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FLUE GAS DISCHARGE FROM COOLING TOWERS. WIND TUNNEL INVESTIGATION OF BUILDING DOWNWASH EFFECTS ON GROUND-LEVEL CONCENTRATIONS

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Abstract—German power plants are required to meet new emission standards which limit the maximum sulfur dioxide (SO_2) concentration in flue gas discharges to 400 mg m^{-3}. To achieve this level of reduction in SO_2 concentration, wet scrubbing is necessary for large plants using lignite or hard coal.

Wet scrubbing results in a significant reduction in the flue gas temperature leading to low effective stack heights. Instead of using stack gas reheating to achieve the plume rise necessary to satisfy local environmental standards, it was proposed to discharge the scrubbed flue gas from the existing natural-draft cooling towers (NDCT). This method should be effective in reducing local ground-level concentrations since NDCT-plumes are typically very buoyant (densimetric Froude number below 1) and normally reach considerable heights of rise. Only under strong wind conditions does the situation reverse itself. For such strong winds, the NDCT-plume is subject to tower and building downwash with the possibility of unacceptably high ground-level concentrations.

For a 2700 MW$_e$ lignite-fired power plant near Cologne, a wind tunnel study was carried out to investigate the effects of tower and building downwash effects on the ground-level concentrations of SO_2 produced by discharging the scrubbed flue gas from the natural-draft cooling towers. Also, a comparison was made between the ground-level concentrations produced by the cooling tower discharge method and those produced by a traditional stack. It was found that for low and intermediate wind speeds, the ground-level concentrations are lower for the case of the cooling tower discharge. Only for strong winds, which occur only very rarely at most German sites, did the conventional stack discharge appear to be superior.

Key word index: Dispersion, flue gas, cooling tower, wind tunnel, scrubber plumes, ground-level concentration.

1. INTRODUCTION

New German emission standards (Dreißigacker *et al.*, 1983) require that for combustors with a thermal output of more than 300 MW, the sulfur content in the flue gases be reduced to 400 mg SO_2 m^{-3}. Also, 85% of the sulfur content of the coal must be removed before flue gas emission to the atmosphere. In addition to compliance with these emission control regulations, the utility must prove that the ground-level air concentrations resulting from the flue gas release will not exceed standards promulgated by the German Clean Air Act (TA Luft) (Kalmbach and Schmölling, 1983).

In order to comply with the new regulations, the Rheinisch-Westfälisches Elektrizitätswerk AG (RWE) is carrying out comprehensive retrofitting of its existing plants with flue gas desulfurization (FGD) systems. FGD backfitting for the lignite-fired power stations at Frimmersdorf, Neurath, Niederaussem and Weisweiler involves 33 units with a total electric power output of 9300 MW$_e$. The lime scrubbing method which has already proved successful in flue gas scrubbing in many hard coal fired power stations has again been used.

During wet scrubbing, the flue gases are cooled to approximately 65°C and are saturated with water vapor. If the scrubbed gas is to be discharged from a stack, regulations require reheating to at least 72°C in order to ensure that the plume has sufficient buoyancy. An alternative method avoids altogether the reheating of the flue gas. In this method, the release of the flue gas is mixed with the cooling tower plume from natural-draft wet cooling towers. This method provides an alternative for 6000 MW$_e$ of the 9300 MW$_e$ scheduled for retrofitting.

The licensing process for flue gas discharge from cooling towers was somewhat of a problem, however, as the relevant environmental regulations were not prepared for this type of release. They regulate only the conventional discharge of flue gases by means of chimney stacks. Due to the lack of assessment criteria, RWE has commissioned comprehensive studies concerning the dispersion of flue-gas laden cooling tower plumes in the atmospheric boundary layer (Gebhard *et al.*, 1985; Leidinger *et al.*, 1985; Schatzmann *et al.*, 1986). For example, the Associations for Technical Monitoring (TÜV) in Cologne and Essen developed, in cooperation with experts from several universities and the German Weather Service, a means of evaluating the environmental impact of such releases in accordance with the German Clean Air Act. This method follows, wherever possible, the rules laid out in Appendix D of this Act. The approach in Appendix D parallels closely the EPA ISC model. The revision to Appendix D mainly involves the substitution of an integral model (Schatzmann and Policastro, 1984a) for cooling tower plume dispersion for the simple plume rise formulas for stacks. Those stack plume rise formulas are not applicable to cooling tower plume rise calculations. When this new method was applied to the scrubbed flue gases from a 600 MW_e lignite fired unit discharging from a 126 m natural-draft cooling tower, ground level concentrations of SO_2 were found to be small as compared to the maximum concentrations permitted in the environmental regulations.

Cooling tower plumes, by comparison with plumes from stacks, have a small vertical momentum. The wind velocity at the height of the cooling tower is generally larger than the tower exit velocity, causing parts of the plume to be washed down into the wake of the tower. The integral model which is used to provide the effective plume height of rise in the calculation scheme accounts for such 'downwash' effects only for the case of a single cooling tower in unobstructed surroundings. The RWE power stations under investigation, however, consist of several units each cooled by a separate tower. In addition, there is the possibility of plume interaction with nearby boiler buildings which are of similar height as the cooling towers. Therefore, German authorities requested evidence that the Clean Air Act standards would also be met under high wind conditions with significant downwash. This evidence was provided by means of wind tunnel experiments for the four power plants carried out at the universities of Hamburg and Karlsruhe under coordination and with participation of Lohmeyer Consulting Engineers. A summary of the wind tunnel study for the Niederaussem lignite-fired power station follows and is representative of the studies carried out at all four sites.

2. WIND TUNNEL INVESTIGATION FOR NIEDERAUSSEM POWER STATION

2.1. *Statement of problem*

The Niederaussem Power Station (Fig. 1) has eight units with a total installed electrical capacity of 2700 MW_e. Units A and B (150 MW_e each) and C (300 MW_e) employ forced-draft cooling towers that are about 38 m high, whereas units D, E and F (300 MW_e each) and G and H (600 MW_e each) have natural-draft wet cooling towers (height 103 m and 126 m, respectively). The plan was to discharge the scrubbed flue gases from units D to H through the natural-draft cooling towers. The flue gases from units A to C which are cooled by the low-rise mechanical-draft cooling towers were to be reheated after scrubbing and discharged from a new 196 m-stack.

The wind tunnel study was aimed at investigating the dispersion characteristics of the flue gas-laden cooling tower plume under high wind conditions. Effective heights of rise were identified for four unfavorable wind directions in order to quantify the effect of downwash. In addition, ground-level concentrations of SO_2 were measured to determine the absolute SO_2-concentration maximum.

2.2. *Similarity analysis*

Certain similarity requirements must be fulfilled in order to transfer results from small-scale wind tunnel experiments to prototype scale. These similarity laws are usually obtained by dimensional analysis, a method which makes use of the fact that physical equations must be dimensionally homogeneous and hence the parameters occurring therein can only appear in certain combinations. This method will be outlined briefly as it applies to the present application.

The problem under consideration is sketched in Fig. 2. It consists of a power station with several boiler houses, cooling towers, etc., the geometry of which is fully described by numerous length scales l_1 to l_n. This power station is sited in a boundary-layer flow. The vertical profile in that flow (in the area not obstructed by buildings) can be approximated by the power law

$$\frac{u(z)}{u(\delta)} = \left(\frac{z}{\delta}\right)^n \qquad (1)$$

where $u(\delta)$ is the velocity at boundary layer height δ, and n is the wind profile exponent. As only high-wind situations are of interest here, it is reasonable to assume a neutrally stratified boundary layer.

The local concentration c is normalized by its value at the source c_j; here c represents a passive pollutant discharged into the atmosphere from a cooling tower. The tower has height H, exit diameter D and discharge velocity u_j. The ratio c/c_j is then dependent on the following parameters:

$$c/c_j = f_1(x, y, z, H, D, l_1 \ldots l_n, n, \delta, g, u(H), u_j \Delta\rho_j, \rho_\infty, \mu_j, \mu_\infty) \qquad (2)$$

where x, y, z are the Cartesian coordinates, g is the acceleration of gravity, $u(H)$ is the wind velocity at tower height, $\Delta\rho_j$ is the initial density defect of the plume, ρ_∞ is the ambient density and μ_j and μ_∞ are the dynamic viscosity of the plume and ambient flow, respectively.

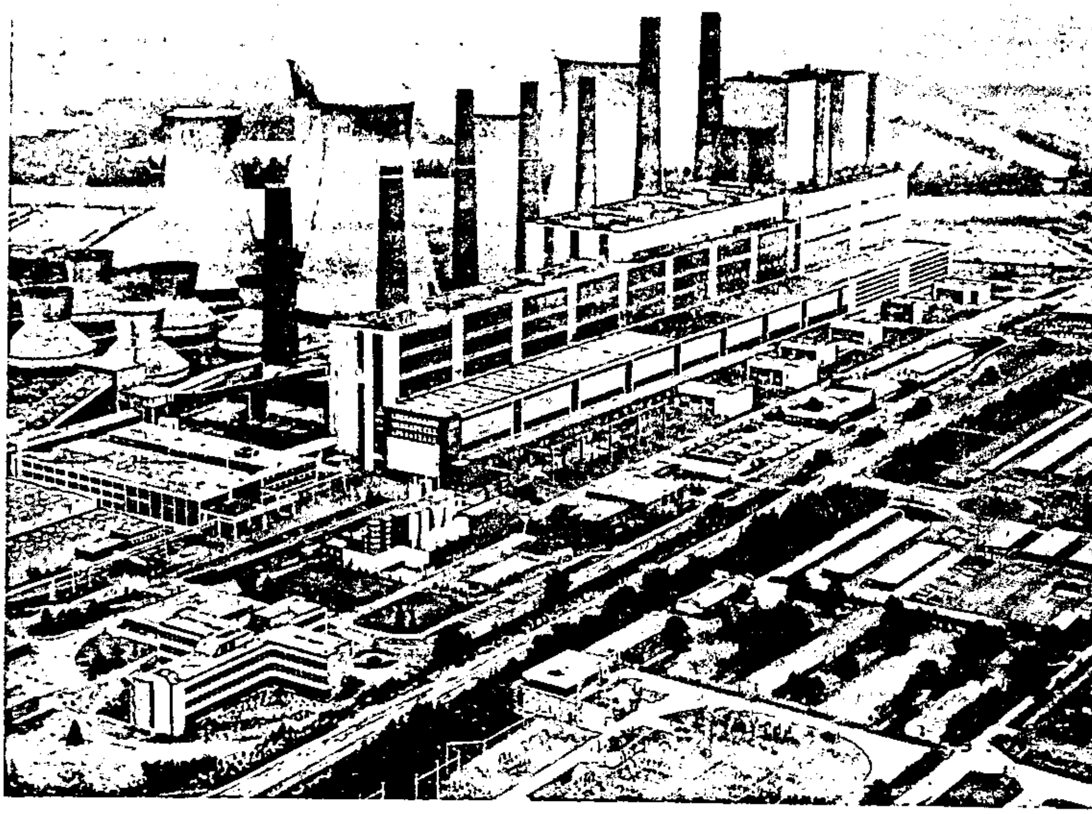

Fig. 1. Aerial view of the Niederaussem Power Plant (before installation of the scrubber) (photograph taken by Aero-Lux, Frankfurt, Germany, permit No. 2125/83, Reg. Präs. Darmstadt).

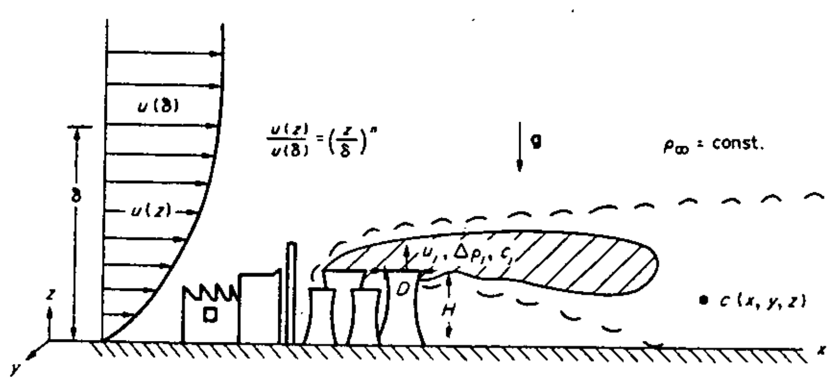

Fig. 2. Definition sketch.

Applying dimensional considerations, Equation (2) can be transformed into

$$\frac{c}{c_j} = f_2\left(\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{H}{D}, \frac{l_1}{D} \cdots \frac{l_n}{D}, n, \frac{\delta}{D}, \frac{u(H)}{u_j}, \frac{u_j}{\sqrt{(\Delta\rho_j/\rho_\infty) g D}}, \frac{\Delta\rho_j}{\rho_\infty}, \frac{Du_j}{\mu_j/\rho_j}, \frac{Du(H)}{\mu_\infty/\rho_\infty}\right). \quad (3)$$

Equation (3) indicates that the normalized concentration c/c_j in both model and prototype takes on identical values at locations determined by the coordinates x/D, y/D and z/D provided that all the remaining dimensionless parameters on the right-hand side of this equation can also be matched in the wind tunnel experiment. These parameters are: a large number of length scales nondimensionalized with reference-length D, the wind profile exponent n, the dimensionless boundary layer thickness δ/D, the velocity ratio $u(H)u_j$, the densimetric Froude number $F_D = u_j/\sqrt{(\Delta\rho_j/\rho_\infty)gD}$, the density defect ratio $\Delta\rho_j/\rho_\infty$ and the two Reynolds numbers $Du_j/(\mu_j/\rho_j)$ and $Du(H)/(\mu_\infty/\rho_\infty)$.

It should be noted that both the dimensional analysis and the wind tunnel experiments apply to dry plumes in a dry atmosphere since moisture effects cannot properly be accounted for in wind tunnel experiments. Therefore, the latent heat contained in the cooling tower plume cannot contribute to plume rise. Consequently, lower effective source heights and higher ground level concentrations (GLC) than observed in the field will result from these small-scale wind tunnel experiments. The wind tunnel results are thus conservative even though the deviation from field conditions is probably slight because under high-wind conditions, the incremental rise of the plume is small compared with the cooling tower building height. It should be remarked, however, that the situation modeled in the wind tunnel is not purely hypothetical but corresponds to an atmosphere with a large saturation deficit. In such a situation, very little condensation takes place and the NDCT-plume behaves in the field approximately like a dry plume (Schatzmann and Policastro, 1984b).

Furthermore, no meandering of wind direction can be treated in the wind tunnel simulation. Such wind direction fluctuations have an important influence on ground-level concentrations above all in the far field of a plume. Due to intermittency local GLC-time averages are expected to decrease. In this way, it can be argued that the wind tunnel predictions are again conservative estimates of field concentrations. However, since under high wind conditions the concentration maxima occur within a distance of less than a mile away from the power plant, the deviation from reality should again be small.

2.3. *Matching of similarity requirements*

The equality of the dimensionless coordinates and length scales in model and prototype was achieved by constructing a wind tunnel model exactly to scale as illustrated in Fig. 3. The scale selected in this case was 1:1000. The model power plant was mounted on a turntable 1.4 m in diameter and positioned at the upwind side of the wind-tunnel test section (see Fig. 4). In this way, various wind directions could be simulated by simply rotating the model. All that had to be adjusted for each individual wind direction were the local terrain features downwind of the power station

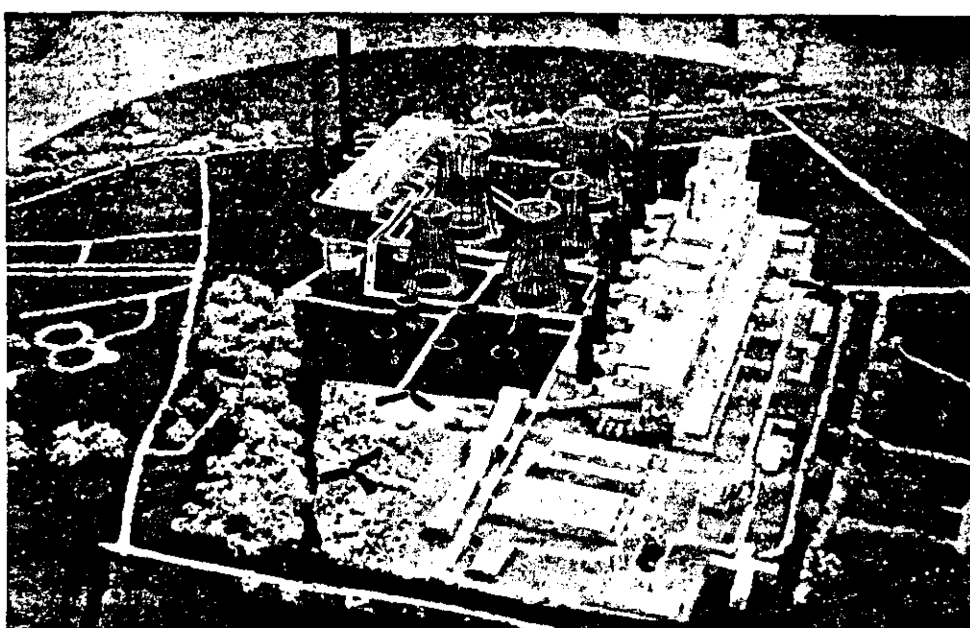

Fig. 3. Model of the Niederaussem Power Plant (after retrofitting with SO_2-scrubber). Surfaces artificially roughened to counteract Reynolds number effects.

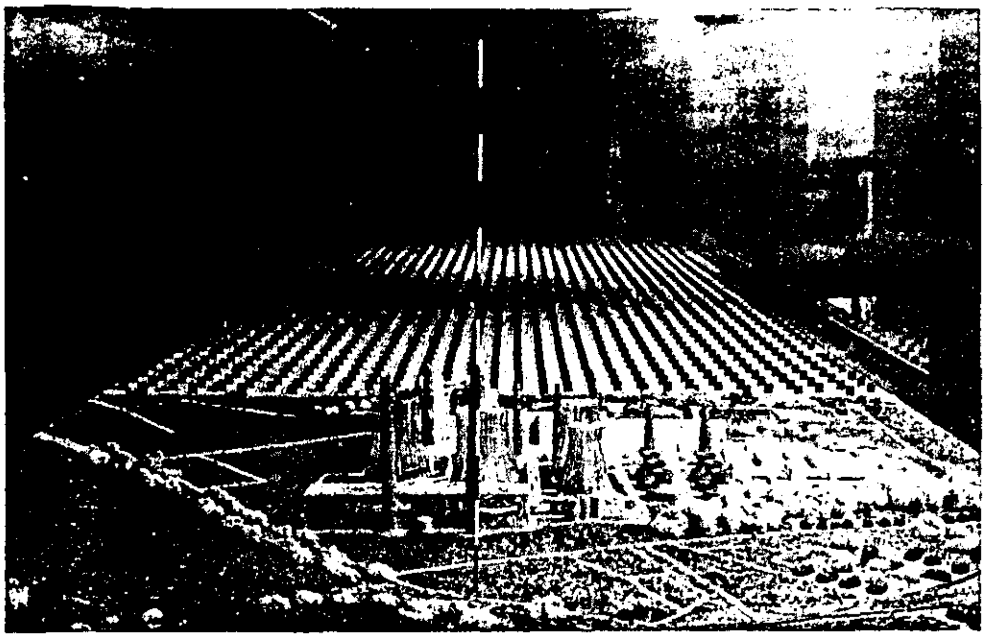

Fig. 4. Model of the Niederaussem Power Plant in the wind tunnel (view from opposite flow direction). Roughness elements and vortex generators in the background.

beyond the turntable. The boundary-layer wind tunnel used had an overall length of 16 m and consisted primarily of an inlet nozzle, flow straighteners, vortex generators, a flow establishment section, a test section and a centrifugal fan. It works with suction in order to keep any disturbances of the flow inside the tunnel to a minimum. An adjustable ceiling is used to establish a zero-pressure-gradient boundary layer. The height and width of the tunnel cross section are 1 m and 1.5 m, respectively (see Fig. 5).

For neutrally stratified atmospheric boundary layers, dispersion calculations according to the German Clean Air Act have to be carried out with a wind profile exponent of $n = 0.28$. In the small-scale experiments, the same value has been chosen. This exponent was achieved by use of vortex generators and sharp-edged artificial roughness elements distributed over the bottom of the flow establishment section.

Under neutral stratification, atmospheric boundary layer thicknesses of several hundred meters height are typical which lead to δ/D ratios in the range of 5–15. The boundary layer thickness obtained in the wind tunnel was about 0.4 m. Though at the lower edge of the range, the δ/D criterion was fulfilled during the scale model experiments.

Several studies have been carried out in the past on the turbulence properties of boundary layers created in this manner. There is a high degree of coincidence between wind tunnel and field measurements with regard to the vertical distribution of turbulence intensity as well as to spectra and correlations (Plate, 1982; Lohmeyer, 1984; Schatzmann *et al.*, 1986).

The next similarity parameter listed in Equation (3) was easy to achieve in the model experiments. It relates the wind velocity at tower top $u(H)$ to the discharge velocity u_j and represents the ratio of horizontal to

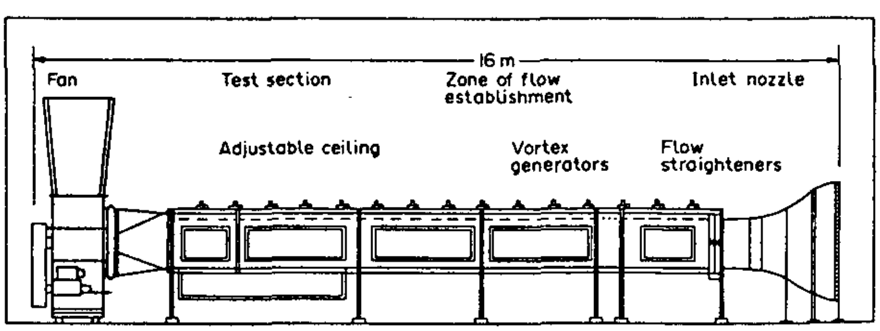

Fig. 5. Boundary layer wind tunnel of Hamburg University (flow direction from right to left).

vertical momentum for the exiting plume. Subsequently from Equation (3), two dimensionless parameters characterizing buoyancy effects are the following: the densimetric Froude number, $F_D = u_j/\sqrt{(\Delta\rho_j/\rho_\infty)gD}$, and the density defect ratio, $\Delta\rho_j/\rho_\infty$. The Froude number relates the plume exit momentum and buoyancy forces to each other. Since it contains the diameter D which in the model is 1000 times smaller than in the field, densimetric Froude number similarity requires all velocity scales in the tunnel to be reduced by a factor of $\sqrt{1000}$, provided $\Delta\rho_j/\rho_\infty$ in model and prototype are the same. Apart from serious Reynolds number problems, this would result in such low tunnel velocities that the simulation would no longer be meaningful. In order to avoid such problems, helium/air mixtures have been used in the experiments to expand the density defect ratio up to a factor of 10. All velocities then need to be reduced only to a tenth of their prototype values even though the densimetric Froude number is exactly matched. Working with a density distorted model is equivalent to applying the Boussinesq approximation in mathematical modeling of initially highly buoyant plumes. Smaller effective heights of rise that result from the application of the Boussinesq approximation lead to larger ground-level concentrations, i.e. conservative results are to be expected (Schatzmann and Policastro, 1984c). Since under high wind conditions, plume rise is small in any case, the error should, however, be low.

The remaining two similarity numbers left in Equation (3) are both Reynolds numbers. In the wind tunnel, they are roughly a factor of 10^4 smaller than under natural conditions. The discharge Reynolds number $Re_j = Du_j/(\mu_j/\rho_j)$ governs the shape of the velocity profile at the exit of each individual tower. Experience has shown that its influence on plume dispersion can be neglected. Much more important is the approach-flow Reynolds number $Re_\infty = Du(H)/(\mu_\infty/\rho_\infty)$, since it determines the flow pattern around obstacles positioned in the boundary layer. Especially in the case of round bodies (cooling towers), a reduction of this Reynolds number causes the internal boundary layer to separate too early with the consequence of creating too large a wake and unrealistically enhanced effects of downwash. It is known, however, that artificial measures such as roughening the surface of the obstacle can be taken to counteract such Reynolds-number effects.

Figure 6 gives a summary of results obtained from *in-situ* measurements on natural-draft wet and dry cooling towers (Niemann, 1976; Pröpper, 1977). Shown is the range of scatter in the pressure distribution around such towers together with some specific values characterizing details of the distribution. During preliminary experiments, the surface of a model cooling tower was coated with various roughness elements and the pressure distribution was measured. The best agreement between model and prototype was achieved by using a strip roughness with the relative height $k/D = 1.8\%$, distributed around the tower at angles of 10° (see Fig. 3).

In conclusion, it can be stated that even for the rather complex dispersion problem under consideration here, good agreement between full scale and wind tunnel experiments is to be expected. Errors resulting from simplifying assumptions (ignoring moisture effects) or the distortion of similarity parameters ($\Delta\rho_j/\rho_\infty$) always lead to increased ground-level concentrations. It is estimated that, combining all errors, ground-level concentrations measured in the wind tunnel may be up to about 20% higher than would occur in the field.

2.4. *Experimental set-up*

The cooling tower data given in Table 1 provided the basis for the experimental work. These data correspond to rated load conditions of the power station. The SO_2 concentration in the scrubbed flue gas stream before mixing with the cooling tower flow was set at 400 mg SO_2 m^{-3}. This corresponds to the

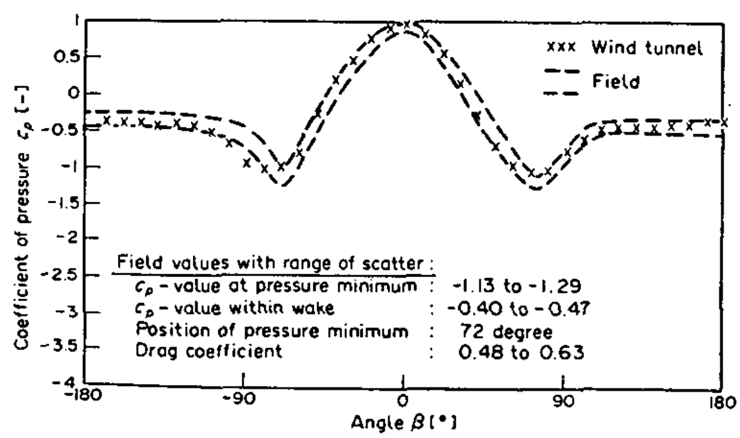

Fig. 6. Comparison of wind tunnel and field measurements on pressure distribution around natural-draft cooling towers.

Table 1. Dimensions and emission data of Niederaussem Power Plant under rated load conditions

Cooling tower of unit	A, B	C	D	E, F	G, H
Tower height (m)	38.0	38.0	117.0	103.0	126.0
Discharge velocity ($m\,s^{-1}$)	7.0	7.0	3.6	4.15	3.94
Exit diameter (m)	26.0	26.0	51.0	46.0	67.0
Ambient air density ($kg\,m^{-3}$)	1.22	1.22	1.22	1.22	1.22
Plume density ($kg\,m^{-3}$)	1.18	1.18	1.13	1.13	1.13
Densim. Froude number (−)	2.4	2.4	0.59	0.64	0.51
Unit capacity (MW_e)	150.0	300.0	300.0	300.0	600.0

limits set up in the German emission control regulations. Even lower SO_2 concentrations are expected from practical operations with wet scrubbers.

The discharge from each individual cooling tower was separately controlled using flow meters, as were the SO_2-emissions which were simulated by adding to the exiting flows small quantities of the passive tracer (SF_6). Buoyancy of the plumes was simulated with the aid of helium. To obtain realistic flow patterns in the area between the individual cooling towers and power station buildings, it was necessary to extract the volume flux emitted per cooling tower by suction through the air inlet openings at the base of each cooling tower.

The selected wind directions for simulation in the wind tunnel were 60°, 150°, 310° and 330°. These angles cover the likely directions of the most unfavorable dispersion conditions and the prevailing wind directions at the site (Fig. 7). The wind velocities at the top height of the largest cooling towers ($H = 126$ m) were chosen to be $u_{126} = 10\,m\,s^{-1}, 20\,m\,s^{-1}, 30\,m\,s^{-1}$, and $40\,m\,s^{-1}$. This wide range in wind speeds was chosen to ensure the worst case would be included within this range.

2.5. *Results and evaluation*

The study concentrated on measuring the plume centerline development with distance from the source and the SO_2 ground-level concentration (GLC) field in the vicinity of the power station. Complementary experiments were carried out with a single cooling tower and a single stack in an otherwise unobstructed boundary layer in order to determine which of the two input methods results in lower GLCs for the same SO_2-emission.

2.5.1. *Plume centerline positions.* Plume centerline positions were determined by measuring the vertical profiles of the tracer concentrations downwind of the

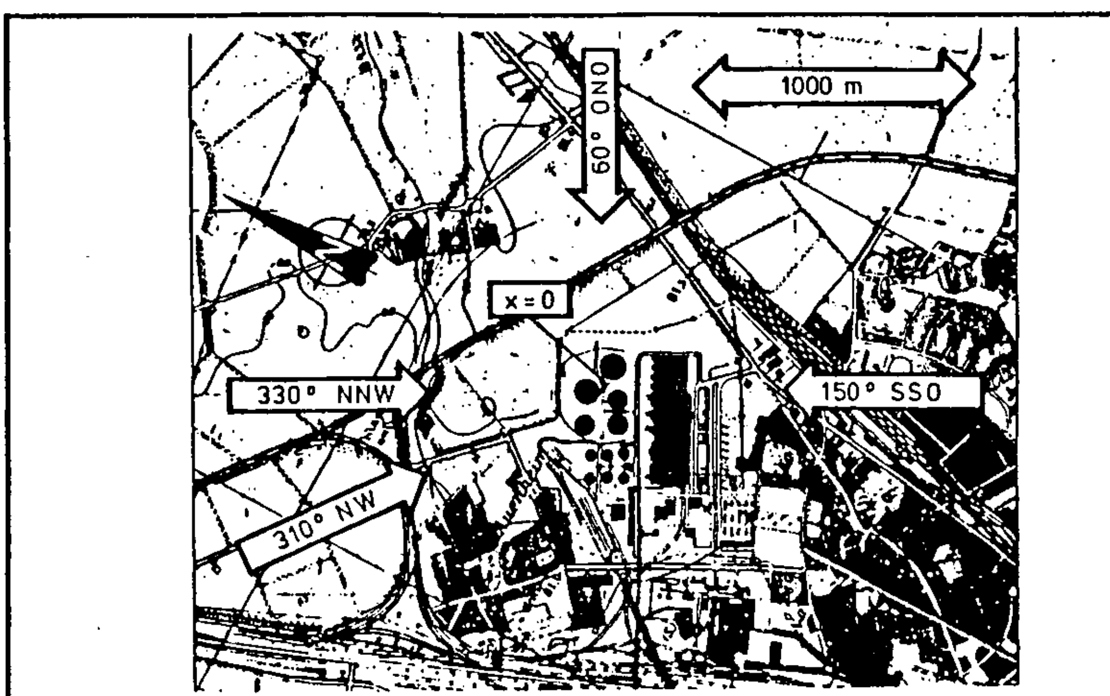

Fig. 7. Top view of the power plant with indication of wind directions investigated.

plant at distances of $x = 300$ m and $x = 500$ m from the center of the cooling tower complex. The aim was to find out whether the plume rise model (Schatzmann and Policastro, 1984a) employed in the calculation scheme would determine a realistic effective source height even under high winds. There were some reservations about this on the part of the licensing authority, as the 'downwash' parameterization contained in the model had been verified only with data from single cooling towers that are unobstructed by neighboring structures. There was concern that the flue-gas laden cooling tower plume might be drawn to the ground as a result of plume/tower and building wake interference.

As the summary of results from this series of measurements clearly shows (see Fig. 8), this possibility did not occur in reality. Even at a wind velocity of $u_{126} = 40\ \mathrm{m\,s^{-1}}$, the trajectory never dropped below the height of the two smaller natural-draft wet cooling towers (units E and F with $H = 103$ m).

From this result, it should, however, not be concluded that downwash effects are only of insignificant importance in the problem. Throughout the experiments, it happened repeatedly that substantial parts of the plume were drawn into the wake of the power plant, especially with the larger of the wind velocities studied. Shreds of the plume were frequently hitting the ground. This is documented by ground-level concentration measurements (results presented in the next section) but was also observed visually. For this purpose, oil smoke was occasionally added to the cooling tower plume and then observed photographically.

Figures 9 and 10 show long-time and short-time exposure pictures of plume cross sections normal to the plume centerline and 500 m apart from the station. The camera position was in the downwind position from the tower. By contrast with field conditions where only the condensed part of the vapor plume would be visible, here the outlines of the entire cloud can be seen. Figure 9 shows clearly that under conditions of a wind velocity of $u_{126} = 40\ \mathrm{m\,s^{-1}}$ and a wind direction of $\phi = 330$°C, the lower edge of the plume touches the ground. The center of the plume is, however, located approximately at the height of the cooling tower, as can be seen from the measuring rod (see Fig. 9) which is marked in 50 m sections. It should be noted, however, that such weather conditions prevail at the Niederaussem site only 0.15% of the hours in the year.

It is interesting that the plumes discharged from five separate cooling towers have already merged into a single plume after a distance of only a few hundred meters from the source. Moreover, the merged plume shows the counter-rotating vortex pair typical of bent-over plumes. This can be seen from the picture shown in Fig. 10 which was taken with a very short exposure time. The wind speed at the tower top for the run in Fig. 10 was $u_{126} = 5\ \mathrm{m\,s^{-1}}$.

It should be noted that field measurements carried out by the Rheinisch-Westfälischer TÜV, Essen, subsequent to the wind tunnel experiments, fully corroborated the findings presented here. By using SODAR equipment, it was found that no substantial drop of the plume trajectory below tower top level had been observed during the period of measurements.

2.5.2. SO_2 *ground-level concentrations.* In addition to the determination of plume rise, ground-level concentration measurements were also made. For this purpose, air samples were taken over periods of 30 min by means of 20 probes positioned at the bottom of the model. The samples were subsequently analyzed using electron capture detection methods.

Figure 11 shows a typical ground measurement pattern recorded at a wind velocity of $u_{126} = 40\ \mathrm{m\,s^{-1}}$ and wind direction of $\phi = 150°$. As can be seen, the concentration maximum occurs unusually close to the source under such very strong winds. This is undoubtedly due to the influence of the power station buildings. The flue gas emitted from the new 196 m-stack which services the small units A–C did not contribute to the ground-level concentration field shown in Fig. 11. Preliminary tests showed that the stack emission GLC-fields were well behind the concentration fields originated by the cooling tower discharge.

It should be emphasized that the concentrations

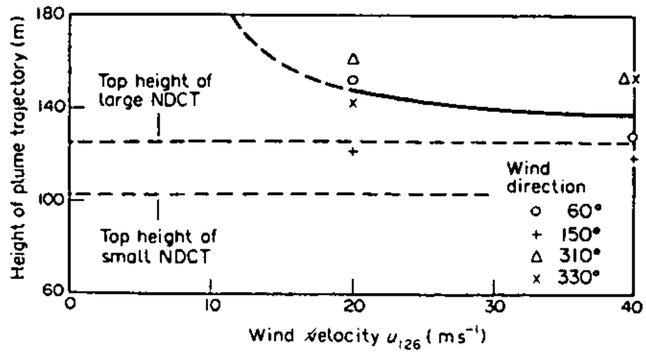

Fig. 8. Height of plume centerline above ground with variation of wind direction and wind velocity, 350 m leeward of Niederaussem Power Plant.

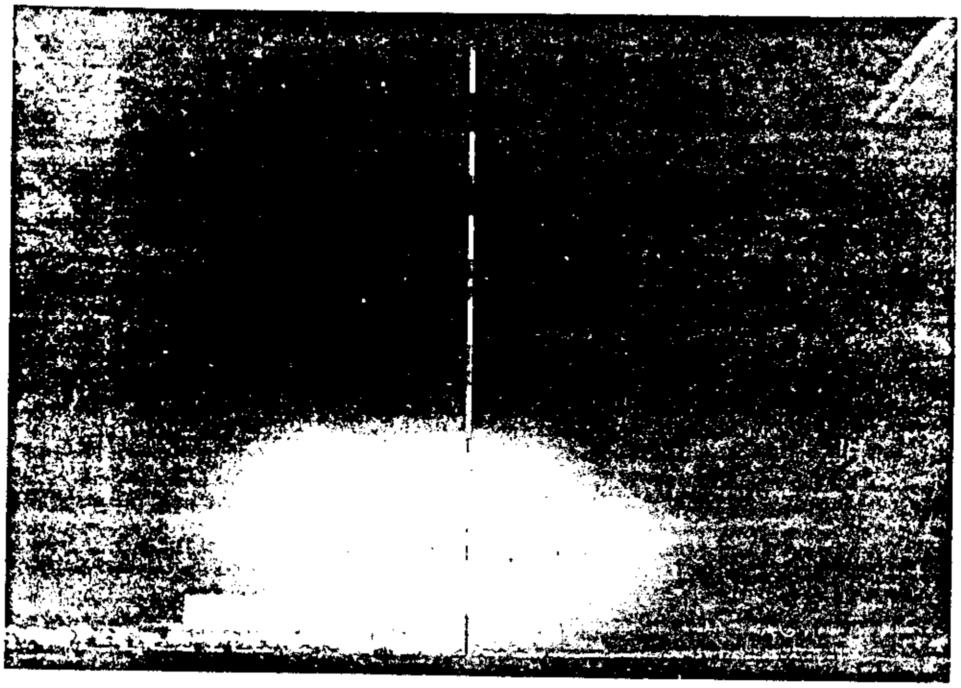

Fig. 9. Long time exposure picture of plume cross section ($x = 500$ m, $u_{126} = 40$ m s^{-1}, $\phi = 330°$).

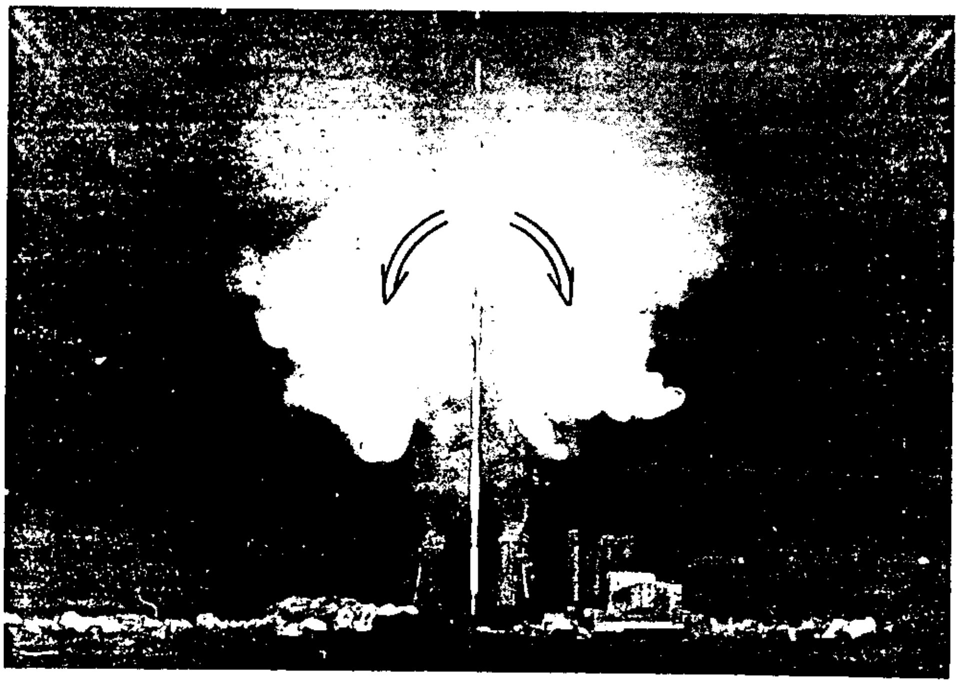

Fig. 10. Short time exposure picture of plume cross section ($x = 500$ m, $u_{126} = 5$ m s^{-1}, $\phi = 60°$).

indicated in Fig. 11 represent point-wise measurements and are thus not representative of area mean values. A direct comparison with the percentile values indicated in the German Clean Air Act would, therefore, be misleading.

Evaluation of concentration measurements cannot be made without considering the frequency of occurrence of the meteorological conditions that each experiment represents. For this reason, the probability of a given wind velocity/wind direction combination at

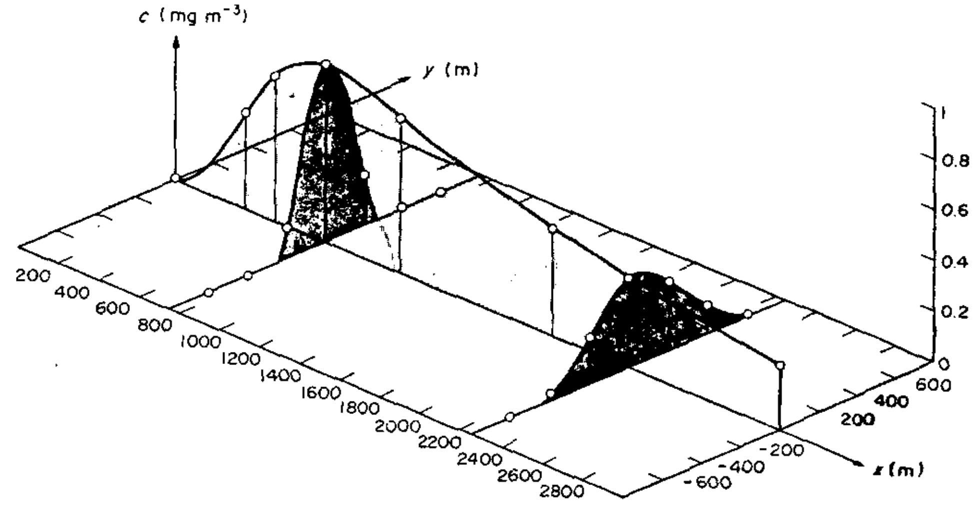

Fig. 11. SO_2 ground-level concentration field (30 min averages, taken pointwise) at wind velocity $u_{126} = 40\ m\,s^{-1}$ and wind direction $\phi = 150°$.

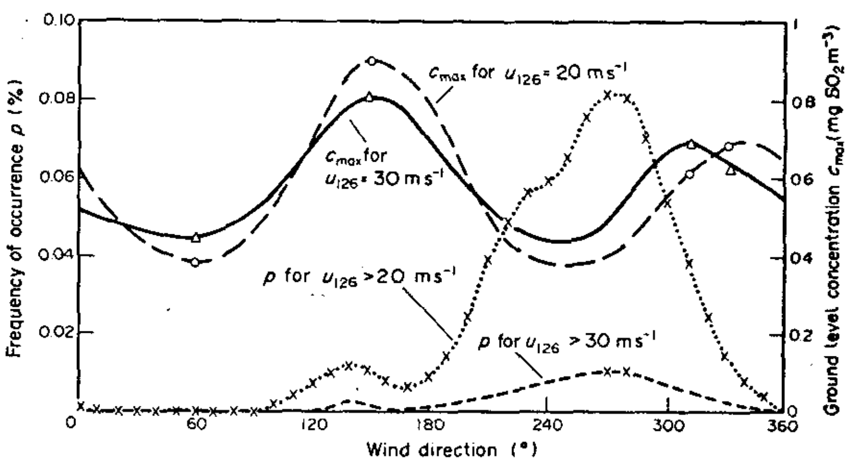

Fig. 12. SO_2 ground-level concentration maxima and frequency of occurrence of given wind velocities as a function of wind direction (30° sectors). Presented are pointwise measured (i.e. not area averaged) concentration values. A comparison with the 98-percentile value of the German Clean Air Act is thus inappropriate.

the Niederaussem site was also included into the summary diagram presented in Fig. 12. In this diagram, the wind direction is shown on the abscissa. The left ordinate indicates the frequency of occurrence p with which the wind exceeds a given speed at cooling tower height, and represents data for a given 10° sector plus the two 10° sectors adjacent to it. The two curves representing p-values for $u_{126} > 20\ m\,s^{-1}$ and $u_{126} > 30\ m\,s^{-1}$ are based on meteorological statistics obtained from the German Weather Service for the area Cologne/Bonn for the period from 1971 to 1980.

The ordinate on the right hand side of Fig. 12 shows ground-level concentration maxima irrespective of the specific locations for which they were measured for a given experiment. Again, the two concentration curves drawn on the figure refer to wind velocities $u_{126} = 20\ m\,s^{-1}$ and $u_{126} = 30\ m\,s^{-1}$. These two velocities were chosen because the highest ground-level concentrations were measured at these velocities regardless of wind direction. For lighter or stronger winds, much smaller concentration maxima were found. The reason for this will be explained in section 2.5.3.

The way the results are presented in Fig. 12 makes it obvious that in the case of the Niederaussem power plant, high winds from a direction of 150° (at which the highest ground level concentrations are expected) occur very rarely, i.e. only about 0.01% of the time. At this site, the largest wind velocities are connected with westerly winds. The most frequent among these are winds from sector 255° to 285° and from 265° to 295°. Wind speeds from those two sectors of more than $20\ m\,s^{-1}$ at cooling tower top height correspond to approximately 10 m s^{-1} at anemometer level. Such speeds have been recorded 0.08 % of the time. For $u_{126} = 30 \text{ m s}^{-1}$, the corresponding p-value is merely 0.01 %. The local GLC maximum for winds from this sector is on the order of $0.6 \text{ mg } SO_2 \text{ m}^{-3}$.

The combination of GLC readings and the frequency of occurrence of certain meteorological conditions makes it clear that the concentration values given represent very short periods of time. They are beyond the 98-percentile limit and describe a worst-case scenario for high wind situations that is seldom observed in the field. A comparison with the 98-percentile SO_2 value of the German Clean Air Act (which is $0.4 \text{ mg } SO_2 \text{ m}^{-3}$) is certainly inappropriate because the latter is based on area mean values. In Fig. 12, however, maximum concentrations were recorded only on a very small strip in the immediate vicinity of the plant (see Fig. 11).

2.5.3. *Comparison of cooling tower and stack gas discharge.* Irrespective of specific meteorological conditions, it was of general interest to determine which of the two flue gas discharge methods—separate discharge from a smoke-stack or mixed with the plume from a cooling tower—would supply more favorable results in terms of ground-level concentration values. As there are no corresponding mathematical models available at present with which an objective comparison of the two methods could be made, wind tunnel experiments again were carried out to answer that question at least for the case of a neutrally stratified boundary layer.

For the comparison, data were chosen that could apply to a single unit lignite-fired 600 MW_e power station furnished with a wet scrubber. The stack used throughout the experiments was 140 m high, with an exit diameter of 8 m and a discharge velocity of 22.5 m s^{-1}. The corresponding data for the cooling tower were 126 m, 65 m and 4.1 m s^{-1}, respectively. For the stack, the minimum flue gas exit temperature of 72°C was assumed as required by the new German emission standards, whereas for the cooling tower the exit temperature was chosen to be 36°C. In both cases, the ambient temperature was 10°C and the SO_2 emission was set to be 1000 kg h^{-1}.

For a comparison of local ground-level concentrations caused by the two concepts of flue gas discharges, the maxima (wherever they were found) were again chosen as an indicator. In Fig. 13, they are presented as a function of wind velocity at cooling tower top height or anemometer height (u_{126} or u_{10}). As can be seen, both concentration curves show a well-defined maximum. This result is to be expected since under low wind conditions, effective source heights of buoyant emissions are generally large resulting in small GLCs. In very high winds, by contrast, ground level concentrations are again small due to the much more intense dilution of the pollutant even though the plume rise is now negligible. Between these two extreme situations a maximum must appear.

The intersection between the cooling tower and stack concentration curves in Fig. 13 occurs at about 8 m s^{-1} at anemometer height. For lower winds, the cooling tower discharge results in lower concentration maxima due to the significant buoyancy of its plume. In higher winds, however, the cooling tower discharge compares unfavorably with the stack discharge. This must be attributed to both downwash and the lower building height of the cooling tower.

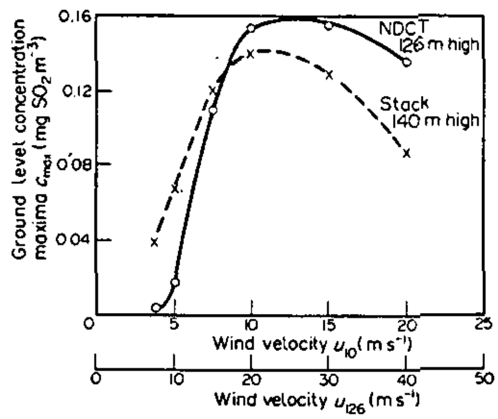

Fig. 13. Maximum ground-level concentrations as a function of wind velocity for a single cooling tower plume and a single stack plume for an assumed emission rate of $1000 \text{ kg } SO_2 \text{ h}^{-1}$ in both cases.

As Fig. 13 also shows, the differences in concentration maxima can be substantial, especially under low wind conditions. For example, for $u_{10} = 5 \text{ m s}^{-1}$, the c_{max}-value of the stack emission is 3.5 times larger than that of the corresponding cooling tower discharge. If now the results are weighted considering the wind statistics of the site (here Cologne/Bonn), it is seen that the cooling tower flue gas discharge causes lower ground-level concentration maxima 97 % of the time in comparison with the conventional stack discharge since wind velocities of $u_{10} > 7.5 \text{ m s}^{-1}$ are recorded there 3 % of the time.

This rather surprising result is not as strong as it may first appear. The height of the stack was only 140 m. Clearly, the taller the stack, the better the stack alternative would look as compared to the cooling tower alternative. It should further be recalled that the comparison is based on several assumptions, the most important of which are the unobstructed single tower or stack and a neutrally stratified boundary layer. If, as in the field, a boiler house would likely be located in the direct vicinity of the source, the disturbances of the wind field caused by the building may, due to the lower structural height of the tower, have a stronger effect on the NDCT-plume than on the stack plume. Thus, the results may change depending on the specific design of the power plant and would need to be investigated in a separate study.

3. CONCLUDING REMARKS

Results from the wind tunnel experiments described in this study contribute to the understanding of the downwash behavior of cooling tower plumes. The results also motivate a methodology for evaluating the ground-level concentrations due to flue gas discharges from cooling towers, as required by the German Clean Air Act. The wind tunnel investigation proved, furthermore, that the release of scrubbed flue gas from natural-draft cooling towers into the atmosphere appears to provide an environmentally acceptable alternative approach to the conventional stack gas discharge.

The time and expense required for such model experiments is considerable. However, general as well as site-specific results can be achieved which are unobtainable in any other way since the power plant units or specific plant buildings may not yet have been built. The alternative for existing plants under consideration for backfitting is only more expensive field experiments.

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