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AN INFRARED METHOD FOR PLUME RISE VISUALIZATION AND MEASUREMENT

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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.

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The field study was conducted at an oil gathering center (GC2) shown in Fig. 1 located in the Prudhoe Bay oil field approximately 10 km from the coast of the Arctic Ocean. The test site and meteorological conditions observed during the study have been described by Guenther and Lamb (1989). The area is extremely flat and during the study the tundra was snow covered. Strong winds between 6 and 17 m s⁻¹ were fairly common during the study. Thermal stratification was slightly stable (1°C/100 m) from the surface to 10 m. In addition to an open area, multi-level meteorological tower, wind speed and direction were measured from a 33 m tower located on the north side of the complex. SF₆ tracer gas was released from one of the two turbine stacks located on the west side of the complex. Each stack is attached to the

Fig. 1. Map of oil gathering center showing turbine stack (0), meteorological tower (x) and typical camera locations (triangles).
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 selected by specifying the temperature 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 W DC/AC inverter from the truck battery. With easterly flow, it was relatively easy to locate the mobile system at a point crosswind to the plume trajectory. Typical camera locations used during these tests are shown in Fig. 1. Time and location data were recorded along with camera range settings and the plume image on video tape.

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

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

Fig. 2. Typical plume image showing the stack outline, plume boundaries, and plume centerline.
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 location 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 approximately 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 downwind distances for various instantaneous scans obtained 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 approximately 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):

\[
h_{\text{mb}} = \left[ \frac{3F_m X}{B_m^2 U^2} + \frac{1.6 F_b X^2}{B_m^2 U^3} \right]^{1/3}
\]

where \(F_m\) is the momentum flux, \(= \rho_e (\rho r)^{1/2} / \rho_a\), \(B_m\) is a buoyancy entrainment factor (=0.6), \(B_b\) is a momentum 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 \(= vr^2(T_s - T_a)/T_s\), \(T_s\) is the stack temperature, \(T_a\) is the ambient temperature, \(r\) is the stack radius, \(\rho_a\) is ambient air density, \(\rho_e\) 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 combined 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 distances, the observed image of the two plumes showed no evidence of the merger needed to produce enhanced 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 behavior 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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