ASHRAE Journal

ROOM PRESSURE FOR CRITICAL ENVIRONMENTS

By Brian Wiseman, P.E., Member ASHRAE

An HVAC design area that has not yet developed a standard "rule-of-thumb" is the quantitative determination of differential pressure and airflow for "proper" room pressurization. This article investigates current design guidelines and field practices for room pressurization. In particular, the author explores current literature that addresses the definition of "proper" pressurization.

The article then examines some practical in-field design considerations for two types of facilities, a tuberculosis BSL-3 research lab and a health-care hematopoietic stem cell transplant unit. In addition to field tests, the author provides a methodology for practitioners for verifying airflow direction, into or out of the room. The author concludes with recommended guidelines or "rules-of-thumb" values that may be a useful reference in designing rooms that require a proper negative or positive pressure.

Review of Literature and Guidelines

Chapter 12 in the *2001 ASHRAE Handbook — Fundamentals* provides a good treatise on air contaminants. Common room contaminants to be contained include airborne/aerosolized infectious diseases in hospitals and vivariums; chemical and biological spills in laboratories; and explosive dusts in manufacturing facilities.

Common rooms that strive to exclude contaminants include protective isolation rooms in hospitals for immunocompromised patients; clean rooms for industrial and pharmaceutical manufacturing; barrier rooms for nude mice in vivariums; and food-processing rooms in a food supply facility. The method to achieve directional airflow is via the control of the supply and exhaust airflows within and adjacent to the concerned room.

The salient question is how much the differential airflow should be to achieve "proper" room pressurization/directional airflow? This leads to the prerequisite question: What is "proper" pressurization/directional airflow?

Room Pressurization Fundamentals

Room pressurization depends on the ability of air to build up within a room. The leakage into or out of room is a key factor. Chapter 26 of the *2001 ASHRAE Handbook—Fundamentals* presents a leakage function relationship that correlates a room or building envelope air leakage to the differential pressure producing the flow.

ASHRAE defines the leakage function with the presentation of the "power law equation" (Equation 32) as:

$$Q = c(\Delta P)^n$$

About the Author

Brian Wiseman, P.E., is president of Airflow Direction Inc., Saugus, Mass.

where Q is the volumetric rate of flow through an orifice. C is a flow coefficient that depends on the geometry of the orifice. C is empirically determined using a fan pressurization test, similar to the duct leakage test performed by air balancers. ΔP is the pressure differential across the orifice and n is the pressure exponent, commonly around 0.65 per ASHRAE. *Figure 1* shows the characteristic "infiltration curve" that represents the power law equation. Thus, if the gaps around a closed door and gaps to adjacent spaces are modeled as an orifice and you know: a) the differential pressure you want to obtain, b) the geometric coefficient of the gaps, and c), the empirical exponent n, you can calculate the differential airflow. However, what is the required differential pressure and related differential airflow to "properly" contain or keep out contaminants?

Recommended Differential Pressure

The Centers for Disease Control's "Guidelines for Preventing the Transmission of Mycobacterium Tuberculosis in Health-Care Facilities" states a minimum differential pressure ΔP of 0.001 in. w.c. (0.249 Pa) is required to achieve a directional airflow into or out of a room. However, this value is challenged as insufficient based on potential thermal stratification in a room, room supply air diffusion and, as this article will show, door swings and eddies.

Chapter 15, Clean Spaces, in the *1999 ASHRAE Handbook — HVAC Applications*, states a differential room to corridor pressure ΔP of 0.05 in. w.c. (12.45 Pa) is considered to be a widely used standard.

The American Institute of Architects' "Guidelines for the Design and Construction of Hospital and Health Care Facilities" states a minimum ΔP of 0.01 in. w.c. (2.49 Pa) differential is required.

Inside of a positive pressure isolation room.

When Ahmed, Mitchell and Klein[1] simulated a model of the dynamics of laboratory pressurization, they used a ΔP of 0.05 in. w.c. (12.45 Pa) based on three references in their article.

Burns and Milburn[2] researched regulatory authority for required differential pressures for biological facilities. They found no quantitative values of pressure in the Federal Standard 209C through E (currently cancelled and replaced with ISO 14644) and current good manufacturing practices (GCMPs) defined in federal regulations 21 CFR, parts 210 and 211 (Federal Register 1995). Burns and Milburn did find a 1987 U.S. Food and Drug Administration publication that stated a ΔP of 0.05 in. w.c. (12.45 Pa) is acceptable.

Recommended Differential Airflow

Aside from the previous references, the author made other initial searches of quantitative references on room pressurization/directional airflows. The search included ANSI/ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality*; the *1999 ASHRAE Handbook—HVAC Applications*, Health Care Facilities; and the National Research Council's "Prudent Practices in the Laboratory," Room Pressure Control Systems. Each of these references provides a good qualitative description of room pressurization. Particular attention is drawn to the *ASHRAE Handbook,* where the qualitative pressure relationship of many types of rooms are detailed and act as a good reference. However, a quantitative guide was not found for differential airflows to achieve room pressurization/directional airflow.

The American Conference of Governmental Industrial Hygienists (ACGIH) *Industrial Ventilation, A Manual of Recommended Practice* addresses a quantitative design differential airflow. It states "the *proper* flow differential will depend on the physical condition of the area, but a general guideline would be to set a 5% flow difference but no less than 50 cfm (24 L/s)" (emphasis added).

The American Industrial Hygiene Association (AIHA) publication "Clarifications of ANSI/AIHA Z9.5 Standard for Laboratory Ventilation takes a position that controls using room differential airflow setpoints are preferred over controls that use room differential pressure. The text suggests a 10% offset between the supply and exhaust airflows and notes this value has no general validity. The text focuses on the containment or exclusion requirements of an open door versus a closed door and the effect on the overall differential airflow to obtain a 50 fpm (0.254 m/s) velocity through an open door.

The text suggests and rightly so, that an open door design criteria is impractical considering a 3 ft (0.9 m) × 7 ft (2.13 m) door would yield 1,050 cfm (495 L/s) makeup air through the door. Often, most communicating corridors are egress corridors and for smoke control purposes, most building codes pro-

hibit the communicating corridor from providing any significant transfer air to the adjacent rooms. Therefore, the high air volume required to contain or keep out contaminants through an open door would violate the code.

The text suggests the use of an airlock for critical applications, thereby obviating the potential for a continuous open door path from the room to the communication corridor. As seen later in this article, an airlock or anteroom is a good idea.

A National Institutes of Health (NIH) publication, *Research Laboratory Design Policy and Guidelines,* recommends a minimum of 94 cfm (44 L/s) of negative makeup air per lab module to adjacent non-lab spaces.

So far, in search of a design differential airflow to put on the drawings, it seems that a 5% to 10% differential cfm is an accepted guide. However, what about the air balancer who has a 5% to10% balancing tolerance? Is a design airflow differential of 5% to 10% enough? In a typical health-care infectious isolation room, a minimum of 12 total air changes per hour (all air exhausted out of the room) is recommended in the AIA/HHS "Guidelines for Design and Construction of Hospital and Health Care Facilities." A typical 12 ft (3.66 m) × 12 ft (3.66 m) room by 8 ft (2.44 m) ceiling would have 230 cfm (109 L/s) of exhaust air. At 10% differential, the supply air would be a maximum of 207 cfm (98 L/s). The air balancer could set the supply to 228 cfm (108 L/s) and the exhaust to 207 cfm (98 L/s) and the room would be positive. The project specifications, of course, must dictate a +0%/–10% for the supply and +10%/–0% for the exhaust. But is 23 cfm (11 L/s) of makeup air enough for a 12 ft (3.66 m) × 12 ft (3.66 m) infectious isolation room?

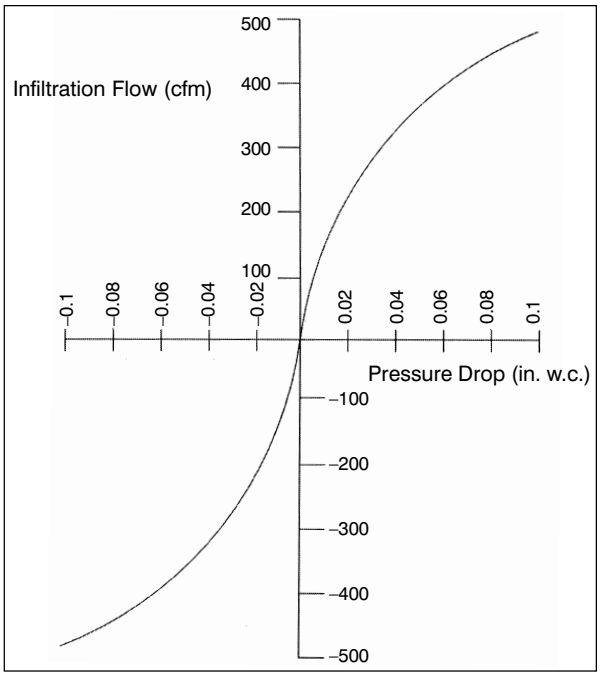

Figure 1: Infiltration curve (power law equation).

Review of Applied Practices

Differential Airflows and Pressures

Ahmed, et al.[1] applied ASHRAE's power law equation in their modeling analysis of the dynamics of laboratory pressurization. Ahmed also calculated a typical leakage value for K =1,000, which Ahmed finds represents a moderately tight envelope. Ahmed found for a typical laboratory module of 30 ft (9.14 m) × 25 ft (7.62 m) by 10 ft (3.05 m) ceiling, maintaining 0.05 in. w.c. (12.45 Pa), a K value =1,000, the differential airflow theoretically should be 153 cfm (72 L/s) through the closed door gaps leading into the room. Coogan[3] applied the same modeling approach as Ahmed and found that the infiltration curve described in ASHRAE is a good approach. Values between 150 cfm (71 L/s) and 300 cfm (142 L/s) were found to "properly" achieve a negative pressure relative to the adjacent rooms.

Dale Hitchings[4] offers the equation: $\text{Offset}_{\text{design}} = 2\ \varepsilon\ S\ F_{\text{max}}$ where the offset is the differential airflow cfm, ε is the instrument error for measuring the airflows (typically 5%), S is a safety factor between 0.5 and 2.0 (typically 1.1) and F is the maximum designed supply or exhaust flow rate. For a lab exhausting 5,000 cfm (2360 L/s), the offset would be 550 cfm (260 L/s). The author finds that in a typical 500 ft^2 (46.45 m^2) lab module with one door and a 1,000 cfm (472 L/s) fume hood exhaust, the transfer would equate to about 110 cfm (52 L/s) through the door to the lab.

Kenneth Gill[5] has found that 75 cfm (35 L/s) to 100 cfm (47 L/s) makeup air through one door to a negative healthcare patient isolation room works well. This range allows 100 fpm (0.508 m/s) minimum through typical openings such as the door undercut. Gill[6] further finds in an application for jail TB isolation rooms that 130 cfm (61 L/s) of transfer air through the door undercut worked well and provided 0.05 in. w.c. (12.45 Pa) differential pressure with the single door to the room closed.

Gaslon and Guisbond[7] present substantive information on room ventilation and air change rates for sepsis control in a health-care setting. Regarding any differential pressures or airflows, Gaslon refers to the previously mentioned 1994 CDC guideline differential pressure value of 0.001 in. w.c. (0.249 Pa).

Andrew Streifel[8] has published a preferred minimum differential cfm of 125 cfm (59 L/s) for a *sealed* positive or negative isolation room as well as a minimum of 0.01 in. w.c. (2.49 Pa) and an ideal differential pressure of 0.03 in. w.c. (7.47 Pa). Streifel bases this on a room with about 0.5 ft^2 (0.047 m^2) of leakage and 12 ACH.

Room Door Swing

Sansone and Keimig[9] state that swinging doors should open in the same direction of airflow. Sansone and Keimig base their conclusion on eddies that travel around the edge of a traveling door, from higher pressure to lower pressure. If the door travel

creates a high pressure on the leading side of the door, then to minimize eddies, the pressure on the leading side should be as less as possible. Thus, a door opening into a negative room is better than opening into a positive room. The author's findings differ from this conclusion. The smoke tests described later, indicate the room is transiently pressurized or depressurized, depending on the direction of door swing. Once the door is opened more than a foot, the anteroom or corridor is virtually the same pressure as the concerned room. Therefore, any contaminants that were pushed out of a negative room with the door opening into it would remain in the anteroom or worse, the corridor.

Sansone and Keimig found that increased door swing velocities affect the containment or exclusion of contaminants in a room and recommend slow door opening and closing. Our findings described below agree with this. The traveling speed control can be accomplished with an adjustable, off-the-shelf dampened door closure.

Figure 2 (left): Airflow direction indicator. Figure 3 (right): Indicator above door that is opening into negative room, smoke is not contained.

Real-World Experience

The author's experience is in design and testing of HVAC systems for health-care and laboratory facilities, with particular attention towards proper airflow directions, into or out of rooms. Tests were performed for room pressure vs. differential airflow in two types of facilities, a health-care hematopoietic stem cell transplant unit and a tuberculosis BSL-3 research lab. In addition to the quantitative test results, the tests present a methodology for practitioners for verifying the airflow direction into or out of the room.

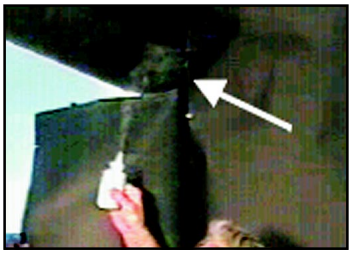

Figure 4 (left): Door opening out of positive room, smoke is contained. Figure 5 (right): Smoke plume is not captured at a negative room ΔP of 0.001 in. w.c. (0.249 Pa). Arrow points to leading edge of plume.

Room Pressure for Containment

To determine a minimum practical containment pressure, we performed tests on two, ±200 ft^2 (18.58 m^2) tuberculosis biosafety level 3 research lab rooms. The wall, floors and all penetrations were sealed, including the electrical conduits where they met the boxes. The windows were inoperable. The light fixtures were surface mounted. There was one door entering into each of the BSL-3 rooms. The doorjambs were not sealed and there was a 0.5 in. (12.7 mm) door undercut.

Because aerosolized TB containment was so critical, we specified and installed an airflow direction indicator[10] as shown in *Figure 2*.

The indicator's translucent tube penetrates the wall with a slight incline up into the room. The sphere inside the tube rolls in the direction of airflow. When the door is closed and there is proper negative room pressure, the sphere is sucked into the room, up the tube's incline and the sphere can be seen inside the room. When the room door is open, the tube's incline rolls the sphere out into the anteroom and thus provides a self-check feature, each time the door is opened.

For the first BSL-3 room tested, we set up the differential airflow corresponding to a 10% differential. The indicator sphere properly rolled into the room with the door closed. For this room, the door swung into the room. When the door was opened, the sphere was rapidly pushed out into the vestibule. The indicator sphere was to roll out of the room slowly, down the tube's incline. The investigators suspected the room was transiently under positive pressure. We performed a smoke test to watch the eddies around the top and latch side edges of the door. When we opened the door, the smoke trailed the door travel and portions of the smoke in the door's wake were pushed out of the room. The trail of smoke can be seen in *Figure 3*.

The airflow direction indicator was sensitive and visual in showing the transient reversal of airflow direction through the doorway. We performed the same test with the door closing and the room went further negative. With the negative condition, the smoke was contained and therefore the closing of a door that swings into a negative room has no detriment.

We proceeded to perform the transient door test on another BSL-3 negative pressure room where the door opened out into the corridor. When the door was opened, the eddy smoke trails followed the door in the beginning of the door travel, but the smoke was sucked back into the room as shown in *Figure 4*.

The next set of tests explored the capture velocity of a partially opened door as a function of room differential pressure. The tests were done on the first BSL-3 lab room. The differential pressure was set with the door closed, using a micromanometer. The door was opened and held partially open to observe the trail of the smoke plume in the plane of the door. *Figure 5* shows the smoke plume not being captured at 0.001 in. w.c. (0.249 Pa). *Figure 6* shows the plume being about to be captured at 0.003 in. w.c. (0.747 Pa). The capture significantly improved at a dif-

ferential pressure of 0.008 in. w.c. (1.992 Pa), shown in *Figure 7*. The purpose of this test was to challenge the 0.001 in. w.c. (0.249 Pa) stated in the CDC guidelines mentioned earlier. We recognize that people walking through the doorway will cause disturbances and thus an anteroom is a good idea.

Regarding the differential airflow required to obtain 0.015 in. w.c. (3.735 Pa) in the above BSL-3 rooms, the airflow differential was equal to about 150 cfm (71 L/s) differential, of which was made up through the 0.5 in. (12.7 mm) door undercut.

Room Pressure for a Protective Environment

The next test performed was on a health-care stem cell transplant positive pressure isolation room (±200 ft^2 [18.58 m^2]). The elevator lobby/entry airlock leads to the suite of isolation rooms. The airlock protects the suite against building pressure fluctuations caused by the elevator shafts. The entry door was 4 ft (1.2 m) wide with top and side seals and a 0.75 in. (19 mm) nominal undercut.

The photo on Page 35 shows the inside the room where on the left, was a bathroom with a separate door that had side and top seals but no bottom seal (good for air change rate). The 2 ft (0.61 m) x 2 ft (0.61 m) fluorescent lights were recessed solid acrylic lense and the windows were non-operable. The ceiling was gasketed lay-in tile frame. The high-hat light fixtures were heat-removal type of which were changed after the test to fixtures with lenses.

The walls and floor penetrations were sealed to best of general construction standards that can be from excellent to sufficient. Two access panels, later sealed, penetrated the corridor-to-room wall above the ceiling. The toilet exhaust was common to other toilet exhausts. A special sink in the patient room (not bathroom) had an open gap drain to another space below (no P-trap) for sanitation purposes.

The room supply was via a pressure independent primary air HEPA filtered fan-powered series box. The return to the fan-powered box was in the room. The house exhaust for the room was served by a pressure independent exhaust box. The supply and exhaust airflows were measured with an air volume hood. The differential pressures were measured by placing the static probe in the middle of the room, routing the tube through the door undercut and connecting the probe to the digital manometer outside the room. An airflow direction indicator was placed above the entry door to show when the room was under positive pressure.

We conducted various airflow versus differential pressure tests on the room. *Table 1* summarizes the tests in two states: the entry door to the positive pressure isolation room completely sealed and then with the undercut to the entry door not sealed. The bathroom/toilet exhaust and the house exhaust were not physically altered but they slightly responded to the room pressure changes caused by our alterations of the primary air supply to the room.

Figure 6: Smoke plume starting to be captured at a room differential pressure of 0.003 in. w.c. (0.747 Pa). Arrow points to leading edge of plume.

Figure 7: Smoke plume showing definite capture at a room differential pressure of 0.008 in. w.c. (1.992 Pa). Arrow points to leading edge of plume.

After performing the above tests on the positive pressure isolation room, we conducted tests on the remaining isolation rooms to determine the differential airflow to obtain a minimum 0.01 in. w.c. (2.49 Pa). The differential airflow ranged from 150 cfm (71 L/s) to 400 cfm (189 L/s).

Based on this empirical experience, we arrived at a room differential airflow at 300 cfm (142 L/s) for rooms of this construction and with door seals all-around, 400 cfm (189 L/s) with no door bottom seal with a closed bathroom door.

Door Swings and Anterooms

Based on the BSL-3 lab test observations of door swing effect on room pressure, we recommend for a negative or positive pressure room that the entry doors be gasketed, sliding break-away doors. If a standard swing door is used, we recommend it swing out of the room for a negative room and swing into the room for a positive room. This may not always be practical. For example, hospital isolation room doors that are located off the main corridor cannot swing out into the corridor. In such cases, we advise a room be found that can incorporate an anteroom.

An airlock (anteroom) should be used whenever possible. The anteroom "traps" any escaped air from a negative room and isolates corridor air from a positive room. Because the anteroom is a trap, it should incorporate a high air change rate of around 12 ACH or higher and the differential cfm should be zero or neutral to allow overall desired directional airflow between the corridor and the concerned room.

Conclusion and Summary

Based on the tests on the three rooms, some basic points for designing for proper room pressurization based on differential airflow settings include: seal the room, meet or exceed minimum codes for air change rates, incorporate industry regulations and practice for minimum air change rates and room pressure. However, as a minimum, strive for 0.01 in. w.c. (2.49 Pa) to 0.05 in. w.c. (12.45 Pa) differential pressure and consider an initial 400 cfm (189 L/s) room differential capacity with throttling capability.

When designing the HVAC system to obtain the desired room pressurization/directional airflow for ±200 ft² (18.58 m²) rooms, consider these points (this article is not intended to substitute for an HVAC design by a registered, licensed professional engineer):

Toilet Exhaust cfm (L/s)	House Exhaust cfm (L/s)	Total Exhaust cfm (L/s)	Primary Air Supply cfm (L/s)	Differential cfm cfm (L/s)	Room Pressure in. w.c. (Pa)
Bathroom door closed with 0.5 in. × 36 in. undercut, entry door sealed on sides, top and bottom					
110 (52)	85 (40)	195 (92)	390 (184)	195 (92)	+0.001 (0.249)
115 (54)	80 (38)	195 (92)	425 (201)	230 (109)	+0.0065 (1.619)
110 (52)	85 (40)	195 (92)	495 (234)	300 (142)	+0.010 (2.49)
Same bathroom door closed, entry door unsealed undercut 0.75 in. × 48 in., sealed on sides and top					
110 (52)	80 (40)	190 (90)	420 (198)	230 (109)	+0.002 (0.498)
110 (52)	80 (40)	190 (90)	500 (236)	310 (146)	+0.0045 (1.121)
90 (42)	90 (42)	180 (85)	650 (307)	470 (222)	+0.015 (3.74)

Table 1: Delta-cfm vs. Delta-P for positive pressure isolation room with bathroom inside isolation room.

- Rooms should have a minimum negative or positive pressure of 0.01 in. w.c. (2.49 Pa) where 0.05 in. w.c. (12.45 Pa) or higher is preferred. Codes and industry regulations and practice may dictate specific limits.
- Rooms should have a differential airflow to obtain the 0.01 in. w.c. (2.49 Pa) or higher. For ±200 ft² (18.58 m²) rooms, the best approach is to have the differential capability of 400 cfm (189 L/s) and the ability to throttle down the differential to satisfy the 0.01 in. w.c. (2.49 Pa) or higher. For 0.01 in. w.c. (2.49 Pa), the author has seen 400 cfm (189 L/s) of differential airflow for a room thought to be well sealed. Another room required only 150 cfm (71 L/s) of differential airflow. The range depends on ceiling, wall and window tightness, door seals and the existence of other supply or exhausts in the room.
- Air balancer specs for positive rooms should be (+10%/–0%) for supply, (+0%/–10%) for exhaust. Negative rooms should be (+10%/–0%) for exhaust, (+0%/–10%) for supply.
- For negative rooms, the makeup air should be provided via a supply outside the room. For positive rooms, exfiltration of air should be accommodated by an exhaust outside the room.
- All room penetrations above and below the ceiling and the ductwork should be well sealed.
- The ceiling should be tight as possible, preferably sheetrock or concrete deck.
- Specify surface mount or recessed vapor-tight, or non-return-air light fixtures.
- Each entry door to the room should be sealed on its top and sides (including astragal vertical joint seal for leaf or double doors) and include an adjustable bottom seal.
- A sliding entry door is preferred over a swing door. If a swing door is used, it should open out of a negative room or open into a positive room.
- Anterooms should be used whenever possible with 12 air changes per hour (ACH) minimum (codes and industry regulations and practice may dictate higher values) and a neutral pressure where the supply and exhaust airflow quantities are equal.
- An airflow direction indicator should be installed to visually see the dynamics of the room pressurization.

References

1. Ahmed, O., et al. 1993. "Dynamics of laboratory pressurization." *ASHRAE Transactions* 99(2):223–229.
2. Burns, J.T. and W.F. Milburn. 1999. "Specification and performance of testing and balancing in biologics facilities." *ASHRAE Transactions*.
3. Coogan, J.J. 1996. "Effects of surrounding spaces on rooms pressurized by differential flow control." *ASHRAE Transactions* 102(1):18–25.
4. Hitchings, D.T. 1994. "Laboratory space pressurization control systems." *ASHRAE Journal.* 36(2):36–40.
5. Gill, K.E. 1994. "HVAC design for isolation rooms." *Heating/Piping/Air Conditioning.* February, pg. 45.
6. Gill, K.E. 1997. "Tuberculosis isolation room design using CDC guidelines." *Heating/Piping/Air Conditioning.* September, pg. 69.
7. Galson, E.L. and J. Guisbond. 1995. "Hospital sepsis control and TB transmission." *ASHRAE Journal*, 37(5):48–52.
8. Streifel A J. 2000. "Health-care IAQ: guidance for infection control." *Heating/Piping/Air Conditioning.* October, pg. 28.
9. Sansone E.B. and S.D. Keimig. 1987. "The influence of door swing and door velocity on the effectiveness of directional airflow." *ASHRAE IAQ '87*. May, pg. 372–381.
10. Airflow Direction Inc. ADI Indicator is protected under one or more U.S. Patents U.S. [5,291,182], [5,410,298], [5,798,697] [5,661,461] and Canada Patent [2,107,396].