COMPUTED TOMOGRAPHY AND INFRARED ABSORPTION: DEVELOPMENT OF A NEW TECHNIQUE FOR THE STUDY OF INDOOR AIR POLLUTANT TRANSPORT AND DISPERSION

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ABSTRACT

We present the idea of applying optical remote sensing and computed tomography (CT) to the study of indoor air quality and pollutant transport. Potential applications include research on the motion and mixing of indoor air, leading to better-designed heating, cooling and ventilation systems, and remote locating of pollutant sources in indoor and outdoor settings. A source-detector combination for infrared sensing of the tracer gas sulfur hexafluoride (SF_6) has been constructed and calibrated. We have designed a proof-of-principle experiment to measure the distribution of SF_6 in a plane with this infrared detection method combined with CT. A computed tomography program based on an iterative algorithm has been written for the proof-of-principle experiment and has performed well on synthetic data. Several general factors critical to the successful application of the suggested new method are discussed.

INTRODUCTION

Air mixing and pollutant dispersal in indoor spaces are generally poorly characterized and not well understood. The rates at which indoor air mixes and the extent to which pollutants, such as environmental tobacco smoke, disperse are frequently unknown (1). Solving the governing equations of indoor transport and dispersion is difficult. Direct measurement of pollutant dispersion by point sampling is intrusive, time and labor intensive and suffers from poor spatial and/or temporal resolution. Therefore, the simplifying assumption of complete and instantaneous mixing is commonly made when investigating indoor air quality. The validity of this assumption often goes untested due to experimental limitations. Yet, ventilation standards are based on this premise. A new experimental tool is therefore needed to efficiently measure pollutant or tracer gas concentrations in indoor air non-intrusively and with high spatial and temporal resolution.

Non-intrusive measurements of gas concentration can be made with remote sensing technologies. Such optically based methods have become widespread in the last few years for sensing outdoor pollutants. However, most of these technologies yield only path integrated concentrations, along a laser beam, for instance. To determine the spatial distribution of contaminant gas by remote sensing, the domain under consideration may be crossed from various directions by many intersecting beams. One may then calculate the distribution of species concentration in a plane section from its average value along these various paths by means of computed tomography. Computed tomography is most commonly known for its use in medical imaging (2). It has also recently been suggested as a tool for monitoring indoor workplaces for gaseous contaminants (3).

The purpose of this research is to explore whether computed tomography coupled with optical remote sensing could be developed into a new tool for studying pollutant transport and dispersion in indoor air. To this end, a bench-top proof-of-principle experiment was designed to reconstruct gas concentrations in the cross-section of a neutrally buoyant cylindrical plume of sulfur hexafluoride (SF_6). This gas is frequently used as a tracer gas in ventilation studies.

Infrared absorption was the method chosen to detect the gas, since SF_6 absorbs strongly near 10.6 µm.

We investigated a variety of numerical reconstruction methods, to determine which would be most appropriate for the purpose of this project. Several computed tomography algorithms exist, the most common being analytic, back-projection and iterative techniques. Since the iterative techniques are the most flexible with respect to beam geometry, one such technique known as Algebraic Reconstruction Technique, or ART (4), was used for this study. The method essentially involves dividing the space under consideration into pixels, making an initial guess of the concentration in each pixel and refining this estimate with each iteration by comparing measured path average concentrations to those calculated from estimated pixel concentrations.

METHODS

The first step in this project was to establish a suitable method for remote optical detection of SF_6. The apparatus comprised a source of infrared radiation collimated into a single beam and located at a fixed distance from an infrared detector sensitive to radiation near 10.6 µm. SF_6 gas in the beam path reduces the intensity of the radiation arriving at the detector. A single-ray experiment was set up to calibrate a liquid-nitrogen-cooled HgCdTe detector for a range of path-average SF_6 concentrations. The apparatus is shown schematically in Figure 1. A heated NiCr filament placed in a ceramic tube provided the source of radiation. The beam was collimated with a lens, passed through a 1 cm diameter iris and chopped at 350 Hz by a chopper wheel connected to a lock-in amplifier. The lock-in amplifier also picked up the signal from the infrared detector, which has a filtered window (narrow bandpass filter centered at 10.6 µm) and was located approximately 80 cm from the source. The detector was calibrated by placing a plastic box fitted with special infrared-transparent windows in the beam path and filling it with various concentrations of SF_6, from about .03% to 100%.

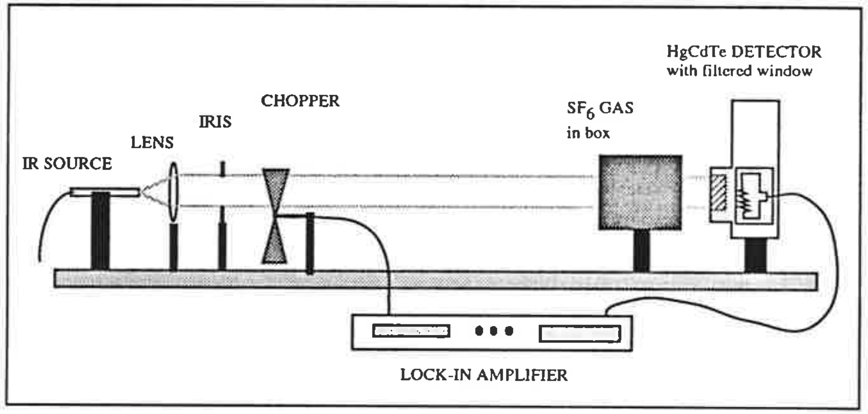

Fig. 1. Single-ray experiment for detector calibration (not to scale).

To determine whether two-dimensional gas concentration profiles could be adequately reconstructed, a computed tomography program based on ART was written and first tested on synthetic data. Several concentration profiles were simulated on a 12 by 12 grid, including a circular 'plateau', an annular 'plateau', an annular 'plateau' with a high spike rising from the center and an asymmetric distribution of peaks of various heights. The circular plateau, shown in Figure 2, most closely represents the gas distribution we expect to generate from the cylindrical plume of SF_6 in the proof-of-principle experiment.

The ray pattern that will be used to scan the cross section of the SF_6 plume is illustrated in Figure 3. It was also used to test the computed tomography program on synthetic data. The area to be reconstructed is crossed by 12 sets of parallel rays, called projections, spaced at regular angles between 0 and π radians, and each containing 12 rays. Thus, the number of rays, 144, equals the number of pixels. This is a necessary condition for reconstructing the correct (unique) image, because each ray represents an equation for the unknown pixel concentrations. The width of the rays used for reconstruction of the synthetic data was equal to both their spacing and the width of the pixels.

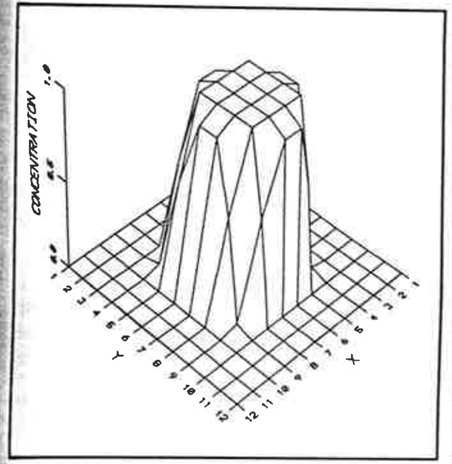

Fig. 2. Simulated SF_6 concentration distribution for the proof-of-principle experiment (units are arbitrary).

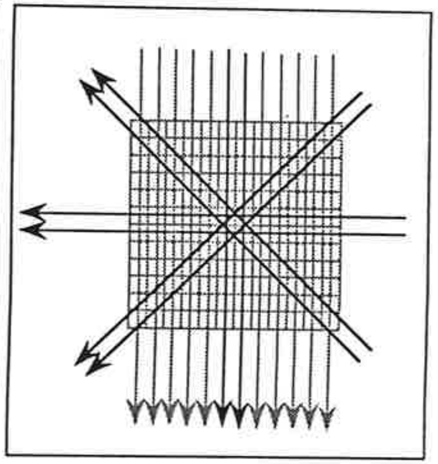

Fig. 3. Schematic of the ray pattern for scanning the plane of reconstruction (12 by 12 pixels). Only 4 of the 12 angles are shown; some rays are omitted for clarity

The quality of the reconstructions was quantified using two parameters, defined below. σ_p compares true and reconstructed pixel concentrations (**p**). σ_r similarly compares ray path-average concentrations (**r**) and is the only computable parameter when reconstructing real remote sensing data. For parameter x, with x_{true} being its true value and x_{calc} being its reconstructed value, σ_p is defined by equation 1 and σ_r is given by equation 2.

$$\sigma_p = \frac{\sum_{\text{all pixels}} (p_{true} - p_{calc})^2}{\sum_{\text{all pixels}} p_{true}^2} \qquad (1)$$

$$\sigma_r = \frac{\sum_{\text{all rays}} (r_{true} - r_{calc})^2}{\sum_{\text{all rays}} r_{true}^2} \qquad (2)$$

The closer the σ values are to zero, the closer the match between pixel (ray) concentrations of the true distribution and the reconstructed one.

RESULTS

In the single-ray experiment, the unattenuated infrared beam produced a signal of $(200 \pm 1)\ \mu V$ at the lock-in amplifier. Given that the path length of light through the box was 7 cm and the lowest detectable SF_6 concentration was approximately 14 ppm, the sensitivity of the setup was on the order of 100 ppm-cm or 1 ppm-m. When the box was filled with 2% SF_6 in air, the signal was $(34.5 \pm 0.5)\ \mu V$. Pure SF_6 in the box produced a signal that was still easily detectable: $(0.23 \pm 0.02)\ \mu V$. Thus, the highest measured path integrated concentration was 7×10^6 ppm-cm. The dynamic range of the detector is therefore approximately five orders of magnitude.

In the bench-top experiment, the same beam of infrared light used in the single-ray experiment will scan the cross section of a cylindrical plume of 0.81% (by volume) SF_6 in nitrogen. The diameter of the plume will be 10 cm. This represents a path-integrated concentration of 81 ppm-m, a value easily detectable to within 2% by the present single-ray setup.

Results of applying the computed tomography program to synthetic data are as follows: Agreement between actual and reconstructed concentration profiles for the simulated concentration data was excellent. This is evident from visual comparison of the surface plots of concentration, as shown in Figures 4a and 4b for the most challenging reconstruction, the asymmetric distribution. The reconstruction shown is the result of 171 iterations, and has $\sigma_r = 1.5 \times 10^{-6}$ and $\sigma_p = 4.4 \times 10^{-3}$. The other simulated profiles tested, all of which had radial symmetry, converged more rapidly. After only 20 iterations, all of these reconstructions had values of σ_r on the order of 10^{-7} and values of σ_p around 10^{-4}. In these cases, the plotted original and reconstructed concentration profiles were indistinguishable.

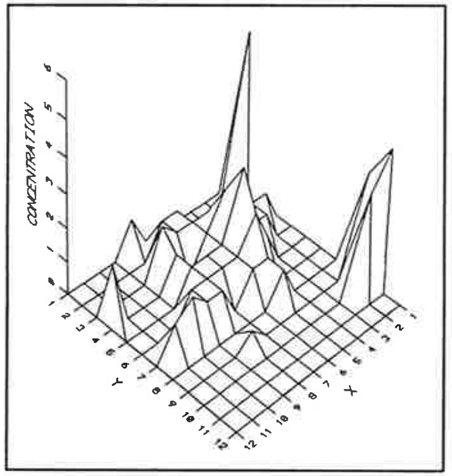

Fig. 4a. Simulated SF_6 concentration in a plane (random distribution): used to generate synthetic ray-average concentration data (units are arbitrary).

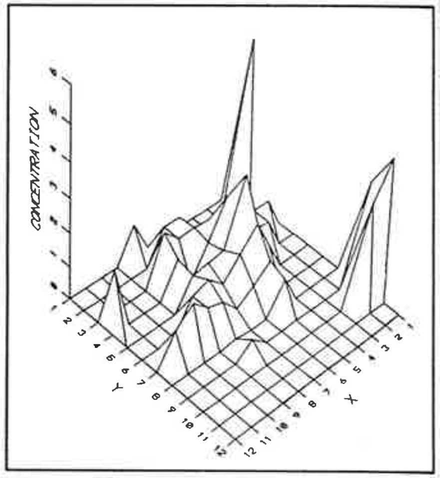

Fig. 4b. Reconstructed SF_6 concentration in a plane; from synthetic data generated from profile 4a (units are arbitrary).

DISCUSSION

The sensitivity of the infrared detector has been shown to be adequate for the two-dimensional scanning experiment we have designed. Furthermore, computed tomography reconstructions of the numerically simulated plume and other synthetic concentration distributions show that the primary features of the plume we expect to generate can be accurately determined from 'noise-free' ray-average data. Thus, the basic conditions for undertaking a successful proof-of-principle experiment have been met.

We are now in the process of constructing the apparatus that will produce the SF_6 plume and the scanning mechanism to probe it with the infrared beam from different directions. In addition, the computed tomography program will be tested for its performance with 'noisy' data. This, together with the bench-top experiment will provide valuable insight into the capabilities and limitations of extending computed tomography to room-sized applications and possibly to three dimensions.

In general, the usefulness of computed tomography in conjunction with optical remote sensing for studies of indoor air motion and pollutant dispersal will be limited by several factors. The applicability of the method will depend, for instance, on whether sufficient path average concentration data can be gathered in a short enough time to accurately follow the changes in the system under investigation. Even stationary-state situations, such as the steady release of a pollutant from a fixed position within a room having a constant ventilation rate, will exhibit fluctuations in concentration about some mean value at every point in space. The time scale of these fluctuations is critical in determining the rate at which ray path average data must be gathered for computed tomography. The spatial concentration gradients will also affect the feasibility of using this method, because they will dictate the necessary spatial sampling frequency. The critical issues raised here have been discussed recently by Yost et al. (5) based on experiments involving a continuous tracer gas release in a room-sized controlled ventilation chamber.

Applying tomographic reconstruction methods to the measurement of gas concentrations in indoor air offers many advantages. Iterative algorithms are simple and flexible: any scanning geometry can be used and information about pixel concentrations (for example, that they are always non-negative and below a certain maximum value) can easily be incorporated. The main barriers to successful, large-scale application of CT and remotes sensing in indoor air lie in the hardware for detection and scanning. Ideally, all path average concentrations would be measured simultaneously, essentially producing 'snapshot' profiles of gas distribution. However, this would require a large number of sources and detectors. Thus, either cheap detection methods must be found, or clever scanning mechanisms must be developed that do not require many sources and detectors and offer rapid scanning with minimum disruption of the air motion being studied.

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