Smoke Studies: Clearing the Mystery of Air Flow Visualization

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"The Aseptic Core" discusses scientific and regulatory considerations for aseptic processing, with an emphasis on aseptic formulation and filling. This column has been developed with the intention of providing practical advice to professionals involved in the qualification of aseptic processes and myriad support processes involved. The primary objective for this column: Useful information.

Reader comments, questions, and suggestions are needed to help us meet our objective for this column. Discussion topics and case studies related to aseptic processing submitted by readers are invited. Please e-mail your suggestions to journal coordinating editor Susan Haigney at shaigney@advanstar.com.

KEY POINTS

The following key points are discussed:

- Smoke studies, or airflow visualization tests, are a key activity in the qualification, maintenance, and monitoring of an aseptic facility
- Discussions of the specific methods and techniques to conduct and record airflow visualization are not readily available
- Basic airflow characteristics for the cleanroom environment are described
- Desirable airflow in a manufacturing cleanroom is unidirectional
- Commercial cleanroom foggers are used in smoke studies
- Pictures and video taken in the manufacturing environment must be conducted with rigorous compliance to good manufacturing practice policies and procedures
- Basic photographic considerations such as "white-on-white," reflections, panning, and other techniques must be addressed in filming smoke studies
- Smoke studies are filled under static (at rest) and dynamic (operational) conditions
- Smoke studies must have specific acceptance criteria
- Narration and music may be considered in producing the smoke study video
- The final report must include basic information including results, discussion, and conclusions.

INTRODUCTION

Smoke studies, or airflow visualization tests, are a key activity in the qualification, maintenance, and monitoring of an aseptic facility (1,2). Smoke studies are conducted to confirm unidirectional airflow exiting high efficiency particulate air (HEPA) or ultra low particulate air (ULPA) filters in a manufacturing cleanroom. These studies provide visual evidence of airflow direction—a useful demonstration and diagnostic of facility performance.

Although smoke studies have been referenced for many years, discussions of the specific methods and techniques to conduct such studies have been lacking. Further, discussions of methods and techniques to

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record airflow visualization are not readily available. The author and staff started performing these tests using hot plates, water, and dry ice. When the mixture was in the correct proportions, the "smoke" output was great. It would provide enough smoke output to film a scene using a video recorder for a few minutes. Of course, while filming the scene, and after getting the proper techniques prepared, the smoke would fizzle out to nothing at the most critical moment. The end result was a video produced with frustration and with the bare requirements being met. The staff's methods and techniques improved with experience. The training and understanding of the science associated with smoke studies is critically important. The final production of the report and subsequent video was a culmination of fluid dynamics, photography, manufacturing in a clean room environment, and creativity. Photographic techniques involving lighting, background impacts, photo angles, and other techniques are vital to produce a good video.

This discussion addresses theoretical background information on smoke studies as well as practical suggestions for producing video documentation.

BACKGROUND

So why produce a smoke study and what does it tell us? Smoke studies tell you about the air flow characteristics in your International Organization for Standardization (ISO) Class 5 environment. Specifically, if you have a particle or an airborne contaminant entrained in the air within your clean room, the smoke test will demonstrate where the particle will likely move. It is desired that the particle will be driven in one direction (unidirectional airflow) past the product path and toward the floor, and then to the room air returns. Studies are typically performed with new installations or when there are changes to existing systems. There should also be periodic verification that there are no changes in a given timeframe (e.g., every two years).

Desired Airflow Characteristics Within A Class 5 Environment

The following are desired airflow characteristics with a Class 5 cleanroom environment:

- Air flow moves toward potential sources of contamination and away from the product path. As an example, HEPA (High Efficiency Particulate Air) filtered air should not flow over clean room personnel and then over the product path.
- Air should be flowing smoothly in one direction with no turbulence or eddies.
- For movement within the air stream, such as a person manipulating materials or product, air disruption should recover quickly (within seconds) to regain unidirectional flow.
- When doors are opened within Class 5 areas, air flow is disturbed and becomes turbulent as it sweeps through the air stream when opening. Smoke studies should capture the effects of the disturbance and document the air recovery to smooth unidirectional air flow.

Unidirectional And Turbulent Airflow

There are two types of airflow characteristics in the industry: unidirectional airflow and turbulent airflow. Unidirectional smoke studies are designed to demonstrate HEPA filtered air moving in one, smooth direction known as "unidirectional." These systems can be horizontal airflow or vertical airflow. As an example, in the case of a clean room application, air will typically enter the room vertically through ceiling-mounted HEPA filters at an expected velocity rate, flow through the defined work zone or space, then through the exit plane of the work area.

EQUIPMENT AND SUPPORT

There are minimal equipment and support requirements for performing a smoke study. The cleanroom fogger (Figure 1) that generates a fog or smoke from water vapor using water for injection (WFI) or deionized water is recommended. Methods for generating the water vapor fog include megasonic vaporization, steam (liquid nitrogen), and dry ice. These units are commercially available. Be careful when selecting a cleanroom fogger. There are other methods of producing smoke, but many of these methods are not suitable for a cleanroom installation. Some of these methods, such as glycol or glycerin-based smoke, are known to leave residue or activate fire alarms (2). A video camera, trained manufacturing personnel, and trained smoke study personnel are also required for conducting these studies. Training is essential for these studies. Strict adherence to procedures is mandatory.

SMOKE STUDY TECHNIQUE AND MANUFACTURING PROCEDURES

Pictures and video taken in the manufacturing environment have inherent risks. Even though the intent of the video may be the smoke study and illustration of airflow, all other aspects of the aseptic area are illustrated. For example, aseptic techniques of manu-

facturing operators, gowning, equipment setup, and all other associated activities may be scrutinized for compliance to procedures and industry expectations. Sometimes, the better the smoke studies are, the more attention the viewer (auditors) pays to techniques that are apart from the smoke study. They start looking at the implements used, the movement, proper gowning, operational speed, etc. The smoke studies can lead the investigator to raise other questions about your process from viewing the video, so it is important to be mindful of using proper technique, tools, and to follow your procedures for the process being filmed. As an example, when an operator breaches the barrier to remove a tipped vial, sterile sleeves should be worn by the operator. The sterile sleeves should cover the arms from the elbow to the wrist. If in the filming sterile sleeves are not covering the areas appropriately, the investigator can change their attention away from your airflow program to focus on questions with gowning practices, standard operating procedure review, etc.

The point here is while sterile sleeves may be inappropriately worn on the arm but have little if any impact on air flow, their improper use can implicate other aspects of manufacturing. It is vital to follow your well-established good manufacturing practice (GMP) procedures and processes during airflow visualization studies.

FILMING THE SMOKE STUDY

Photography is an art all its own. Unless this is a hobby for those involved or if there is a natural artful inclination for persons responsible for filming, it can be very tricky to record in a cleanroom environment. The following are comments on topics associated with photography and filming the smoke study.

White On White

Everything in a typical cleanroom tends to be white, such as gowning and walls. The smoke generated is often lost and becomes invisible to the camera because it is white and introduced against the white walls in the background (i.e., white on white). To overcome the issue, it is appropriate to hang a dark material in the background such as black plastic sheeting taped to the wall. This way the smoke can clearly be seen and the plastic can easily be removed and moved to other areas of filming until the smoke studies are completed (see Figure 1).

Reflections

Filming smoke in the air stream from the ceiling moving downward to stainless surfaces can also be challenging. In highly-reflective stainless areas, the surfaces can have mirror-like properties. Smoke can look like it is moving downward, hitting the surface, and then changing direction and moving upward. This is due to the reflections of the shiny surfaces of the stainless steel. To overcome this, the photographer should be aware of this phenomenon, and even film from a couple of different angles in order to present the actual airflow.

Figure 1: Smoke generator that utilizes WFI as the source. Note the black plastic sheeting that is temporarily hung in the background to aid in filming white smoke against white walls.

Source: Smoke study video. Baxter Healthcare Corporation.

Starting At The Top

Be sure to capture the area where the HEPA-filtered air is introduced, commonly at the ceiling, and slowly pan down following the smoke direction as it flows toward work surfaces and equipment. The smoke should be introduced with the nozzle pointed into the airstream. This will demonstrate that the room air supply is sufficient to carry the smoke in the direction of the airflow.

Use the zoom function of the camera to capture the area around the product path and pay particular attention to open product. Take your time in filming and camera movement. The use of a tripod can help, but often times the areas being filmed are restrictive and without a lot of room to allow for tripod equipment. Be sure to hold the camera very steady. When panning the camera, move slowly and deliberately in one direction.

Other Room Activities

Airflow studies are performed while production areas are "down" (no production activities). Because of this, there will often be competition for time in the production area for purposes of preventative maintenance, calibration, validation, training, and other activities. The team performing smoke studies will have to coordinate with others in the area to assure

Figure 2: Technician performing at-rest study under each HEPA filter.

Source: Smoke study video. Baxter Healthcare Corporation.

that movement within the facility is controlled, that doors are kept in their normal condition for manufacturing in order to protect the air pressure cascades between classified areas. The normal airflow patterns should be protected and maintained by controlling activities and ingress and egress of personnel.

Another consideration while filming is making sure others don't walk in front of the camera or disrupt the smoke study production. More typically, I've seen personnel inadvertently filmed while performing calibration or preventative maintenance activities by capturing their activities through windows or doors in adjacent rooms. The photographer needs to watch for reflections in glass (windows) and other polished materials. It can be a disruption to the viewer when instead of watching the air flow characteristics, their attentions turn to reflections showing someone on a ladder or doing something on the floor. Again, the discussions during an audit can move away from the smoke study itself, and into other areas such as maintenance access activities, etc.

Panorama

An overview picture scanning the work area can help to orient the viewer as to where they are in the process. It can also introduce the viewer to the areas of focus and the layout of the room or area. This is very helpful to capture before focusing in on a close shot of the process area of interest.

It is recommended that map floor plans and room numbers be filmed to document exactly where the study is taking place.

Angles

The Institute of Environmental Sciences and Technology (IEST) recommends maintaining not more than a 14° angle from vertical. The concern is that with a given velocity, a particulate will drop out of air control if the angle is steeper than 14°. A plumb bob is often used if the angles require a reference point or straight line to measure the angle. Refer to IEST-RP-CC006.3 for guidance and application.

FILMING THE AT-REST STUDY (STATIC CONDITIONS)

This portion of the study is intended to capture airflow without the effects of personnel or manufacturing. The areas that will be captured are walkways or corridors, equipment protrusions, and work surfaces that are a potential pathway for the product. Care should be taken to film the simulated smoke where it is introduced, typically 12 to 24 inches from the filter face, and follow the smoke cascade slowly down to the work height. It may be necessary to move the smoke supply closer to the work area so that sufficient smoke is generated and can capture the airflow patterns and their effect as the air flows over and through the equipment. The photographer will follow the product pathway and capture the smoke flowing over the equipment. It is ideal to follow the production sequence.

For long walkways, the use of a cart holding the smoke generator with a mounting bracket holding the nozzle in the correct position can help verify each ceiling HEPA filter. Be sure to capture all processing areas including sterile connections, conveyor systems, loading operations, etc. (see Figure 2).

FILMING THE OPERATIONAL STUDY (DYNAMIC CONDITIONS)

Operational testing is intended to simulate routine manufacturing activities. Two areas are captured in this portion of the study. The focus is on the effects of moving production equipment and components and human interventions.

Smoke is introduced at the entrance plane, just below the HEPA filter usually at the ceiling, and followed downward through the product path. The camera should follow the product, such as a vial moving along the conveyor system, that moves through the downward flowing smoke. There should be no turbulence or airflow bouncing off production equipment or any eddies (air moving in a circular pattern). Smoke should wash over process equipment and product pathways smoothly in one direction then continue through the work area toward the floor. Care should be taken to ensure that barrier doors and curtains remain as closed as possible to maintain the normal air movement conditions as present during manufacturing.

Simulations include the use of appropriate gowning, appropriate implements, proper techniques, and following established procedures. Movement is important because we are capturing the airflow patterns where an operator breeches the barrier and performs simulations such as removing a tipped vial, making a hose connection, and other pre-described interventions. It may be necessary to capture the scenes from a couple of different angles to fully capture the affects of airflow to dynamic conditions or to help when working in tight or constrictive areas and barriers.

The photographer should take care to film the sequence carefully to avoid sudden movement of the camera. It is best to slowly move the camera view in one direction following the product pathway. This will help the viewer follow the product path in order of processing. Use caution when zooming in and out of the scene or quick camera movements that can cause confusion or a dizzy collection of scenes. Remember the camera will ultimately be the eye of the viewer.

Doors that are accessed as part of manufacturing are also tested to demonstrate air recovery patterns after they have been opened or closed. The air pattern recovery should be within a few seconds. Doors that are not used during manufacturing, such as maintenance access doors or emergency exit doors, would be exempt from visualization studies (see Figure 3).

Figure 3: An operator intervention using proper implements and techniques demonstrated during operation study.

Source: Smoke study video. Baxter Healthcare Corporation.

ACCEPTANCE CRITERIA

The air supply should continually wash the product-exposed area, equipment, and personnel. Airflow should be unidirectional in nature and should show uniform flow patterns with minimum turbulence. Any turbulence or "dead spots" should be justified with environmental monitoring studies or other justifications.

OPTIONS

Narration and music are two options that may be considered in support of the smoke study video.

Narration

Narration adds an element of professionalism to the video. A sound track with the video production of your smoke study helps to describe what the viewer is seeing. It's a way of answering questions before they are asked. Some of the elements to be described in the video should include the study number, the date, process, the room name and number, a picture of floor plans or other diagrams that may be helpful to describe the location, what part of the process is being filmed, any anomalies that may need further explanation, and the description of the location where you are in the area being filmed. Each time a smoke study is viewed, note any questions or discussions and be sure to include those items in future smoke study presentations. Again, the goal of the video and associated narration is to have a complete description, so ultimately the viewer never has to ask questions or get clarification of what they are seeing.

The narration should be recorded separately in a quiet controlled room within a close timeframe of filming the video. It can be too disruptive to try to capture the video, perform the study, and use the proper techniques at the same time as narrating the video. The background noise of the HEPA systems may also be too loud to hear what is being said in the video.

Music

Music is an option that may add a further level of professionalism to the video. Carefully chosen, appropriate music can add a relaxing atmosphere and provide continuity between scenes. It helps to fill the void between the periods of narration. We typically use an instrumental musical loop of "elevator music style" that is played in a continuous loop. It really has no beginning or end and we use the same loop throughout the video. It is played quietly in the background and we are careful that it does not drown out the important narration.

REPORT CONTENTS

Reports typically contain the following elements:

- Study number
- Date
- Production area name
- Company name

- Results and discussion
- Conclusions.

The results and discussion, and the conclusions sections of the document are the most important sections of the smoke study final report. The report must clearly indicate the results of the work and end with a concluding statement whether or not the smoke study demonstrated the intended objective —that the laminar airflow system is validated.

CONCLUSION

Consider the following elements in your airflow visualization program:

- Predefined study
  - At-rest
  - Operational
- Predetermined acceptance criteria
- Production personnel (process experts)
- Study execution personnel (airflow experts)
- Smoke generator
- Camera
- Video editing equipment
  - Narration
  - Music (optional)
- Approved final study report.

In closing, if you take the time to plan the at-rest and operational studies, remember that the camera is representing the viewer's eye and provide an explanation (narration) of what the viewer is seeing. Using each opportunity to continually improve your airflow visualization program, you should produce a quality smoke study.

REFERENCES

1. White, Ed, "The Aseptic Core: Cleanroom Design, Construction, and Validation," *Journal of Validation Technology*, Volumn 15, No. 4, Autumn 2009.
2. Brande, David, "Clean Room Certification and Particulate Testing," *Environmental Monitoring for Cleanrooms and Controlled Environments*, Anne Marie Dixon, ed. Informa Healthcare, New York, 2007.

GENERAL REFERENCES

ISO 14644-1, *Cleanrooms And Associated Controlled Environments*–Part 1: Classification of Air Cleanliness.

ISO 14644-2, *Cleanrooms And Associated Controlled Environments*–Part 2: Specification for Testing and Monitoring to Prove Continued Compliance with ISO 14644-1.

ISO 14644-3, *Cleanrooms And Associated Controlled Environments*–Part 3: Test Methods.

ISO 14644-4. *Cleanrooms And Associated Controlled Environments–Part 4*: Design, Construction and Startup.

ISO 14644-5. *Cleanrooms And Associated Controlled Environments*–Part 5: Operations.

ISO 14644-6. *Cleanrooms And Associated Controlled Environments*–Part 6: Vocabulary,

IEST-RP-CC002.3, *Unidirectional-Flow, Clean-Air Devices*.

IEST-RP-CC006.3, *Testing Cleanrooms*. **JVT**

DEFINITIONS

At-rest (static): Condition where the effects of airflow patterns are moving as designed in a smooth, unidirectional flow, washing over equipment, without manufacturing process or production personnel.

Classification: See ISO 14644-1 *Cleanrooms and Associated Controlled Environments–Part 1: Classification of Air Cleanliness*, 1999 for classifications.

Cleanroom: A room in which the air supply, air distribution, filtration of air supply, materials of construction, and operating procedures are regulated to control airborne particle concentrations to meet appropriate cleanliness levels as defined by ISO 14644.

Cleanroom fogger: Generates a "fog" or "smoke" from water vapor using WFI or deionized water.

Dynamic (operational): Condition where the installation is functioning in the specified manner, with the specified number of personnel present and working in the manner agreed upon.

Entrance plane: Perpendicular to the unidirectional airflow located immediately upstream of the work zone and having the same dimensions as the cross section of the clean zone perpendicular to the direction of the airflow.

Laminar: Federal Standard 209E made the transition from using "laminar flow" to "unidirectional airflow." Note: Term no longer used except informally by those who previously used the term regularly.

Laminar airflow module: A unit on a bench, ceiling, wall, or work station that incorporates both HEPA-filtered air and unidirectional airflow for the purpose of providing clean air to the work zone.

Turbulent airflow: A cleanroom in which the filtered air enters the room in a non-uniform velocity or turbulent flow. Such rooms exhibit non-uniform or random airflow patterns throughout the enclosure.

Unidirectional: Air that flows in a single pass, in a single direction, through an air device or clean zone, with generally parallel streamlines.

Velocity: Part of the HEPA certification program. A velocity from 90 to 100 fpm +/- 20% (as a guideline value—higher or lower velocities may be more appropriate depending on the specific process) is generally established with a range used since the 1960s when it was mentioned in the "Non-Mandatory Appendix" of Federal Standard 209A, based on a calculation that a 5μm particle would stay airborne (settle less than 2 feet) over a distance of 20 feet in a horizontal flow clean room.

Work zone: The volume within the cleanroom that is designated for contamination-controlled operations, typically defined with an entrance plane and an exit plane.

ARTICLE ACRONYM LISTING

GMP	Good Manufacturing Practice
HEPA	High Efficiency Particulate Air
IEST	Institute of Environmental Sciences and Technology
ISO	International Organization for Standardization
ULPA	Ultra Low Particulate Air
WFI	Water-for-Injection