REVIEW ON VENTILATION RATE MEASURING AND MODELLING TECHNIQUES IN NATURALLY VENTILATED BUILDINGS

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ABSTRACT

Direct and indirect measuring techniques are available for determination of ventilation rate in naturally ventilated buildings. Direct measuring methods include measuring fan, propeller gauge, hot wire anemometer, particle image velocimetry, laser Doppler anemometer, and transit time sonic anemometer. Basic disadvantage of direct measuring techniques is that they are generally used for point or local measurements of air velocity. In order to have the total ventilation rate through the whole building, a "system" is required to measure simultaneously the airflow both in magnitude and direction at a number of locations.

Indirect measuring techniques are; heat balance, CO_2 balance, pressure difference, CFD analysis, tracer gas measurements, multizone modelling, and zonal models. These methods consider the whole system, and therefore, provide a possible tool for determining air flux through the building envelopes. Methods based on computer simulations (CFD, multizone models, etc.) should be validated against experimental data. However, in most of the cases, those validations are lacking, or do not indicate the accuracy of the method. Tracer gas measurements are mostly used as reference method in validations. However, accuracy of this technique should also be studied. Most indirect measuring techniques suffer from the problem of imperfect mixing of air within the ventilated structure. Therefore, the accuracy of tracer gas measurements should be improved by using information of imperfect mixing within the building.

KEYWORDS

Ventilation rate, natural ventilation, measuring techniques, accuracy

INTRODUCTION

Due to limited energy sources, countries are looking for alternative solutions to decrease energy needs. In that context, natural ventilation can be seen as a very attractive sustainable technique in building design (Simonson, 2005). However, understanding of ventilation dynamics is needed to provide an efficient control.

Ventilation rate has to be determined not only in terms of energy, but also for controlling indoor air quality and emissions. For these reasons, agricultural buildings (livestock houses, greenhouses, etc.), naturally ventilated industrial buildings, and residences require a reliable ventilation rate measuring technique.

Objective of this study was to review available techniques for ventilation rate measurement while putting emphasise on their accuracies. Additionally, operational principals and advantages/disadvantages of available methods were discussed. At the end, a summary table can be found with related reference list.

DIRECT MEASURING TECHNIQUES

Direct measuring techniques are mostly practical and accurate tools for air speed measurements. Although some techniques can be used to measure air flux through the buildings in and outlet sections such as free running impeller, most of them can only measure air speed at certain point in the air stream. Those measurements can be converted into ventilation rate by multiplying with the cross section area where the flow is passing through. However, since the flow through an opening is not uniform especially in naturally ventilated buildings, measuring a point at the opening does not give the total ventilation. Therefore, the accuracy on air speed does not indicate the accuracy on ventilation rate.

One common solution to point measuring problem is to use multiple sensors at the opening. However, this application is costly and affects the behavior of flow due to physical impedance.

Free Running Impeller

These types of sensors can also be called as measuring fan, free impelling turbine or propeller fans. The sensor is placed in a circular duct or ventilation opening and directly measures the air stream through it (Berckmans, 1986; Vranken, 1999; Berckmans et al., 2001). They are the most common means of measuring ventilation rate in mechanically ventilated stables. Operational ventilation rate of these sensors is high, that is, from 60 m^3/h to 14,000 m^3/h. The inaccuracy of fans depends on design. Nowadays, they can measure down to 5% inaccuracy.

These fans cannot be used in all kinds of naturally ventilated buildings, since they need defined inlet/outlet and circular cross-section.

Propeller Gauge

With this method, air speed is measured using a small propeller. Depending on the quality, accurate measurements of air velocity are possible (2 %) within a range of 0.2 – 30 m/s (Kinsey *et al*., 2004; NovaLynx Corporation, 2005; Davis Instruments, 2005).

This method also measure local air speed, which may not be representative for overall ventilation rate. Additionally, if the instrument is not properly calibrated, the inaccuracy can reach up to 25 %.

Hot Wire Anemometer

Basic principle of the hot wire anemometers is based on heat loss of a thin heated wire or amount of heat needed to keep the wire at constant temperature along the air stream. They can measure steady-state to transient temperature differences and air speed of 0.05 to 20 m/s (Perry, 1982; Scholtens and van ‘t Ooster, 1994).

Although these devices can measure very accurately (0.5 %), if calibration and calculations are not done accurately the inaccuracy can go up to 25%. One apparent disadvantage of these devices is that they are very susceptible to dust and thus corrosion. Moreover, as mentioned before, since they measure gas velocity at a certain point, a representative measuring point should be determined. Due to lack of physical robustness, these instruments are very fragile. Finally, the cost of installation is considerably high.

Laser Doppler Anemometer

Laser Doppler Anemometry, or LDA, is a technique for measuring the flow velocity of fluids or gases. Acoustic pulses sent and received by transducers at a fixed frequency collide with particles in water, allowing for a determination of velocity. It is a non-intrusive technique with a high frequency response and large dynamic range capabilities. The method’s other particular advantages are: high spatial and temporal resolution, no need for calibration and the ability to measure in reversing flows (DeGraaff and Eaton, 2001). LDA is one of the most popular methods to validate CFD results (Posner *et al.,* 2003, Temperley *et al.,* 2004).

This method is also accurate at determining air velocities (< 2 %). But main shortcomings are; they can only log local speeds, expensive, and sufficient transparency is required between laser source and target. Besides, accuracy is highly dependent on alignment of emitted and reflected beams.

Particle Image Velocimetry

Particle image velocimetry is a technique which allows the fluid velocity to be measured simultaneously throughout a region illuminated by a two-dimensional light sheet. The PIV monitor the motion of particles, with velocities of particles being taken as representative of local element (Hu *et al.*, 2002).

PIV is accurate in velocity measurements (< 3 %). However, it can also be used for local measurements. Like LDA, this method is also used in CFD validations.

Transit Time Sonic Anemometer

A pair (or pairs) of transducers, each having its own transmitter and receiver, are placed on the pipe wall, one (set) on the upstream and the other (set) on the downstream. The time for acoustic waves to travel from the upstream transducer to the downstream transducer t_d is shorter than the time it requires for the same waves to travel from the downstream to the upstream t_u. From this time difference and reflection angle, average air flux through the path can be found.

Since there is no obstruction in the flow path, the equipment causes no pressure drop. It has low maintenance cost due to no moving parts. Multi-path models have higher accuracy for wider ranges of Reynolds number. Portable models are also available for field analysis and diagnosis.

This type of anemometers is already used in practice to measure ventilation rates through long openings. However, airflow variation in space and time is usually found under natural ventilation results certain inaccuracy. In order to have a general picture of air movement through the whole building, a “system” was required to measure simultaneously the airflow both in magnitude and direction at a number of locations. Additionally, the instrument has a higher initial set up cost and the uncertainties caused by the geometry of the system, that is, the difference between the internal diameter and roughness of the meter body and the measuring section, influence the final accuracy (Calogirou et al., 2001; Iooss et al., 2002).

Average accuracy of the instrument changes between 0.1 to 4 % in a velocity range of 0 to 60 m/s. In a current project, sonic anemometer technique has been improved using multiple measuring points (Van Buggenhout *et al*., 2005). This method was suggested as a practical technique to be used in naturally ventilated buildings taking contactless measurements.

INDIRECT MEASURING TECHNIQUES

Indirect measuring techniques are based on measuring certain parameters that related to ventilation rate, such as pressure, temperature, and concentration and modelling the relation between them. Indirect measuring techniques are the ones that used mostly to determine the ventilation rate in naturally ventilated buildings. These methods are subject to constant improvement.

Complexity of the models does not necessarily indicate a better accuracy (for example, CO_2 balance versus CFD). In addition, more complex systems can hardly be used for online control purposes. On the other hand, they may provide a useful tool for design purposes.

Pressure Difference

Techniques based on this method calculate pressure difference between indoor and outdoor and correlates it to air exchange (Bruce, 1978; Brockett and Albright, 1987; Boulard and Baille, 1995; Demmers, 1997; Richardson et al., 1997). Main advantage of pressure difference systems is being cheap and direct measuring technique. If it is coupled with tracer gas experiments, physical description of ventilation mechanism can be acquired, and ventilation rate per opening depending upon physical environment can be predicted.

Basic disadvantage of pressure difference methods in naturally ventilated buildings is inaccuracy due to low wind speed and low pressure difference. Additionally, accuracy depends on type, size, and number of the ventilation opening(s), the position of the openings and building size. These devices are also sensitive to corrosion. High fluctuation in and around the buildings (6.5 – 250 Pa) affects also the robustness of the method. An inaccuracy of 2 % is possible with pressure difference method, but due to above mentioned reasons, inaccuracy would be more.

CO_2 Balance

CO_2 balance is performed by continuous or intermittent measurement of CO_2. This method already used in naturally ventilated buildings in number of studies (Penman and Rashid, 1982; Van Ouwerkerk, 1993; Van't Klooster and Heitlager, 1994; Pedersen et al., 1998). Main handicaps of this method are originated from CO_2 produced from other sources (respiration, manure, etc.) and solubility of CO_2 in water. High numbers of living organisms are needed to obtain high concentration differences. Since at low concentration levels, small error in concentration measurement can result larger error in ventilation rate. This method also depends on organism type, activity level, etc. It is possible to measure ventilation rates between 18 – 1400 m^3/h with an inaccuracy of 15 to 40 %.

Heat Balance

Ventilation rate can be calculated from heat loss through building by means of simple temperature measurements (Kotani *et al*., 2003). However, this indirect method needs complex calculations afterwards (Yam *et al*., 2003, Fatnassi *et al*., 2004). It is difficult to determine exact heat gains and loses. At high k-values, measurement of radiation, wind speed and direction are also needed. Furthermore, this method is not suitable for fast and simple determination of ventilation rate (Van't Ooster, 1994). It can be used in mechanically ventilated buildings where sources are better known, although for those buildings easier methods are already available. This method can be used with ventilation rates of maximum 696 m^3/h with an inaccuracy of -31 to +101 %.

Tracer Gas

Tracer gas method is one of the most popular methods used in ventilation rate determinations in naturally ventilated buildings. The method is based on conservation of mass of a inert tracer gas injected to a building section. Three types of measurement techniques are available: i. rate of decay (Snell et al., 2003), ii. rate of accumulation (Zhang *et al*., 1995), iii. constant rate (Demmers *et al*., 2000).

In current calculations with tracer gas method, perfect mixing assumed in the volume. Therefore, injection and sampling points should be chosen carefully to represent the average air flow in the room. Measurements up to 235,000 m^3/h are possible with an inaccuracy range of 10 to 50% (Sandberg and Blomqvist, 1985).

CFD Analysis

CFD softwares use Navier-Stokes equations to simulate the whole system. The volume is divided into huge number of cells and interactions between the cells are calculated (Ayad, 1999). The main advantage of CFD models is that they can be applied to any type of the building. However, these models have many disadvantages. First of all, good assumptions are needed for system parameters (Demmers et al., 2000). Due to complexity of the software, expertness is needed and calculations are time consuming. Final results reflect a condition at certain time step; therefore, dynamic analyses are not possible. Although these models cannot be used at online control of ventilation rate, they can be effective tools for early building design purposes. Any range of ventilation rate can be simulated. Inaccuracy of CFD models are estimated around 30% (Campen and Bot, 2003).

Multizone Modelling

In classical multizone modelling, air speed or temperature is simulated using doors and windows as connectors. These models also use mass transfer between the zones as CFD models. However, since number of zones is much far less than former one, calculations can be done quickly (Feustel, 1999). This method can also be used at any range of ventilation rate.

Zonal Models

Zonal models are based on the same principal that multizone modelling utilises. The main difference in zonal modelling is that they aim to model large halls or empty zones by assuming fictitious zones in these spaces (Inard et al., 1996). Again, mass balances were constructed among imaginary zones, and those equations are solved successively to define the whole system. Zonal models uses less time and computer memory in their calculations compared to CFD.

CONCLUSIONS AND DISCUSSIONS

Available techniques used for ventilation rate measurement and simulation for naturally ventilated buildings were summarised. While both direct and indirect measuring techniques have particular advantages, they have also certain drawbacks that cannot be disregarded. Main disadvantage of direct measuring techniques is providing local measurements that cannot be representative for whole system. On the other hand, simulation techniques are laborious and not accurate enough.

Nowadays, none of the methods provides accurate and robust mechanism for natural ventilation measurements. Constant evaluation and improvement of current methods observed in the last decades. Alternatively, combination of measuring and modelling techniques can provide a reliable online control system in these buildings.

Table 1. Literature Survey on Measuring Techniques for Ventilation Rate and Air Velocities

METHOD	ADVANTAGE	DISADVANTAGE	INACC.	REFERENCE
Direct Measuring Techniques				
Free Running Impeller	- used in most of the mechanically ventilated stables	- need defined inlet/outlet - circular cross-section	5-25%	Berckmans et al., 1991; Vranken, 1999; Berckmans et al. 2001
Propeller Gauge	- Depending on the quality, accurate measurements are possible	- local measurements - accuracy depend on pressure difference, temperature, static pressure, and density measurements	2 – 25 %	NovaLynx Corporation, 2005; Davis Instruments, 2005; Kinsey et al., 2004
Hot wire anemometer	- can measure steady-state to transient temperature differences	- susceptibility to dust - need for a representative measuring point due to local measurement - lack of physical robustness	0.5 - 25 % *	Perry and Morrison, 1971; Scholtens and van ‘t Ooster, 1994; Watmuff, 1995; Dantec Dynamics, 2005
Laser Doppler Anemometer	- accurate - non-intrusive - no need for calibration - ability to measure reversing flows	- local measurements - accuracy is highly dependent on alignment of emitted and reflected beams - expensive - sufficient transparency is required between laser source and target	< 2 % *	Yeh and Cummins, 1964; George, 1988; De Graaff and Eaton, 2001 Dantec Dynamics, 2005
Particle Image Velocimetry	- accurate - non-intrusive	- local measurements	< 3 % *	Shandas et al., 1995; Hu et al., 2000, 2002; Meyer et al., 2002; Dantec Dynamics, 2005
Transit Time Sonic Anemometer	- accurate - no obstruction in the flow path - low maintenance cost - can be used in corrosive environments - portable models are available	- local measurements - high initial set up cost - susceptible to construction errors	0.1 - 4 % *	Quaranta et al., 1985; Wang et al., 1999; Windsonic, Gill Instruments; Airflow UA6, Davis Instrumets

* inaccuracies in terms of air velocities

METHOD	ADVANTAGE	DISADVANTAGE	INACC.	REFERENCE
Indirect Measuring Techniques				
Pressure Difference	- cheap and direct measuring technique for mechanical ventilation - if coupled with tracer gas experiments, physical description of ventilation mechanism, ventilation rate per opening depending upon physical environment can be predicted - local ventilation rates can be determined	- depends on type size, and number of the ventilation opening(s), the position of the openings and building size. - at low wind speed inaccuracy is bigger - sensitive to corrosion -mostly underestimation - high fluctuation in and around the buildings	20 - 35 %	Bruce, 1978; Brockett and Albright, 1987; Boulard and Baille, 1995; Demmers, et al., 1997; Richardson et al., 1997; Boulard et al., 1998
CO_2 balance	- used in naturally ventilated buildings	- CO_2 from other sources (respiration, manure, etc.) - solubility of CO_2 in water - small error in concentration can result larger error in ventilation rate	15 - 40 %	Penman and Rashid, 1982; Van't Klooster and Heitlager, 1994; Pedersen et al., 1998
Heat Balance	- only temperature measurements are enough - can be used in naturally ventilated buildings	- complex calculations and difficulty in determination of heat gains/loses - not suitable for fast and simple determination of ventilation rate - for high k-values, measurement of radiation, wind speed and direction is needed	31 - 101 %	Van't Ooster, 1994; Wang and Deltour, 1996; Kotani et al., 2003; Yam et al., 2003 ; Fatnassi et al., 2004
Tracer Gas	- can be used for total ventilation rate calculations - suitable for natural ventilation	- perfect mixing assumed	10 - 50%	Abu-Jarad et al., 1982 Sandberg and Blomqvist, 1985; Jung et al., 1994; Zhang et al., 1995;
CFD Analysis	- can be applied to any type of the building	- good assumptions are needed for system parameters -requires huge processing time	10 - 40%	Ayad, 1999; Demmers et al., 2000; Campen and Bot, 2003; Jiang et al., 2003
Multizone Modelling	- mostly used in building design calculations	- boundary conditions should be well defined	15 - 50%	Sherman, 1989; Feustel and Dieris, 1992; Dascalaki et al., 1995, 1999; Roulet et al., 1999; Posner et al., 2003
Zonal Models	-less zone is needed than CFD - less execution time	- need a good reference method for comparison -more experimental validation needed	20-50 %	Inard et al., 1996; Wurtz et al., 1999; Brehme and Krause, 2001; Ren and Stewart, 2003

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