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INFLUENCE OF FAN OPERATION ON FAN ASSESSMENT NUMERATION SYSTEM (FANS) TEST RESULTS

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ABSTRACT OF THESIS

INFLUENCE OF FAN OPERATION ON FAN ASSESSMENT NUMERATION SYSTEM (FANS) TEST RESULTS

The use of velocity traverses to measure in-situ air flow rate of ventilation fans can be subject to significant errors. The Fan Assessment Numeration System (FANS) was developed by the USD-ARS Southern Poultry Research Laboratory and refined at the University of Kentucky to measure air flow of fans *in-situ*. The procedures for using the FANS unit to test fans *in-situ* are not completely standardized. This study evaluated the effect of operating fan positions relative to the FANS unit for ten 1.22 m diameter fans in two types of poultry barns, with fans placed immediately next to each other and 1.6 m apart. Fans were tested with the FANS unit placed near both the intake and discharge sides of the tested fans. Data were analyzed as two Generalized Randomized Complete Block designs (GRCB), with a 2 (FANS inside or outside) x 6 (operating fan combinations) factorial arrangement of treatments. Results showed significant differences as much as 12.6 ± 4.4% between air flow values obtained under conditions of different operating fan combinations. Placing the FANS unit outside provided valid fan test results. A standardized procedure for using the FANS unit to test fans *in-situ* was elaborated and presented in this work.

KEYWORDS: Fan Assessment Numeration System (FANS), Fan Performance, Ventilation Rate, *In-Situ* Fan Performance, Poultry Houses.

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THESIS

Gabriela Munhoz Morello

The Graduate School

University of Kentucky

2011

INFLUENCE OF FAN OPERATION ON FAN ASSESSMENT NUMERATION SYSTEM (FANS) TEST RESULTS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biosystems and Agricultural Engineering At the University of Kentucky

By

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Lexington, Kentucky

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2011

To those who inspire and guide me

on accomplishing my dreams.

Àqueles que me inspiram e conduzem

a realizar meus sonhos.

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CHAPTER 1
INTRODUCTION

1.1 Summary

The FANS (Fan Assessment Numeration System) Unit is a device that was developed to measure fan performance *in-situ*. Testing a fan *in-situ* provides the actual fan performance as it is installed and operating with all accessories in place. The FANS device was invented by the USDA-ARS Southern Poultry Research Laboratory (Simmons *et al.*, 1998) and refined at University of Kentucky (Gates *et al.*, 2004, Sama *et al.*, 2008).

The FANS Unit has been adopted as a reference method of measuring *in-situ* fan performance (air flow versus static pressure) in livestock barns for numerous field research projects. Researchers take the FANS unit to livestock barns, place it against the intake or discharge side of the test fan and measure air flow for different values of barn static pressure, so that fan performance curves can be built. However, procedures for using FANS units to conduct *in-situ* fan tests are not completely standardized.

One procedure for changing barn static pressure is to turn on and off different fans inside a barn. Morello *et al*. (2010) studied the effect of different fans operating inside a barn on fan test results using a 1.22 m FANS unit when placed next to the intake side of the test fans and verified that the FANS unit provided significant differences in air flow as a function of its position relative to the other operating fans in the barn. There is no true guideline developed describing the procedure for testing fans using the FANS unit *in-situ*, thus, a more complete study of static pressure management during fan tests with the FANS unit is needed in order to avoid possible air flow penalties during fan tests *in-situ*.

The purpose of this study was to determine how the operation of different fan combinations during *in-situ* fan performance tests affect results obtained from a FANS unit, as well as to elaborate a procedure of using the FANS unit *in-situ* which minimizes possible air flow penalties. Tests were conducted in ten tunnel ventilated broiler barns, and one or two 1.22 m diameter exhaust fans per barn were chosen for repeated testing while different combinations of fans were operated.

1.2 Justification

The FANS unit measures fan performance *in-situ*. Ventilation fans are tested under their actual conditions, including present state of maintenance, dust and dirt on blades and shutters, belt and pulley wear, and blade and pulley replacements. Casey *et al.* (2008) found that fans presented differences in fan performance up to 24% owing to dirt and corrosion, resistance to flow imposed by different shutters (made of aluminum or plastic), differences in motor, as well as bearing wear (run time and age).

FANS units have been adopted in building emissions studies as well as to test fan performance inside animal housing. Gates *et al.* (2005) presented a method of measuring ammonia emission from poultry barns, in which ventilation rate was obtained from fan performance curves (air flow vs. static pressure) provided by a FANS unit. The total ventilation rate obtained was then used to calculate ammonia emission rates in poultry barns. Gay *et al.* (2006) determined ammonia emission rates in four tom turkey houses (two brooder and two growout). Liang *et al.* (2005) and Wheeler *et al.* (2006) used similar methods for layer and broiler housing, respectively.

These researchers all obtained ammonia concentrations by using electrochemical sensors in a PMU (portable monitoring unit). Ventilation rates were obtained from fan performance curves, which were established by using a FANS unit. In this study, all individual fans in the growout houses were tested with a FANS unit over a range of static pressure from 0 to 60 Pa. More recently, numerous researchers working under the U.S. EPA (Environmental Protection Agency) Air Consent Agreement have determined baseline emissions for dairy, swine and poultry. FANS units were used in most cases to provide calibrations for mechanically ventilated buildings used in the study (Moody *et al.*, 2008).

FANS units have been thoroughly tested and calibrated inside laboratory, however, it is not known if the FANS units may affect the results of a fan tested *in-situ* when nearby fans are operating simultaneously. Simmons *et al.* (1998) studied the effect of proximity of adjacent 1.22 m diameter fans on the volumetric flow rates of each fan and detected a substantial reduction in air flow rate when adjacent fans were 0.3 m from each other. Li *et al.* (2009) studied the effect on fan test results when using a FANS unit placed next to the intake side of the test fan versus placing the unit near the discharge of a test fan and sealing it to the FANS unit with a non-permeable fabric. Less than 5% differences, not statistically significant, were found on FANS test results when the unit was placed next to the intake side of the test fan as compared to the discharge side of it. However, no standardized methodology exists relative to which fans or how many fans can be turned on and off in order to control the static pressure.

An evaluation of fan performance obtained with FANS units with different conditions of fan tests in the barn is needed to develop a procedure for testing fans *in-situ*. The objective of this study was, therefore, to determine how the operation of different fan combinations during *in-situ* fan performance tests affect results obtained from a 1.22 m FANS unit, as well as to elaborate a procedure of using the FANS unit *in-situ* which minimizes possible air flow penalties.

1.3 Objectives

1.3.1 Goal

The goal of this study was to evaluate the effect of different operating fan combinations relative to a FANS unit and test fan position and, based on the results of this evaluation, to develop a standardized procedure for testing ventilation fans *in-situ* using FANS.

1.3.2 Specific Objectives

1. Assess the influence of the position of different operating fan combinations on the fan performance curve obtained using a 1.22 m FANS unit.

2. Assess the effect on fan test results using a 1.22 m FANS unit placed near the intake side versus the discharge side of the test fan.

3. Evaluate if the FANS unit is the cause of possible differences in fan performance results by analyzing the interaction between the effects of operating fans combination (1) and placing FANS near the intake or discharge sides of the FANS (2).

CHAPTER 2
LITERATURE REVIEW

Measuring fan performance *in-situ* is essential to obtain information about the actual performance of a determined fan. Section 2.1 of this work presents an overview of fan performance curves. Zhu *et al.* (2000) reported that ventilation rate plays a key role in determining the gas and odor emissions rates for animal buildings. Gates *et al.* (2009) described the uncertainty analysis for a measurement system used in emissions research. The authors concluded that emission rate uncertainties are primarily associated with the uncertainty of building ventilation rate estimate. The authors reported that the ventilation rate uncertainty contributed to 78% and 98.9% of emission rate uncertainty for a 5% and 25% standard uncertainty in fan ventilation rate measurement, respectively. Gates *et al.* (2009) inferred that the use of an accurate method for building ventilation rate measurement, such as the FANS unit, is critical in controlling uncertainty in emission rate.

Several factors cause the fan performance to degrade over time, such as dust and dirt accumulation on the blades and belt wear (Bottcher *et al.*, 1996). Casey *et al.* (2008) reported up to 24% variation in fan performance attributed to accumulated dirt and corrosion, resistances imposed by shutters, as well as motor and bearing wear due to run time and aging. Janni *et al.* (2005) monitored sow gestation barns for emissions of ammonia (NH_3), carbon dioxide (CO_2), hydrogen sulfide (H_2S), odor, and particulate matter, 10 μm or less (PM_{10}). Fan performances were obtained using a FANS unit and it was found that the air flow was reduced by 30 to 60% when the fan drive belts were slightly loose compared to the air flow obtained when the belts were properly tightened.

Casey *et al.* (2006) reported three main methods of obtaining air flow rates *in-situ* which have been used to estimate ventilation rates in mechanically ventilated facilities. One of the methods is the FANS unit method, which is described in Section 2.5 of the present work. The second method is based upon the CO_2 and heat produced by the livestock, as described in Section 2.2. The third method is based upon the use of the manufacturer`s data of fan performance and static pressure measured in the building

(Section 2.3). There are several other methods that can be used for assessing barn ventilation rate, as well as fan performances and a few examples of them are given in Section 2.4.

2.1 Fan Performance Curve

A combination of efficiency, relative cost, acoustics and physical size should be considered when selecting a fan to provide a specific air flow rate (McQuiston, 2005). The efficiency is related to a fan`s capacity for moving air at the operational static pressure and to the power consumption. Fan performance curves provide useful data for fan selection, as well as information about the fan and system interaction. Also, building ventilation rates can be estimated from fan performance curves. These curves are obtained by measuring air flow rate of fans at different values of system static pressure. Air flow rate can be regressed as a second order polynomial function of static pressure, as illustrated in Figure 2.1.

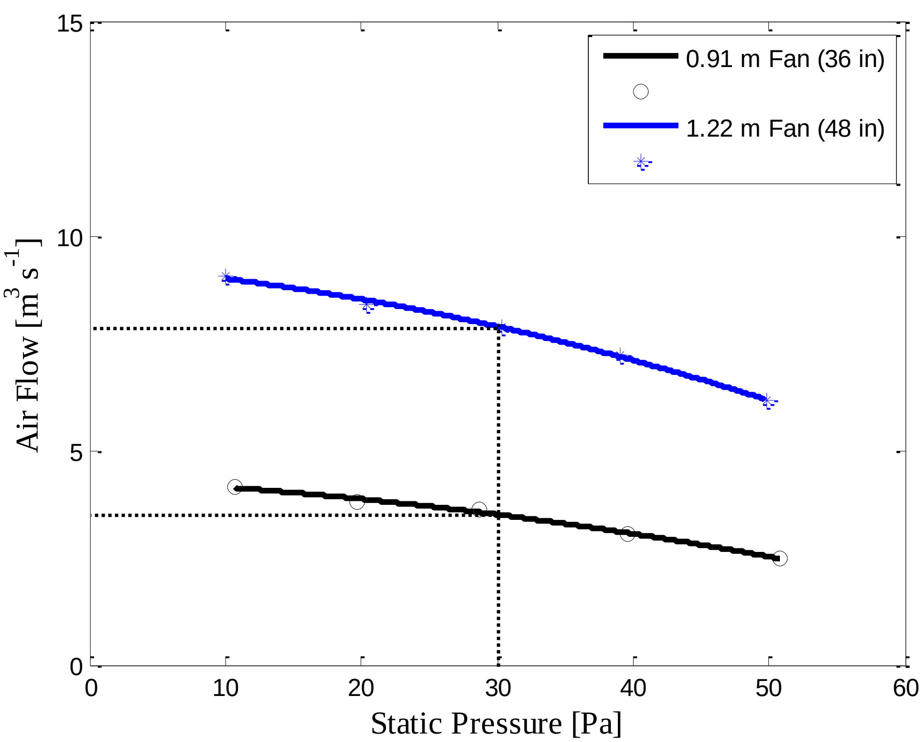

Figure 2.1. Example of fan performance curves.

Figure 2.1 shows examples of fan performance curves obtained with a 1.22 m FANS unit for a 0.91 m and a 1.22 m diameter fan. Both fans have plastic shutters and fiber glass housing. The 1.22 m diameter fan was also equipped with a plastic discharge cone. Fan tests were run at five values of static pressure (10, 20, 30, 40, 50 Pa), which are common static pressure conditions inside poultry barns. The vertical and horizontal lines in Figure 2.1 indicate the fan performances at 30 Pa. The 0.91 m diameter fan was capable of moving approximately 3.5 $m^3\ s^{-1}$ at 30 Pa, while the 1.22 m diameter fan was capable of moving approximately 7.8 $m^3\ s^{-1}$ at the same static pressure.

The system, such as livestock buildings, interacts with fan performance, thus fan performance curves can be plotted with system curves to determine the real fan performance in a building (Figure 2.2). The real fan performance is important information to determine number and size of fans that can provide enough air flow or the air velocity necessary in a building.

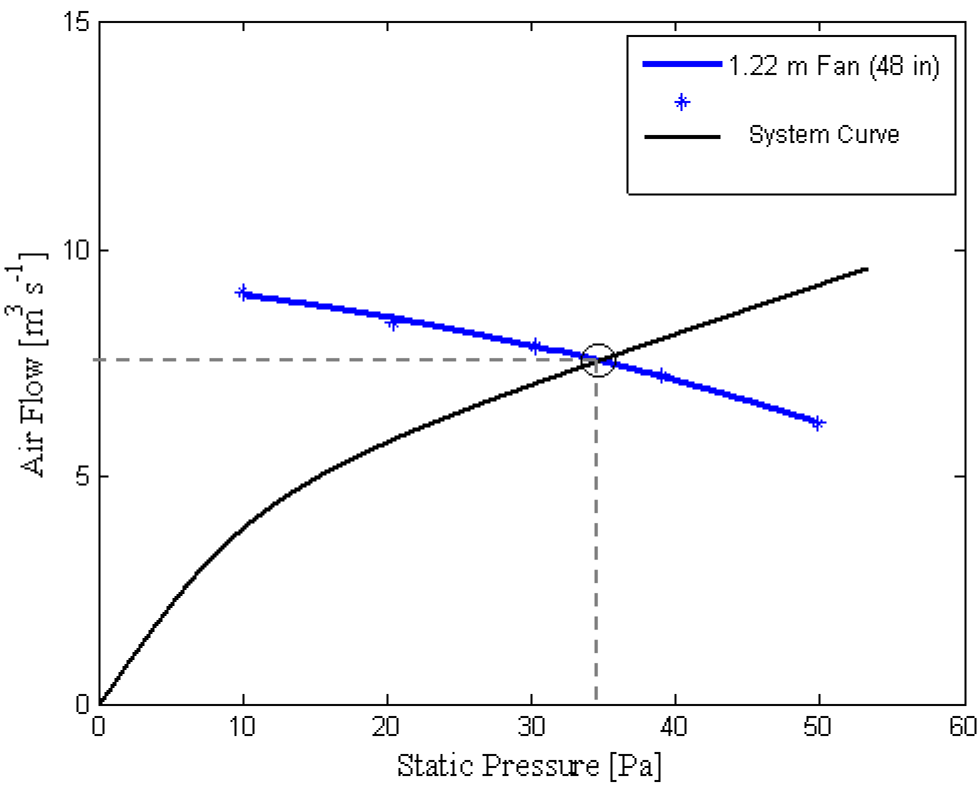

Figure 2.2. 1.22 m diameter fan and system performance curves.

Figure 2.2 shows an example of a 1.22 m diameter fan and system performance curves. If the 1.22 m diameter fan of Figure 2.2 is added to the system, the system will operate at a static pressure of 35 Pa and the fan will move approximately 7.5 $m^3.s^{-1}$. If instead of one fan, two 1.22 m diameter fans were added to the same system, the static pressure in the building would be higher and the fans would operate at a lower capacity.

Fan performance curves can also contribute to assessing building leakage. Lopes *et al.* (2010) evaluated the air leakage in 14 poultry barns located in Kentucky, U.S.A. Fan performance curves were obtained with a FANS unit for representative fans in each of the 14 buildings. The barn was then completely closed and different fan combinations were energized and the static pressure was recorded. The previously determined fan performance curves were used to calculate the amount of air leaking at the recorded static pressure values.

The ventilation rate in the building can be estimated once fan performances, fan operation time and system static pressure are known. Ventilation rate provides essential information for emission calculations, energy efficiency studies and potential building modification. Fan performance curves provide a clear and simple way of evaluating fan capacity at different static pressure conditions.

2.2 Measuring Ventilation Rate – Indirect Animal Calorimetry

Ventilation rate can be obtained from mass balance methods, which are governed by indirect calorimetry relationships. Gates *et al.* (2005) proposed using the FANS unit and indirect CO_2 balance as methods for determining ventilation rates at poultry barns, in ammonia emission studies. These methods have been successfully used to establish baseline values of ammonia emissions for the U.S.A.

Li *et al.* (2005) compared direct and indirect measurements of ventilation rate obtained from fans located in layer barns using manure belts. Direct measurement of ventilation rate was performed using a FANS unit, whereas the indirect ventilation rate measurement was accomplished using the CO_2 balance method, based on the principle of indirect animal calorimetry. The indirect method relied primarily on updated metabolic rate of birds. Daily manure removal allowed the CO_2 emission from manure to be neglected. The indirect method was shown to be a viable alternative to determine building ventilation rate in this work.

Liang *et al.* (2005) investigated ammonia emissions from U.S.A. laying hen houses in Pennsylvania and Iowa and used the CO_2 balance method to calculate the building ventilation rates. Two electrochemical ammonia sensors and an infrared CO_2 sensor were used in a Portable Measurement Unit (PMU) for this study. Ammonia and CO_2 concentrations were measured in cycles consisting of 24 min purging with fresh outside air and 6 min sampling of the exhaust air stream to avoid errors caused by the saturation of electrochemical sensors owing to continuous exposure to ammonia-laden air. Equation 2.1 shows how the ventilation rates are calculated from the CO_2 balance in the buildings.

$$Q = \frac{(\mathrm{CO2, bird} + \mathrm{CO2, manure})\ \mathrm{x}\ 3600}{[\mathrm{CO2}]\mathrm{e} - [\mathrm{CO2}]\mathrm{i}} \qquad \text{Equation 2. 1}$$

Where,

Q = Ventilation rate of building;

CO_2, bird = Rate of production of CO_2, from birds;

CO_2, manure = Rate of production of CO_2, from manure;

$[CO_2]$e = CO_2 concentration in the exhaust air from the building;

$[CO_2]$I = CO_2 concentration in the incoming air from the building.

This method of obtaining ventilation rate has long been recognized and explored (Liang *et al.*, 2005). However, this method depends on heat production data from the literature and/or estimations of the bird and manure production of CO_2. Liang *et al.* (2005) derived bird CO_2 production from recently updated total heat production (THP) and respiration quotient (RQ) for laying hens of different ages. Manure CO_2 production was experimentally obtained during downtime (in between flocks), by monitoring CO_2 concentration when one to four fans were operating at different static pressures. Also, the four fans used for determining manure CO_2 production rates were calibrated using a FANS unit.

Xin *et al.* (2009) compared ventilation rates obtained directly by continuously measuring fan performance through the FANS unit method with the indirect methods of estimating building ventilation rate by CO_2 balance or by CO_2 concentration difference. This last method consisted of regressing ventilation rate as a function of CO_2 concentration difference between the inside and outside of broiler barns. The authors verified that both indirect methods of estimating ventilation rate were not significantly different from the direct measurement of ventilation rate for an averaging period of 30 min. The authors emphasized that the use of up-to-date metabolic rate data for the animals is imperative in deriving the CO_2 balance ventilation rate to maximize the quality of the results.

The CO_2 balance method can be used to estimate ventilation rates of naturally ventilated houses, where the use of fan-wheel anemometers to measure the building air flow rate would be labor intensive and expensive to install (Phillips *et al.*, 1998). However, the use of this CO_2 production technique is less accurate than the direct measurement of ventilation rate. Also, certain heat production data from literature dating 20 to 50 years ago has been questioned because of the significant advancement in animal genetics and nutrition (Casey *et al.*, 2006).

Chepete and Xin (2002) performed a comprehensive review and comparative analysis of poultry heat production (HP) and moisture production (MP) data in the literature. The authors found that poultry total heat production (THP), sensible heat production (SHP), latent heat production (LHP) and MP substantially changed over the years owing to factors such as genetics, nutrition, housing and management improvements. This study demonstrated the need to conduct an intensive and systematic program of research to update HP and MP for modern poultry.

Chepete and Xin (2004) evaluated the effects of applying newly collected bird SHP and MP data versus relatively old literature data to design ventilation rates in laying hen barns. The authors evaluated SHP and MP data at the bird level and the room level (birds and surroundings). Chapete and Xin (2004) found that ventilation rate obtained using the old room level SHP and MP data was 10% higher and 18% lower for temperature control and moisture control, respectively, than ventilation rate calculated from new room level data. Also, ventilation rate obtained from the old bird level SHP and MP was 5% higher and 57% lower for temperature and moisture control, respectively than ventilation rate derived with new bird level data.

2.3 Measuring Ventilation Rate – Manufacturer Fan Performance Curves

Gay *et al.* (2003) quantified odor, total reduced sulfur (TRS) and ammonia levels emitted from 200 distinct animal facilities in Minnesota. During their study, static pressure was measured and ventilation rates for mechanically ventilated houses were calculated by summing the air flow from all of the fans in the facilities, obtained from fan performance curves provided by the manufacturers. The authors developed a valuable database on odor, TRS and ammonia emissions for the Minnesota livestock producers. The emission data obtained from swine and dairy were similar to data provided by other researchers.

Ni *et al.* (1998b) studied the ammonia emission of a grow-finish swine building with a deep pit. Ventilation rate was calculated by summing all the air flow from the fans in the barns. Fan air flow was calculated from an equation of air flow as a linear function of static pressure, obtained from the manufacturer. The authors quantified ammonia emissions from the swine facility and found a higher mass of ammonia emitted per day per 500 kg of pig than emission values from other studies. They attributed their higher emission rates per 500 kg of pig mainly to the warm summer weather during this experiment.

Researchers have used the manufacturer fan performance data to calculate ventilation rates in animal buildings. However, there are some factors to be considered when using this method to estimate air flow rates. When fans are mounted inside animal houses, there are a few accessories that are added to fans, such as shutters, cones and safety guards. When there is dirt accumulation in any of these accessories or corrosion of blades fan performance can be altered.

Casey *et al*. (2008) reported up to 24% variation in fan performance attributed to accumulated dirt and corrosion, resistances imposed by shutters, as well as motor and bearing wear due to run time and aging. When comparing the manufacturer fan performance curve with the *in-situ* fan performance curves, Casey *et al*. (2008) found that the manufacturer curve provided air flow up to 21% higher than the air flow obtained *in-situ* from the worst performing fan in one of the experiment sites and up to 14% lower air flow than the best performing fan in another experiment site.

A few other design factors, such as outer diameter, blade numbers, shapes and angles affect fan performances. Wang *et al*. (2010) studied the influence of these design factors on the performance of small cooling fans. The authors found that within the same blade height, air flow rate increases with the increasing blade twist angle. Also, within the same revolution, the air velocities were found to increase from the hub surface to the tip of the blades. Many times, animal producers will replace fan blades and other accessories that are damaged or corroded, which could change the original fan performance, measured by the manufacturer, demonstrating the importance of *in-situ* fan performance measurements.

Janni *et al*. (2005) monitored sow gestation barns for emissions of ammonia (NH_3), carbon dioxide (CO_2), hydrogen sulfide (H_2S), odor, and particulate matter 10 μm or less (PM_{10}). Fan performances were obtained using a FANS unit and it was found that the air flow was reduced by 30 to 60% when the fan drive belts were slightly loose compared to the air flow obtained when the belts were properly tightened. Therefore, factors such as belt wear and slippage can cause substantial under ventilation in the barns. Using the fan performance data from the manufacturers to calculate ventilation rates could overestimate the total air flow in barns where fans have different belt condition from the original design.

Bottcher *et al.* (1996) measured the speed of fans of 0-5 versus 5 years of age. The authors found significant differences in RPM Performance Ratio (RPR) between the new and older fans. RPR was slightly lower for the older fans. Also, belt wear alone reduced fan speed by up to 20%, even with the belts under appropriate tension. Bottcher *et al.* (1996) inferred that timely replacement of belts is essential to keep the fan performance closer to original specifications and emphasized that measuring fan speed of fans inside facilities may be necessary to diagnose ventilation problems, since air flow is proportional to fan speed.

During the present study, one fan was tested with the original driving pulley (outer diameter of 87.76 mm) and with a new larger pulley (outer diameter of 95.17 mm). The test was performed at Farm 1 (Section 3.1.1). Fan curves were obtained with a 1.22 m FANS unit for five values of static pressure (10, 20, 30, 40, 50 Pa), as shown in Figure 2.3.

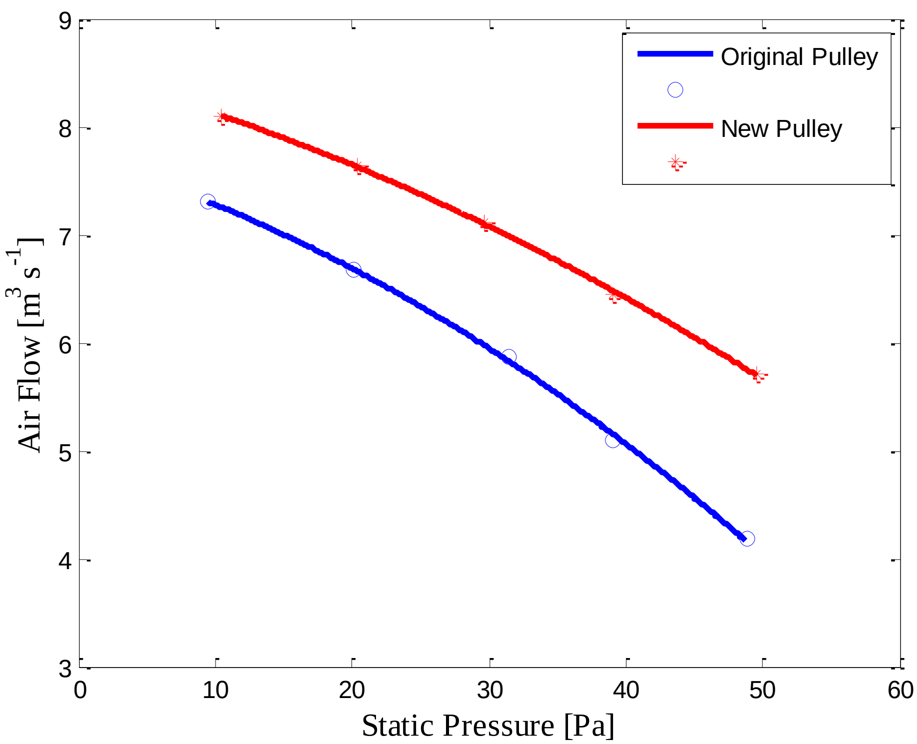

Figure 2.3. Fan performance – Farm 1, same fan – old vs. new pulley.

The new driving pulley was larger than the original one, thus the diameter ratio between the new driving pulley and the driven pulley was reduced, thus increasing the fan rotational speed. Test results showed that the fan moved approximately 20.2 ± 8.9 % more air with the larger driver pulley than it did with the original pulley for all values of static pressure measured. Also, the fan rotated 8.98 ± 0.08 % faster with the larger driver pulley for all values of static pressure measured. Despite the drop in fan efficiency, increase in motor wear and possible safety issues related to the pulley replacement, the fan capacity was improved and, for this reason, the producer replaced the original driving pulley with the larger one. Ventilation rate information in this type of situation should only be measured *in-situ*, once the manufacturer fan performance data is no longer applicable to this fan.

2.4 Alternative Methods for Measuring Ventilation Rate or Fan Air Flow *in -situ*.

Lima *et al.* (2010) evaluated negative and positive pressure ventilation systems in poultry buildings. The author studied the litter quality, environmental conditions, as well as ammonia and carbon dioxide emissions from poultry barns equipped with either ventilation system. Fan ventilation rate was obtained through the traverse method (ASHRAE, 2005), using a *hot-wire* anemometer. Lacey *et al.* (2003) studied particulate matter and ammonia emission factors for tunnel ventilated broiler houses and used a vane thermo–anemometer (451126, Extech, Waltham, Mass.) to measure building ventilation rates. However, velocity rates were not obtained at the fan cross sections, but from 15 points across the building section, 40 m from the house exhaust end.

The fan traverse method consists of a straight average of individual point velocities measured in the center of equal areas over the plane through which the air is flowing. The velocities can be determined by the Log – Tchebycheff (log-T) rule, which is recommended for rectangular ducts, or by the equal – area method (ASHRAE, 2005). When using the Log – T rule in a rectangular duct, a minimum of 25 measurement points should be used, whereas for a circular duct the Log-Linear method should be used at three symmetrically disposed diameters. The traverse measurement may be performed with various types of anemometers. This method is effective, however it requires time and implies labor to measure air velocities at many different points.

The hot-wire anemometer consists of a Thermal Resistance Device (RTD), thermocouple junction or thermistor sensor enclosed within the end of a probe (ASHRAE, 2005). Hot – wire anemometers measure air velocity directly and are able to sense low air velocities (from 0 to 0.51 m s^{-1}) with a typical accuracy of 2 to 5% over the entire velocity range. However, the hand–held type of hot-wire anemometer has a few limitations for its use in the field. The unidirectional sensor, for example, must be carefully aligned in the air stream to achieve accurate results. Also, the sensor must be kept clean, since its calibration can be compromised by dirt or contaminants. Although the sensor provides a high speed response, there may be fluctuating velocity measurements for turbulent flows.

Vane anemometers are light wind-driven wheels connected through a gear train to a set of recording dials that read linear distance of air passing during a period of time (ASHRAE, 2005). This type of anemometer is available in different sizes and each one requires individual calibration. This type of anemometer has limitations at low air velocities. Many vane anemometers have starting speeds of 0.25 m s^{-1} and do not sense extremely low air velocities as well as the hot-wire anemometer.

Demmers *et al.* (1999) evaluated ammonia emissions from two mechanically ventilated livestock buildings in the UK. A tracer gas (CO) method was used for measuring ventilation rates from naturally ventilated livestock buildings. The ventilation rates were compared to the rates estimated using fan wheel anemometers and significant correlations were found between the estimated ventilation rate using the tracer method and the measured ventilation rate using fan wheel anemometers.

The tracer gas method is performed by introducing a known mass of tracer into a building and estimating the ventilation rate using the equation of conservation of mass (Equation 2.2, Demmers *et al.*, 1999).

$$Q(t) = \frac{\varphi p\ (t)}{\mathrm{Ci(t)} - \mathrm{Ce(t)}} \qquad \text{Equation 2.2}$$

Where,

Q(t) = Ventilation rate;

φp (t) = Tracer production rate;

Ci(t) = Internal tracer concentration;

Ce(t) = Background tracer concentration.

Demmers *et al.* (1999) chose carbon monoxide (CO) as a tracer gas, because its density is similar to air density, it is reasonably chemically inert and has a low background concentration. Also, an introduced tracer provides more accurate ventilation rates than tracers resulting from animal metabolic activities, such as carbon dioxide or heat. Although the authors found ventilation rates to be 6 to 12% underestimated compared to the direct method of measuring air flow rate, this variation is generally accepted for the gas tracer method of estimating building ventilation.

The difficulties with this method include keeping the CO concentrations within maximum allowable and minimum measurable limits, identifying all air inlets and outlets in the buildings, delayed response in CO concentrations to changes in the CO release and to variation in the ventilation rate. Also, perfect air mixing in the building is assumed to use the gas tracer method, which can result in uncertainty in the calculation of ventilation rates.

Maghirang *et al.* (1998) evaluated a freely rotating propeller to measure fan air flow rates in livestock buildings. The device consisted of two 20 cm blades that rotated freely in proportion to the flow rate moved by test fans. A photoelectric sensor was placed on each blade to measure the rotational speed of the impeller, while a power supply/display unit monitored and recorded the measured speeds. The impeller device was validated in a wind tunnel test chamber constructed according to the Air Movement and Control Association AMCA Standard 210-85 and air flow was regressed as a linear function of the impeller rotational speed.

Strong relationships between air flow and impeller rotational speed were obtained in the laboratory. Still, care should be taken when using this device to test fans *in – situ*.

Reductions in performance of test fans of up to 12.8% were found during the field tests. These reductions were related to the size of test fans and to static pressure conditions, when the impeller was placed next to the intake of a test fan. According to the authors, reduction in air flow can be accounted for the pressure loss associated with the impeller and by the restriction in air flow associated with the duct where the impeller was mounted. The authors, therefore, suggested that larger diameter ducts could be used to minimize pressure loss during fan tests. On the other hand, placing the impeller device on the discharge side of the test fan tended to increase the air flow moved by 41cm and 51cm fans in up to 11.8%.

2.5 Measuring Ventilation Rate - FANS Unit

2.5.1 Design Features

The FANS (Fan Assessment Numeration System) Unit is a device that was developed to measure fan performance *in-situ*. Testing a fan *in-situ* provides the actual fan performance as it is installed and operating with all accessories in place. The FANS unit was invented by the URSDA-ARS Southern Poultry Research Laboratory (Simmons *et al.*, 1998) and refined at University of Kentucky (Gates *et al.*, 2004, Sama *et al.*, 2008).

The 1.22 m FANS unit has an array of five propeller anemometers (Gill Propeller Anemometer, model 27106T, R. M. Young Company) mounted on a horizontal bar that travels upward and downward measuring air speed of fans up to 1.37 m in diameter. The anemometers consist of four 20 cm blades made of carbon fiber thermoplastic. The propeller anemometer operational range is 0 – 40 m s^{-1} for axial flow and 0 – 35 m s^{-1} for all angles flow, with an accuracy of ± 1%.

The array of propeller anemometers is located on a rectangular bar constructed from 25.4 mm square tubing with a 1.6 mm wall thickness (Gates *et al.,* 2002). The array is supported on vertical traverses consisting of dual rail linear bearings connected to rotating lead screws. One of the screws is driven by a gear motor, while the second screw is driven by a chain, which connects both screws. The side frame sections are identical and have vertical square tubes on the inside section that support the traverses, through holes drilled every 50 mm (1.97 in). On the outside section of the side frames, there are 4.8 mm (3/16 in) thick aluminum plates with attached carry handles to facilitate the transport of the FANS unit. The bottom and top frames have tubing for mounting the control box and motor, as well as a chain tensioner, respectively (Gates *et al*., 2002).

The front section of the frame was faced with a curved surface, made of 0.4547 mm aluminum sheets (26 gauge) to promote a smooth air flow entrance with low dynamic loss (Gates *et al*., 2002) through the FANS unit. The motor output shaft located near the bottom frame of the FANS unit was joined to the vertical screw via flexible coupling. Figure 2.4 and Figure 2.5 show the FANS unit assembled with all the components previously described.

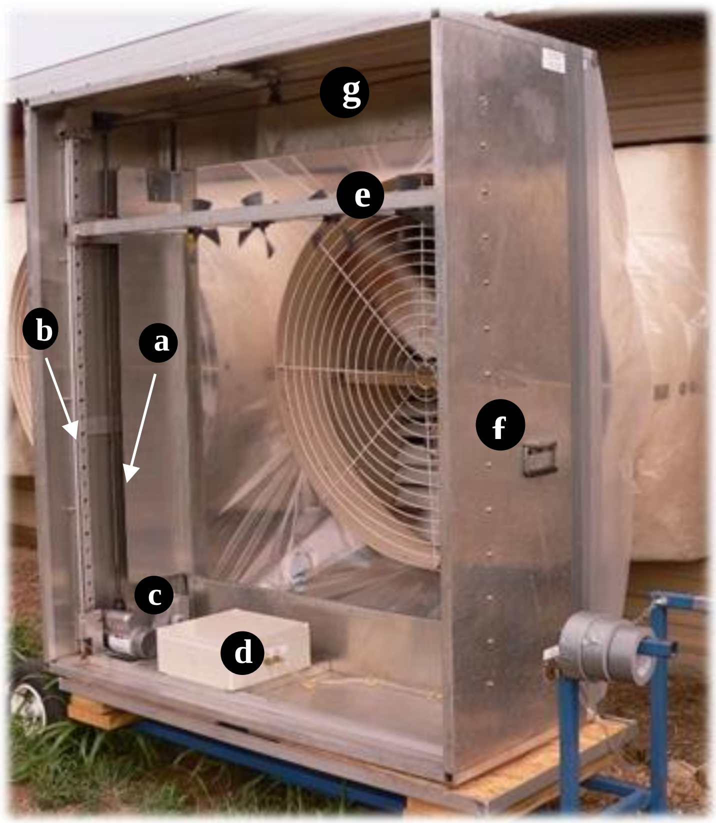

Figure 2.4. Back view of the 1.22 m (48 in) FANS unit set up near the discharge side of the fan: a. Screw, b. Vertical traverse, c. Motor, d. Control box, e. Array with propeller anemometers, f. Carry handle, g. Chain drive.

Figure 2.5. Front view of the 1.22 m (48 in) FANS unit set up next to the intake side of an exhaust fan.

The motor (Figure 2.4) runs the screw which moves a sprocket, which moves the chain located on the top frame. The chain, in turn, moves the other screw on the opposite side frame. Therefore, both screws rotate at the same speed, making the array travel up and down in a horizontal position. More information and details about the FANS unit design and calibration can be found in Simmons *et al.* (1998b), Gates *et al.* (2002), Gates *et al.* (2004) and Sama *et al.* (2008).

2.5.2 Fan Test and Data Acquisition

Five thousands samples of air velocity are acquired per second from each of the five analog inputs of the anemometers (Sama *et al.*, 2008), while the array traverses from one limit switch to the other (bottom or top of FANS), during a fan test using a 1.22 m FANS unit. These samples are averaged and result in approximately 1340 averaged velocity readings, uniformly distributed across the FANS section. These readings comprise one test, which lasts about 185 seconds. The FANS computer software calculates a total average air speed during a fan test and multiplies it by the FANS opening area, which produces an average air flow through the FANS unit during a performance test.

FANS software was developed specifically to operate FANS units. The most updated version of the FANS unit software is FANS Interface 1.4.0.1 (2010), written in VisualBasic and developed at the Biosystems and Agricultural Engineering Department at the University of Kentucky. Figure 2.6 shows the FANS User Interface 1.4.0.1.

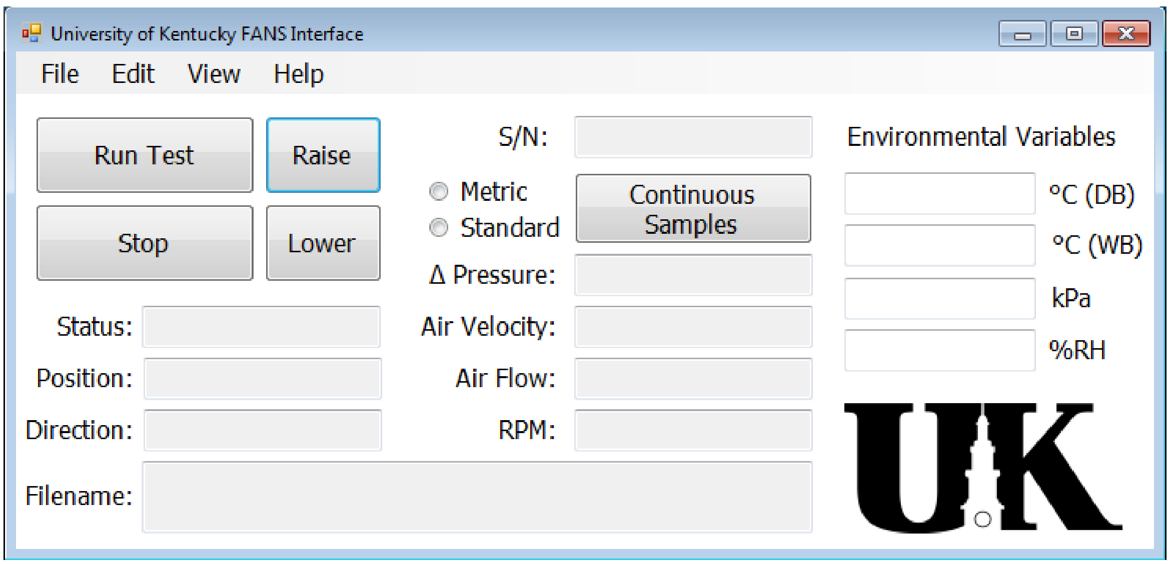

Figure 2.6. FANS Interface 1.4.0.1, Biosystems and Ag. Engineering Department, University of Kentucky.

A fan test is started by clicking on the button "Run Test" shown in Figure 2.6. After clicking on "Run Test", the array will travel up or down towards the limit switch, while the propeller anemometers measure air speed. The array can be stopped, raised or lowered, if desired. When the test is done, approximately 185 seconds after its start, the interface will show an average air flow measured during the entire test in the box "Air Flow". Also, the average static pressure will be given in the box "Δ Pressure". The test results of air flow and static pressure, as well as averaged values of voltage output from each anemometer are automatically saved in a Comma Separated Value data file during the test. Environmental conditions, such as temperature, barometric pressure and relative humidity can be added in the respective boxes, shown in Figure 2.6, and thus automatically saved in the same file. However, the environmental measurements must be performed separately from the FANS unit (Sub-section 3.3.3.5).

2.5.3 Use of the FANS unit

Casey *et al.* (2007) reported that a principal source of uncertainty in measuring air emissions has to do with measurement of the building ventilation rates, since effects such as harsh environment, fan maintenance, wind effects and others make the ventilation rate measurement difficult even for mechanically ventilated buildings. The authors studied the repeatability when using FANS unit to measure air flow of ventilation fans. Also, fan tests were performed at the fan test chamber at the University of Illinois Bioenvironmental and Structural Systems (BESS) Laboratory, with and without the FANS unit. Fan performance curves obtained when the FANS unit was present were compared with fan performance curves obtained when there was no FANS unit near the test fan.

The authors found that the FANS unit is very repeatable in its determination of air flow rate and there does not appear to be any need to conduct repeated measurements. The FANS unit induced an air flow penalty of 2% only on 1.22 m diameter Chore Time Turbo fans (38233-2) used in the study at static pressure lower than 30 Pa. However, the authors reported that there was no penalty associated with the FANS unit when testing fans with diameters of 0.91 m or less and 1.22 m diameter fans with capacities of less than 34.000 $m^3 h^{-1}$.

Jacobson *et al.* (2001) measured baseline emission rates of odor, ammonia, hydrogen sulfide, carbon dioxide and particulate matter from six types of livestock buildings located at different states. The authors emphasized that measuring ventilation rate is critical for estimating building emission rates. The ventilation rates used in this study were obtained by using the fan status (on/off), static pressure measurement and with the ventilation capacity of the fans located in the barns, obtained with a FANS unit.

Hoff *et al.* (2004) evaluated the hydrogen sulfide, ammonia, PM_{10} and odor emissions from swine and poultry houses in six regions throughout the United States. The authors mentioned that the gas tracer method of estimating the building ventilation rate, although long recognized and used for years, suffers from inaccuracy when there is incomplete air mixing in the building and is very instrument intensive. Therefore, Hoff *et al.* (2004) reported that the gas tracer method is not accurate enough for emission studies and opted to use a FANS unit to measure performance of ventilation fans during this study.

Gates *et al.* (2005) proposed a method for measuring ammonia emissions from broiler and layer barns, which suggested the direct measurement of ventilation rate using the FANS unit and the CO_2 balance method for larger layer houses. The suggested method of estimating ammonia emissions has been successfully used to establish baseline values for the U.S.A. The authors calculated that if the direct measurement of ventilation rate using the FANS unit was not used, the building emission rate could be overestimated up to approximately 17.5% using BESS laboratory data for fan tests. The cause of the differences between the ventilation rates obtained from *in-situ* measures and ventilation rates obtained in the laboratory was mainly attributed to installation, operation and maintenance factors (Gates *et al.* 2005).

Several factors cause fan performance to degrade over time, such as dust and dirt accumulation on the blades and belt wear (Bottcher *et al.*, 1996). Casey *et al.* (2008) reported up to 24% variation in fan performance attributed to accumulated dirt and corrosion, resistances imposed by shutters, as well as motor and bearing wear due to run time and aging. Janni *et al.* (2005) monitored sow gestation barns for emissions of ammonia (NH_3), carbon dioxide (CO_2), hydrogen sulfide (H_2S), odor, and particulate matter 10 μm or less (PM_{10}). Fan performances were obtained using a FANS unit and it was found that the air flow was reduced by 30 to 60% when the fan drive belts were slightly loose compared to the air flow obtained when the belts were properly tightened.

Gay *et al.* (2006) determined the ammonia emission rates in four tom turkey houses (two brooder and two growout). The ventilation rates were obtained using the FANS unit and fan run time data. All individual fans were tested with a FANS unit, except for fans from one of the brooder houses. Fan performances of fans from this house were than estimated, based on the fan performance curves obtained with FANS unit in the other houses.

Burns *et al.* (2007) continuously monitored ammonia emissions from two commercial broiler houses located in the Southeastern U.S.A., during a one year period. Static pressure was also measured continuously and ventilation rates were obtained from fan performance curves obtained with a FANS unit. Topper *et al.* (2008) quantified the ammonia emissions of two empty broiler houses with built-up litter. Static pressure and run time of the fan motors were monitored to calculate the ventilation rate through the fans. Fan capacities were obtained through fan tests using a FANS unit.

Wheeler *et al.* (2003) evaluated ammonia emissions from 11 poultry barns in Kentucky and Pennsylvania. This study was part of a bigger project to develop a comprehensive database of ammonia emissions from U.S.A. poultry facilities. The authors also evaluated the influence of common management strategies on reducing ammonia emissions. Ventilation rate was obtained with a FANS unit. Wheeler *et al.* (2006) monitored a total of 12 commercial broiler houses in the U.S.A., over the course of one year to obtain ammonia emission data. House ventilation rates were obtained from fan performance curves as measured with a FANS unit, and fan run-time data. The FANS unit was used to develop fan performance curves using six values of static pressure within a 0 to 60 Pa range.

Li *et al.* (2011) continuously monitored ammonia and particulate matter emissions from tom and hen turkey barns for 16 and 10 months, respectively. The study contributed to an air emission baseline for turkey barns in Iowa and Minnesota. The authors used mobile air emission monitoring units (MAEMUs) in the continuous monitoring. Ventilation rates were calculated from fan performance curves obtained *in-situ* with a 1.37 m and a 1.22 m FANS unit. All exhaust fans were calibrated with a FANS unit and fan run time was monitored and recorded continuously using an inductive current switch attached to the power supply cord of each fan motor.

Moody *et al.* (2008) estimated possible errors in emission rates due to uncertainties on calibration standards, concentration measurements and building ventilation rates. Gates *et al.* (2009) reported that the ventilation rate uncertainty contributed to 78% and 98.9% of emission rate uncertainty for a 5% and 25% standard uncertainty in fan ventilation rate measurement, respectively. Moody *et al.* (2008) inferred that ventilation rate uncertainty is critical for controlling emission rate uncertainty and the FANS unit contributed to reducing ventilation rate uncertainties. Moody *et al.* (2008) emphasized that if less sophisticated methodologies were used to estimate ventilation rate, the emission rate uncertainties could be substantially larger. Therefore, researchers working under the US EPA (Environmental Protection Agency) Air Consent Agreement adopted the FANS unit method to measure fan performance and determine baseline emissions for dairy, swine and poultry houses.

CHAPTER 3
MATERIALS AND METHODS

3.1 Farms visited

Data were collected at five poultry barns in western Kentucky. Tests were conducted with empty barns (between flocks), during the months of July through August, 2010. A total of ten 1.22 m diameter fans were tested at four farms operated by two different poultry companies, designated as Poultry Company 1 and Poultry Company 2. Five fans were tested in three different barns at Farm 1, under contract to Poultry Company 1, while the other five fans were tested in one barn at each of Farms 2, 3 and 4, all growout facilities for the Poultry Company 2. Additional information about the fans tested in this study is available in Sub-sections 3.1.1 trough 3.1.4 of this chapter.

3.1.1 Farm 1 – under Contract to Poultry Company 1

A total of five fans were tested from three different barns (1, 2 and 3, Figure 3.1), in Farm1, from Poultry Company 1.

Figure 3.1. Poultry barns at Farm 1, under contract to Poultry Company 1. Numbers 1, 2 and 3 designate Barns 1, 2 and 3 at Farm 1.

Each of the barns from Poultry Company 1 were 14 x 164 m, oriented East to West, equipped with ten 1.22 m diameter Glass Pac Canada belt-driven fans (GP 48100299), placed immediately next to each other (Figure 3.2) on the sidewalls at the exhaust end of the barn. The fans had plastic shutters, fiber glass housing and no discharge cones. The motor information is given in Table 3.1.

Figure 3.2. Exhaust end of a representative barn at Farm 1 with exhaust fan placement illustrated. Fans were placed immediately next to each other.

Table 3.1. Motor information for Glass Pac Canada fans.

Motor	A O Smith
Model	K56A25A78
Series	2098
Amperage	11/5.5 A
Voltage	115/230 V
Power	1 HP
Speed	1725/1425 RPM

Figure 3.3 shows two additional fans on the exhaust end of a barn at Farm 1, which were 1.32 m diameter Hired Hand Funnel Flow fans (FF-52-B-3F-SE-1.5S-246S-0-0-VB), with butterfly dampers, fiber glass housing, and cones.

Figure 3.3. Exhaust end of a representative barn at Farm 1. Five 1.22 m diameter Glass Pac Canada fans and two 1.32 m diameter Hired Hand fans.

The Hired Hand fans were neither tested nor used in the treatments. Figure 3.4 shows the North sidewall of Barn 2 in Farm 1, equipped with five 1.22 m diameter Glass Pac Canada fans and four 0.91 m diameter Glass Pac Canada fans (GPSW 3650, serial 2099) denoted by the yellow arrows in Figure 3.4. These smaller fans were used to help increase the static pressure in the barn for one of the treatments, as described in Sub-section 3.3.4 of this chapter.

Figure 3.4. Representative barn at Farm 1 with fans placement illustrated. The circle indicates the test fan among five 1.22 m diameter Glass Pac Canada fans placed immediately next to each other. The arrows indicate four 0.91 m diameter Glass Pac Canada fans.

Fans tested inside barns 1, 2 and 3 from Farm 1 were all 1.22 m diameter Glass Pac Canada fans located right in the center of each group of five exhaust fans, as illustrated in Figure 3.4 and denoted by the red oval. The reason for choosing the fans located at the center of each group of five fans for the fan testing was to allow all treatments to be applied for the same fan. Table 3.2 shows the locations of each test fan, inside barns from Poultry Company 1 (Farm 1).

Table 3.2. Position of test fans inside Farm 1, poultry barns in Kentucky – U.S.A.

Barn	Fan tested	Location
1	F1	South sidewall, third fan from the exhaust end of the barn
	F2	North sidewall, third fan from the exhaust end of the barn
2	F3	North sidewall, third fan from the exhaust end of the barn
	F4	South sidewall, third fan from the exhaust end of the barn
3	F5	North sidewall, third fan from the exhaust end of the barn

3.1.2 Farm 2 – under Contract to Poultry Company 2

A total of two fans were tested in barn 4, at Farm 2 under contract to Poultry Company 2 (Figure 3.5).

Figure 3.5. Poultry barns from Farm 2, operated by Poultry Company 2. Number "4" designates Barn 4 at Farm 2.

Farm 2, from Poultry Company 2, has four 13 x 166 m barns, oriented East to West. Each barn is equipped with eight 1.22 m diameter belt driven Chore Time Turbo Fans (38233-2) spaced 1.6 m apart (Figure 3.6) on the exhaust end sidewalls, with plastic shutters, fiber glass housing and plastic cones. Table 3.3 contains information about the fan motors.

Figure 3.6. Representative barn at Farm 2 with exhaust fan placement illustrated. Fans were spaced 1.6 m from each other. The circle indicates the test fan.

Table 3.3. Motor information for Chore Time Turbo fans.

Motor	General Electric Industrial Systems
Model	5KCR49UN0462AT
Amperage	4.4/5.1 A
Voltage	230 V
Power	1 HP
Speed	1725/1425 RPM

- Motor capable of operating with two frequency supplies (60 and 50 Hz).

Figure 3.7 shows one additional fan on the exhaust end of a barn in Farm 2 from Poultry Company 2, which was a 0.91 m diameter Chore Time fan, with plastic shutters, fiber glass housing, and no cone. The 0.91 m diameter Chore Time fan was neither tested nor used in the treatments.

Figure 3.7. Exhaust end of a representative barn at Farm 2. Four 1.22 m diameter Chore Time Turbo fans and one 0.91 m diameter Chore Time fan.

Figure 3.8 shows the West end wall of Barn 1 at Farm 2, from Poultry Company 2, equipped with two 0.91 m diameter Chore Time fans. Those 0.91 m diameter fans were used to help increase the static pressure in the barn for one of the treatments, as described in Sub-section 3.3.4 of this chapter.

Figure 3.8. West end of Barn 1at Farm 2. Two 0.91 m diameter Chore Time Fans.

The two test fans from Farm 2, from Poultry Company 2, were the 1.22 m diameter Chore Time Turbo fans located right next to the first 1.22 m diameter fan from the inlet curtain end (West side) to the exhaust end of the barn (East end wall), as illustrated in Figure 3.6 by the circle. Table 3.4 indicates the locations of each tested fan, at Farm 2.

Table 3.4. Position of test fans in Farm 2, poultry barn in Kentucky – U.S.A.

Barn	Fan tested	Location
1	F1	North sidewall, third fan from the exhaust end
	F2	South sidewall, third fan from the exhaust end

3.1.3 Farm 3 – under Contract to Poultry Company 2

A total of two fans were tested in Barn 4 (Figure 3.9) located at Farm 3, a growout facility under contract to the Poultry Company 2.

Figure 3.9. Poultry barns at Farm 3, under contract to Poultry Company 2. Number "4" designates Barn 4 at Farm 3.

Farm 3 had four 12 x 166 m barns, oriented East to West, each equipped with eight 1.22 m diameter belt – driven Chore Time Turbo Fans (38233-2), spaced 1.6 m apart (Figure 3.10) on the exhaust end sidewalls, with plastic shutters, fiber glass housing and plastic cones. Figure 3.10 also shows a 0.91 m diameter chore time fan on the exhaust end wall, which was neither tested nor used in the treatments. Figure 3.9 shows two other 0.91 m diameter chore time fans on the curtains end, which were used for increasing static pressure when needed, as described on Sub-section 3.3.4 of this chapter. Table 3.5 shows information about the fan motors in Farm 3.

Figure 3.10. Exhaust end of a representative barn at Farm 3. Four 1.22 m diameter Chore Time Turbo fans and one 0.91 m diameter Chore Time fan. 1.22 m diameter fans were spaced 1.6 apart. Red circle indicates test fan.

Table 3.5. Motor information for 1.22 m diameter Chore Time Turbo fans.

Motor	General Electric Industrial Systems
Model	5KCR49UN0462AT
Amperage	4.4/5.4A
Voltage	230 V
Power	1 HP
Speed	1725/1425 RPM

- Motor capable of operating with two frequency supplies (60 and 50 Hz).

The two test fans in Farm 3 were 1.22 m diameter Chore Time Turbo fans located right next to the first 1.22 m diameter fan from the tunnel curtains (West side) to the exhaust end of the barn (East end wall), as indicated in Figure 3.10 by the red circle. Table 3.6 shows the locations of each tested fan, in Farm 3.

Table 3.6. Position of test fans in Farm 3, poultry barn in Kentucky – U.S.A.

Barn	Fan tested	Location
4	F3	North sidewall, third fan from the exhaust end of the barn
	F4	South sidewall, third fan from the exhaust end of the barn

3.1.4 Farm 4 – under Contract to Poultry Company 2.

One fan (T5) was tested in Barn 3 (Figure 3.11) at Farm 3.

Figure 3.11. Poultry barns at Farm 4, under contract to Poultry Company 2. Number "3" designates Barn 3 at Farm 4.

Farm 4 had three 13 x 164 m barns, oriented East to West, equipped with eight 1.22 m diameter Chore Time Turbo fans (38233-2) spaced 1.6 m apart (Figure 3.12) on the exhaust end sidewalls, with plastic shutters, fiber glass housing and plastic cones. Figure 3.11 shows two 0.91 m diameter Chore Time fans on the inlet curtain end, which were used for increasing static pressure when needed, as described on Sub-section 3.3.4 of this Chapter. Table 3.7 contains information about the fan motors in Farm 4.

Figure 3.12. Representative barn at Farm 4 with exhaust fans placement illustrated. Fans were spaced 1.6 m apart. The circle denotes the test fan.

Table 3.7. Motor information for Chore Time Turbo fans.

Motor	General Electric Industrial Systems
Model	5KCR49UN0462AT
Amperage	4.4/5.4 A
Voltage	230 V
Power	1 HP
Speed	1725/1425 RPM

- Motor capable of operating with two frequency supplies (60 and 50 Hz).

The test fan (F5) from Poultry Company 2 Farm 4 was a 1.22 m diameter Chore Time Turbo fan located right next to the first 1.22 m diameter fan from the curtain end (East side) to the exhaust end of the barn (West end wall). F5 was located on the South sidewall from the exhaust end.

3.2 FANS Unit Calibration

A 1.22 m FANS Unit (serial number: 48-0023) was calibrated in the BioEnvironmental Structural Systems Laboratory (BESS Lab), Agricultural and Biological Engineering, University of Illinois, Urbana, IL.

FANS calibration was performed by placing the FANS unit against the outlet face of the BESS Lab chamber and sealing the gap between the chamber outlet and FANS unit with Styrofoam (Figure 3.13). The tests were run within the static pressure range 0 to 62 Pa. Air flow was read by FANS unit once for each of the ten values of static pressure set in the chamber. Also, air flow was calculated based on the pressure difference across calibrated chamber nozzles for the ambient conditions of temperature, relative humidity and barometric pressure, for every test run. Chamber air flow data were calculated based on the ANSI/AMCA Standard 210-07 ANSI/ASHRAE 51-07, Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating.

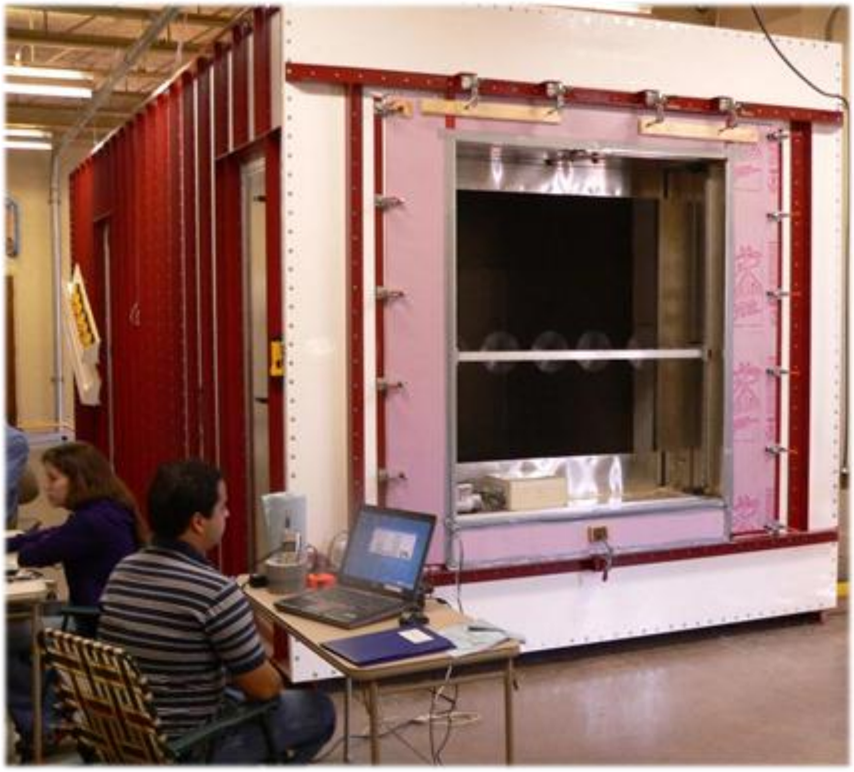

Figure 3.13. FANS calibration being run in the BESS Lab Chamber, Bioenvironmental and Structural Systems Laboratory, University of Illinois, Urbana – IL.

Air flow obtained by the FANS unit was regressed as a linear function of the air flow obtained from the BESS Lab chamber. The parameters obtained from the regression, slope and intercept, were inserted into the FANS software.

Figure 3.14 illustrates the calibration curve for the 1.22 m FANS unit (serial number: 48-0023).

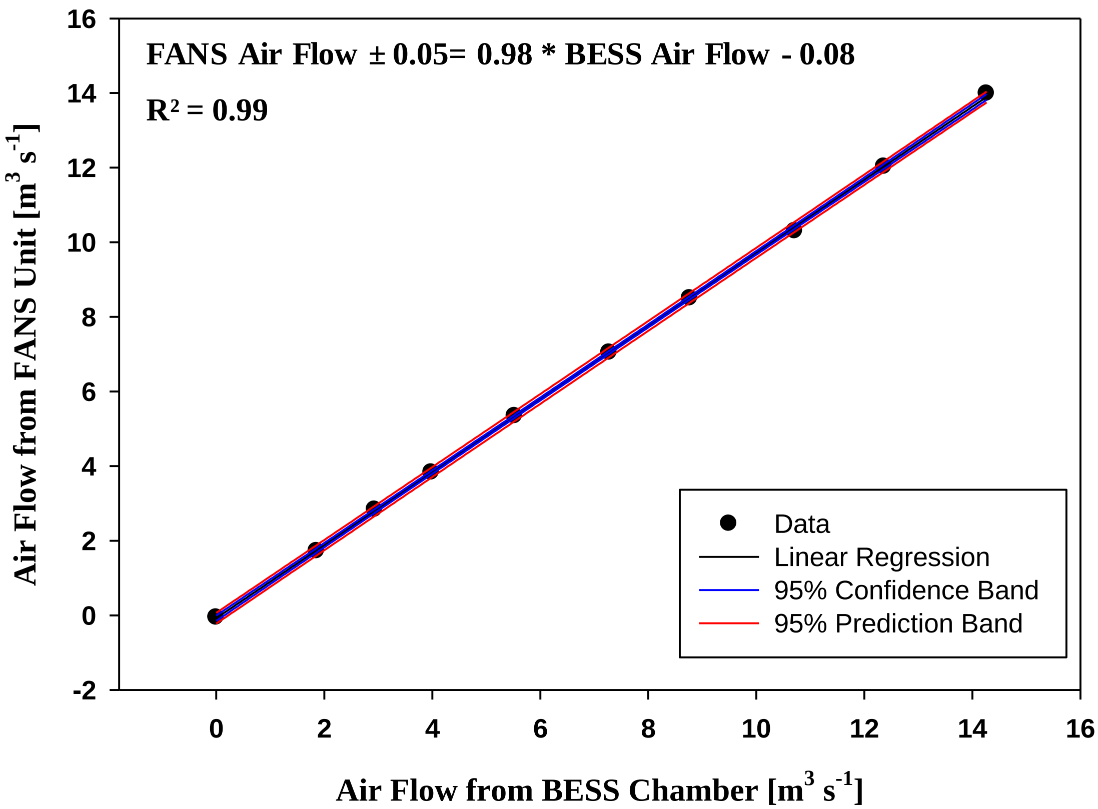

Figure 3.14. 48-0023 FANS calibration.

The regression slope of 0.98 ± 0.004 and intercept of 0.08 ± 0.03 $m^3\ s^{-1}$ from the linear regression were added to the FANS unit software to correct the FANS air flow readings. The FANS software used in this study (FANS Interface 1.4.0.0.1) has a specific place where calibration information can be input, as shown in Figure 3.15. The slope and intercept from the regression described were then input in the FANS software (Figure 3.15).

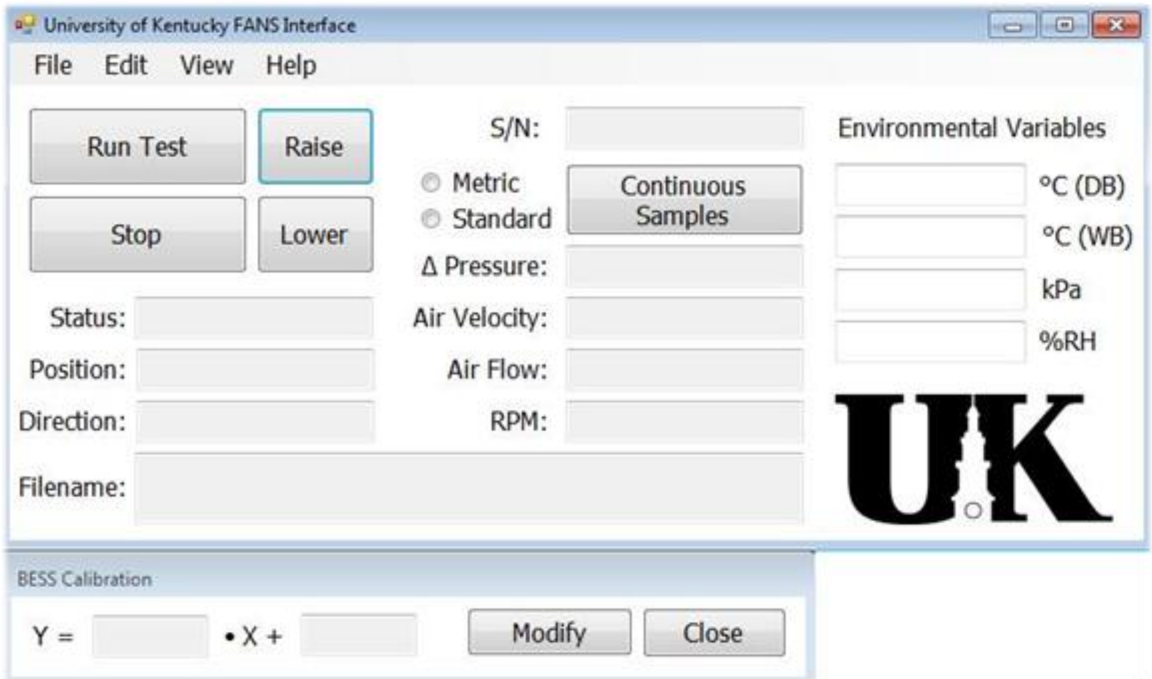

Figure 3.15. FANS Interface 1.4.0.0.1 – calibration procedure.

The FANS software automatically inverted the regression to provide an air flow reading as close as possible of the reference air flow (BESS Lab chamber air flow output). The estimation of the real air flow is indicated by Equation 3.1, which is a regression of the BESS Chamber air flow as a linear function of the FANS unit air flow.

$$\mathbf{RAF = B_o + B_1 * FANS\_AF} \qquad \text{Equation 3.1}$$

Where,

RAF = Reference Air flow [$m^3\ s^{-1}$] obtained from the BESS Lab Chamber;

B_o = Intercept = 0.0802 ± 0.0314 [$m^3\ s^{-1}$];

B_1 = Slope = 1.0207 ± 0.0040;

FANS_AF = FANS Air flow [$m^3\ s^{-1}$].

3.3 Fan Performance Tests *In-situ*

3.3.1 Fan Performance Test Setups – FANS Unit next to the Intake Side of the Test Fan

The FANS unit (serial number: 48-0023) was placed next to the intake side of the fans to be tested, as shown in Figure 3.16. A foam gasket was placed between the wall and FANS in order to seal the crack between FANS and wall, as shown in Figure 3.16. Two straps were attached to the wall and used to tighten the FANS unit against the wall. The height of the FANS unit was set by a cart, so that the FANS unit height matched the height of the fan under test.

Figure 3.16. FANS unit (serial number: 48-0023) placement next to the intake side of the test fan, cart, foam gasket and straps.

3.3.2 Fan Performance Test Setups – FANS Unit near the Discharge Side of the Test Fan

The FANS unit was placed near the discharge side of the test fans and a sheet of either 4 or 6 mil of polyethylene clear plastic was tightened around the fan and FANS (Figure 3.17) with duct tape and a rope to provide a makeshift transition. Thus, all the air moved by the fan passed through the FANS unit during the tests. A cart was used to adjust the FANS to the test fan height.

Figure 3.17. FANS unit (serial number: 48-0023) near the discharge side of the test fan, outside setup**.**

3.3.3 Fan Performance Test Setups – Readings Setup

3.3.3.1 Static Pressure Measurement

The white box located on the bottom of the FANS unit (Figure 3.18) contains a differential pressure transducer (Setra Systems Model 265, series 0811) shown in Figure 3.19, which measures static pressure from 0 to 62 Pa (0 to 0.25 in H_2O), with an advertized accuracy of ± 1% FS (Full Span).

Figure 3.18. FANS unit (serial number: 48-0023) outside setup, static pressure sensor.

Figure 3.19. Differential Pressure Transducer (Setra Systems Model 265, series 0811)

Figure 3.20 shows an outlet for two hoses that connect with the static pressure sensor. One hose goes inside the barn, while the other hose goes outside the barn. In this way, the sensor could provide the difference in pressures from outside and inside the barn during the tests.

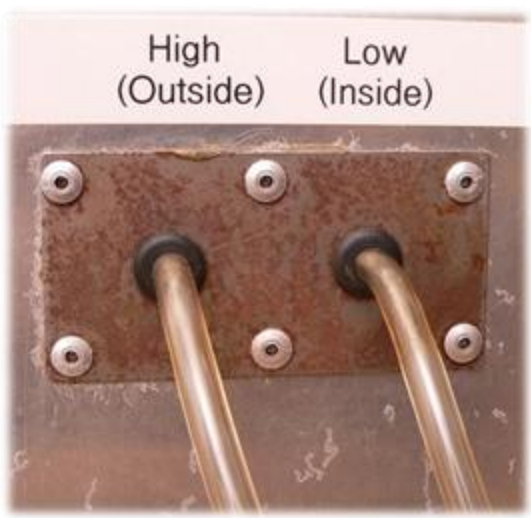

Figure 3.20. Hoses on the FANS unit for static pressure measurement.

The inside hose was placed approximately 12.2 m from the exhaust fans, during all tests. The outside hose was placed about approximately 12.2 m from the exhaust end, inside an open-top bucket to buffer the overall interference of the wind.

3.3.3.2 Air Flow and Static Pressure Readings

The air flow rate and static pressure were averaged during 185 second tests by FANS Interface 1.4.0.0.1 software, developed at the University of Kentucky, Lexington, U.S.A. A serial cable (Figure 3.21) connects the FANS unit to a computer (Figure 3.22), where an average air flow and static pressure are calculated at the end of each test.

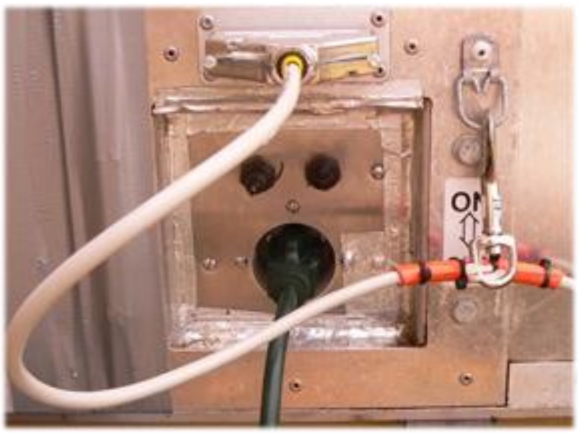

Figure 3.21. Serial cable connected to the FANS unit.

Figure 3.22. Reading through computer software.

The FANS user interface records approximately 1340 averaged air velocity readings (Sub-section 2.5.2) that are automatically stored in comma separated type of files that can be accessed after each fan test.

3.3.3.3 Power Readings

The visited farms were equipped with emergency backup generators that provide electricity during power outage. Periodically these generators are exercised and tested as part of their regular maintenance. A slight change in the magnitude of the power supply can occur during these maintenance periods, which can change the fan speed. During the fan tests, power, current, voltage and power factor at the fan motor were recorded in order to verify if the supply conditions were about the same for all treatments. The power readings also helped to determine if the electrical supply was from the transmission system (grid) or if the farm generator was running.

The power monitoring was useful to assure that all the treatments within a farm were done under the same conditions of electricity supply. Figure 3.23 shows the power meter (AEMC single-phase, model 8230) used to record the power information during all tests. Before the data collection, the AEMC power meter was sent to an authorized laboratory for proper calibration.

Figure 3.23. Power Meter - AEMC PowerPad Jr, Model 8230. Corporate & Manufacturing Address: Chauvin Arnoux®, Inc. d.b.a. AEMC® Instruments 15 Faraday Drive Dover, NH 03820 U.S.A, http://www.aemc.com/.

Two extension power cords were connected between the electrical outlet and the fan plug, as indicated by the arrows in Figure 3.24. An improvised power cord was installed in the fan-supply circuit with plugs to accommodate voltage probes and to facilitate the use of an amperage clamp, as shown in Figure 3.25. The power meter recorded averages of power (watts), current (amperes), voltage (volts) and power factor at one minute intervals during all tests.

Figure 3.24. Power cords. Arrow 1 indicates the extension cord between the power supply and power meter. Arrow 2 indicates the extension power cord between the power meter and the fan.

The power cords re-routed the electricity supply (Figure 3.24) to the power meter (Figure 3.25) and back to the fan motor.

Figure 3.25. Setup of AEMC PowerPad Jr, Model 8230. The arrow indicates the connector cord with separated wires for clamp-on measurements and spliced connections for voltage probes.

3.3.3.4 Barn Air Speed Readings

Barn air speed (BS) was recorded at approximately 12 m from the tunnel fans, at 1.5 m height, using a Kestrel 4200, Pocket Air Flow Tracker (Figure 3.26). The air speed measurements were done at three different spots across the barn section, spaced approximately 2 m from the sidewalls and 4 m from each other, as illustrated in Figure 3.27.

Figure 3.26. Kestrel 4200, Pocket Air Flow Tracker (operational range of 0 – 99.999,00 m^3 h^{-1} ± 3.0%)

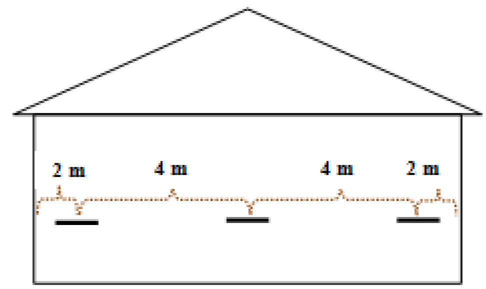

Figure 3.27. Barn Air Speed Measurements – 12 m from tunnel fans at the height of the center of tunnel fans, 1.5 m, (not to scale).

Barn air speed was measured for all the treatments at all different static pressure tested. Averages were calculated from measurements taken at the three locations illustrated in Figure 3.27. The average barn air speed was tested as a dependent variable to describe differences in air velocities obtained from anemometers 1 and 5 of the FANS unit, as described in Section 4.3.

3.3.3.5 Other Measurements – Temperature, Barometric Pressure, Relative Humidity

The air conditions and fan speed were recorded during all tests and the barometric pressure was read and recorded twice every test day approximately at 8:00 a.m. and 2:00 p.m. Figure 3.28 through Figure 3.30 show the temperature and humidity sensor (Rotronic Hygroskop GT-1, temperature and relative humidity operational ranges of -10°C – 50°C ± 0.3 °C/ 5% – 100% ± 2%, respectively) as well as the barometer (Airguide Instrument Co.) and the tachometer (Monarch, Pocket Tach. 10, operational range of 5 RPM – 100.000 RPM ± 1 RPM).

Figure 3.28. Temperature/Humidity sensor - Rotronic Hygroskop GT-1 Rotronic Instrument Corp. 135 Engineers Rd Suite 150 Hauppauge NY,11788

Figure 3.29. Barometer Airguide Instrument Co.

Figure 3.30. Tachometer, Monarch Pocket Tach 10 Monarch Instrument 15 Columbia Drive Amherst, NH, 03031.

The Rotronic Hygroskop had the temperature checked against a mercury thermometer inside an insulated container and the humidity sensor was calibrated using saline humidity standards. All the treatment comparisons were done for the same values of static pressure, therefore the air density was not corrected for standard values.

3.3.4 Fan Performance Test - Procedure

An array of five propeller anemometers (Figure 3.31) are attached to a rack that traveled up and down during a fan performance test, measuring air speeds continuously in real-time. Computer software calculated the average air flow, from approximately 1340 averaged air velocity readings obtained during the traverse measurement for each single run with the FANS unit (Gates *et al.*, 2004 and Sama *et al.*, 2008).

A traverse test was run for all treatments for each of eight static pressures set for the treatment within the range 0 to 60 Pa. This data was used to build fan performance curves of air flow versus static pressure. The static pressure (SP) step within the range 0 to 60 Pa was dependent on the minimum static pressure that could be established in the building for each treatment. Static pressure was set by opening and closing the inlet curtains and by energizing 0.91 m diameter fans on the inlet curtain end of the barn when higher static pressures were needed.

Figure 3.31. FANS unit (serial number: 48-0023), anemometer propellers.

3.4 Experiment Protocol

The fan under test was selected mainly for its position on the sidewall and by considering the desired combinations of fans to be operated for the treatments. One or two fans were chosen for testing in each barn, as described in Section 3.1, to be tested twelve times, once for each combination of operating fans (treatment). A total of ten 1.22 m diameter fans were tested. Six main treatment combinations were evaluated with the FANS unit, when placed next to the intake side of the test fan and near the discharge side of it, as described in Sub-section 3.4.1.

Five fans were tested at Farm 1 (under contract to Poultry Company 1), where fans were placed immediately next to each other. Additionally five fans were tested at Farms 2, 3 and 4 (under contract to Poultry Company 2) where fans were spaced 1.6 m apart from each other. Data were treated as two different experiments, since there were differences regarding the spaces between fans at Farm 1 (no space between fans) and fans at Farms 2, 3 and 4 (spaced 1.6 m apart). Experiment 1 (E 1), therefore, was conducted with fans placed immediately next to each other, at Farm 1, while Experiment 2 (E 2) was conducted with fans spaced 1.6 m apart from each other, at Farms 2, 3 and 4.

3.4.1 Treatments

3.4.1.1 Treatments to Satisfy Objective 1 – Treatments "P" (operating fan positions relative to FANS unit and test fan).

- Upstream treatment: FANS unit and test fan upstream from adjacent operating fans (Figure 3.32);
- Downstream treatment: FANS unit and test fan downstream from adjacent operating fans (Figure 3.33);
- Middle treatment: FANS unit and test fan between adjacent operating fans (Figure 3.34);
- Test Fan Alone treatment: Test fan operating alone – no other exhaust fans operating (Figure 3.35);
- Same Sidewall: Operating fans on the same sidewall as the FANS unit and test fan (Figure 3.36);
- Opposite Sidewall: Operating fans on the opposite sidewall from the FANS unit and test fan (Figure 3.37);

Figure 3.32 through Figure 3.37 show the plan view of a representative broiler barn operated by Poultry Company 2, with the FANS unit placed next to the intake side of the test fan along with the various combinations of operating fans. Each selected test fan was tested 12 times, with six tests performed inside the barn (FANS next to the intake side of the test fan) and six tests outside (FANS near the discharge side of the test fan).

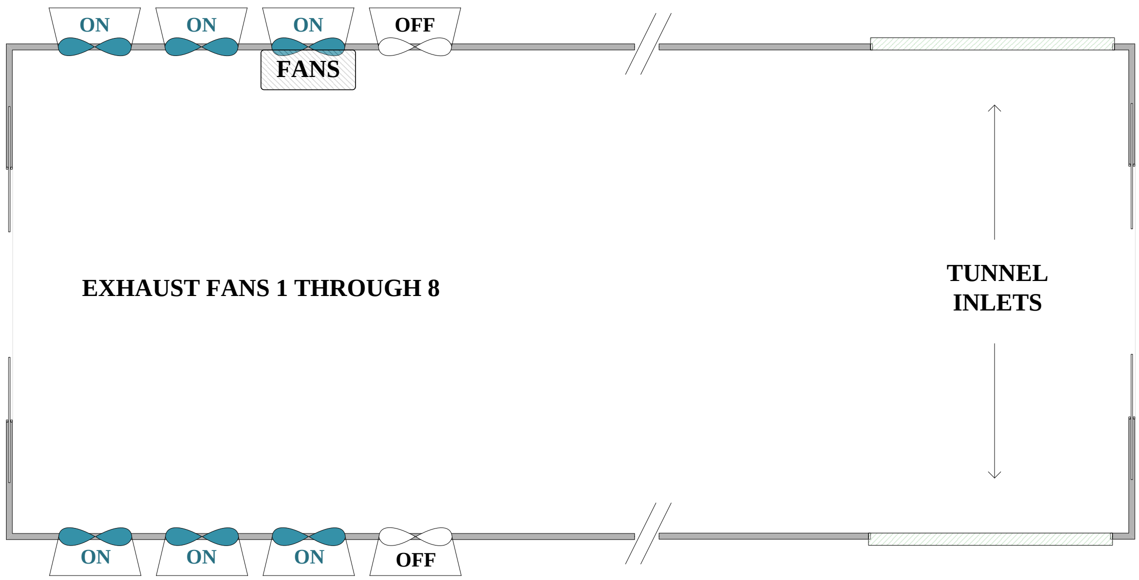

Figure 3.32. FANS unit and test fan in the Upstream position (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

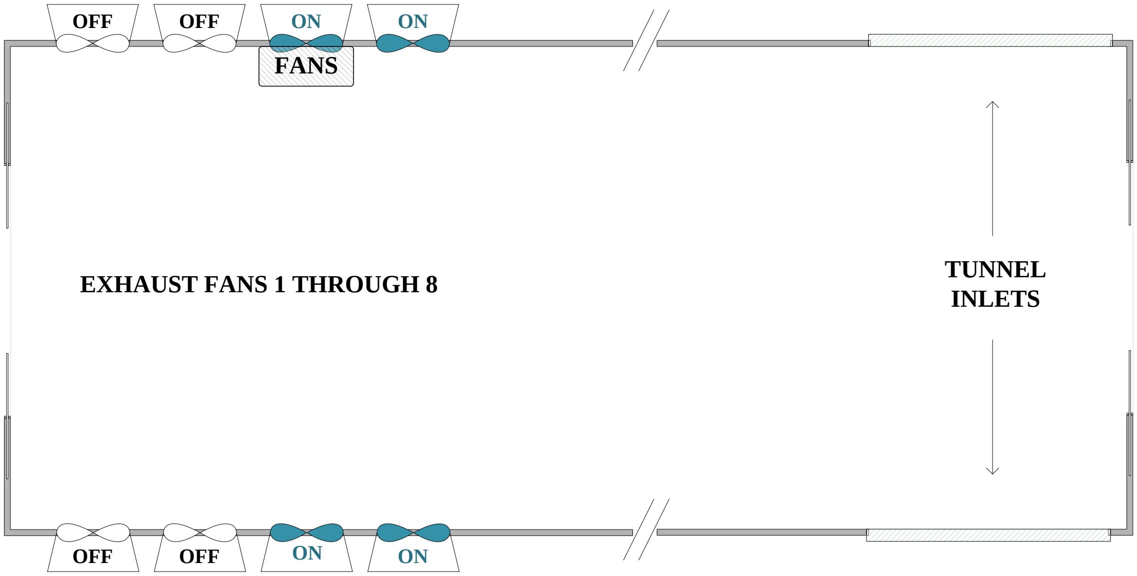

Figure 3.33. FANS unit and test fan in the Downstream position (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

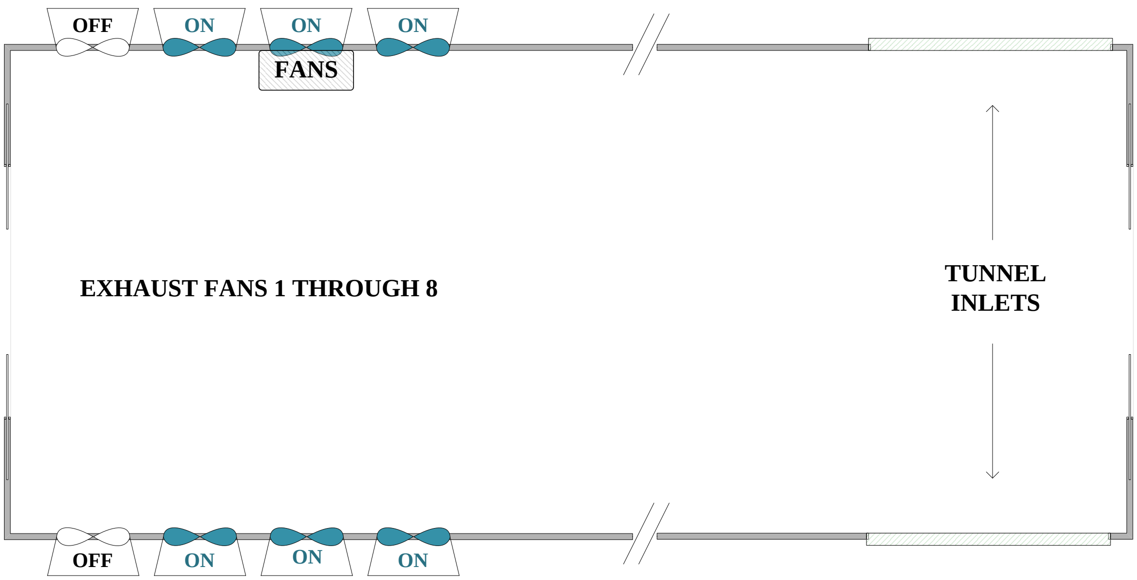

Figure 3.34. FANS unit and fan test in the Middle position (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

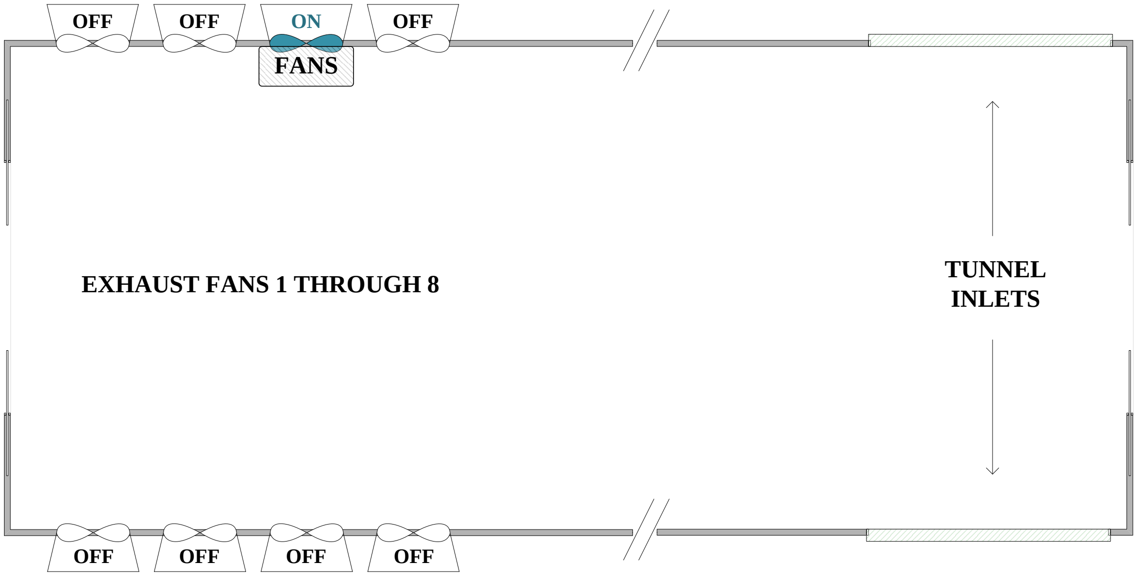

Figure 3.35. Fan being tested Alone by the FANS unit (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

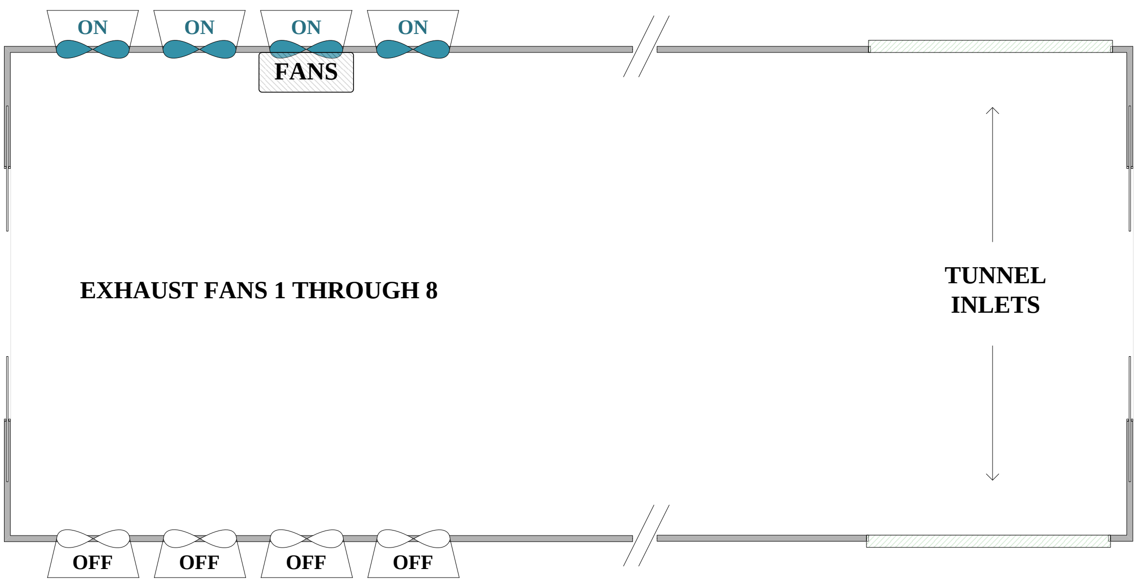

Figure 3.36. Operating fans on the Same Sidewall as the FANS unit and the test fan (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

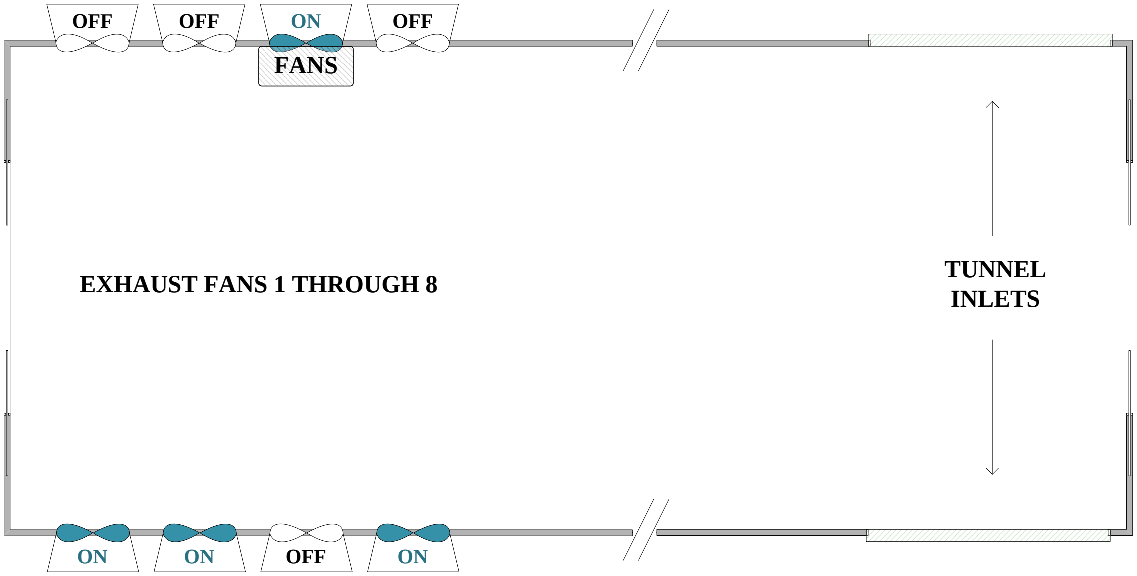

Figure 3.37. Operating fans on the Opposite Sidewall from the FANS unit and the test fan (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farms 2, 3 or 4.

- **Treatment "P" Specifications:**

The previous images describing the treatments represent barns operated by Poultry Company 2, containing a total of eight 1.22 m diameter exhaust fans, whereas the barns operated by Poultry Company 1 had ten 1.22 m diameter exhaust fans. Therefore, some treatments in Experiment 1 and Experiment 2 differed in the number of operating fans. The treatment specifications for each farm are presented in Table 3.8.

Table 3.8. Treatment specifications.

Treatments	**Farm from Poultry Company 1**		**Farms from Poultry Company 2**	
	Test Fans Location	**Number of Fans Operating on Treatment**	**Test Fans Location**	**Number of Fans Operating on Treatment**
Upstream	Centered - 3rd from the exhaust end of the barns.	6	Not Centered – 3rd from the exhaust end of the barns.	6
Downstream		6		4
Middle		6		6
Alone		1		1
Same Sidewall		5		4
Opposite Sidewall		5		4

The treatments that differed in barns from Poultry Company 1 and Poultry Company 2 were "Downstream", "Same Sidewall" and "Opposite Sidewall", as shaded in Table 3.8. Figure 3.38 through Figure 3.40 illustrate these treatment configurations for fans tested inside barns in Farm 1, operated by Poultry Company 1.

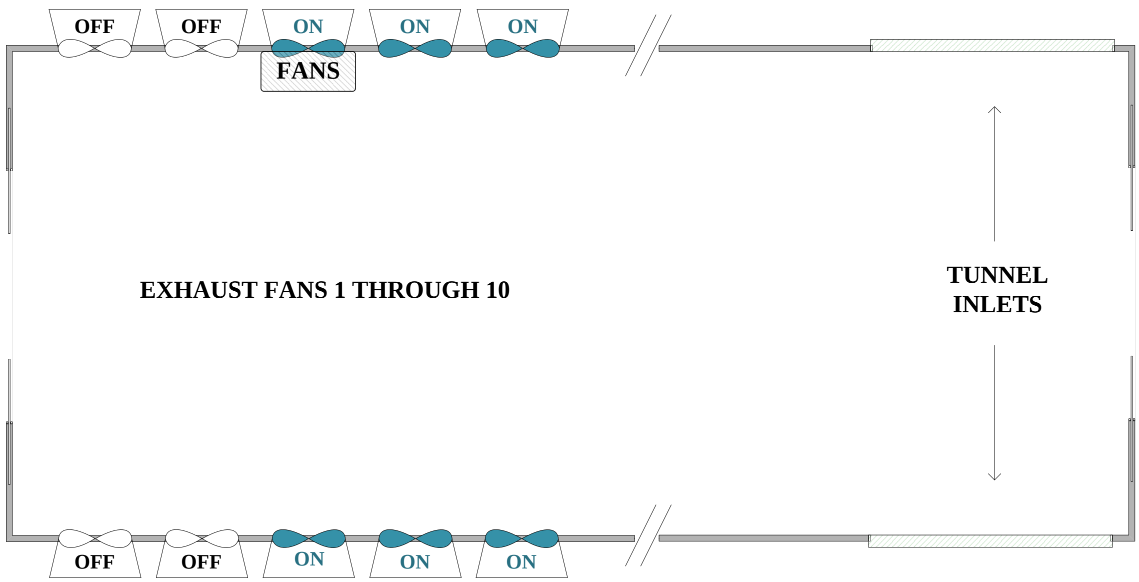

Figure 3.38. FANS unit and test fan in the Downstream position (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farm 1.

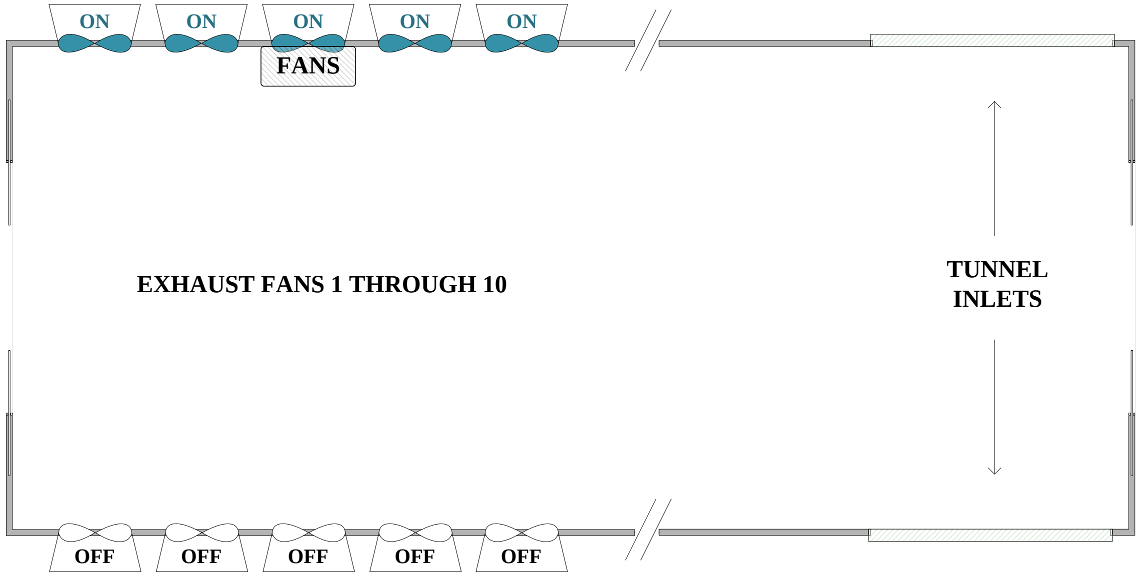

Figure 3.39. Operating fans in the Same Sidewall as the FANS unit and the test fan (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farm 1.

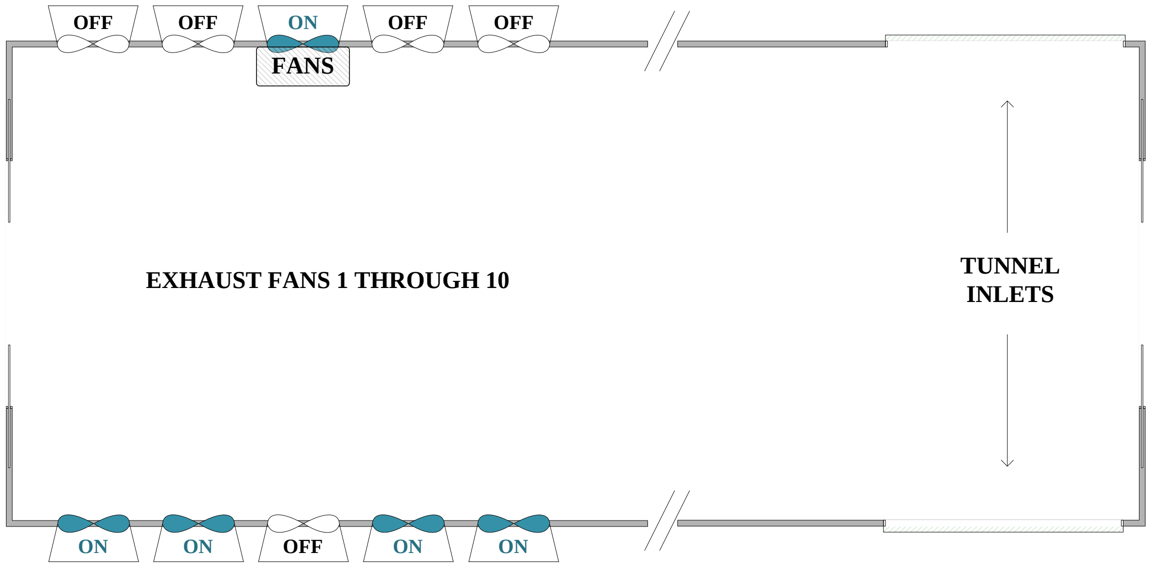

Figure 3.40. Operating fans in the Opposite Sidewall from the FANS unit and the test fan (plan view, not to scale) - FANS next to the intake side of the test fan in a representative barn of Farm 1.

3.4.1.2 Treatments to Satisfy Objective 2 – Treatments "S" FANS unit side: Inside the barn (FANS next to the Intake Side of the Test Fan) or Outside the barn (FANS near the Discharge Side of the Test Fan).

(1) - Inside treatment: FANS unit on the intake side of the test fan (inside the barn, Figure 3.41);

(2) – Outside treatment: FANS unit near the discharge side of the test fan (outside the barn, Figure 3.42);

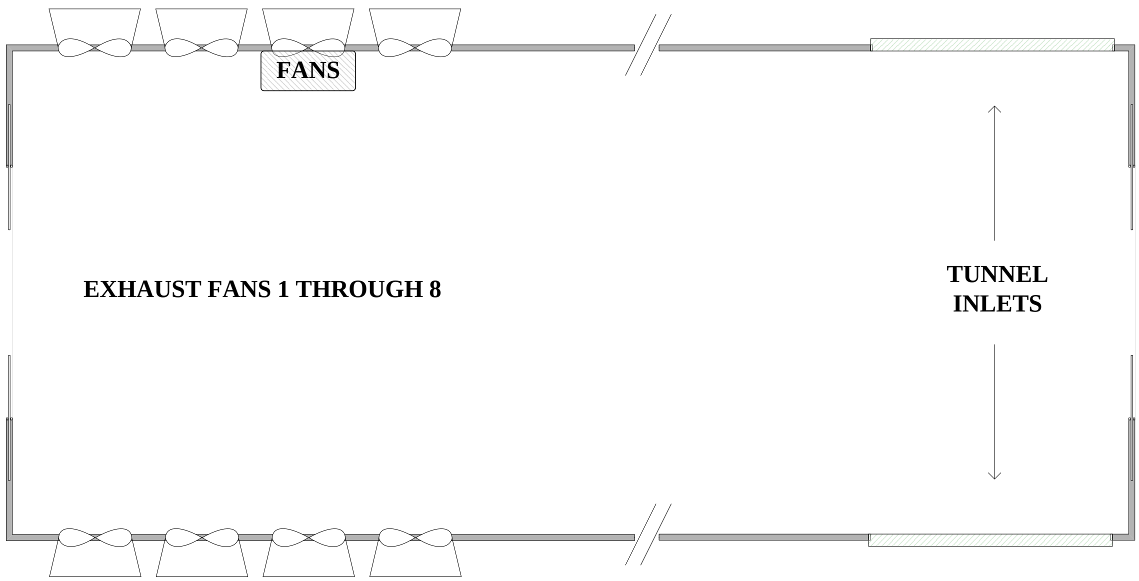

Figure 3.41. FANS unit on the intake side of the test fan, inside the barn (plan view, not to scale).

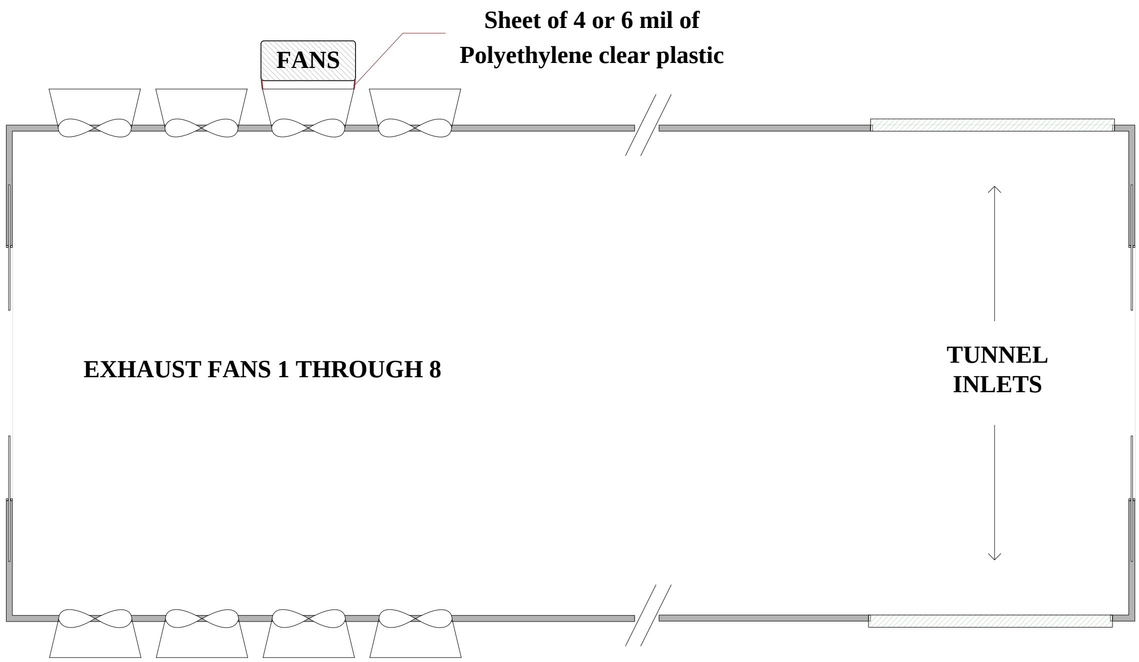

Figure 3.42. FANS unit near the discharge side of the test fan, outside the barn (plan view, not to scale).

Six treatments were performed with the FANS unit placed inside the barn on the intake of the test fan. The treatments were repeated with the FANS unit placed outside the barn near the discharge side of the test fan, as shown in Figure 3.43 through Figure 3.48.

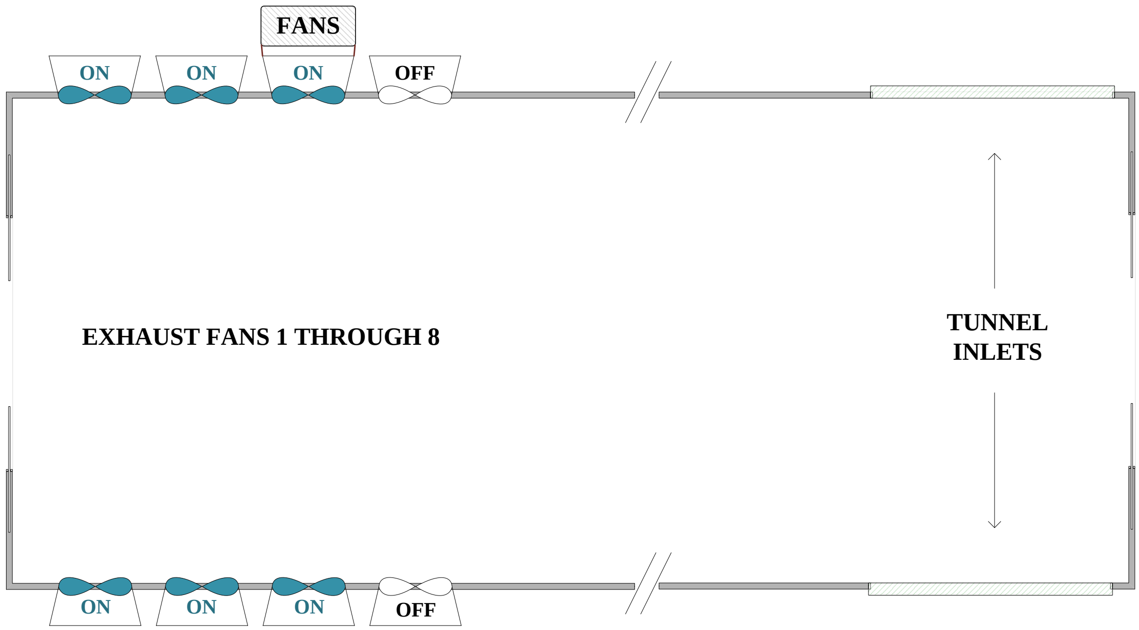

Figure 3.43. FANS unit and test fan in the Upstream position (plan view, not in scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

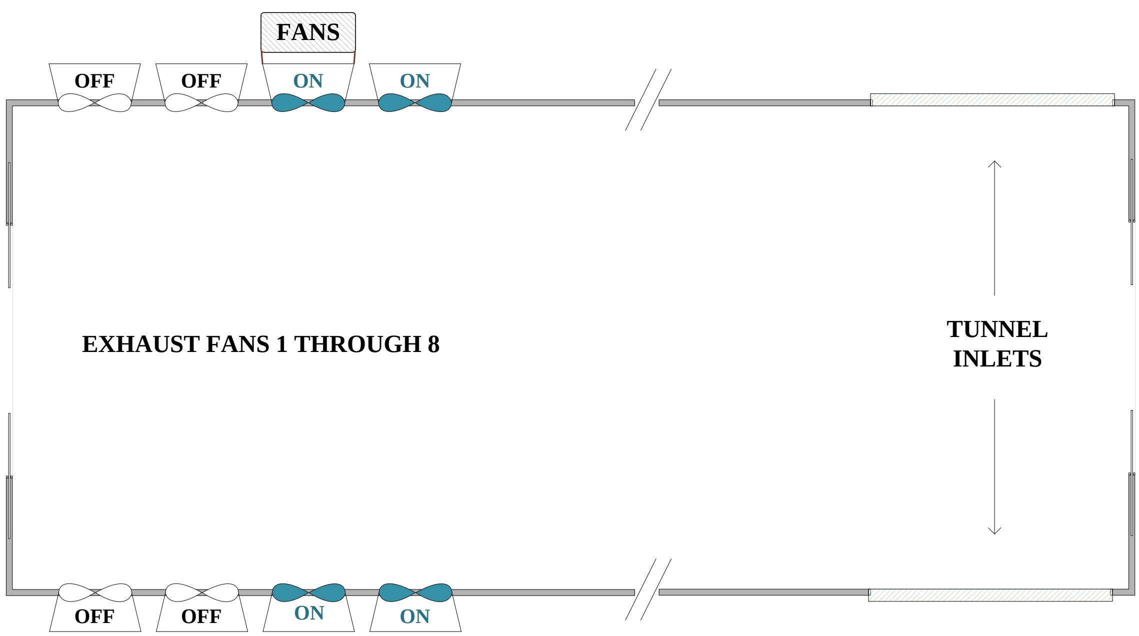

Figure 3.44. FANS unit and test fan in the Downstream position (plan view, not to scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

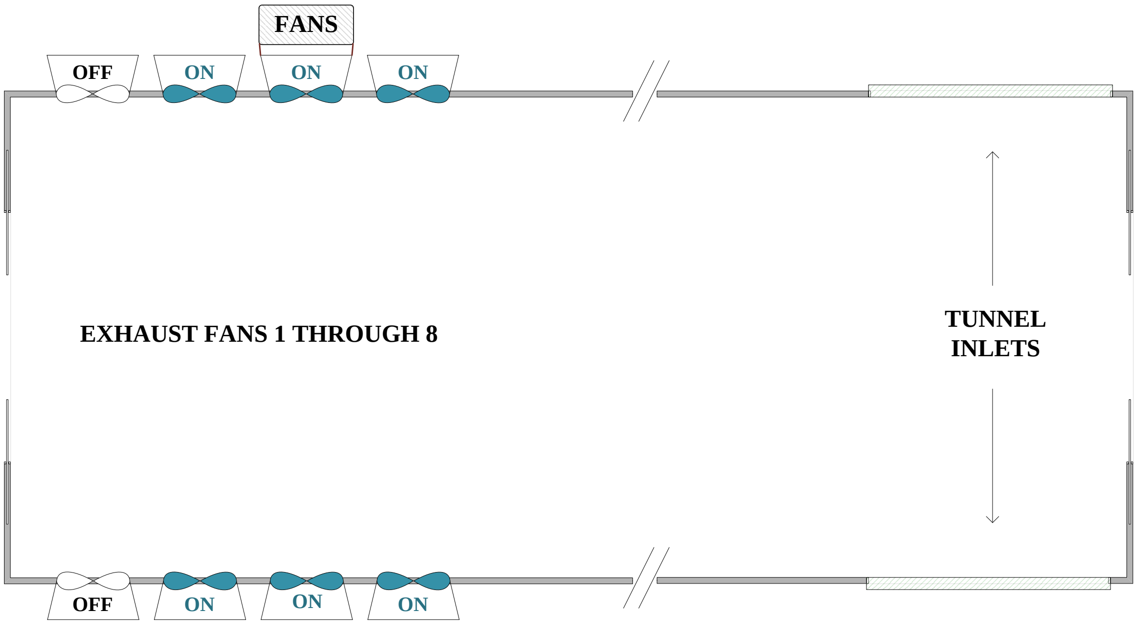

Figure 3.45. FANS unit and test fan in the Middle position (plan view, not to scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

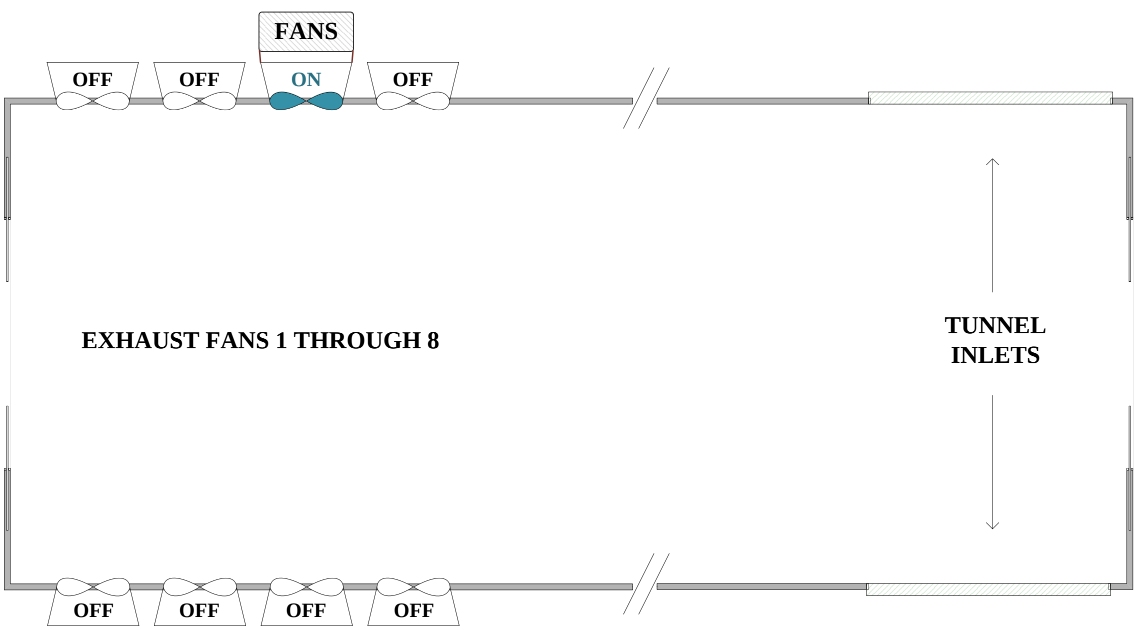

Figure 3.46. Fan being tested Alone by the FANS unit (plan view, not to scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

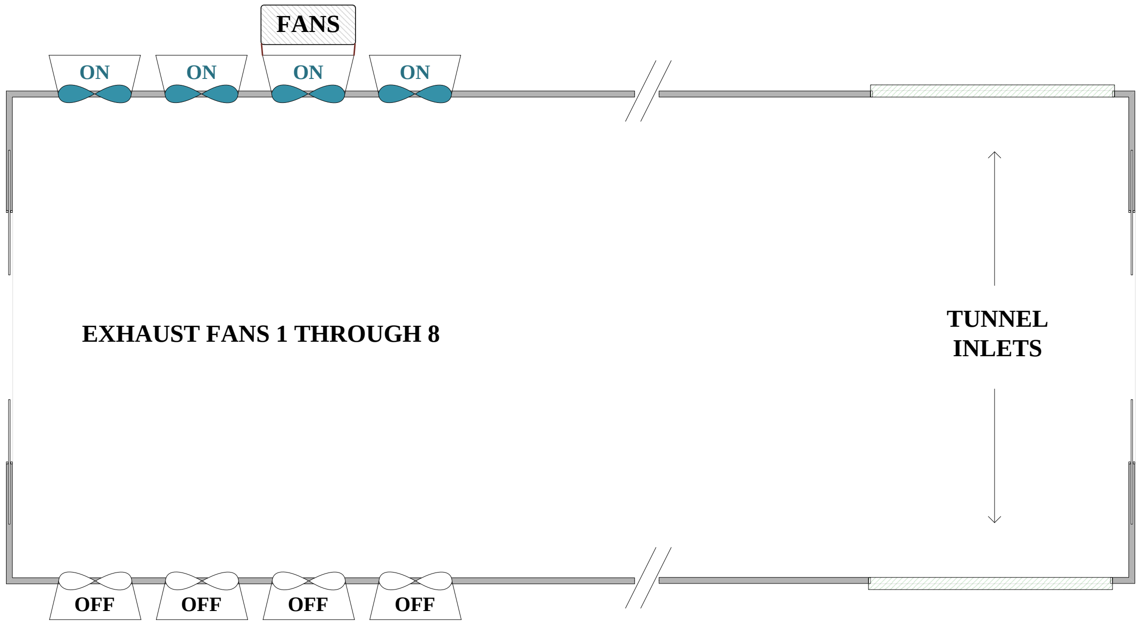

Figure 3.47. Operating fans on the Same Sidewall as the FANS unit and test fan (top view, not to scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

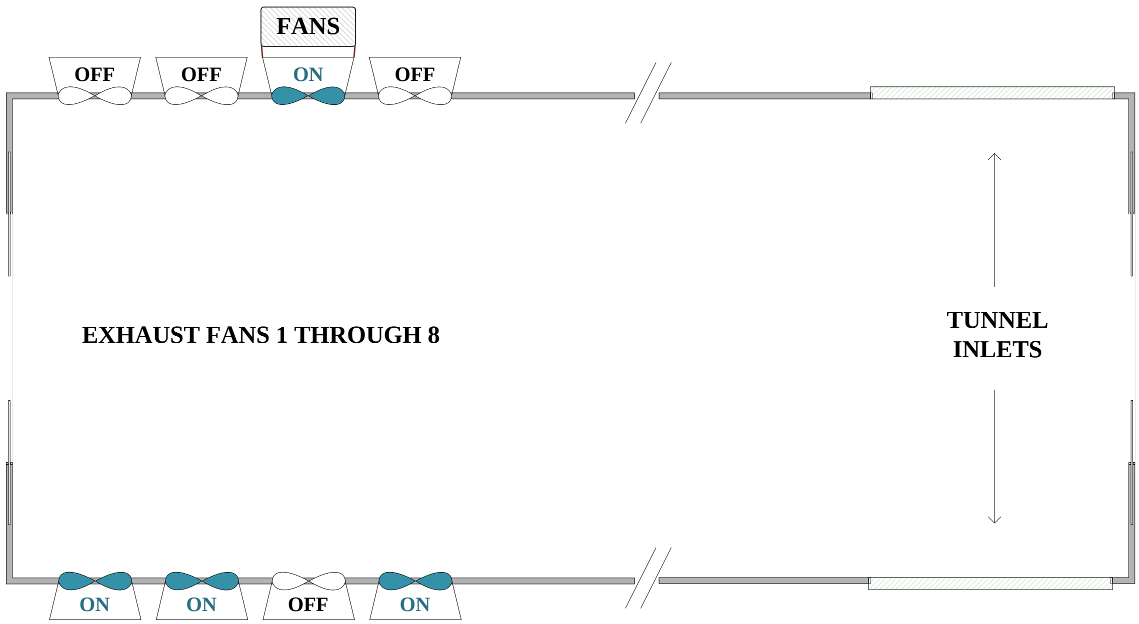

Figure 3.48. Operating fans on the Opposite Sidewall from the FANS unit and the test fan (top view, not to scale) – FANS unit near the discharge side of the test fan in a representative barn of Farms 2, 3 or 4.

3.4.1.3 Satisfying Objective 3

Objective 3 was to evaluate if the FANS unit is the cause of possible differences on fan performance results. Fan performance results are expected not to be significantly different from each other when placing the FANS Unit on the intake side of the test fan as compared to placing the FANS unit near the discharge side of the test fan (Li *et al.*, 2009). Therefore, if fan test results behave differently among the "P" treatments when the FANS unit is placed next to the intake side of the test fan (Inside treatment) as compared to placing the FANS unit near the discharge side of the fan (Outside treatment), it can be concluded that the FANS unit causes possible air flow penalties during fan performance tests. Thus, the approach used to satisfy objective 3 was to evaluate the interaction of objectives 1 and 2.

3.4.1.4 Air Flow Readings per Treatment

Eight static pressures were set in the poultry barns for each treatment and one value of air flow was obtained with the FANS unit and recorded for each of the eight static pressure values. The ambient air conditions (Sub-section 3.3.3.5) during the tests, as well as power information (Sub-section 3.3.3.3) and barn air speed (Sub-section 3.3.3.4) were recorded for each test run.

3.5 Experimental Design

Data gathered at the two different types of barn (with exhaust fans spaced 1.6 m apart or not spaced) were treated as two different experiments owing to the fact that treatments were not exactly the same from one experiment to the other. Treatments had different numbers of fans operating from one farm to the other, as shown in Table 3.8. Also, poultry barns operated by Poultry Company 1 had fans placed immediately next to each other, while the barns operated by Poultry Company 2 had fans spaced 1.6 m apart from each other.

Experiment 1(E 1) was carried out at Farm 1, operated by Poultry Company 1, where the barns were equipped with ten 1.22 m diameter fans placed immediately next to each other (Figure 3.2). Experiment 2 (E 2) was carried out at Farms 2, 3 and 4, operated by Poultry Company 2, where the barns were equipped with eight 1.22 m diameter fans each placed 1.6 m apart from each other (Figure 3.6). The treatments were classified as a 2 (FANS inside or outside) x 6 (operating fan combinations) factorial arrangement.

Test fans were selected according to their position on sidewalls and the desired combinations of operating fans for the treatments. Further, all fans inside a barn had to be operating correctly, so that all treatments could be applied. The barns used for fan testing were the ones available, which were not under cleaning or maintenance operations in between flocks. Eight values of static pressure were tested per treatment per fan within the range 0 to 60 Pa.

All treatments in an experiment were applied to all fans tested. Treatments were applied to groups of eight experimental units, since each treatment was tested at eight values of static pressure in the barn. In this study, fan was designated by the experiment and fan numbers, for example: E2_F1 means fan 1(F 1) in Experiment 2 (E 2). Group of experimental units were designated by the fan name and instance of fan test: E1_F2_I3 means fan 2 (F 2) in Experiment 1 (E 1) at instance 3 (I 3). Each experimental unit was tested under one single condition of static pressure in the barn and received one single treatment combination described in Sub-section 3.4.1. The total number of experimental units was, therefore, 480 (96 per block) which is the number of treatment combinations (12) multiplied by number of static pressure (8), multiplied by the number of blocks (5). Treatment combinations 1 through 12 (6 x 2 factorial arrangement) were randomized before being assigned to groups of experimental units.

The structure design of Experiments 1 and 2 was the Generalized Randomized Complete Block (GRCB) design, in which the test fans were blocked in order to minimize experimental error. Blocking the test fans allowed removing the variation among fans from the experimental error. In this way, blocks contained one single fan, but 96 experimental units (eight groups of 12 fan-instances). Static pressure was used as a covariate in the experiment. Using static pressure (SP) as a covariate in the statistical model allowed the removal of the variation owing to the SP before estimating the treatment effects on air flow (response variable), thus reducing experimental error. Figure

3.49 exemplifies the treatments application to group of experimental units within one block in Experiment 1. The same structure design was applied to Experiment 2.

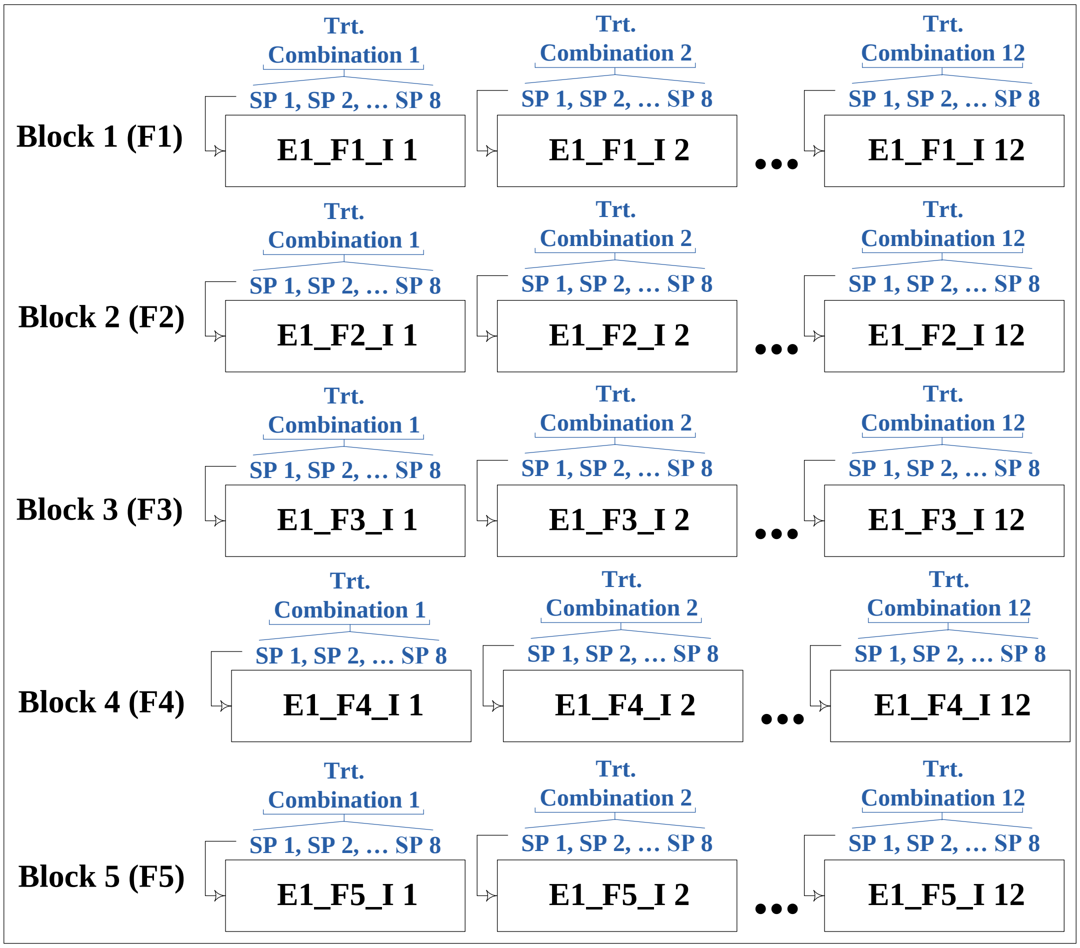

Figure 3.49. Layout of the GRCB design for E 1 with five blocks, eight SP`s (covariates), 12 groups of experimental units (represented by squares) with a total of 96 experimental units per block, 6 x 2 treatment combinations and 40 replications. Same design structure was applied to E 2.

3.6 Statistical Analysis

Second order polynomial regressions were fitted to the data, using SAS® (9.2, SAS Institute Inc., 2002-2008 Cary, NC, U.S.A), to represent the fan performance for each treatment combination, for each fan (block). B_o, B_1 and B_2 represent the intercept, linear and quadratic parameters of the curves. The form of the regression equation was:

$$\mathbf{AF_{(treatment)} = B_o + SP * B_1 + SP^2 * B_2} \qquad \text{Equation 3.2}$$

A Student t- test was performed to verify the hypothesis of the parameters being significantly differently from zero, testing the significance of the polynomial relationship. The differences between air flows provided in different treatments were calculated for the same values of static pressure (SP), with the following equation:

$$\textbf{Difference (\%)} = (AF_{treatment\ ps(i)} - AF_{treatment\ ps(j)}) * 100 / AF_{treatment\ ps(i)} \qquad \text{Equation 3. 3}$$

Where,

p = Refers to treatment "P" (operating fans *position* relative to the FANS unit and test fan), p = {Alone, Upstream, Downstream, Middle, Same Sidewall, Opposite Sidewall};

s = Refers to treatment "S" (FANS near the intake or discharge *side* of the test fan), s={Inside, Outside};

i,j ⟶ $i \neq j$, refers to distinct "**p s**" treatment combination;

$AF_{treatment\ ps}$ = Predicted Air flow at the "**p s**" treatment combination [$m^3\ s^{-1}$];

The significance of the differences among the treatments was tested through the statistical model:

$$Y_{(hijl)k} = \mu + F_h + P_i + S_j + (P * S)_{ij} + SP_l + E_{(hijl)k} \qquad \text{Equation 3.4}$$

Where,

μ = overall mean considered common to all observations [$m^3\ s^{-1}$];

F_h = random effect of the h-th block;

P_i = fixed effect on the i-th level of treatment "P", i = {1,2,3,4,5,6}, FANS position relative to operating fans;

S_j = fixed effect on j – th level of treatment "S", j = {1,2}, FANS near the intake (Inside treatment) or discharge side of test fan (Outside treatment);

SP_l = fixed effect on the l – th level of SP reading, l = {1 through 8};

$E_{(hijl)k}$ = random component, which explains the random variation or experimental error to the k-th experimental unit;

$Y_{(hijl)k}$ = air flow observation from the effect of the h-th block (fan), the l-th covariate (SP), the i-th and j-th treatment effects, to the level of the k-th experimental unit.

Pair wise comparisons were performed using the Least Significant Difference (LSD) procedure, in order to identify differences between treatments. Proc Mixed of SAS® (9.2, SAS Institute Inc., 2002-2008 Cary, NC, U.S.A) was used.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Experiment 1 (E1) – Fans from Poultry Company 1

Air flow rate obtained from each treatment was regressed as a second order polynomial function of static pressure (SP), as described in section 3.6. The intercept, first and second order parameters of the regressions are provided in Appendix A, Table A.1. The addition of the quadratic term was significant at 90% confidence level for approximately 83% of the regression curves. Therefore, the second order polynomial regression was performed among all fan tests. The overall models of fan performance were all significant at 95% confidence level and presented a strong second order relationship between air flow rate and SP. Approximately 85% of the curves had a coefficient of determination (R^2) of at least 98% and overall p-value less than 0.0001. The remaining fan curves presented an R^2 of at least 95% and overall p-value less than 0.0004.

4.1.1 Fan Tests with the FANS Unit on the Intake Side of each Test Fan (Inside Treatment)-Experiment 1

Figures 4.1 through 4.5 show the fan performance curves obtained in Experiment 1 (E 1), with the FANS placed next to the intake side (Inside treatment) of the test fans.

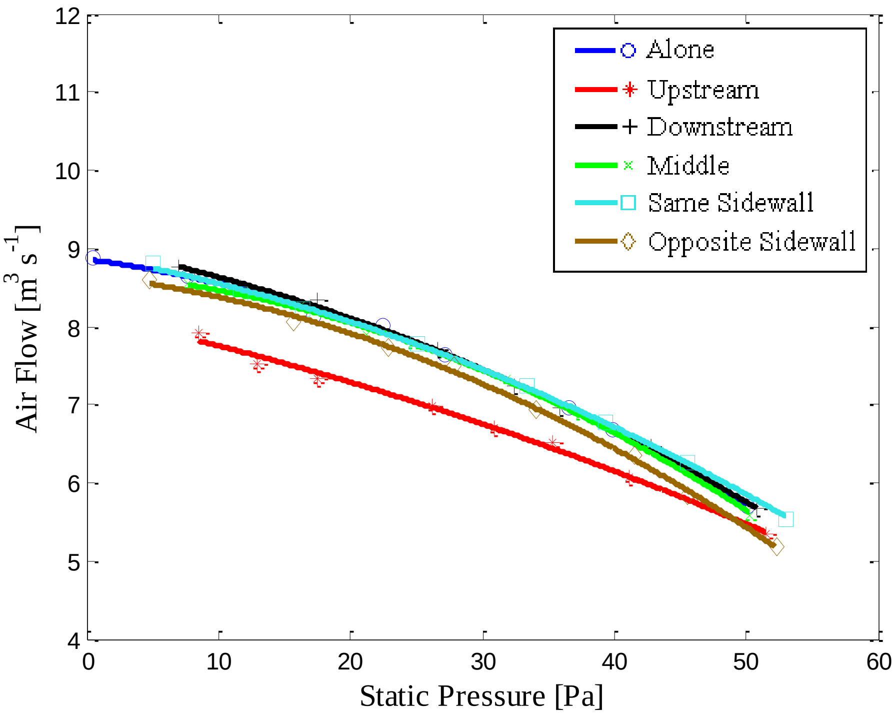

Figure 4.1. Fan performance curves, FANS unit Inside, E1_F1.

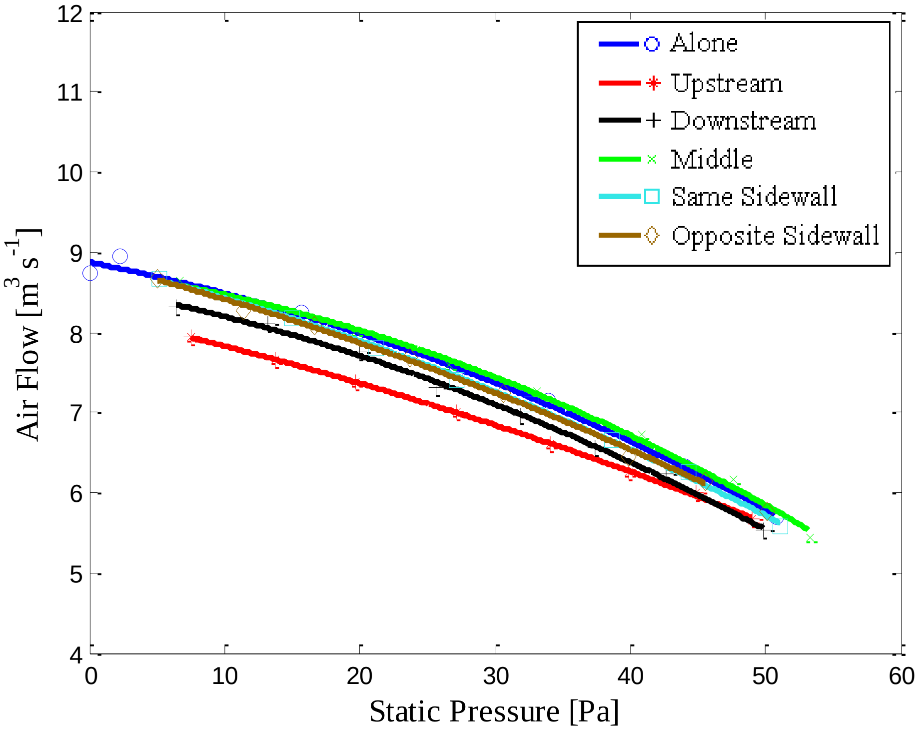

Figure 4.2. Fan performance curves, FANS unit Inside, E1_F2.

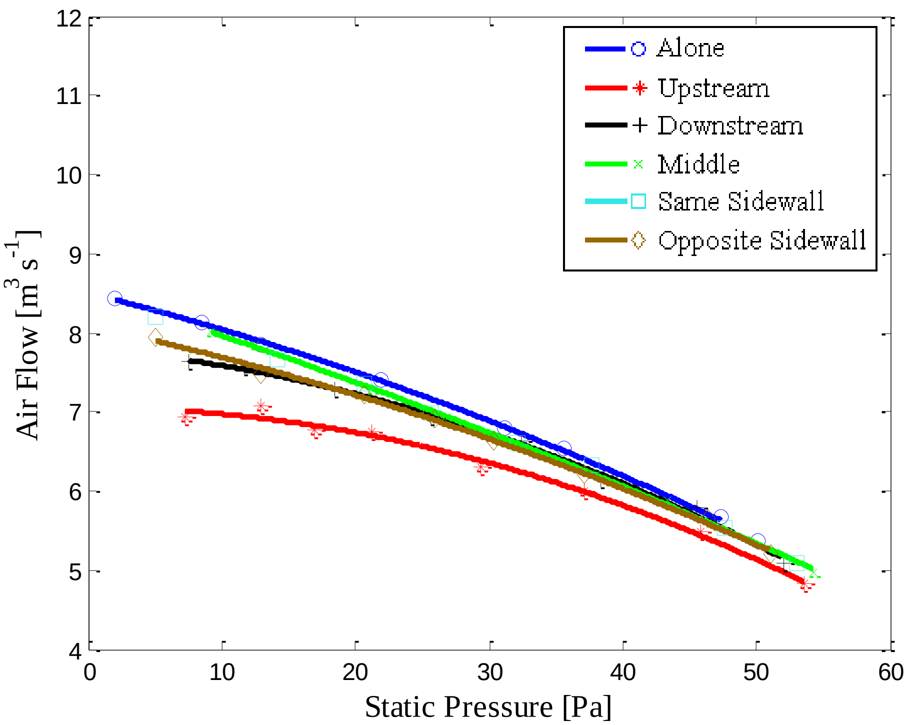

Figure 4.3. Fan performance curves, FANS unit Inside, E1_F3.

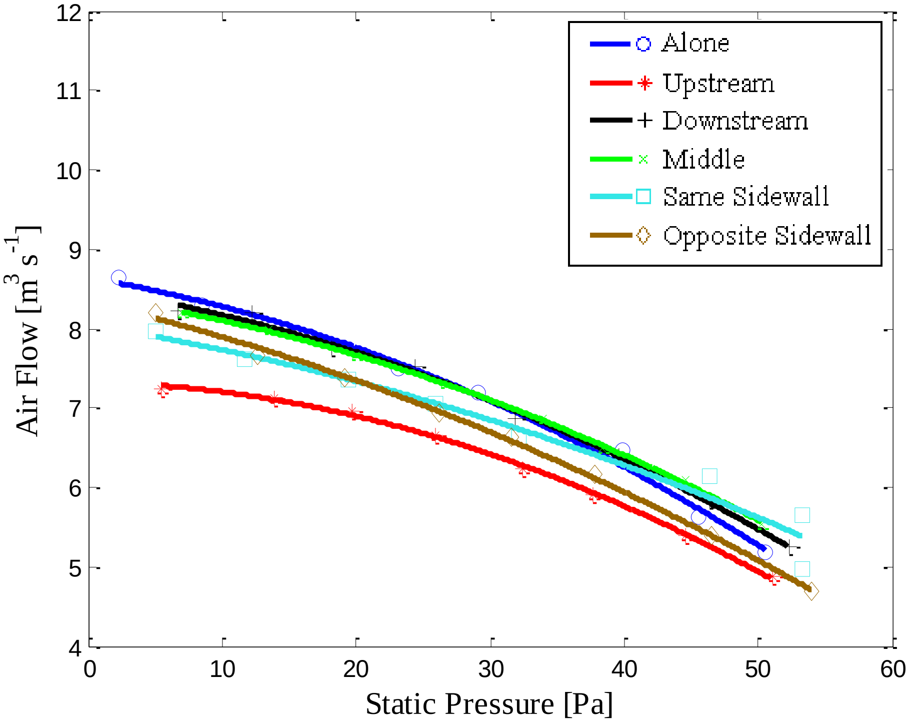

Figure 4.4. Fan performance curves, FANS unit Inside, E1_F4.

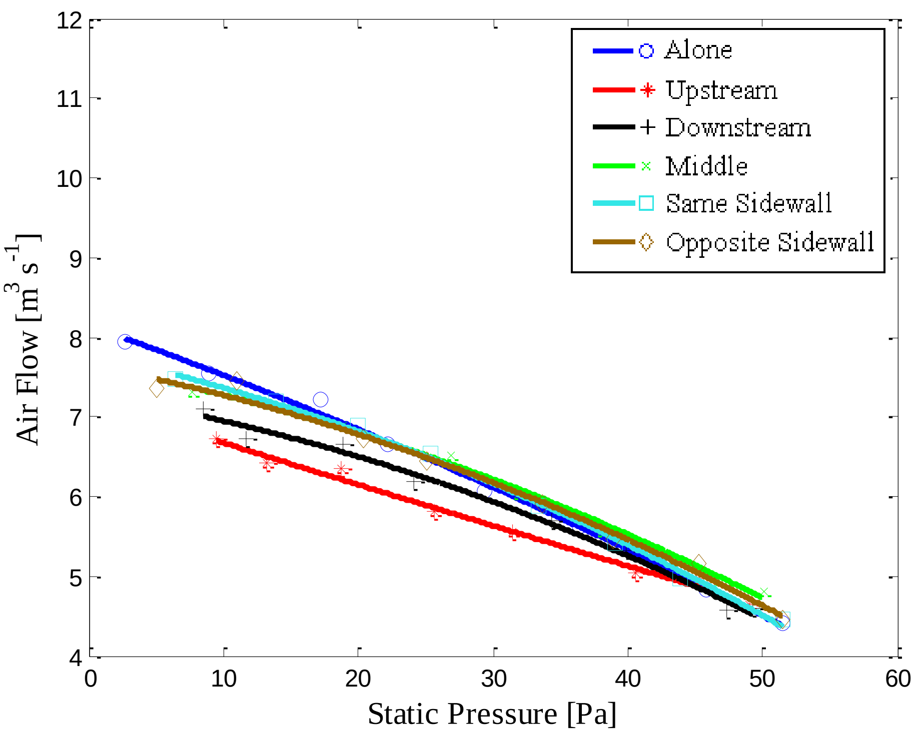

Figure 4.5. Fan performance curves, FANS unit Inside, E1_F5.

Figure 4.1 through Figure 4.5 show that the fan performance curves differed from each other among the treatments, for the tests with FANS inside the barn. The "P" (position of operating fans relative to FANS and test fan) treatments had a significant effect ($p < 0.0001$) on air flow test results. Generally, Alone and Middle treatments presented the highest air flow results among the five test fans in Experiment 1 when the FANS unit was placed next to the intake side of the test fan. The Alone treatment significantly ($p < 0.05$) differed from the Downstream, Upstream and Opposite Sidewall treatments.

The Upstream treatment produced significantly lower air flow values among the same five test fans with FANS next to the intake side of the fans. All remaining "P" treatments were significantly ($p < 0.0001$) different from the Upstream treatment. The Downstream, Same Sidewall and Opposite Sidewall treatments were characterized by intermediate fan performance curves, generally falling between the Alone/Middle and the Upstream treatments. Downstream was significantly ($p < 0.05$) different from Middle and Alone, whereas Opposite Sidewall was significantly different from Middle, Same Sidewall and Alone. The differences between the "P" treatments were quantified and are presented in Table 4.1.

Fan performance curves within the "P" treatments are not parallel, which demonstrates that there was interaction between static pressure (SP) and "P" treatments ($p = 0.0018$). The curves converged at higher SP values, as shown in Figure 4.1 through Figure 4.5. The number of operating fans was the same for all the SP values measured at each treatment. Therefore, the curves converged as the barn air speed was reduced. It is suggested that a further study is performed in order to understand the relationship of air velocities through the FANS unit and through the barn and air flow penalties.

Lim *et al.* (2010) evaluated the differences in air flow between a 1.22 m diameter test fan operating freely and the same fan operating with a FANS unit on its intake side. The authors found air flow rate reduction of approximately 3.0% from the original laboratory fan test curve attributed to an air flow restriction caused by the FANS unit structure. Similar to the results of Experiment 1 of this work, the authors found that the air flow rate differences increased with lower static pressure values.

Average differences between treatments were calculated for low values of SP ($0 \leq SP \leq 30$ Pa) and high values of SP (30 Pa < SP) for all tested fans, using Equation 3.3. Table 4.1 presents averaged air flow differences between the treatments that were significantly different from each other. The Least Square Means Difference procedure was performed on SAS® for all values of SP to compare treatment combinations. Negative differences mean that air flow from the first treatment in a paired comparison was lower than air flow from the second compared treatment.

Table 4.1. Significant averaged differences in air flow rate between "P" Treatments with the FANS unit next to the intake side of the test fan – Experiment 1.

Comparisons:	**Average Differences ± Std. Error**						
	At Low SP`s			**At High SP`s**			
Upstream vs. Alone	-10.9%	±	2.0%	-6.8%	±	2.5%	*
Upstream vs. Downstream	-8.2%	±	3.1%	-6.2%	±	3.6%	*
Upstream vs. Middle	-10.3%	±	1.4%	-8.7%	±	3.2%	*
Upstream vs. Same Sidewall	-9.1%	±	1.9%	-7.1%	±	3.0%	*
Upstream vs. Opp. Sidewall	-8.0%	±	1.5%	-5.0%	±	1.9%	*
Alone vs. Downstream	2.5%	±	2.3%	0.6%	±	2.1%	**
Alone vs. Opp. Sidewall	2.7%	±	1.7%	1.7%	±	2.5%	*
Opp. Sidewall vs. Middle	-2.2%	±	1.4%	-3.5%	±	2.5%	*
Opp. Sidewall vs. Same Sidewall	-1.0%	±	1.2%	-2.0%	±	3.0%	**
Downstream vs. Middle	-2.0%	±	-2.6%	-2.4%	±	3.7%	**

- * Significantly different at 99% confidence level (for both SP ranges); ** Significantly different at 95% confidence level (for both SP ranges).
- Differences were calculated using Equation 3.3 and averaged for all tested fans. Estimates of air flow [$m^3\ s^{-1}$] can be found in Appendix B, Table B.3 (for both SP ranges).

Table 4.1 shows that the Upstream treatment was at least 8.0 ± 1.5% lower than any other treatment, at low static pressures ($0 \leq SP \leq 30$ Pa). Differences between Upstream and the other treatments were considered large enough to have a substantial effect on the predicted barn ventilation. If all ten 1.22 m diameter fans were tested inside a barn at 30 Pa using a FANS unit in the Upstream position, the total predicted barn ventilation could be up to 10.4 $m^3\ s^{-1}$ lower than ventilation rates predicted by FANS conducted in the Alone or Middle positions. This 10.4 $m^3\ s^{-1}$ (22,036 cfm) difference in air flow is approximately equivalent to the amount of air that a new 1.22 m (48 in) diameter fan moves at the same static pressure.

The substantial air flow differences encountered between the Upstream and the remaining "P" treatments indicate that either the fan was operating in a lower capacity or the FANS unit was possibly causing an air flow penalty when the Upstream configuration of operating fans was used inside the barns of Farm 1. The Upstream treatment configuration should, therefore, be avoided when testing fans using the FANS unit inside barns similar to the ones studied in Farm 1 (Sub-section 3.1.1).

There were also significant differences between other treatments, as shown in Table 4.1. However, these differences were approximately 3.5 ± 2.5 % or less. Still, those differences could be large enough to cause a substantial total air flow error in the building ventilation estimation. Therefore, care should be taken during fan tests *in-situ* to select additional fans to operate during fan tests with FANS, so that the test results represent as closely as possible the real air flow performance of the test fan. The Opposite Sidewall treatment produced lower air flow results than other "P" treatment configurations (Table 4.1). Therefore it is suggested that this treatment configuration is also avoided when testing fans using the FANS unit inside barns similar to the ones studied in Farm 1 (Sub-section 3.1.1).

The fans inside the poultry barns studied are located on the sidewalls, therefore, the air has to make a 90^{o} turn to pass through the FANS unit and test fan (see Figure 3.32 through Figure 3.37). It is, therefore, reasonable to assume that the FANS unit frame can actually work as an obstacle in the air path from the curtain inlets through the exhaust fans. Placing the FANS unit near the discharge side of the test fan (Outside treatment) would remove any potential obstruction from the fan intake and allow air to flow freely into the fan. Therefore, fan tests were performed with the FANS unit placed near the discharge side of the test fans (Figure 3.43 through Figure 3.48) and an analysis was performed to determine if the differences were caused by penalties related to the FANS unit frame or by a real change in the actual fan performance (Sub-section 4.1.2).

4.1.2 Fan Tests with the FANS Unit near the Discharge Side of each Test Fan (Outside Treatment)-Experiment 1.

The FANS unit was placed outside the barn near the discharge side of test fans as described in Section 3.3.2 and the same "P" treatments were repeated. This FANS unit placement allowed air to go straight through the FANS unit after it had passed through the test fan. Therefore, it was expected that differences between the "P" treatments would be reduced when the fan tests were performed with the FANS unit outside the barn. Figures 4.6 through 4.10 show the fan performance curves obtained in Experiment 1 (E 1), with FANS placed near the discharge side (Outside treatment) of the test fans.

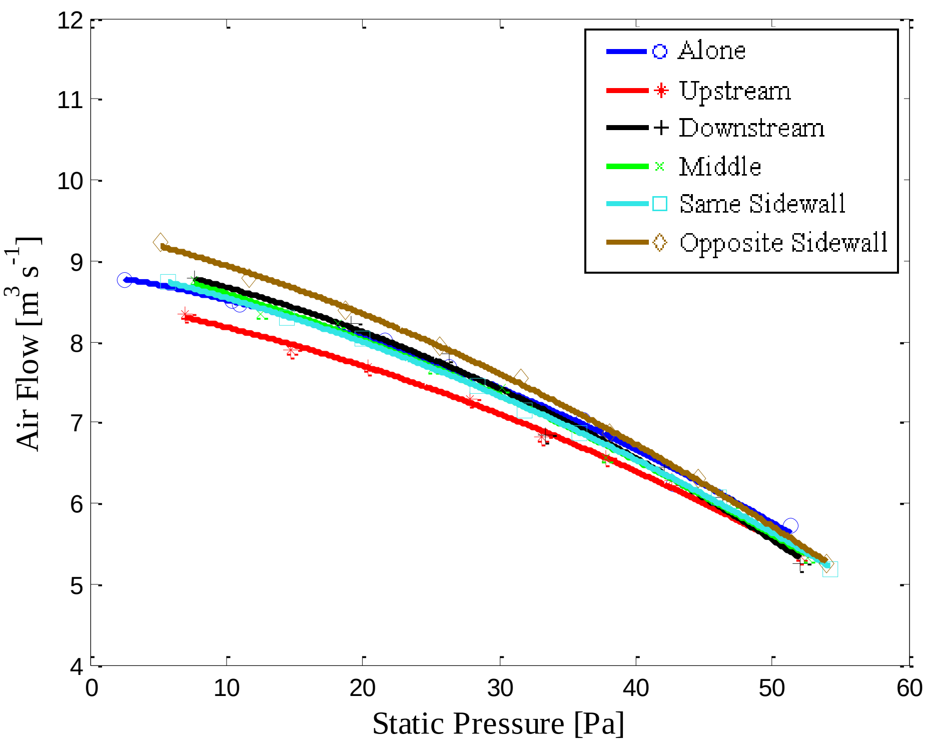

Figure 4.6. Fan performance curves, FANS unit Outside, E1_F1.

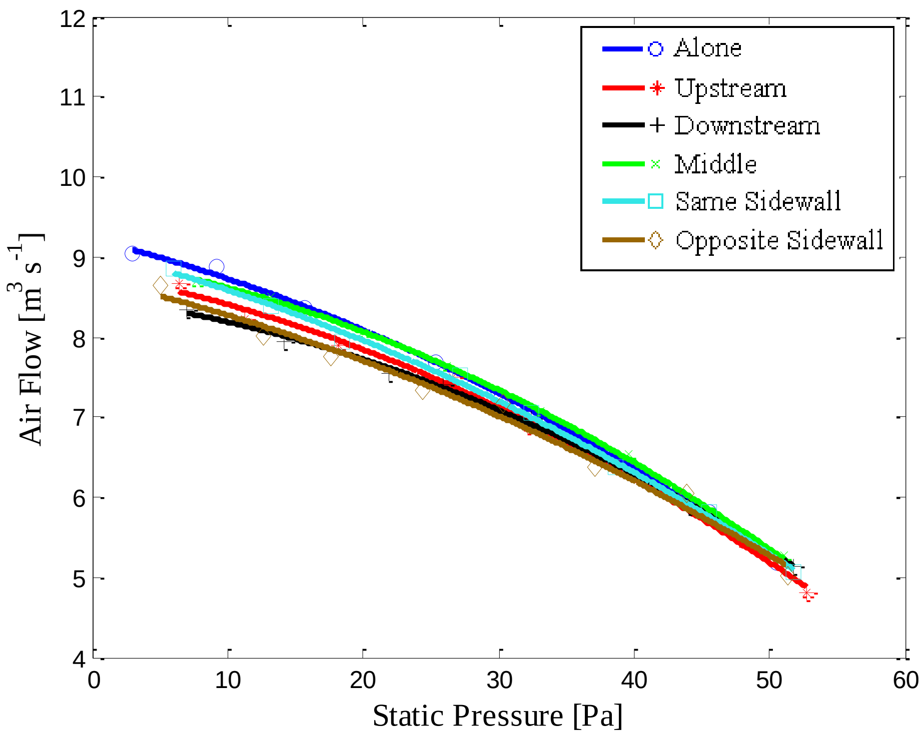

Figure 4.7. Fan performance curves, FANS unit Outside, E1_F2.

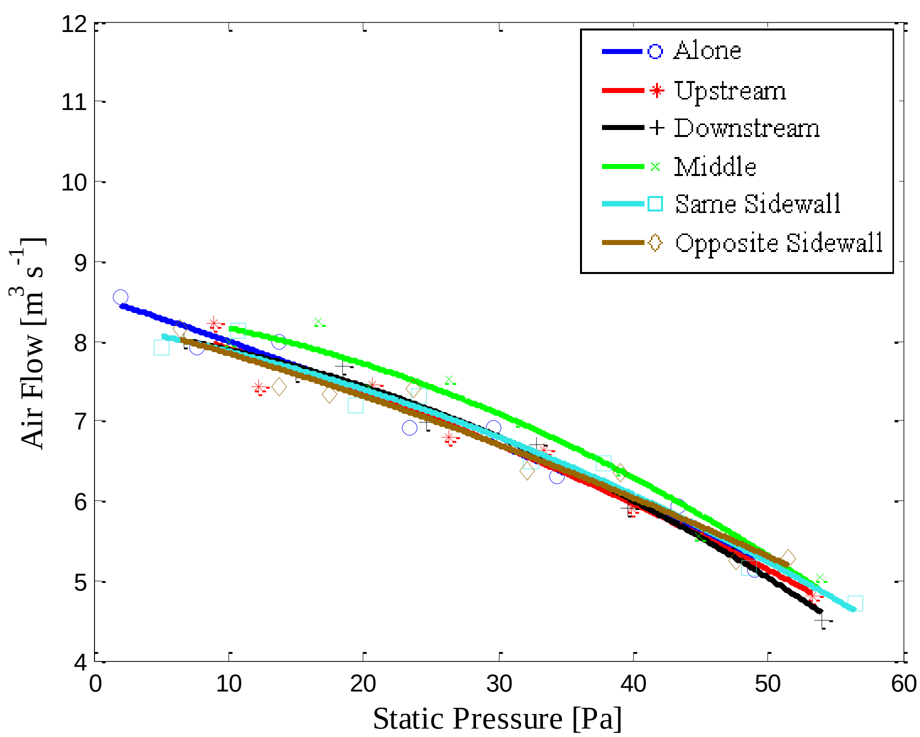

Figure 4.8. Fan performance curves, FANS unit Outside, E1_F3.

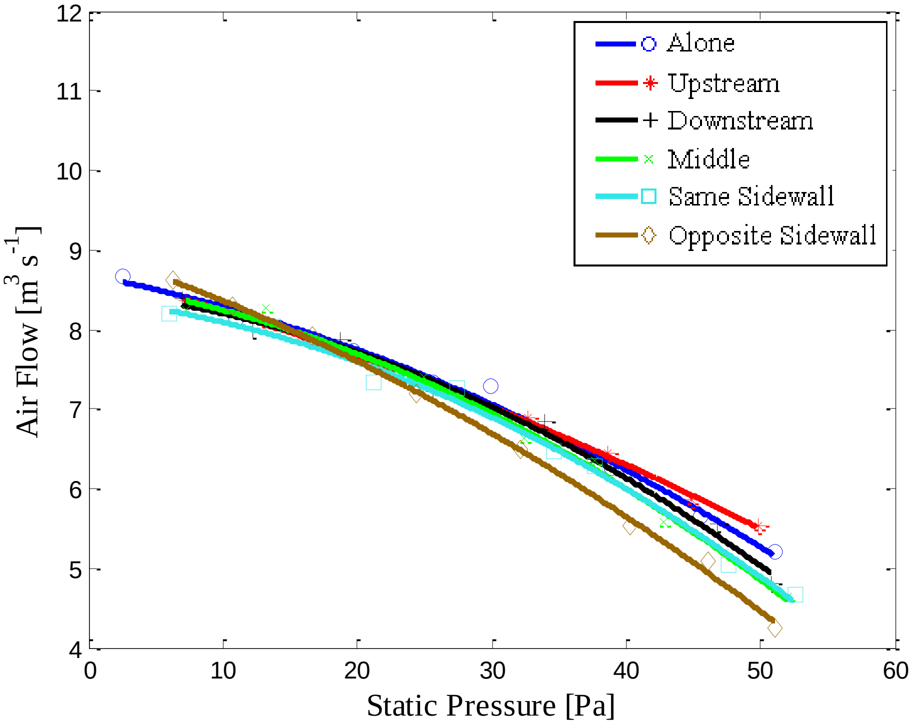

Figure 4.9. Fan performance curves, FANS unit Outside, E1_F4.

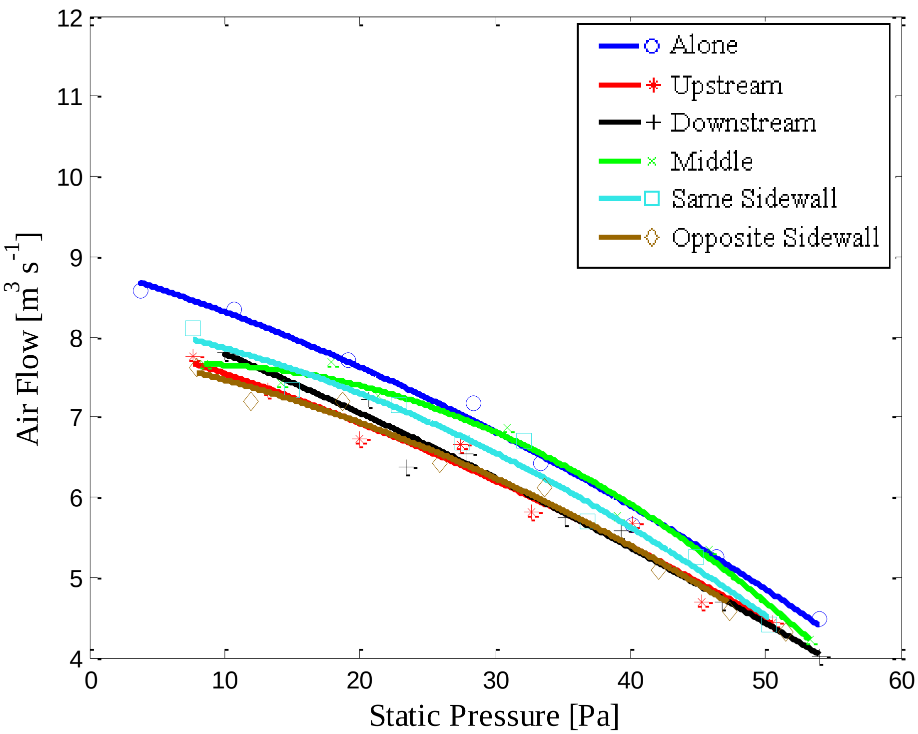

Figure 4.10. Fan performance curves, FANS unit Outside, E1_5.

Figure 4.6 through Figure 4.10 show that the fan performance curves were closer together for all “P” treatment with the FANS unit outside than with the FANS unit inside the barn (Figure 4.1 through Figure 4.5). This demonstrates that there was interaction between “P” and “S” treatments ($p < 0.0001$). Generally, Alone and Middle treatments provided higher air flow values than the remaining “P” treatments, similar to the results with the FANS unit placed inside the barn. On the other hand, the Upstream treatment provided fan curves closer to the remaining treatments with the FANS unit outside than with the FANS unit inside the barn.

The statistical tests showed that the “S” treatments (FANS inside vs. FANS outside) had a significant ($p < 0.0001$) effect on air flow measurements. The Upstream treatment obtained with FANS next to the intake side of the test fan was significantly ($p < 0.0001$) different from the Upstream treatment obtained with the FANS unit near the discharge of the test fan. However, all remaining “P” treatments obtained with the FANS unit next to the intake side (Inside treatment) of the test fan were not significantly different from the same “P” treatments obtained with the FANS unit near the discharge side of the test fan at 95% confidence level (Table 4.2). These results indicate that a FANS unit can be used on the discharge side of a test fan to measure fan performance of fans located in barns similar to the ones of Farm 1.

Li *et al.* (2009) studied the effect on fan test results when using FANS unit placed next to the intake side of the test fan (Inside treatment) versus placing the unit near the discharge side of the test fan. In accordance with this study, the FANS unit was sealed to the fan outlet, using a makeshift transition, such that all of the air moved by the fan would pass through the FANS unit. Less than 5% differences, not statistically significant, were found in FANS test results from testing on the intake and on the discharge sides of a test fan. Li`s results are similar to most of the comparisons between FANS results obtained from tests on the intake and discharge sides of a fan within the same “P” treatment in this study.

Table 4.2. Comparison of FANS Inside versus FANS Outside within the same "P" treatment – Experiment 1. Average differences in air flow calculated for all tested fans and SP.

Comparison	Average Differences ± Std. Error			
Alone IN vs. OUT	-1.78%	±	5.26%	n
Upstream IN vs. OUT	-6.92%	±	4.40%	**
Downstream IN vs. OUT	-0.71%	±	3.78%	n
Middle IN vs. OUT	-0.90%	±	4.68%	n
Same Sidewall IN vs. OUT	-0.46%	±	4.03%	n
Opposite Sidewall IN vs. OUT	-0.59%	±	3.73%	n

- ** The shaded line shows the only treatment that provided significantly different results between FANS placed on the intake of test fan or on the discharge of the test fan at 95% confidence level;
- n Not significantly different at 95% confidence level.

The "P" treatments found to be significantly different from other "P" treatments when the FANS unit was placed next to the intake of the test fan were compared again with the FANS unit placed near the discharge side of the test fan. Alone and Middle were significantly ($p \leq 0.0005$) different from the Upstream treatment. However, the Upstream treatment was not significantly different from the Downstream, Opposite Sidewall and Same Sidewall ($p > 0.1600$). Alone remained significantly different from Opposite Sidewall and Downstream ($p < 0.0030$), whereas Opposite Sidewall was not significantly ($p = 0.1595$) different from Same Sidewall. Downstream remained significantly different from Middle ($p = 0.0045$) and Opposite Sidewall was also significantly different from Middle ($p = 0.0005$).

Placing the FANS unit near the discharge side of the test fans contributed to reduce the number of significantly different "P" treatments (Table 4.3). When the FANS unit was placed next to the intake of test fans, ten of the 15 possible pair wise comparisons among the "P" treatments were found to be significantly different. However, when the FANS unit was placed near the discharge of the test fan, only six of the 15 possible pair wise comparisons were found to be significantly different.

Differences among the significantly different "P" treatments obtained with the FANS unit near the discharge side of the test fans were similar to the differences found among the same "P" treatments when FANS was on the inside, except for the Upstream treatment comparisons, as shown in Table 4.3. Once again, the differences were calculated using Equation 3.3 and averaged for all tested fans and for groups of low ($0 \leq SP \leq 30$ Pa) and high ($30 \text{ Pa} < SP$) static pressures (SP), since there was interaction between SP and "P" treatments ($p = 0.0018$). Table 4.3 presents averaged air flow differences among the treatments that were significantly different from each other. The Least Square Means Difference procedure was performed on SAS® for all values of SP to compare treatment combinations. Negative differences mean that air flow from the first treatment in a paired comparison was lower than air flow from the second compared treatment.

Table 4.3. Significant and no longer significant averaged differences in air flow rate between "P" treatments with the FANS unit near the discharge side of the test fan – Experiment 1.

Comparisons:	**Average Differences ± Std. Error**						
	At Low SP`s			**At High SP`s**			
Upstream vs. Alone	-3.9%	±	3.5%	-3.4%	±	3.7%	*
Upstream vs. Downstream	-1.4%	±	2.4%	-0.5%	±	2.0%	n.o.
Upstream vs. Middle	-3.6%	±	2.5%	-3.1%	±	5.2%	*
Upstream vs. Same Sidewall	-2.0%	±	2.4%	-1.2%	±	3.6%	n.o.
Upstream vs. Opp. Sidewall	-1.1%	±	3.9%	0.5%	±	5.7%	n.o.
Alone vs. Downstream	2.3%	±	3.3%	2.7%	±	2.9%	*
Alone vs. Opp. Sidewall	2.6%	±	4.5%	3.7%	±	5.0%	*
Opp. Sidewall vs. Middle	-2.6%	±	4.0%	-3.7%	±	4.5%	*
Opp. Sidewall vs. Same Sidewall	-1.0%	±	3.4%	-1.8%	±	3.4%	n.o.
Downstream vs. Middle	-2.2%	±	2.8%	-2.6%	±	4.3%	*

- * Significantly different at 99% confidence level (for both SP ranges);
- The shaded lines show the treatment comparisons that were found to be significantly different with FANS inside and not significantly (n. o.) different with FANS outside at 95% confidence level;
- Differences were calculated using Equation 3.3 and averaged for all tested fans. Estimates of air flow [m^3 s^{-1}] can be found in Appendix B (for both SP ranges), Table B.3.

Placing the FANS unit outside the barn reduced the number of "P" treatments that were significantly different from each other and also reduced the magnitude of the differences between the Upstream and the remaining "P" treatments. The differences between the Upstream treatment and the other "P" treatments obtained with FANS outside were approximately 75.6 ± 13.8 % lower than the same differences encountered with FANS inside. This reduction in the differences between Upstream and remaining "P" treatments is evidence that the FANS unit causes an air flow penalty in the Upstream treatment, when placed next to the intake side of the test fan.

Still, there were significant differences up to 3.9 ± 3.5% (Table 4.3) between the Upstream and Alone treatments when the FANS unit was placed near the discharge side of each test fan. This difference indicates that there may also be an actual difference in fan performance between those two treatment configurations. The Upstream treatment provided the lowest air flow values with FANS inside and outside. Therefore, that treatment configuration should be avoided for all fan tests, regardless whether the FANS unit is placed at the intake or at discharge side of the test fan.

The Opposite Sidewall treatment produced results statistically different from the results of two other "P" treatments (Table 4.3). The Opposite Sidewall treatment produced air flow results up to 3.7 ± 5.0% lower than the Alone treatment, which could lead to a substantial error on the estimation of building ventilation. It is suggested that the Opposite Sidewall configuration should also be avoided during fan tests with FANS.

Based on the results of this Section, it is reasonable to conclude that the FANS unit frame is responsible for a substantial portion of the air flow penalty observed in the Upstream treatment configuration. The other differences found among the remaining "P" treatments may be attributed to an actual change in fan performance, the FANS unit error and random error, since some differences were found either when the FANS unit was placed next to the intake or near the discharge sides of the test fans.

Placing the FANS unit on the discharge side of test fans reduces major air flow penalties. Still, this configuration should be used with as much care as if the FANS unit was placed next to the intake side of test fan inside barns similar to the one studied in this experiment (Sub-section 3.1.1).

4.1.3 Contour Plots for Results with the FANS Unit Inside and Outside – Experiment 1

Anemometer output data across the FANS section was plotted to illustrate air speed distribution across the FANS opening area. Contour plots of air velocity across the FANS unit are presented for the Alone, Middle and Upstream treatments with FANS placed next to the intake of a test fan. Figure 4.11 through Figure 4.13 show the air velocity distribution obtained from testing the fan E1_F2, at the same SP (26.5 ± 0.7 Pa) for the referred treatment configurations. Table 4.4 shows the average air velocities obtained by each of five anemometers, as illustrated on Figure 4.11 through Figure 4.13.

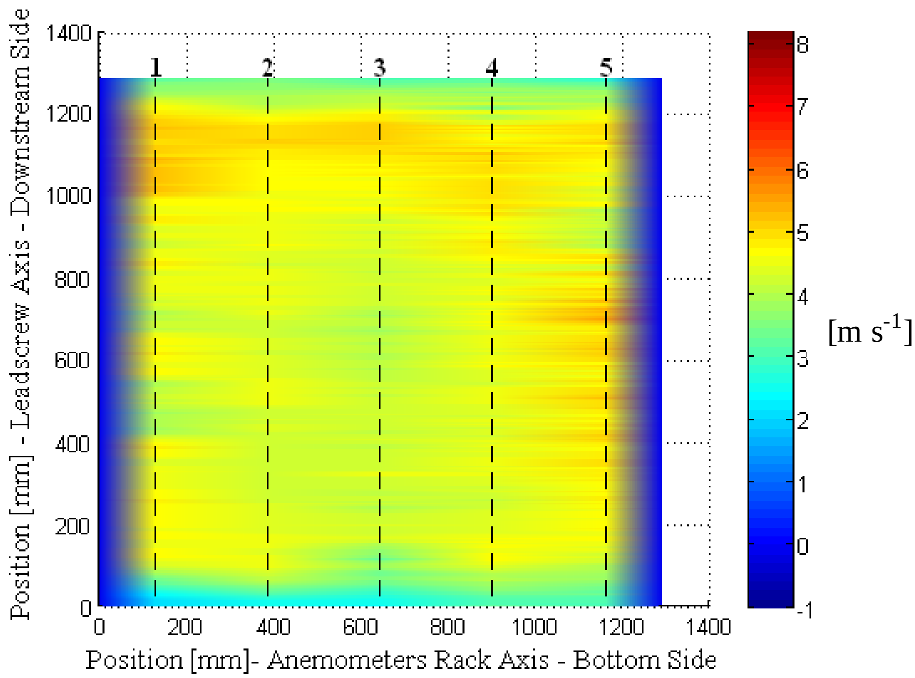

Figure 4.11. Air velocity across the FANS unit opening – Alone Inside, E1_F2. Dashed lines indicate the positions of Anemometers 1 through 5.

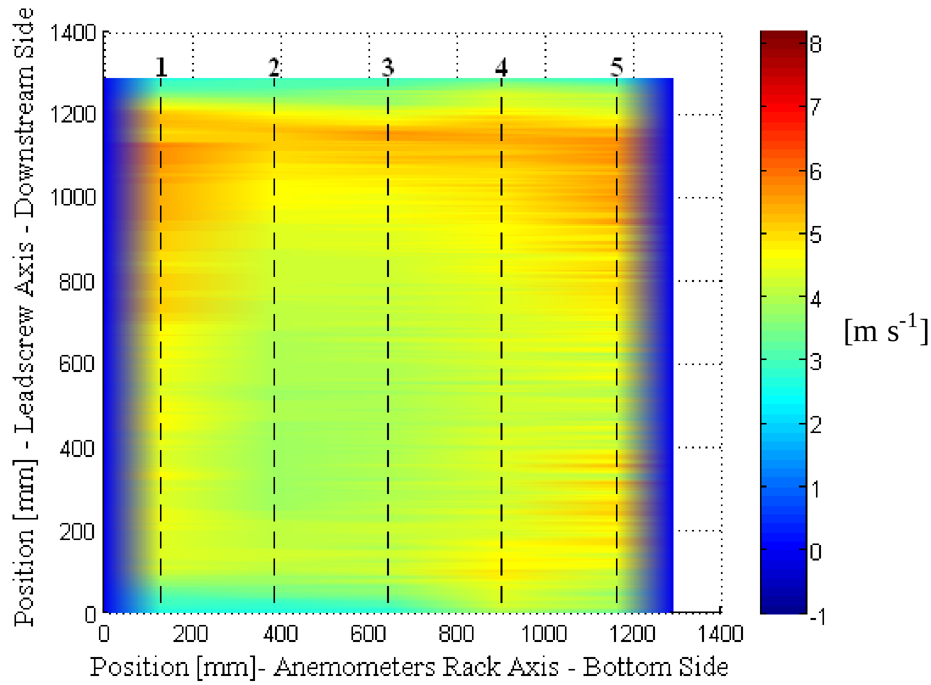

Figure 4.12. Air velocity across the FANS unit opening – Middle Inside, E1_F2. Dashed lines indicate the positions of Anemometers 1 through 5.

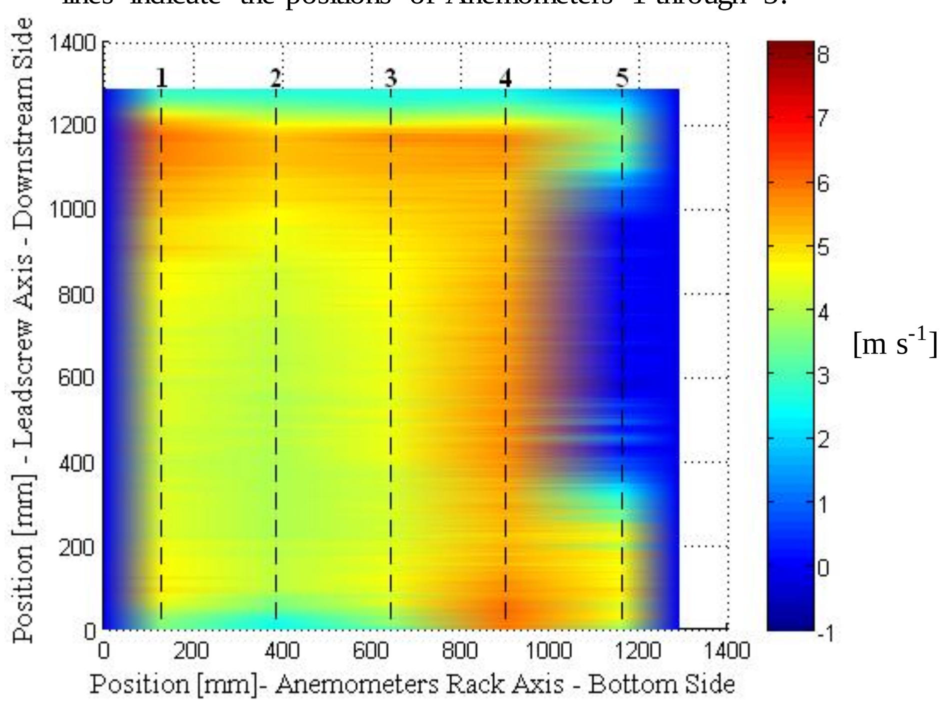

Figure 4.13. Air velocity across the FANS unit opening – Upstream Inside, E1_F2. Dashed lines indicate the positions of Anemometers 1 through 5.

Table 4.4. Average air velocities from Anemometers 1 through 5 for the Alone, Middle and Upstream treatments - Inside.

Treatment	**Average Air Velocity ± Std. Error [m s^{-1}]**				
	Anemometer 1	Anemometer 2	Anemometer 3	Anemometer 4	Anemometer 5
Alone (Inside)	4.43 ± 0.58	4.36 ± 0.39	4.18 ± 0.48	4.44 ± 0.38	4.56 ± 0.50
Middle (Inside)	4.66 ± 0.65	4.14 ± 0.49	4.19 ± 0.47	4.52 ± 0.36	4.71 ± 0.54
Upstream (Inside)	4.64 ± 0.57	4.17 ± 0.55	4.53 ± 0.54	5.39 ± 0.60	1.76 ± 1.76

Figure 4.11 and Figure 4.13 show that air velocities were nearly symmetric across the FANS unit section during the Alone and Middle – Inside treatments. Total average air velocities were approximately 4.4 and 4.5 m s^{-1}, respectively. Figure 4.13 shows a large asymmetric blue area (low air speeds) near Anemometers 4 and 5 of the FANS unit, which corresponds to the upstream side of the FANS (right side of contour plot) during the fan test on the Upstream configuration. The average air speed for the Upstream – Inside test was approximately 4.1 m s^{-1}. Air velocity on the downstream side (near Anemometer 1) of the FANS relative to the barn air flow, however, remained similar to that observed on FANS downstream side during the Alone and Middle - Inside treatments.

During the Upstream - Inside test, average air velocity through Anemometer 1 (dowstream side of FANS unit relative to the air flow in the barn, Figure 4.13) was approximately 2.6 times higher than the average air velocity obtained from Anemometer 5 (upstream side of FANS unit relative to the air flow in the barn, blue area, Figure 4.13). The Alone and Middle (Inside) test results, however, indicated that Anemometer 5 presented average air velocities of approximately 3.0% and 1.0% higher than the air velocity provided by Anemometer 1, for the respective tests.

Air velocity provided by Anemometer 5 in the Upstream configuration was substantially lower than the air velocity provided by the same anemometer in the Middle and Alone configurations (Table 4.4). On the other hand, Anemometer 3 and 4 provided higher air velocity readings in the Upstream configuration than in the Alone and Middle configurations, as shown on Table 4.4. The air velocity profiles shown in Figure 4.11 and

Figure 4.12 for the Alone and Middle treatments - Inside are similar to the one found by Sama *et al.* (2008) shown in Figure 4.14, which was obtained in laboratory fan tests using a 1.22 m FANS unit.

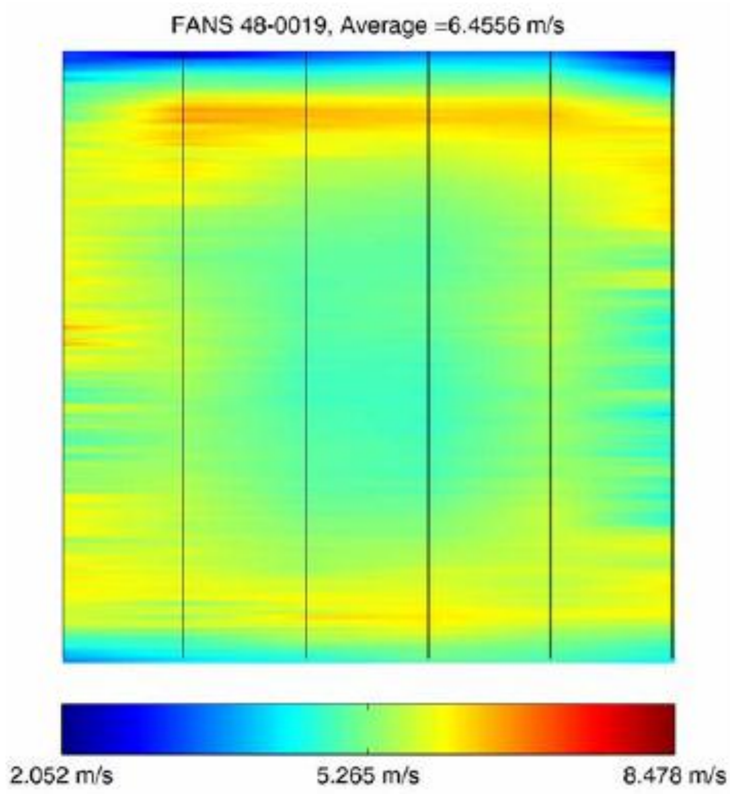

Figure 4.14. Air velocity across a 1.22 m FANS unit opening, Sama *et al.* (2008).Vertical lines represent the anemometer positions.

Figure 4.15 through Figure 4.17 show contour plots of the anemometer air velocity outputs across the FANS section for the Alone, Middle and Upstream treatments with FANS placed near the discharge side of the same test fan (E1_F2) at the same SP (26.5 ± 0.7 Pa).

Table 4.5 shows average air velocities obtained from the five anemometers for the same treatments.

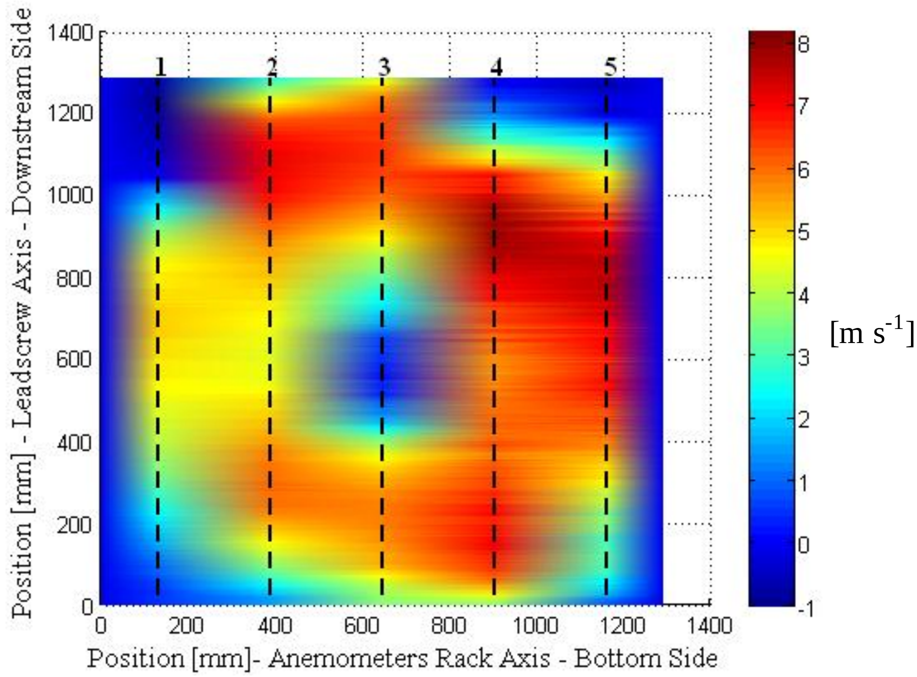

Figure 4.15. Air velocity across the FANS unit opening – Alone Outside, E1_F2. Dashed lines indicate the positions of Anemometers 1 through 5.

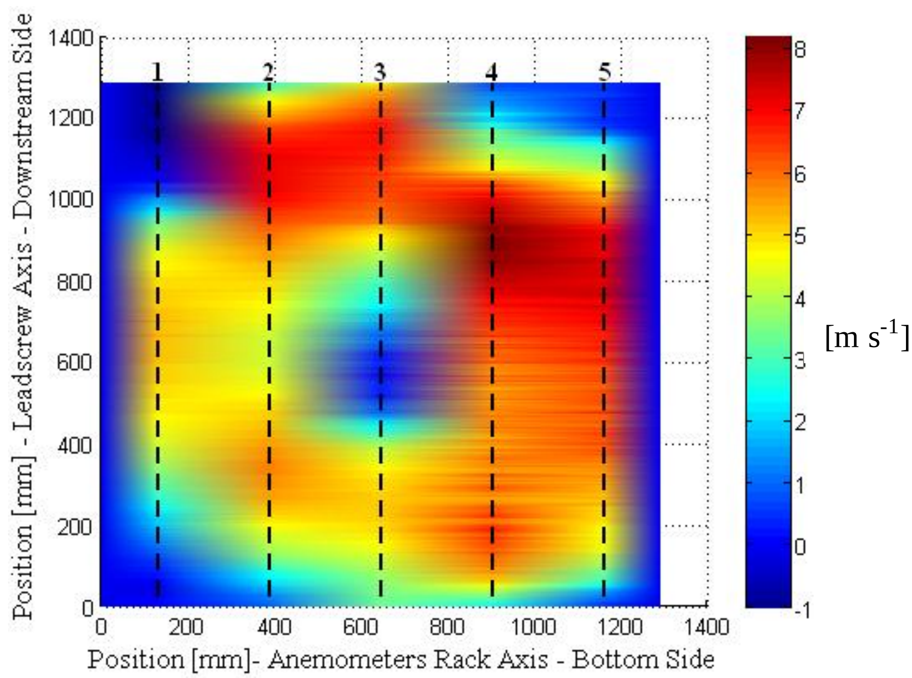

Figure 4.16. Air velocity across the FANS unit opening – Middle Outside, E1_F2. Dashed lines indicate the positions of Anemometers 1 through 5.

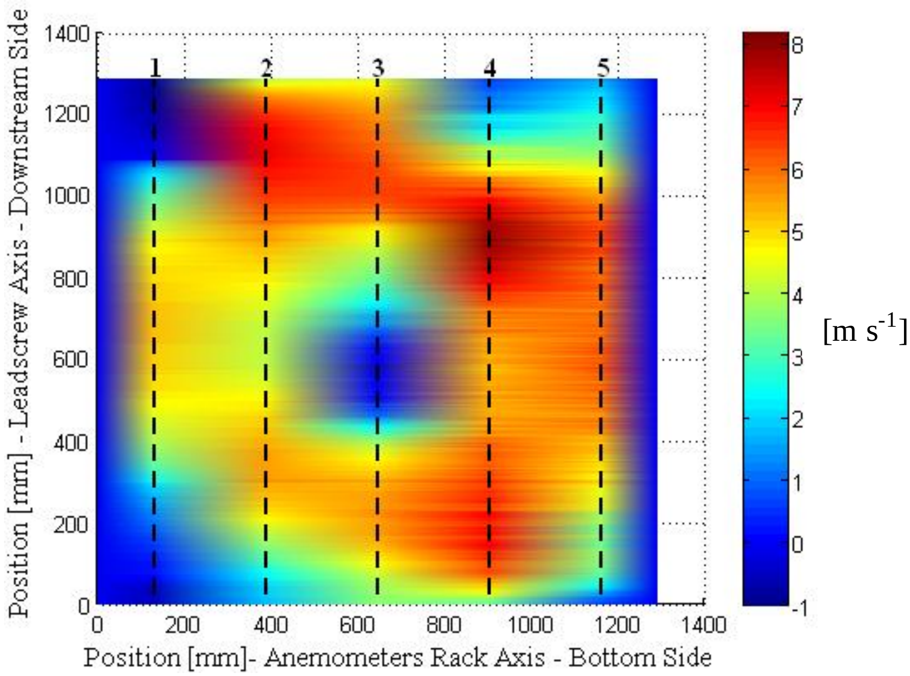

Figure 4.17. Air velocity across the FANS unit opening – Upstream Outside, E1_F2 Dashed lines indicate the positions of Anemometers 1 through 5.

Table 4.5. Average air velocities from Anemometers 1 through 5 for the Alone, Middle and Upstream treatments - Outside.

Treatment	**Average Air Velocity ± Std. Error [m s^{-1}]**				
	Anemometer 1	Anemometer 2	Anemometer 3	Anemometer 4	Anemometer 5
Alone (Inside)	2.62 ± 2.52	5.22 ± 1.23	4.12 ± 2.02	5.79 ± 1.91	4.77 ± 2.37
Middle (Inside)	4.60 ± 2.31	5.04 ± 1.34	3.99 ± 2.02	5.67 ± 1.71	5.01 ± 2.12
Upstream (Inside)	2.68 ± 2.21	5.00 ± 1.27	3.93 ± 2.07	5.59 ± 1.76	4.75 ± 1.47

Figure 4.15 through Figure 4.17 show that the Alone, Middle and Upstream – Outside treatments provided similar air velocity distributions through the FANS unit section, with average air velocities of 4.5, 4.5 and 4.4 m s^{-1}, respectively. The average air velocity through the FANS unit obtained in the Alone and Middle treatment were approximately the same with FANS placed inside and outside the barn. However, the average air velocity on the Upstream treatment was approximately 7.0% higher when the FANS unit was placed outside the barn (4.4 m s^{-1}) than inside (4.1 m s^{-1}) the barn.

Therefore, placing the FANS unit near the discharge side of test fans substantially reduced the differences between the “P” treatments and the Upstream treatment (Figure 4.11 through Figure 4.13), which is evidence that the FANS unit causes an air flow penalty, when placed next to the intake side of the test fan in the Upstream treatment.

4.2 Experiment 2 (E2) – Farms 2, 3 & 4, Operated by Poultry Company 2

Air flow obtained from each treatment was regressed as a second order polynomial function of static pressure (SP), as described in section 3.6. The intercept, first and second order parameters of the regressions are provided in Appendix A, Table A.2. The addition of the quadratic term was significant at 90% confidence level for approximately 72% of the regression curves. Therefore, the second order polynomial regression was performed among all fan tests. The overall models of fan performance were all significant and presented a strong relationship between air flow and static pressure. Approximately 82% of the curves had a coefficient of determination (R^2) of at least 98% and overall p-value less than 0.0001. The remaining fan curves presented an R^2 of at least 95% and overall p-value less than 0.0006.

4.2.1 Fan Tests with the FANS Unit next to the Intake Side of each Test Fan (Inside Treatment)-Experiment 2

Figure 4.18 through Figure 4.22 show the fan performance curves obtained in Experiment 2, with FANS placed next to the intake (Inside treatment) of test fans.

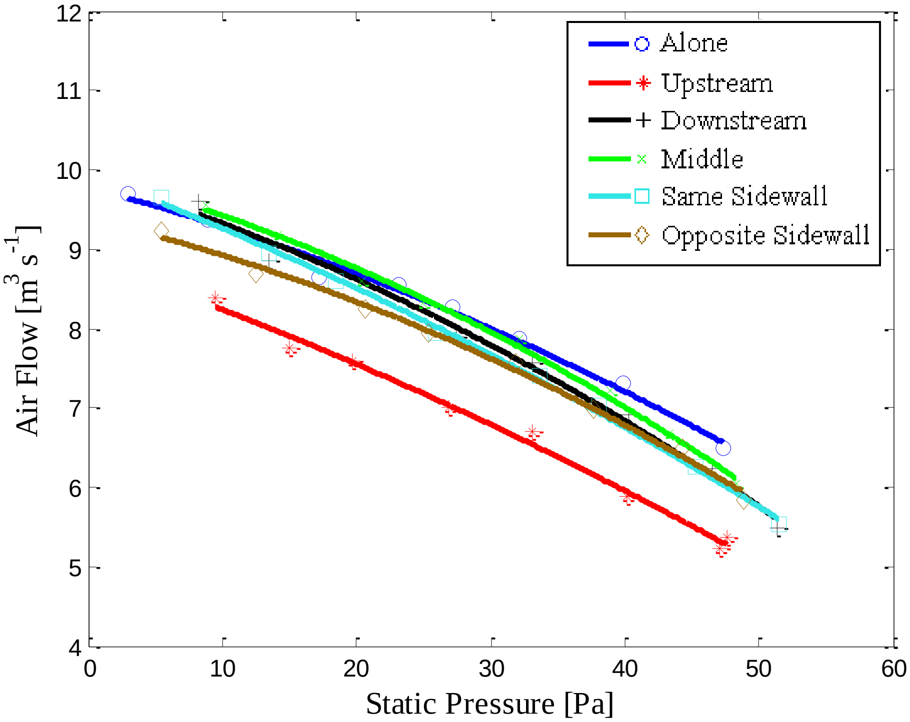

Figure 4.18. Fan performance curves, FANS unit Inside, E2_F1.

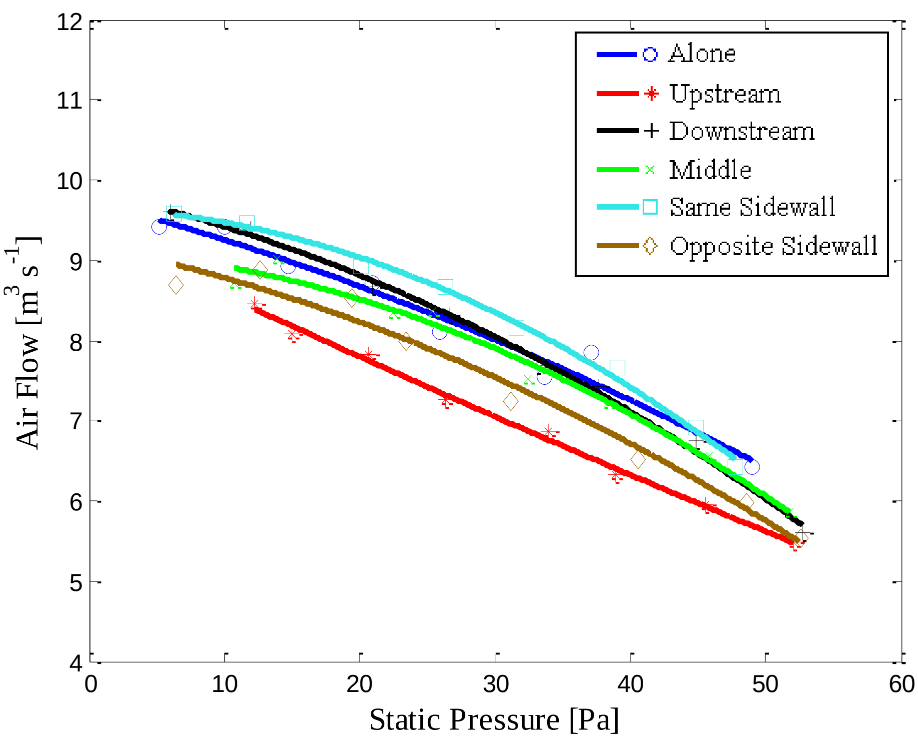

Figure 4.19. Fan performance curves, FANS unit Inside, E2_F2.

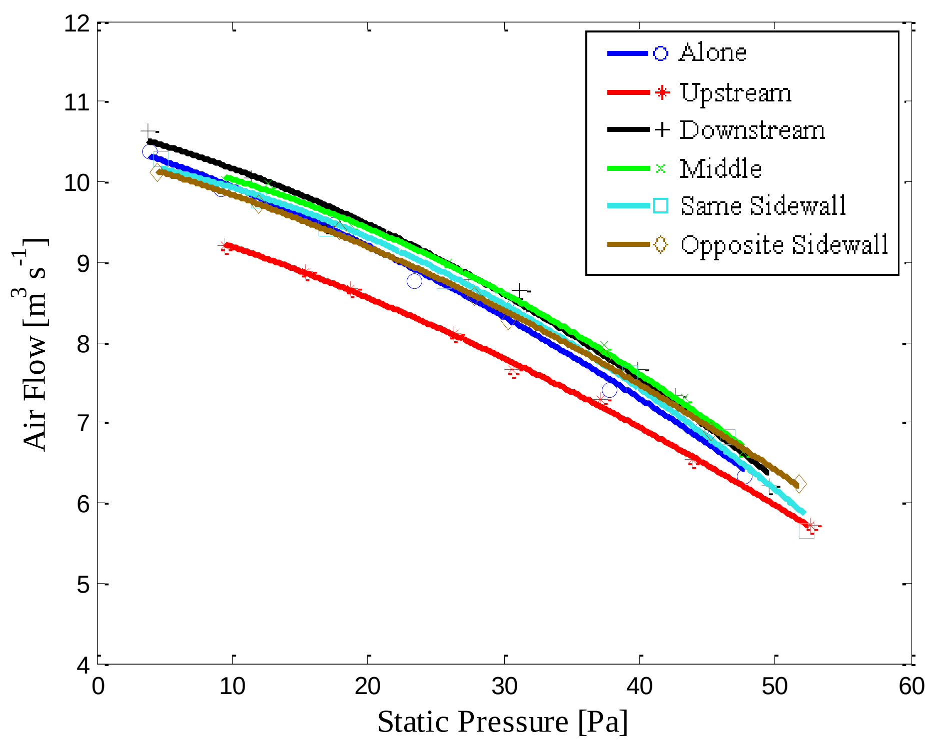

Figure 4.20. Fan performance curves, FANS unit Inside, E2_F3.

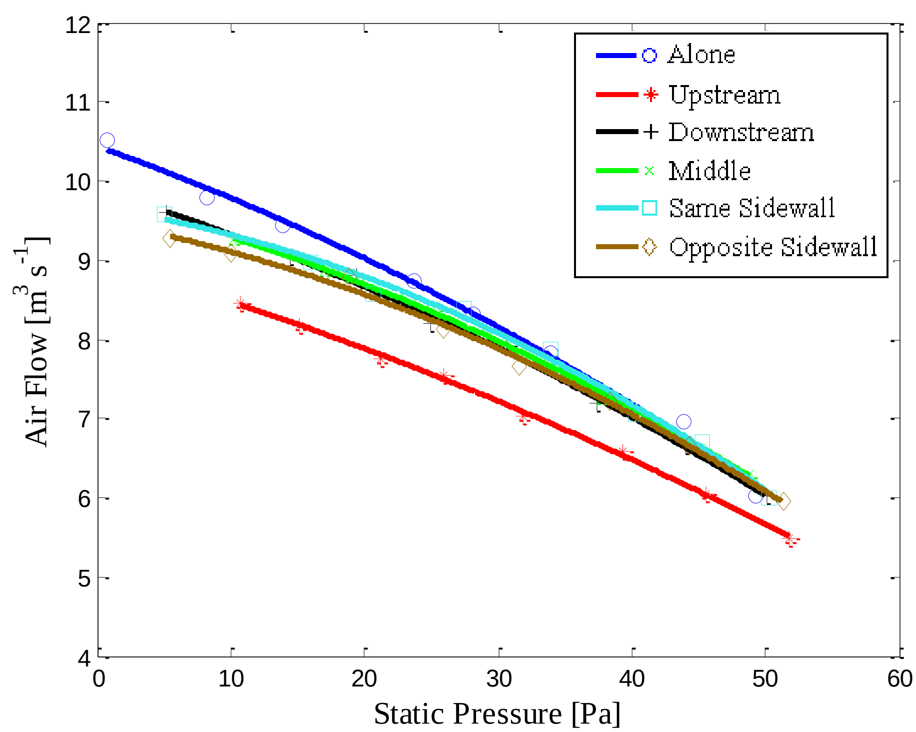

Figure 4.21. Fan performance curves, FANS unit Inside, E2_F4.

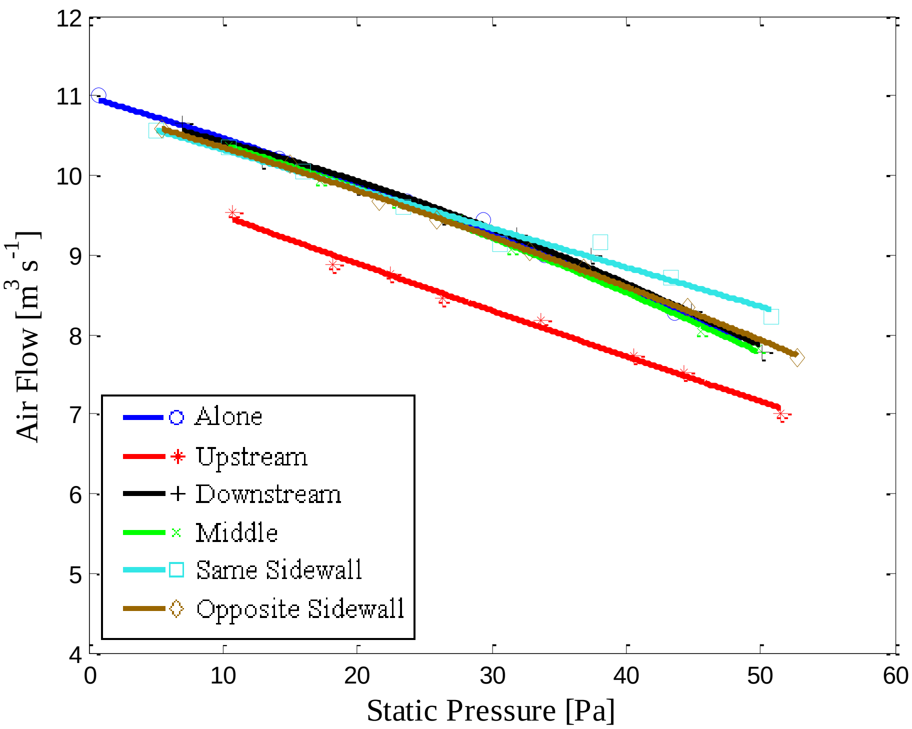

Figure 4.22. Fan performance curves, FANS unit Inside, E2_F5.

Figure 4.18 through Figure 4.22 show that the fan performance curves were generally similar and close together, except for the fan curves produced by the Upstream treatment, which generated lower air flow values. The "P" (position of operating fans relative to FANS and test fan) treatments had a significant ($p < 0.0001$) effect on air flow. The treatments Alone, Middle, Same Sidewall and Downstream were not significantly ($p > 0.5000$) different from each other and presented, in general, the highest fan performance curves among the five test fans in Experiment 2, when the FANS unit was placed next to the intake side of the test fan. The Opposite Sidewall provided fan performance curves right below the highest fan performance curves.

Similar to Experiment 1, the "Upstream" treatment produced the lowest fan performances for all test fans with FANS positioned on the intake side. All "P" treatments were significantly ($p < 0.0001$) different from the Upstream treatment. Also, the Opposite Sidewall treatment was significantly ($p < 0.0100$) different from the remaining "P" treatments. The difference in air flow between Opposite Wall fan curves and the other treatment curves were, however, substantially less than the differences in air flow between Upstream and the other treatments (Table 4.6).

Unlike Experiment 1, the fan performance curves within the "P" treatments in Experiment 2 were more nearly parallel, which demonstrates that there was not a significant ($p = 0.8263$) interaction between static pressure (SP) and "P" treatments. Therefore, average differences between treatments were calculated for all values of SP ($0 \leq SP \leq 57$ Pa) and for all tested fans, using Equation 3.3. Table 4.6 presents averaged air flow differences among the treatments that were significantly different from each other. Negative differences mean that air flow from the first treatment in a paired comparison was lower than air flow from the second compared treatment.

Table 4.6. Significant averaged differences in air flow rate between "P" treatments with the FANS unit next to the intake side of the test fan – Experiment 2.

Comparisons:	**Average Differences ± Std. Error**			
Upstream vs. Alone	-12.6%	±	4.4%	*
Upstream vs. Downstream	-11.9%	±	2.2%	*
Upstream vs. Middle	-11.6%	±	3.1%	*
Upstream vs. Same Sidewall	-12.5%	±	3.3%	*
Upstream vs. Opp. Sidewall	-9.3%	±	2.9%	*
Opp. Sidewall vs. Alone	-3.1%	±	3.4%	*
Opp. Sidewall vs. Downstream	-2.4%	±	2.6%	*
Opp. Sidewall vs. Middle	-2.5%	±	1.9%	*
Opp. Sidewall vs. Same Sidewall	-3.0%	±	4.2%	*

- * Significantly different at 99% confidence level;
- Differences were calculated using Equation 3.3 and averaged for all tested fans and for all SP measured. Estimates of air flow [m^3 s^{-1}] can be found in Appendix B, Table B.7.

Table 4.6 shows that the air flow rates from the Upstream treatment were at least 9.3 ± 2.9% lower than the air flow rates from all remaining treatments. The differences between the Upstream and the other treatments in Experiment 2 were also considered large enough to have a substantial effect on the predicted barn ventilation rate. If all eight 1.22 m diameter fans were tested inside a barn with fans spaced 1.6 m apart at 30 Pa using a FANS in the Upstream position, the estimate of total barn ventilation rate could be up to 8.5 m^3 s^{-1} lower than the estimate that would be obtained by using test results from the Alone or Middle treatments. An 8.5 m^3 s^{-1} (18,010 cfm) difference in air flow rate is roughly equivalent to the amount of air that two new 0.91 m (36 in) diameter fans move at the same static pressure.

Once again, substantial differences between the Upstream and the remaining "P" treatment results indicate that either the test fans were operating at lower air flow capacities or the FANS unit was possibly causing an air flow penalty when the Upstream configuration of operating fans was used inside the barns of Farm 2, 3 and 4. The Upstream treatment configuration should, therefore, be avoided when testing fans using the FANS unit inside barns similar to the ones studied in Farm 2, 3 and 4 (Sub-sections 3.1.2, 3.1.3 and 3.1.4).

Average differences between the Opposite Sidewall and the remaining treatments were approximately 3.1 ± 3.4% or less. Still, those differences could be large enough to cause a substantial total air flow error in the building ventilation rate estimation. Therefore, it is recommended that the Opposite sidewall treatment configuration should also be avoided when testing fans using the FANS unit inside barns similar to the ones studied in this work (Sub-sections 3.1.2, 3.1.3 and 3.1.4).

Fans that were tested in this study were located on the sidewalls of the exhaust end of the barns. Therefore, the air has to make a 90^o turn to pass through the FANS unit and test fan (see Figure 3.32 through Figure 3.37). It is reasonable to assume that the FANS unit frame can actually work as an obstacle in the air path from the curtain inlets through the exhaust fans. Placing the FANS unit near the discharge side of the test fan (Outside treatment) would remove any potential obstruction from the fan intake and allow air to flow freely into the fan. Similar to Experiment 1, fan tests were performed with the FANS unit placed near the discharge side of test fans (Figure 3.43 through Figure 3.48) and an analysis was performed to determine if the differences were caused by penalties related to the FANS unit structure or by a real change in the actual fan performance (Sub-section 4.1.2).

4.2.2 Fan Tests with the FANS Unit near the Discharge Side of each Test Fan (Outside Treatment) – Experiment 2.

The FANS unit was placed outside of the barn, near the discharge side of test fans as described in Sub-section 3.3.2 and all “P” treatments were run again. This FANS unit placement allowed air to go straight through the FANS unit after it had passed through the test fan. Therefore, it was expected that the differences between the “P” treatments would be reduced when fan tests were performed with FANS outside of the barn. Figure 4.23 through Figure 4.27 show fan performance curves obtained in Experiment 2, with FANS placed near the discharge side (Outside treatment) of test fans.

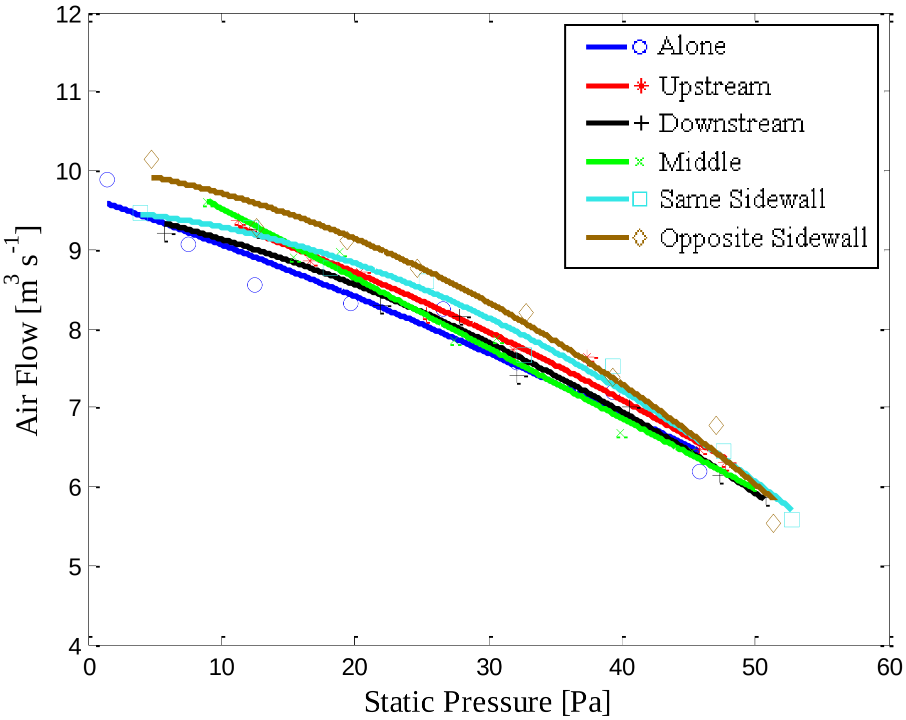

Figure 4.23. Fan performance curves, FANS unit Outside, E2_F1.

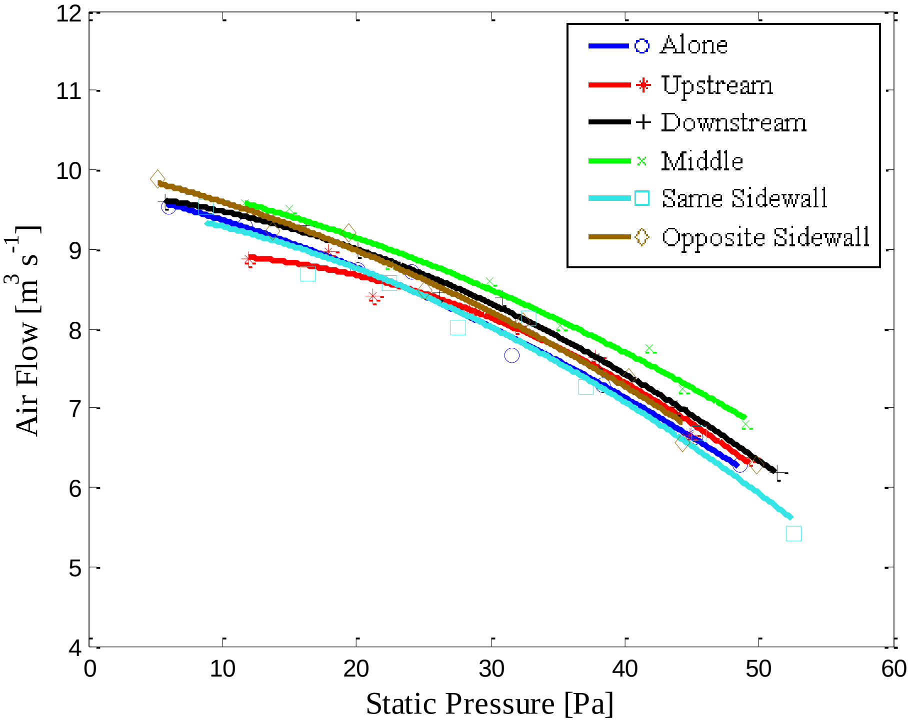

Figure 4.24. Fan performance curves, FANS unit Outside, E2_F2.

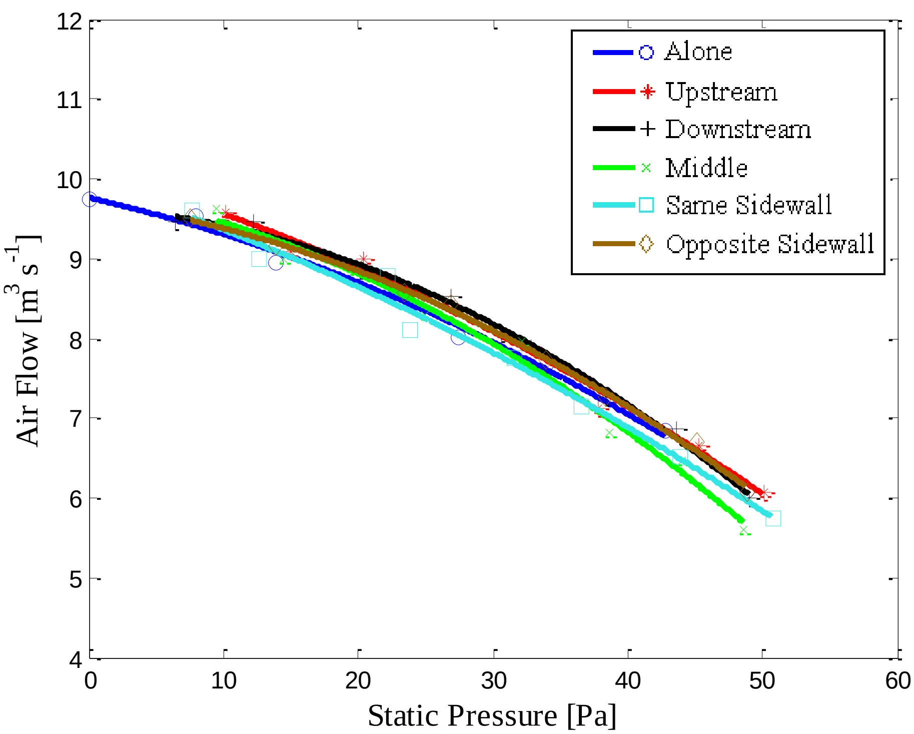

Figure 4.25. Fan performance curves, FANS unit Outside, E2_F3.

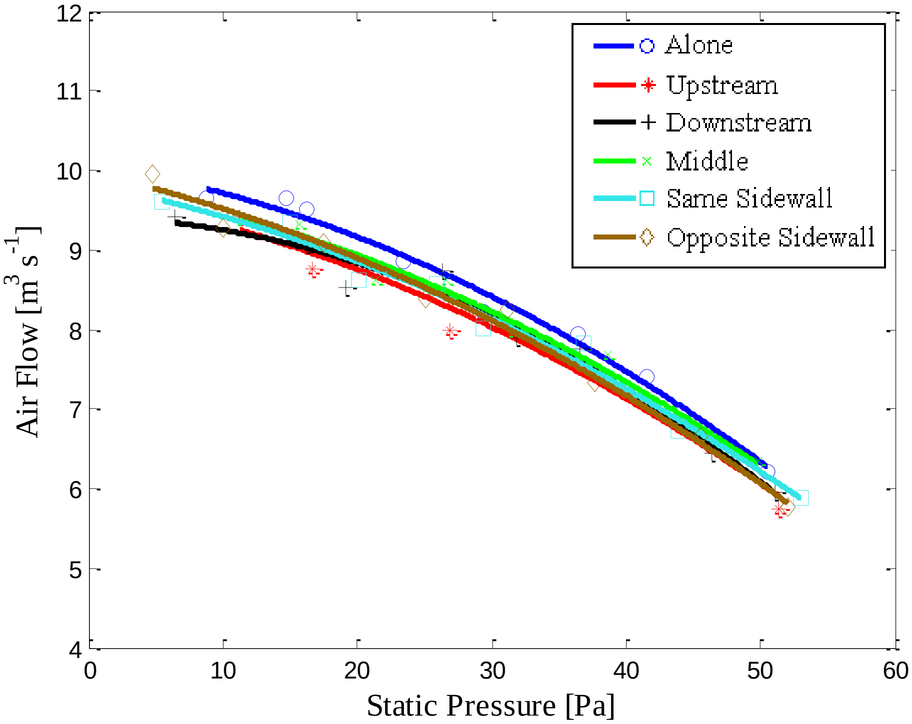

Figure 4.26. Fan performance curves, FANS unit Outside, E2_F4.

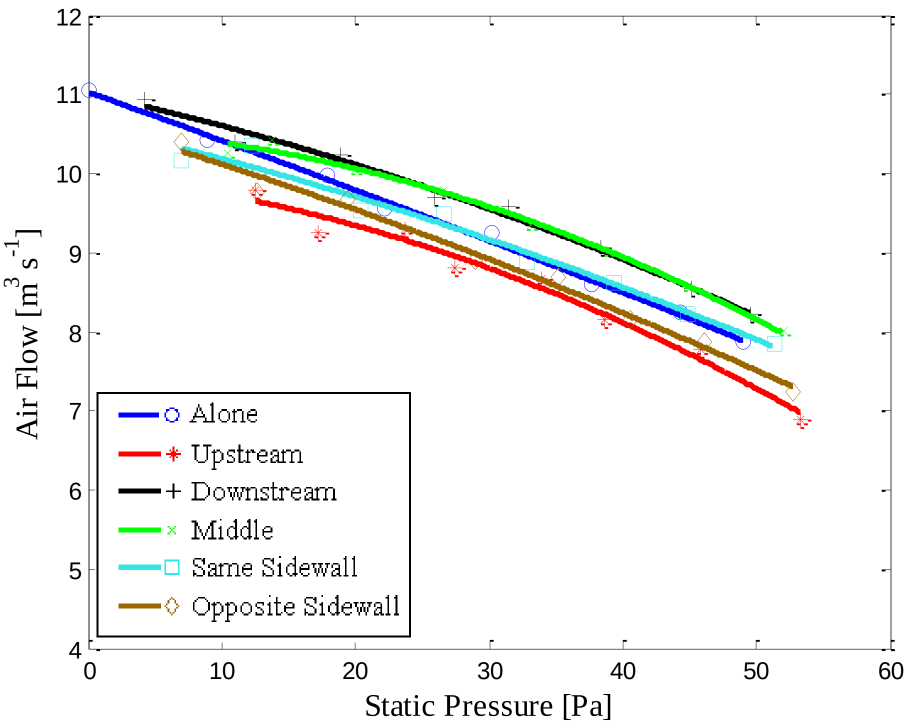

Figure 4.27. Fan performance curves, FANS unit Outside, E2_F5.

Figure 4.23 through Figure 4.27 show that the fan performance curves were closer together for all "P" treatments with the FANS unit outside than with the FANS unit inside the barn (Figure 4.18 through Figure 4.22). Performance curves obtained from the Upstream treatment were generally closer to performance curves from the remaining treatments when the FANS unit was placed near the discharge side the test fans than when the FANS unit was placed next to the intake side of test fans. The change in air flow results caused by placing the FANS unit outside the barn demonstrates that there was interaction between the "P" and the "S" treatments ($p<0.0001$).

Statistical tests showed that the "S" treatments (FANS inside vs. FANS outside) had no significant ($p = 0.0631$) effect on air flow measurements. The "P" treatments obtained with the FANS unit next the intake side of the test fan (Inside treatment) were not significantly different ($p < 0.05$) from the same "P" treatments obtained with the FANS unit near the discharge side of the test fan, with exception of the Upstream and Opposite Sidewall treatments (Table 4.7). Therefore the Alone, Downstream, Middle and Same Sidewall treatments presented similar results to the ones found by Li *et al.* (2009), who did not find significant differences between fan test results obtained by placing the FANS unit next to the intake side of the test fan versus placing the FANS unit near the discharge side of the test fan.

Table 4.7. Comparison of FANS Inside versus FANS Outside within the same "P" treatment – Experiment 2. Average differences in air flow calculated for all tested fans and SP.

Comparison	Average Differences ± Std. Error			
Alone IN vs. OUT	1.56%	±	2.47%	n
Upstream IN vs. OUT	-10.08%	±	5.81%	**
Downstream IN vs. OUT	-0.23%	±	3.36%	n
Middle IN vs. OUT	-0.44%	±	5.66%	n
Same Sidewall IN vs. OUT	1.68%	±	4.00%	n
Opposite Sidewall IN vs. OUT	-2.31%	±	5.67%	**

- [n] Not significantly different at 95% confidence level.
- [**] Shaded lines show treatments that provided significantly different results between FANS placed on the intake of test fan or on the discharge of the test fan at 95% confidence level;

The “P” treatments found to be significantly different from other “P” treatments when the FANS unit was placed next to the intake of the test fan were compared again with the FANS unit placed near the discharge side of the test fan. When the FANS unit was placed outside the barn, the Upstream treatment was no longer significantly different from all other treatments, as was found when the FANS was placed on the inside of the barn. The Upstream treatment with the FANS near the discharge side of the test fan provided fan performance curves significantly ($p < 0.05$) different from the curves obtained from the Downstream and Middle treatments. Also, with FANS placed near the discharge side of the test fans, the Opposite Sidewall treatment was no longer significantly different ($p<0.05$) from the remaining treatments, as was found when the FANS was placed next to the intake of the test fans.

This change among the differences between the “P” treatments indicates that placing the FANS unit near the discharge side of the test fans contributed to reduce the number of significantly different “P” treatments. When the FANS unit was placed next to the intake of the test fan, 11of the 15 possible comparisons among the “P” treatments were found to be significantly different. However, when the FANS unit was placed near the discharge of the test fan, only four of the 15 possible comparisons were found to be significantly different.

Although placing the FANS unit near the discharge side of the test fans caused some treatments not to be significantly ($p < 0.05$) different from each other, the Middle treatment differed from Alone, Upstream and Same Sidewall treatments, when the FANS unit was placed near the discharge side of the test fan. These differences, however, were less than 2% of the fan air flow rate (Table 4.8) and are unlikely to be of any practical importance.

The differences among the “P” treatments with the FANS unit placed on the outside of the barns were calculated among the treatments that were significantly different from each other when the FANS unit was placed both on the inside and outside of the barn. The static pressure (SP) did not interact with treatments at 95% confidence level. Differences were calculated using Equation 3.3 for all static pressure values and for all tested fans.

Table 4.8. Significant and no longer significant averaged differences in air flow rate between "P" treatments with the FANS unit near the discharge side of the test fan – Experiment 2.

Comparisons:	Average Differences ± Std. Error			
Upstream vs. Alone	-0.8%	±	3.5%	n.o.
Upstream vs. Downstream	-2.0%	±	3.9%	**
Upstream vs. Middle	-2.2%	±	4.6%	*
Upstream vs. Same Sidewall	-0.5%	±	3.0%	n.o.
Upstream vs. Opp. Sidewall	-1.5%	±	1.9%	n.o.
Opp. Sidewall vs. Alone	0.7%	±	3.7%	n.o.
Opp. Sidewall vs. Downstream	-0.5%	±	4.3%	n.o.
Opp. Sidewall vs. Middle	-0.7%	±	4.8%	n.o.
Opp. Sidewall vs. Same Sidewall	1.0%	±	2.8%	n.o.
Middle vs. Alone	1.3%	±	0.04%	**
Middle vs. Same Sidewall	0.1%	±	0.03%	*

- The shaded lines show the treatment comparisons that were found to be significantly different with FANS inside and not significantly (n.o.) different with FANS outside at 95% confidence level;
- * Significantly different at 99% confidence level; ** Significantly different at 95% confidence level;
- Differences were calculated using Equation 3.3 and averaged for all tested fans. Estimates of air flow [m^3 s^{-1}] can be found in Appendix B (for both SP ranges), Table B.7.

Placing the FANS unit outside the barn reduced the number of "P" treatments significantly different from each other and reduced the magnitude of differences between the Upstream and the remaining "P" treatments. The differences between the Upstream treatment and the other "P" treatments obtained with FANS outside were approximately 87.5 ± 6.8 % lower than the same differences encountered with the FANS inside, which is evidence that the FANS unit causes an air flow penalty in the Upstream treatment, when placed next to the intake side of a test fan.

Still, there were significant differences up to 2.2 ± 4.6% (Table 4.3) between the Upstream and Middle treatments when the FANS unit was placed near the discharge side of each test fan. This result indicates that there may be also an actual difference in fan performance between these treatment configurations. Also, the difference standard error is relatively high compared to the average difference between these two treatments

Therefore, this treatment configuration should be avoided either when the FANS unit is placed next to the intake or near the discharge sides of the test fan.

Unlike when the FANS unit was placed next to the intake side of the test fan, the Opposite Sidewall treatment did not produce air flow results statistically different from results from the other "P" treatments (Table 4.3) with the FANS unit placed near the discharge side of the test fans. The Opposite Sidewall configuration should be avoided during fan tests with the FANS unit placed next to the intake of the test fan. However, this treatment configuration may be used to test fans with the FANS unit near the discharge side of the test fan, inside barns similar to the ones studied in this experiment, with fans spaced 1.6 m apart (Sub-sections 3.1.2, 3.1.3, and 3.1.4).

Based on the results of this Section, it is reasonable to conclude that the FANS unit frame is responsible for a substantial portion of the air flow penalty observed in the Upstream and Opposite Sidewall treatment configurations. Differences between other "P" treatments may be attributed to real variations in fan performance, FANS unit error and random error, since some similar differences were found when the FANS unit was placed on both the intake and discharge sides of the test fans. Placing the FANS unit on the discharge side of the test fan minimizes the potential air flow penalties without adversely affecting fan performance results. Thus it appears to be a good configuration option to test fans *in-situ*.

4.2.3 Contour Plots for Results with the FANS Unit Inside and Outside – Experiment 2

Anemometer output data across the FANS section was plotted to illustrate the air speed distribution across the FANS opening area. Contour plots of air velocity through the FANS unit are presented for the Alone, Middle and Upstream treatments for the FANS placed next to the intake side of a test fan. Figure 4.28 through Figure 4.30 show the air velocity distribution obtained from testing the fan E2_F3 at the static pressure (SP) 30.7 ± 1.9 Pa. Table 4.9 shows the average air velocities obtained by each of five anemometers for the referred treatments.

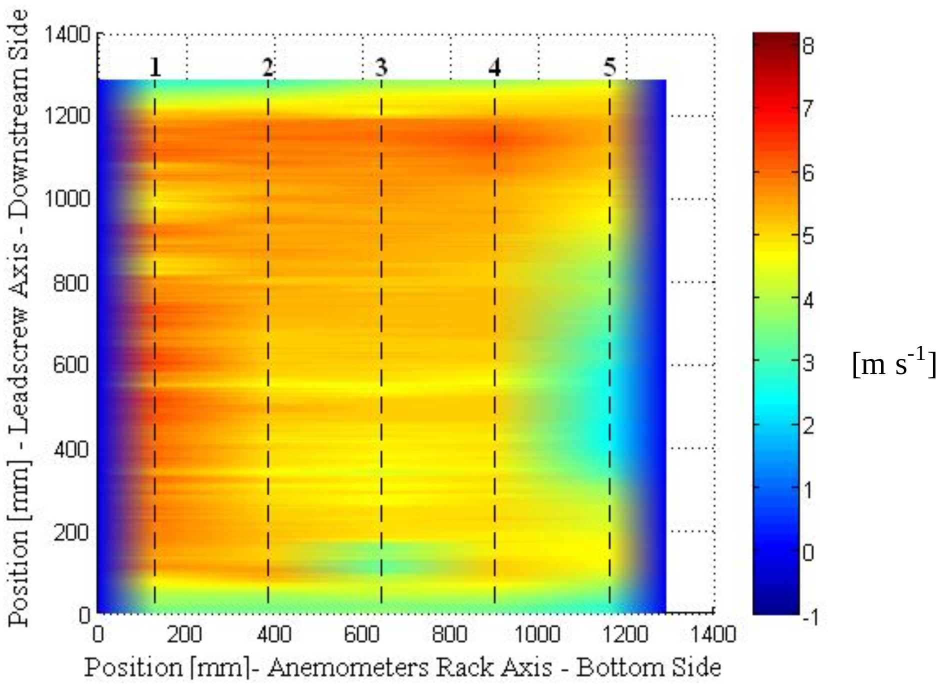

Figure 4.28. Air velocity across the FANS unit opening – Alone Inside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

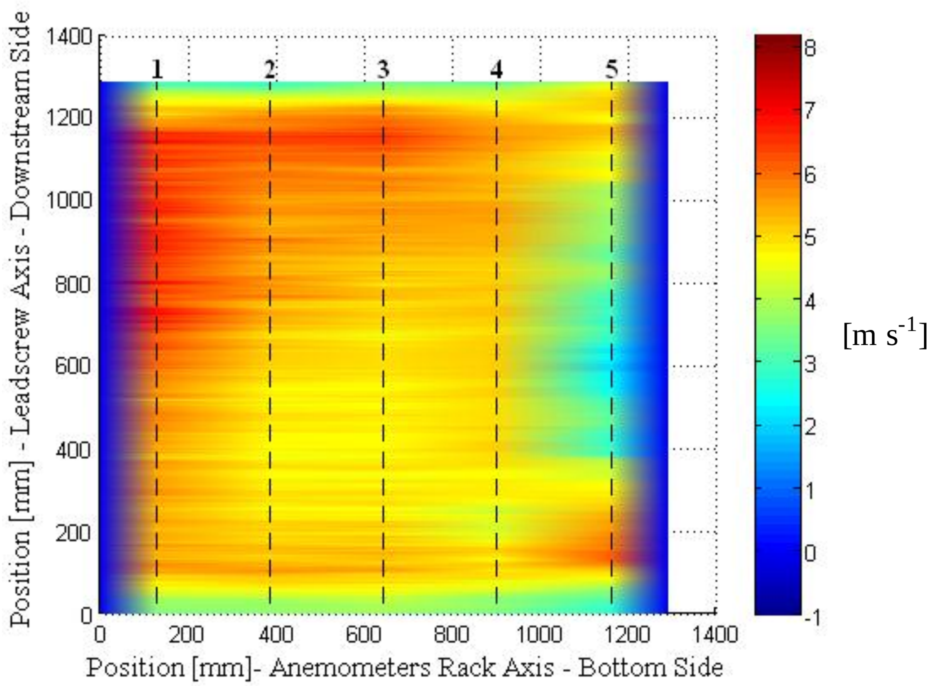

Figure 4.29. Air velocity across the FANS unit opening – Middle Inside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

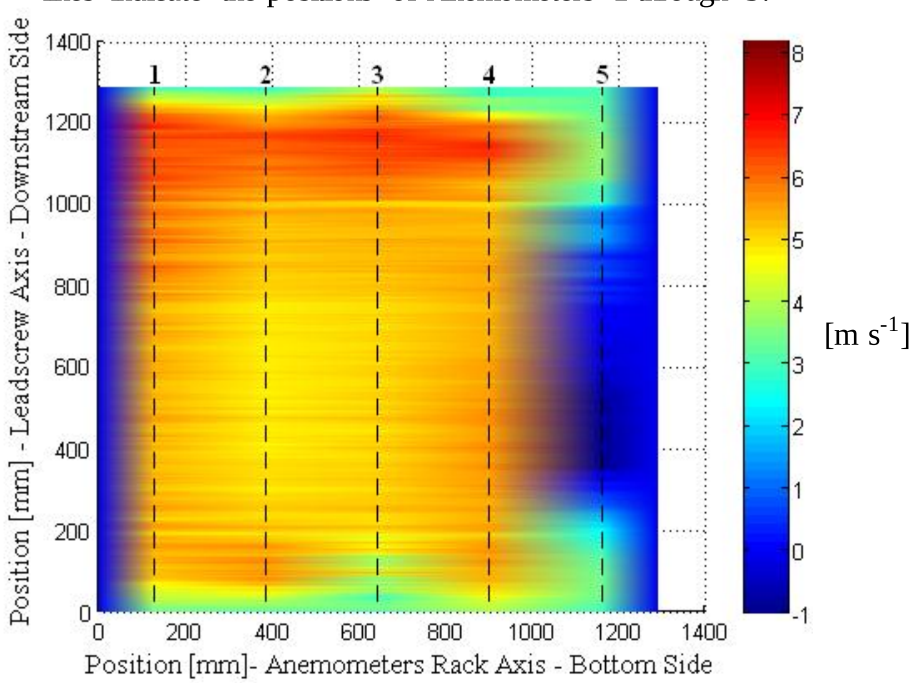

Figure 4.30. Air velocity across the FANS unit opening – Upstream Inside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

Table 4.9. Average air velocities from Anemometers 1 through 5 for the Alone, Middle and Upstream treatments (Inside).

Treatment	Average Air Velocity ± Std. Error [m s^{-1}]				
	Anemometer 1	Anemometer 2	Anemometer 3	Anemometer 4	Anemometer 5
Alone (Inside)	5.53 ± 0.72	5.15 ± 0.54	4.97 ± 0.61	5.11 ± 0.48	3.88 ± 0.97
Middle (Inside)	5.77 ± 0.79	5.15 ± 0.60	5.09 ± 0.55	4.96 ± 0.46	3.91 ± 1.06
Upstream (Inside)	5.46 ± 0.58	5.10 ± 0.55	5.12 ± 0.68	5.39 ± 0.60	1.33 ± 1.69

Figure 4.28 and Figure 4.29 show that there were small areas of reduced air velocity on the upstream side of the FANS unit (right side of contour plots) in both Alone and Middle - Inside treatments. Anemometer 1 (downstream side of FANS unit, relative to the air flow in the barn) produced average air velocities 42.6% and 47.5% higher than Anemometer 5 (upstream side of FANS unit relative to the air flow in the barn), for the Alone and Middle - Inside treatments, respectively. The average air velocities obtained in the Alone and Middle - Inside treatments were approximately 4.9 and 5.0 m s^{-1}, respectively. Similar patterns of air velocity distribution were found for the Alone treatment Inside for Fans 1, 2 and 4 as well.

Contour plots shown in Figure 4.28 and in Figure 4.29 differ from Figure 4.11 and Figure 4.12 obtained in Experiment 1 since the Alone and Middle - Inside treatments in Experiment 1 (E 1) provided air velocities more uniformly distributed across the FANS opening. The difference in air velocity profiles through the FANS opening could be an indication that air velocity through the FANS unit is related to air flow penalties obtained with the FANS unit, since this difference in air velocity profile was observed for four of the five tested fans in this experiment. Therefore, a further analysis of air velocity differences between FANS anemometers was performed to verify if these differences were related to average barn air speed, described in Section 4.3.

Figure 4.30 shows a larger asymmetric blue area (low air speeds) on the upstream side of the FANS unit relative to the barn air flow (right side of contour plot). The average air speed for the Upstream – Inside test was approximately 4.5 m s^{-1}. Anemometer 1 provided an average air velocity approximately 4.1 times higher than the air speed obtained from Anemometer 5. Air velocity provided by Anemometer 5 in the Upstream configuration was substantially lower than the air velocity provided by the same anemometer in the Middle and Alone configurations (Table 4.5). On the other hand, Anemometer 3 and 4 provided higher air velocity readings in the Upstream configuration than in the Alone and Middle configurations, as shown on Table 4.5.

Figure 4.31 through Figure 4.33 show contour plots of the anemometer air velocities output across the FANS section for the Alone, Middle and Upstream treatments with FANS placed near the discharge side of the same test fan , E2_F3, at the same SP (30.7 ± 1.9 Pa). Table 4.10 shows the average air velocities obtained by each of five anemometers for the referred treatments.

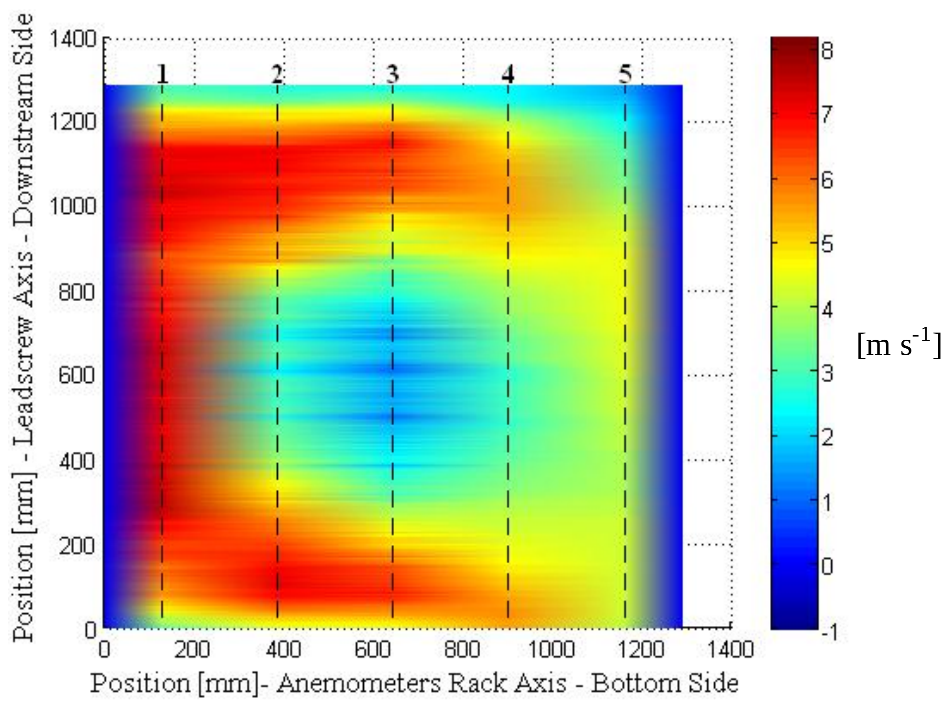

Figure 4.31. Air velocity across the FANS unit opening – Alone Outside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

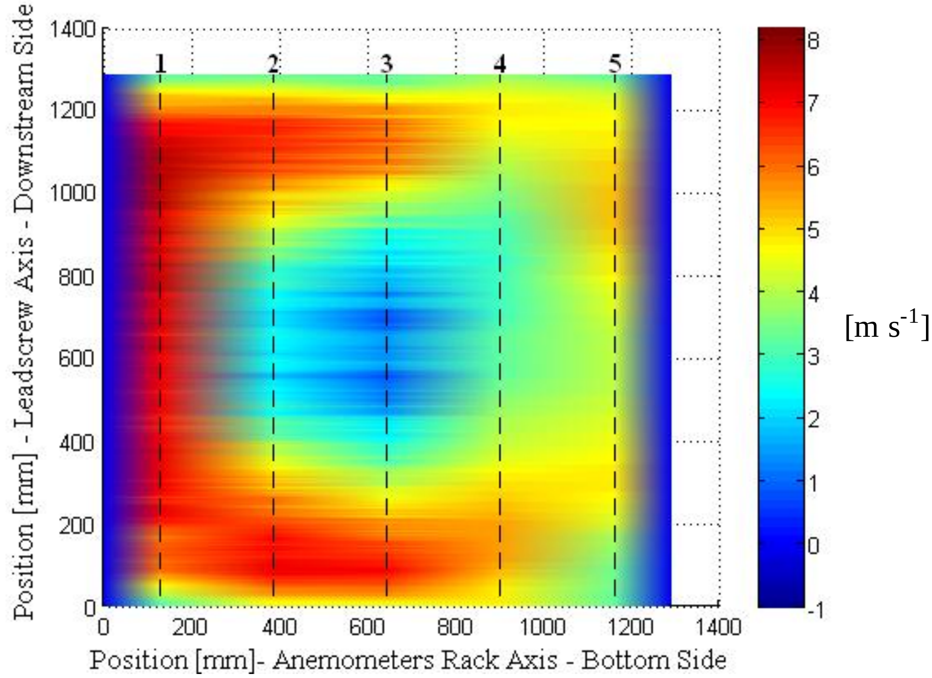

Figure 4.32. Air velocity across the FANS unit opening – Middle Outside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

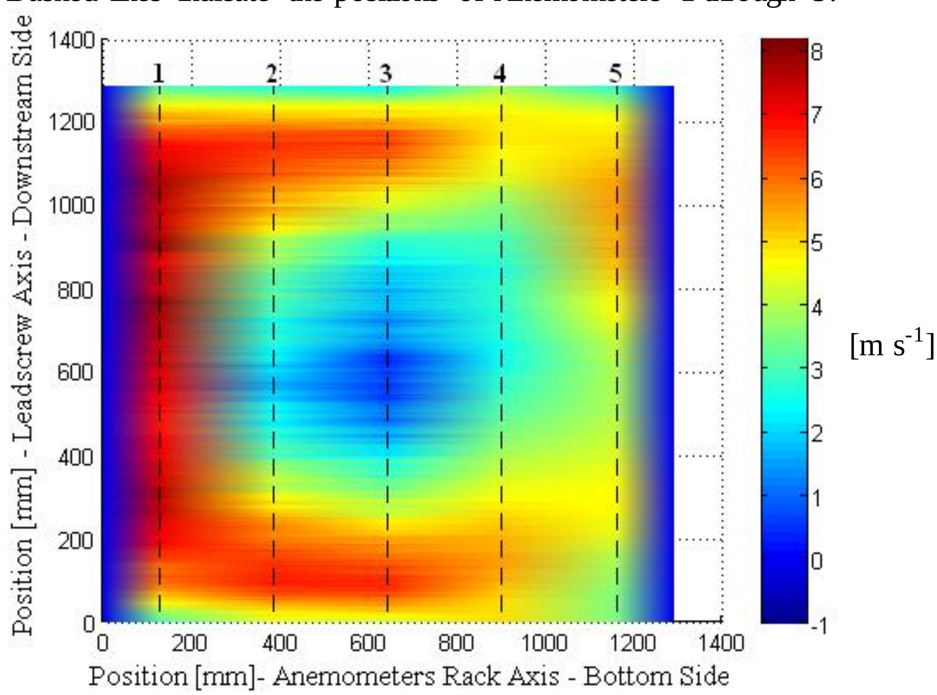

Figure 4.33. Air velocity across the FANS unit opening – Upstream Outside, E2_F3. Dashed lines indicate the positions of Anemometers 1 through 5.

Table 4.10. Average air velocities from Anemometers 1 through 5 for the Alone, Middle and Upstream treatments (Outside).

Treatment	Average Air Velocity ± Std. Error [m s^{-1}]				
	Anemometer 1	Anemometer 2	Anemometer 3	Anemometer 4	Anemometer 5
Alone (Inside)	6.59 ± 1.04	4.85 ± 1.56	3.90 ± 1.81	4.15 ± 0.97	3.97 ± 0.69
Middle (Inside)	6.71 ± 0.99	4.51 ± 1.65	3.65 ± 1.89	4.03 ± 0.87	4.43 ± 0.53
Upstream (Inside)	6.83 ± 1.07	4.32 ± 1.53	3.48 ± 1.94	3.92 ± 0.98	4.51 ± 0.65

Figure 4.31 through Figure 4.33 show that the Alone, Middle and Upstream – Outside treatments provided similar air velocity distributions through the FANS unit section, with average air velocities of 4.7, 4.7 and 4.6 m s^{-1}, respectively. The average air velocity through the FANS unit obtained in the Upstream – Inside treatment was approximately 9.1% lower than the average air velocity obtained in the Middle and Alone treatments. However, when FANS was placed outside, the average air velocity through the FANS unit in the Upstream treatment was only 2.1% lower than the average air velocity produced in the Alone and Middle treatments.

Therefore, placing the FANS unit near the discharge side of test fans substantially reduced the differences between the "P" treatments and the Upstream treatment (Figure 4.11 through Figure 4.13), which is evidence that the FANS unit causes an air flow penalty, when placed next to the intake side of the test fan in the Upstream treatment.

4.3 Barn Air Velocity Analysis

An additional analysis was performed in order to determine if the average air velocity through the barn influenced air velocity profiles through the FANS unit, independently of treatment. Average air velocities were calculated for Anemometer 1 (Downstream side of FANS unit) and compared with average air velocities provided by Anemometer 5 (Upstream Side of FANS unit) for fan tests done with FANS inside the barn for all the static pressure (SP) values. Equation 4.1 was used to calculate the differences in air velocity between Anemometers 1 and 5.

$$\textbf{Differences\_An. (\%)} = (\textbf{ANEM}_1 - \textbf{ANEM}_5)*100/\textbf{ANEM}_5 \qquad \text{Equation 4.1}$$

Where,

Differences_An. = Differences [%] between the average air velocities provided by Anemometers 1 and 5;

$ANEM_1$ = Average air velocity [m s^{-1}] provided by the Anemometer 1;

$ANEM_5$ = Average air velocity [m s^{-1}] provided by the Anemometer 5;

An analysis of variance (Equation 4.2) was performed in order to determine if the differences between Anemometers 1 and 5 could be described as a function of "P" treatments and barn air speed (BS). A completely randomized design with a one way treatment classification approach was used in this analysis. Data of BS at the Alone treatment was not used in the analysis, once the equipment used to measure air velocity through the barn (Figure 3.26) was not accurate enough to measure the low air speeds achieved in the barn during this treatment.

Equation 4. 2

$$\textbf{Differences\_An}_{(ij)k} = \mu + P_i + BS_j + (P * BS)_{ij} + E_{(ij)k}$$

Where,

μ = overall mean considered common to all observations [%];

$\mathbf{P_i}$ = fixed effect on the i-th level of treatment "P", i = {1,2,3,4,5}, FANS position relative to operating fans;

$\mathbf{BS_k}$ = continuous variable, air velocity through the barn [m s^{-1}] to the level of the k-th experimental unit;

$\mathbf{E_{(ij)k}}$ = random component, which explains the random variation or experimental error to the k-th experimental unit;

$\mathbf{Differences\_An._{(ijl)k}}$ = air flow difference between anemometers from the effect of the i-th and j-th treatment effects, to the level of the k-th experimental unit.

PROC GLM was used on SAS® (9.2, SAS Institute Inc., 2002-2008 Cary, NC, U.S.A) to test the model of analysis of variance described in Equation 4.2. Fans were not blocked, once they were rejected as significant source of variability among Differences_An.

The statistical results showed that the overall model of analysis of variance was significant ($p < 0.0001$) for Experiments 1 and 2 (Appendix C). Barn air speed significantly ($p = 0.0020$) influenced the differences between Anemometers 1 and 5 in Experiment 2. However, only 2.4% (R^2) of the variation in the differences between anemometers were explained by the variation in barn airspeed. Barn air speed did not significantly ($p=0.5290$) affect the differences between Anemometers 1 and 5 in Experiment 1. The average air velocity through the barns during the fan tests were 1.3 ± 0.3 m s^{-1} and 1.5 ± 0.4 m s^{-1} for Experiments 1 and 2 respectively.

These results reject the hypothesis that the average air velocity through the barn influence air velocity profiles through the FANS unit. Still, it is suggested that a further study is performed in laboratory to evaluate the relationship between air velocity and possible air flow penalties obtained with the FANS unit.

CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 Experiment 1 (E 1) – Farm 1, Operated by Poultry Company 1

Fan performance curves were obtained by regressing air flow as a quadratic function of static pressure (SP), using PRO REG on SAS® (9.2, SAS Institute Inc., 2002-2008 Cary, NC, U.S.A). All the fan performance curves obtained in this study were significant. Also, at least 95% of the variation in air flow was explained by the variation in static pressure.

All the "P" treatments (position of operating fans relative to FANS and test fan) significantly affected FANS test results. The "S" treatments (FANS inside/outside the barn) also significantly affected FANS test results. However, for the same "P" treatment, with exception of the Upstream treatment, fan test results obtained with the FANS unit placed next to the intake of the test fan (Inside treatment) were not significantly different from fan test results obtained with the FANS unit placed near the discharge side of the test fan (Outside treatment). These results agree with those found by Li *et al.* (2009). Therefore, a FANS unit can be used on the discharge side of the test fan to measure performance of fans located in barns similar to those of Farm 1.

The Upstream treatment produced air flow rates as much as 10.9 ± 2.0% lower than the air flow values obtained from remaining "P" treatments. The Opposite Sidewall treatment produced air flow results up to 3.5 ± 2.5% lower than the Middle treatment. Therefore care should be taken during fan tests *in-situ* to select fans to operate during fan tests with the FANS unit, so that the test results are as close as possible to the real flow performance of the test fan.

Placing the FANS unit near the discharge side of test fans provided different results within the "P" treatments. Some of the "P" treatments that were considered significantly different from each other based on results with FANS inside the barn were not found to be significantly different when the FANS unit was placed near the discharge side of the test fans (Table 4.3). Also, the differences between Upstream and the other

“P” treatments were reduced in approximately 75.6 ± 13.8 %. This reduction leaded to the conclusion that part of the air flow reduction in the Upstream treatment is attributed to the FANS unit frame, possibly acting as an obstruction to the air as it moves toward the fan intake.

The other differences found among the “P” treatments may be attributed to an actual change in fan performance, FANS unit error and random error, since some differences were found either when the FANS unit was placed next to the intake or near the discharge sides of the test fans. Placing the FANS unit on the discharge side of the test fan minimizes the air flow penalties, thus it is a good configuration option to test fans *in-situ*.

It was concluded that the Upstream and Opposite Sidewall treatment configurations should be avoided during fan tests *in-situ* with the FANS unit placed both on the intake and on the discharge side of test fans located inside barns similar to the ones studied in Experiment 1 of this work (with fans placed immediately next to each other).

The results of Experiment 1and 2 were used to elaborate a procedure for using the FANS unit for *in-situ* testing of ventilation fans, as described in Section 5.4. Recommendations were provided regarding number of runs and, especially, regarding ways of changing static pressure in the barn during fan tests with FANS.

5.2 Experiment 2 (E 2) – Farms 2, 3 and 4, Operated by Poultry Company 2

Fan performance curves were obtained by regressing air flow as a quadratic function of static pressure, using PROC REG in SAS® (9.2, SAS Institute Inc., 2002-2008 Cary, NC, U.S.A). All fan performance curves presented significant relationship between air flow and static pressure. Also, at least 95% of the variation in air flow was explained by the variation in static pressure.

All “P” (position of operating fans relative to FANS and test fan) treatments had a significant effect on air flow. On the other hand, the “S” treatments (FANS inside/outside the barn) did not present significant effect on air flow. Similar to Experiment 1, fan tests results obtained with FANS unit placed next to the intake of the test fan (Inside treatment), within the same "P" treatment with exception of the Upstream and Opposite Sidewall treatments, were not significantly different from fan test results obtained with FANS placed near the discharge side of the test fan (Outside treatment, P – value > 0.07), which agrees with findings by Li *et al.* (2009). Therefore, the FANS unit can be used on the discharge side of the test fan to measure fan performance of fans located in barns similar to the ones of Farms 2, 3 and 4.

Static pressure did not interact with "P" treatments. The absence of this interaction may be seen graphically by observing that the fan performance curves were nearly parallel among all the treatments.

Fan test results from the Upstream treatment were as much as 12.6 ± 4.4% lower than the remaining "P" treatments. Also, the Opposite Sidewall produced air flow results up to 3.1 ± 3.4% lower than results obtained from the remaining "P" treatments. Therefore, these two treatments should be avoided when testing fans *in-situ* using the FANS unit inside barns similar to the ones studied in this experiment (Sub-sections 3.1.2, 3.1.3 and 3.1.4).

Placing the FANS unit near the discharge side of the test fans provided different responses of the "P" treatments. Some "P" treatments that were considered significantly different from each other based on results with the FANS unit inside the barn were not found to be significantly different when the FANS unit was placed near the discharge side of the test fans (Table 4.8). The Opposite Sidewall treatment configuration may be used in fan tests with FANS near the discharge of test fans. Also, differences between Upstream and other "P" treatments were reduced by approximately 87.5 ± 6.8 %. This reduction in air flow differences led to the conclusion that part of the air flow reduction in the Upstream treatment is attributed to the FANS unit frame, possibly acting as an obstruction to the air as it moves toward the fan intake.

Other differences found among the "P" treatments may be attributed to an actual change in fan performance, FANS unit error and random error, since some differences were found either when the FANS unit was placed next to the intake or near the discharge sides of the test fans.

The results of Experiment 1 and 2 were used to elaborate a procedure for using the FANS unit for *in-situ* testing of ventilation fans, as described in Section 5.4. Recommendations were provided regarding number of runs and, especially, regarding ways of changing static pressure in the barn during fan tests with FANS.

5.3 General Findings

The fan performance setups (Sub-sections 3.3.1 and 3.3.2) and the fan test procedure with the FANS unit used in this study (Sub Section 3.3.4) were adequate and provided good models to predict air flow rate based on static pressure (SP) values. The second order polynomial fan performance curves were all significant at 95% confidence level and presented strong relationships between air flow and SP (R^2 > 95%). Therefore, either the setup or the procedure used in this work are recommended for testing fans *in-situ* with the FANS unit.

The FANS unit position relative to the operating fans in the barns ("P" treatments) significantly affected air flow results for both types of poultry barns evaluated in this study, described in Section 3.1. The Upstream treatment was as much as 12.6 ± 4.4% lower than the remaining "P" treatments. The Opposite Sidewall treatment was as much as 3.1 ± 3.4% lower than the remaining treatments in Experiment 2. Therefore, the Upstream and Opposite Sidewall treatment configuration should be avoided during fan tests *in-situ* using the FANS unit inside barns similar to the ones studied in this work.

Placing the FANS unit on the outside of the barn, near the fan discharge cone (Outside treatment), reduced the differences between the Upstream and the remaining "P" treatments in at least 75.6 ± 13.8 %. The inside and outside placement of the FANS unit ("S" treatments) did not influence air flow results for the same "P" treatment, with exception of the Upstream treatment in Experiment 1and the Upstream and Opposite Sidewall treatments in Experiment 2. Therefore, it was established in this study that the position of the FANS unit relative to operating fans in the Upstream and Opposite Sidewall treatment configurations in the barns affects fan performances results, owing mainly to the FANS unit frame, change in the fan actual performance, FANS unit error and random error.

The Upstream and Opposite sidewall treatment configuration should also be avoided when testing fans *in-situ* with the FANS unit placed near the discharge side of fans located inside barns similar to those of Experiment 1 (Sub-section 3.1.1). However, when testing fans *in-situ* with the FANS unit placed near the discharge side of fans located in barns similar to the ones studied in Experiment 2 (Sub-sections 3.1.2, 3.1.3 and 3.1.4), all the treatment configurations may be used, with exception of the Upstream configuration.

Results from this study showed the need of a standardized method for using the FANS unit to test fans *in-situ*, minimizing possible penalties related to the FANS unit. A procedure for testing fans with the FANS unit was proposed based on the results of this work and was presented in Section 5.4. Changing the SP in the barn, as well as the FANS unit setup and number of test runs were considered when developing the procedure for using the FANS unit *in-situ*.

5.4 Procedure for Using the FANS Unit *in-situ*

Field conditions for testing fans are different from laboratory conditions, therefore it is beneficial to make a few recommendations for using the FANS unit *in-situ*. These recommendations are listed below and are based on the results of this study.

1. Properly Seal the FANS unit to the intake/discharge of the test fan: All fan performance curves obtained in this study presented strong and significant relationships between air flow and static pressure. Therefore, before using the FANS unit to perform fan testing, it is recommended that the FANS unit be sealed to the intake or discharge of the test fan, since this practice provided good fan test results in this study. Further, it is recommended that the FANS unit opening area is not smaller than the opening area of the fan discharge cones;

2. Static Pressures/Number of Runs: It is recommended that a few values of static pressure (SP) are chosen to build fan performance curves that represent the fan

operation *in-situ*. Eight values of SP provided strong and significant fan performance curves in this study. However, Lopes *et al*. (2010) also obtained good fan performance results with readings at five different SP. Therefore, the number of SP readings can be flexible depending on the SP range needed to be covered. It is not recommended to use SP values above 60Pa (≡ 0.24 in.H2O) inside poultry barns, since high SP could possibly damage surfaces such as the ceiling. Also, the differential pressure transducer used in the FANS unit has an operational range of 0 – 62 Pa (0 - 0.25 in.H_2O, Figure 3.19).

3. <u>Changing the SP in the Barn</u>:

Changing the SP in the building is necessary to build performance curves of ventilation fans. Therefore, a few recommendations for changing SP during fan tests with the FANS unit are presented in this Sub-section.

Fan tests with FANS next to the intake side of test fan (Inside the barn):

a) Preference should be given for changing the SP by closing the tunnel curtains and doors before activating additional fans;
b) If closing the barn does not provide sufficiently high SP values, other fans should be activated, beginning with fans located in the other end of the barn (the greatest distance from the test fan);
c) If more operating fans are needed to raise the SP, activate fans upstream of the test fan, making the FANS unit and test fan in the downstream position relative to the tunnel air flow (Figure 3.33). Activate as many fans as possible upstream from the FANS unit and test fan, starting with fans on the same sidewall as FANS and then turning on the fans upstream to the FANS on the opposite sidewall from the FANS unit;
d) If the upstream operating fans are not enough to raise the SP, keep the upstream fans operating and activate fans downstream from the FANS, making the test fan and FANS unit to be in the Middle position (Figure 3.34). Activate as many fans as possible downstream from the test fan and FANS unit, starting with the fans on the same sidewall as the FANS and

test fan. Then, activate fans downstream from the FANS unit on the opposite sidewall from the FANS unit and test fan, if necessary;

e) If there are no fans downstream from the test fan (test fan in the exhaust end corner, for instance), activate fans on the same sidewall as the test fan and FANS unit. If higher SP is needed inside the barn, keep the fans operating on the same sidewall as the FANS unit and turn on fans on the opposite sidewall from the FANS unit, which will put the FANS unit in the Downstream configuration;

f) If there are no fans upstream from the test fan (last test fan from the exhaust end, for instance), the fan should be tested alone (Figure 3.35). In this configuration, all other tunnel fans would be downstream to the FANS unit which would replicate the Upstream treatment (Figure 3.32). This research has shown this condition provided the highest air flow differences from the other treatments in this study. If it is not possible to reach the SP needed for the fan test, turn on fans located in the other end of the barn (the greatest distance from the test fan). Activating additional fans in this situation is not recommended. If higher SP values are really needed, place the FANS unit near the discharge side of the test fan and run tests turning on the least number of tunnel fans as possible. However, this configuration should be avoided, once it could cause air flow penalties up to 3.9 ± 3.5%.

Fan tests with FANS near the discharge side of test fan:

g) Placing the FANS unit near the discharge side of the fan is a good option if the conditions of topography and vegetation allow placement outside of the barn. Still, all the steps for testing fans with the FANS unit next to the intake side of the test fans should be followed even when the FANS unit is near the discharge side of the test fan. Fans downstream of the FANS unit should be avoided to raise the SP in the barn. This would set the FANS unit and test fan in the Upstream position (Figure 3.43), which provided the highest differences in air flow compared to the other treatments in this study. The Opposite Sidewall configuration should also be avoided

(Figure 3.48) in barns similar to the ones of Farm 1. However, this configuration may be used in barns similar to the ones of Farms 2, 3 and 4 with the FANS unit placed near the discharge side of the test fan.

5.5 Recommendations for Future Work

This study evaluated procedures to change static pressure in the barn during fan tests with FANS related to its position to other operating fans in the barn. Future work could evaluate the effect of number of operating fans, within the same "P" treatment and static pressure, on air flow measurement using FANS.

Static pressure interacted with "P" treatments in test results performed in barns of Farm 1. The fan performance curves converged at higher SP values ($30 < SP \leq 60$ Pa), which indicated that the penalties in air flow may be related to the air velocity through the FANS. The contour plots presented in Sub-section 4.2.2 contributed to formulate the hypothesis that the differences between FANS anemometers may be related to the air flow through the FANS unit. An additional analysis tested the hypothesis of the barn air velocity be related to the differences between Anemometers 1 and 5 of the FANS unit. However this hypothesis was rejected based on the results of this work. Still, it is recommended a further study inside laboratory to evaluate if air flow penalties are related with the air velocity through the FANS and through the barn.

It was established that operating fan configurations in the barn can affect fan test results with FANS. Barns with exhaust fans located on sidewalls obligate the air from the curtain inlets to make 90^{o} turns to pass through the exhaust fans. Since the air has to make turns in order to pass through the FANS unit and test fan, the width of the FANS unit frame becomes a potential blockage in the air path through the test fan. Alternative designs of the FANS structure should be studied in order to minimize possible penalties in air flow readings in test conditions similar to the ones in this study.

APPENDICES

Appendix A. Second Order Polynomial Regressions

A.1. Regression Results of Experiment 1 (E 1)

Table A.1. Second order polynomial regressions (fan performance curves) – intercept (B_o), first - order term (B_1), quadratic Term (B_2) – Experiment 1 (E 1).

Fan	Trt_S	Trt_P	B_o ± Std Error [$m^3\ s^{-1}$]	B_1 ± Std Error [$m^3\ s^{-1}\ Pa^{-1}$] * 10^{-2}	B_2 ± Std Error [$(m^3\ s^{-1})^2\ Pa^{-1}$] * 10^{-4}
E1_F1	IN	Alone	8.86 ± 0.05	-2.31 ± 0.42	-8.00 ± 0.81
E1_F2	IN	Alone	8.87 ± 0.07	-3.30 ± 0.67	-5.73 ± 1.30
E1_F3	IN	Alone	8.50 ± 0.04	-4.20 ± 0.33	-3.95 ± 0.61
E1_F4	IN	Alone	8.64 ± 0.12	-2.80 ± 1.05	-7.86 ± 1.91
E1_F5	IN	Alone	8.15 ± 0.10	-6.02 ± 0.86	-2.54 ± 1.52
E1_F1	OUT	Alone	8.85 ± 0.10	-2.56 ± 0.94	-7.21 ± 1.71
E1_F2	OUT	Alone	9.22 ± 0.06	-4.15 ± 0.53	-7.49 ± 0.96
E1_F3	OUT	Alone	8.56 ± 0.22	-5.37 ± 2.04	-2.73 ± 3.89
E1_F4	OUT	Alone	8.68 ± 0.13	-3.28 ± 1.11	-7.11 ± 1.98
E1_F5	OUT	Alone	8.88 ± 0.18	-5.09 ± 1.46	-5.93 ± 2.48
E1_F1	IN	Down	9.03 ± 0.08	-3.29 ± 0.66	-6.50 ± 1.15
E1_F2	IN	Down	8.57 ± 0.08	-3.12 ± 0.63	-5.87 ± 1.09
E1_F3	IN	Down	7.80 ± 0.09	-1.45 ± 0.75	-7.00 ± 1.24
E1_F4	IN	Down	8.50 ± 0.12	-2.62 ± 0.95	-6.87 ± 1.57
E1_F5	IN	Down	7.28 ± 0.20	-2.73 ± 1.67	-5.80 ± 2.81
E1_F1	OUT	Down	9.07 ± 0.26	-3.19 ± 2.06	-7.69 ± 3.42
E1_F2	OUT	Down	8.49 ± 0.09	-2.20 ± 0.68	-8.25 ± 1.13
E1_F3	OUT	Down	8.18 ± 0.25	-2.03 ± 1.86	-8.51 ± 2.96
E1_F4	OUT	Down	8.48 ± 0.22	-1.76 ± 1.74	-10.2 ± 2.94
E1_F5	OUT	Down	8.46 ± 0.44	-6.39 ± 2.95	-3.34 ± 4.44
E1_F1	IN	Midd	8.69 ± 0.10	-1.30 ± 0.77	-9.56 ± 1.29
E1_F2	IN	Midd	8.77 ± 0.12	-2.30 ± 0.93	-7.09 ± 1.49
E1_F3	IN	Midd	8.51 ± 0.07	-5.23 ± 0.48	-2.22 ± 0.76
E1_F4	IN	Midd	8.41 ± 0.05	-2.44 ± 0.42	-6.41 ± 0.71
E1_F5	IN	Midd	7.64 ± 0.14	-3.12 ± 1.14	-5.39 ± 1.91
E1_F1	OUT	Midd	9.05 ± 0.18	-3.99 ± 1.38	-5.77 ± 2.24
E1_F2	OUT	Midd	8.99 ± 0.10	-2.81 ± 0.78	-8.94 ± 1.29
E1_F3	OUT	Midd	8.43 ± 0.50	-1.78 ± 3.53	-8.91 ± 5.44
E1_F4	OUT	Midd	8.59 ± 0.20	-2.51 ± 1.53	-9.94 ± 2.55
E1_F5	OUT	Midd	7.58 ± 0.29	2.25 ± 2.21	-16.1 ± 3.51

E1_F1	IN	Opp.S.	8.66	±	0.09	-1.92	±	0.65	-9.07	±	1.09
E1_F2	IN	Opp.S.	8.88	±	0.08	-4.22	±	0.71	-4.04	±	1.24
E1_F3	IN	Opp.S.	8.09	±	0.07	-3.61	±	0.56	-3.85	±	0.95
E1_F4	IN	Opp.S.	8.34	±	0.07	-3.89	±	0.52	-5.24	±	0.86
E1_F5	IN	Opp.S.	7.65	±	0.16	-3.22	±	1.31	-5.63	±	2.26
E1_F1	OUT	Opp.S.	9.40	±	0.08	-3.91	±	0.60	-6.92	±	0.99
E1_F2	OUT	Opp.S.	8.72	±	0.21	-3.89	±	1.69	-6.00	±	2.91
E1_F3	OUT	Opp.S.	8.32	±	0.37	-4.37	±	2.98	-3.31	±	4.93
E1_F4	OUT	Opp.S.	8.98	±	0.11	-5.47	±	0.92	-7.15	±	1.58
E1_F5	OUT	Opp.S.	7.84	±	0.26	-2.98	±	2.05	-7.82	±	3.38
E1_F1	IN	S.S.	8.91	±	0.06	-3.02	±	0.50	-6.21	±	0.85
E1_F2	IN	S.S.	8.86	±	0.05	-3.90	±	0.43	-4.78	±	0.73
E1_F3	IN	S.S.	8.41	±	0.06	-4.56	±	0.44	-3.14	±	0.73
E1_F4	IN	S.S.	8.04	±	0.32	-2.66	±	2.53	-4.37	±	4.00
E1_F5	IN	S.S.	7.80	±	0.11	-3.74	±	0.89	-5.65	±	1.49
E1_F1	OUT	S.S.	8.97	±	0.05	-3.66	±	0.37	-5.99	±	0.60
E1_F2	OUT	S.S.	9.08	±	0.11	-4.29	±	0.89	-6.58	±	1.51
E1_F3	OUT	S.S.	8.22	±	0.29	-2.91	±	2.19	-6.13	±	3.46
E1_F4	OUT	S.S.	8.38	±	0.20	-1.92	±	1.54	-10.1	±	2.53
E1_F5	OUT	S.S.	8.24	±	0.39	-2.88	±	2.92	-9.10	±	4.88
E1_F1	IN	Up	8.15	±	0.12	-3.61	±	0.92	-3.47	±	1.53
E1_F2	IN	Up	8.23	±	0.03	-3.76	±	0.23	-2.91	±	0.40
E1_F3	IN	Up	7.05	±	0.13	-0.06	±	1.01	-7.57	±	1.62
E1_F4	IN	Up	7.33	±	0.06	-0.43	±	0.49	-8.72	±	0.84
E1_F5	IN	Up	7.21	±	0.17	-5.37	±	1.36	0.44	±	2.28
E1_F1	OUT	Up	8.54	±	0.10	-3.01	±	0.79	-5.86	±	1.31
E1_F2	OUT	Up	8.81	±	0.15	-3.18	±	1.15	-8.10	±	1.90
E1_F3	OUT	Up	8.37	±	0.37	-4.18	±	2.75	-4.58	±	4.43
E1_F4	OUT	Up	8.71	±	0.08	-4.38	±	0.63	-4.12	±	1.08
E1_F5	OUT	Up	8.06	±	0.38	-4.66	±	2.97	-5.02	±	4.99

Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Table A.2. Second order polynomial regressions (fan performance curves) – coefficient of determination (R^2), coefficient of variation, mean air flow rate, overall p-value - Experiment 1 (E 1).

Fan	Trt_S	Trt_P	R^2	Coeff. Var.	Root MSE [$m^3.s^{-1}$]	Mean Air Flow [$m^3.s^{-1}$]	Overall p-value
E1_F1	IN	Alone	0.9982	0.71	0.05	7.58	<.0001
E1_F2	IN	Alone	0.9948	1.28	0.10	7.56	<.0001
E1_F3	IN	Alone	0.9992	0.54	0.04	7.02	<.0001
E1_F4	IN	Alone	0.9936	1.66	0.12	7.10	<.0001
E1_F5	IN	Alone	0.9958	1.56	0.10	6.29	<.0001
E1_F1	OUT	Alone	0.9937	1.39	0.10	7.55	<.0001
E1_F2	OUT	Alone	0.9987	0.80	0.06	7.38	<.0001
E1_F3	OUT	Alone	0.9716	3.31	0.23	6.95	0.0001
E1_F4	OUT	Alone	0.9923	1.80	0.13	7.03	<.0001
E1_F5	OUT	Alone	0.9911	2.49	0.17	6.70	<.0001
E1_F1	IN	Down	0.9979	0.79	0.06	7.46	<.0001
E1_F2	IN	Down.	0.9977	0.77	0.05	7.10	<.0001
E1_F3	IN	Down	0.9962	0.99	0.07	6.63	<.0001
E1_F4	IN	Down	0.9958	1.21	0.08	7.01	<.0001
E1_F5	IN	Down	0.9883	2.13	0.12	5.86	<.0001
E1_F1	OUT	Down	0.9866	2.44	0.18	7.25	<.0001
E1_F2	OUT	Down	0.9977	0.88	0.06	6.97	<.0001
E1_F3	OUT	Down	0.9858	2.60	0.17	6.61	<.0001
E1_F4	OUT	Down.	0.9895	2.21	0.15	6.87	<.0001
E1_F5	OUT	Down	0.9758	3.87	0.23	6.00	<.0001
E1_F1	IN	Midd	0.9972	0.84	0.06	7.35	<.0001
E1_F2	IN	Midd	0.9957	1.17	0.08	7.25	<.0001
E1_F3	IN	Midd	0.9987	0.64	0.04	6.71	<.0001
E1_F4	IN	Midd	0.9990	0.50	0.03	7.02	<.0001
E1_F5	IN	Midd	0.9935	1.51	0.09	6.15	<.0001
E1_F1	OUT	Midd	0.9930	1.65	0.12	7.28	<.0001
E1_F2	OUT	Midd	0.9982	0.90	0.06	7.18	<.0001
E1_F3	OUT	Midd	0.9591	3.98	0.27	6.89	0.0003
E1_F4	OUT	Midd	0.9921	1.98	0.14	6.85	<.0001
E1_F5	OUT	Midd	0.9862	2.71	0.18	6.53	<.0001
E1_F1	IN	Opp.S.	0.9977	0.95	0.07	7.02	<.0001
E1_F2	IN	Opp.S.	0.9974	0.89	0.06	7.29	<.0001
E1_F3	IN	Opp.S.	0.9974	0.83	0.06	6.65	<.0001
E1_F4	IN	Opp.S.	0.9984	0.84	0.06	6.63	<.0001

E1_F5	IN	Opp.S.	0.9892	2.14	0.13	6.12	<.0001
E1_F1	OUT	Opp.S.	0.9984	0.84	0.06	7.54	<.0001
E1_F2	OUT	Opp.S.	0.9859	2.34	0.16	7.04	<.0001
E1_F3	OUT	Opp.S.	0.9567	3.89	0.26	6.70	0.0004
E1_F4	OUT	Opp.S.	0.9981	1.23	0.08	6.67	<.0001
E1_F5	OUT	Opp.S.	0.9876	2.75	0.17	6.07	<.0001
E1_F1	IN	S.S.	0.9986	0.68	0.05	7.38	<.0001
E1_F2	IN	S.S.	0.9989	0.57	0.04	7.21	<.0001
E1_F3	IN	S.S.	0.9987	0.68	0.05	6.72	<.0001
E1_F4	IN	S.S.	0.9546	3.90	0.26	6.67	0.0004
E1_F5	IN	S.S.	0.9963	1.30	0.08	6.10	<.0001
E1_F1	OUT	S.S.	0.9992	0.54	0.04	7.22	<.0001
E1_F2	OUT	S.S.	0.9971	1.17	0.08	7.12	<.0001
E1_F3	OUT	S.S.	0.9704	3.75	0.25	6.67	0.0002
E1_F4	OUT	S.S.	0.9906	2.25	0.15	6.66	<.0001
E1_F5	OUT	S.S.	0.9712	3.80	0.24	6.41	0.0001
E1_F1	IN	Up	0.9939	1.14	0.08	6.80	<.0001
E1_F2	IN	Up	0.9997	0.27	0.02	6.81	<.0001
E1_F3	IN	Up	0.9908	1.42	0.09	6.27	<.0001
E1_F4	IN	Up	0.9979	0.74	0.05	6.30	<.0001
E1_F5	IN	Up	0.9895	1.63	0.09	5.69	<.0001
E1_F1	OUT	Up	0.9962	1.01	0.07	7.03	<.0001
E1_F2	OUT	Up	0.9952	1.58	0.11	6.98	<.0001
E1_F3	OUT	Up	0.9684	3.56	0.24	6.61	0.0002
E1_F4	OUT	Up	0.9981	0.75	0.05	7.00	<.0001
E1_F5	OUT	Up	0.9705	3.93	0.24	6.13	0.0001

Treatments Abbreviation: IN (Inside), OUT (Outside), Downst. (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

A.2. Regression Results of Experiment 2 (E2)

Table A.3. Second order polynomial regressions (fan performance curves) – intercept (B_o), first - order term (B_1), quadratic term (B_2) – Experiment 2 (E 2).

Fan	Trt_S	Trt_P	B_o ± Std Error [m^3 s^{-1}]	B_1± Std Error [m^3 s^{-1} Pa^{-1}] * 10^{-2}	B_2± Std Error [(m^3 $s^{-1})^2$ Pa^{-1}] * 10^{-4}
E2_F1	IN	Alone	9.78 ± 0.14	-4.43 ± 1.22	-5.00 ± 2.37
E2_F2	IN	Alone	9.75 ± 0.28	-4.47 ± 2.42	-4.38 ± 4.43
E2_F3	IN	Alone	10.54 ± 0.17	-5.30 ± 1.59	-6.96 ± 2.96
E2_F4	IN	Alone	10.44 ± 0.11	-6.00 ± 1.06	-5.37 ± 2.01
E2_F5	IN	Alone	10.98 ± 0.07	-4.82 ± 0.65	-2.98 ± 1.26
E2_F1	OUT	Alone	9.67 ± 0.29	-5.74 ± 2.88	-2.82 ± 5.91
E2_F2	OUT	Alone	9.82 ± 0.21	-3.83 ± 1.76	-7.24 ± 3.09
E2_F3	OUT	Alone	9.76 ± 0.11	-3.84 ± 1.00	-7.35 ± 1.95
E2_F4	OUT	Alone	10.07 ± 0.29	-2.61 ± 2.29	-9.72 ± 3.83
E2_F5	OUT	Alone	11.03 ± 0.07	-6.03 ± 0.65	-0.76 ± 1.24
E2_F1	IN	Down	9.91 ± 0.28	-5.20 ± 2.18	-6.19 ± 3.61
E2_F2	IN	Down	9.86 ± 0.14	-3.63 ± 1.07	-8.10 ± 1.79
E2_F3	IN	Down	10.68 ± 0.19	-4.21 ± 1.69	-9.07 ± 3.09
E2_F4	IN	Down	9.88 ± 0.10	-5.03 ± 0.80	-5.35 ± 1.39
E2_F5	IN	Down	10.83 ± 0.16	-3.55 ± 1.30	-4.79 ± 2.22
E2_F1	OUT	Down	9.56 ± 0.28	-3.50 ± 2.20	-7.56 ± 3.72
E2_F2	OUT	Down	9.75 ± 0.14	-1.68 ± 1.08	-10.3 ± 1.82
E2_F3	OUT	Down	9.64 ± 0.16	-0.94 ± 1.34	-13.1 ± 2.36
E2_F4	OUT	Down	9.42 ± 0.34	-0.38 ± 2.61	-12.6 ± 4.31
E2_F5	OUT	Down	11.02 ± 0.13	-3.74 ± 1.11	-3.78 ± 1.99
E2_F1	IN	Midd	9.95 ± 0.19	-4.53 ± 1.48	-7.05 ± 2.53
E2_F2	IN	Midd	9.13 ± 0.34	-1.04 ± 2.47	-10.2 ± 3.91
E2_F3	IN	Midd	10.45 ± 0.17	-3.14 ± 1.36	-9.91 ± 2.36
E2_F4	IN	Midd	9.75 ± 0.14	-3.95 ± 1.06	-6.48 ± 1.73
E2_F5	IN	Midd	10.87 ± 0.14	-4.47 ± 1.00	-3.44 ± 1.60
E2_F1	OUT	Midd	10.39 ± 0.32	-8.71 ± 2.46	-0.28 ± 4.06
E2_F2	OUT	Midd	10.03 ± 0.34	-3.04 ± 2.55	-6.95 ± 4.18
E2_F3	OUT	Midd	9.87 ± 0.38	-2.98 ± 3.00	-11.5 ± 5.06
E2_F4	OUT	Midd	9.83 ± 0.40	-2.76 ± 2.91	-8.68 ± 4.67
E2_F5	OUT	Midd	10.56 ± 0.16	-0.93 ± 1.17	-7.75 ± 1.88
E2_F1	IN	Opp.S.	9.39 ± 0.14	-4.00 ± 1.16	-6.28 ± 2.06
E2_F2	IN	Opp.S.	9.19 ± 0.33	-3.43 ± 2.56	-6.90 ± 4.15
E2_F3	IN	Opp.S.	10.35 ± 0.07	-4.42 ± 0.57	-6.90 ± 0.99

E2_F4	IN	Opp.S.	9.50 ± 0.10	-3.20 ± 0.87	-7.27 ± 1.51
E2_F5	IN	Opp.S.	10.85 ± 0.06	-4.78 ± 0.42	-2.11 ± 0.69
E2_F1	OUT	Opp.S.	10.05 ± 0.35	-2.28 ± 2.80	-11.6 ± 4.77
E2_F2	OUT	Opp.S.	10.05 ± 0.25	-3.66 ± 2.04	-8.18 ± 3.56
E2_F3	OUT	Opp.S.	9.71 ± 0.12	-2.27 ± 0.97	-10.3 ± 1.67
E2_F4	OUT	Opp.S.	9.97 ± 0.22	-3.76 ± 1.79	-8.12 ± 3.09
E2_F5	OUT	Opp.S.	10.64 ± 0.19	-4.98 ± 1.47	-2.56 ± 2.44
E2_F1	IN	S.S.	9.93 ± 0.11	-6.29 ± 0.90	-4.13 ± 1.52
E2_F2	IN	S.S.	9.66 ± 0.14	-0.62 ± 1.17	-12.5 ± 2.09
E2_F3	IN	S.S.	10.33 ± 0.19	-2.97 ± 1.55	-10.7 ± 2.62
E2_F4	IN	S.S.	9.66 ± 0.17	-2.51 ± 1.33	-9.23 ± 2.29
E2_F5	IN	S.S.	10.82 ± 0.17	-4.94 ± 1.45	0.03 ± 2.56
E2_F1	OUT	S.S.	9.51 ± 0.23	-1.14 ± 1.82	-11.5 ± 3.07
E2_F2	OUT	S.S.	9.61 ± 0.46	-2.15 ± 3.32	-10.4 ± 5.27
E2_F3	OUT	S.S.	9.96 ± 0.30	-5.45 ± 2.35	-5.59 ± 3.95
E2_F4	OUT	S.S.	9.82 ± 0.29	-3.22 ± 2.17	-7.97 ± 3.56
E2_F5	OUT	S.S.	10.60 ± 0.24	-3.87 ± 1.92	-3.06 ± 3.25
E2_F1	IN	Up	8.86 ± 0.26	-5.78 ± 2.01	-3.65 ± 3.35
E2_F2	IN	Up	9.36 ± 0.19	-8.01 ± 1.37	1.07 ± 2.14
E2_F3	IN	Up	9.72 ± 0.10	-4.76 ± 0.76	-5.51 ± 1.22
E2_F4	IN	Up	8.99 ± 0.11	-4.76 ± 0.77	-3.76 ± 1.22
E2_F5	IN	Up	10.10 ± 0.18	-6.16 ± 1.27	0.56 ± 2.00
E2_F1	OUT	Up	9.90 ± 0.38	-4.85 ± 2.83	-5.35 ± 4.62
E2_F2	OUT	Up	8.90 ± 0.40	1.70 ± 2.84	-14.1 ± 4.52
E2_F3	OUT	Up	10.09 ± 0.28	-4.59 ± 2.09	-6.94 ± 3.40
E2_F4	OUT	Up	9.69 ± 0.45	-2.93 ± 3.27	-8.62 ± 5.16
E2_F5	OUT	Up	9.98 ± 0.37	-1.71 ± 2.52	-7.37 ± 3.80

Treatments Abbreviation: IN (Inside), OUT (Outside), Downst. (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Table A.4. Second order polynomial regressions (fan performance curves) – coefficient of determination (R^2), coefficient of variation, mean air flow rate, overall p-value - Experiment 1 (E 2).

Fan	Trt_S	Trt_P	R^2	Coeff. Var.	Root MSE [$m^3.s^{-1}$]	Mean Air Flow [$m^3.s^{-1}$]	Overall p-value
E2_F1	IN	Alone	0.9894	1.55	0.13	8.27	<.0001
E2_F2	IN	Alone	0.9647	2.76	0.23	8.30	0.0002
E2_F3	IN	Alone	0.9922	1.80	0.15	8.45	<.0001
E2_F4	IN	Alone	0.9947	1.52	0.13	8.45	<.0001
E2_F5	IN	Alone	0.9962	0.82	0.08	9.50	<.0001
E2_F1	OUT	Alone	0.9485	3.76	0.31	8.13	0.0006
E2_F2	OUT	Alone	0.9890	1.90	0.15	8.01	<.0001
E2_F3	OUT	Alone	0.9933	1.52	0.12	8.16	<.0001
E2_F4	OUT	Alone	0.9857	2.06	0.17	8.43	<.0001
E2_F5	OUT	Alone	0.9962	0.86	0.08	9.37	<.0001
E2_F1	IN	Down	0.9893	2.26	0.17	7.68	<.0001
E2_F2	IN	Down	0.9956	1.34	0.11	7.93	<.0001
E2_F3	IN	Down	0.9908	1.94	0.17	8.60	<.0001
E2_F4	IN	Down	0.9974	0.94	0.07	7.93	<.0001
E2_F5	IN	Down	0.9904	1.20	0.11	9.31	<.0001
E2_F1	OUT	Down	0.9813	2.71	0.21	7.66	<.0001
E2_F2	OUT	Down	0.9947	1.24	0.10	8.19	<.0001
E2_F3	OUT	Down	0.9940	1.43	0.12	8.06	<.0001
E2_F4	OUT	Down	0.9743	2.92	0.23	7.97	0.0000
E2_F5	OUT	Down	0.9903	1.15	0.11	9.58	<.0001
E2_F1	IN	Midd	0.9949	1.30	0.10	7.93	<.0001
E2_F2	IN	Midd	0.9811	2.34	0.18	7.70	<.0001
E2_F3	IN	Midd	0.9961	1.07	0.09	8.61	<.0001
E2_F4	IN	Midd	0.9973	0.85	0.07	7.92	<.0001
E2_F5	IN	Midd	0.9959	0.74	0.07	9.14	<.0001
E2_F1	OUT	Midd	0.9868	2.29	0.18	7.79	<.0001
E2_F2	OUT	Midd	0.9839	1.83	0.15	8.29	<.0001
E2_F3	OUT	Midd	0.9854	2.56	0.20	7.83	<.0001
E2_F4	OUT	Midd	0.9814	2.27	0.18	8.07	<.0001
E2_F5	OUT	Midd	0.9927	0.92	0.09	9.43	<.0001
E2_F1	IN	Opp.S.	0.9940	1.37	0.10	7.62	<.0001
E2_F2	IN	Opp.S.	0.9771	3.13	0.23	7.42	<.0001
E2_F3	IN	Opp.S.	0.9987	0.71	0.06	8.38	<.0001
E2_F4	IN	Opp.S.	0.9963	1.09	0.09	7.85	<.0001

E2_F5	IN	Opp.S.	0.9986	0.45	0.04	9.22	<.0001
E2_F1	OUT	Opp.S.	0.9761	3.39	0.28	8.14	<.0001
E2_F2	OUT	Opp.S.	0.9858	2.27	0.18	8.14	<.0001
E2_F3	OUT	Opp.S.	0.9970	0.98	0.08	7.93	<.0001
E2_F4	OUT	Opp.S.	0.9878	2.30	0.19	8.09	<.0001
E2_F5	OUT	Opp.S.	0.9887	1.51	0.13	8.84	<.0001
E2_F1	IN	S.S.	0.9973	1.11	0.08	7.67	<.0001
E2_F2	IN	S.S.	0.9948	1.20	0.10	8.22	<.0001
E2_F3	IN	S.S.	0.9929	1.87	0.16	8.36	<.0001
E2_F4	IN	S.S.	0.9925	1.59	0.13	7.90	<.0001
E2_F5	IN	S.S.	0.9790	1.47	0.14	9.47	<.0001
E2_F1	OUT	S.S.	0.9857	2.46	0.19	7.91	<.0001
E2_F2	OUT	S.S.	0.9678	3.54	0.28	7.79	0.0002
E2_F3	OUT	S.S.	0.9834	2.55	0.20	7.83	<.0001
E2_F4	OUT	S.S.	0.9786	2.71	0.22	8.07	<.0001
E2_F5	OUT	S.S.	0.9743	1.86	0.17	9.14	0.0001
E2_F1	IN	Up	0.9906	1.97	0.13	6.74	<.0001
E2_F2	IN	Up	0.9948	1.29	0.09	7.03	<.0001
E2_F3	IN	Up	0.9982	0.77	0.06	7.76	<.0001
E2_F4	IN	Up	0.9981	0.76	0.05	7.14	<.0001
E2_F5	IN	Up	0.9920	1.04	0.09	8.26	<.0001
E2_F1	OUT	Up	0.9836	2.11	0.17	7.91	<.0001
E2_F2	OUT	Up	0.9778	2.13	0.17	7.90	<.0001
E2_F3	OUT	Up	0.9906	1.81	0.14	7.98	<.0001
E2_F4	OUT	Up	0.9768	2.75	0.22	7.84	<.0001
E2_F5	OUT	Up	0.9763	1.99	0.17	8.58	<.0001

Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Appendix B. Statistical Results

B.1. Mixed Procedure Syntax used for Experiment 1 and 2

Table B.3. Mixed Procedure syntax for SAS® for analyzing the Generalized Randomized Complete Block (GRCB) design.

```
PROC MIXED DATA=SASUSER.Experiment_1/2;
   CLASS TRT P TRT S Fan;
   MODEL AIRFLOW = TRT_P|TRT_S|SP;
   RANDOM Fan;
   LSMEANS TRT_S * TRT_P/DIFF;
   RUN;
```

B.2. Mixed Procedure Results of Experiment 1 (E1)

Table B.1. Model information - SAS® output for Experiment 1 (E 1), using the Generalized Randomized Complete Block (GRCB) design.

Data Set	SASUSER.E1
Dependent Variable	Airflow
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment
Covariance Parameters	2
Columns in X	42
Columns in Z	5
Subjects	1
Max Observations Per Subject	480
Number of Observations Read	480
Number of Observations Used	480
Number of Observations Not Used	0
Covariance Parameter Estimates	
Covariance Parameters	**Estimate**
Fan	0.1695
Residual	0.0561
Fit Statistics	
-2 Res Log Likelihood	156.6
AIC (smaller is better)	160.6
AICC (smaller is better)	160.6
BIC (smaller is better)	159.8

Table B.2. SAS® Type III of fixed effects for Experiment 1 (E 1), using the Generalized Randomized Complete Block (GRCB) design.

Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Trt_P	5	452	15.43	<.0001
Trt_S	1	452	101.55	<.0001
Trt_P*Trt_S	5	452	5.16	0.0001
SP	1	452	9232.69	<.0001
SP*Trt_P	5	452	3.91	0.0018
SP*Trt_S	1	452	77.73	<.0001
SP*Trt_P*Trt_S	5	452	1.42	0.2150

Num, Den DF = Numerator, Denominator Degrees of Freedom.

Table B.3. Least Square Means estimates for Experiment 1 (E 1), using the Generalized Randomized Complete Block (GRCB) design in SAS®.

Effect	**Trt_P**	**Trt_S**	**Estimate [$m^3.s^{-1}$]**	**Standard Error [$m^3.s^{-1}$]**	**DF**	**t Value**	**Pr > |t|**
Trt_P*Trt_S	Alone	IN	6.92	0.19	452	36.80	<.0001
Trt_P*Trt_S	Alone	OUT	7.00	0.19	452	37.21	<.0001
Trt_P*Trt_S	Down	IN	6.81	0.19	452	36.22	<.0001
Trt_P*Trt_S	Down	OUT	6.84	0.19	452	36.38	<.0001
Trt_P*Trt_S	Midd.	IN	6.94	0.19	452	36.94	<.0001
Trt_P*Trt_S	Midd.	OUT	6.99	0.19	452	37.19	<.0001
Trt_P*Trt_S	Opp. S.	IN	6.76	0.19	452	35.96	<.0001
Trt_P*Trt_S	Opp. S.	OUT	6.80	0.19	452	36.2	<.0001
Trt_P*Trt_S	S. S.	IN	6.86	0.19	452	36.52	<.0001
Trt_P*Trt_S	S. S.	OUT	6.88	0.19	452	36.59	<.0001
Trt_P*Trt_S	Up	IN	6.37	0.19	452	33.89	<.0001
Trt_P*Trt_S	Up	OUT	6.80	0.19	452	36.19	<.0001

DF = Degrees of Freedom. Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Table B.4. SAS® Least Square Means Difference output for Experiment 1 (E 1), using the Generalized Randomized Complete Block (GRCB) design.

Trt_P	Trt_S	Trt_P	Trt_S	Estimate [$m^3.s^{-1}$]	Std. Error [$m^3.s^{-1}$]	DF	p - value
Alone	IN	Alone	OUT	-0.08	0.05	452	0.1609
Alone	IN	Down	IN	0.11	0.05	452	0.0362
Alone	IN	Midd.	IN	-0.02	0.05	452	0.6534
Alone	IN	Opp. S.	IN	0.16	0.05	452	0.0028
Alone	IN	S. S.	IN	0.06	0.05	452	0.3005
Alone	IN	Up	IN	0.56	0.05	452	<.0001
Alone	OUT	Down	OUT	0.16	0.05	452	0.0034
Alone	OUT	Midd.	OUT	0.01	0.05	452	0.9175
Alone	OUT	Opp. S.	OUT	0.20	0.05	452	0.0003
Alone	OUT	S. S.	OUT	0.12	0.05	452	0.0278
Alone	OUT	Up	OUT	0.19	0.05	452	0.0003
Down	IN	Down	OUT	-0.03	0.05	452	0.5672
Down	IN	Midd.	IN	-0.14	0.05	452	0.0105
Down	IN	Opp. S.	IN	0.05	0.05	452	0.3613
Down	IN	S. S.	IN	-0.06	0.05	452	0.2847
Down	IN	Up	IN	0.44	0.05	452	<.0001
Down	OUT	Midd.	OUT	-0.15	0.05	452	0.0045
Down	OUT	Opp. S.	OUT	0.04	0.05	452	0.5082
Down	OUT	S. S.	OUT	-0.04	0.05	452	0.4567
Down	OUT	Up	OUT	0.04	0.05	452	0.5060
Midd.	IN	Midd.	OUT	-0.05	0.05	452	0.3893
Midd.	IN	Opp. S.	IN	0.18	0.05	452	0.0005
Midd.	IN	S. S.	IN	0.08	0.05	452	0.1352
Midd.	IN	Up	IN	0.57	0.05	452	<.0001
Midd.	OUT	Opp. S.	OUT	0.19	0.05	452	0.0005
Midd.	OUT	S. S.	OUT	0.11	0.05	452	0.0354
Midd.	OUT	Up	OUT	0.19	0.05	452	0.0005
Opp. S.	IN	Opp. S.	OUT	-0.04	0.05	452	0.4103
Opp. S.	IN	S. S.	IN	-0.11	0.05	452	0.0478

Opp. S.	IN	Up	IN	0.39	0.05	452	<.0001
Opp. S.	OUT	S. S.	OUT	-0.08	0.05	452	0.1595
Opp. S.	OUT	Up	OUT	0.00	0.05	452	0.9969
S. S.	IN	S. S.	OUT	-0.01	0.05	452	0.8038
S. S.	IN	Up	IN	0.49	0.05	452	<.0001
S. S.	OUT	Up	OUT	0.08	0.05	452	0.1586
Up	IN	Up	OUT	-0.43	0.05	452	<.0001

DF = Degrees of Freedom. Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

B.3. Mixed Procedure Results of Experiment 2 (E 2)

Table B.5. Model information - SAS® output for Experiment 2 (E 2), using the Generalized Randomized Complete Block (GRCB) design.

Data Set	**SASUSER.E2**
Dependent Variable	Airflow
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment
Covariance Parameters	2
Columns in X	42
Columns in Z	5
Subjects	1
Max Observations Per Subject	480
Number of Observations Read	480
Number of Observations Used	480
Number of Observations Not Used	0

Covariance Parameter Estimates	
Covariance Parameters	**Estimate**
Fan	0.313
Residual	0.097
Fit Statistics	
-2 Res Log Likelihood	403.8
AIC (smaller is better)	407.8
AICC (smaller is better)	407.8
BIC (smaller is better)	407.0

Table B.6. SAS® Type III of fixed effects for Experiment 2 (E 2), using the Generalized Randomized Complete Block (GRCB) design.

Effect	**Num* DF**	**Den* DF**	**F Value**	**P > F**
Trt_P	5	452	5.98	<.0001
Trt_S	1	452	3.47	0.0631
Trt_P*Trt_S	5	452	6.2	<.0001
SP	1	452	5943.1	<.0001
SP*Trt_P	5	452	0.43	0.8263
SP*Trt_S	1	452	0	0.9440
SP*Trt_P*Trt_S	5	452	1.24	0.2914

**Num, Den DF = Numerator, Denominator Degrees of Freedom.*

Table B.7. Least Square Means estimates for Experiment 2 (E 2), using the Generalized Randomized Complete Block (GRCB) design in SAS®.

Effect	**Trt_P**	**Trt_S**	**Estimate [$m^3.s^{-1}$]**	**Standard Error [$m^3.s^{-1}$]**	**DF**	**t Value**	**Pr > |t|**
Trt_P*Trt_S	Alone	IN	8.34	0.26	452	32.67	<.0001
Trt_P*Trt_S	Alone	OUT	8.23	0.26	452	32.25	<.0001
Trt_P*Trt_S	Down	IN	8.30	0.26	452	32.53	<.0001
Trt_P*Trt_S	Down	OUT	8.31	0.26	452	32.59	<.0001
Trt_P*Trt_S	Midd.	IN	8.31	0.26	452	32.59	<.0001
Trt_P*Trt_S	Midd.	OUT	8.38	0.26	452	32.86	<.0001
Trt_P*Trt_S	Opp. S.	IN	8.10	0.26	452	31.76	<.0001
Trt_P*Trt_S	Opp. S.	OUT	8.26	0.26	452	32.41	<.0001
Trt_P*Trt_S	S. S.	IN	8.31	0.26	452	32.6	<.0001
Trt_P*Trt_S	S. S.	OUT	8.19	0.26	452	32.11	<.0001
Trt_P*Trt_S	Up	IN	7.49	0.26	452	29.37	<.0001
Trt_P*Trt_S	Up	OUT	8.17	0.26	452	32.03	<.0001

DF = Degrees of Freedom. Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Table B.8. SAS® Least Square Means Difference output for Experiment 2 (E 2), using the Generalized Randomized Complete Block (GRCB) design.

Trt_P	Trt_S	Trt_P	Trt_S	Estimate [$m^3.s^{-1}$]	Std. Error [$m^3.s^{-1}$]	DF	p - value
Alone	IN	Alone	OUT	0.11	0.07	452	0.1145
Alone	IN	Down	IN	0.05	0.07	452	0.5262
Alone	IN	Midd.	IN	0.03	0.07	452	0.6776
Alone	IN	Opp. S.	IN	0.24	0.07	452	0.0007
Alone	IN	S. S.	IN	0.03	0.07	452	0.7138
Alone	IN	Up	IN	0.85	0.07	452	<.0001
Alone	OUT	Down	OUT	-0.08	0.07	452	0.2363
Alone	OUT	Midd.	OUT	-0.15	0.07	452	0.0307
Alone	OUT	Opp. S.	OUT	-0.04	0.07	452	0.6041
Alone	OUT	S. S.	OUT	0.04	0.07	452	0.5792
Alone	OUT	Up	OUT	0.06	0.07	452	0.4154
Down	IN	Down	OUT	-0.02	0.07	452	0.8228
Down	IN	Midd.	IN	-0.02	0.07	452	0.8255
Down	IN	Opp. S.	IN	0.20	0.07	452	0.0052
Down	IN	S. S.	IN	-0.02	0.07	452	0.7868
Down	IN	Up	IN	0.81	0.07	452	<.0001
Down	OUT	Midd.	OUT	-0.07	0.07	452	0.3216
Down	OUT	Opp. S.	OUT	0.05	0.07	452	0.5020
Down	OUT	S. S.	OUT	0.12	0.07	452	0.0801
Down	OUT	Up	OUT	0.14	0.07	452	0.0448
Midd.	IN	Midd.	OUT	-0.07	0.07	452	0.3202
Midd.	IN	Opp. S.	IN	0.21	0.07	452	0.0026
Midd.	IN	S. S.	IN	-0.00	0.07	452	0.9603
Midd.	IN	Up	IN	0.82	0.07	452	<.0001
Midd.	OUT	Opp. S.	OUT	0.12	0.07	452	0.0971
Midd.	OUT	S. S.	OUT	0.19	0.07	452	0.0063
Midd.	OUT	Up	OUT	0.21	0.07	452	0.0029
Opp. S.	IN	Opp. S.	OUT	-0.16	0.07	452	0.0186
Opp. S.	IN	S. S.	IN	-0.21	0.07	452	0.0022

Opp. S.	IN	Up	IN	0.61	0.07	452	<.0001
Opp. S.	OUT	S. S.	OUT	0.08	0.07	452	0.2799
Opp. S.	OUT	Up	OUT	0.09	0.07	452	0.1802
S. S.	IN	S. S.	OUT	0.13	0.07	452	0.0725
S. S.	IN	Up	IN	0.82	0.07	452	<.0001
Up	IN	Up	OUT	-0.68	0.07	452	<.0001

DF = Degrees of Freedom. Treatments Abbreviation: IN (Inside), OUT (Outside), Down (Downstream), Midd (Middle), Opp. S. (Opposite Sidewall), S.S. (Same Sidewall), Up (Upstream).

Appendix C. Barn Air Velocity Analysis

C.1. Results for Experiment 1 (E 1)

Table C.1. Model information and SAS® output for testing differences between anemometers as a function of barn average air speed and treatments "P" - Proc GLM (Completely Randomized design – E 1).

Class	**Levels**	**Values**	**Number of Observations Read/Used**
TRT_P	5	Downstream Middle Opposite Sidewall Same Sidewall Upstream	200
R^2	**Coefficient of Variation**	**Root MSE [%]***	**Differences Mean [%]***
0.2371	1789.18	53.84	3.01

- *** % of mean air velocity from anemometers.**

Table C.2. ANOVA table and Type III sums of squares for testing differences between anemometers as a function of barn average air speed and treatments "P" - Proc GLM on SAS® (Completely Randomized design – E 1).

Source	**DF**	**Sum of Squares**	**Mean Square**	**F - Value**	**P > F**
Model	9	171227.82	19025.31	6.56	<0.0001
Error	190	550830.97	2899.11		
Corrected Total	199	722058.80			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**P > F**
Barn_AirSpeed	1	1154.67	1154.67	0.4	0.529
TRT_P	4	1831.00	457.75	0.16	0.959
Barn_AirSpeed*TRT_P	4	12699.93	3174.98	1.1	0.360

C.2. Results for Experiment 2 (E 2)

Table C.3. Model information and SAS® output for testing differences between anemometers as a function of barn average air speed and treatments "P" - Proc GLM (Completely Randomized design – E 2).

Class	Levels	Values	Number of Observations Read/Used
TRT_P	5	Downstream Middle Opposite Sidewall Same Sidewall Upstream	200
R^2	**Coeff Var**	**Root MSE [%]***	**Differences Mean [%]***
0.2385	-364.27	44.81	-12.30

- *** % of mean air velocity from anemometers.**

Table C.4. ANOVA table and Type III sums of squares for testing differences between anemometers as a function of barn average air speed and treatments "P" - Proc GLM on SAS® (Completely Randomized design – E 2).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	119495.67	13277.30	6.61	<0.0001
Error	190	381486.33	2007.82		
Corrected Total	199	500982.00			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Barn_AirSpeed	1	19960.72	19960.72	9.94	0.002
TRT_P	4	11573.47	2893.37	1.44	0.222
Barn_AirSpeed*TRT_P	4	18872.11	4718.03	2.35	0.056

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