Use of Air Infiltration in Swine Housing Ventilation System Design

Harishchandra T. Jadhav
Iowa State University

Steven J. Hoff
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/abe_eng_pubs

Part of the Agriculture Commons, and the Bioresource and Agricultural Engineering Commons

The complete bibliographic information for this item can be found at https://lib.dr.iastate.edu/abe_eng_pubs/1128. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.

This Article is brought to you for free and open access by the Agricultural and Biosystems Engineering at Iowa State University Digital Repository. It has been accepted for inclusion in Agricultural and Biosystems Engineering Publications by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Use of Air Infiltration in Swine Housing Ventilation System Design

Abstract
The objective of this research was to develop and analyze the procedure for using recent air infiltration (AI) data collected from commercial swine finishing rooms (SFRs) in the design of negative pressure mechanical ventilation systems (VSSs). Air infiltration is an integral part of any ventilation process. Infiltration reduces the pressure differential across planned inlets and at very low pressure differences, cold air jets may drop directly on the animals causing significant discomfort. In this article, a design procedure is proposed for swine housing ventilation systems with the influence of air infiltration included. The method was used on one SFR for which air infiltration data was collected by in-field testing. The air-jet throw, jet momentum number, a newly developed coverage factor, and Archimedes number were used to assess the influence of infiltration on predicted air-jet and fresh-air distribution and to help guide the design of planned inlets in SFR VSSs with known infiltration. The analysis completed quantifies the severity of AI on air-jet and air distribution performance, and suggests that for the analysis room to ventilate properly requires a 50% reduction in AI levels beyond field measured curtain and fan infiltration. The analysis completed suggests a method for systematically planning three-dimensional ceiling inlet placement and operation and provides design guidance for new ceiling inlets suitable for SFR VSSs.

Keywords
Air distribution, Air-jets, Archimedes number, Infiltration, Jet Momentum Number

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
USE OF AIR INFILTRATION IN SWINE HOUSING VENTILATION SYSTEM DESIGN

H. T. Jadhav, S. J. Hoff

ABSTRACT. The objective of this research was to develop and analyze the procedure for using recent air infiltration (AI) data collected from commercial swine finishing rooms (SFRs) in the design of negative pressure mechanical ventilation systems (VSS). Air infiltration is an integral part of any ventilation process. Infiltration reduces the pressure differential across planned inlets and at very low pressure differences, cold air jets may drop directly on the animals causing significant discomfort. In this article, a design procedure is proposed for swine housing ventilation systems with the influence of air infiltration included. The method was used on one SFR for which air infiltration data was collected by in-field testing. The air-jet throw, jet momentum number, a newly developed coverage factor, and Archimedes number were used to assess the influence of infiltration on predicted air-jet and fresh-air distribution and to help guide the design of planned inlets in SFR VSS with known infiltration. The analysis completed quantifies the severity of AI on air-jet and air distribution performance, and suggests that for the analysis room to ventilate properly requires a 50% reduction in AI levels beyond field measured curtain and fan infiltration. The analysis completed suggests a method for systematically planning three-dimensional ceiling inlet placement and operation and provides design guidance for new ceiling inlets suitable for SFR VSS.

Keywords. Air distribution, Air-jets, Archimedes number, Infiltration, Jet Momentum Number.

Intensive animal production buildings, such as Midwestern U.S. style swine finishing rooms (SFRs), are commonly used in North America. The Midwestern U.S. region is characterized by severe winters and moderately hot summers and is internationally known for its swine production. Almost all SFRs located in this region are ventilated using negative-pressure mechanical ventilation systems comprised of planned inlets, side- and/or end-wall curtains, and fans. Winter and spring ventilation air entry is typically introduced through inlet diffusers placed on the ceiling while during summer periods side- or end-wall curtains provide the necessary open area for fresh-air entry. During winter, supplemental space and/or zone heaters are used to provide any required make-up heat.

The ventilation system (VS) for SFRs is designed to remove air contaminants (moisture, gases, particulates, etc.) emitted by animals and the surroundings and/or inside temperature control during warmer weather. Ideally, entering fresh-air should be distributed appropriately in the building. Albright (1990) identified the velocity of entering air-jets, inlet opening gaps (IOGs), placement of inlets, and total airflow rate through a livestock room as key components for proper fresh-air mixing within livestock buildings. During cold weather periods, the design ventilation rates (DVRs) are extremely small and can at times be dominated by air infiltration (AI) (Albright, 1990). The low DVRs combined with AI makes it hard to maintain a desired pressure difference (PD) to optimize fresh-air distribution. A lower than desired PD will generate lower than desired air-jet velocities and thus inlet momentum, both contributing to poor fresh-air distribution.

Entering low momentum cold air-jets may drop immediately on entry and can chill the animals if sufficient momentum is not imparted before entering the animal occupied zone (AOZ). Hence, imparting sufficient momentum to the entering air-jets, especially during cold weather, is of immense importance to promote a better thermal environment within the AOZ (Albright, 1990; Zhang et al., 2001).

Maintaining a minimum PD across a SFR is challenging. Zhang et al. (2001) suggested that the typical operating PD range for SFRs is 10 to 20 Pa while, Albright (1990) recommended a minimum PD of 10 to 15 Pa to resist high wind speeds up to 40 km h⁻¹. Albright (1990) added that it is difficult to achieve complete mixing in SFRs. In general, a higher PD promotes vigorous air mixing, but PDs above 30 Pa add very little towards proper air mixing. In connection to maintaining the desired PD while ventilating a SFR, Albright (1990) and ASABE Standard EP270.5 (ASAE Standards, 1986) suggested adding AI and inlet airflow rates together and equate the combined rate with the DVR at a desired PD. Many questions arise on using AI in the design of SFR VSS, and recent updated AI data could be used to assess the level of influence on the broader goal of efficient ventilation performance. The main objective of this article...
was to develop a procedure for using AI data in the design of SFR VSs to maintain desired fresh-air distribution and guide fresh-air inlet diffuser design and placement within a SFR.

**BACKGROUND**

Limited research has been done on the use of AI in VS design and the resulting effects on fresh-air distribution in commercial SFRs. Some research is reported in the literature on air-jet behavior studied using SFR scale-models and prototypes. Only two studies related to SFRs (Randall and Battams, 1979; Berckmans et al., 1993) used commercial-scale rooms to develop criteria for air-jets. All of the prior research on air-jets was done for continuous slot inlets (two-dimensional; 2D air-jets) and not a single study reported on the general performance for non-continuous (i.e., three-dimensional, 3D) air-jets commonly used in modern SFRs. Additionally, the SFR VS designed in this article assumes air-jets enter the room during winter and mild weather conditions and no specific design criteria is available for non-isothermal air-jets originating from modern SFR 3D inlets. Hot weather inlets are assumed as curtains or a similar non-ceiling inlet diffuser system.

Fresh-air distribution depends on many factors. In general, the most complete fresh-air mixing occurs during isothermal conditions (Krueger, 2017). Albright (1990) attributed the problem of fresh-air mixing to thermal stratification. In regions which experience severe winters, like the Midwestern United States, cold air-jets entering a room should be analyzed as non-isothermal air-jets (Chen and Rodi, 1980), relating buoyant and inertial forces. The magnitude of these forces at each point of a developing air-jet determines the characteristic of the air-jet at that point. Chen and Rodi (1980) added that the Archimedes number \((An)\) solely dominates air-jet behavior at very low velocities or at large temperature differences. As air-jet velocities increase or temperature differences decrease, non-isothermal air-jets behave similar to isothermal air-jets. Under these conditions (high velocities or low temperature differences), the non-isothermal air-jets are dominated by Reynolds’s number or Euler’s number. Yu (1996) reported that non-isothermal air-jets behave similar to isothermal air-jets when the Archimedes number \((An)\) is below 0.005 or the corrected Archimedes number \((ARc)\) is below 30 and the results agreed with those reported by Randall and Battams (1979). In addition, the lack of research on non-isothermal air-jet behavior in SFRs adds to the difficulty in analyzing non-isothermal air jets. Under these circumstances, if the data (i.e., air-jet throw, spread etc.) for isothermal air-jets is to be used for non-isothermal air-jets, then a correction factor of about 0.75 is required due to higher air densities. If the air-jets need to overcome small obstructions, the correction factor further reduces to 0.70 (Price, 2017).

Many studies have tested and analyzed the stability criteria for cold air-jets. If sufficient air velocity is not maintained at entry, cold air-jets are affected by buoyant forces (ASHRAE, 2013). Albright (1990) cautioned that cold weather may suppress the Coanda effect in ceiling air-jets as well. At very low air-jet velocities, incoming air-jets during cold weather may fall immediately on entry, making them undesirably stable. By a simple rule of thumb, the centerline terminal velocity of air-jets changes about 1% for every 2°C difference between the air-jet and inside temperature (Int-Hout and Kloostra, 1999).

Kaul et al. (1975) proposed the concept of jet momentum to check proper fresh-air distribution in SFRs. Barber et al. (1982) further developed the Kaul et al. (1975) jet momentum concept into the jet momentum number (JMN) criteria for stable overall mixing patterns. The JMN for stable overall mixing should be higher than 7.5×10⁻⁴ at -20°C (air density 1.33 kg m⁻³) outdoor conditions. Albright (1990) cautioned that the JMN criteria has not been verified for various types of agricultural building ventilation systems, but added that the JMN criteria uses the principle of momentum conservation and therefore it may not depend on the type of inlet. Furthermore, Albright (1990) added that the minimum value of JMN (7.5×10⁻⁴) is difficult to achieve for SFRs during winter due to the low required DVR and the potential for AI. Further, higher JMNs are undesirable as they create draftiness and too much air mixing in the AOZ which can chill and cause cold stress to animals during cold weather (Albright, 1990). The higher limit for JMN suggested by Ogilvie et al. (1988) is 15×10⁻⁴. If the JMN is greater than 15×10⁻⁴, the level of cold stress will be determined by the temperature of the incoming air-jet, the resulting airspeed in the AOZ, and the maturity level of the occupants.

In general, Albright (1990) reported that air-jets generated while ventilating SFRs should have enough momentum to induce one large recirculation zone for the zone serviced by an inlet. Randall and Battams (1979) studied air-jets in scale-model animal buildings and recommended that a corrected Archimedes number (ARc) below 30 will generate enough momentum to keep ceiling air-jets horizontal while, when ARc numbers were above 75, air-jets dropped on entry. For ARc numbers between 30 and 75, air-jets were intermediately unstable. The ARc criteria (between 30 and 75) defined by Randall and Battams (1979) were confirmed by Berckmans et al. (1993) for commercial piggeries where the pigs were simulated using heating pads. The air-jet velocities during the experiment changed from 0.3 to 10 m s⁻¹ while temperature of incoming air-jets changed between -2°C to 15°C. Also, Berckmans et al. (1993) confirmed that the criteria holds true regardless of room size and inlet type. Randall and Battams (1979) added that an air-jet velocity of about 5 m s⁻¹ would yield an ARc equal to 30. Leonard and McQuitty (1986) studied the behavior of cold air-jets in an experimental room having dimensions of 7.2 × 5.4 × 1.9 m, in which the inlet was fitted along the entire 5.4 m width of the room such that they could produce a maximum throw of 7.2 m, parallel to the 7.2 m length of the room and found that maintaining the ARc number below 50 was satisfactory for a single stable rotary pattern.

Leonard and McQuitty (1988) worked on a prototype animal building and reported that an ARc of 5 gave better inlet air-jet trajectories and air mixing, but also cautioned that confirming the results for commercial animal rooms was needed. Yu and Hoff (2002) used SFR scale-models to study
the stability criteria for rooms fitted with slot inlets under non-isothermal conditions. The study reported that for ARc numbers above 75, two-circulation zones resulted implying that ARc numbers between 30 and 75 could be a good assumption for single-circulation air-jets desired in SFRs. These numbers need to be verified on commercial animal rooms. While studying airflow patterns of two-dimensional (2D) slot-inlet rooms under non-isothermal conditions, Wang and Ogilvie (1994) found that once an air-jet penetrates 50% of the distance between inlet and an opposing wall, the secondary circulation zone (counter clockwise) collapses and the air-jet will reach the opposite wall. Randall (1980) used a commercial SFR to study air-jets in moderate non-isothermal conditions. Sensible heat from pigs was simulated with hot water filled containers. For a stable rotary airflow pattern, and for proper mixing, the air-jet velocity upon room entry should be at least 4 m s⁻¹. Furthermore, Barber et al. (1982) highlighted that both criteria (ARc and JMN) must be met to ensure better ventilation in animal buildings. In summary, Wang and Ogilvie (1994) commented that no universal criteria exists which predicts airflow characteristics of both isothermal and non-isothermal air-jets for SFR VSs.

In practice, agricultural buildings are typically ventilated by a generalized guideline that provides 0.09 m² of inlet area per 0.28 to 0.57 m³ s⁻¹ of airflow (MWPS, 1987). Fabian (2017) recommended an inlet area 0.16 to 0.19 m² per 0.47 m³ s⁻¹ for animal housing ventilation systems. Furthermore, Fabian (2017) suggested an entering air-jet velocity of 3.6 to 5.1 m s⁻¹ will provide better air mixing. To maintain the desired PD for leaky animal buildings, MWPS (1987) advises to reduce the planned inlet areas by 30% to 50% to develop a sufficient PD, while Fabian (2017) suggested to reduce the inlet area of animal housing up to 50% during cold weather to achieve the desired PD. Furthermore, the desired PD across the inlets should be adjusted to produce the desired airspeed in the AOZ, which varies from 0.2 to 0.4 m s⁻¹ depending on incoming air-jet temperature (Albright, 1990) and animal maturity level.

Air-jet spread and air-jet throw depend primarily on the incoming air-jet velocity and physical size of the inlet. Awbi (2003) found that air-jets produced by rectangular openings with aspect ratios less than 40 (inlet length/inlet opening height) can be analyzed as 3D air-jets. In general, free isothermal air-jets diverge at a constant angle of about 22° (ASHRAE, 2013; Krueger, 2017). The discharge coefficient, Cd, for animal housing inlets varies between 0.60 and 0.80 (Fabian, 2017) and Berckmans et al. (1993) recommended a Cd of 0.80 for more streamlined agricultural inlets. Oberreuter and Hoff (2000) tested 3D sidewall air inlets and reported Cds ranging from 0.58 to 0.90 based on inlet aspect ratio, deflecting vane angle, and weather hood approach angle. In addition, inlets should be placed in animal buildings such that entering air will travel less than about 23 m before exiting through fans (Fabian, 2017) and fresh-air inlets should be placed at least 2.44 m away from fans to avoid short-circuiting (MWPS, 1987).

**Materials and Methods**

**Room Selected for Analysis**

A Midwestern U.S. swine finishing room (SFR) was selected for analysis. This type of room is widely used for swine production in North America. The selected room was located in Schleswig, Iowa, and was made from wooden structural members and other materials such as concrete, wood panels, metal sheets, polyethylene fabric, and either blown-in cellulose insulation (attic space) or fiberglass batt insulation (wood constructed walls). Concrete was used for the underfloor manure pit and the lower portion of all walls. Metal sheets were used for the roof and wall siding. Curtains were made from single layer polyethylene fabric. On the basis of layout, this room was classified as a single barn defined as one room under one roof (Jadhav et al., 2018a).

The internal length, width, and floor-to-ceiling height was 58.52 × 12.19 × 2.44 m, respectively. This room was fitted with a negative-pressure mechanical ventilation system with fresh-air inlet diffusers in the ceiling. Seven exhaust fans were present located on the end (five fans) and side wall pit exhaust (two fans). Three curtains were installed – one on each sidewall and one at an end wall. The arrangement of fans, inlets, and curtains was typical for ventilating SFRs in the Midwestern United States (fig. 1). The analysis presented in this article used the actual field measured infiltration for the analysis room with the dimensions as given and the same number and placement of bi-flow inlets as the analysis room, using bi-flow inlet data available from one manufacturer. Therefore, inlet performance data (airflow vs. static pressure) was not actually measured for the analysis room, rather an inlet was selected for analysis that was accompanied with detailed manufacturer provided performance data.

**Inlet System Analysis**

Ceiling inlet diffusers, where fresh-air from the attic was delivered into the SFR, was used for this analysis with two (rectangular) openings on each inlet (i.e., bi-flow inlets) allowing fresh-air into the room with two air-jets similar to the inlet depicted in figure 2a. The analysis presented in this paper required a bi-flow inlet with detailed performance data and this was available with the Model ACI4000P2 inlet (Automated Production Systems, Inc., Assumption, Ill.).

![Figure 1. Inside view of typical Midwestern U.S. swine finisher. Note that the feeders were dislodged to clean the room.](image)
analysis inlet had a fixed length (IL) of 1.18 m with an adjustable inlet opening gap (IOG) that could be varied between 0-204 mm. The IOG was controlled using a hinged baffle cabled to a computer-controlled inlet actuator as depicted in figure 2a. Because inlet length was fixed, the IOG and resulting Cd governed the airflow rate delivered by each inlet diffuser at any given PD. The airflow characteristics of one inlet, with both baffles opening the same, is shown in figure 2b. Detailed data on airflow was available from the manufacturer for varying PDs between 12.5 and 99.6 Pa (increments of about 12.5 Pa) and IOGs from 2.54 to 20 cm at increments of about 2.54 cm. The inlet airflow ($\dot{V}$) was best represented by a power law equation $\dot{V} = c (PD)^n$ at each IOG. The airflow characteristic curves for intermediate IOGs were generated by interpolation. It was assumed that the inlet controller for actuating the IOG could control the inlets to a minimum IOG of 5 mm. After the minimum opening of 5 mm, it was assumed that the controller could maintain any desired IOG depending on controller demands up to the maximum 204 mm opening. Ten bi-flow inlets (5 per row) were installed as shown in figure 3a with an assumed 22° air-jet spread (11° spread at each air-jet edge) shown. Each bi-flow inlet developed an air-jet 180° from each other, transverse to the long axis of the room (fig. 3a). Additional air-jet throw and air-jet spread details are given in figure 3b and addressed in future discussions.
AIR INFILTRATION RATE MEASURED

The room AI data used was obtained from in-field testing reported by Jadhav et al. (2018a). Infiltration was assessed using the ‘pressurization’ method as outlined in standards CGSB 149.15-96 (1996) and ASTM E779-10 (2010). The AI data was collected by conducting two infiltration measurement tests on each room. In Test I, all planned ceiling inlet diffusers were sealed (as depicted in fig. 2a) and the room was allowed to function similar to cold weather operating conditions (i.e., doors and curtains were closed normally, fan backdraft shutters closed, etc.). At least six airflows were exhausted from the room using existing exhaust fan(s) to create at least six different PDs (range 0 to ~50 Pa) across the room envelope. The Fan Assessment Numeration System (FANS), comprised of an array of moving anemometers (Gates et al., 2004), was used to measure in-situ fan airflow during testing. Combinations of inclined manometers with ±1.24 Pa reading resolution and micro-manometers with ±0.249 Pa reading resolution were used to measure PD across the room envelope during testing. The airflow measured at the generated PD was designated as ‘total’ air infiltration (TAI) of the room. Test III was similar to Test I except that in Test III, along with the sealing of planned ceiling inlets, curtains, fans, and manure pump-outs were sealed. The AI rate measured in Test III was designated as ‘other’ air infiltration (OAI). Test II was an intermediate AI test not discussed here (see Jadhav et al., 2018a).

The AI data collected was normalized to fresh-air changes per hour (ach) using the internal empty barn volume (excluding pit and attic volumes). Power law models (Siren, 1997; Walker et al., 1998) were fitted on the normalized AI data. Model fitting was done to get TAI and OAI rates up to any desired PD measured (up to ~50 Pa). It was assumed that the fitted power law models (table 1) predicted the true AI rate for the analysis room. Details on the complete infiltration study can be found in Jadhav et al. (2018a).

If measured AI data for a specific SFR is not available, power law models (Jadhav et al., 2018a) and multiple linear regression models (Jadhav et al., 2018b) can be used to predict TAI and OAI of the SFR within reasonable uncertainty.

VENTILATION DESIGN REQUIREMENTS FOR THE ANALYSIS ROOM

SFR ventilation rates change with the ambient environment, required inside environment, and the growth stage of the pigs. Thus, the design ventilation rates (DVRs) change from some minimum to maximum (MTM) value. In practice, the DVRs are satisfied by moving varied airflow through rooms in stages over the MTM range (MWPS, 1987; Albright, 1990). In this article, for clarity purposes, the VSs were designed for the combinations between two critical weather conditions (cold, mild) and four pig growth stages (prenursery, nursery, growing, finishing). The resulting design requirements (DRs) are shown in table 2. The DVRs and design indoor air temperatures in table 2 are as recommended by MWPS (1987) for the different DRs. These recommendations are based on the mass balance of water vapor or various gases generated, or inside temperature control, whichever is largest at any design outdoor temperature. DVRs are reported in multiple units for clarity. Note that the DVRs are for one pig or per head basis. The cold weather design outdoor air temperature (DOAT) in table 2 is the 97.5% design temperature (ASHRAE, 2013). The mild weather temperature was taken by general recommendations as no specific recommendation was available.

The design procedure outlined in this article aims to include accurate AI data into the design of SFR VSs. The impact of AI on the overall design was reviewed by assessing the effect on room fresh-air distribution, which in turn is affected by the behavior of air-jets entering the room from ceiling fresh-air inlet diffusers. The inputs required to predict air-jet behavior originating from the ceiling inlets is included in table 2 and will be referenced elsewhere in this article.

Design outdoor relative humidity (DORH) values reported in table 2 are monthly averages for January 2017 (cold weather) and April 2017 (mild weather) for the room site. The RH data used was obtained from the AWOS automatic weather station (AWOS, 2017) nearest to the site (24 km away). DOAT and DORH were used to calculate design outdoor air density (DOAD; site elevation=417 m). DOADs were calculated using the online ambient density calculator (BARRANI, 2017). It was assumed that an air-jet would enter the SFR at the outside design conditions (specifically at DOAT and DOAD) implying that air-jet behavior was analyzed using critical cold and mild weather conditions in Iowa. No attempt was made to estimate attic air tempering.

VENTILATION SYSTEM DESIGN PROCEDURE

The capacity of the analysis room was 1000 pigs (~0.70 m² per animal). Ideally, the VS should satisfy the DVRs reported in table 2 for various DRs and at the same time should maintain desired air-jets for promoting acceptable fresh-air distribution (Albright, 1990; Zhang et al., 2001). Acceptable fresh-air distribution is promoted primarily by allowing air-jets to fully develop with one rotary airflow pattern for the width of building the air-jet services. In addition, fresh-air diffusers should be spaced laterally in such a manner that the entire room is serviced by the inlet diffuser system. Finally, the air-jet should be stable enough as to offset buoyancy effects of cold air-jets entering much warmer rooms. Proper PD across the inlet system is the prime necessity for fulfilling desired air-jet behavior for any ventilated room, and most importantly, at the required DVR at any given time of season. AI plays an important role in this regard making the desired PD difficult to achieve (Albright, 1990; Zhang, 2001). The design analysis presented in this article actively uses the measured AI rate in the design procedure.

Table 1. Total (TAI) and other (OAI) air infiltration exchange rate (ach) prediction models as a function of the operating room static pressure differential (PD, Pa) for the analysis room (at sea level; Jadhav et al., 2018a).\(^{(a)}\)

<table>
<thead>
<tr>
<th>Infiltration Component</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total room</td>
<td>( TAI_{ach} = 1.693 \times (PD)^{0.4547} )</td>
</tr>
<tr>
<td>Total room less curtains and fans</td>
<td>( OAI_{ach} = 0.5217 \times (PD)^{0.6219} )</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Empty barn room volume was 1741 m³ (excludes attic and manure pit volumes).
Quality Indices for Fresh-air Distribution

Each design requirement (DR1-DR8; table 2) was evaluated by assessing fresh-air distribution using the jet momentum number (JMN) and the Archimedes number (Ar) recommended by Awbi (2003). The minimum JMN (7.5 × 10^4) recommended by Barber et al. (1982) was used since this JMN was found useful for non-isothermal air-jets having an entry temperature up to -20°C. The upper limit for JMN (15 × 10^4) was also used to assess the air-jets influence in the AOZ (Ogilvie et al., 1988). The Ar was used (Berckmans et al., 1993; Yu and Hoff, 2002; Yu et al., 2007) to predict premature dropping of cold air-jets into the AOZ. The overall desire was to design fresh-air distribution such that a single rotary airflow pattern existed for each air-jet, and this was assumed to be achieved if the air-jet throw was greater than 50% of the room width (Wang and Ogilvie, 1993; Yu and Hoff, 2002; Yu et al., 2007) to ensure the majority of the room was covered by any row of air-jets entering perpendicular to the building length. Air-jet spread (lateral expansion) was calculated considering a 22° lateral spread (11° on each inlet edge) as depicted in figures 3a,b using the air-jet throw distance as limited by the vena contracta velocity (Awbi, 2003). The air-jet spread was calculated as a wall/ceiling air-jet as all inlets were installed in the ceiling (fig. 3b). Isothermal air-jet throw was calculated using equation 1 (ASHRAE, 2013). In this equation, Kc for a ceiling air-jet from a 3D rectangular area (one way; horizontal along ceiling) was 5.5. For all calculations, a terminal velocity (v_t) of 0.2 m s^-1 was used (Awbi, 2003). The 0.8 multiplier in equation 1 was recommended for fully-developed air-jets (ASHRAE, 2013). In equation 1, the inlet area (A_o) was considered equal to the actual area of the inlet opening (IO). 

\[ x_d = 1.1 \left( C_d A_o \right)^{0.5} (Ar)^{0.5} \]  

(2)

where

\[ x_d = \text{air-jet detachment distance due to buoyancy (m)} \]

interpreted as the non-isothermal air-jet throw,

\[ Ar = \text{Archimedes number}, \]

\[ \beta = \text{coefficient of thermal expansion (} (273.15+T_j)^{-1} \text{)}, \]

\[ C_d = \text{discharge coefficient (0.80)}, \]

\[ g = \text{gravitational constant (9.81 m s}^{-2}), \]

\[ T_j = \text{air-jet entering temperature (°C)}, \]

\[ T_r = \text{room temperature (°C)}, \]

\[ v_{vc} = \text{air-jet vena contracta velocity (m s}^{-1}). \]

The jet momentum number (JMN) was calculated using equation 3 (Barber et al., 1982).

\[ JMN = V_j v_{vc} g^{-1} V^{-1} \]

(3)

where

\[ V_j = \text{airflow of entering air-jet into volume V serviced by a single air-jet (excludes infiltration; m}^3 \text{s}^{-1} \text{)}, \]

\[ V = \text{volume of room serviced by a single air-jet (m}^3 \text{)}. \]

Air-jet spread (lateral expansion) was calculated considering a 22° lateral spread (11° on each inlet edge) as depicted in figures 3a,b using the air-jet throw distance as limited by \( x_d \) or the maximum achievable of \( x_{d,\max} = 3.05 \text{ m} \) for the analysis room. The maximum achievable \( x_{d,\max} \) is interpreted as the limit dictated by a sidewall or centerline between two opposing air-jets (fig. 3a). Air-jet spread was incorporated into the analysis to account for air-jet distribution in the room. For example, the JMN does not account for the actual distribution of fresh-air into the building. The same JMN for any room volume could be achieved with multiple inlets, or likewise, with one single inlet. A method was needed to account for not only a representative momentum level, as in JMN, but also in the distribution of this momentum. To account for fresh-air distribution, row and room coverage factors (CF_{row}, CF_{room}) were developed as shown in equations 4 and 5. CF_{row} represents the fraction of the building length covered by any row of air-jets entering perpendicular to the building length. CF_{room} represents the fraction of the ceiling area covered by all air-jets entering the building of a given length and width.

\[ CF_{row} = k \{ IL + 2 x_{c, \text{net}} Tan(\theta) \} BL^{i} \]  

(4)
\[
CF_{room} = m \{[IL + x_{i, net} \tan(\theta)] x_{i, net} \} BL^{-1} BW^{-1} \tag{5}
\]

where

\begin{align*}
  k &= \text{number of air-jets entering room in the same direction in any row under consideration (5; fig. 3a),} \\
m &= \text{total number of air-jets entering a room in any direction (20; fig. 3a),} \\
  IL &= \text{physical length of inlet issuing an air-jet (1.18 m for the inlets as installed; figs. 2a, 3b),} \\
x_{i, net} &= \text{Min(\text{Min}(x_c, x_d), x_{i, max}) (m; fig. 3b),} \\
x_{i, max} &= \text{air-jet throw dictated by a sidewall or centerline between opposing air-jets (3.05 m for analysis room; fig. 3a),} \\
  BL &= \text{length of building perpendicular to air-jet throw and parallel to IL (58.52 m for the analysis room; fig. 3a),} \\
  BW &= \text{width of building (12.19 m for the analysis room; fig. 3a),} \\
  \theta &= \text{air-jet spread angle at an inlet edge (assumed at 11°).}
\end{align*}

For a row of 3D ceiling inlets, the absolute maximum achievable \(CF_{row}=1.00\). For a row of 3D ceiling inlets, the maximum achievable \(CF_{room}\) relative to the ceiling area will always be less than 1.00 due to the ceiling area between expanding air-jets not directly covered by the entering air-jet. Assuming uniformly spaced 3D ceiling inlets, and assuming all air-jets converge where required (opposing wall or center-line between inlet rows), the absolute maximum achievable \(CF_{room}\) is,

\[
CF_{room, max} = \frac{\{IL + x_{i, max} \tan(\theta)\}/[IL + 2 x_{i, max} \tan(\theta)]}{1} \tag{6}
\]

Using the analysis room inlet length (fig. 3a), \(CF_{room, max}=0.75\), i.e. \(1.18 + 3.05 \tan(11°)/1.18 + 2 \times (3.05) \tan(11°)\). To achieve this absolute maximum for the \(IL=1.18\) m installed in the analysis room, however, requires an inlet spacing of 2.37 m (=\(IL+2 x_{i, max} \tan(\theta)=1.18 + 2(3.05)\tan(11°)\)). For the analysis room inlets and as-installed spacing (fig. 3a), the actual maximum achievable \(CF_{room}\) for this configuration is 0.15, i.e. \((20 \times 1.18 + 3.05 \tan(11°))/3.05 58.52 reverses 12.19 \times 12.19\) and the actual maximum achievable \(CF_{row}=0.20\), i.e. \((5 \times 1.18 + 2 \times 3.05 \tan(11°))/58.52 \times 12.19\)). Two cases will be used to explain the use of coverage factors. If the DR1 ventilation rate (0.94 m³ s⁻¹; table 2) was introduced into the analysis room volume (1741 m³) from one center placed ceiling inlet with one operational 2.0 m long opening (\(IL\)) at a \textit{vena contracta} air-jet velocity of 5 m s⁻¹, the \(JM\) (eq. 3) would be \(2.7 \times 10^{-4}\), i.e. \(0.94 \times 5.0 \times 9.81 \times 1741 \times 1\). If this single ceiling inlet introduced 0.94 m³ s⁻¹ with two air-jets opposite each other (0.47 m³ s⁻¹ per air-jet for half the room volume) the \(JM\) would be the same \(2.7 \times 10^{-4}\), i.e. \((0.47 \times 5.0 \times 9.81 \times 1 \times 870 \times 1)\). Clearly, although both cases are bad for air distribution, the single air-jet case is worse. Assuming the maximum air-jet throw desired can be achieved (\(x_{i, max}=6.10\) m due to opposing walls), the single air-jet case has a \(CF_{row}\) of 0.075, i.e. \((1 \times 2.0 + 2 \times 6.10 \tan(11°))/58.52 \times 12.19\) for the room half containing the air-jet and a \(CF_{row}\) of 0.0 for the room half not being directly ventilated. On a room basis, \(CF_{room}\) is 0.027, i.e. \((1 \times [2.0 + 6.10 \tan(11°)]/12.19 \times 58.52 \times 12.19\times 1)\). For the double air-jet case, \(CF_{row}\) is 0.075 for both rows of air-jets with an improved \(CF_{room}\) of 0.054, i.e. \((2 \times [2.0 + 6.10 \tan(11°)]/6.10 58.52 \times 12.19 \times 1)\). The two added factors, \(CF_{row}\) and \(CF_{room}\), account for the number of air-jets spaced laterally in any row relative to the room length, and, the total air-jet coverage area relative to the ceiling area, respectively, adding clarity to a given \(JMN\).

Isothermal air-jet throw (eq. 1), non-isothermal air-jet detachment distance (eq. 2), and air-jet spread using the row and room coverage factors (eqs. 4 and 5) were used for overall air-jet and air distribution assessment and the influence that AI has on these parameters.

**Results and Discussion**

The results presented will demonstrate the use of air-jet throw and coverage factors to assess the adequacy of fresh-air delivery with infiltration incorporated into the design process. Ideally, the inlet operating PD, at any ventilation rate, should be established at a level that maximizes air-jet throw and air-jet coverage without AOZ chilling. Infiltration affects this process and the results will bear this out. All operating PDs given are assumed across the ceiling inlet system which is assumed equal to the analysis room operating PD, implying that adequate attic intake area exists to make this assumption.

**Ventilation System Design without Air Infiltration Considered**

Table 3 lists key air-jet and air distribution parameters and results assuming the analysis room was designed without infiltration considered. In table 3, the potential PD for all DVRs analyzed was above 20 Pa; a generally accepted target PD (Zhang et al., 2001). For the 10 inlets as spaced in figure 3a, the maximum achievable \(CF_{row}\) and \(CF_{room}\) levels are 0.20 and 0.15, respectively. The \(CF_{row}\) level was near the maximum achievable for all DRs, with \(CF_{room}\) levels well below the maximum achievable (0.15) for DR1 and DR2 given the inlets as arranged in the analysis room, with significant improvements beginning at DR3. The resulting net air-jet throw (\(x_{i, net}\)) would be predicted to service the required 3.05 m width with the inlet layout shown in figure 3a, with the exception of DR1 and DR2 where buoyancy affects the air-jet, yet essentially achieving 50% of the required air-jet throw (1.53 m) as has been suggested previously (Wang and Ogilvie, 1994). The recommended minimum \(JMN\) (eq. 3) of 7.5 \times 10⁻⁴ was achieved beginning with DR3 and above. With the operating conditions used in table 3, the recommended minimum \(JMN=15 \times 10^{-4}\) is exceeded for DR4 and above. An excessive \(JMN\) can be reduced while still maintaining the maximum achievable \(CF\) by lowering the operating PD and increasing IOG accordingly (inlet maximum 204 mm) as shown at the bottom of table 3 using DR7 and DR8 as examples. Overall, without infiltration considered, the ventilation system as installed could be adjusted to meet desired air-jet throw. Maximum achievable row and
Balance is infiltration.

Principal operating parameters which in turn has significantly affected the probable operating PD which in turn has clearly, the TAI level measured for this room has significantly reduced air-jet throw and subsequent CF_{row} and CF_{room} levels. As shown in table 4, if AI is reduced to the measured OAI level, the DR1 and DR2 operating PD improved, however the final net air-jet throw levels were still well below desired resulting in a nominal increase in CFs. Reducing the infiltration rate from TAI to OAI improved air-jet and air distribution parameters, but still far below the achievable parameter levels with no infiltration considered (table 3).

The inability of the analysis room to perform at maximum possible air-jet and air distribution parameters is related to the fraction of fresh-air entering the room through the planned ceiling inlet system. As shown in table 4, a significant amount of fresh-air enters through unplanned leakage areas. For example, for the TAI conditions, only 15.5% and

### Table 3. Air-jet and air distribution parameters for the analysis room considering no AI.[a]

| DRs (b) | No of Inlets Used | Design Ventilation Rate (m³/s) | % Fresh-air through Ceiling Inlet System (c) | Achievable PD Across the Room (Pa) (d) | v_c (m/s) | IOG (l) Used (cm) | JMN (x 10⁻⁴) | Ap (l) (m) | Isothermal Air-jet Throw x_t (m) | Non-isothermal x_t (m) | Final Air-jet Throw (m) | CF_{row}/CF_{room} (l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DR1 | 10 | 0.94 | 15.5 | 0.99 | 1.21 | 0.50 | 0.64 | 0.103 | 2.58 | 0.26 | 0.26 | 0.11/0.01 |
| DR2 | 10 | 1.42 | 16.0 | 2.40 | 1.89 | 0.50 | 1.5 | 0.038 | 3.05 | 0.44 | 0.44 | 0.12/0.02 |
| DR3 | 10 | 3.30 | 30.9 | 10.00 | 3.86 | 1.10 | 7.9 | 0.011 | 3.05 | 1.21 | 1.21 | 0.14/0.05 |
| DR4 | 10 | 4.72 | 34.0 | 20.00 | 5.46 | 1.20 | 15 | 0.006 | 3.05 | 1.75 | 1.75 | 0.16/0.07 |
| DR5 | 10 | 4.72 | 33.9 | 20.00 | 5.73 | 1.20 | 16 | 0.003 | 3.05 | 2.30 | 2.30 | 0.18/0.10 |
| DR6 | 10 | 7.08 | 47.0 | 30.00 | 7.02 | 2.00 | 10 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |
| DR7 | 10 | 11.33 | 66.9 | 30.00 | 7.02 | 5.70 | 47 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |
| DR8 | 10 | 16.52 | 77.3 | 30.00 | 7.02 | 11.0 | 11 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |

[a] Entering air-jet properties evaluated at conditions given in table 2 for each DR. The room was designed to house 1000 finishing pigs.

[b] Design requirement condition from table 2.

[c] Balance is infiltration.

[d] Vena-contracta air-jet velocity.

[e] A selected PD with a selected IOG to achieve DR condition.

[f] Characteristic length (see eq. 2).

[g] Inlet opening gap (each of bi-flow inlets).

[h] Archimedes number (see eq. 3).

[i] Inlet opening gap (each of bi-flow inlets).

[j] Isothermal air-jet throw (eq. 1) maximized at 3.05 m for room analyzed (fig. 3a).

[k] Final air-jet throw dictated by the minimum of x_t or x_{max} maximized at 3.05 m.

[l] Row and room coverage factors (respectively; eq. 5).

### Table 4. Air-jet and air distribution parameters for the analysis room using measured TAI and OAI.[a]

| DRs | No of Inlets Used | Design Ventilation Rate (m³/s) | % Fresh-air through Ceiling Inlet System (c) | Achievable PD Across the Room (Pa) (d) | v_c (m/s) | IOG (l) Used (cm) | JMN (x 10⁻⁴) | Ap (l) (m) | Isothermal Air-jet Throw x_t (m) | Non-isothermal x_t (m) | Final Air-jet Throw (m) | CF_{row}/CF_{room} (l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DR1 | 10 | 0.94 | 15.5 | 0.99 | 1.21 | 0.50 | 0.64 | 0.103 | 2.58 | 0.26 | 0.26 | 0.11/0.01 |
| DR2 | 10 | 1.42 | 16.0 | 2.40 | 1.89 | 0.50 | 1.5 | 0.038 | 3.05 | 0.44 | 0.44 | 0.12/0.02 |
| DR3 | 10 | 3.30 | 30.9 | 10.00 | 3.86 | 1.10 | 7.9 | 0.011 | 3.05 | 1.21 | 1.21 | 0.14/0.05 |
| DR4 | 10 | 4.72 | 34.0 | 20.00 | 5.46 | 1.20 | 15 | 0.006 | 3.05 | 1.75 | 1.75 | 0.16/0.07 |
| DR5 | 10 | 4.72 | 33.9 | 20.00 | 5.73 | 1.20 | 16 | 0.003 | 3.05 | 2.30 | 2.30 | 0.18/0.10 |
| DR6 | 10 | 7.08 | 47.0 | 30.00 | 7.02 | 2.00 | 10 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |
| DR7 | 10 | 11.33 | 66.9 | 30.00 | 7.02 | 5.70 | 47 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |
| DR8 | 10 | 16.52 | 77.3 | 30.00 | 7.02 | 11.0 | 11 | 0.002 | 3.05 | 3.05 | 3.05 | 0.20/0.15 |

[a] Entering air-jet properties evaluated at conditions given in table 2 for each DR. The room was designed to house 1000 finishing pigs.
16.0% of the fresh-air enters through planned ceiling inlets for the DR1 and DR2 cases, respectively. This improved to 33.5% and 31.6% for DR1 and DR2, respectively, if the infiltration rate was lowered to OAI levels. If an option exists to lower the operating PD, and still achieve desired air-jet and air distribution performance, these percentages improve as shown at the bottom of table 4 using DR6 as an example. At the OAI infiltration level, and using DR6 as an example, the percent through planned inlets improved to 85.4% at a 10 Pa PD versus 71.2% at a 30 Pa PD. The JMN decreased from 30×10⁻⁴ to 17×10⁻⁴ and in this case was lowered closer to the recommended maximum of 15×10⁻⁴.

**Inlet Design and Placement to Improve Air-Jet and Air Distribution Parameters**

The maximum achievable C\textsubscript{F\textsubscript{row}} and C\textsubscript{F\textsubscript{room}} for the analysis room was 0.20 and 0.15, respectively, an artifact of the inlet length, number of inlets, and the resulting net air-jet throw achieved at each DR condition. For the original inlet system as analyzed (fig. 3a), the maximum possible air-jet spread was 2.37 m, i.e. \((1.18 + 2 \times 3.05 \tan(11°))\) and this, combined with the inlet spacing of 11.7 m, was the driver for this limitation. Since inlet size, inlet spacing, and maximum air-jet throw (3.05 m) dictate coverage factor, a better match of inlet size and performance might improve overall air distribution parameters. If a target of C\textsubscript{F\textsubscript{row\textsubscript{max}}} = 0.50 is used as an example target, and 10 bi-flow inlets per row were selected (20 total inlets), then each inlet would need to have an air-jet spread of 2.93 m, and less the 11° air-jet edge spreading, requires that each inlet be physically 1.74 m long (one of many potential combinations of IL and number of air-jets). Table 5 summarizes air-jet and air distribution parameters if 20-1.74 m long inlets (10 inlets per row) were installed in the same two rows shown in figure 3a, evaluated at the measured OAI rate.

The results shown in table 5, at the OAI rate, indicate that at the minimum assumed inlet opening of 5 mm, notable improvements to C\textsubscript{F\textsubscript{s}} were realized. The operating PD was reduced due to the added inlet area resulting in an increase in the percentage of fresh-air entering through the planned ceiling inlet system. The operating PD for DR1 and DR2 can be increased if the active opening during these conditions is less than the physical 1.74 m long inlet. For example, if at DR1 and DR2, a portion of the inlet length were open, at “full inlet closure,” then air-jet spread requirements along with the required air distribution parameters might be achieved as well (assuming a uniformly distributed partial opening). Figure 4 is an example inlet configured in this manner. For the 10-1.74 m long inlets per row (as in table 5 results), if at full inlet closure only 43.5 cm of a uniformly distributed inlet length existed (i.e., 25% of 1.74 m) with a fixed 1.27 cm inlet opening (at “full inlet closure”), the conditions as shown in table 6 would result. As indicated, the final net air-jet throw for all DRs improved with increases in the potential operating PD. For this hypothetical inlet, any opening/closing movement develops two unique inlet lengths per inlet installed. The cases for DR3 and DR4 are shown in table 6 as an illustration. A myriad of choices exists for the active inlet area (A\textsubscript{j}) at full closure with the air-jet throw (x\textsubscript{t} and x\textsubscript{d}), JMN, and C\textsubscript{F\textsubscript{s}} used as a guide for optimizing a selection.

**Target Air Infiltration Requirements**

AI, even at the OAI levels measured for the analysis room, is at a level that negatively affects air-jet and air distribution performance. The hypothetical inlet proposed with the results shown in table 6 was re-evaluated assuming that OAI was reduced by 50%, 75%, and 100% (i.e., no infiltration) of that measured. The results are shown in table 7 for the DR1 to DR4 conditions. Improvements were made to the operating PD at DR1-DR3 along with improvements to the resulting air-jet detachment distance. Clearly, reducing the OAI to 50% of the field measured OAI value, will significantly improve cold weather ventilation performance. Further improvements to air-jet and air distribution parameters are realized if the AI rates were reduced to 25% and 0% of the field measured OAI levels, as shown in table 7.

As shown at the bottom of table 7, if the room was completely devoid of infiltration, and using the hypothetical 10-1.74 m long inlets per row, the DR1 through DR4 conditions result. These can be compared directly with table 3 results (original inlet set-up as analyzed; no infiltration assumed) and have been reproduced at the bottom of table 7 for ease of comparison.

The significance of the measured OAI for the analysis room, with the inlet system as analyzed, is evident in figure 5a showing the airflow originating from the primary inlet system and OAI areas (fig. 5a) as a function of operating PD. As shown in figure 5a and further evaluated in figure 5b, the contribution from OAI as inlet operating PD increases dominates the total airflow.

**Systematic Ceiling Inlet Design**

For non-isothermal DRs as reviewed in this article, the air-jet detachment distance (x\textsubscript{d}) defines the net effective air-jet throw (fig. 3b depiction). This limitation is in turn negatively affecting the coverage factors. For non-isothermal air-jet behavior, expanding equation 2 results in an overall design equation predicting x\textsubscript{d} which in turn was used to predict the coverage factors for a proposed symmetrical 3D inlet layout. The result is equation 7 as shown below:

<table>
<thead>
<tr>
<th>Table 5. Air-jet and air distribution parameters for the analysis room with 10-1.74 m long inlets installed per row, using measured OAI.(^{[a]})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No of Inlets</strong></td>
</tr>
<tr>
<td><strong>DRs</strong></td>
</tr>
<tr>
<td><strong>ventilation</strong></td>
</tr>
<tr>
<td><strong>(Pa)</strong></td>
</tr>
<tr>
<td>DR1</td>
</tr>
<tr>
<td>DR2</td>
</tr>
<tr>
<td>DR3</td>
</tr>
<tr>
<td>DR4</td>
</tr>
</tbody>
</table>

\(^{[a]}\) Assumes constant discharge coefficient of Cd=0.80 for all inlet settings.
where
\[ \rho_j = \text{density of entering air-jet at a given DR (kg m}^{-3}), \]
\[ \alpha = \{(T_r-T_j)(T_j+273.15)^{0.50})\] for all inlet settings.

For isothermal air-jet behavior, expanding equation 1 results in an overall design equation predicting \( x_j \) which in turn was used to predict the coverage factors for a proposed symmetrical 3D inlet layout. The result is given below.

\[ x_j = \frac{2}{\rho_j} \left[ \frac{V - cPD^n}{m} \right]^{0.25} \]

As was shown in tables 3-7 and considering the size and inlet layout (fig. 3a) of the analysis room, isothermal air-jet throw \( (x_j) \) rarely predicted a level less than \( x_{t,max} \) (3.05 m).

### Table 6. Air-jet and air distribution parameters for the analysis room with 10-1.74m long inlets installed per row, with 25% of the baffle length (0.435 m) fixed at a 1.27 cm opening at full inlet closure.[a]

<table>
<thead>
<tr>
<th>Drs Used</th>
<th>Rate (m³s⁻¹)</th>
<th>System</th>
<th>% Fresh-air through Ceiling Inlet</th>
<th>Achievable PD across the Room (m)</th>
<th>JMN (x 10⁻⁴)</th>
<th>Ar</th>
<th>Non-isothermal isopotential (m)</th>
<th>CF iso/CF non</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR1 10</td>
<td>0.94</td>
<td>42.9</td>
<td>3.50</td>
<td>2.28</td>
<td>1.27</td>
<td>1.3</td>
<td>0.025</td>
<td>0.35/0.52</td>
</tr>
<tr>
<td>DR2 10</td>
<td>1.42</td>
<td>40.8</td>
<td>7.20</td>
<td>3.28</td>
<td>1.27</td>
<td>2.6</td>
<td>0.001</td>
<td>0.52/0.79</td>
</tr>
<tr>
<td>DR3 10</td>
<td>3.30</td>
<td>66.1</td>
<td>11.30</td>
<td>4.14</td>
<td>1.27</td>
<td>8.2</td>
<td>0.010</td>
<td>1.45/1.45</td>
</tr>
<tr>
<td>DR4 10</td>
<td>4.72</td>
<td>62.4</td>
<td>13.18</td>
<td>5.44</td>
<td>1.27</td>
<td>16</td>
<td>0.005</td>
<td>2.00/2.00</td>
</tr>
</tbody>
</table>

[b] Results using OAI in direct comparison to table 6 results. Assumes constant discharge coefficient of Cd=0.80 for all inlet settings.

[c] 1.74 m long inlet, at full closure, has a fixed 1.27 cm wide inlet 0.435 m long (25% of the physical inlet length), uniformly distributed.

[d] The inlet has opened 0.635 cm, resulting in a 1.91 cm wide inlet along 0.435 m of the inlet, with the balance at 0.635 cm.

### Table 7. Air-jet and air distribution parameters for the analysis room with 10-1.74m long inlets installed per row, with 25% of the baffle length (0.435 m) fixed at a 1.27 cm opening at full inlet closure.[a]

<table>
<thead>
<tr>
<th>Drs Used</th>
<th>Rate (m³s⁻¹)</th>
<th>System</th>
<th>% Fresh-air through Ceiling Inlet</th>
<th>Achievable PD across the Room (m)</th>
<th>JMN (x 10⁻⁴)</th>
<th>Ar</th>
<th>Non-isothermal isopotential (m)</th>
<th>CF iso/CF non</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR1 10</td>
<td>0.94</td>
<td>58.3</td>
<td>6.40</td>
<td>3.09</td>
<td>1.27</td>
<td>1.3</td>
<td>0.025</td>
<td>0.35/0.52</td>
</tr>
<tr>
<td>DR2 10</td>
<td>1.42</td>
<td>56.1</td>
<td>13.50</td>
<td>4.49</td>
<td>1.27</td>
<td>3.8</td>
<td>0.006</td>
<td>0.52/0.79</td>
</tr>
<tr>
<td>DR3 10</td>
<td>3.30</td>
<td>78.9</td>
<td>16.20</td>
<td>4.92</td>
<td>1.91/0.635</td>
<td>9.5</td>
<td>0.007</td>
<td>1.45/1.45</td>
</tr>
<tr>
<td>DR4 10</td>
<td>4.72</td>
<td>86.4</td>
<td>22.00</td>
<td>5.73</td>
<td>1.91/0.635</td>
<td>16</td>
<td>0.005</td>
<td>2.00/2.00</td>
</tr>
</tbody>
</table>

[a] Results using 50%, 25%, and 0% of room measured OAI in direct comparison to table 6 results. Assumes constant discharge coefficient of Cd=0.80 for all inlet settings.

[b] The 1.74 m long inlet, at full closure, has a fixed 1.27 cm wide inlet 0.435 m long (25% of the physical inlet length), uniformly distributed.

[c] The inlet has opened 0.635 cm, resulting in a 1.91 cm wide inlet along 0.435 m of the inlet, with the balance at 0.635 cm.
and thus can be defaulted to $x_{c,max}$ with little error (for this analysis room).

Finally, the fraction ($f$) of fresh-air entering through the planned ceiling inlet system is

$$f = 1.0 - \frac{cPD^n}{V}$$  \hspace{1cm} (8)

with the required physical individual air-jet area ($A_o$) determined as

$$A_o = \left[ \frac{V - cPD^n}{mCDv_e} \right]$$  \hspace{1cm} (9)

and $CF_{row}$ and $CF_{room}$ determined using $x_d$ (fig. 3b).

Figures 6 and 7 summarize the results for DR1-DR4 considering 100% and 50% of measured OAI, respectively. These figures compare the as-analyzed inlet system (‘1’; $IL=1.18$ m, $k=5$, $m=20$) and the hypothetical inlet system (‘2’; $IL=1.74$ m, $k=10$, $m=40$) in terms of the fraction of fresh-air entering through the primary inlet system (6a, 7a), the non-isothermal air-jet detachment distance (eq. 7; 6b, 7b), the row coverage factor (eq. 6; 6c, 7c), and the individual air-jet area required ($A_o$; 6d, 7d). In figures 6 and 7, the air-jet area is determined using equation 9 assuming a constant $Cd=0.80$, resulting in slight differences between table results and figures 6 and 7 results.

Comparing inlet systems (‘1’ vs. ‘2’) at the measured OAI rate, significant improvement in the row coverage factor is shown for the hypothetical inlet system (fig. 6c2) versus the as-installed system (fig. 6c1); an artifact of the $CF_{row}=0.50$ design criteria for the hypothetical inlet system. To achieve these improved $CF_{row}$ levels, the individual air-jet area $A_o$ needed to be significantly reduced as shown in figure 6d2 versus figure 6d1, leading to the prior discussion on the need for a dual-opening inlet. The results are useful in assessing inlet design options and the overall influence of AI on expected performance. For example, operating the analysis room at the measured OAI, with the as-analyzed inlet system, indicates that the maximum achievable $x_d$ is 0.56 m and 0.85 m for DR1 and DR2 (fig. 6b1), and these occur at operating PDs of about 5 and 10 Pa, respectively, as was previously shown in table 4. Reducing the OAI to 50% of the measured OAI significantly improves predicted $x_d$ as shown in figures 6b1,2 versus 7b1,2.

**CONCLUSIONS**

Ventilation system air-jet and air distribution performance, as part of a larger infiltration quantification study, was evaluated to determine the influence of measured infiltration on these parameters. The analysis conducted support the following conclusions:

1. Air-jet and air distribution parameters suggested for evaluating SFRs were negatively affected by the level of field measured infiltration.
2. The influence of air infiltration can be reduced by lowering the operating PD, provided air-jet and air distribution parameters are not compromised.
3. Buoyant force on air-jets had a significant influence on the effective net air-jet throw for SFR cold weather ventilation rates and this was exacerbated by the level of field measured infiltration.
4. Air-jet and air distribution parameters, along with known infiltration levels, can be used in a systematic way to maximize air-jet throw, jet momentum, and air-jet spread to optimize fresh-air distribution in SFRs.
5. Significant effort will be required to minimize infiltration in existing swine finishing rooms and designed into new swine finishing rooms to optimize ventilation system performance with results from the analysis room suggesting a reduction to 50% of field measured ‘other air infiltration (OAI)’ levels required, and
6. Significant effort is required to quantify and catalog in-field 3D ceiling inlet performance for inlets commonly used in animal housing systems, as affected by buoyancy, discharge coefficient, and ceiling roughness.
Figure 6. Summary of DR1-DR4 operation with 100% of measured OAI considered. (a) Primary inlet fresh-air fraction, (b) air-jet detachment distance, (c) row coverage factor, and (d) individual air-jet area \( A_o \) required (assumes constant \( C_d = 0.80 \)) for the ('1') as analyzed inlet system and the ('2') hypothetical inlet system.
Figure 7. Summary of DR1-DR4 operation with 50% of measured OAI considered. (a) Primary inlet fresh-air fraction, (b) air-jet detachment distance, (c) row coverage factor, and (d) individual air-jet area $A_o$ required (assumes constant $C_d=0.80$) for the ('1') as analyzed inlet system and the ('2') hypothetical inlet system.
ACKNOWLEDGEMENTS

The authors wish to thank the Iowa Pork Producers Association for funding this research project under contract Ventilation improvements for controlling swine production systems, NPB Project 13-213. Authors are also grateful to the Indian Council of Agricultural Research, New Delhi for fellowship funding for Dr. H. T. Jadhav. Finally, this work would not have been possible without the support from Katlyn DeVoe, M.S., E.I.T., Craig Blass E.I.T., and Jessica Miller.

REFERENCES


