AN INFRARED METHOD FOR PLUME RISE VISUALIZATION AND MEASUREMENT

CINDY RICKEL, BRIAN LAMB,* ALEX GUENTHER and EUGENE ALLWINE
Laboratory for Atmospheric Research, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164-2910, U.S.A.

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Abstract—An infrared video camera and recording system were used to record near source plume rise from a low turbine stack at an oil gathering center at Prudhoe Bay, AK. The system provided real-time, continuous visualization of the plume using a color monitor while the images were recorded with a standard video tape recorder. Following the field study, single frame images were digitized using a micro-computer video system. As part of the digitization, the plume centerline was determined as well as an isotherm of the plume outline. In this application, one frame from each 2-min period in the record was digitized. The results were used to calculate the variability in plume centerline during each hour. During strong winds with blowing snow, the mean plume rise for the hour at 15 m downwind was 6 ± 2 m. The observed plume rise from the turbine stack was greater than that calculated using momentum-only or buoyancy-only plume rise models and only slightly larger than that estimated from combined momentum–buoyancy plume rise models.

Key word index: Plume rise, infrared, video, image analysis, Arctic, building dispersion.

1. INTRODUCTION

Maximum pollutant concentrations downwind of industrial complexes are very sensitive to the combined effects of plume rise, plume downwash due to building effects, and building enhanced vertical dispersion. In current air quality models, such as the Industrial Source Complex model, plume rise is calculated using a combined momentum and buoyancy plume rise algorithm, while building effects are parameterized in the treatment of vertical dispersion (see Guenther et al., 1990). Since this parameterization is a function of plume height relative to building height, accurate calculation of plume rise is doubly important for low industrial stacks.

As part of an extensive evaluation of industrial complex modeling methods applied to Arctic oil production facilities, we have conducted a field study of plume downwash and dispersion at an oil gathering center in Prudhoe Bay, AK, during October–November 1987 (Guenther et al., 1990), and we have completed an analysis of wind tunnel tests of the same facility (Guenther et al., 1989). To obtain a direct measure of plume rise during the field study, we employed an infrared video camera and recorder. Huber (1988) has reported on the use of a video system for recording smoke plumes in a wind tunnel, but it appears that this is a novel application of the commercial infrared camera. In this paper, we describe the video system, field measurements, and image analysis methods. The results are used for comparison to current plume rise models as part of our analysis of plume behavior under Arctic conditions.

Fig. 1. Map of oil gathering center showing turbine stack (0), meteorological tower (x) and typical camera locations (triangles).

* To whom correspondence should be addressed.
exterior of a large turbine building. The building height was 35 m, stack height was 39 m, and stack diameter was 3.7 m. Winds were from the east during all tests, so that the stacks were located on the downwind side of the oil gathering center. Hourly averaged stack temperature and velocity were measured continuously during the study. Over the 3 week period, stack temperature ranged from 270 to 331°C, and stack gas velocity was in the range 15.6–21.2 m s⁻¹.

The video system was a Hughes model 4300 infrared video camera with a color monitor. Images were recorded continuously using a standard portable video recorder (1/2" tape). Camera specifications are listed in Table 1. The camera system uses a 16 color scale to depict 16 temperature ranges. The minimum temperature resolution is 0.1°C. The absolute accuracy of the temperature output depends upon using a calibrated emissivity. For our purpose, we assumed an emissivity equal to 1. The extent of the temperature coverage is specified by the accuracy of the lowest range. In our application, we optimized the plume image by selecting a minimum temperature slightly less than ambient (typically −20°C) and setting the range width to 1.5°C. With these settings, the edges of the plume were quite distinct, while the central volume of the hot plume appeared as a single color (i.e. the color of the top range).

During each test, the camera was positioned on a tripod outside a van and the monitor and recorder were operated from inside the van. Power was supplied from a 500 watt DC/AC inverter from the truck battery. With easterly flow, it was relatively easy to locate the mobile system at a point perpendicular to the mean wind direction, and the accuracy of the apparent plume trajectory represented the edge of the plume and used the software to display only the plume outline. Both the plume centerline and plume outline were stored for each frame. The results for a typical frame are shown in Fig. 2. In the analysis that follows only the plume centerline data are used. However, it appears that the plume volume data could be used to estimate entrainment and plume growth rates for short distances downwind.

The plume centerline coordinates obtained from the video analysis represent an apparent trajectory which must be corrected for the camera position and the actual direction of the plume travel. The trajectory was converted to real distance units by using the known stack diameter as a distance scale.

Estimates of true plume height were determined using methods outlined by Halitsky (1961) and Fanaki and Lesins (1975). In this approach, the actual plume height and distance along the plume trajectory are calculated using the horizontal distance from the camera to the stack base, measured from a detailed map of the site, the known stack height, the appropriate 5-min average wind direction measured immediately upwind of the stack on a 33 m tower, and the horizontal angle between the camera view axis and the mean wind direction. Halitsky (1961) has shown that for cases where the camera view axis is within approximately 20° of perpendicular to the mean wind direction, errors associated with the calculated plume rise are less than approximately 25% even if the correction for wind angle is omitted. During each test, the camera position was chosen so that the view axis was close to perpendicular to the plume transport direction. This was possible because the winds were very steady with hourly values of ԰ typically less than 8°. Halitsky (1961) also showed that horizontal wind direction fluctuations less than ±20° produced errors in the calculations of less than approximately 10%.

The accuracy of the observed plume trajectory depends upon the accuracy of the camera location relative to the stack, the accuracy of the observed wind direction, and the accuracy of the apparent plume

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Table 1. System specifications for the PROBEYE 4300 IR video system

| Specification          | Value          |
|------------------------|----------------|
| Sensitivity            | 0.1°C          |
| Temperature range      | −20 to 280°C   |
| Spectral range         | 2.0–5.6 μm     |
| Scan rate              | 16 Hz          |
| Scan lines             | 60 lines/frame |
| Field of view          | 15 horizontal, 7.5 vertical |
| Focus range            | 0.2 m to infinity |
| Spatial resolution     | 0.126° horizontal and vertical |
| Scan resolution        | 256 x 300 pixels |

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3. DATA REDUCTION AND ANALYSIS

Single frames from each video record were digitized by playing the video tape through a micro-computer video image analysis system (Imaging Technologies, Series 150). One frame was stored from every 2 min of the video record. This provided a reasonable number of images per hour, while keeping the data storage and analysis time within reasonable limits.

For each frame, the operator manipulated the computer screen cursor to draw the stack and the plume centerline on the monitor. Although this is a subjective method for determining the centerline, the plume outlines were quite clear and it was straightforward to draw a line through the approximate center of the plume image. The method was very fast and avoided the need to do any elaborate calculations to find the center of the plume. After the plume centerline was obtained, the operator selected an isotherm value representing the edge of the plume and used the software to display only the plume outline. Both the plume centerline and plume outline were stored for each frame. The results for a typical frame are shown in Fig. 2. In the analysis that follows only the plume centerline data are used. However, it appears that the plume volume data could be used to estimate entrainment and plume growth rates for short distances downwind.

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The accuracy of the observed plume trajectory depends upon the accuracy of the camera location relative to the stack, the accuracy of the observed wind direction, and the accuracy of the apparent plume.
Plume rise visualization and measurement

trajectory obtained from the image of the plume. In
the first case, camera location was easily obtained to
within 5 m from locations recorded on a detailed map.
This corresponds to less than 5% of the distance of the
camera from the stack. Wind directions appear to be
correct to within 2–3° based upon comparison with
other measurements and upon the ground-level loca-
tion of the observed maximum tracer concentration.
The vertical range of the plume volume was typically
of order 5–10 m so that within this range the plume
centerline can be correctly positioned to within ap-
proximately 2 m.

Typical results from the plume rise measurements
are shown in Fig. 3 for an hour from test 10 of the
study. Winds during this period were 14 m s⁻¹ from
51° measured at 10 m above the surface. The stack
temperature was 295°C and stack gas velocity was
19.4 m s⁻¹ for the hour. The data points in Fig. 3
represent plume centerline points at various down-
wind distances for various instantaneous scans ob-
tained every 2 min during the hour. The scatter of
points thus describe the domain of the plume center
during the hour. With a mean plume rise of approxim-
ately 6 m at 15 m downwind, the plume center varied
between approximately 4–8 m above the stack during
the hour.

For comparison, Fig. 3 also includes the calculated
plume rise based upon momentum-only, buoyancy-
only, and combined momentum–buoyancy plume rise
models. These are taken from Briggs (1984):

\[
\begin{align*}
  h_m &= \left(\frac{3F_m X}{B^2 m U^2}\right)^{1/3} \\
  h_b &= 1.6F_b X^{2/3} / U
\end{align*}
\]

(1)  
(2)

where \(F_m\) is the momentum flux, \(B_m\) is a
momentum entrainment factor (=0.6), \(B_b\) is a
buoyancy entrainment factor (=0.4+1.2u/v), \(u\) is
the ambient wind speed, \(v\) is the stack gas velocity, \(F_b\)
is the buoyancy flux, \(T_s\) is the stack temperature, \(T_a\) is the
ambient temperature, \(r\) is the stack radius, \(\rho_a\) is
ambient air density, \(\rho_s\) is stack
exhaust density, and \(x\) is the downwind distance.

For the hour shown in Fig. 3 and for all other hours
with data available, the calculated plume rise based
upon momentum only or buoyancy only is less than
the lower bound of the observed plume centerlines
near the stack. The combined momentum–buoyancy
plume rise model slightly underestimates the average
observed plume centerline. In other hours, the com-
bined plume rise model underestimated the hourly
averaged observed plume rise by 17–38% at short
distances from the stack. It is significant that these
models underestimate the observed plume rise near
the stack even though the models do not account for
any plume downwash due to stack or building effects.
It is possible that for this near stack domain, the mean
streamlines of air passing over the building are still
rising and actually carrying the plume upward in this
region. It is not possible from the available data to
determine the likelihood for this streamline effect.
Another possibility to explain the differences between
observed and predicted plume rise is that plume rise is
enhanced by the close position of two turbine stacks
(20 m apart). However, at these small downwind dis-

tances, the observed image of the two plumes showed
no evidence of the merger needed to produce en-

tanced plume rise. A third possibility to explain the
gap between observed and predicted plume rise is that
the large roof-top heat exchangers on the turbine
buildings released sufficient volume of warm air to
cause enhanced plume rise. Although the warm air
from the turbine roof vents was not apparent in the
infrared image, it is possible that entrainment of this
warm air into the turbine plumes could cause the
plumes to rise several meters higher than predicted
near the stacks.

4. SUMMARY AND CONCLUSIONS

A unique method for visualizing near stack be-
havior of plumes has been used to determine plume
rise from a turbine stack at an Arctic oil production
facility. Because the plume gases are very hot and
ambient temperatures are quite cold, the infrared
signature of the plume produces a clear image which
can be recorded with a commercial infrared video
camera. The major limitation of the approach is the
relatively short downwind distances over which the
plumes can be visualized. However, for the case where
plume downwash may be important due to stack or
building effects, the ability to measure initial plume rise is quite useful for interpreting observed tracer gas concentrations downwind of the stack at ground-level. In our application of this visualization system, we observed plume rise during very strong wind conditions which was approximately 1 m higher than predicted from a combined momentum-buoyancy plume rise model at 15 m downwind of the stack.

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