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Use of Infrared Imaging to Determine the Mixing Performance of Supply Air Diffusers

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ABSTRACT

A technique has been developed to both visualize airflow patterns from supply air diffusers and provide quantitative information about overall ventilation jet performance. The technique provides a large number of data points in one image, can be used for dynamic flows (up to 30 images per second), does not require the use of tracer gases or particles, and can provide a quick assessment of jet behavior, airflow patterns, and jet mixing effectiveness.

INTRODUCTION

The performance of supply air jets and the distribution of air within a room are important from several aspects. First, poor distribution of air may lead to overconditioning and occupant discomfort. Poor distribution may result in either low or excessive local air velocity, temperature, or humidity and cause reduced productivity. Short-circuiting of the air outside the occupied zone increases energy use, and unbalanced distribution of air within a room will lead to occupant complaints. Second, poor distribution of air can contribute to poor indoor air quality because some areas of the occupied zone may be inadequately ventilated. Poor air distribution not only reduces the delivery of outside air to certain parts of the occupied zone but may also reduce the rate of removal of contaminants from particular locations of the room.

Typically, air distribution performance and airflow patterns have been determined by using a large number of point measurements (for example, Tuve and Priester [1944], Koestel [1955], Straub et al. [1956], and Straub and Chen [1957]). At the time, these methods were the state-of-the-art measuring techniques. However, they were cumbersome, time consuming, and labor intensive. Certain results, such as interpolating the readings, were subject to operator bias. The advent of the microcomputer and digital measurement techniques removed many of these problems. However, the results from individual point measurements are still highly dependent on sensor location and on key assumptions for extrapolating the results for an entire room. Three-dimensional effects and turbulence significantly limit the ability of these devices to accurately and quickly measure ventilation jet performance and air distribution within a room.

Distribution of contaminants in a room and measurements to determine ventilation efficiency have also relied on the use of a small number of sensors (for example, Alfonso et al. [1986], Woods [1986], Grieve [1989], Fisk et al. [1988], and Rask and Sun [1989]). The use of only a few sensors requires that large portions of the space be considered well mixed (which can lead to serious error in poorly ventilated spaces or those with transients [Heinsohn 1988]) or that a stratification factor be used (Janssen 1984). Various measures, such as decay time constant, age of air (local or exhaust), and displacement efficiency, can give an overall measure of ventilation performance in a room but cannot identify problem areas without multiple sensors (Farrington et al. 1990). Using a small number of local sensors can lead to general conclusions about air flow to a room but generally cannot provide much detail about local flow distribution and local contaminant removal within that room.

The use of a few point measurements cannot identify the complete airflow pattern within a room or the performance of a diffuser. Significant zones of poor ventilation can be entirely missed. An image-based analytical system with subsequent digitization and data analysis can quickly supply several orders of magnitude more information about the performance of jets and airflows in rooms than point-based measurement systems. The use of an imaging system leads to information on more than 50,000 locations within the room at a rate of 30 images per second. This results in a data collection rate of greater than 1.5 million pieces of information every second. Although this high speed is generally not required, it is available. The increased information is orders of magnitude greater than can be obtained by using individual sensors.

A variety of imaging techniques can be used, such as laser sheet light imaging, video imaging of visible particles, and infrared imaging. Other researchers have used either visible particles or laser-induced luminescent particles to visualize flow (Saunders and Albright 1989; Nakatani and Yamada 1986). Typically, laser imaging uses seed particles, which also cause respiratory concern and require fixed optics and a protected operating environment. Scale modeling has also been used to visualize flow within rooms (Yao et al. 1986; Farrington et al. 1990). However, there remain questions about properly scaling turbulence in these models and the effect of modeling three-dimensional flows with a two-dimensional model.

The advantages of infrared imaging include actual field measurements or full-scale testing, collecting a very large number of data points, and very rapid and visual understanding of the test results.

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PRINCIPLES OF INFRARED IMAGING

Infrared imaging detects radiation from emitting surfaces. All surfaces emit radiation as a function of the surface emissivity and surface temperature. An infrared detector determines the total radiation, sometimes termed radiosity, coming from an object. This includes emitted, transmitted (for a non-opaque surface), and reflected radiation. When determining the temperature of the surface, the reflected and transmitted energy must be subtracted from the total energy.

Radiant energy for air diffusion is in the infrared range and generally has wavelengths between 8 and 12 microns. A detector in this wavelength band would be insensitive to the lower wavelengths from higher-temperature heat sources, although it would detect the infrared portion of that radiant source. By using a bandwidth filter, undesirable wavelengths can be eliminated.

Air is transparent to infrared radiation, with the exception that water molecules absorb and emit in the infrared region and must be accounted for when absolute measurements for temperature are made if the bandwidth includes the absorption band of water. Because air is transparent, some method of detection is required. Two approaches are possible: using an emitting target or using an infrared absorbing gas. An emitting target will give a two-dimensional image of the flow, which, when moved throughout the space of interest, can provide a three-dimensional result. Using an absorbing tracer provides a volume-averaged measurement of flow integrated along a line through the gas to the infrared detector. Both of these approaches have distinct advantages (Martin et al. 1989).

One type of an absorbing tracer is an infrared absorbing gas that remains suspended in the air. Because the concentration is very low (the specific gravity of the air and gas mixture is 0.4% higher than air), as is the molecular weight compared to visible particles and luminescent particles, the gas follows the airflow path without disturbing the airflow. An infrared absorbing gas has been used to visualize air turbulence caused by objects in laminar airstreams in cleanroom environments (Schmalz 1990). One disadvantage of using an infrared absorbing gas is the need for a heat source to visualize the gas, which may cause undesirable natural convection currents. In tests that we performed, the resolution was inadequate to accurately define concentration levels needed to determine jet mixing and ventilation efficiency in a room.

The second approach is to use an emitting target such as a fiber mesh screen. We used a screen with 0.01-in.-diameter fibers and a porosity of 70%. Energy is imparted from the airstream to the screen, which then emits radiation. We corrected the result for energy transmitted through the screen and energy reflected from the screen by using algorithms that estimated the amount of radiation emitted from the environment at a constant background temperature. Additional algorithms are under development to account for applications with nonuniform background temperatures. It is also possible to digitally subtract a background image from the final image. This process corrected for nonuniformities in the background (including reflected radiation) but also had the effect of removing real thermal stratification in the room. The time constant of the screen was approximately 0.3 seconds based upon the thermal properties of the target material. The response time was fast enough to see rapid changes of the boundary of the jet, but the frequency was too low to see dynamic behavior of higher-frequency vortices.

KEY PARAMETERS FOR AIR DIFFUSION MEASUREMENTS

The comfort of an individual in a building depends on many factors (ASHRAE 1981, 1989). The effective draft temperature (Koestel and Tuve 1955) accounts for both velocity and temperature that would lead to objectionable drafts. A method called the air diffusion performance index (ADPI) uses measurements to determine the percentage of locations in an occupied zone that fall into the range of acceptable effective draft temperatures and velocities (Nevins and Ward 1968; Miller and Nevins 1969; Miller 1979). Other researchers have included such parameters as odor (Fanger 1988) and air turbulence (Fanger et al. 1988). Additional comfort parameters include humidity, clothing, personal preference, room stratification, and the mean radiant temperature.

The infrared imaging method described in this paper records information on radiant energy that can be used to determine local air temperature profiles that result from thermal mixing produced by ventilation jets. Infrared imaging and most other flow visualization techniques show either the concentration of a tracer or the thermal profile. Care must be used when inferring velocity profiles from thermal images or concentration profiles. Typically the thermal or concentration boundaries of a jet are greater than the velocity boundaries of a jet.

Diffusers are designed to promote thermal mixing of the jet before it reaches the occupied zone and to reduce the air velocity to an acceptable value. This is done through the process of entrainment by the jet of the surrounding ambient air. Entrainment brings ambient air into the jet, where it mixes with the jet air. It causes thermal mixing and reduces the jet velocity.

DESCRIPTION OF FACILITIES AND METHODOLOGY

Tests were and are being conducted in actual commercial buildings. The present facility is a one-story commercial building with dimensions of 8.5 ft by 17.2 ft by 35 ft. Our procedure is to install the diffuser to be tested in the ceiling or prepare other test arrangements as necessary, take a background image, turn on the chiller and adjust the fan to the proper flow rate, let the system come to quasi steady state, and begin recording infrared images. The image can be digitally processed, such as subtracting the background image, averaging the points, adjusting the span, or correcting for background (transmitted and reflected) radiation. The processed image can then be plotted or analyzed for temperature profiles or mixing efficiencies.

PRACTICAL APPLICATIONS OF INFRARED MEASUREMENTS OF THERMAL MIXING

We have used the infrared imaging system to determine behavior of conventional diffusers when used with normal and cold air jets. Figure 1 shows the isotherms of a ceiling jet as it remains attached to the ceiling. The ceiling jet will remain attached as long as the momentum forces are greater than the buoyancy forces (the ratio of these is sometimes expressed as the Archimedes or Richardson number). This ceiling-mounted slot diffuser was operated with an Archimedes number of 0.01244 with the characteristic dimension based upon the square root of the diffuser opening. The room temperature was 61°F and the temperature difference between the room and the diffuser was 29.5°F. Figures such as these can be used to determine the jet temperature profile, spread, and separation point. The distribution of cold air within the room can also be seen. Figure 2 shows catastrophic failure of a different diffuser as it dumps cold air directly below it. It was operated at an Archimedes number of

0.0118 with a room temperature of 77.5 °F and a temperature difference of 36 °F. Occupant discomfort would result from excessively cold temperatures and high velocities that result from poor mixing. Poor flow distribution leading to indoor air quality problems in other parts of the room would also result. A comparison of the temperature profile of the jet determined from the infrared image with the temperature profile determined from local measurements is given in Figure 3. The results from the infrared image show the effect of the boundary layer at the ceiling, which is not evident in Wilson's curve fit. Although there is greater scatter in the data than may be expected, it generally follows the expected temperature profile. Figure 4 shows velocity measurements from a hot wire anemometer probe in comparison with data from Wilson et al. (1970). These results show that the velocity profile without the screen in place follows the expected profile.

We have also studied the detailed behavior of free jets with the infrared imaging system. Figure 5 shows a cold jet flowing vertically upward from a 1-in. by 2-in. slot and impinging on the ceiling. The isotherms show stratification in the room with the cold jet overhead. This represents an unstable situation, and the cold air will flow along the ceilings and walls back to the floor. By controlling the jet parameters, the effect of distribution of the air is significantly affected.

Analysis of the infrared images can be used to estimate the effects of changing the flow parameters in a room. The sequence in Figure 6 shows the initial stratification in the room (Figure 6a), an upward-flowing cold jet (Figure 6b), and the same setup with 30% less flow rate (Figure 6c). By digitally subtracting the results of Figure 6b from Figure 6c, areas of significant differences can be seen. The numerical values in Figure 6d no longer represent temperatures but are estimates of differences, with a value of 56.7 representing little difference between the two jets. Areas with high gradients indicate possible areas with significant differences.

We are currently developing techniques to estimate the degree of entrainment by jets using infrared imaging and better measurements of temperature profiles.

CONCLUSIONS

This paper has shown the advantages of using infrared imaging and digitization to analyze jet performance and air distribution in rooms. Some key issues remain to be examined in more detail, such as the effect of the thermal screen on the air

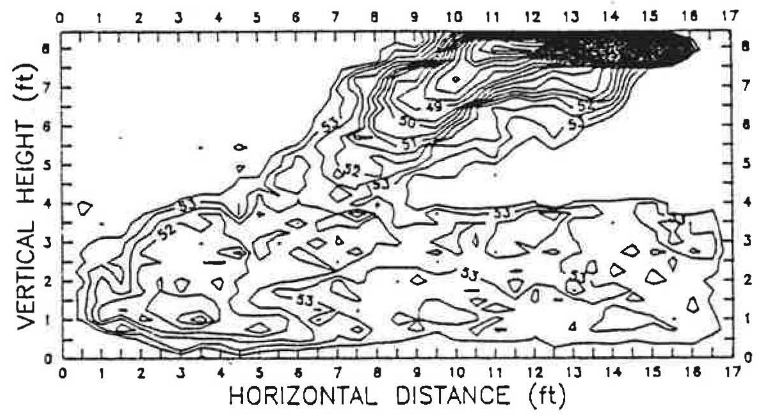

Figure 1 Isotherms (°F) of ceiling-mounted slot diffuser, Image SJ126B

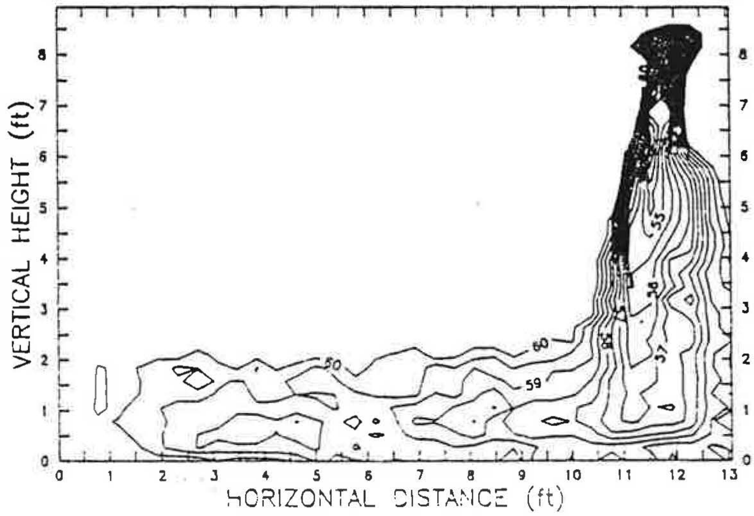

Figure 2 Isotherms (°F) of ceiling-mounted slot diffuser, Image SJ730A

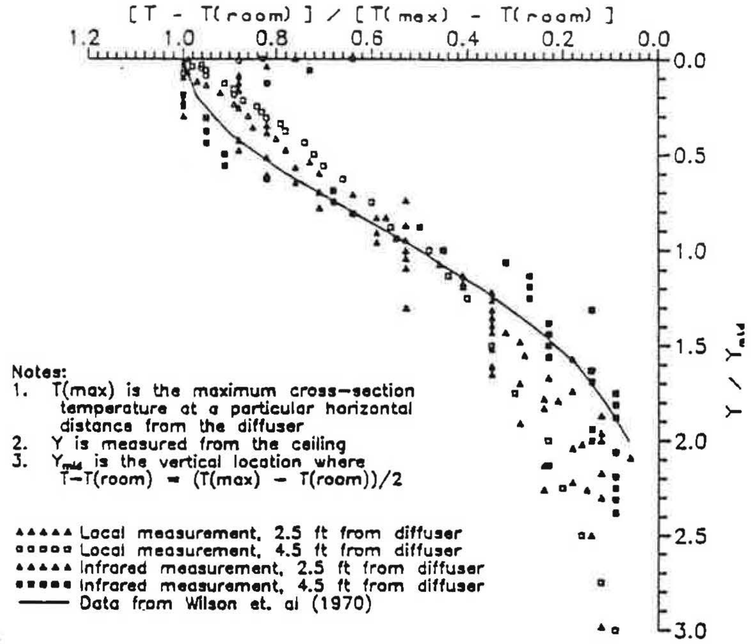

Figure 3 Comparison of temperature profiles from an infrared image and local measurements

flow in the room and the use of other types of screen materials. We are investigating the effect of the screen on the flow field by measuring the velocity field with a hot wire anemometer system with and without the screen in place. We will also be comparing the infrared results with the predictions from a computational fluid dynamics code.

The current status of the system already permits the use of this technique to determine airflow patterns in rooms and jet performance, such as jet throw, spread, and drop. Techniques are being refined that determine entrainment rates and mass mixing rates using infrared images.

HVAC engineers and consultants no longer have to rely on point measurements to determine ventilation jet performance and airflow distribution within a room. A technique is available that provides rapid evaluation of diffuser performance and room air distribution.

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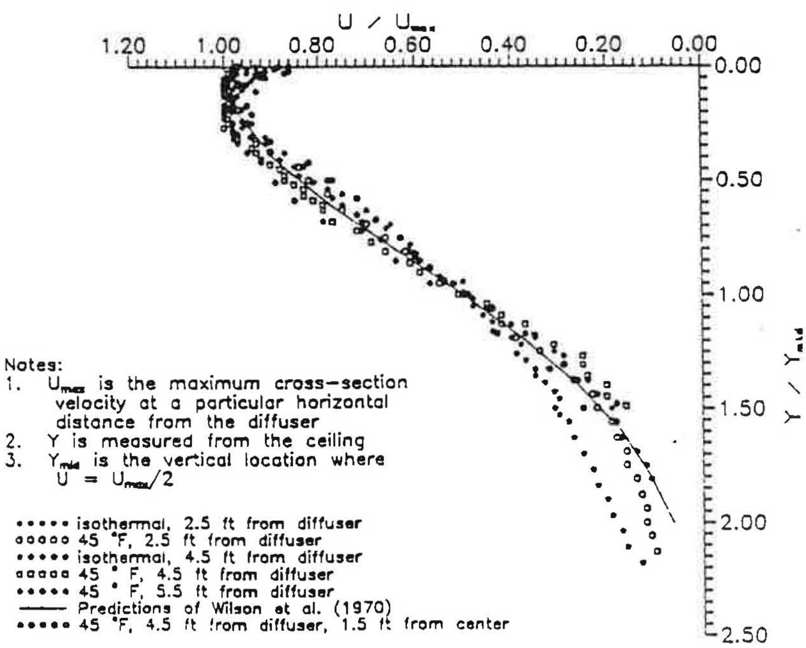

Figure 4 Local velocity measurements of a ceiling jet

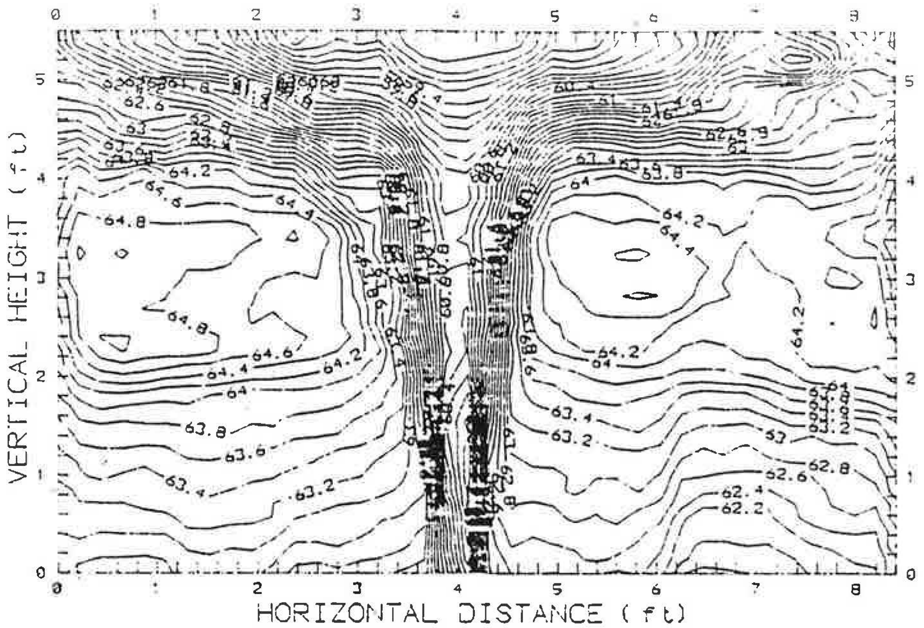

***Figure 5** Free vertical jet impinging on a ceiling*

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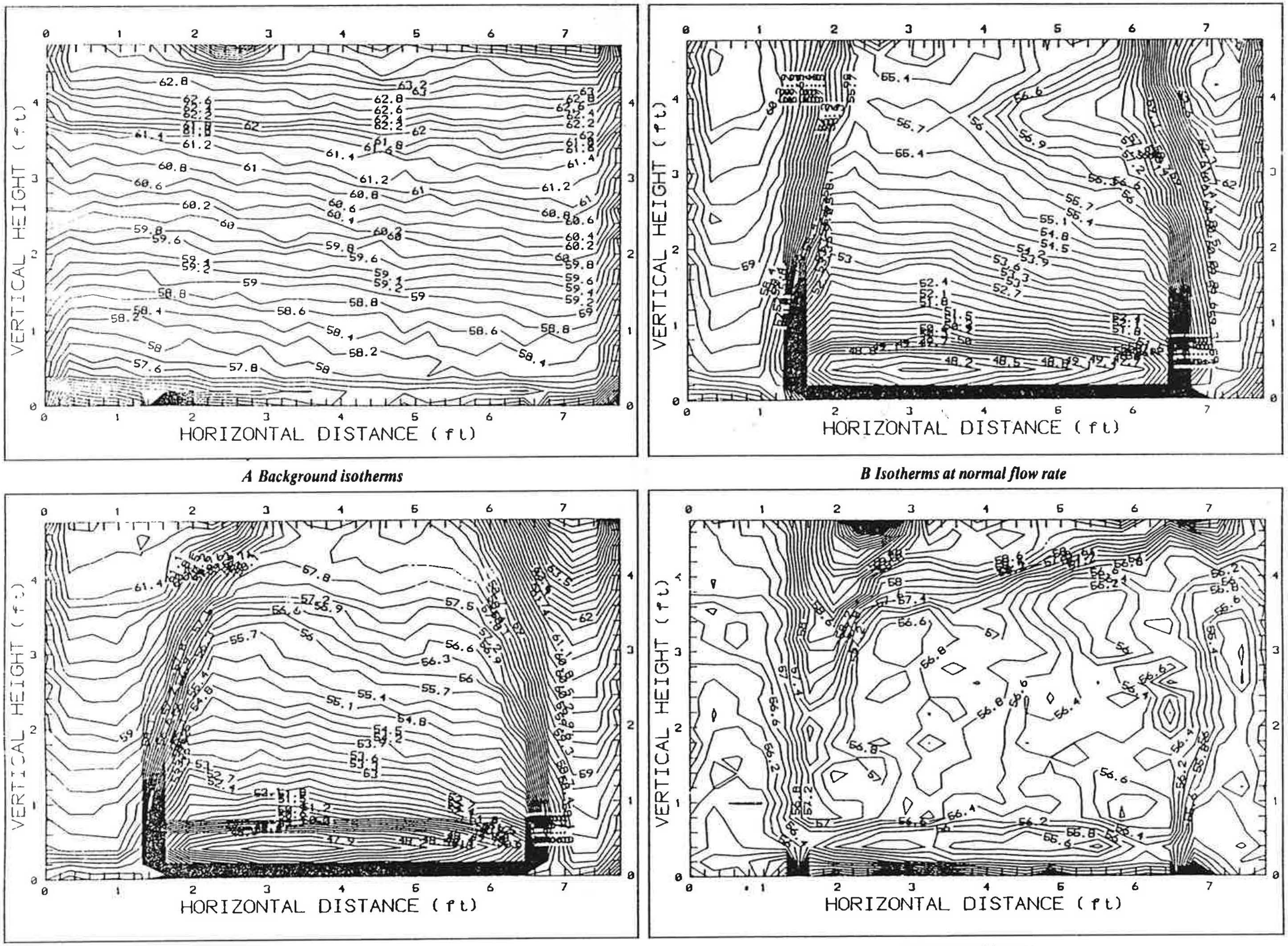

A Background isotherms

B Isotherms at normal flow rate

C Isotherms at 30% less flow rate

D Subtracted image

Figure 6 Side view of vertical cold jet

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