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Laboratory Space Pressurization Control Systems

Maintaining proper differential pressure in lab spaces is one of the most challenging tasks facing the environmental control engineer

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When choosing or designing a laboratory space pressurization control system, the engineer should consider the following topics and choices:

- Hazard assessment;
- Constant volume systems versus VAV systems;
- Differential pressure systems versus differential volume systems;
- Negative versus positive pressure requirements;
- Control signal-to-noise ratio;
- Control stability and speed of response;
- Failure mode analysis;
- Building construction impact on space pressure control; and
- Duct leakage impact on space pressure control.

Laboratories and clean rooms may require that a differential pressure be maintained between them and the adjoining spaces. This requirement may come from code considerations or from the operational requirements of the space.

For example, *NFPA-45* states, "laboratory units and laboratory work areas in which hazardous chemicals are being used shall be maintained at an air pressure that is negative relative to the corridors or adjacent non-laboratory areas. . . ."[1] This is to prevent the migration of fire, smoke and chemical releases out of the laboratory space.

Labs containing radiation hazards or biohazards may also be required by different agencies to maintain a negative pressure to contain these hazards. Clean rooms, on the other hand, are normally operated at a positive static pressure to prevent infiltration of particulates. Even if your building codes and regulatory agencies do not require pressurization, you may wish to include this feature in your facility anyway for the reasons described above.

Control strategies

The desired result of all space pressurization control systems is to control the infiltration into or the exfiltration out of a space. Space pressurization control strategies can be divided into two major categories: passive and active.

For constant volume laboratories, a passive method involves simply balancing the system so that the desired space pressurization is achieved. However, this method has *serious limitations* that should be considered carefully before choosing to design a constant volume system with passive space pressurization control. This type of system will work *only* if:

- All fume hoods remain on and at constant speed or volume at all times;
- No exhaust sources (hoods) are added or removed;
- The offsets are large enough to mask changes in exhaust and supply system performance caused by filter loading, etc.;
- The system is tested and balanced frequently to design conditions; and
- The system is adequately maintained. If you cannot guarantee (or even desire) all these restrictions, then this design approach is inappropriate for your application.

An active method for use in a constant volume laboratory involves the utilization of pressure independent, constant volume control devices in the exhaust and supply ducts to actively and dynamically adjust the flow rates to keep them constant and decoupled from system static pressure fluctuations.

VAV labs require active methods to control space pressure due to the continuously changing exhaust volume from the fume hoods and other exhaust sources. Active VAV space differential pressure control methods may be subdivided into two types: pure differential pressure measurement/control (ΔP); and differential volume or flow-tracking (ΔV).

Differential pressure systems

The ΔP method of space static pressure control is relatively straightforward; a schematic of it is shown in *Figure 1*. In this method, the differential pressure is controlled with a differential pressure sensor and a controller. The supply air volume is simply a function of the ΔP, the setpoint and the PID constants α and β.

Another similar method of static pressure control utilizes the Bernoulli principle, which states that a pressure gradient will accelerate a fluid to a velocity proportional to the square root of the pressure differential. These "pseudo-ΔP" systems utilize an air velocity probe mounted in a tube

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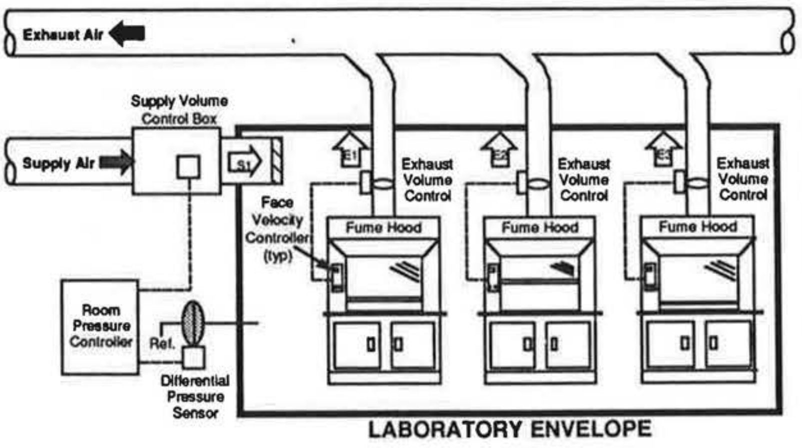


Room Supply Volume Equation: $S1 = f_{P\text{-}I\text{-}D}(\Delta P, \text{Setpoint}, \alpha, \beta)$

Figure 1. Differential pressure (ΔP) room control.

inserted into a hole in the wall between the controlled space and the reference space.

The differential pressure will induce air to flow through the tube, and the velocity of the air is sensed by the velocity probe. A controller then varies the supply air volume to the laboratory to maintain a velocity setpoint.

Differential volume systems

The ΔV method of space pressurization control utilizes analog or digital electronic controls to measure the real-time variables and solve the dynamic air balance equation. A typical ΔV system is shown in *Figure 2*.

The exhaust volume is either measured after convergence into a manifold or the individual sources are measured and summed as shown. The supply volume is then controlled (tracked) to achieve the offset.

The offset is the desired infiltration or exfiltration in cfm. A negative offset will reduce the supply volume below the exhaust volume and will result in a negative space pressure. A positive offset will increase the supply volume above the exhaust volume and will result in a positive space pressure.

Although the equation in *Figure 2* implies that the offset is a constant, in practice, it is a variable. As the volume sensors drift in accuracy, the actual offset will change.

It is necessary to choose an offset that is large enough to compensate for tight versus loose envelope construction, duct leakage, and the accuracy of the flow measuring devices. You should choose an offset using *Equation 1*:

$$\text{Offset}_{design} = 2\,\epsilon\,S\,F_{max} \qquad (1)$$

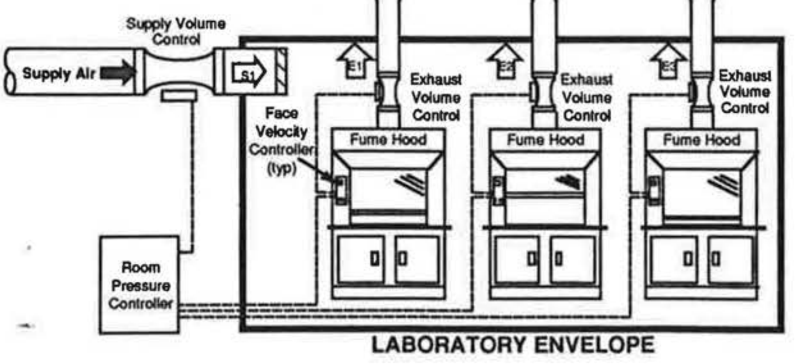
where, ϵ is the instrument error in percent of full scale or percent of reading; S is the safety factor (which depends on tightness of envelope, amount of unmeasured duct leakage and degree of laboratory hazard present; recommended range is 0.5 to 2.0.); and F_{max} is the design maximum exhaust or supply flow rate, whichever is greater.

This will assure (if the safety factor is greater than 1) that, under worst case conditions, you still have some actual offset in the desired direction of flow. For example, in a negatively pressurized lab, the exhaust flow rate will be higher than the supply flow rate, so the F_{max} is the maximum exhaust volume.

If F_{max} is 5,000 cfm (2360 L/s), ϵ is 5% (0.05), and S is 110% (1.1), then the $\text{Offset}_{design} = (2)(.05)(1.1)(5{,}000) = 550$ cfm (260 L/s). Therefore, the worst case scenario would be a system where the exhaust volume reading is 5% below actual, and the supply volume reading is 5% above actual, giving a total air flow error of +500 cfm (+260 L/s). If the design offset is −550 cfm (−260 L/s), then the *actual* offset will be −50 cfm (−24 L/s).

Normally, air flow errors are random and will tend to cancel. In large labs with multiple flow measuring instruments, you would expect the total error to be less than the maximum cited in the example. If this is the case, and there is minimum duct leakage, the laboratory envelope is very tight, and the laboratory hazard is low, then a safety factor less than 1 may be appropriate.

In any case, verification of actual operating ΔP and tuning of lab offsets should be done at a predetermined frequency based on the level of hazard in the laboratory. A maximum of six months between offset calibrations is recommended.



Room Supply Volume Equation: $S1 = E1 + E2 + E3 + \ldots En + \text{Offset}$

Figure 2. Differential volume (ΔV) room control.

Hybrid systems

In laboratories containing extremely toxic or infectious agents such as Biosafety Level 3 or 4 laboratories, it may be prudent to utilize both a ΔP and a ΔV system to assure that an adequate differential pressure is maintained at all times.

The most common way of doing this is to design a basic ΔV system as previously described, and add a ΔP sensor and controller that are used to reset the ΔV system offset. Here, the long time delays required to produce an accurate average do not affect the response speed of the system.

The ΔP system can dynamically calculate an appropriate offset. As the characteristics of the room change (such as duct leakage and envelope tightness), the offset will change (it usually grows) to maintain the desired laboratory space pressure.

Once the offset has grown to a predetermined value, it may be necessary to recalibrate flow measuring instruments, seal ductwork or seal bypasses in the laboratory envelope to bring the system back into specification. Monitoring the offset in a hybrid system of this type is a good way to monitor the integrity of the total duct/control/envelope system.

Stability versus speed of response

ΔP and pseudo-ΔP control schemes have certain characteristics that the designer/owner must be aware of. A reasonable pressure differential to maintain using normal construction techniques is approximately 0.01 in. wg (2.5 Pa).

To put this into perspective, 0.01 in. wg equals 0.00036 psi (0.0025 kPa). This is an extremely small pressure differential (signal) to measure, and providing adequate calibration for the instrument is also difficult.

The fluctuations (noise) in this signal —which are caused by the opening and closing of doors, people traffic, elevators, stack effects and atmospheric disturbances like wind—are on the order of 0.1 in. wg (25 Pa). This represents a signal-to-noise ratio of approximately 1:10.

Imagine trying to determine the level of a lake to within an inch when the waves are a foot high. To do so, it would be necessary to average out the wave crests and troughs. It can be done, but it takes lots of time.

If you want great accuracy, you have to average over a long period of time. If you need to respond quickly to the signal, then you cannot be as accurate. Accuracy and speed of response are in direct conflict.

For true stability in most ΔP systems, the response time is usually measured in minutes. Therefore, many of these systems and instruments sacrifice stability for speed and may oscillate about the setpoint for quite some time before settling down to stable control. Unfortunately, this settling period is often greater than the frequency of upsets and the controlled device may oscillate all day long until everyone goes home.

Pseudo-ΔP systems that measure the air velocity are somewhat faster and more stable because the velocity signals and noise are proportional to the square root of the differential pressure. This improves the signal-to-noise ratio to approximately 1:3. This simple change in the measured variable improves the system performance by a factor of three.

However, the noise is still about three times as large as the signal and you still may wait as long as 60 seconds for marginally stable output after an upset in the space pressure. The performance of this type of equipment varies from manufacturer to manufacturer and care should be exercised when selecting them for your facility.

Another undesirable characteristic of both of these pressure measuring devices is that the measured variables (pressure or velocity) totally disappear when the laboratory door is opened. Some controllers have the ability to freeze the output for a predetermined time delay to compensate for this.

However, if the door is left open long enough, the pressure control system will start to shut down the supply volume to bring the space back to a negative setpoint. When this occurs, the air from the hallway flows into the open laboratory to replace the exhaust air and the hallway pressure may drop.

Other lab pressure controls that use this hallway as a pressure reference may also start to close down the supply air to their labs, thereby creating a cascade effect. As more air is drawn into the affected labs from the hallway, the pressure will continue to drop even more. As you can imagine, this can cause serious building pressure problems.

However, for facilities not requiring critical room pressure control, where the effects of settling time and stability are not an issue from a hazard assessment standpoint, and where the HVAC system and architectural designs can minimize the cascade failure effect mentioned above, this control system may be used with some success.

In comparison, the signals from flow measuring devices in ΔV systems are on the order of 1,000 cfm (472 L/s) and the noise is on the order of 100 cfm (47 L/s), resulting in a signal-to-noise ratio of approximately 10:1. This allows a much more accurate, stable and rapid response to changing inputs which are characteristic of a VAV laboratory.

However, all air flow measuring devices are not created equal. For example, there are types that employ arrays of hot wire anemometers. These are very accurate and have a relatively wide turndown, but they are sensitive to build-up of particulates and corrosives on the sensors, which affects their response time and reliability.

Averaging pitot-tube arrays have a similar problem with build-up plugging the sensing ports and causing non-averaging response. They are also extremely inaccurate at low velocities due to the exponential nature of the velocity pressure signal.

A velocity sensing technology that has been used for years to measure liquids is now being applied to air flow stations. It is called vortex shedding, and it is appearing in some newer laboratory pressure control systems. There is some debate over the theoretical accuracy of these devices at large turndowns due to reynolds numbers, but field testing will prove if these devices can be effective in ΔV control systems.

There is also a device on the market that controls volume flow using a linearized, pressure-independent control valve that provides electronic flow feedback based on the valve position. Although it is more of an integrated air flow metering device as opposed to a flow measuring station, independent sources have verified the accuracy of the flow feedback using backup instrumentation. The author has used these devices successfully in many laboratory facilities.

Other design considerations

Construction techniques can also influence the performance and effectiveness of space pressurization controls. Loose construction makes it difficult to establish an effective differential pressure in the space and large offsets are necessary to compensate.

When large offsets are used (pulling in large amounts of secondary air from adjoining spaces), temperature and humidity control problems may result. Plugging all the holes and bypasses in the laboratory envelope during the renovation or construction process may be required to eliminate this problem.

Duct leakage may also affect the accuracy and performance of ΔV systems. Air leaking out of or into the duct system between the flow measurement device and the laboratory envelope can result in significant error. In constant pressure systems, this error may be relatively constant as well; but, if the system static pressure floats, then the error will float also.

The author recommends that supply and exhaust ductwork be specified and leak tested to allow a maximum of 0.5% leakage. This is easily achievable by most contractors with some practice and guidance in duct sealing and construction techniques.

Using welded and/or flanged and gasketed duct construction can make ducts virtually leak-free. Also, placing flow measuring devices close to the wall penetration in a tight section of duct is recommended because it minimizes errors by reducing the duct length where leakage affects the flow measurement.

Assuming that the flow measuring device is located *inside* the laboratory envelope, leakage that occurs upstream of the exhaust flow measuring device and downstream of the supply flow measuring station has already been measured and should not effect the error.

Cost comparisons

Due to their simplicity, the ΔP and pseudo-ΔP systems will typically cost less than a ΔV system for the same laboratory. How much less depends on the size and complexity of the laboratory ventilation system and the type of fume hood controls.

As the number of measured and controlled devices increases, so will the differential cost. If exhaust and supply volumes are measured at only one position each, the cost differential will decrease.

However, if you have chosen VAV fume hood controls and general exhaust controls that have flow measurement capability built into each, then only a supply air flow measuring device and controller are needed to complete the system. In this case, the cost of the two systems may be negligible. It is difficult to divorce the cost of the space pressure controls from the cost of the fume hood controls because they are often integrated.

Failure modes and symptoms

The easiest way to assure proper space pressurization control system operation is to monitor it with sensitive equipment that has been properly calibrated and to provide alarms to alert personnel when conditions are outside specifications.

One simple qualitative measure of space pressurization control system effectiveness is smell. If you can smell the chemicals that are used in the laboratory when you are in the corridor, this may indicate that your space pressurization controls are ineffective. It may also mean that contaminated air from the laboratory is being reingested back into the building air supply due to inadequate stack design. In the case of a clean space, excessive particulate counts may indicate a space pressure problem causing infiltration.

Another simple experiment that can be done quickly and easily is the foot-in-the-door test. Specifically, open the lab door and place your foot in the doorway next to the jamb and allow the door to close against it. Next, feel the air flow through this opening with your hand, or use a smoke tube to determine its direction.

This test is not quantitative, but it will sure tell if the lab is positive when it should be negative (or vice versa), or if there is an excessive pressure differential. If either of these conditions are detected, then a more quantitative approach should be used to diagnose the magnitude and cause of the problem.

Failure mode analysis

During the design of the laboratory environmental control system, a careful analysis of the failure modes of each component and the effect of a failure on the operation of the system should be undertaken. There are many methods to do this, most of which are beyond the scope of this article.

One of the more popular methods is called a fault tree analysis. This method may be used on entire systems, subsystems and individual components. For example, if attempting to do a fault tree analysis on a room pressure control system, choose the component you wish to analyze, such as a through-the-wall velocity sensor. List this at the top of the tree. Next, consider all of its failure modes and list them underneath.

Next, for the most serious failure modes, consider all the effects on controlled components and other coupled and decoupled systems and list them underneath that mode. Repeat this process until all the paths are complete. It may be necessary to do all branches of the tree to discover which paths represent the worst scenarios.

When all failure modes of all components, subsystems and systems have been completed, you can make some strategic design modifications to eliminate or ameliorate the most serious scenarios. For example, you can install more reliable components in key locations or install redundant controls or systems to provide back-up and thus truncate the fault tree.

Hazard assessment

Before choosing a space pressure control system, the design team should assess the hazards present in the laboratory and choose a system that is appropriate given its failure modes, the level of hazard and the level of risk that the owner is willing to accept.

The laboratories chapter of the 1991 *ASHRAE Handbook—Applications* is currently being rewritten for the 1995 volume.[2] The first section of this chapter is entitled "Risk Assessment."

During a discussion of this topic by the Handbook Subcommittee of ASHRAE TC 9.10 (Laboratory Systems), it was decided that the words *risk assessment* and *risk analysis* were often mixed up and misinterpreted. Furthermore, the word *risk* has certain legal definitions associated with it.

The general opinion of the subcommittee was that risk analysis, if interpreted literally, involves the assimilation of hundreds of pieces of design and hazard information as well as the calculation of the probable frequency of accidents and the probable results of those accidents using experience and/or actuarial data.

The subcommittee felt that most mechanical engineers were not qualified to perform an analysis of this type and that it should be undertaken by the owner who is probably more familiar with the specific hazards and processes in the laboratory than the laboratory designer could ever be.

The designer should, of course, participate in the exercise to supply data about the facility and systems design and their

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impact on the risk of operating the facility, including the space pressurization systems.

Accordingly, the title of this *Handbook* section has now been changed to "Hazard Assessment" because the discussion of risk was considered to be beyond the scope of the chapter (and this article).

Conclusion

There are many types of space pressurization control systems, methods and equipment to choose from. You can make your decision based on instinct, vendor data, your own experience, objective testing, or by seeking advice from a laboratory consultant.

The instinct and vendor data methods involve more risk than some engineers are comfortable with. User experience is the least risky option, but only if you have the experience with the equipment. Objective testing provides excellent results but is expensive and time-consuming. Seeking advice from a laboratory design consultant will cost less than objective testing and much less than replacing equipment that does not meet owner specifications.

However, the equipment is only one piece of a complex puzzle. The design of the laboratory envelope, its layout and the supply and exhaust systems all interact in an intricate fashion.

An experienced laboratory consultant can also lead you around the pitfalls, help avoid common problems and show you how *all aspects* of the facility affect its performance and help assure that the laboratory facility operates as safely and efficiently as possible. ■

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