

# Ventilation in Agricultural Buildings: Characteristics and Measurements Methods (Review)

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**Abstract** – A ventilation system is used to control the physical micro-environment within a livestock and agricultural building. Information about ventilation systems in livestock and agricultural building is presented in this review, this review covers:

1) Information about air ventilation systems including contribution of the ventilation system to control micro-environment, methods for ventilation rate control, principles of modulating ventilation control, ventilation efficiency, ventilation effectiveness, ventilation for animal's houses, ventilation for greenhouses and ventilation parameters;

2) Ventilation system performance covering natural ventilation, supplemental cooling fans and tunnel ventilation;

3) Methods used to measure the ventilation rate through a ventilated space. The distinction between direct and indirect measuring methods was clarified.

The following findings were obtained by this review: For continuous and accurate measurements under field conditions, the method of a free running impeller gives high accuracy. Methods based on velocity point measurements (eg. pitot tubes, hot wire anemometers, vane anemometers) require a large number of sensors and therefore considered costly methods. Pressure based methods like orifices and nozzles need expensive pressure transducers and can only operate in relatively long ventilation ducts with clean air. Indirect methods (eg. tracer gas method, CO<sub>2</sub> -balance method) for measuring ventilation rate give only an indication of the ventilation rate over an extended period of time (e.g. several hours). Besides the problem of accuracy, the relatively high cost of a reliable gas monitors makes the tracer gas method not suitable as a continuous feed-back sensor in a ventilation rate controller.

**Keywords** – Natural Ventilation, Mechanical Ventilation, Tunnel Ventilation, Impeller Method, Hot Wire, Van, Ultrasonic, Anemometers, Pitot Tube, Tracer Gas.

## I. INTRODUCTION

### 1. Air Ventilation

Ventilation can be defined as the intentional introduction of air from the outside into the building [1]. Moreover, ventilation system can be used to positively control the environmental parameters within a building.

#### 1.1. Contribution of Ventilation System to Control Micro-Environment

The ventilation system consists of all elements that contribute to the air exchange level and the distribution of fresh air within the building. In most applications in agriculture, the ventilation system consists of an air inlet and distribution system, an air outlet system and some control equipment.

Ventilation plays a main role in sustaining the welfare and performance of farmed livestock, by affecting thermal exchanges between the animal's body surface and the environment and by removing aerial pollutants, which

originate from animals and their excreta. Indeed, poor ventilation can lead to increased airborne particulate and gaseous pollutant concentrations, which can present a significant burden to the respiratory tract of humans and livestock [2]. Previous studies have shown that poor ventilation is responsible for increased aerial concentrations of viable microbes, NH<sub>3</sub> and CO<sub>2</sub>, reduced feed efficiency, and enhanced aggressive interactions in cattle, in pigs, and in broiler chickens [3]. In addition, it is known that inefficient ventilation systems result in animals avoiding more contaminated areas of livestock buildings [4]. This may lead to an uneven use of space with very low and highly densely stocked areas in animal houses.

According to Bruce [5], the role of the ventilation system is to control the gas concentration, the relative air humidity and the temperature within acceptable levels to the animal. The major purpose of a ventilation system is to provide an aerial environment in which animal health is maintained and productivity is satisfactory. The need for ventilation is governed by two requirements. The maximum ventilation rate is necessary to prevent hyperthermia, while the minimum ventilation rate is set to provide an acceptable thermal and aerial environment for animal performance [6].

The purpose of ventilation is to supply fresh air to, and meet the heating/cooling and air quality requirements of, occupants within an indoor environment. It fulfils this purpose by bringing fresh air into the airspace to replace and dilute the heat, moisture, and gaseous and particulate contaminants that eventually build up indoors. The effectiveness of this dilution process depends on the ventilation system design and air distribution within the airspace. Ventilation effectiveness has been increasingly used in studies of ventilation and air quality control. Contaminant concentrations, especially particulate contaminants, vary widely within a ventilated airspace [7],[8]. Because the contaminant spatial distribution is not uniform, it is possible to improve the contaminant removal efficiency by properly designing the ventilation and air distribution systems. One of the commonly used assumptions in livestock building ventilation design has been that the location of air outlets or exhaust fans has little effect on the air distribution and contaminant removal. Klooster et al. [9] compared two different ventilation systems with different air inlet and outlet locations and showed a 40% difference in dust removal. Wang [10] showed that the mean dust removal rate for the room airspace was improved by 196% only by properly positioning the air outlet. Ventilation control systems are a critical element of modern animal production systems, yet they are often misunderstood and mismanaged. For example, mismanagement can result in excessive energy usage for heating due to improper heater or minimum

ventilation settings, an uncomfortable environment which reduces swine productivity, or animal heat stress [11]. The measurement of gas, dust and odor concentrations can be achieved, with adequate accuracy, by using a wide variety of techniques [12]. However, measuring the airflow rate in an animal house is one of the main challenges [13].

### 1.2. *Methods to Control Ventilation*

Two basic principles can be used to achieve the desired ventilation rate of any building. These are: natural or mechanical (forced) ventilation, or a combination of both.

#### 1.2.1 *Natural Ventilation*

Natural ventilation of buildings is the flow generated by temperature differences and by the wind. The governing feature of this flow is the exchange between an interior space and the external ambient. Although the wind may often appear to be the dominant driving mechanism, in many circumstances temperature variations play a controlling feature on the ventilation since the directional buoyancy force has a large influence on the flow patterns within the space and on the nature of the exchange with the outside [14].

The driving forces for natural ventilation are wind and buoyancy. Differences in wind pressure along the façade and differences between indoor and outdoor temperatures create a natural air exchange between indoor and outdoor air. The ventilation rate depends on the strength and direction of these forces and the resistance of the flow path. These physical processes are complex, and predicting ventilation rates is difficult. Hence, it is challenging to control natural ventilation in order to obtain the required indoor environment conditions [15].

#### 1.2.2 *Mechanical Ventilation*

In mechanical ventilation, a fan used to create a pressure difference over the building envelope, resulting in an air stream through the building. At constant voltage, the ventilation rate increases when fan static pressure decreases. The obtained ventilation rate is a function of both the applied voltage and the static pressure difference over the ventilation opening in which the fan is placed. Consequently, to modify the ventilation rate in a mechanical ventilation system different basic methods can be applied [16]:

- keeping fan voltage constant and recirculating a proportion of the building air,
- keeping fan voltage constant and changing the pressure difference by restricting these throughout of the fan
- varying the voltage applied to the fan altering the number of fans in operation.

### 1.3. *Principles of Modulating Ventilation Control*

A temperature controller is mostly used to control both the cooling and heating system (on/off control) and the voltage applied to a fan (proportional control) or the size of a ventilation opening in the case of natural ventilation. Modulating control means that the control force (voltage applied to the fan) is continually changing with time, mostly dependent on the difference between the desired and the measured indoor temperature, and consists in most cases only of proportional control. Instead of voltage control, frequency control is sometimes used to vary the fan speed because this makes the rotational speed of the

fan less dependent on the pressure difference, which is a major problem with voltage controlled fans. However, because of the higher investment costs of this type of power control and the use of more expensive fans, up till now voltage based controllers are used more for modulating fan control. A study by Van Cuyck et al. [17] showed that the extra cost for a frequency transformer compared with a trial controlled fan in a pig house compartment was about 100 Bft per pig place, and a yearly energy saving of 2.4 Bft/pig place. This results in a payback period of more than 40 years. Field research has shown that voltage control is used in more than 90% of all investigated mechanically ventilated buildings in Belgium [18] due to its relatively low cost and its wide control range.

### 1.4. *Ventilation Efficiency*

Ventilation efficiency is a criterion for energy and fan performance, not directly related to ventilation effectiveness and air quality control. It refers to the mass of air delivered per unit of power consumed by the ventilation system, in kg of air per watt of power (kg/W), at a given pressure. The more air delivered per watt, the more efficient the ventilation system. It is also referred to as the ventilation efficiency ratio (VER) or energy efficiency ratio (EER) [19]. The ventilation efficiency ratio is not a non-dimensional term and has a value greater than zero. Ventilation effectiveness is a criterion for contaminant removal in the air space of concern. Several qualitative methods, including air exchange efficiency, purging flow rate, and purging time, have been used to study the ventilation effectiveness [20]. Those qualitative methods can be further analyzed and represented by the mean age of air concept [21], which describes the relationship among the contaminant concentrations in the airspaces of concern and the ventilation rate. Liddament [22] proposed a relative ventilation effectiveness to evaluate the ventilation effectiveness for a location of concern or an overall room airspace.

### 1.5. *Ventilation for Animal's Houses*

The influence of the physical microenvironment (temperature, humidity, light intensity, air velocity, etc.) on animal physiological responses and related performance has been demonstrated [23]. Controlling the physical microenvironment in animal production houses is an important element in optimizing the production process. For instance, ventilation flow in livestock buildings is related with two important aspects of the animal production. Firstly, it determines indoor climate and air quality inside the house, and so it affects the comfort of the animals. Secondly, ventilation rate is also connected with environmental issues, as it has a great influence on gas emission rates from animal houses [24].

The response of the animal to its environment is the most important part [25]. However, this is neither routinely measured in production facilities nor taken into account for climate control purposes. In practice, automatic control actions are based on feedback of inside air temperature, generally measured at one or more positions within the total building and rarely on ventilation rate [26]. An improvement in controller efficiency could

be obtained by taking responses of the animals to their physical microenvironment into account in the climate control actions [23].

Using model-based control theory, two conditions must be fulfilled [27]:

(1) The process responses must be measured continuously and this information fed back to the controller.

(2) A mathematical model of the system is required to predict the dynamic process response to the controller.

The success of this approach is demonstrated in many applications (mechanical systems, transport systems). However, for most animal systems, these conditions of model based control theory have not been developed. One of the main problems is the lack of accurate dynamic models, which describe the static and dynamic response of animals to their process environment in a form compact enough to be implemented in a digital process controller. In practice, most of the time static responses are described which are often outdated [27].

### 1.6. Ventilation for Agricultural Production

The best way to meet the needs of commercial agricultural production is an optimal management of the greenhouse climate. It should include the effective use of solar energy, air and soil heating, ventilation and cooling, humidity control, CO<sub>2</sub> enrichment, nutrient supply and so on. An essential process is the air exchange between the inside and outside of the greenhouse [28].

Greenhouse ventilation is a necessary process to remove solar radiation heat, to control the level of relative humidity, and to replenish carbon dioxide that plants consume during the daylight hours in the process of photosynthesis [29].

### 1.7. Ventilation Parameters

#### 1.7.1 Air Distribution

Good air distribution implies that fresh air is consistently delivered to all animals, or more succinctly, to all interior regions of a barn. This parameter is more qualitative than is air exchange, which is readily definable using a single number. A common way of assessing air distribution is to compare air properties (speed, temperature, RH, etc.) at various interior locations. Uniform flow of air through a building is usually considered ideal. Over the years, on farm improvements have eliminated dead spots by removing exterior and interior obstructions to airflow. For all buildings, building dimensions, shape and layout are major factors of air distribution, as are interior animal density and room construction. Additionally, interior layout (stalls, roof slope and design, 2 ceiling) and cow density affect how air moves within a facility, with the resulting channeling effect increasing with airflow length [30].

#### 1.7.2 Air velocity

Basic heat-transfer theory specifies that the rate of convective heat transfer from an object within an air stream to the air is a function of the velocity of the air flowing past the object. For a fairly wide range of airspeeds (Reynolds number) and situations, the rate of heat transfer is roughly proportional to the square root of the velocity [31]. That is, the rate of heat transfer doubles

for a four-fold increase in air velocity past the object [32] confirmed that this relationship holds for dry and wet hair coats of dairy cattle. One of the purposes of airflow pattern control is to provide a suitable air velocity in the occupied region of ventilated livestock buildings [33]. The air velocities near the floor are the result of interaction between the supply air jet and the geometry of the confined space. To predict floor velocity, its dependency on inlet jet momentum and room geometry has to be established. Ogilvie et al. [34] studied the relationship between floor air velocities, jet momentum number and the ratio of airflow rate per floor area. Their analysis indicated that a good correlation exists between the air velocity at floor level, the energy of the supplied air jet, and the airflow rate per unit floor area.

Hoff [35] carried out a set of measurements to quantify the spatial variability in air velocity levels in the animal zone of an empty swine building. He found that for his specific building a correlation existed between the air velocity at floor level and the square of the inlet jet velocity. Nielsen [36] presented a method to predict the floor velocity on the basis of the velocity decay equation for a jet.

#### 1.7.3 Rate of Air Exchange

Air exchange is the basis for maintaining air quality inside a building. In its definition of a ventilation system, ASAE EP270.5 [37] specifically addresses the control of interior temperature, relative humidity (moisture level), and contaminant levels (ammonia, carbon dioxide, dust, etc.). Each of these air-quality parameters is addressed in the design of ventilation systems through consideration of air exchange. As an example of the effectiveness of plentiful summertime air exchange [38] documented that elevated rates of air exchange (in this case, achieved by full-wall natural ventilation) were able to keep air temperatures within a stocked freestall barn at or below ambient outdoor temperature during the heat of the day.

Air-exchange rates are usually specified on the basis of total animal weight or, if the animal size is specified, per head. Current recommendations [39] for hot weather call for at least 220 L/s (470 cfm) per mature Holstein (i.e. 1400-lb animal). In some cases, rates twice this amount are being considered the minimum acceptable for new facilities.

Some ventilation systems may be designed on the basis of achieving a specified number of 'air changes' per minute or per hour. In these cases, one air change (A.C.) is the volume of the ventilated air space inside a barn and is not directly dependent on the number or size of animals in the facility. Air-exchange rates upwards of 1 air change per minute (60-100 A.C. per hour) are commonly recommended for summer conditions.

#### 1.7.3.1 Factors Affecting the Rate of Air Exchange

##### 1.7.3.1.1 Air Inlets and Outlets

The function of openings in a building; particularly in naturally ventilated buildings, is not always known. Therefore, criteria are needed to identify the instantaneous function of any opening at the time of measurement; i.e. either it is an air inlet or an air outlet.

Three measurements are available to distinguish

between inlets and outlets:

- Pressure difference over the opening.
- Temperature gradient over the opening.
- Concentration gradient of the tracer over the opening.

The pressure different measurement is the most direct and depends only on winds for the driving force of ventilation. However, it can therefore not be used in mechanically ventilated buildings. Use of the temperature gradient over the opening as a criterion for the determination of its function is suitable as long as the sensors are not affected by radiative heat from the sun or building, either of which could cause the opening to be wrongly identified as an air outlet. Use of the tracer gas concentration gradient has the disadvantage that if air which has previously left from another opening re-enters the building, e.g. because of eddies, then an opening" may be wrongly identified as an air outlet [40].

The size of an air inlet opening must be sufficient enough to allow adequate air volumes to enter the barn without having to overcome excessive resistance to flow from friction and turbulence. Higher resistance creates increased static pressure within a barn and decreases effective fan capacities. Inlets are best sized to provide a minimum of 930 cm<sup>2</sup> (1 sq. ft.) of area for every 0.19 m<sup>3</sup>/sec (400 cfm) of fan capacity. With less than 930 cm<sup>2</sup> (1 sq. ft.) of inlet area per 0.33 m<sup>3</sup>/sec (700 cfm) of fan capacity, increased static pressure reduces fan performance and provides less-than-adequate air exchange [41].

#### 1.7.3.1.2 Factors Affected by Rate of Air Exchange

Based on literature, it was illustrated that the ventilation rate is one of the most important variables in climate control in agricultural buildings. It was found that, in one way or another, the ventilation rate does effect:

- The indoor climate and the micro-environmental conditions around the animals, as a result of energy and mass transfer throughout the building [42],
- The spatial distribution of these internal environmental conditions in a non- perfectly mixed fluid, as a result of the obtained air flow pattern [43],
- The resulting response of the living organism and the impact on animal welfare, the health and behavior and the technical production results such as growth rate, feed conversion ratio, etc. [44],
- The energy costs for heating and ventilation [45],
- The emission of pollutants form livestock buildings, such as ammonia, carbon dioxide, methane, etc. [46].

The advantages of an adequate control of the ventilation rate through livestock buildings have been proven many times in literature. Field analysis show however, that a lack of control of the ventilation rate is one of the major causes of ventilation related health problems. Consequently, a lack of improvement in the production results and animal welfare was found in houses with automatic ventilation control, compared to low cost, manually operated naturally ventilated ones. Neither naturally ventilated, nor mechanically ventilated systems have succeeded in controlling ventilation rate properly.

These findings suggest that one precondition for improving animal production results, their welfare, the

reduction of the energy costs for heating and ventilation, and the reduction of environmental pollution, is to improve and simplify the control of the ventilation rate in livestock buildings [26].

## II. VENTILATION SYSTEM PERFORMANCE

Several methods are being used in an attempt to control the ventilation rate in agricultural buildings but most of these have proved inadequate, resulting in poor indoor climatic conditions [47], [48]. Data from literature and field research have demonstrated that the possible benefits of highly sophisticated control algorithms, improved ventilation and heating systems, improved building envelope or high-tech equipment will only be realized if the ventilation rate can be controlled in a more efficient way. Berckmans et al. [49] concluded in their research that the three dimensional energy and mass transfer in a non-perfectly mixed ventilated space, which is responsible for the resulting micro-environmental conditions in the animal occupied zone, can be modeled and controlled on the condition that the ventilation rate through the building can be controlled properly.

### 2.1. Natural Ventilation

In an evaluation of several naturally ventilated freestall barns, Stowell and Bickert [50] found that, those exposing large amounts of open wall area to cows (on a per-cow basis) provided a more suitable environment with less interior variation. Barrington et al. [51] assessed the rate of air exchange of naturally ventilated barns as a function of orientation.

Zappavigna and Liberati [52] demonstrated that ventilation is by far the dominant factor for environmental control, representing the effects of wind action for naturally ventilated buildings.

### 2.2. Supplemental Cooling Fans

In a controlled setting, initiation of fan cooling resulted in a rapid reduction in previously elevated core body temperature in lactating dairy cattle under moderate continuous heat stress [53], falling more than 0.5 oC within four hours.

Lin et al. [54] attributed a milk production response in dairy cattle to use of upgraded fans that increased airflow past the cows.

A study by Bottcher et al. [55] determined that vertically directed (downward) airflow from axial-flow fans was alleviated heat stress in broilers. Feed conversion efficiency was better and mortality lower in a barn with vertically directed airflow compared to one with airflow directed horizontally. Bottcher et al. [56] determined that, over a range of tilt angles and fan heights, propeller fans produced area-averaged velocities that were mostly below 1.2 m/s (240 ft/min).

Meanwhile, maximum velocities exceeded 3.8 m/s (750 ft/min), which may be problematic in some settings.

Meyer et al. [57] determined that a row of 0.9 m (36-inch) axial-flow fans directing air over the freestalls outperformed a poly tube air-delivery system or ceiling fans for maintaining milk production, maintaining low respiration rates, improving body condition. The axial-

flow fans also were the most cost effective and required the least amount of water for supplemental cooling.

This wall effect would likely impact local air velocities in barns with adjacent fans and interior obstructions (e.g. cows and free stalls). High-volume, low-speed (HVLS) fans are a recent innovation on dairy operations for producing air movement at cow level. A typical system rotates long blades (resulting diameter is 2.5-6.5 m or 8-24 ft) about a vertical axis at a relatively slow speed (~50-60 rpm). Aynsley [58] reports on airflow and energy-efficiency characteristics of HVLS fans. Aynsley and Thain [59] reported that airflow from HVLS fans should have additional benefits because gusts velocities occur within a desirable range of 0.3-0.5 Hz. Based upon field tests, about 75% of air velocities (5-second averages) at 0.1 m above the floor are greater than 2 m/s, compared to only about 25% at 1.1 m off the floor. Since radial velocity decreases with height above the floor, due to energy losses to turbulence, cattle may not benefit as much as other animals such as floor-raised poultry.

### 2.3. Tunnel Ventilation

In a comparison of naturally ventilated freestall barns with supplemental cooling fans and tunnel ventilated barns, Stowell et al. [60] reported that interior airspeeds at cow level were similar within barns with the two ventilation systems based on several summertime sampling events. The spatial variation in airspeed was similarly high in both systems, meaning that the airspeed at cow level is greatly affected in both systems by where and when measurements are taken. The direction of airflow and average interior airspeed were both more consistent in the tunnel-ventilated barns, which may help explain why these barns maintained a slightly smaller average temperature differential (0.32 C vs. 0.74 C) between indoor and outdoor air when THI 70F.

In the same study, Stowell et al. [61] reported that no consistent differences existed between activity levels of cows within naturally ventilated and tunnel-ventilated barns.

## III. METHODS FOR MEASURING VENTILATION RATE

Measuring the airflow rate in an animal house is one of the main challenges when estimating these emissions. Airflow rates can be determined using several methods. According to Phillips et al. [62] they can be classified in two main groups regarding to their nature: indirect and direct measurement methods [13]. Samer et al. [63] also stated that measuring the ventilation rates and then quantifying the gaseous emissions from naturally ventilated barns is a particularly difficult task and associated with large uncertainties; where no accurate, reliable, and online method is available for ventilation rate measurements.

Several techniques are described in literature to measure the ventilation rate through a ventilated space. Table 1 presented by [26] summarizes the techniques that have been reported for livestock buildings.

Since there is a lower air speed level in the outlet section

of naturally, compared to mechanically ventilated buildings, techniques that do require minimal air speed (e.g. vane anemometers) or a certain pressure to overcome (e.g. orifice plates) cannot be used for natural ventilation.

Table 1. Overview of ventilation rate measurement techniques used in livestock buildings [26].

Measuring principle	Ventilation system	Accuracy	Reference
Tracer gasses	Mechanical / natural	10 – 30%	[64], [65], [66]
Hot wire anemometer	Mechanical / natural	25%	[67], [68], [69]
Orifice plates. Nozzles	Mechanical	1-5%	[70]
Vane anemometers	Mechanical		[71]
CO <sub>2</sub> - balance	Natural / mechanical	20 – 40%	[72], [73]
Heat balance	Mechanical / natural	20 – 40%	[74]
Free running impeller (commercial)	Mechanical	30% 60%	[75], [76] [26]

### 3.1. Direct Methods

Direct measurement methods are based on determining the airflow rates through all openings in a building. This second group of techniques is generally more accurate, but they can be used only in mechanically-ventilated houses and when all openings of the farm can be assessed [13].

Measuring ventilation in mechanically-ventilated buildings may be a challenging task due to the technical difficulties associated (e.g. calibrating the fans may disturb their normal operation procedure). In addition, this task is time-consuming [77].

#### 3.1.1. Impeller Method

A method for continuously measure fan airflow rates in livestock buildings (fig. 1) was demonstrated by [78]. The method involved measurement of the rotational speed of a freely rotating impeller, which was mounted in a round duct.

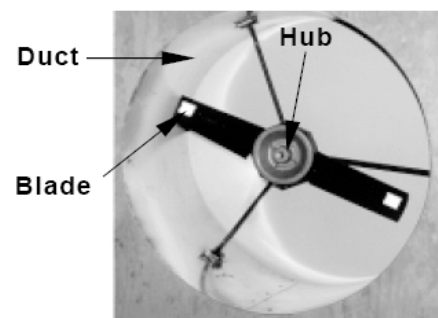


Fig. 1. Measuring the Flow Rate by Impeller Method as Presented by [78].

The principle of a free running impeller was first introduced in 1983 [79]. The sensor was used in a ventilation chimney in combination with an axial fan covering the whole duct section. The first ventilation rate sensor was constructed as an impeller mounted on a free rotating axis (radial turbine principle). The sensor is placed in a circular duct or ventilation opening and directly measures the air stream through it. The sensor blade starts to rotate along a central axis as a result of the flow stream over the blade.

The first sensor used the impeller of an axial fan and was placed in the outlet section in an upstream position of the fan. In this design, it was found that the rotational speed of the sensor was not only a function of the ventilation rate, but also of the static pressure difference over the building. The impeller receives energy from the air movement and transfers this into rotational energy. This ventilation rate sensor is used in a chimney with a diameter of 0.5m and a length of 1m and permits measuring the ventilation rate with an accuracy of  $\pm 60$  m<sup>3</sup>/h in a range from 200 to 5000 m<sup>3</sup>/h for pressure differences from 0 to 120 Pa. The relationship between the rotational speed and the flow rate was highly linear [80].

### 3.1.2. Hot Wire Anemometers

Hot-Wire Anemometry (HWA) has been used for many years as a research tool in turbulent air/gas studies. It is still applied in many application areas owing to improvements of electronic technology [81]. This method measures air velocity by placing a small heated wire in the air stream. The wire loses heat by convection, conduction and radiation, and its electrical resistance changes. This variation is measured by using a Wheatstone bridge. A second principle is to try to keep the wire temperature constant by controlling the electrical supply to the wire. The power is measured and is proportional to the air velocity over the sensor. Although the relationship between the air speed and the heat loss of the wire is a very complex process, a good calibration allows very fast and accurate point measurements of the air velocity (fig. 2). However, a correction for the changes in environmental temperature is necessary and makes the system quite expensive.

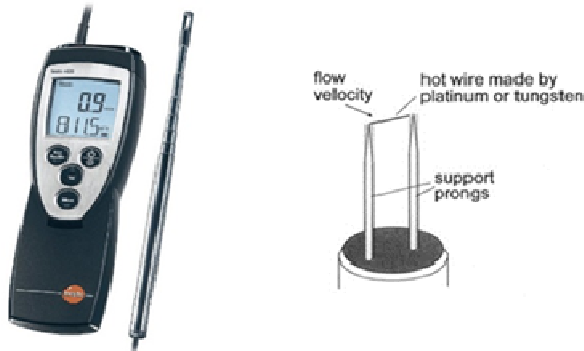


Fig. 2. Testo @ 425 Hot-Wire Anemometer Kit, Schematic diagram of conventional hot-wire anemometer [96]

Furthermore, hot wire anemometers are very fragile and cannot be used for a long time in polluted air. Another disadvantage of hot wire anemometers is the fact that they only measure in a single point. Since in most ventilation ducts, certainly in the neighborhood of a fan, the air velocity profile is not uniform in space and time an array of many sensors will be required to perform accurate measurements of the overall ventilation rate. For a single measurement at a constant ventilation rate one sensor can be positioned at different places in the duct section (ISO 7145) [82], but for continuous measurements such a measuring technique would be too complex and expensive.

### 3.1.3. Vane Anemometers

In most applications, this technique uses small windmill-like turbines with diameters varying between 10 mm and 150 mm to measure the airspeed within the range of 0.5 to 10 m/s. The diameter of these systems is much smaller than the diameter of the ventilation chimney. The system is calibrated in such a way that the rotational speed of the impeller is a measure of the airspeed (fig. 3).



Fig. 3. Testo @ 417 Vane Anemometer.

The available design only allows accurate measurements where there is no static pressure difference over the sensor and on condition that the sensor is placed perpendicular to the air stream direction. In most ventilation chimneys these conditions are not valid because of static pressure differences over the measuring section and changing air velocities and directions within the chimney. Although this type of sensor is commonly used by installers of ventilation equipment and by extension services, their accuracy cannot be guaranteed [26].

### 3.1.4. Ultrasonic Anemometer

The speed of sound propagation in calm-air is superposed by the velocity components of an air-flow in wind direction. A wind velocity component in the direction of the propagation of the sound supports the speed of propagation, thus leading to an increase of speed (fig. 4). A wind velocity component opposite to the direction of propagation, on the contrary, leads to a reduction of the speed of propagation. The speed of propagation resulting from the super position leads to different propagation times of the sound at different wind velocities and directions over a fixed measurement path [83].

After the rectangular velocity components have been measured over the measurement path, they are then transformed by the microprocessor of the anemometer into rectangular coordinates and output as sum and angle of wind velocity [83]. Tammelin [84] stated that ultrasonic anemometers have already proven to perform well even under severe icing conditions.



Fig. 4. Gill® Ultrasonic Anemometers (Precision Wind Speed & Direction, 2, 3-axis ultrasonic anemometers)

### 3.1.5. Pitot Tube

The accurate measurement of both air velocity and volumetric airflow can be accomplished using a Pitot tube (fig. 5), a differential pressure transducer, and a computer system which includes the necessary hardware and software to convert the raw transducer signals into the proper engineering units [85].



Fig. 5. Topac.com ® Pitot Tube Anemometer

### 3.2. Indirect Methods

The principle of the method is to monitor the inlet and outlet concentrations of a tracer gas with a known release rate. The airflow can then be calculated by applying a mass balance. The ideal characteristics of a tracer include low and stable background level, no hazard, acceptability, ease of measurement, stability and low cost [61].

According to Phillips et al. [61] indirect measurement methods consist of using a tracer, which allows determining the ventilation flux both in mechanically and naturally ventilated houses. The indirect method for

measuring the ventilation rate consist of using a tracer, which allows determining the ventilation flux both in mechanically and naturally ventilated houses [13]. Indirect methods arise then as a useful alternative, which allow us to determine airflow rates in most situations. The principle of the method is to monitor the inlet and outlet concentrations of a tracer gas with a known release rate [13]. The airflow can then be calculated by applying a mass balance. The ideal characteristics of a tracer include low and stable background level, no hazard, acceptability, ease of measurement, stability and low cost [62].

#### 3.2.1. Tracer Gas Method

One of the most important techniques for measuring ventilation and leakage rates is the tracer gas technique, which has been used by [86], [87], [88], [89], [90]. The technique is based on a mass balance of a tracer gas in the air. There are two main methods of measuring ventilation and leakage rates with a tracer gas, the continuous injection or static method and the pulse injection or dynamic method. In both methods, selection of the tracer gas is very important. It should have the characteristics of being easy to measure at low concentrations, inert, non-toxic, non-flammable, not a natural component of air and with a molecular weight close to the average weight of the air components. Many gases have been used as a tracer gas, such as sulfur hexafluoride ( $SF_6$ ), methane ( $CH_4$ ), carbon dioxide ( $CO_2$ ), hydrogen ( $H_2$ ), nitrous oxide ( $N_2O$ ), argon 41 and krypton 85.

A very important aspect of the tracer gas technique is the possibility to test occupied buildings. This is not only more convenient but also much more accurate since it takes into consideration the large effect of occupancy on the ventilation rate, and for instance the effect of opened and closed doors and windows. This can represent the normal working conditions that are important in most cases. In fact, there are four known tracer gas injection methods [63] which are:

- (1) Constant tracer gas injection,
- (2) Variable tracer gas injection,
- (3) Fan duct constant flow,
- (4) Concentration decay.

#### 3.2.1.1. Static method {Rate of Accumulation method (ROA)}

In this method, the injection rate of gas into a space is held at a constant value until an equilibrium concentration is reached. The gas supply and sampling system must be distributed around the ventilated area (e.g. greenhouse) in order to obtain good dispersion of the gas and uniform sampling of the air. The advantage of this method is that it provides continuous information, and a range of wind speed and directions can be covered during one measurement. The disadvantage is the high consumption of tracer gas [91].

#### 3.2.1.2. Dynamic Method {Rate of Decay Method (ROD)}

In this case, the tracer gas is injected and distributed uniformly in the ventilated space until a certain pre-determined concentration is reached and then stopped. The decay in the concentration of the tracer gas is then measured. When the concentration has decreased to 80–

90% of the initial value, another pulse of gas is injected, and another decay is measured [92].

The advantages of the decay method over the static method are that it uses less tracer gas and can be used to measure over a wide range of ventilation rates while the continuous injection method requires an appropriate flowmeter to measure the injection rate. The disadvantages are the difficulty in obtaining a uniform concentration of the tracer gas throughout the ventilated space and for high ventilation rates, the concentration of the gas decreases rapidly and the data obtained for analysis can be insufficient.

### 3.2.2. $CO_2$ – Balance Method

The  $CO_2$ -balance method is comparable to the tracer gas method as it also requires the assumption of perfect mixing within the building. The only difference is that a natural gas (produced by the animals) is used instead of an inert gas that is injected into the ventilated space. Besides the limitations of the technique, the accuracy of this indirect method is highly dependent on the accuracy of the estimation of the  $CO_2$ -production rate. The accuracy of this method has become a subject of intense discussion [93].

The accuracy of carbon dioxide balance methods when determining ventilation rates has been demonstrated for most farm species, such as poultry [94], [95].

### 3.2.3. Heat Balance Method

The estimation of ventilation flow by indirect methods based on balance equations avoids drawbacks by calculating the ventilation flow from some specific parameters of the indoor and the outdoor air, whose measurement is not so complicated and time-consuming as the direct measure of ventilation rate [24].

## IV. CONCLUSIONS

A ventilation is used for active control of the physical micro-environment within a livestock and agricultural building. A literature review covering information about ventilation system in livestock and agricultural building is presented where this review covers:

- Information about air ventilation systems including contribution of the ventilation system to control micro-environment, methods for ventilation rate control, principles of modulating ventilation control, ventilation efficiency, ventilation systems for animal's houses, ventilation systems for greenhouses; and ventilation system performance.
- Methods for measuring ventilation rate including.
  - o Methods based on velocity point measurements (pitot tubes, hot wire anemometers, vane anemometers) where these methods require a large number of sensors. For this reason, they are too expensive to be used in a commercial control system.
  - o Since there is a lower air speed level in the outlet section of naturally, compared to mechanically ventilated buildings, techniques that do require minimal air speed (e.g. vane anemometers) or a certain pressure to overcome (e.g. orifice plates)

cannot be used for natural ventilation.

- o Indirect methods for measuring ventilation rate give only an indication of the ventilation rate over an extended period of time (e.g. several hours).
- o Besides the problem of accuracy, the relatively high cost of a reliable gas monitors makes the tracer gas method not suitable as a continuous feed-back sensor in a ventilation rate controller.

## V. ACKNOWLEDGMENT

Author would like to thank either publishers, owners and authors of the articles used in this review, without their efforts this review cannot be done.

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