Microphysical Effects of Irradiating a Fog With a 10.6-μm CO₂ Laser

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ABSTRACT

The microphysical effects due to illuminating a fog with a 10.6-μm CO₂ laser are examined using a microphysical model that accounts for the sensible and latent heat transfers from the drop and the absorption of the laser energy by the liquid drops and by the water vapor. Since the laser radiation is in the “IR window region,” relatively little of the laser energy is absorbed by the water vapor. Thus, the drops absorb the laser energy and dissipate this energy by sensible and latent heat fluxes both directed away from the drops. Since the heating of the ambient air by the sensible heat flux increases the saturation vapor pressure (at the ambient temperature) faster than the vapor (latent heat) flux increases the ambient vapor density, the relative humidity decreases with time.

Since the absorption of laser energy by the drops is proportional to their geometric cross section and the transfer of sensible and latent heat is proportional to the drop radii, larger drops become warmer than the smaller drops. The absorption cross section for drops radius smaller than 8 μm is proportional to their mass and, for this size range, the droplet spectrum narrows as the droplets evaporate, contrary to the normal situation in clouds.

The time required to evaporate a given volume of fog and the resultant rise in the ambient temperature and relative humidity are examined as a function of the initial temperature of the fog, the liquid water content, the drop size, the ambient pressure, and the intensity of the laser radiation. A “multislice” model is used to examine the propagation of the clearing effect for three fog spectra observed at Otis Air Force Base.

1. Introduction

Restricted visibility at airports caused by fog significantly impacts commercial and military aviation by presenting a hazard to safe operations and by imposing economic burdens. At critical locations in the final approach, touchdown, and rollout phases of landings, clear and unobstructed visual contact provides the widest margin of safety. Sophisticated avionics have allowed the industry to adapt to visibility-reducing weather elements to some extent. “The visibility/ceiling syndrome remains the foremost contributor to weather-related (aviation) accidents” (Froeschl 1980).

Efforts to improve visibility by fog modification received considerable attention in the late 1960s and early 1970s. Experimental efforts to clear cold fog met with almost immediate success, and operational programs within the Air Force were initiated. Cold-fog dispersal efforts are operational today at Elmendorf Air Force Base (AFB) near Anchorage, Alaska, at Fairchild AFB near Spokane, Washington, and at several civil airports including the Salt Lake City, Utah, Airport.

Efforts to modify warm fogs have met with only limited success despite their considerably greater economic impact. Warm fog is thermodynamically stable with a relative humidity near 100% and temperatures above 0°C. Silverman and Weinstein (1974) presented four physical processes that can be considered candidates to modify warm fog. These are 1) vaporize the droplets by adding heat, 2) introduce chemicals to enhance coalescence, 3) mix the fog with drier air from above, and 4) collect the fog droplets using some electrostatic or filtering device.

Only the thermal technique introducing heat by combustion has provided results that have led to an effective fog dissipation system. This approach used ground-based heat sources to warm the air, thereby increasing its capacity to hold water vapor. In addition, heating can serve to reduce the static stability and help mix the fog with drier air from above. If the air temperature is raised sufficiently, the fog droplets will completely evaporate.

The most well-known example of a thermal fog dispersal system is the English system known as Fog Investigations and Dispersal Operations (FIDO) de-
scribed by Walker and Fox (1946). Large quantities of aviation fuel were burned in ditches along the runways, providing the heat for warming the air and dissipating the fog. FIDO systems were operated at 12 installations in England between 1943 and 1945 and were responsible for 2500 landings. In 1949, a system patterned after FIDO was installed at the Los Angeles International Airport (LAX). The system was abandoned in 1953 after it was found to be too expensive to operate.

The Turboclair fog dispersal was developed in the early 1970s by Aeroprop de Paris for fog dispersal at the Orly and Charles de Gaulle airports (Sauvande 1976). The system generated hot gases with jet engines located in buried facilities along the runways. The hot gases were used to heat the ambient air and evaporate the fog droplets. The system was used in the late 1970s but is no longer in operation.

Starting in 1971, the Air Force Cambridge Research Laboratories (now the Geophysics Directorate of the Phillips Laboratory) initiated a program to develop an efficient and effective thermokinetic fog dispersal system. A combination of operational expense and lack of continued interest by the Air Force resulted in the research being discontinued in the late 1970s.

The inefficiency associated with ground-based heating of air volumes has imposed critical limitations on effective warm fog dissipation. Ground-based heating of the air relies on burning large quantities of jet fuel or other hydrocarbons. It is difficult to confine the heating to the desired volume, making it necessary to heat a much larger volume than required for the approach, touchdown, and rollout phases of aircraft landings. In addition, the combustion of hydrocarbons yields water vapor as a by-product, requiring additional heating of the air to accommodate this additional water vapor (as well as the water vapor resulting from the evaporation of the fog droplets). This effect is more pronounced at lower temperatures according to Fig. 1, requiring 10% more energy at 0°C than a system that heats the air without adding water vapor. (It should be noted that the relative difference between the methods which add water vapor and those which do not decreases with decreasing pressure.)

Now the technology of moderate power industrial lasers has developed sufficiently to consider their use for providing the energy required to eliminate or reduce warm fog constraints on airfield operations. The use of laser energy provides several advantages over systems previously used. The heating associated with lasers does not add water vapor to the environment as does heating by combustion of hydrocarbons. The laser energy can be deposited directly in the drops, raising their temperature and forcing them to evaporate. Lasers can be directed to illuminate the desired air volume more precisely, further reducing total energy requirements. These characteristics make dissipation of fog by laser illumination feasible; clearing of water droplets in cloud chambers has been accomplished (Smith and Gelbwachs 1989), demonstrating the utility of lasers to evaporate fog droplets.

The deposition of the laser energy directly in the drops presents an interesting microphysical problem. In an evaporating fog under natural conditions, the sensible and latent heat fluxes are in opposite directions at the drop surface; under laser illumination, the sensible and latent heat fluxes are in the same direction with interesting consequences. These energy fluxes are contrasted in Fig. 2. This paper is focused on the microphysical aspects of using lasers to modify fog.

2. The microphysical model

The model assumes that the initial fog environment (ambient air and fog droplets) is at water saturation and at uniform temperature. This is not a restriction of the model but rather simplifies specification of the initial conditions. At time zero, a 10.6-μm CO2 laser is "turned on," illuminating a horizontal path through the fog. The 10.6-μm wavelength is strongly absorbed by liquid water and is weakly absorbed by water vapor and negligibly absorbed by other atmospheric gases. The absorption by water vapor is calculated by the model. Scattering of the laser radiation by the fog droplets is ignored. (For relatively small fog droplets, absorption dominates over scattering. The ratio of absorption to scattering for 10.6-μm radiation by droplets decreases from 29:1 for 1-μm radius droplets, to 4:1 for 2.4-μm droplets, to 1:1 for 8.2-μm droplets, and approaches 0.7:1 for radii > 15 μm.)

A 10⁴ W laser is assumed here. A power density of 1 W cm⁻² yields a cross-sectional area of 1 m².

![Fig. 1. Calculations of the minimum energy required to evaporate 1 m² of fog with a liquid water content of 1 g m⁻³ (P = 1000 mb).
](image)
Each fog droplet intercepts and absorbs radiant energy from the laser according to

$$\frac{dQ}{dt} = (0.238844 \text{ cal J}^{-1}) I \pi r^2 \left( \frac{4}{3} r \alpha \right)$$

for \( r > 7.98 \mu m \)

$$\frac{dQ}{dt} = (0.238844 \text{ cal J}^{-1}) I \pi r^2 \text{ for } r < 7.98 \mu m$$  \(1\)

where \( I \) is the laser intensity in watts per square centimeter, \( r \) is the drop radius in centimeters, and \( \alpha = 940 \text{ cm}^{-1} \), based on VandeHulst (1981). The heat energy absorbed by the droplet \((dQ/dt)\) is then given in calories per second.

Since the droplets are being heated directly by the laser, sensible and latent heat fluxes are generally directed away from the droplet. The sensible heat flux away from the drop is given by Byers (1965) as

$$\frac{dQ}{dt} = 4 \pi r f_2 K(T_d - T_\infty),$$  \(2\)

where \( T_d \) and \( T_\infty \) are the average drop and ambient temperatures during the time step, respectively, \( K \) is the thermal conductivity, and \( f_2 \) is a factor to account for the reduction in the diffusion of heat due to kinetic effects (Fuchs 1959). To reduce computational requirements, the factor \( f_2 \) was estimated using a two-step linear approximation.

The latent heat (and mass) transfer away from the drop is given by Byers (1965) as

$$\frac{dQ}{dt} = L_v \frac{dm}{dt} = L_v 4 \pi r f_1 D (\rho_{v,d} - \rho_\infty),$$  \(3\)

where \( \rho_\infty \) and \( \rho_{v,d} \) are the average ambient vapor density and the saturation vapor density over water at the average drop temperature, respectively, \( D \) is the diffusivity of water vapor in air, \( L_v \) is the latent heat of vaporization, and \( f_1 \) is the kinetic factor for the reduction in the diffusion of mass due to kinetic effects (Fuchs 1959). Here, the factor \( f_1 \) was estimated using a three-step linear approximation.

The net heat balance \((\Delta Q_{\text{bal}})\) for the drops is given by

$$\Delta Q_{\text{bal}} = \Delta Q_{\text{rad}} - \Delta Q_{\text{sen}} - \Delta Q_{\text{lat}} - \Delta Q_{\text{drops}}$$  \(4\)

where \( \Delta Q_{\text{drops}} \) represents the sensible heat required to warm the droplets. The \( \Delta Q \) terms represent the changes in heat calculated for a single group of droplets for a single time step based on Eq. \((1)\), \((2)\), and \((3)\). The drop temperatures are iterated for fixed \( T_\infty \) and \( \rho_\infty \) until \( Q_{\text{bal}} \) is less than \( 1 \times 10^{-4} \) times the largest \( \Delta Q \) term or less than \( 1 \times 10^{-7} \) cal, whichever occurs first.

The change in the ambient temperature depends on
the sensible heat transferred from the droplets and the radiant energy absorbed from the laser beam. The sensible heat transfer is the sum of the $\Delta Q_{\text{sens}}$ terms for all of the drop categories. Since the ambient temperature affects $\Delta Q_{\text{sens}}$, the ambient temperature must be solved by iteration as well.

The absorption of 10.6-\textmu m radiation by water vapor is modeled based on Wolfe and Zissis (1985). They give an empirical fit for the transmittance as a function of wavelength ($\lambda$) and temperature as

$$\tau(\lambda) = \exp(-k_{\text{H}_2\text{O}}s),$$

(5)

where $s$ is the horizontal path length (km) and

$$k_{\text{H}_2\text{O}} = C(\lambda, T)w_{\text{H}_2\text{O}};$$

$w_{\text{H}_2\text{O}}$ is the number of water vapor molecules per square centimeter per kilometer path length. The coefficient $C$ is given by

$$C(\lambda, T) = C_0(\lambda) \exp\left[ 1800 \left( \frac{1}{T} - \frac{1}{295} \right) \right]$$

and

$$C_0(\lambda) = E + F \exp\left( \frac{-G}{\lambda} \right)$$

with

$$E = 1.25 \times 10^{-22} \text{ molecule}^{-1} \text{ cm}^2 \text{ atm}^{-1},$$

$$F = 2.34 \times 10^{-19} \text{ molecule}^{-1} \text{ cm}^2 \text{ atm}^{-1},$$

and

$$G = 83.0 \text{ \mu m}.$$ 

The solution of Eq. (5) was found to compare reasonably well with observed data presented by Grant (1990).

In this model, the ambient temperature ($T_\infty$) and the ambient vapor density ($\rho_\infty$) are iteratively adjusted until the relative change in each quantity between successive iterations is less than 3 parts per 100 000. The relative change in $T_\infty$ is determined in degrees Celsius as $(T_\infty - T_\infty')/T_\infty$. Once $T_\infty$ and $\rho_\infty$ have been determined, the changes in droplet masses and new radii have also been determined.

b. Model structure

The fog is partitioned into slices perpendicular to the laser beam axis. The laser intensity (power density) is assumed to be uniform within each slice and is reduced as the distance from the laser source increases, according to the extinction taking place in the intervening slices. Thus, in the model, the laser intensity decreases as a step function along the laser beam axis. Slices are typically 2 m thick and the change in intensity from one slice to the next is generally very small.

Computations start with the slice closest to the laser, computing the changes in the temperature, humidity, and microphysical structure and the resulting absorption before commencing the next slice. Within each slice, the fog droplets are assumed to be distributed homogeneously and to be stationary. Heating of the air is assumed to have a negligible affect on the turbulence since typical temperature increases are less than 1°C and the atmosphere is assumed to be stable initially. The fog is assumed to be in quiescent air; a subsequent effort to determine the effects of advection through the illuminated region is planned.

3. Model testing with idealized droplet spectra

A single slice version of the model was run under a wide variety of idealized conditions with a "representative" droplet spectrum in order to facilitate understanding of the results for the full, multislice model with natural droplet spectra. The time evolution of the illumination of a typical fog is presented below. The effects of ambient temperature, pressure, liquid water content, droplet size, and laser energy are summarized.

The "standard" droplet spectrum was chosen to obtain a relatively narrow and simple droplet spectrum rather than to represent a typical fog. In fact, it is more representative of newly formed droplet spectra near the bases of cumulus clouds with a droplet concentration of 285 cm$^{-3}$ and a liquid water content ($\chi$) of 0.194 g m$^{-3}$. The standard spectrum is shown in the first panel of Fig. 5.

a. Drop temperatures

Since the absorption of the laser energy by a drop is roughly proportional to $r^2$ and the conduction of sensible and latent heat away from a drop is proportional to $r$, the larger drops will be at warmer temperatures than the smaller drops. Equating the absorption of laser energy (1b) with the conduction terms (2) and (3) and ignoring changes in the drop temperature,

$$I_{\tau} r^2 = 4\pi r (K\Delta T + DL_\nu \Delta \rho).$$

(6)

Assuming that the environment is at water saturation, small values of $\Delta \rho$ can be estimated from the Clausius-Clapeyron equation by integrating

$$d\rho_s = \rho_s \frac{L_\nu - R_\nu T}{R_\nu T^2} dT$$

from $T_\infty$ to $T_s$, assuming $\rho_s$ may be approximated by $\bar{\rho}_s$,

$$\Delta \rho = \bar{\rho}_s \left[ \frac{L_\nu}{R_\nu} \left( \frac{1}{T_\infty} - \frac{1}{T_s} \right) - \ln \left( \frac{T_s}{T_\infty} \right) \right].$$

For small $\Delta T$, the logarithmic term can be neglected and $\Delta \rho$ can be approximated as

$$\Delta \rho \approx \bar{\rho}_s \frac{L_\nu \Delta T}{R_\nu T_\infty}.$$
the latent and sensible heat transfers, although the former is reduced more than the latter. Thus, a higher temperature is required to increase both sensible and latent heat transfers. (A negative droplet temperature elevation may occur for small droplets since the air is subsaturated at this time.)

The time evolution of the ambient temperature and relative humidity are shown in Fig. 4. The most rapid temperature rise is initially when the total absorption cross section of the drops is the greatest. Note that the relative humidity drops below 100%. As both sensible and latent heat are being conducted away from the drops, the ambient temperature and vapor density both increase. The increase in the ambient temperature results in an increase in the saturation vapor density. Under the influence of the laser-absorbed energy, the saturation vapor density increases more rapidly than the ambient vapor density, resulting in a decrease in the relative humidity. Under natural conditions, the sensible and latent heat fluxes are opposite and tend to bring the relative humidity closer to 100%.

The model was run both with and without absorption of the laser energy by the water vapor. In the case without water vapor absorption, the relative humidity reaches a minimum value of 99.72% in around 10 sec. As the droplets decrease in size, the laser-induced heating becomes less important and the evaporation due to the subsaturated environment becomes more important. This results in a small rise in relative humidity to a final value of 99.74%.

Including absorption of the laser energy by water vapor, the relative humidity monotonically decreases with time. The absorption of laser energy by the water vapor produces a heating rate of roughly 0.18°C min⁻¹,
sufficient to overcome the tendency to increase the relative humidity as the drops become small. An inflection in the curve for relative humidity near 10 sec may be noted in Fig. 4. Since the absorption of laser energy by water vapor increases as the water vapor density increases, this effect is greater for warmer fogs and is much less pronounced for colder fogs.

The evolution of the drop spectrum is shown in Fig. 5. Note that the drop spectrum narrows with increasing time. This is contrary to the natural condition wherein droplet spectra tend to narrow as they grow and spread as they evaporate. Since the rate of change of radius is

\[ \frac{dr}{dt} = \frac{D\Delta \rho}{r} , \]

it follows that, for drop radius $> 8 \mu m$, $dr/dt$ is essentially independent of drop size. For drop radius $< 8 \mu m$, the right-hand side of (7) must be multiplied by $4\alpha r^3$. This implies that $dr/dt$ is smaller for smaller drops and that the droplet spectrum should narrow upon evaporation.

**Table 1.** Comparison of key parameters as a function of the initial ambient temperature. The standard droplet spectrum ($n = 285 \text{ cm}^{-3}$, $\chi = 0.2 \text{ g cm}^{-2}$) and a laser intensity of 1 W cm$^{-2}$ were used in these simulations ($P = 1000 \text{ hPa}$). These results assume no absorption of the laser energy by the water vapor.

<table>
<thead>
<tr>
<th>Initial $T_\infty$ ($^\circ \text{C}$)</th>
<th>Time (sec)</th>
<th>Increase in $T_\infty$ ($^\circ \text{C}$)</th>
<th>Minimum RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+30</td>
<td>28</td>
<td>0.136</td>
<td>99.82</td>
</tr>
<tr>
<td>+20</td>
<td>32</td>
<td>0.227</td>
<td>99.72</td>
</tr>
<tr>
<td>+10</td>
<td>38</td>
<td>0.374</td>
<td>99.55</td>
</tr>
<tr>
<td>0</td>
<td>51</td>
<td>0.644</td>
<td>99.29</td>
</tr>
<tr>
<td>-10</td>
<td>78</td>
<td>1.155</td>
<td>98.96</td>
</tr>
</tbody>
</table>

c. The influence of the initial temperature

The temperature influence is primarily a result of lower saturation vapor densities at lower temperatures, reducing the evaporation rate for a given temperature elevation [(Eq. 3)]. This reduces the latent heat transfer, which must result in an increase in the sensible heat transfer. Thus, more time should be required to evaporate the fog at colder temperatures, resulting in larger temperature increases.

The results presented in Tables 1 and 2 verify this picture. The time required to evaporate the fog at $-10^\circ \text{C}$ is twice as long as the time required at $+10^\circ \text{C}$. The resulting temperature rise is three times greater at $-10^\circ \text{C}$ compared to $+10^\circ \text{C}$. Note that the greater temperature rise at the lower temperatures results in lower (minimum) relative humidities.

The effects of including the absorption of laser energy by the water vapor are illustrated by comparing Tables 1 and 2. As noted above, the effects are greatest for the warmest fogs. The direct heating of the air reduces the relative humidity more quickly, increasing the latent heat transfer and decreasing the time required to evaporate the fog. These differences are relatively small for fogs colder than $10^\circ \text{C}$.

d. The influence of liquid water content

The drop concentration for the standard droplet spectrum was halved to produce a spectrum with $\chi = 0.1 \text{ g cm}^{-3}$ and was multiplied by 1.5 to produce a

**Table 2.** Comparison of key parameters as a function of the initial ambient temperature. The standard droplet spectrum ($n = 285 \text{ cm}^{-3}$, $\chi = 0.2 \text{ g cm}^{-2}$) and a laser intensity of 1 W cm$^{-2}$ were used in these simulations ($P = 1000 \text{ hPa}$). These results include absorption of the laser energy by the water vapor.

<table>
<thead>
<tr>
<th>Initial $T_\infty$ ($^\circ \text{C}$)</th>
<th>Time (sec)</th>
<th>Increase in $T_\infty$ ($^\circ \text{C}$)</th>
<th>Minimum RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+30</td>
<td>19</td>
<td>0.232</td>
<td>99.29</td>
</tr>
<tr>
<td>+20</td>
<td>26</td>
<td>0.270</td>
<td>99.43</td>
</tr>
<tr>
<td>+10</td>
<td>35</td>
<td>0.380</td>
<td>99.42</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td>0.636</td>
<td>99.28</td>
</tr>
<tr>
<td>-10</td>
<td>77</td>
<td>1.133</td>
<td>98.95</td>
</tr>
</tbody>
</table>
spectrum with \( x = 0.3 \text{ g m}^{-3} \). These spectra were run for the same temperatures as shown in Table 2, although only the results for \( T_{\infty} = 20^\circ\text{C} \) are shown in Table 3.

The most notable feature of Table 3 is that the time required to evaporate the fog is virtually independent of the liquid water content. Actually, the fog with the highest \( x \) evaporates the most rapidly. This apparent anomaly results from the assumption of a single (thin) slice of fog that is being illuminated. Since attenuation of the beam is negligible within the slice, a given drop absorbs the same amount of laser energy, regardless of the droplet concentration. Thus, the evaporation rate for a given drop is largely independent of the droplet concentration.

The temperature rise is not quite proportional to the liquid water content. This suggests that the ratio of latent heat transfer to sensible heat transfer is greater for higher \( x \). Coupled with the exponential increase in the saturation vapor density with increasing temperature, the minimum relative humidity is roughly the same for all three cases.

It should be noted that this does not imply the entire fog will evaporate more quickly with a higher \( x \) than with a lower \( x \). The attenuation at higher \( x \) is much greater and the beam illuminates a smaller volume of the fog. That is, the intensity of the laser beam drops rapidly with distance in a dense fog compared to a sparse fog. This problem is treated in more detail in section 4.

e. The influence of the droplet size

The effects of droplet size were investigated using monodispersed spectra with \( x = 0.2 \text{ g m}^{-3} \). A wide range of droplet sizes was investigated. The results are presented in Table 4 for the case with absorption of the laser energy by water vapor.

- Obviously, large droplets will take longer to evaporate than small droplets. Without the absorption of laser energy by the water vapor, the ambient temperature rise is smaller for the larger drops. Even though the larger droplets have warmer temperatures than the smaller droplets, the rate of sensible and latent heat transfers summed over a collection of small drops is greater than that summed over a population of large drops with the same \( x \). Since the saturation vapor density increases exponentially with temperature, the latent heat transfer is enhanced to a greater degree by the warmer temperatures for large drops than is the sensible heat transfer.

- Including the effects of the absorption of laser energy by the water vapor, the increased time required to evaporate the larger drops allows greater direct heating of the air. This results in larger ambient temperature rises and lower relative humidities with increasing drop size.

f. The influence of ambient pressure

The ambient pressure has the greatest affect on the air density and the diffusivity of water vapor. The lower air density implies that a given increase in sensible heat will produce a larger temperature change. The greater diffusivity would be expected to enhance the latent heat transfer relative to the sensible heat transfer. Table 5 shows that the effect of lower air density is dominant, resulting in larger temperature rises for lower pressures.

The time required for complete evaporation is less at lower pressures. This results primarily from the in-
crease in water vapor diffusivity at decreased pressures. The final relative humidity decreases with decreasing pressure, a result of the increased temperature rise (since the ambient saturation vapor density increases more than the ambient vapor density).

g. The influence of the laser power density

Higher laser power densities are expected to result in higher drop temperatures according to (7). Thus, the sensible and latent heat transfer should both increase, resulting in more rapid evaporation. Since the latent heat transfer increases more rapidly than the sensible heat transfer as the drop temperature is elevated (see section 3e above), the ambient temperature rise would be expected to decrease with increasing power density.

Contrary to expectations, Table 6 shows that the temperature rises are greatest for the highest power densities. This is explained by the role of evaporation (and cooling) due to the reduced relative humidity. At lower power densities, more time is allowed for the droplets to evaporate due to the reduced relative humidity. This results in a much higher final humidity and a smaller temperature rise.

The total energy deposited in the fog (power multiplied by time) varies by less than 10% over the range of power densities considered. At lower power densities, a larger fraction of the energy appears as latent heat; at higher power densities, a larger fraction appears as sensible heat. To help ensure against additional fog formation in the same air, one would be advised to use a higher power density since that will result in a greater degree of subsaturation. The continued illumination of a cleared volume as the clearing effect propagates away will result in a continued decrease in the relative humidity with time.

4. Multislice simulations using observed fog spectra

The single-slice microphysical model described in the preceding section was configured in a 200 slice mode with each slice being 2 m thick. The laser beam was assumed to be nondivergent and horizontal. The laser beam intensity for these simulations was assumed to be 1 W cm⁻² at zero distance. The results are summarized in terms of the geometrical cross section,

\[ \sum_{i=1}^{k} n_i r_i^2, \]

where \( k \) represents the number of droplet size categories.

Three different fogs were selected from the fog spectra given by Mack et al. (1980). These are designated Otis A, Otis B, and Otis C; their characteristics are summarized in Table 7. The A and C fogs have fairly high liquid water contents and low visibilities. Otis C contains a higher concentration of small drops than A, which has fewer but larger drops. Otis B has a relatively low liquid water content and correspondingly higher visibility.

The results for the three fog clearing simulations are shown in Figs. 6–8. The geometrical cross section is not intended to provide a direct estimate of visibility but rather is a measure of the effect of the laser radiation on the fog optical properties. The manner in which the geometrical cross section changes with time varies with distance. Further from the laser source, the initial stages of the clearing are at a lower laser intensity due to the absorption by fog droplets between the slice and the laser. As the intervening fog is cleared, the laser intensity passing through a given slice increases and the geometrical cross section decreases more rapidly.

The slope of the cross section isopleths in these figures gives a measure of the propagation of the “clearing” boundary. For the A and C cases, the clearing boundary seems to reach a constant velocity near 12 m s⁻¹. For the B case, although the slopes of the isopleths appear to be constant, they are slightly concave and it is not likely that the clearing boundary has reached a constant velocity. The average propagation velocity for the “B” fog is about 45 m s⁻¹.

5. Discussion and conclusions

A number of interesting features result from the illumination of a fog with a laser for which the energy is largely absorbed by the drops. Since the drops absorb

<table>
<thead>
<tr>
<th>Date/time (July 1980)</th>
<th>Otis A</th>
<th>Otis B</th>
<th>Otis C</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/2108 EDT</td>
<td>0.204</td>
<td>0.0384</td>
<td>0.193</td>
</tr>
<tr>
<td>Water content (g m⁻³)</td>
<td>48.74</td>
<td>13.3</td>
<td>211</td>
</tr>
<tr>
<td>Drop concentration (cm⁻³)</td>
<td>110</td>
<td>510</td>
<td>82</td>
</tr>
<tr>
<td>Visibility (m)</td>
<td>19.9</td>
<td>20.0</td>
<td>18.8</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
laser energy (roughly) proportional to radius squared and dissipate the energy as sensible and latent heat proportional to radius, the larger drops are warmer. For drop radius < 8 μm, absorption is proportional to radius cubed and large drops evaporate \( (dr/dt) \) faster than the small drops. Thus, the droplet spectrum narrows on evaporation, contrary to the natural situation.

The sensible heat and water vapor fluxes are such that the ambient relative humidity decreases as the laser energy is absorbed by the drops and transferred to the air. The sensible heat flux increases the saturation vapor density at a faster rate than the water vapor flux increases the actual vapor density. The evaporation of a fog containing 0.2 g m\(^{-3}\) of liquid water may reduce the relative humidity from saturation to between 99.0% and 99.5%, depending on the ambient temperature, pressure, laser intensity, and drop size spectrum.

For light fogs (visibilities more than 300 m), the absorption of the laser energy is so weak for any slice that the entire fog is illuminated from the start. Thus, the visibility gradually improves throughout the fog. For dense fogs (visibilities less than 200 m), the ab-

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**Fig. 6.** Time evolution of the geometric cross section in the multislice model for the Otis A fog. The cross section is given for a 1 cm\(^2\) section through the 2-m slice.

**Fig. 7.** As in Fig. 6 but for the Otis B fog.
The absorption of the laser energy is strong so that most of the absorption takes place in a 100–200-m zone of the fog. Thus, the clearing propagates through the fog away from the laser source.

Because of these differences in the manner in which the fog is illuminated, one may expect significant differences in the efficiency as determined by the ratio of the energy used to clear the fog in the desired volume to the total laser energy expended. Since the light fog absorbs relatively little of the laser energy, the efficiency of clearing such fogs may be expected to be much lower. This is balanced by the fact that less clearing needs to be done, that is, it does not take as long to improve the visibility to the airport minimums.

Scattering of laser radiation out of the beam has not been considered in this paper. A proper treatment of the scattering problem would in itself be a major undertaking. Scattering of laser radiation out of the illuminated volume would be expected to increase the time required to produce a given improvement in the visibility in the illuminated volume by perhaps a factor of 2. This radiation would act to evaporate fog outside of the illuminated volume, some of which may advect into the volume at a later time.

Subsequent work will focus on the use of arrays of CO₂ lasers capable of delivering 10⁴ W each to clear substantial volumes of fog. The improvement in visibility that may be expected under different fog advection scenarios will be examined. This subsequent work is expected to provide a basis for estimating the costs of clearing fog at airports.

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