Solar Multi–Spectral Radiometric Observations of Atmospheric Optical Thickness over Pasarlapudi Gas Well Blow–Out Site in India

G. Pandithurai and *P.C.S. Devara*
Indian Institute of Tropical Meteorology, Pune 411008, India
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ABSTRACT

Multi–spectral observations of solar radiation using a Volz sun–photometer have been carried out during February 24–March 2, 1995 in the vicinity of the blow–out of the gas well at Pasarlapudi, Andhra Pradesh, India. These unique and special observations have been utilized to study the aerosol, Rayleigh molecular and gaseous optical thicknesses. The results of the analysis of the observations indicated, besides low gas concentrations well below their background values, significant variations in aerosol optical thickness (AOT) at visible and near–infrared wavelength regions. The wavelength dependence of AOT revealed wide variations in the Junge aerosol size exponent from 0.98 to 6.70 indicating the presence of both sub–micron and coarse–mode aerosol particles over the observational site. A close correspondence between AOT and surface–level meteorological parameters during the period of observations was also noticed.

Key words: Gas well blow–out, Sun–photometry, Solar radiation, Aerosol optical thickness, Aerosol size distribution

I. INTRODUCTION

The potential effects of increased human activities on climate and / or the chemistry and physics of the atmosphere have prompted increased efforts to characterize the atmospheric properties during the past several years. Much of the impetus for this work has been stimulated by the conspicuous presence and observed impact of emissions, often anthropogenic, associated with combustion processes. In the absence of physical removal mechanisms, these emissions can be transported over long paths and act as a conservative tracer for airmasses that originate near combustion sources. Radiative effects can occur in the atmosphere through the introduction of elevated concentrations of non–absorbing and / or absorbing particles. The effects of such particles on the optical characteristics of the atmosphere or, in the end, climate depends importantly on the size, refractive index, and shape of the particles in relation to the wavelength of light.

The gas well blow–out that had occurred on January 8, 1995 at Pasarlapudi, Andhra Pradesh, India, however regrettable the accident may be, offered unusual opportunity for conducting observations and studies of considerable value to different Disciplines of Sciences. The unique features of the blow–out of natural gas well are as follows. Natural gas under a pressure of about 6000 psi. from a depth of about 2750 metres spewing out at the rate of 1 million cubic metres a day, rising to a height of about 100 metres had caught fire. The extent of the column of fire was about 10 metres in diameter. The temperature of the fire was estimated to be upwards of 1200 degrees celsius. A hiss or roar–like noise and occasional thunder clap–type sounds were reported to be heard. There was no visible smoke or soot in the fire, unlike in cases of blow–outs in oil wells. The fire was visible at night to a distance of about

25 km. A field observational programme was conducted in the vicinity of the blow–out site by the Indian Institute of Tropical Meteorology (IITM), Pune, during February 24–March 2, 1995. As part of this programme, multi–wavelength sun–photometer observations of directly transmitted solar radiation have been carried out at 5 discrete wavelengths between 0.4 and 1.63 μm. These observations have been used to derive the spectral optical thickness of the atmospheric aerosol particles over the blow–out site. By inverting the AOT measurements made at different wavelengths, aerosol size distributions (ASD) have been obtained. In this paper, we present a brief description of the blow–out site, together with the spectral characteristics of AOT and corresponding ASDs, and their relationship with variations in the concurrent surface–level meteorological parameters during the observational period. In the absence of the observations that could not have been carried out during the ordinary condition, the results presented in the paper represent the conditions of the atmosphere during the blow–out period.

II. EXPERIMENTAL SITE AND OBSERVATIONS

The experimental site, Pasarlapudi (16°N, 82°E, 4 m AMSL) of East Godavari District, Andhra Pradesh state, India, is surrounded by coconut fields and sparsely populated areas. A photograph depicting an aerial view of the flame and gas well is shown in Figure 1. Eventhough the initial conditions of the blow–out of the gas well were more regrettable, the situation was brought very much under control by the time the present field experiment was conducted i.e. after a time gap of about 48 days. This was accomplished mainly by using a specially designed machine called a Halliburton sandcutter, which sprays silica and water at tremendous force which resulted in narrowing the horizontal extent of the flame. The vertical and horizontal extends of the blow–out generated flame were found to be about 50 and 5 m, respectively, during the period of observations. The surface–level temperature and relative humidity were observed to vary from 22 to 32°C and 65 to 96%, respectively.

The spectral optical thickness of the atmosphere was obtained by making observations of the directly transmitted solar radiation using narrowband, multi–wavelength solar radiometer (i.e. sun–photometer) at discrete wavelengths of 400, 600, 940, 1060 and 1630 nm. The details of this radiometer can be found in Devara et al. (1996a). The sunphotometer was operated at an aerial distance of about 1 km east to the gas well as depicted in Figure 2. The sunphotometer used in the present study has been in regular operation at Pune (18°32′N, 73°51′E, 559 m AMSL) an urban station in India and it was calibrated thoroughly before taking it for the field observation. The observations were carried out from sunrise till sunset, at 10 minute interval, on the days when the field of view was free from visible clouds, and none were near the line–of–sight to the sun during February 24–March 2, 1995. Errors that are expected due to misalignment of optics and invisible clouds, were detected and removed from the raw data to avoid improper weights to the derived optical thickness estimates and to reduce the scatter of points in the Langley plot. The coincident surface–level meteorological parameters were also collected during the above experimental period.

III. MEASUREMENT OF SPECTRAL OPTICAL THICKNESS

The spectral optical thickness, a function of the number, size, composition, and shape of particles present in a given column of air, is a fundamental optical property of the atmosphere. Spectroradiometry or sun–photometry has been proven to be a successful technique for measuring multi–wavelength AOT (Yamamoto and Tanaka, 1969; Rangarajan, 1972; Shaw et al., 1973; King et al., 1978; Asano et al., 1985, Ramachandran, 1994; Devara et al., 1996b). The governing equation for the measurement of AOT may be written as

$$V_\lambda = V_{o\lambda} \cdot e^{-m\tau_\lambda},$$

where V_λ is the output voltage of the detector at a given wavelength, λ; $V_{o\lambda}$ is the zero airmass voltage intercept for the Earth–Sun separation at the time of observation, m is atmospheric airmass (a function of solar zenith angle) and τ_λ is the wavelength dependent total optical thickness above the multi–wavelength sun–photometer altitude. The AOT, denoted by $\tau_a(\lambda)$, is determined from the total optical thickness by subtracting optical thickness due to Rayleigh molecules and gas molecules at wavelengths where there is appreciable gaseous absorption. Absorption by gases (NO_2 and O_3) contributes significantly to the non–Rayleigh atmospheric attenuation. Such effects were removed by suitable methods as explained in Devara et al. (1996b). Because of strong absorption of water vapour at the 940 nm wavelength, the observations recorded at this wavelength were not considered for deriving AOT in the present study. The instantaneous AOTs are estimated from the slope of a line drawn through the zero airmass intercept voltage and the data point for a particular time.

The ASDs are obtained from the AOT data collected at different wavelengths following the inversion scheme suggested by King et al. (1978) and King (1982) which relates the AOT to an ASD as

$$\tau_a(\lambda) = \int_0^\infty \pi r^2 Q_{ext}(x,m) n_c(r) dr,$$

where r is the particle radius, x is the particle size parameter ($=2\pi r/\lambda$); $Q_{ext}(x,m)$ is the extinction efficiency factor and $n_c(r)$ is the columnar ASD, that is, the number of particles per unit area per unit radius interval in a vertical column through the atmosphere. m is the complex refractive index and the imaginary component is assumed to be zero in the inversion analysis. The day–to–day variation in AOT and corresponding ASD and their association with surface–level meteorological parameters are discussed in the section that follows.

IV. TEMPORAL VARIATIONS IN AOT AND ASD

The day–to–day variability in AOT observed at different wavelengths during the period of observations is shown in Figure 3. The ratio between the AOTs observed at wavelengths 400 and 1060 nm on each day is shown with parentheses in the figure. These values indicate the dominance of the concentration of coarse–mode particles over that of sub–micron particles on different days of observations. It follows from the figure that AOT decreases with increase in wavelength except at 1060 nm which is attributed to the combined effect of gas–to–particle conversion process and combustion–influenced water droplets over the experimental site. The increase in AOT at 1060 nm could also be due to the existence of an unidentified weak atmospheric absorption band at 1010 nm wavelength. This absorption is

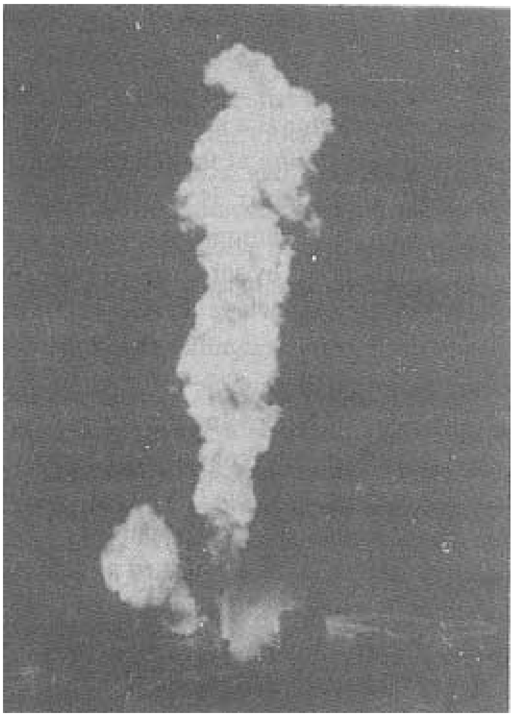

Fig. 1. Photograph showing the gas well and blow-out at Pasarlapudi, Andhra Pradesh, India.

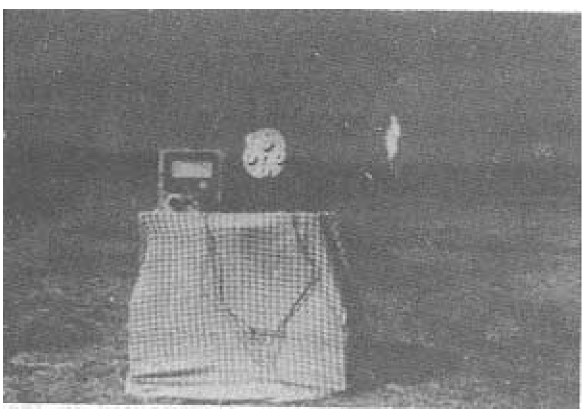

Fig. 2. Photograph showing the experimental site where the sunphotometer has been operated.

apparently a weak continuum and may be water vapour absorption feature between the $\rho\sigma\tau$ and φ bands, with an absorption coefficient 20–40 times larger than that listed in the literature (Shaw, 1980). The high AOTs noticed on February 28, 1995 are considered to be due to the presence of some invisible high-altitude cloud formations and the associated well known multiple scattering phenomenon.

The daily as well as 6-day mean variation of AOT at the observed wavelengths and those in ASDs, inverted from the spectral variation of AOTs, are displayed in Figure 4(a) and 4(b), respectively. The inversion method for retrieving the aerosol size distribution from aerosol optical thickness data has been carried out mainly in two steps. The first step is for finding out the optimum particle radius range. Having found this, next step is for finding out the number concentration $[dN(r)/d\log r]$ at these radii and also for finding out a factor $\sum \varepsilon_i^2$ which monitors the deviations between the observed and back-calculated optical thickness for a number of iterations. The size distribution corresponding to the iteration for which $\sum \varepsilon_i^2$ value is minimum is considered as the best and plotted in Fig. 4. The observed ASDs exhibit a power-law type distribution with different exponents changing at an intermediate size. Hence this modified Junge power-law distribution can be approximated by combining the distribution factors with different components with a switching radius, r_0 in the following form

$$n(r)=\begin{cases} C(0.1)^{-v_1}, & r_{\min}\leqslant r\leqslant 0.1\mu m \\ Cr^{-v_1} & 0.1\mu m\leqslant r\leqslant r_0 \\ Cr_0^{(v_1-v)}r^{-v_2}, & r_0\leqslant r\leqslant r_{\max} \\ 0, & r<r_{\min} \text{ or } r>r_{\max} \end{cases}$$

where v_1 and v_2 are the exponents corresponding to $r<r_0$ and $r>r_0$, respectively. These exponents and switching radius can be determined by fitting the above function to the inverted mean size distributions shown in Figure 4(b) and they are presented in Table 1. This figure also points out that the ASD observed on 25 February 1995 was different from those on the other days of the experiment. This could be due to the strong winds observed on this day which might have brought fresh airmass from the surroundings to the observational site. Thus the resulted abundance of coarse mode particles, besides sub-micron size particles, in the size distribution on February 25, 1995 is considered to be due to high positive correlation between AOT and wind speed on that day.

Table 1. Junge Size Exponents (v_1 and v_2) and Switching Radius (r_0 in μm) Observed on Different Experimental Days

Date	v_1	v_2	r_0
25.02.1995	3.96	2.21	0.77
26.02.1995	2.04	5.68	0.77
27.02.1995	1.38	2.51	0.40
28.02.1995	0.98	6.70	0.63
01.03.1995	1.22	4.55	0.59
02.03.1995	2.72	0.83	0.89
Average	2.08	2.37	0.45

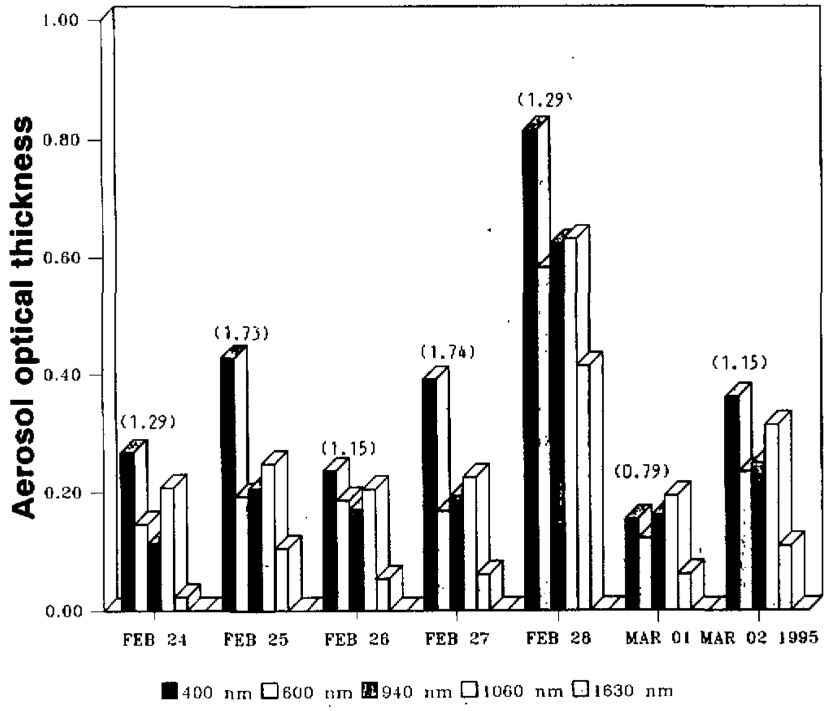

Fig. 3. Spectral AOT variations over the Pasarlapudi gas well blow-out site during February 24–March 2, 1995. The numbers enclosed with parantheses indicate the ratios between the AOTs observed at *400* and *1060* nm wavelengths.

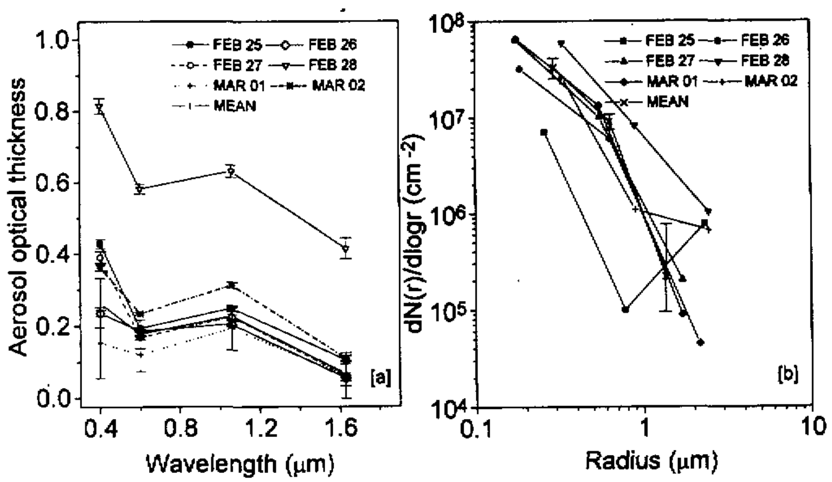

Fig. 4. Aerosol spectral and size characteristics, (a) wavelength dependence and (b) size distributions. Vertical bars indicate standard errors.

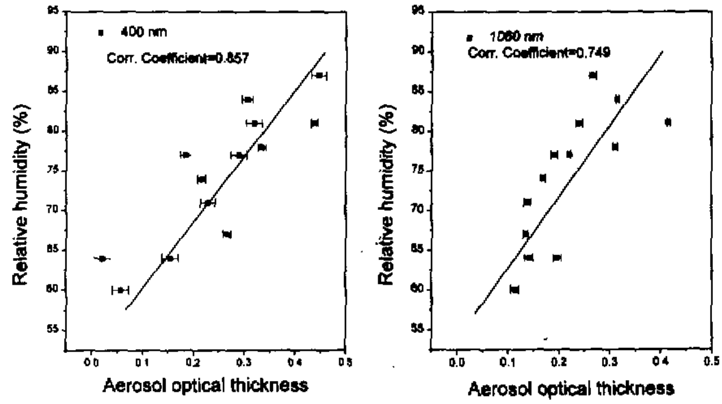

Fig. 5. Scatter plots depicting correlation between the relative humidity and AOT at 400 nm and 1060 nm. Vertical bars indicate standard errors.

The results of the correlation analysis between the variations in AOTs and surface-level relative humidity (RH) and wind speed indicated significant positive correlation of AOT with RH while that with wind speed is not clear which is considered to be due to smaller speeds and varying direction of wind during the experimental period. Scatter plots showing the relationship of relative humidity with the AOT at 400 nm and 1060 nm for the entire 6-day period are depicted in Figure 5. Examination of this figure reveals a monotonic increase of AOT with increase in relative humidity.

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REFERENCES

Asano, S., Sekine, M., Kobayashi, M., and K. Murai (1985), Atmospheric turbidity and aerosol size distribution in winter at Tsukuba: Effects of the Eruptions of El Chichon, *J. Meteor. Soc. Japan*, **63**: 453-463.

Devara, P.C.S., Raj, P.E., Pandithurai, G. and S. Sharma (1996a), High-spectral resolution radiometer for atmospheric monitoring, *J. Instrum. Soc. India*, **25**: 142-154.

Devara, P.C.S., Pandithurai, G., Raj, P.E. and S. Sharma (1996b), Investigations of aerosol optical depth variations using spectroradiometer at an urban station, Pune, India, *J. Aerosol Sci.*, **27**: 621-632.

King, M.D. (1982), Sensitivity of constrained linear inversions to the selection of the Lagrange multiplier, *J. Atmos. Sci.*, **39**: 1356-1369.

King, M.D., Byrne, D.M., Herman, B.M., and J.A. Regan (1978), Aerosol size distribution obtained by inversion of spectral optical depth measurements, *J. Atmos. Sci.*, **35**: 2153-2167.

Ramachandran, S., Jayaraman, A., Acharya, Y.B. and B.H. Subbaraya (1994), *Features of aerosol optical depths over Ahmedabad as observed with a sun- tracking photometer*, **67**: 57-70.

Rangarajan, S. (1972), Wavelength exponent for haze scattering in the tropics as determined by photoelectric photometer, *Tellus*, **24**: 56–64.

Shaw, G.E. (1973), Sun photometry, *Bull. Amer. Meteor. Soc.*, **64**: 4–10.

Shaw, G.E. (1980), Absorption continuum in the near IR near 1.0 μm, *Appl. Opt.*, **19**: 480–482.

Yamamoto, G., and M. Tanaka (1969), Determination of aerosol size distribution from spectral attenuation measurements, *Appl. Opt.*, **8**: 447–453.