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AN EXPERIMENTAL STUDY OF STACK PLUME RISE AND
DISPERSION AT THE POWER STATION(U) FOREIGN TECHNOLOGY
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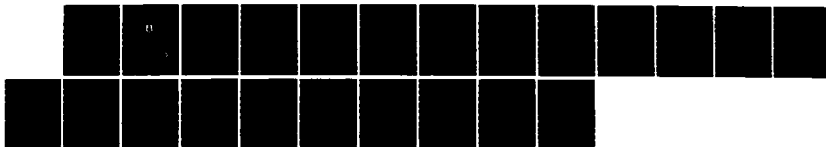
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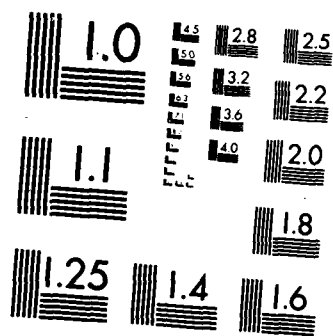
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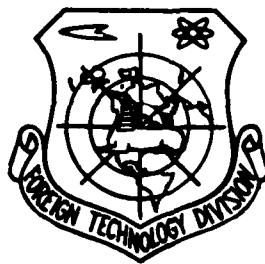
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AN EXPERIMENTAL STUDY OF STACK PLUME RISE AND DISPERSION AT THE POWER STATION



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PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WPAFB, OHIO.

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AN EXPERIMENTAL STUDY OF STACK PLUME RISE AND DISPERSION AT THE POWER STATION

(Meteorological Department, Nan Jing University)

ABSTRACT

In this paper, the primary results of stack plume rise and dispersion experiment at Xu Zhou power station during Nov.—Dec., 1978, are described.

Chief conclusions are as follows:

(1) Under neutral and near-neutral stratification conditions, the $H^{2/3}$ power law is the optimizing formula up to date, because of its calculated values in coincidence with observed, over. And those from the Holland formula are 2—3 times lower. It is indicated that the plume rise formula takes the form as

$$H = 5.38 \frac{Qh}{u}$$

which is suitable for middle-sized power station.

(2) The vertical diffusion of the buoyant plume from the tall stack is obviously stronger than that of non-buoyant plume from the low stack. It is shown that the concepts of Pasquill (1976) model are acceptable, but formula should be modified according to

$$\sigma_z^2 = \sigma_z^2(Pasquill) + \frac{JH^2}{5.86}$$

(3) From reliable monitoring data of SO_2 ground concentration, it is found that the effects of topography and stack height should be comprehensively taken into account in estimating dispersion by Gaussian model. Thus, parameters are taken

$$\sigma_y = 0.32x^{0.75}$$

$$\sigma_z = 0.32x^{0.75}$$

(4) It is suggested that in analyzing the stereophoto grammetric data of fluctuating plume, the square deviation of plume distribution should be considered as the sum of two parts, which are (a) the distribution square deviation of the plume particulates relative to the instantaneous center line of the plume, and (b) the distribution square deviation of the instantaneous center line relative to the average center line of the plume. (5) $\sigma_y = 0.32x^{0.75}$

(5) It is shown that Lidar is a valuable tool as effective as stereographic method in studying behaviour of chimney plumes.

AN EXPERIMENTAL STUDY OF STACK PLUME RISE AND DISPERSION AT THE POWER PLANT

Turbulence Group of Department of Meteorology, Nanjing University

I. PREFACE

As modern industries progress, air pollution has gradually become one of the most important problems to be solved around cities and large industrial areas. In order to reduce pollution, tall stacks are constantly being built. Super tall stacks with a height of over 400-500 meters are already very common in other countries. The stack heights of many of the newly built power plants in our country have also reached over 100-200 meters. The exhaust from a power plant stack is usually a thermal plume. And with our country's vast territory and complex terrain, many tall stacks of power plants are being built in mountainous or hilly areas. This provides new research subjects in plume rise and distribution rule of the tall stack and buoyant plume under complex terrain conditions. Some of the original theories and application methods which were based on the experimental basis of the low stack and flat terrain conditions can no longer satisfy the needs for solving the new subjects.

Since the late 60's, there had been many studies developed in other countries on plume rise and dispersion of plumes from a power plant's tall stack. Especially since the advent of advanced probing means, such as Lidar, new and effective probing means have become available, thus enabling the characteristics of tall stack plumes to be studied more thoroughly, and substantial progress has been made. For instance, the "Full Scale Study on Plume Rise of Large Power Plants" project ^[1] carried

out by TVA [Tennessee Valley Authority] since 1962 was an early effort promoted by the U.S. Bureau of Public Health, and the LAPPES project^[2] carried out by the Bureau of Air Pollution Management. One of the main research goals of the project was to propose and verify a model which could be used to calculate plume rise and dispersion transport of exhaust from tall stacks of power plants. Substantial results were obtained. The British C.E.R.L. also developed a series of rather successful experiments and theories on this subject^[3].

Given these, the study of plume rise and dispersion rules in the atmospheric dispersion and pollution problem still represents a field which has not been sufficiently studied. Especially for the study on the buoyant plume from a tall stack of a power plant, many proposed topics and their studies are still at the beginning stage and are quite a distance from making systematic conclusions on the experiments and satisfactory verification on the theories.

There has been little development in the research of this area in our country. Starting in 1976, the Ministry of Electrical Power headed and organized the effort to conduct investigation and experiments on air pollution and dispersion from a power plant, and it had accumulated some experience for the development of studies on a power plant's plume rise and dispersion rules.

Between November and December of 1978, a large scale overall atmospheric testing was conducted at the Xuzhou power plant*.

*

This experiment was headed and organized by the Ministry of Electrical Power. Units that participated in the testing were: Bureau of Electrical Power, Jiangsu Province, Xuzhou Power Plant, Northwestern Institute of Electrical Power Design, Air Survey Squadrons of Zangban and the 11th Bureau, Xuzhou City Health and Immunization Station, Fudan University, Shangwu 23rd plant and Department of Meteorology, Nanjing University and a couple of dozen affiliated and non-affiliated units of the Ministry of Electrical Power. The Department of Meteorology, Nanjing University, was in charge of all technical aspects.

the plume rise and dispersion rule of a buoyant plume from the tall stack of a power plant. It was hoped that, through a concentrated and typical study of a power plant, some of the practical application problems could be resolved and some of the theoretical questions explored. For instance, the search for a plume rise formula and estimation method for dispersion of a buoyant plume from a tall stack suitable for our country's practical applications has provided some basic studies in setting stack design specifications and emission standards.

II. EXPERIMENTAL CONDITIONS

There are two 180 meter stacks at the Xuzhou power plant, and only the No.1 stack was in use during the experiment. The inner diameter at the exit of this stack is 5.5 meters. The plant burns coal. During the first part of the experiment, only one 125MW generator assembly was in operation and during the second part, two 125MW generator assemblies were in operation. There are no other large industrial pollution sources within a 6-7km range around the stack, making it a more ideal isolated and elevated source. The measured exhaust temperature was generally in the 70-90° range; exit flow velocity was 7m/sec (one generator assembly) and about 13-15m/sec (two generator assemblies).

The No.2 stack, which is located 87 meters from the No.1 stack, was used as an observation post for meteorological parameters at the source height. The instrument was installed on a 14 meter high stand on top of the No.2 stack. The plant site and observation field layout are shown in Fig.1.

The experimental testing items were:

1. Plume Testing. Using the optical profile method. The plume profile photographs were obtained by using the ground synchronized stereographic method. They were analyzed to obtain plume rises and vertical dispersion parameters at a different distance downwind of the plume. Through internal processing, a

total of 106 groups of plume profile data were obtained (17 pairs of photographs to a group with a grand total of 1802 pairs). The accuracy of stereography satisfied the needs of this study.

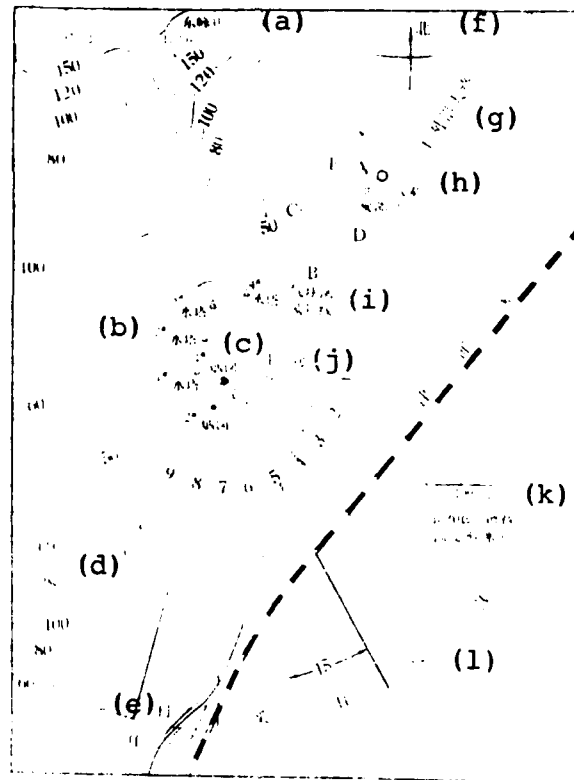


Fig.1. Plant site and observation field layout
Key: (a) Dongfong Mt.; (b) Water tower;
(c) Stack; (d) Fong Mt.; (e) Village; (f) North;
(g) Main road outside the plant; (h) ground
meteorological observation point; (i) Balloon
wind measurement baseline; (j) Main plant
building; (k) (Xuzhou power plant is 41m above
sea level); (l) Sampling arc.

2. Plume testing using Lidar. Lidar was used to measure the distribution of relative concentrations on the cross-sections of plume, thereby obtaining the two standard deviations σ_y and σ_z of concentration distribution in two directions on the cross-sections of plume, and the plume rises at a different distance downwind of the plume. A total of 42 groups were observed and a total of 277 plume cross-sections were scanned. The Lidar observations conducted in this experiment were primarily for the purpose of comparing with those of the stereographic method in order to evaluate the practical capability of Lidar in testing the plume from a power plant; meanwhile, it was used as a necessary backup for the stereographic method, and it concentrated on the study of the characteristics of an instantaneous plume.

3. SO₂ ground concentration monitoring. Sampling points were laid out in a fan shape downwind of the emission source (No.1 stack) and the distribution of ground SO₂ concentrations were measured, as shown in the bottom portion of Fig.1. The sampling not spread from the east to south by southwest of the plant site. Seven sampling lines were selected for each sampling with 15° between each line for a total sampling angle of 90°. The sampling points on the main line were set to be 1, 2, 3, 4, 5, 6 and 7km from the source. On the branch line 3-4 intervals in the middle were selected. The number of sampling points were guaranteed to be no less than 25 for each sampling. There were a total of 24 groups of data collected in this testing. The sampling time for each group was 20 minutes. The accuracy of concentration analysis was 0.01mg/m³; therefore, the data were reliable.

4. Source parameter measurements. Primarily the exhaust temperature, exit flow velocity and source strength were measured.

5. Meteorological observations. They were conducted simultaneously with the aforementioned observations primarily to provide the basic meteorological parameters required for the study of plume

rise and dispersion rules. Items of meteorological observation included:

(1) Ground temperature, pressure, humidity, wind and sun radiation, sky conditions, etc. as well as the bivane anemometer balloon observation during the experiment period. All observations must be conducted according to the guidelines for meteorological observation.

(2) Average wind direction, wind velocity and fluctuating wind direction, wind velocity observation at the source height. The time constants of the wind measurement sensor were all smaller than 1 second. The readings recording interval was set as 3 seconds. The starting wind velocity of the wind measurement sensor was smaller than 0.4m/sec.

Two single direction anemometers were installed at the source height to separately measure vertical and horizontal wind direction fluctuations, thereby obtaining the standard deviations σ_φ , σ_θ of wind direction fluctuations on these two directions.

Ambient temperatures at the source height and ground (4m) and the temperature gradient between the two layers were measured by a platinum electric resistance thermometer. The accuracy of temperature measurement was 0.2°C. Air reconnaissance data from a nearby weather station were selected as a reference when conducting the analysis.

The records of meteorological observation were reliable. The data basically satisfied the needs of the plume rise and dispersion study in this experiment.

III. Primary results of the experiment

1. On the problem of power plant plume rise

Through analysis and study, the main factors which affect plume rise were investigated. The existing primary plume rise formulae both in our country and abroad were compared and a preliminary

evaluation was made. Finally, a practical formula was recommended according to the results of this experiment. The main results obtained were^[4]:

(1) Plume rise ΔH is approximately inversely proportional to wind velocity to the first power, i.e. $\Delta H \propto \frac{1}{u}$. The proportionality of ΔH and heat exhaust rate Q_H is between $Q_H^{1/3} - Q_H^{1/4}$. Under neutral stratification conditions, the average slope of the relationship curve for plume rise with respect to downwind distance x is very close to $2/3$, slightly smaller.

(2) Under neutral or near-neutral stratification conditions, the "2/3 power law" is the best among various plume rise formulae. The results from the existing Holland formula are 2-3 times lower than the observed ones, and the results from the other formulae are also verified to be not as good. Under stable stratification conditions, the results from the "measuring net analytical formula" are in the best agreement with the observed values; yet the non-power coefficient is selected a little smaller than that of the Briggs formula, and it is best to select 2.3. The comparison of calculated plume rise values obtained by using data from this experiment with the observed values is shown in Table 1:

Table 1. Comparison of calculated plume rise values with observed values

(A) Comparison of calculated plume rise values with observed values under neutral stratification condition

(a)	(b) 比较指数	-(c) 单机组			-(d) 双机组		
		I	I	II	I	I	II
"2/3" law	(e)	0.84	0.95	31	0.82	1.12	22
Concawe		0.39	0.85	63	0.30	1.04	33
Lea		0.44	1.82	52	0.31	1.69	34
Moxa-Carson		0.45	0.56	52	0.28	0.66	34
Holland		0.45	0.32	52	0.28	0.55	34
Briggs		0.44	0.67	71	0.25	0.67	47

Key: (a) Plume rise formula; (b) Comparison index; (c) One generator assembly; (d) Two generator assembly; (e) Power law.

(B) Comparison of calculated plume rise values with observed values under stable stratification condition

(a) 比较指标	I	II	III
(b) 公式			
(c) 测量值	0.62	1.06	28
Moses-Carson	0.30	0.50	37

In the table: I - correlation coefficient between calculated plume rise values and observed values

II- average values of the ratio between calculated and observed values

III-ratio(1%) of standard deviation of ratio and the average values of ratio

Key: (a) Comparison index; (b) Plume rise formula; (c) Measuring net analytical formula.

(3) If the "2/3 power law" is used to conduct distance correction for those observed values that have not reached the terminal plume rises, then the correlation between the calculated values from each formula and the observed values increases markedly, and the degree of deviation decreases. Therefore, it follows that since the photographed plume lengths are different, their effects on the observed values are obvious. The comparison of calculated values after distance correction with the observed values is shown in Table 2.

Table 2. Comparison of calculated plume rise values with corrected observed values.

(a) 公式	(b) 比较指标	一(c) 台 机 组			二(d) 机 组			(e) 国外资料
		I	II	III	I	II	III	
2/3 定律		0.78	0.95	31	0.76	1.12	22	
Concawe		0.70	0.67	33	0.42	0.94	30	0.46—0.69
Luzas		0.62	1.46	36	0.42	1.52	31	0.47—0.81
Moses-Carson		0.65	0.44	35	0.40	0.59	31	0.48—0.76
Holland		0.69	0.25	34	0.40	0.50	31	0.40—0.65
Rosati-Quei		0.65	0.48	62	0.37	0.50	43	

Key: (a) Plume rise formula; (b) Comparison index; (c) One generator assembly; (d) Two generator assemblies; (e) Data from abroad.

(4) The "2/3 power law" did not consider the effects of environmental turbulence, thus did not resolve the problem of terminal plume rise distance. The Briggs^[5] terminal plume rise distance $X_T = 10H_g$ was not suitable for the Xuzhou power plant. The calculated value is about 60% higher than the observed value. (H_g is the stack height).

(5) According to the observed data of plume rise at the Xuzhou power plant, the terminal distance set by the "2/3 power law" was 868 meters. Since the observed terminal plume rise was set rather conservatively, this data, in general, was smaller than the actual one. Based on these results, along with data from abroad, we believe that: for medium-sized power plants, it is appropriate to use the following plume rise formula in calculating plume rises, i.e.

$$\Delta H = 5.38 \frac{Q_p}{u}$$

The above conclusions still require further experimental verification and theoretical analysis, and we shall present further study reports.

2. On the dispersion problem of plume rise from a tall stack

Through actual observation of the buoyant plume from the 180m tall stack at the Xuzhou power plant and analysis of data, we obtained the following conclusions^[6-7]:

(1) The vertical dispersion of a buoyant plume from a tall stack is distinctively larger than the vertical dispersion of a non-buoyant plume from a short stack. Within the range of 400-1000 meters downwind of the source, the dispersion rate is higher than the P-G classification toward the unstable direction by one to one and half class. Analysis has shown that this is due to increase in stack height causing the effects of topography and the thermal plume buoyancy to decrease. Within a range 400m from the source, the buoyancy effects on a plume are especially obvious. As the distance increases, the accumulated effects

approach a constant.

(2) The observed data within a range 1km from the Xuzhou power plant were used to verify the calculation model of vertical dispersion parameters for a buoyant plume proposed by Pasquill (in 1976) [8]:

$$\sigma_z^2 = \sigma_{z, Pasquill}^2 + \frac{H^2}{10}$$

The verification results showed fair agreement, only a slight difference in the coefficient. Based on the analysis of observed data from this experiment, the formula takes the following form:

$$\sigma_z^2 = \sigma_{z, Pasquill}^2 + \frac{H^2}{5.86}$$

The calculated values then are in even better agreement with actualities. The results are shown in Fig.2. These results indicate that: A. the effects of a hot buoyant plume from the stack at the Xuzhou power plant on dispersion are obvious; B. within a range close to the source, the Pasquill (1976) calculation scheme can be extensively applied.

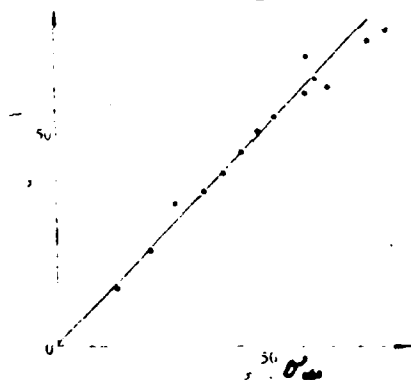


Fig. 2 Relation between observed values and calculated values by $\sigma_z^2 = \sigma_{z, Pasquill}^2 + \frac{H^2}{5.86}$

(3) The Gaussian plume model can be used in the dispersion calculation of a buoyant plume from a tall stack. But the scheme for calculating the diffusion coefficient must be properly modified in order to make the estimated ground maximum concentration and distance where the maximum concentration occurs close to actualities.

(4) The effects on dispersion of the roughness of terrain and undersurface are obvious. The distance where maximum SO₂ ground concentration was measured around the Xuzhou power plant was very close to the source (about 2-3km downwind of the source). This fact reflected the above point. Using the ASME model and the P-G model with its stability classification raised by one and half class to calculated dispersion, the results were not in good agreement with actualities. Only when the effects of the terrain and underside roughness on dispersion are considered and the vertical dispersion parameters are increased to be even longer than the horizontal dispersion parameters, then can the calculated values be in good agreement with the observed values. Under neutral and near-neutral stratification conditions for the terrain features surrounding the Xuzhou power plant, we proposed the following method for the calculation of dispersion parameters, and obtained more satisfactory predicted results, i.e.

$$\sigma_y = 0.32x^{0.45}$$

$$\sigma_z = 0.32x^{0.45}$$

The comparison of calculated values using several models with the observed values is shown in Table 3.

Table 3. Evaluation of calculated dispersion model

(A) Comparison of predicted SO₂ concentration with observed concentration

(a) 式 号	(b) 预 报 和 观 测 的 比 值			
	P-G	(c) 调整后的P-G	ASME	(d) 调整后的
S001-3	0.16	0.24	0.26	0.58
S002-4	0.24	0.49	0.52	1.15
S005-7	0.42	0.65	0.51	1.14
S006-8	0.46	0.72	0.58	1.32
S009-11	0.13	0.25	0.32	0.72
S010-12	0.10	0.18	0.22	0.50
S013-15	0.16	0.31	0.36	0.82
S014-16	0.11	0.23	0.33	0.76
S017-19	0.08	0.17	0.19	0.41
S018-20	0.10	0.18	0.22	0.48
S021-23	0.70	1.46	1.03	2.29
S022-24	0.69	1.47	1.01	2.33
(e) 平均值	0.28	0.52	0.46	1.04
(f) 标准差 σ_R	0.22	0.46	0.28	0.63
(g) σ_R/K	0.80	0.89	0.61	0.61
(g) 合格率以内的百分数	33%	42%	50%	100%

Key: (a) Experiment Number; (b) Comparison of predicted and observed data; (c) Adjusted P-G; (d) Corrected; (e) Average value $\bar{R}$; (f) Standard deviation; (g) Percentage within two and half times.

(B) Comparison of distances where maximum ground SO_2 concentrations occurred

(a) 试验编号	(b) 实测值 (km)	(c) 预 报 值			
		P-G (km)	(d) 调整一级半后的 P-G	ASME (e) 改进后的 (km)	
S001-3	<3	4	1300(m)	4058.6(m)	1.8
S002-4	<3	5	1650	4058.6	1.8
S005-7	≤2	2	600	4637.4	2.0
S006-8	≤2	2	600	4611.3	2.0
S009-11	2	≥7	2250	5809.6	2.5
S010-12	2	≥7	2250	6223.9	2.7
S013-15	4.3	≥7	2625	6712.2	2.9
S014-16	4.5	≥7	2667	6712.2	2.9
S017-19	2	≥7	2250	5656.6	2.4
S018-20	4	≥7	2170	5609.9	2.4
S021-23	2	4	1000	5447.4	2.8
S022-24	2.4	4	1000	5641.6	2.8

Key: (a) Experiment Number; (b) Observed values(km); (c) Predicted values; (d) P-G adjusted by one and a half class; (e) Corrected(km).

3. On the Processing Method of the Stereophotogrammetric Data of the Fluctuating Plume

The use of stereophotogrammetric data to analyze the vertical diffusion parameters is generally processed according to the optical contour method. But for fluctuating plume, which is more obviously affected by large scale turbulent vortex, like that at the Xuzhou power plant, it is inappropriate to use the enveloping line method. Even though the enveloping lines are analyzed very objectively, it is still not enough to eliminate the influences of the aforementioned plume axis fluctuation.

We considered the Gifford concept^[9] for analyzing a fluctuating plume and expanded its application to the analysis and process of vertical dispersion. It is suggested that, for a fluctuating plume, the dispersion parameters are the sum of dispersion (expressed as σ_{zr}) of the plume particulates relative to the center line and the fluctuating dispersion (expressed as σ_{zM}) of the instantaneous plume center line relative to the average center line of the plume. The following model is adopted to estimate dispersion coefficient, i.e.

$$\sigma_z^2 = \sigma_r^2 + \sigma_M^2$$

and more satisfactory analytical results are obtained. σ_{zr}^2 in the formula is the distribution square deviation of plume particulates relative to the instantaneous plume center line. Assume the vertical distribution of the instantaneous plume concentration is uniform, then $\sigma_{zr} = \frac{\bar{R}}{\sqrt{3}}$. σ_{zM}^2 is the distribution square deviation of the instantaneous plume center line relative to the average center line of plume (i.e. the average horizontal wind direction at the source height). In fact, this is the square deviation of instantaneous plume rise, i.e. $\sigma_{zM}^2 = \sigma_{\Delta H}^2$. Thus, the above formula can be written as: $\sigma_z^2 = \sigma_H^2 + \frac{\bar{R}^2}{3}$, where $\bar{R}$ is the average value of half width of the instantaneous plume within 20 minutes. Good results were obtained using the above method to process the stereographical data^[6].

(4) Lidar is a more advanced and ideal method for studying a plume. It can be independently used as a probing tool to obtain more detailed and reliable plume characteristics data. The preliminary analysis of the Lidar data from this experiment shows that: the plume rise values obtained from the stereographical and Lidar studies are in good agreement (See Fig.3)^[10]. Due to its transmissive capability, Lidar can be used to conduct measurements on two instantaneous plume cross-sections xz and yz simultaneously, and it can directly measure the concentration

distribution of plume particulates in the plume cross-section, thereby many plume characteristics are analyzed. The distribution data of instantaneous plume relative concentration we obtained using the Lidar have verified the assumption that the instantaneous plume concentration is uniformly distributed. They also verified that, within 1000m of the source, it is appropriate to take this assumption as the approximate situation of the concentration distribution of the instantaneous plume.

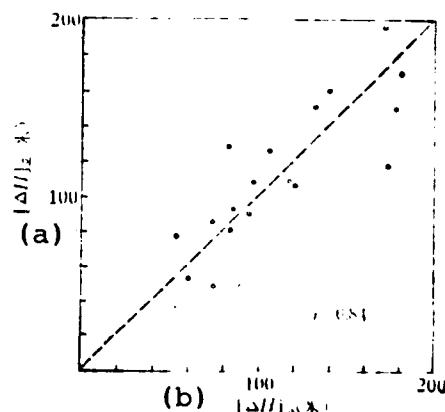


Fig.3 Comparison of ΔH values obtained from stereographical and Lidar studies.
Key: (a) $[\Delta H]$ stereograph(m);
(b) $[\Delta H]$ Lidar(m).

5. On the boundary layer flow field features at the Xuzhou power plant.

The local flow field features exert great influences on the plume rise and dispersion. We considered the fact that the Xuzhou power plant is located at the edge of a hilly area. There are hills with an altitude of around 100m to the northwest and west, and the area to the east and southeast is rather flat and open. This kind of terrain will certainly influence the local flow field. This experiment has shown that: the effects of

terrain on the average flow field at the plume height are not obvious; however, its effects on the fluctuation field are worth paying attention to. By rough estimation, the turbulence strength of air flow from hills is about twice as strong as that from flat terrain. It can be seen from the analysis of the data of this experiment that although the average effects of terrain on plume rise are not obvious, some obvious effects on individual cases can still be found. The effects of local terrain on dispersion are being reflected to different extents in the ground SO_2 concentration monitoring data and plume distribution data. It is very necessary to further analyze these problems^[11].

IV. CONCLUSIONS

Abundant and systematic data were obtained from the first plume rise and dispersion experiment at the Xuzhou power plant. The testing items were quite complete and the quality of data could satisfy the needs for analytical study. These data and their analytical results could provide an experimental basis for the setting of reasonable emission standards in our country and for the Ministry of Electric Power's modification of stack design specification.

In the analysis, we made a preliminary evaluation on several plume rise formulae, e.g. the Holland, Bosanquet, etc. commonly used in our country. We found that their deviations from actualities were too large, and temporarily recommended the corrected "2/3 power law" as a practical formula for calculating plume rise. The study of dispersion problems of the buoyant plume from a tall stack has very important values from both the standpoints of scientific development and practical significance. For a stack with a height between 100-200m and emitting a thermal plume, can its dispersion rules be expressed by a Gaussian plume model? How are the dispersion parameters estimated under different under side

conditions? These are current problems that attract attention and are worth further studying. The analytical results of the experiment at the Xuzhou power plant have shown that the Gaussian plume model can be used in estimating the dispersion of a buoyant plume from a tall stack. But for different under surface conditions, different schemes for estimating dispersion parameters must be obtained. We proposed an estimation scheme for the actual conditions at the Xuzhou power plant. It has provided certain referencing values for estimating dispersion of a thermal plume from a tall stack under rough under surface conditions.

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