Asia's Largest Lignite Based Power Plant's Success Story: Efficient Removal of SO_2 Through A Manmade Forest Canopy

U. K. Seth, S. Sarkar, R. Bardhan, and S. Ghosh

***Abstract* - One of the crucial issues that confronted world leaders in the recently concluded Copenhagen summit was that of achieving sufficient power generation for developing countries without exacerbating the problem of global warming. Developing countries, like India, are poised on the path of massive infrastructural project development still requiring power from conventional sources. Power generation at the point of origin of a particular natural resource such as lignite will still continue for some decades to come. The district of Tamil Nadu in South India is rich in lignite. Hence, it is quite natural that the Ministry of Coals, Government of India, should generate power from this rich natural resource at Neyveli Lignite Corporation (N.L.C.). In fact, N.L.C. is indeed Asia's largest lignite based power plant. The generation of power however comes with a price – this involves the release of large quantities of SO_2, which should be removed effectively.**

The dry deposition of sulphur dioxide over forested canopies is a subject of intense new research. Ours is a first study over coastal Tamil Nadu in the Indian subcontinent. In this case study, it is shown through fluid mechanical models, how SO_2 pollution emanating from stacks is removed effectively by a hand planted, manmade, forest canopy. This power plant is situated in a hot humid tropical belt, giving one the meteorological advantage of a suitable micro-climate for the proliferation of lush green vegetation in a short span of time. N.L.C.'s astonishing success story really rests on the fact that the founding fathers planted 17 million trees within the complex which acts as an efficient sink for SO_2 capture.

Deposition velocity of SO_2 is determined for a particular month, April, where the effects of wet scavenging are non-existent. Particular emphasis is placed on various resistances including stomatal, mesophyllic, upper canopy, and buoyant convection resistances which are simulated using actual data from N.L.C., during April. Canopy resistance values are determined to be 158.87 and 124.45 $s.m^{-1}$ at 8:30 a.m. and at 2:30 p.m. respectively. The respective deposition velocities at those times are calculated to be 0.55 and 0.73 $cm.s^{-1}$.

***Index Terms* - Canopy resistance, Dispersion, Dry deposition velocity, Tropical boundary layer.**

I. Introduction

The Neyveli Lignite Corporation (N.L.C.) is among the largest lignite based power plants in South East Asia. Each elevated stack from this power plant emanates a substantial amount of sulphur dioxide into a tropical boundary layer [1]. Modelling dry deposition is challenging and warrants a full treatment. Dry deposition, which is the vertical downward flux of a species, is represented by the deposition velocity, v_d, multiplied by the concentration of the material at some reference height above the surface.

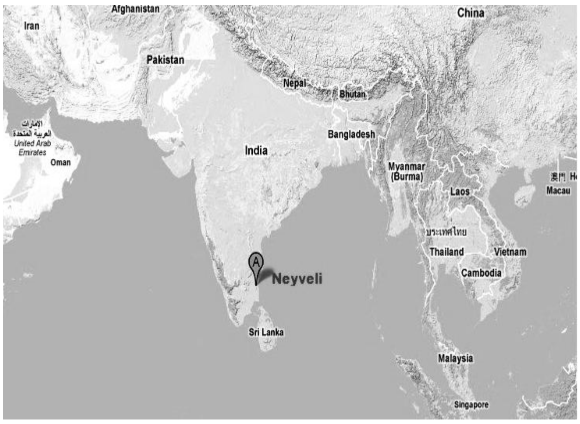

Fig. 1. Map of India showing the location of NLC

Manuscript received February 27, 2010. This work is being carried out as a funded industrial project for Neyveli Lignite Corporation under Grant No. CARD/ENVT/MAP/Project1218/2009.

S. Ghosh is with the School of Mechanical and Building Sciences, VIT University, Vellore, Tamil Nadu, India-632014. He is also affiliated to the School of Earth and Environment, University of Leeds. (phone:0416-2202207; fax:0416-2243092; email: satyjitg@vit.ac.in)

U. K. Seth is with VIT University, Vellore, Tamil Nadu, India-632014. (Email: umeshseth87@gmail.com)

S. Sarkar is with VIT University, Vellore, Tamil Nadu, India-632014. (Email: sayan.inc@gmail.com)

R. Bardhan is with VIT University, Vellore, Tamil Nadu, India-632014. (Email: rishi_bardhan2000@yahoo.com)

A. *Local Meteorology around NLC*

Neyveli is a mining and power generation township in the Cuddalore district of Tamil Nadu in the Indian sub-continent (see Fig. 1). It is located at 11.30° N - 79.29° E. Neyveli is at an average elevation of 87 meters (285 feet). It is 52 km inland from Bay of Bengal, lies west of Pondicherry and 197 km south of Chennai. The location of Neyveli is such that the boundary layer is strongly influenced by (i) the diurnal variation of solar insolation within the tropical belt, (ii) wind flow patterns owing to its proximity to the Bay of Bengal, (iii) the effect of added roughness elements in the surface boundary layer due to the extensive greening of the N.L.C. complex. The solar insolation varied between 95 $W.m^{-2}$ to 332 $W.m^{-2}$ and 107 $W.m^{-2}$ to 664 $W.m^{-2}$ at 8:30 a.m. and 2:30 p.m. respectively, as inferred from April 2009 data.

April is one of the hottest months with temperatures varying between 24.3 ^{0}C to 38.8 ^{0}C. In order to single out the effects of dry deposition removal, this study concentrated on the month of April when showers were virtually non-existent.

II. MASS TRANSFER OF SO_2 IN A FORESTED CANOPY

The factors that govern the dry deposition of a gaseous species or a particle are atmospheric turbulence, chemical properties of the depositing species, and the nature of the surface itself [2]-[4]. The depositing species experience resistances mainly in three forms: the aerodynamics resistance r_a, the quasi-laminar layer resistance r_b, and the canopy (vegetation canopy) resistance r_c. The total resistance, r_t, is the sum of the three individual resistances and is the inverse of the deposition velocity, v_d.

$$v_d^{-1} = r_t = r_a + r_b + r_c \tag{1}$$

In this study, we focused on canopy resistance given by

$$\mathrm{r_c} = \left(\frac{1}{\mathrm{r_{sm}}} + \frac{1}{\mathrm{r_{lu}}} + \frac{1}{\mathrm{r_{dc}} + \mathrm{r_{cl}}} + \frac{1}{\mathrm{r_{ac}} + \mathrm{r_{gs}}}\right)^{-1} \tag{2}$$

where r_{sm} is the combined stomatal and mesophyllic resistance, r_{lu} is the outer surface resistance in the upper canopy, which includes the leaf cuticular resistance in healthy vegetation and the other outer surface resistances; the third term is the resistance in the lower canopy, which includes the resistance to transfer by buoyant convection, r_{dc}, and the resistance to uptake by leaves, twigs, and other exposed surfaces, r_{cl}; and the fourth term is the resistance at the ground, which includes a transfer resistance, r_{ac}, for processes that depend only on canopy height and a resistance for uptake by the soil, leaf litter, and so on at the ground surface, r_{gs}.

The bulk canopy stomatal resistance is calculated by

$$\mathrm{r_{st}} = \mathrm{r_j}\left[1 + \left(\frac{200}{\mathrm{G}+1.1}\right)^2\left(\frac{400}{\mathrm{T_s}\,(40-\mathrm{T_s})}\right)\right]. \tag{3}$$

where r_j is the minimum bulk canopy stomatal resistance for water vapour, G is the solar radiation ($W.m^{-2}$), T_s is surface air temperature (^{0}C).

The combined minimum stomatal and mesophyllic resistance, r_m, is calculated from

$$r_{sm}^i = \mathrm{r_{st}^i} + \mathrm{r_m^i} = \mathrm{r_{st}}\left(\frac{\mathrm{D_{H_2O}}}{\mathrm{D_i}}\right) + \frac{1}{3.3\times10^{-4}\mathrm{H}+100\,\mathrm{f_0}} \tag{4}$$

where $\frac{D_{H_2O}}{D_i}$ is the ratio of the molecular diffusivity of water to that of the species gas, H is the effective Henry's law constant ($M.atm^{-1}$) for the gas, and f_0 is a normalized reactivity factor for the dissolved gas.

The second term on the R.H.S. of (4) is the mesophyllic resistance for the gas of interest. The other resistances r_{lu}, r_{dc}, r_{cl}, r_{gs} are computed from the method outlined in [5].

We show the mesophyllic, the stomatal and the canopy resistances in Figs. 2, 3, and 4 respectively. These resistances depend on parameters like solar insolation, ambient temperature and concentration of gases. As expected, at 2:30 p.m., the resistances are lower than those in the morning (8:30 a.m.) because the stomatal openings depend sensitively on the extent of solar insolation.

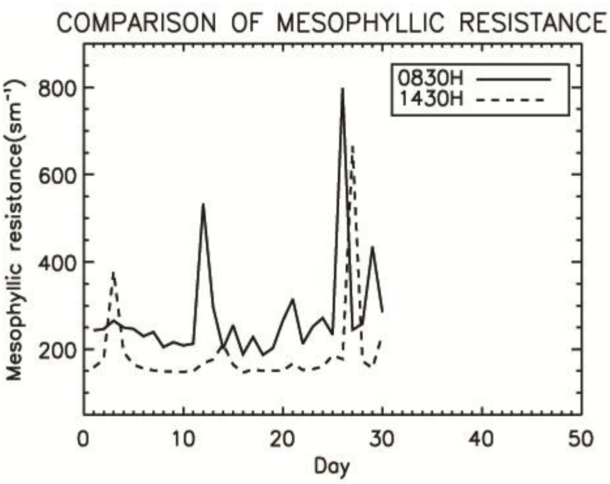

Fig. 2. Range of variability of mesophyllic resistance at 8:30 a.m. and 2:30 p.m. Note that the peaks correspond to days with cloud cover.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

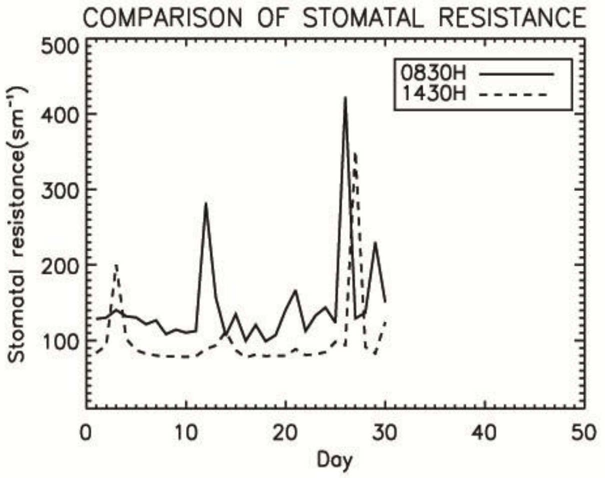

Fig. 3. Range of variability of stomatal resistance at 8:30 a.m. and 2:30 p.m. Note that the peaks here are located at approximately the same position as in Fig. 2.

We have not shown the values of the canopy resistance at 2:30 a.m. - it is a straight line with high values ranging between 400 to 500 $s.m^{-1}$. This is to be expected as the solar insolation is negligible at 2:30 a.m.

It can be inferred from the plots that the mesophyllic, stomatal and canopy resistances decrease as the day progresses, and concomitantly rise up as the solar insolation decreases. The average values of these respective resistances are 274.18, 145.05, and 158.87 $s.m^{-1}$ at 8:30 a.m.; and 189.22, 100.09, and 124.45 $s.m^{-1}$ at 2:30 p.m. Also note that the dry deposition rate for 8:30 a.m. is significantly lower than that at 2:30 p.m. Finally, in Fig. 5 we show v_d values over the N.L.C. canopy. The average dry deposition velocity at 2:30 p.m. and 8:30 a.m. are 0.73 and 0.55 $cm.s^{-1}$ respectively. It is important to note that we have shown the deposition velocities in $cm.s^{-1}$ rather than in SI units because reported observational values are conventionally expressed in $cm.s^{-1}$.

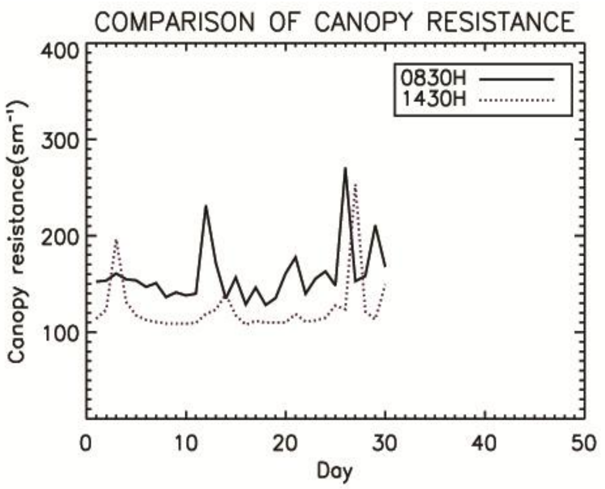

Fig. 4. Range of variability of canopy resistance at 8:30 a.m. and 2:30 p.m.

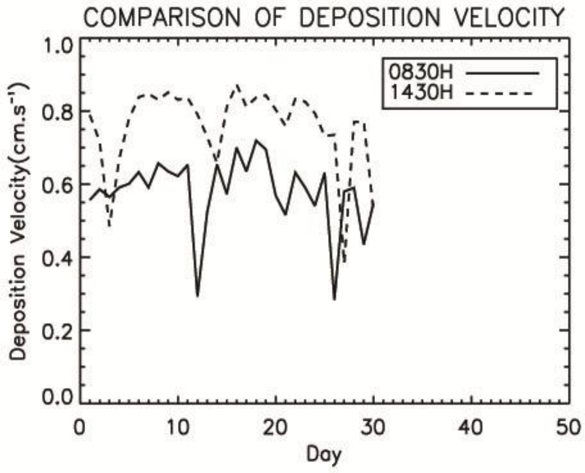

Fig. 5. Dry deposition velocities of sulphur dioxide at 8:30 a.m. and 2:30 p.m.

We can see that the depressions in Fig. 5 correspond to peaks in Figs. 2, 3, and 4. This is expected since the dry deposition velocity is inversely proportional to the sum of the resistances, as in (1).

It is interesting to compare these values with other estimates worldwide [6]-[8]. Reported values range from 0.1 to 0.31 $cm.s^{-1}$ over the dry season for teak forests in Northern Thailand [9] and elsewhere in Asia [10]. Our values are considerably higher because N.L.C. in Tamil Nadu is at a more southerly latitude with correspondingly higher solar insolation-the foliage patterns however are broadly similar over the two forest types i.e. within Southern India and Northern Thailand.

III. CONCLUSIONS

In this paper we have shown the efficacy of the dry deposition removal from a heavily forested canopy around Asia's largest lignite based power plant. We have elucidated the mechanistic details of the actual process of mass transfer of SO_2 from a turbulent boundary layer to the canopy surface. The transfer rate is controlled by the deposition velocity-the substantial deposition velocity computed from this study indicates high removal rates of sulphur dioxide which significantly improve the air quality. The deposition rates are modulated by the amount of solar insolation and the canopy resistance. We find that averaged deposition velocities at 8:30 a.m. and 2:30 p.m. are 0.55 and 0.73$cm.s^{-1}$ respectively. These are first calculations for an evergreen forest within a tropical belt in the Indian subcontinent. Our computed v_d values can be directly used by town planners for Environmental Impact Analyses of future Power Plant projects within the subcontinent.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

ACKNOWLEDGMENT

The authors are grateful to the Deputy General Manager, Centre for Applied Research and Development (C.A.R.D) Neyveli Lignite Corporation for providing us with observational data.

REFERENCES

[1] Generating Power for Generations, *Neyveli Lignite Corporation Ltd NLC publication, Tamil Nadu, India*. 2006, pp. 1-20.
[2] J. A. Garland, "Dry and wet removal of Sulphur from the atmosphere", *Atmospheric Environment*, vol. 12, pp. 349-362, 1978.
[3] L. Granat, C. Johansson, "Dry deposition of SO_2 and NO_x in winter", *Atmospheric Environment*, vol. 17, pp. 191-192, 1983.
[4] B. B. Hicks, D. R. Matt, "Combining biology, chemistry, and meteorology in modelling and measuring dry deposition", *J. Atmos. Chem.*, vol. 6, pp. 117-131, 1988.
[5] J. H. Seinfeld, S. N. Pandis, *Atmospheric Chemistry and Physics: From Air Pollution To Climate Change*. J. Wiley & Sons. New York. 1997, pp. 971-977.
[6] J. L. Tsai, B. J. Tsuang, P. H. Kuo, M. L. Tang, P. J. Chu, **"**Observation of SO_2 dry deposition velocity at a high elevation flux tower over a evergreen broadleaf forest", presented at the 16th Conf. on Air Pollution Metrology, American Meteorological Society, USA. 2010.
[7] D. R. Matt, R. T. McMillan, J. D. Womack, B. B. Hicks, "A comparison of estimated and measured SO_2 deposition velocities", *Water Air Soil Pollution*, vol. 36, pp. 331- 347, 1987.
[8] T. P. Meyers, D. D. Baldocchi, "A comparison of models for deriving dry deposition fluxes of O_3 and SO_2 to a forest canopy", *Tellus*, vol. 40B, pp. 270-284, 1988.
[9] K. Matsuda, I. Watanabe, V. Wingpud, P. Theramongkol, T. Ohizumi, "Deposition velocity of O3 and SO2 in the dry and wet season above a tropical forest in northern Thailand", Atmospheric Environment, vol. 40, pp. 7557-7564, 2006.
[10] Y. Xu, G. R. Carmichael, "Modeling the dry deposition velocity of Sulfur Dioxide and Sulfate in Asia", *J. Applied Meteorology*, vol. 37, pp. 1084-1099, 1998.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)