TWO PAPERS WHICH WERE READ AT MEETINGS OF THE NACA DURING 1975

The first of these papers was held over from the last issue of the Clean Air
Journal. The second paper was presented at a recent meeting.

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SOME INFLUENCES ON POWER STATION CHIMNEY PLUMES
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SUMMARY

The behaviour of a plume as it leaves a chimney and progresses into the
atmosphere is discussed. It is shown that the plume is subject to numerous
influences but careful chimney design can eliminate some effects and make
adequate allowance for others.

INTRODUCTION

The use of pulverised coal in the generation of electricity inevitably means
that considerable quantities of dust and sulphur dioxide are produced which
need to be disposed of harmlessly and without nuisance. In common with other
utilities throughout the world, the method of control employed by ESCOM is to
firstly reduce the dust burden using electrostatic precipitators and then to
emit the residual dust together with the sulphur dioxide and the other
combustion gases to atmosphere from tall stacks. The significance of the
plume thus formed depends on its basic composition and on how well the
undesirable constituents are diluted by the atmosphere before reaching ground
level. The composition of the coal and plant operation control the first
factor whilst the second is determined by meteorological conditions and other
external effects. It is the latter category which is given consideration in
the present paper.

The basic requirement of a plume is that it should progress upwards as it
leaves the chimney and not immediately start on a downward path to ground.
The greater the plume rise the lower is the pollution concentration at
ground level and the latter can be calculated knowing the height to which
the plume rises. The potential for the plume to rise derives largely from

its thermal buoyancy and the rise can substantially increase the effective height of the chimney as shown in Figure (1). In these circumstances the source of emission is effectively at a position much higher than the chimney mouth and this is very helpful in reducing ground level concentrations of pollutants. However, this desirable plume behaviour is very sensitive to a number of external effects which by careful chimney design need to be avoided or otherwise catered for. Some of the external influences on the plume and their recognition in chimney design will be discussed.

DOWNDRAUGHT

A first significant consideration affecting plume behaviour is the layout and dimensions of the station buildings with respect to the chimney. This is because the buildings disturb the airflow patterns by their presence. A general indication of what happens is shown in Figure (2) which is a typical side view of a power station. Vortices are shed by the various structures causing a downdraught and if the chimney is not sufficiently high the smoke may be caught in these downward sweeping currents and be swept to ground before having time to dilute sufficiently. It has been found that this effect can be avoided by making the chimney at least $2\frac{1}{2}$ times as high as the tallest immediately adjacent structure, which is the boiler house, and this policy has been adopted by ESCOM for its modern stations. A comparison between old and new stations is shown in Table 1. Moreover, the pattern and severity of vortices shed by a building are such that it is best to arrange the building with its long axis perpendicular to the wind. Clearly it cannot be arranged that this is always the case for the wind is continually changing direction, but the boiler house axis is chosen to be perpendicular to the prevailing wind in recognition of the above effect.

TABLE 1 : BOILER HOUSE AND CHIMNEY HEIGHTS

Station	Size MW	Date	Boiler House Height m	Chimney Height m	Ratio of Heights
Taaibos	480	1954	49	91	1,9
Arnot	2 100	1971	74	195	2,6

DOWNWASH

If the emission speed from the chimney is too low compared with the wind speed then the plume does not rise cleanly from the stack but, rather, dips slightly as it enters the atmosphere and does not fully recover, Figure (3). The plume becomes caught in the vortices shed by the chimney. If this downwash is very marked it can bring the plume down into the region of the downdraught from the boiler house and hence quickly to ground. To counter this the chimney should be as slender as possible in order that its vortices will be of small scale. Also, tests have shown that downwash can often be avoided if the emission speed is greater than the wind speed, a condition encouraged by a slender chimney. But if the chimney is made too slender then the pressure drop over its height becomes undesirably high and a considerable increase in fan power would be required. Moreover, too high an emission speed can be detrimental to plume rise because it can cause excessive entrainment of cold air from the general atmosphere thereby cooling the plume and reducing its buoyancy, Figure (3). A compromise is required and a typical emission speed nowadays is about 20 m/s at full capacity, having been increasing over the years as indicated in Table 2. At less than full capacity the emission speed drops making downwash more likely and in recognition of this and other factors CEGB in UK now use multiflue chimneys as shown in Figure (4). With such a design the full capacity discharge is through all flues and when the operation level reduces only one of the flues need bear a reduction in emission speed. The flue openings are grouped very closely together in order that the separate discharges merge into one plume immediately after emission thus ensuring good plume rise due to the combined buoyancy. With this configuration wind tunnel tests showed that downwash was best avoided by terminating the chimney shell about $\frac{1}{3}$ of a diameter below the top of the flues. Multiflue chimneys do not feature in ESCOM current planning because the load factors at their power stations are quite constant and the extra expense is not warranted.

TABLE 2 : EMISSION SPEEDS

Station	Size MW	Date	Chimney Diameter m	Emission Speed m/s
Taaibos	480	1954	5,4	15
Arnot	2 100	1971	10,4	21

METEOROLOGICAL EFFECTS

Having ensured that the plume leaves the chimney in a suitable manner, its
behaviour as it progresses away from the power station is next considered.
It is common experience that wind speed influences the rise of a plume but
there are two other meteorological conditions to consider as well, namely
atmospheric turbulence and lapse rate. Turbulence refers to the small
random fluctuations in wind speed which exist within the overall wind flow
and which account for the spreading and mixing of the plume. It is generated
by the passage of the wind over the earth's surface and also by vertical
streams caused by the earth's surface heat. Lapse rate refers to the
variation with height above ground of the temperature of the air. Fortunately,
the two are interlinked to a considerable degree and categorising lapse rate
is normally sufficient to give recognition to changes in turbulence levels
also. In cases where differences in average turbulence level from one
location to another are significant they can be catered for by a simple
general appraisal as will be mentioned later.

A common lapse rate found during daytime is one with a temperature drop of
about 1°C per 100 metres. This is the rate at which a pocket of gas would
cool during expansion upon rising if mixing did not occur and therefore is
commonly referred to as an adiabatic lapse rate and the atmosphere as neutral.
In these circumstances the plume rises and disperses in a well behaved manner,
called coning, as shown in Figure (5a). This is in distinct contrast to the
plume behaviour when the lapse rate is superadiabatic as occurs when there is
intense solar heating of the ground and hence of the air near the ground.
The atmosphere is then unstable with much colder layers of air above and
pockets of air continuously rise and fall giving a high level of turbulence
and resulting in a plume appearance as shown also in Figure (5b). This is
known as looping and large variations occur in both vertical plane, as shown,
and in the horizontal plane. A further distinctive lapse rate is the inversion
lapse rate in which the air temperature increases with height giving a stable
atmosphere with low turbulence. This commonly occurs at night when the earth's
surface cools quite rapidly by radiation thus causing the air near the ground
to cool as well. In these circumstances, as the plume rises and cools it
progresses into increasingly warmer air and therefore its buoyancy decreases

with height and its rise is supressed. It is called a fanning plume because its vertical spread is restricted, Figure (5c). However, the heights of chimneys at modern stations (around 150 to 200 metres) are such that they usually protrude through inversion layers and the plume rises quite normally. In view of this and recognising the very transient effects of a looping plume, the commonly occurring neutral conditions have received much attention by research workers and equations predicting plume rise in these conditions have been established. It has been found that if such equations are used in conjunction with a diffusion equation to calculate ground level concentrations of pollutants then such estimates give a good general indication of pollution severity for all conditions. However, confidence in the application of plume rise equations to South African conditions has first to be gained and ESCOM conducted experiments at two power stations for this purpose. The following simple equation was found to be appropriate for tall chimneys:

plume rise $\Delta h = \propto Q^{\frac{1}{4}}/U$ where   Q   is the power in the stack

gases,   U   is the wind speed in the vicinity of the plume and

(the plume rise factor) is approximately a constant.

This equation was first developed in the UK by CEGB and the study by ESCOM showed it to be suitable for the Highveld provided a slightly greater value of $\propto$ was used than in the UK. This is probably reflecting a lower average level of turbulence on the Highveld due to its flatness and freedom from extensive industrial and housing estates. Thus, although turbulence does not appear explicitly in the equation it can be catered for in $\propto$ but changes in turbulence appear not to play a particularly dominant role.

The equation assumes that downdraught and downwash have been avoided and then the only plant parameter required is the power in the stack gases. This can be calculated from the furnace combustion design data and from estimates of heat losses in the ducting and dust collector, etc. The equation shows that at a modern 2 000 MW Highveld power station with two chimney stacks $(Q = 150\ MW)$ of 195 metres the plume rise in a high wind of say 10 m/s would be a very significant 200 metres. The seeming wastage of energy in the hot combustion gases is now of distinct value in plume rise. The most dominant parameter in the equation is the wind speed at high level and for this reason good knowledge of wind speeds and directions should be known for any

proposed site, particularly in densely populated areas.

TOPOGRAPHICAL EFFECTS

A further consideration in plume behaviour is the landscape of the countryside
surrounding the power station. Hills, ridges, lakes, or other prominent
features can cause significant changes in the air flow pattern around power
stations thereby affecting the path of the plume. For example, with a ridge
downstream of the station, Figure (6a), if the chimney height is insufficient
then the plume will be caught in the boundary layer over the ridge and brought
to ground. But if the chimney is designed a little higher so as to avoid the
boundary layer, which may extend to a height of 30 metres above a 100 metre
ridge for example, then the ridge may actually result in an uplifting of the
plume. With an upwind ridge a significant depression of the plume can result
as shown in Figure (6b). The wind coming off the ridge has a downward
tendency for a considerable distance and can cause the plume rise to be lower
than it otherwise would have been. For example, a 50 metre ridge at a
distance of 1 000 metres might cause a depression of 30 metres. In extreme
cases the vortices from the ridge may actually bring the plume to ground near
the station. Plume rise above a plain in a neutral atmosphere provides a
basis from which to consider these influences of topography.

Past experience of the above effects allows estimates of such influences to
be made at the planning stage of new power stations but it is quite common
for wind tunnel studies to be made for surety. Scale models of the country-
side and the proposed power stations are made and by using a dense smoke in
a helium/air mixture issuing from the chimney the plume behaviour can be
quite readily observed. Also, on-site studies of wind patterns using flares
dropped from aeroplanes are sometimes used. The general philosophy is to
bring as much evidence as is reasonably possible to bear on the problem.

CLOSURE

It has been shown how the behaviour of a plume in the atmosphere can be
influenced by numerous effects, some of which are avoidable and others of
which have to be accepted and accounted for. Even if downdraught and
downwash are absent the plume behaviour remains complex but fortunately the

somewhat more tractable and well studied case of a plume in a neutral atmosphere yields ultimate results of ground level concentrations which are quite generally applicable to other atmospheres. Equally, the plume rise in neutral conditions provides a basis from which to consider effects of topography.

Considerable knowledge exists about the behaviour of plumes but environment standards are continually becoming stricter and therefore more detailed analyses of plume behaviour are constantly being sought.

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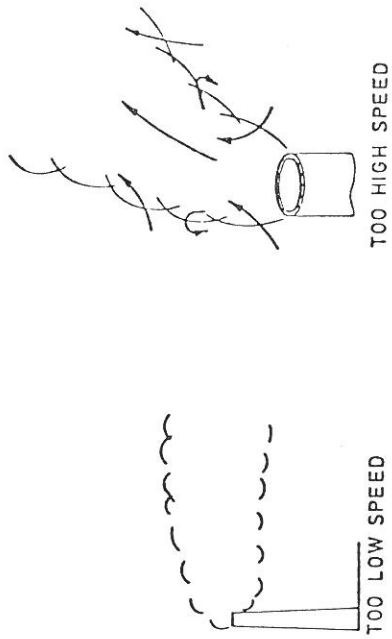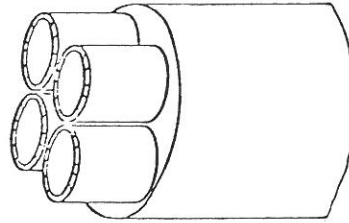   Air Pollution Handbook
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TOO HIGH SPEED
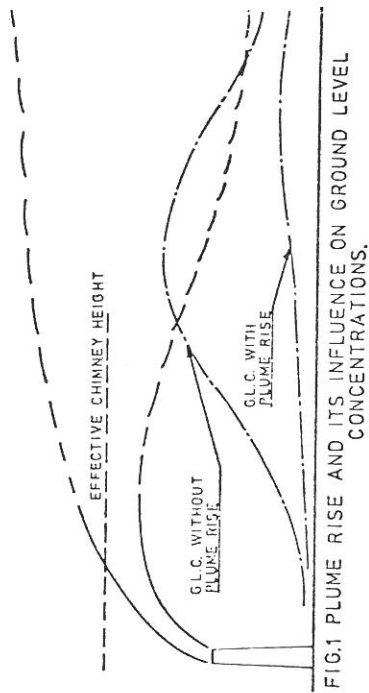
TOO LOW SPEED

FIG. 3 EFFECT OF EMISSION SPEED

FIG. 4 MULTIFLUE CHIMNEY

EFFECTIVE CHIMNEY HEIGHT

G.L.C. WITHOUT PLUME RISE

G.L.C. WITH PLUME RISE

FIG.1 PLUME RISE AND ITS INFLUENCE ON GROUND LEVEL CONCENTRATIONS.
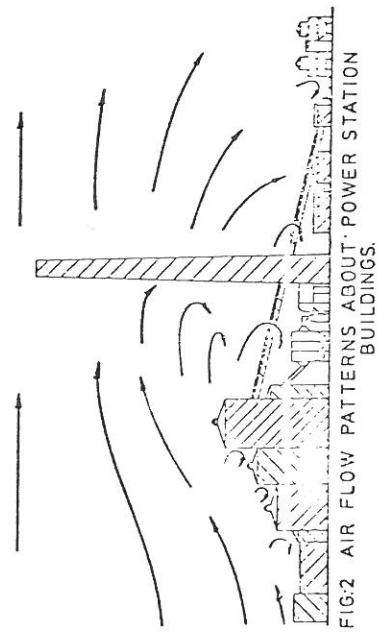
FIG.2 AIR FLOW PATTERNS ABOUT POWER STATION BUILDINGS.
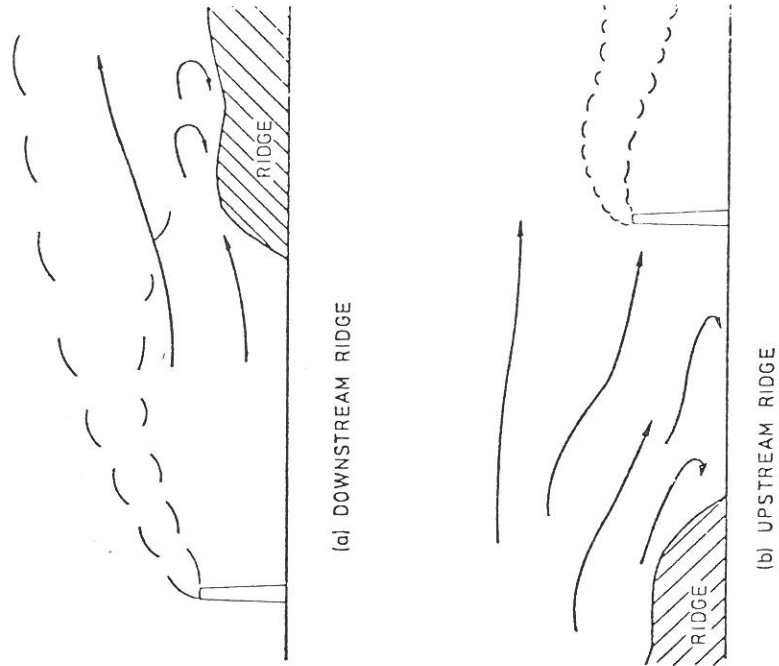
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FIG. 6 THE INFLUENCE OF RIDGES

(a) DOWNSTREAM RIDGE

(b) UPSTREAM RIDGE
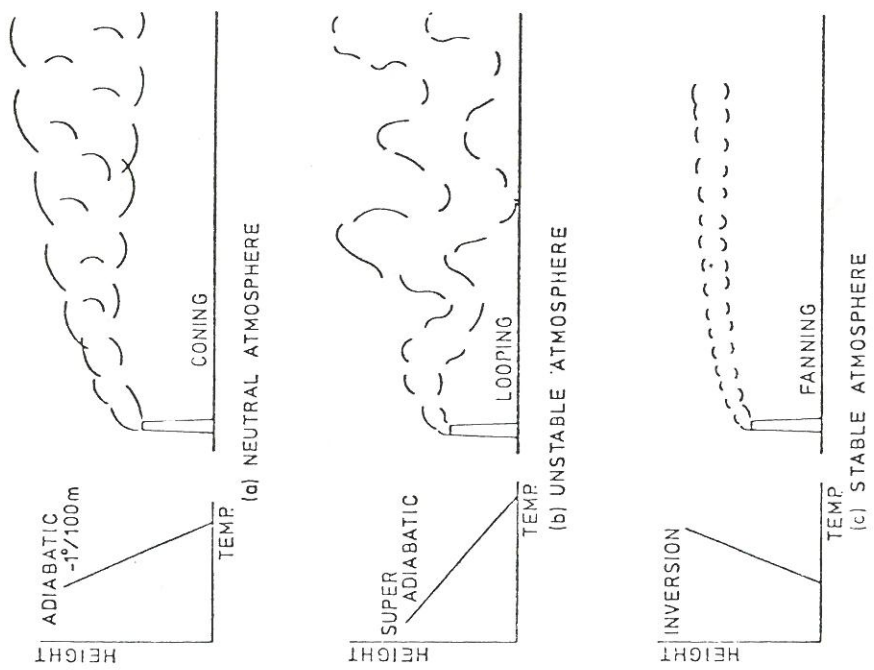
FIG.5 PLUMES IN DIFFERENT ATMOSPHERES

(a) NEUTRAL ATMOSPHERE — CONING — ADIABATIC -1°/100m — TEMP. — HEIGHT

(b) UNSTABLE ATMOSPHERE — LOOPING — SUPER ADIABATIC — TEMP. — HEIGHT

(c) STABLE ATMOSPHERE — FANNING — INVERSION — TEMP. — HEIGHT