm/cc, experimental $\beta_{av}(\theta)$ *vs* θ plot (8) corresponds to the plot (11), which is the theoretical $\beta(\theta)$ *vs* θ plot for air having water droplets with model radius 1.0µm. Finally, when the water vapour density is 4.60 x 10^{-5}gm/cc, experimental $\beta_{av}(\theta)$ *vs* θ plot (9) corresponds to the plot (10), which is the theoretical plot for air having water droplets with model radius 0.9µm. This shows that while there has been a relatively large decrease, that is a change of 14.0µm, in the size of the water droplets when the density of water vapour increased from 4.20 x 10^{-5}gm/cc to 4.40 x 10^{-5}gm/cc, for an equal increase in water vapour density from 4.40 x 10^{-5}gm/cc to 4.60 x 10^{-5}gm/cc, the size of the water droplets changed by only 0.1µm. It can thus be concluded that when air contains CO_2 density equivalent to the density of CO_2 in pure air, with increasing density of water vapour in the air, the droplet size of the water vapour will decrease non-linearly. From Figure 4 it can be deduced that in air having increased CO_2 densities of 4.97x10^{-6}gm/cc and 7.14 x 10^{-6}gm/cc the modal radius of the water vapour droplet is almost constant as the density of water vapour in the air increases from 4.20 x 10^{-5}gm/cc to 4.60 x 10^{-5}gm/cc with the modal radius being greater than 30.0 µm, which is again the greatest possible modal radius for which theoretical $\beta(\theta)$ *vs* θ plot is accurately given.

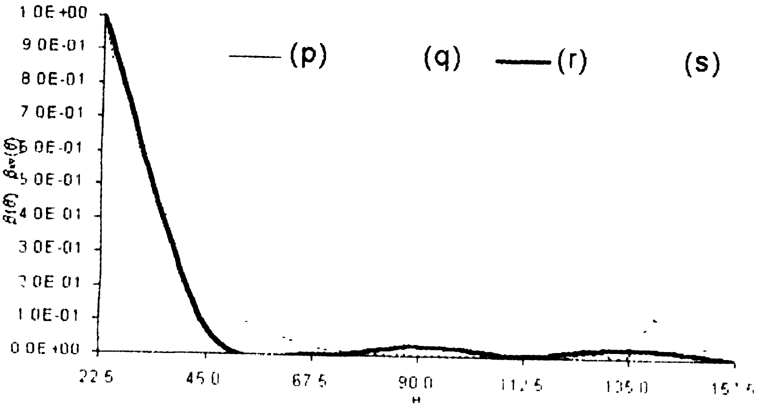

Figure 4. Experimentally measured $\beta_{av}(\theta)$ and theoretical $\beta(\theta)$ *versus* scattering angle θ graphs Experimental $\beta_{av}(\theta)$ *vs* θ are for air having CO_2 density of 4.97 x 10 ^{6}gm/cc and (p) water vapour density = 4 20 x 10^{-5} gm/cc, (q) water vapour density = 4 40 x 10^{-5} gm/cc and (r) water vapour density = 4 60 x 10^{-5}gm/cc Theoretical $\beta(\theta)$ *vs* θ graphs (s) is for water vapour with a size distribution around the modal radius = 30.0µm

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