BN-97-17-1

Schlieren Flow Visualization in Commercial Kitchen Ventilation Research

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ABSTRACT

This paper presents a new technology for capture and containment testing in commercial kitchen ventilation research. It is called large-scale focusing schlieren system and offers a nonintrusive approach to effluent flow observation. Schlieren systems can be added to conventional kitchen ventilation research laboratories or other hood testing facilities and allow continuous observation of a large area around a hood-appliance setup. This paper presents the conceptual design of an existing large-scale focusing schlieren system and some test results from this system with various kitchen appliances.

INTRODUCTION

Health and safety codes require capture and containment of grease-laden effluent from cooking processes. In most commercial kitchens, capture and containment is accomplished using an exhaust hood. The performance of exhaust hoods and the determination of satisfactory exhaust flow rates have historically been based on the subjective judgment of observers using flow visualization tools. This paper reviews the commonly used tools and introduces a new one based on an optical principle called the "schlieren effect".

TRADITIONAL FLOW VISUALIZATION TECHNIQUES IN CKV RESEARCH

In the past only methods that allow airflow observation by means of the naked human eye were used for capture and containment testing. Under cooking conditions, proper capture and containment can be analyzed through observation of cooking effluent such as water and grease vapor that is produced from the food product. This method provides good information about capture and containment of these pollutants. However, information about hot air spillage into kitchen space under appliance idle conditions cannot be gained through plain observation of the airflow. This problem can be resolved through seeding the air in an area of interest around the cooking appliance and hood with neutrally buoyant soap bubbles or theater fog. These tracers can then be observed with the human eye. Although there are several other flow visualization techniques, only these two methods were traditionally used for flow visualization. They are described in more detail below.

The Neutrally Buoyant Bubble Method

This method is based on the observation of neutrally buoyant soap bubbles that are machine produced from a soap-water mixture and helium gas. Since the bubbles are neutrally buoyant, they don't sink to the ground or rise to the ceiling but follow the air flow within the laboratory. If the air is at rest, the bubbles will remain at rest, wherever they are. During the capture and containment test, the tracer bubbles can be observed to determine the airflow pattern as it is created through natural convection and through the supply and exhaust airflow. In addition to observation under uniform illumination, this method can be enhanced with the so-called light sheet method. A light sheet is a two-dimensional plane of light that is used to illuminate only particles (bubbles) in that plane. As a result, the area of interest can be split into a series of two-dimensional planes and the resulting bubble movement can be videotaped. It is then possible to analyze the video recording and calculate the air velocity in the individual planes to create a three-dimensional flow velocity pattern. This method is known as particle displacement velocimetry (PDTV). PDTV is a very powerful tool for the analysis of stationary flow regimes. However, since scanning the individual observation planes takes time, this method is not suitable for transient flow analysis as is necessary for kitchen ventilation research. Generally this method is very vulnerable to soap bubble

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production problems because the equipment needs time-consuming fine tuning and cleaning before and during each test for proper operation.

The Theater Fog Method

In this method the air around the tested kitchen appliance is seeded with a small amount of theater fog. Differences in fog density can be used as airflow indicators, e.g., a plume of foggy air rising in a fog-free environment. Since theater fog is long-term stable, the deployed fog cloud can be traced with the human eye until it is either removed by the exhaust hood or vanishes through dilution with air. Visualization of the theater fog can be improved through illumination with a high- intensity light. A great advantage of this method over the neutrally buoyant bubble method is that theater fog can be produced at any required rate almost instantaneously. The fog can be deployed whenever and wherever it is desired during the test, and the equipment needs little maintenance. A drawback with this method, however, is that the injected theater fog represents a certain volume of additional air. As a result, it may change the airflow pattern due to its injection velocity and due to thermal expansion when mixing with the hot plume rising from the cooking appliance.

Limitations Of The Traditional Methods

Both of the previously mentioned methods present limitations for transient flow analysis because they require seeding of the air with tracer particles. This seeding process cannot be done continuously without affecting the airflow pattern. This type of measurement is called "intrusive" because the media of interest needs to be modified (seeded) to allow flow observation. Most of the previously listed limitations can be overcome with a nonintrusive flow visualization method. The schlieren method for flow visualization is nonintrusive. It is based on refraction of light as it passes through media with differing refractive indices.

Although the schlieren effect had been known for about three centuries, it is only recently that it gained popularity as a tool for flow visualization. There are two main historical reasons for its low popularity: first, schlieren images only provide mostly qualitative information about airflow phenomena (exception: velocity measurement of thermal plumes), and second, schlieren systems for large fields of view used to be extremely expensive to build because of the required large optical mirrors or lenses. Only very recently through the work of Weinstein (1991) has the second limitation been removed through the successful development of large-scale schlieren systems.

SCHLIEREN FLOW VISUALIZATION

Figure 1 illustrates the basic setup of a schlieren system according to Schardin (1970). It illustrates the physical phenomenon that is utilized for schlieren flow visualization. The essential components are a light source and two shading elements with a very sharp edge. The first shading element covers part of the light source with a knife edge and thereby creates a shadow image with a very sharp transition between light and dark. A second knife edge is placed in front of an imaging screen and adjusted to barely cover up the remaining light from the light source. This element is called a "schlieren stop." In this situation, the two straight shadow lines from both shading elements just touch each other. Any change in refractive index along the path of light between light source and imaging system will result in a "bent" light path due to light refraction. This deflection of the light will then lighten up or darken the image screen.

Although the change in refractive index of air with temperature is small, it is still possible to detect even small temperature offsets in the range of a few degrees Fahrenheit (or degrees Celsius) with schlieren systems. Other detectable phenomena are the mixing of air with other gases and other events that cause even small changes in refractive index of the

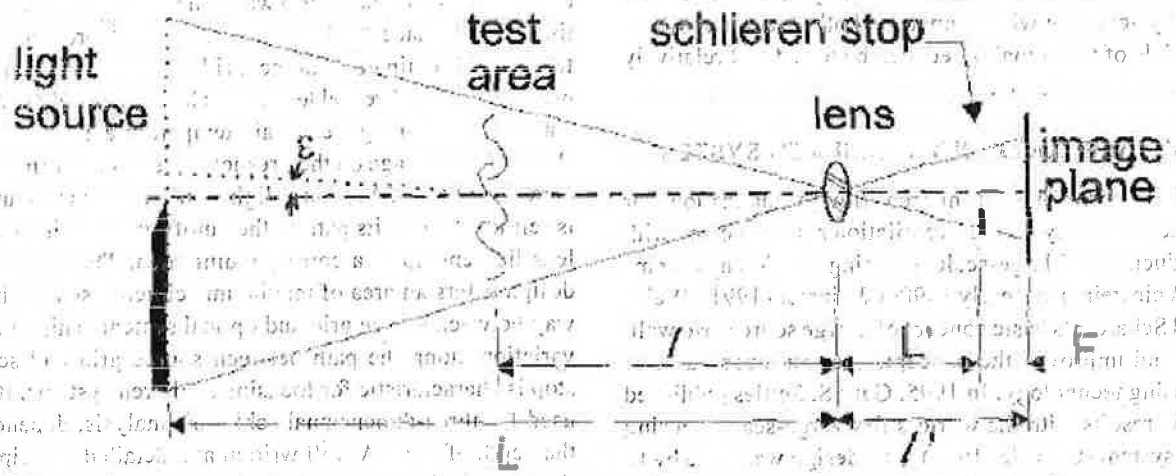

Figure 1 Basic schlieren system according to Schardin.

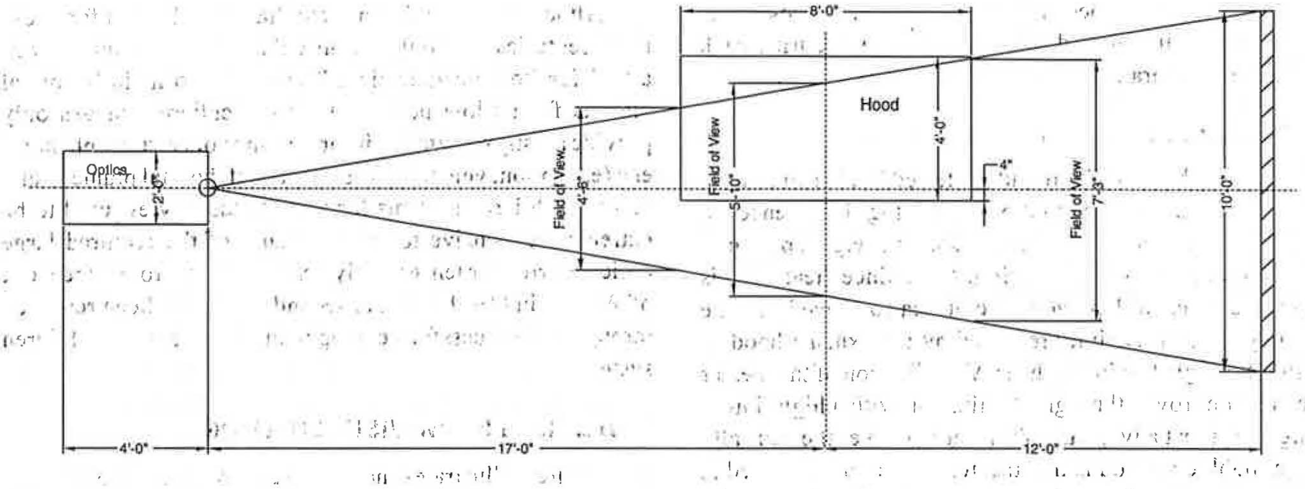

Figure 2. Focusing schlieren system setup.

penetrated media. A limitation of the schlieren system in Figure 1 is that it only provides a one-dimensional image along the line where the two shadows meet. This problem can be overcome through the scanning of an area with this system. The requirement for a scanning process and some other limitations caused the schlieren concept to be unpopular. Schardin (1970) explored several other approaches to utilizing the schlieren effect for flow visualization, including a system that uses a source grid that consists of bright and dark stripes instead of one single knife edge to obtain a two-dimensional schlieren image. However, he did not follow through, in part due to criticism of his work from the scientific community at the time. Schardin's results were neglected and other scientists developed schlieren systems that use a parallel light source or lasers to eliminate the need for scanning an area while still providing a two-dimensional schlieren view. These systems use a simple slit or point light source and a knife edge schlieren stop in addition to special optics to provide parallel light. However, the cost of these systems rises rapidly with growing image size due to the large-diameter optics that are required. As a result, the main application for the parallel light type, schlieren system is in wind tunnels and other facilities where small models of the actual object can be tested and relatively high prices are acceptable.

LARGE-SCALE FOCUSING SCHLIEREN SYSTEM

A break through in schlieren flow visualization for HVAC and especially kitchen ventilation research came with the introduction of large-scale focusing schlieren systems through Weinstein in the early 1990s (Weinstein 1991). Weinstein used Schardin's basic concept of a large source grid wall, analyzed and improved the concept, and introduced a large field focusing technology. In 1995, Gary S. Settles published a report on results with the world's first large-scale focusing schlieren system (Crowder 1995). The design was done by L. Weinstein, and G. Settles built the system in a university research facility. This system offers a schlieren test area of about 9 ft × 7 ft (2.7 m × 2.1 m), which is big enough to view entire kitchen appliances under an exhaust hood. Preliminary kitchen ventilation test results with that system demonstrated the value of large-scale schlieren flow visualization. Subsequently, a custom designed and enhanced focusing schlieren system was installed at a commercial kitchen ventilation (CKV) laboratory. Figure 2 shows the setup of the system at the CKV laboratory.

The system essentially consists of three optical components plus a video system for observation and result recording. The three parts are source grid, imaging optics, and a cutoff grid. This setup works similarly to the previously described Schardin schlieren system. The knife edge shaded light source is replaced by an illuminated wall with a pattern of highly reflective dots on black background. The reflective dots are about 0.5 in. (1.3 cm) in diameter and cover 50% of the source grid area. The entire source grid wall is illuminated through a high-intensity halogen lamp with appropriate reflectors for even brightness. An image of the source grid is projected through imaging optics onto a schlieren stop called a cutoff grid. This cutoff grid is manufactured as a photographic negative image of the source grid wall. The black spots on the negative exactly shade the bright points that are projected onto it from the illuminated source grid. The resulting image is projected onto a Fresnel lens that is located closely behind the cutoff grid. Homogeneous air temperature in the test area shows on the image on the Fresnel screen as uniform and very dark background. As soon as light coming from the source grid is refracted along its path to the cutoff grid, the image on the lens lightens up in a corresponding area. The nature of this design offers an area of maximum schlieren sensitivity halfway between source grid and optical system. This sensitivity variation along the path between source grid and schlieren stop is characteristic for focusing schlieren systems. It can be used for three-dimensional schlieren analysis, depending on the depth of field. A well written and detailed description on the topic, including equations, is given by Weinstein (1991).

The test area of the described system lies within the most sensitive area of the schlieren system. The focal area of this system can be moved back and forth by ±5 ft (±1.5 m) to allow for some three-dimensional information. Its depth of field is about 6 ft (1.8 m). If required, the depth of field for this system can be reduced through relocation of the schlieren optics box and source grid wall. All imaging components of this design, including the video system, are located inside a compact enclosure. In addition to shielding outside light, this enclosure protects delicate parts of the system from dust and spilled cooking effluent. As a result, this system is well suited for operation in a well-illuminated test kitchen environment.

SCHLIEREN IMAGE RESULTS FROM CAPTURE AND CONTAINMENT TESTS

Figures 3 through 7 show images that were digitized from S-VHS videotapes that were recorded during capture and containment tests. Since exhaust flow is a dynamic event, these still images can in no way provide as much information about the hood function as the actual moving video. However, these pictures are adequate to illustrate proper capture and containment or spillage through schlieren effect in areas where hot air is present. The presented pictures are contrast-enhanced for laser printing because this printing process limits the available color depth to about 16 gray shades. The trade-off for this enhancement is a less clear outline of the canopy hood and the appliances. Hot airlow causing schlieren effect is represented in all images as a turbulent steam jet. With increasing temperature of the air, the schlieren pattern in the image reaches higher saturation toward white and black. Faster flow and higher disturbance in the airflow are represented through a finer schlieren pattern.

The schlieren image in Figure 3 shows a six-element electric range top, operating at idle condition. A hot plume is starting right above the cooking surface. Schlieren effect allows continuous visualization of the plume until it is finally captured and exhausted through the canopy hood.

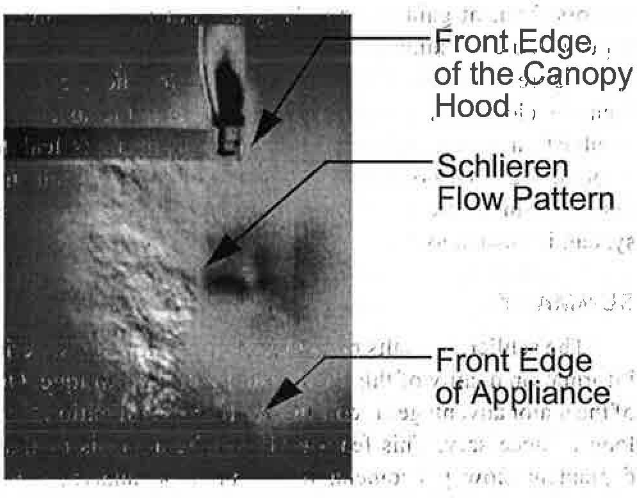

Figure 3 Proper capture and containment of a six-element electric range top at idle condition.

The fading schlieren effect toward the left side of the picture is caused through a systematic limitation of the schlieren setup. The field of view for schlieren observation is limited by an 8 ft wide back wall, as sketched in Figure 2. The system is only schlieren sensitive within the triangle between source grid wall and optical lens. As a result, the schlieren effect washes out toward the left side of the image with shrinking thickness of the schlieren sensitive area under the hood. Consequently, the system can only detect schlieren effect as far left of the image as the field of view limitation line in Figure 2 indicates.

Figure 4 pictures the electric range top from Figure 3 at a lower exhaust flow rate. Schlieren effect in front of the exhaust hood shows hot air escaping the exhaust system and entering the laboratory space. This image demonstrates a second limitation of schlieren flow visualization. As the air velocity goes down or the temperature of the escaping air gets closer to ambient, the schlieren effect washes out, as can be seen with the warm plume that rose past the front lip of the canopy hood.

Schlieren flow visualization offers only qualitative information about the air temperature. It cannot be used for absolute measurements except for observation of thermal airstreams or other tracer gases and measuring the overall plume velocity. The velocity measurement can be done through videotaping the schlieren view and then following a certain schlieren pattern over several video frames. Since NTSC video frames are recorded 1/30 s apart, it is possible to calculate a velocity from the video timing information and the traveled distance in the video image. A more sophisticated approach to velocity measurement with schlieren systems, called "optical deflectometry," has been developed (Alvi et al. 1993).

The schlieren system described is sensitive enough to visualize the thermal plume arising from a human body. That means that temperatures less than 10°F (5.6°C) above ambient

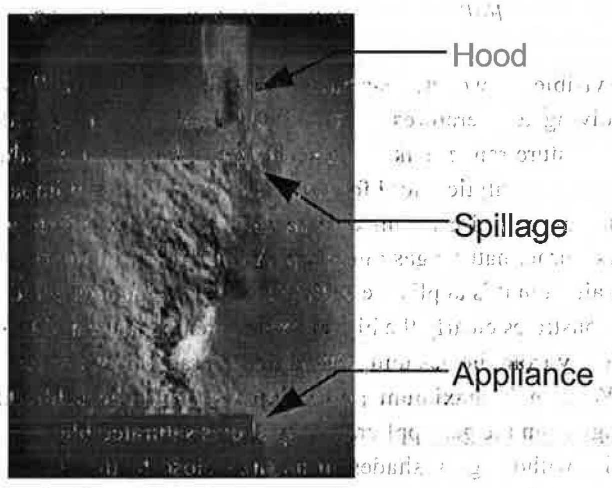

Figure 4 Electric range top with improper exhaust rate setting.

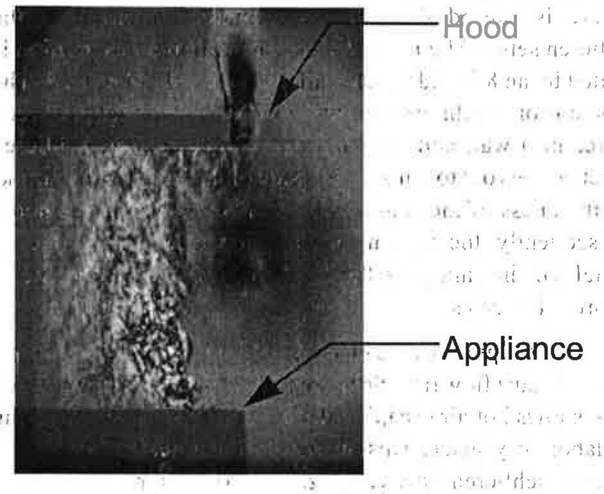

Figure 5 *Properly ventilated six-burner gas range top.*

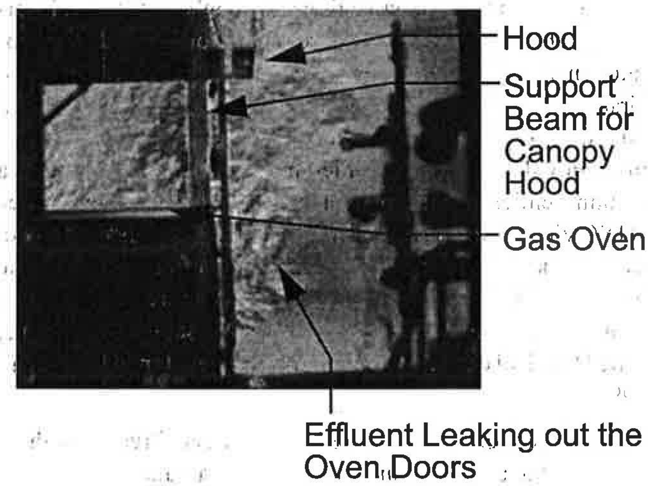

Figure 7 *Full-size gas convection oven during spillage.*

are visible. However, tests have shown that the system allows resolving temperatures up to 3300°F (1800°C). This wide temperature range makes the schlieren technique very valuable as an analytical tool for rating the environmental impact of hot air emissions from kitchen appliances. Figure 5 shows a six-burner natural gas range top. A comparison of the rising hot air from this appliance with the images in Figures 3 and 4 demonstrates clearly the higher exhaust temperature and flow velocity from the gas unit, although both range tops are set to 33% of their maximum power input rating. The schlieren image from the gas appliance only shows saturated black and white without gray shades in an area close to the cooking surface. This result can easily be understood since the flame temperature of gas burners is much higher than the temperature of heated air over electric cooking surfaces. This high flame temperature, in addition to the combustion products

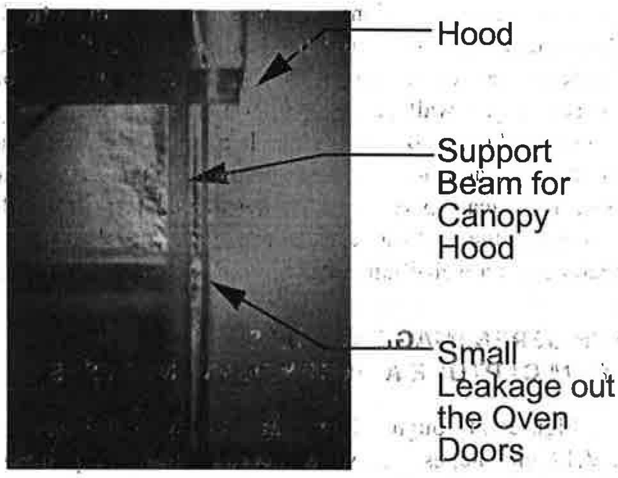

Figure 6 *Full-size electric convection oven at capture and containment.*

produced by the gas range leads to the higher exhaust requirements. In addition to determining exhaust flow requirements, the results from these schlieren images can also be used to predict the impact of appliances on the comfort level in the working environment of the operator, the cook.

One of the major advantages of this large-view schlieren system is the comprehensive view that it provides around the entire test setup. The convection oven in Figure 6, as received for testing, has a leaking front door that leads to spillage of hot air into the environment even at high exhaust flow rates. Ovens, however, are treated as low heat emissions equipment. Without this schlieren image, however, the cause is difficult to find since no other flow visualization technique that is available for kitchen ventilation research is able to show this problem so clearly. The seal was tightened and an additional gasket was inserted before additional testing was started. The equipment shown on the right end of the image are temperature sensors for heat gain testing. They are not used during the capture and containment tests.

Figure 7 shows the schlieren picture for the case of an identical electric oven model. However, due to the absence of combustion process inside the oven, less hot air is leaking through the oven doors. The outside surface of the electric oven remains cooler during operation such that the schlieren system is pushed to the limits of its sensitivity.

SUMMARY

The schlieren results presented clearly show the superior information quality of this flow visualization technique. One of the major advantages is continuous flow visualization for as long as necessary. This feature allows the analysis of time-dependent flow phenomena that cannot be analyzed with theater fog, neutrally buoyant bubbles, or other invasive visualization techniques due to seeding problems. A schlieren system offers a comprehensive view of all hot air that is present in the area of interest since it does not require any seeding. The fact that it does not provide information about spillage at the sides of the hood is a minor constraint given the air dynamics of exhaust hood systems. If required, additional tests can still be performed with conventional methods as described in the first section of this paper.

Schlieren flow visualization is nonintrusive and as a result does not influence the airflow pattern, unlike theater fog, which adds volume to the exhaust flow. However, capture and containment results that were carefully performed with theater fog do compare well to schlieren results (Swierczyna et al. 1997). But the most important advantage of schlieren flow visualization is its sensitivity to hot or polluted air. By its very nature, it focuses on the phenomenon of interest, the production and exhaustion of hot air, fuel combustion products, and cooking effluent. All of these features make schlieren flow visualization a very valuable and accurate tool for commercial kitchen ventilation research.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Wayne Krill of the Electric Power Research Institute and Mr. Charles Claar of the International Facility Management Association for the financial and technical support that made the reported research possible. Professor Gary Settles, Director of the Gas Dynamics Laboratory at Penn State University, was instrumental in demonstrating that the schlieren effect could be used in a large-scale system to visualize capture and containment of cooking effluent. Dr. Leonard Weinstein with Viewstar, Inc., was the chief architect and manufacturer of the schlieren system used at the CKV laboratory. Mr. Don Fisher with Pacific Gas and Electric's Food Service Technology Center and Mr. Joseph Knapp with McDonald's Corporation provided their extensive kitchen ventilation experience in evaluating the schlieren system performance in comparative theater fog - schlieren tests.

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