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Visualizing Full-Scale Ventilation Airflows

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Member ASHRAE

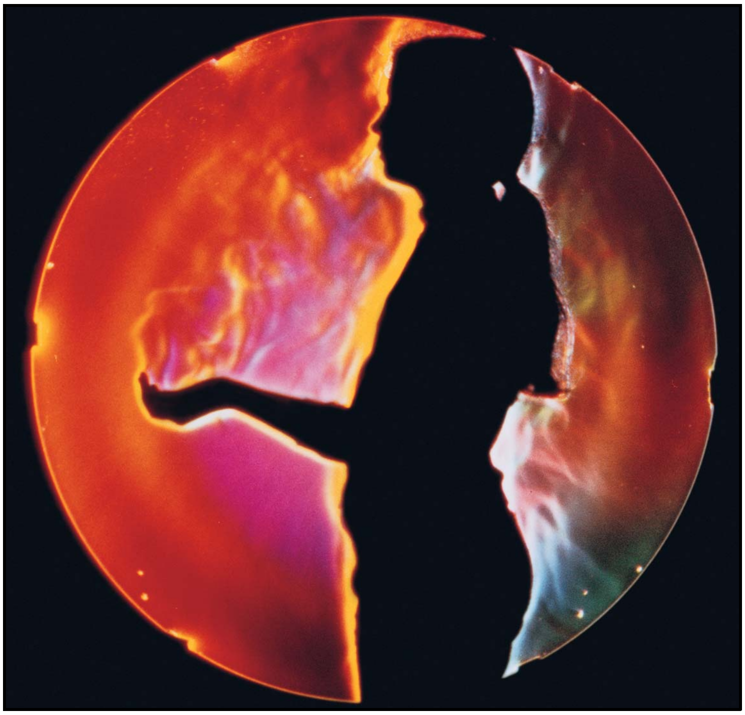

Figure 1: Schlieren photograph of the human thermal boundary layer of a teenage girl.

The patterns of airflow are central to almost everything associated with HVAC. However, since these patterns are normally invisible, it is difficult to know how the airflow is behaving and the possibility of error is significant. In many studies no attempt is made to visualize the airflow, and only conceptual sketches are drawn of how we think it behaves. This is partly due to the traditional difficulty of clearly visualizing air currents.

Most traditional flow visualization methods involve seeding the air with tracer particles. Smoke, fog, and neutrally-buoyant soap bubbles have been used. A classic study of this type was done by Daws (1970).

Unfortunately, many of the flow phenomena he describes cannot be seen definitively in his photographs.

In particular, tracer particles are not keyed to thermal differences in the flow, so what one observes often depends upon the way the particles were introduced.

The Schlieren Optical Technique

However, there is another approach which *is* keyed to thermal differences in the flow. Optical flow visualization involves no tracer particles, but passes a light beam through the flow and then examines this beam for distortions caused by temperature differences. This works because the optical refractive index of air varies linearly with temperature. Of several possible approaches, the one taken here is known as the *schlieren* technique. Its unique name is derived from the German word for streaks or striations.

Why is this technique not already used in routine HVAC airflow studies? The traditional reason has to do with scale. The schlieren technique normally requires a precise lens or mirror of the same size as the flowfield under study, which is impractical for full-scale ventilation flows. For example, *Figure 1* shows a schlieren photograph of the warm air rising from the body of a teenage girl, made visible using a parabolic telescope mirror 39 in (1 m) in diameter.

Although this mirror is part of one of the largest conventional schlieren optical systems available, it is obviously still too small and not portable enough for full-scale ventilation work. Scale-model schlieren studies have been done, but are

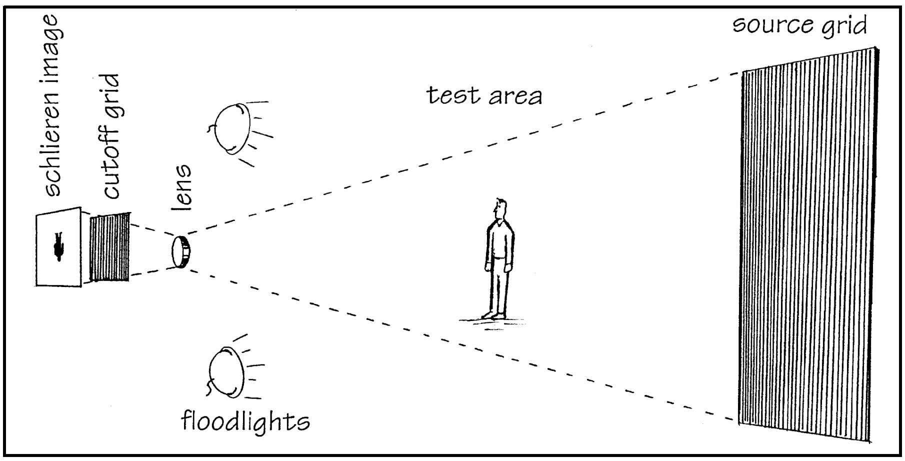

Figure 2: Diagram of full-scale schlieren optical system.

About the Author

Gary S. Settles, Ph.D., Member ASHRAE, is a professor of mechanical engineering at Penn State University and director of the Penn State's Gas Dynamics Laboratory, which specializes in high-speed airflows, experimental techniques, and industrial applications of fluid dynamics. He is currently writing a book titled *Schlieren and Shadowgraph Techniques*, to be published by Springer-Verlag.

Figure 3: A commercial kitchen griddle and exhaust hood in use with cooking fumes made visible by the schlieren technique.

Figure 4: Full-scale schlieren photograph of a domestic room with person, lamp, and electric space heater.

of limited use due to concerns about modeling and scale-up accuracy. To see full-scale airflows this way, one would first need to borrow the primary telescope mirror from Mt. Palomar!

Or so it seemed until recently, when a new approach to full-scale schlieren flow visualization became feasible. As diagrammed in *Figure 2*, one wall of a large room is covered with a uniform "source" grid made of parallel black and white lines. At the other end of the room a lens forms an image of this grid on a sheet of photographic film placed in the "cutoff" position. When the film is exposed, developed, and placed precisely back in position, it is an exact negative of the image of the source grid, with dark lines matching the white lines of the source, so little light gets past it.

If one now heats the air locally in the "test area," halfway between the lens and source grid, some light rays are refracted or bent by thermal gradients in the air. The exact correspondence between the negative cutoff grid and the image of the source grid is now spoiled. This causes some gridlines to shift so that light gets past the cutoff grid to form a schlieren image of the test area, which can be observed, photographed, or videotaped in real time. The light which thus gets past the cutoff grid corresponds to zones in the test area where temperature differences occur.

The advantage of this approach compared to that of a parabolic mirror is obvious when the source grid is made very large and the lens is small: the size of the test area can be about half the size of the source grid. Given a room of sufficient size, the test area can therefore be as large as one wishes.

A Full-Scale Schlieren Optical System

Acting on this possibility, a full-scale schlieren system has been constructed in a warehouse building. Its source grid is 16 × 18 feet (4.9 × 5.5 m) and consists of alternating 0.2 in (5 mm) black lines silkscreened on white retroreflective highway-sign material. The test area is 7 × 9 feet (2.1 × 2.7 m). Both the cutoff grid and the schlieren image are about 8 × 10 in (20 × 25 cm) in size. Powerful floodlamps are used to illuminate the source grid and the test subject for schlieren photography or videography. In effect, the entire 40 × 45 ft (12 × 14 m) building has been converted into a huge specialized camera for this purpose. The full-scale visualization of HVAC flows was one of the main justifications to build such a device. It is easily the largest schlieren optical system in the world (Weinstein, 1993, Settles et al., 1995).

The principal use of this system is for qualitative airflow visualization. Though sometimes confused with infrared thermography, the schlieren technique is actually totally different. It cannot generally yield quantitative air temperature distributions, though it is typically sensitive to temperature *gradients* on the order of 5°F/inch (1°C /cm). However, videotaped schlieren results can be used, in some cases, to extract air velocity data using an approach known as image correlation velocimetry (Tokumaru & Dimotakis, 1993). This works because typical ventilation air currents move only a small distance in the 1/30 sec between successive video frames, so the positions of individual turbulent structures in the flow can be followed in time and their velocities can be calculated. Information on the turbulence intensity of the flow might also be extracted from video this way, but this possibility is still under study.

Initial Results

This new instrument has only been in full operation for about a year. Some early results are given next, to illustrate what we have learned thus far.

Commercial Kitchen Ventilation: A gas-fired commercial griddle and front-face-discharge canopy exhaust hood were set up in the test area of the full-scale schlieren system to study the

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Figure 5: Full-scale schlieren photograph of a shopper removing a frozen pizza from a chest-type grocery store freezer.

Figure 6: Full-scale schlieren photograph of an air curtain which produces a planar turbulent jet of heated air.

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airflows associated with the important problem of kitchen ventilation. Space does not permit the details of the experiment to be given here, but a future ASHRAE paper is planned.

Figure 3 is one of a series taken during this study, in which turbulent air currents are seen by the schlieren system in relief, as if illuminated obliquely from the right. A strong buoyant plume of combustion products rises, from a slot at the rear of the griddle, directly into the canopy hood. Turbulent entrainment by this plume evidently causes the cooking fumes to be drawn into it. While *Figure 3* illustrates excess exhaust airflow, other photos with insufficient exhaust reveal a visible migration of a portion of the cooking fumes underneath the front lip of the canopy hood. Thus the important point of capture and containment can be observed visually by the full-scale schlieren technique.

Briefly, this experiment also demonstrated the stark difference in airflows between gas-fired and electric griddles, the dominant plume of combustion gases being absent in the latter. Another surprise was seen when makeup air exited through the front-face-discharge vents of the canopy hood: Entrainment by the makeup airstream induced spillage of cooking fumes underneath the nearby hood lip. Hood design flaw of this type are clearly revealed by full-scale schlieren visualization.

Room Air Currents: A typical domestic scene was set up in the test area of the schlieren system, with results shown in *Figure 4*. A person sits reading the newspaper while being warmed by the output of a small (1 kW) electric heater in the lower left corner of the figure. Buoyant plumes like this one have been diagrammed in many HVAC publications, but few have actually been visualized. There can be no doubt that such indoor airflows are fully turbulent. Transition to turbulence can even be seen in the weak thermal plume from the electric lamp bulb.

Figure 4 illustrates the possibility of many useful studies of indoor ventilation and air distribution using the schlieren technique. Entrainment, stratification, recirculating flows, wall jets, window design for draft elimination, and energy conservation studies are all feasible.

The Human Body and IAQ: Returning to *Figure 1*, the thermal boundary layer of the human body (appearing here in yellow and white) is very difficult to see with tracer particles, but shows up strikingly in schlieren images. The breath from the nose and convection from the hand are also seen. A schlieren study of airflows associated with the human body shows these flows definitely to be buoyancy-driven. Moreover the human particulate field, consisting of millions of microscopic skin scales, migrates vertically and traverses the body of a standing person, from the ankles to the head and above, in a matter of seconds. This has been misconstrued in some IAQ studies, where the term “pigpen effect” has been used to describe a presumed amorphous cloud of randomly-moving air and particles surrounding a person.

The true nature of the human thermal plume, as revealed by schlieren imagery, is important for IAQ researchers to understand. Not only are all human bioeffluents transported in this way, but also the differences often seen between stand-alone and personal particle samplers can be explained, at least in part, by the direct transport of particles from the floor to the breathing zone in the human thermal boundary layer.

Schlieren images further reveal that walking people drag columns of warm, contaminated air behind them – the “human thermal wake.” One final lesson from these schlieren observations is that one should never use a cold department-store mannequin to represent a warm human body in airflow studies.

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Other HVAC&R Applications

In addition to the examples just given, many other HVAC&R applications of the full-scale schlieren technique come to mind. For example, ASHRAE members have an interest in laboratory fume hoods, where the direct visualization of the associated airflow patterns can be quite useful. Refrigerated grocery display cases and their airflow interactions with the surrounding atmosphere can be investigated as well, using the actual full-sized equipment (*Figure 5*).

Full-scale air curtains, their entrainment of surrounding air, and their susceptibility to disruption by external air currents can be observed (*Figure 6*). Hospital ventilation schemes present special problems, like the flow recirculations caused by large overhead lights, which could benefit from schlieren visualization. Similar ventilation problems occurring in cleanrooms have already been studied using conventional schlieren optics (Settles & Via, 1986). All types of full-sized HVAC&R equipment items and their heat interactions with the surrounding air can be observed in this way.

Schlieren Flow Visualization as a Learning Tool: One learns a lot about the behavior of HVAC&R airflows from schlieren photos like those shown here. The use of such illustrations, for example, in textbooks or in the ASHRAE Handbook, would add to the impact of the flow pattern diagrams currently used. Even more can be learned from videotaped schlieren imagery, where many subtle details of the flow patterns are noticeable. It would be possible, for example, to assemble a demonstration schlieren videotape of typical HVAC&R airflow visualizations as a new learning tool. Since few of us have ever actually seen these airflows, flow visualization can be as valuable to the professional as to the student.

Validation of Airflow Computations: The ability to predict complex airflow patterns by computer is rapidly becoming more important in this field. However, since HVAC&R airflows are mainly turbulent and we do not understand the physics of turbulence, such computations remain approximate. Experimental validation is thus a continuing concern. Local validation by way of checking a few points with a velocity probe is often done, but can be misleading. Global validation, in terms of the realism of the overall computed flow pattern, can now be done by direct comparison with full-scale airflows visualized by the schlieren technique. Air velocity data extracted from these visualizations, as described earlier, is also expected to be useful in this regard.

Possible Field Use of Full-Scale Schlieren: The apparatus described here fills an entire building and is thus not portable. However, there are many applications where a portable system would obviously be useful. This requires the source grid to be made portable (e.g. folding) and the other optical components to be integrated in compact form. While it is unlikely that a system of the size shown here (i.e. with a test area of 7 × 9 feet or 2.1 × 2.7 m) can be made portable, the study of smaller portable systems is under way. One prototype has already been

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assembled elsewhere, and simplifications to overcome the clumsiness of a large portable grid and the need for precise alignment are being studied.

Related Applications

In a related application, a full-sized automobile can be positioned in the test area of the full-scale schlieren system described here. This suggests that both external and internal airflows and convective heat transfer patterns of automobiles can be observed and studied. The fumes produced by filling the gasoline tank will also be clearly visible, since they have a significantly higher refractive index than air.

This, in turn, suggests an application in industrial leak detection, which is a critical concern in the natural gas and chemical industries. Current approaches rely on optical absorption or sniffing, and tend to be quite expensive. A portable schlieren apparatus of the sort described above appears feasible, and could provide a significant advantage in cost and utility.

Finally, fire safety studies are traditionally conducted at full scale because their nonlinear combination of airflow, heat transfer, and combustion phenomena cannot be scaled up. This could be another area where full-scale schlieren visualization is useful.

Conclusion

In summary, the direct observation of full-scale HVAC&R airflows by the schlieren technique has been shown to be feasible and useful. The innovation which permits this is the use of a large grid and a small lens in place of the optical elements which formerly limited the size of the schlieren field-of-view. Thus a new tool is now available for full-scale ventilation and IAQ studies, validation of computational results, and the diagnosis of airflows created by all types of HVAC&R equipment.

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