OPPORTUNITIES TO UPGRADE: THE EFFECT OF A FAN FAULT IN AN AIR HANDLING UNIT FAN GRID

Daniel HOPKINS, Andrew BURGOYNE

ebm-papst UK Ltd, Chelmsford, Essex, CM2 5EZ, United Kingdom

SUMMARY

It has become commonplace to refresh air handling units in non-residential buildings with an array of high efficiency fans arranged in a grid pattern. These arrays provide an opportunity to lower power consumption, reduce carbon footprint of the building, and provide operational redundancy should one of the fans in the array fail. This paper examines the effect of a fan failure in conditions where airflow can recirculate back into the supply air path, and when recirculation is prevented using a gravity shutter.

BACKGROUND

With climate change upon us, reducing our carbon footprint is more important than ever. Across the non-residential building sector, owners and occupiers are looking at building services equipment within their estates, to exploit running cost savings, reduce carbon footprint and smarten up using Internet of Things (IoT) technology. One area being refreshed is Air Handling Units (AHU's) which provide fresh air, remove stale air, heat, cool and control humidity.

Many buildings operational today will still be operational for years to come and are installed with legacy air handling units using AC induction motor fans, commissioned to deliver the same performance every day. Recent efforts to deliver energy savings via demand control has seen installation of inverter drives to vary the performance of the fans via speed control. The cumulation of impeller aerodynamic efficiency, the efficiency of the belt and pulley transmission, motor efficiency and inverter drive efficiency provide an opportunity optimize air movement. In addition, a legacy AHU that employs one fan per supply or extract flow path that has a breakdown during service, has no back-up.

Existing AHU's due for refurbishment are increasingly being upgraded to use multiple Electronically Commutated (EC) plug fans arranged in a grid. Sharing the required airflow across multiple fans allows flexibility in selecting fan diameter, number of fans in the grid and provide n+1 redundancy. In addition, fitting inlet rings with a flow measurement pressure tapping can monitor, control, and adjust the fan grid behavior to deliver the required flowrate using a constant volume control system.

But what happens if one of the fans fail? In a single fan AHU, if there is no functioning fan there is no airflow, in a multiple fan system one failure does not stop the delivery of air.

INTRODUCTION

Inlet rings on backward curved centrifugal fans can be fitted with a pressure tapping installed in the mouth of an inlet ring. This uses Bernoulli's theory which explains that the total pressure in moving air is the sum of static and dynamic pressure.

i.e., Total Pressure (p_{tot}) = Fan Static Pressure (p_{fs}) + Fan Dynamic Pressure (p_{fd})

Slower moving air in the suction side plenum is accelerated as it passes through the inlet ring, increasing its dynamic pressure and reducing the static pressure. Dynamic pressure can be measured or calculated from the velocity of the air flow

Fan Dynamic Pressure (p_{fd}) = $\frac{1}{2} \rho v^2$

Where ρ is the density of the air in kg/m^3 and v is the air velocity in m/s.

The static pressure difference between the suction side plenum and the inlet ring pressure tapping can be measured and together with the K-factor of the inlet ring, the volume flow can be calculated as follows:

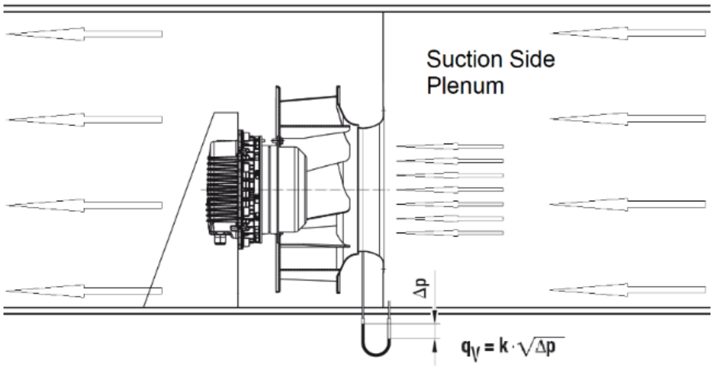

Fig. 1 – Inlet ring Volume flow measurement

Where qv = volume flow in m^3/h
K = inlet ring K-factor
Δp = static pressure difference (Pa)

Using this relationship, it is possible to control the fan to maintain a constant differential pressure between the two measurement points, in effect maintaining a constant volume of air through the fan. This type of airflow measurement system also forms the bases of one of the forms of volume flow measurement in BS EN ISO 5801:2017 "*Fans. Performance testing using standardized airways*".

This volume flow measurement system has been found to have a close correlation between calibrated test rig measurements and an installed real-world monitoring and control system. It compensates for changes in the resistance of air delivery system, (e.g., particulate filters becoming progressively blocked), because it determines only the difference between the upstream and inlet ring pressure tappings. Measuring the pressure differential as air passes through the fan to monitor and control the fan to maintain a constant volume flow rate by varying the speed of the fan.

Another feature the control system can provide is to calculate the effect of the loss of one of the fans in an array, and to accelerate the remaining fans to compensate for the loss of performance (N+1 redundancy).

Multiple fan arrays can monitor the pressure tapping of each fan to calculate the volume flow passing through each fan individually. Alternatively, the pressure tapping of each fan can be linked together in an averaging circuit to calculate the volume flow through the complete fan array in one calculation

OBJECTIVES

This paper explores several aspects of Fan Grid installation in Air Handling Units:

Assess the measurement accuracy of the volume flow measurement system of a 4-fan array in comparison to an airflow test rig designed to BS EN ISO 5801 in fault free conditions (all fans running).

Assess the difference between measuring the flowrate of each fan individually and when the fans are connected in a pressure measurement circuit.

Assess the behavior of the Air Handling unit and the accuracy of the airflow measurement system and the effect on the airflow through the air handling unit when one fan is non-operational under the following conditions:

- Accuracy of the inlet ring measurement and control system when air is allowed to recirculate through the non-operational fan
- Accuracy of the inlet ring measurement and control system when recirculation through the non-operational fan is prevented

METHOD

Test piece

The test sample is a control system demonstration tool used for research, product development and training. It consists of 4 x 250 mm diameter, single phase EC, single inlet backward curved RadiPac fans (K3G250-PR17-I2), mounted in a grid pattern on a diaphragm plate separating the suction and exhaust plenums.

Two of the fans were connected to the mains supply using remote control connection plugs that could be switched off to simulate fan failure. One of these fans when switched off had no means of recirculation prevention, however the other fan prevented recirculation in the fan fault tests by the use of a basic gravity shutter fitted on the intake of the fan.

Fig 2. – Test Piece mounting

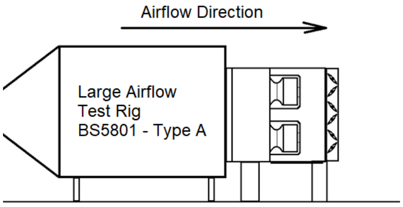

Fig. 3 – Airflow direction

Fig. 4 – Recirculation prevention

Each Inlet ring was installed with a pressure tapping for individual flow sensor monitoring and a second pressure tapping for connection into a pressure averaging circuit which was measured with a single central sensor.

<u>Individual Sensor Monitoring and Control</u>

Four 0–500Pa pressure transducers (SN1120-A500) with a 0-10 V analog signal output were used. The negative air connection of the sensor was applied to the inlet ring pressure tapping, and the positive air connection in an area in the suction side plenum where the air is still and not affected by

the velocity of the air passing through the fan array. The output voltage signal from the pressure transducer was connected to the control input of the fan which was interrogated using the on-board Modbus capability of the fan over an RS485 connection. The data from the control input of each fan was collected by an ebm-papst CN1116 Modbus display and control unit, configured to maintain a constant volume flow through the AHU.

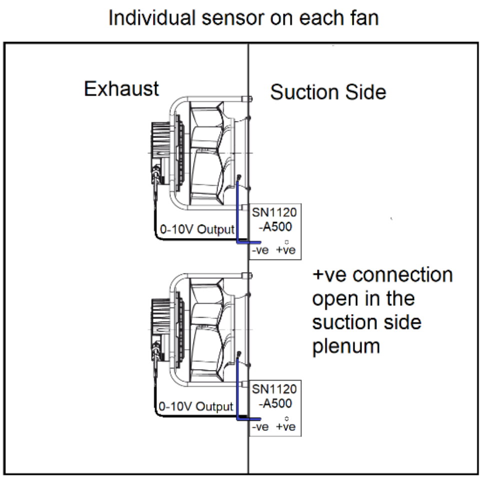

Fig. 5 – Individual fan measurement

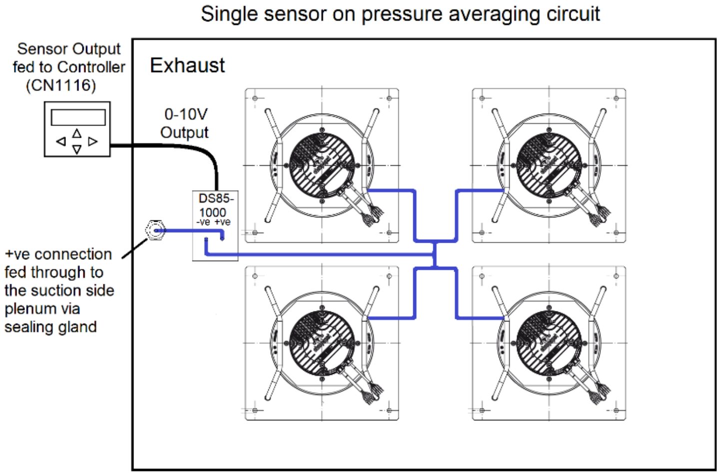

Fig. 6- Averaging pressure circuit measurement

Averaging Pressure Circuit Monitoring and Control

One 0–1000 Pa pressure transducer (DS85-1000) was installed in the exhaust plenum. The negative air connection of the transducer was applied to pressure tapping on all four fans which had been connected in a pressure averaging circuit. The positive air connection was fed through a sealing gland in the fan array diaphragm plate, in an area in the suction side plenum where the air is still and not affected by the velocity of the air passing through the fan array. The output voltage signal from the single sensor was connected to an ebm-papst CN1116 Modbus display and control unit set to maintain a constant volume flow through the AHU.

Airflow Measurement Test Rig

The test piece was mounted at the end of the ebm-papst UK airflow test rid which has been designed to BS 848 pt1:1997 / ISO 5801:1997 Type A test, for free inlet / free discharge. The volume flow rate range is between 50 and 7500 m³/h and measurement is achieved using an orifice plate with a D and ½ D pressure tapping circuit

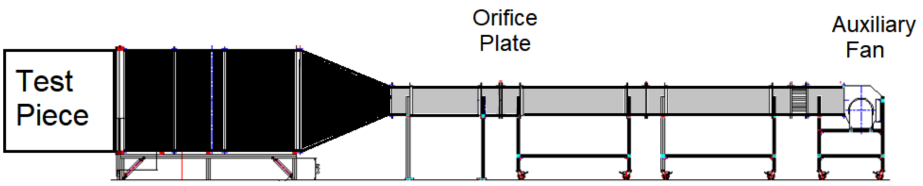

Fig 7 - ebm-papst Type A airflow test rig designed to BS EN ISO 5801

Measurement Schedule

For each test conducted, an airflow measurement was taken with the test unit in a fault free running condition as a benchmark to compare the accuracy of the test piece measurement system with the airflow test rig.

Once the benchmark measurement was performed, the test piece was tested with one fan powered off to simulate a fault. Two tests were conducted in the fault condition:

- Fan in fault with no recirculation prevention
- Fan in fault with recirculation prevention (Blanking plate / Back-draught gravity shutter)

For each measurement run, the CN1116 controller was configured to deliver the specified flow rate and the test was started by adjusting the auxiliary fan to produce a balanced 0 Pa in the test rig plenum chamber.

Measurements were taken as the speed of the auxiliary fan was increased to deliver a positive pressure into the test rig plenum chamber in steps. This was repeated until the auxiliary fan took over the work of delivering air through the test piece. The test rig and auxiliary fan was then rebalanced to return to an operating pressure of 0 Pa in the test rig plenum chamber. Measurements were taken as the speed of the auxiliary fan was decreased to create a negative pressure in steps. This was repeated until the auxiliary fan was turned off and the test piece was the only source of air movement.

The following test measurements were performed to compare the individual inlet ring pressure measurement method to the pressure averaging circuit method where all inlet ring pressure tappings are joined together:

Table 1 - Fan flowrate monitored on each individual fan and controlled over the RS485 Modbus network

Operating Condition	Set Point	Test Description
Fault Free	6,000 m^3/h	CN1116 configured for individual fan measurements with sensor output on fan control input interrogated via Modbus
Fan Fail	4,500 m^3/h	Three fans operating with one fan powered off and no recirculation prevention
Fan Fail	4,500 m^3/h	Three fans operating with one fan powered off, recirculation prevented using a back-draught gravity shutter

Table 2 - Fan flowrate monitored using an averaging pressure circuit and controlled over the RS485 Modbus network

Operating Condition	Set Point	Test Description
Fault Free	6,000 m^3/h	CN1116 configured for individual fan measurements with sensor output on fan control input interrogated via Modbus
Fan Fail	4,500 m^3/h	Three fans operating with one fan powered off, with no recirculation prevention
Fan Fail	4,500 m^3/h	Three fans operating with one fan powered off, recirculation prevented using a back-draught gravity shutter

RESULTS

Benchmark Testing – All Fans Operational

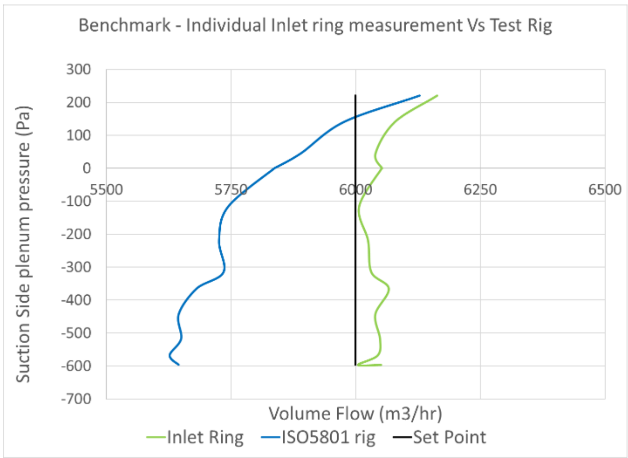

Fig 8 – Individual flow measurement vs. test rig

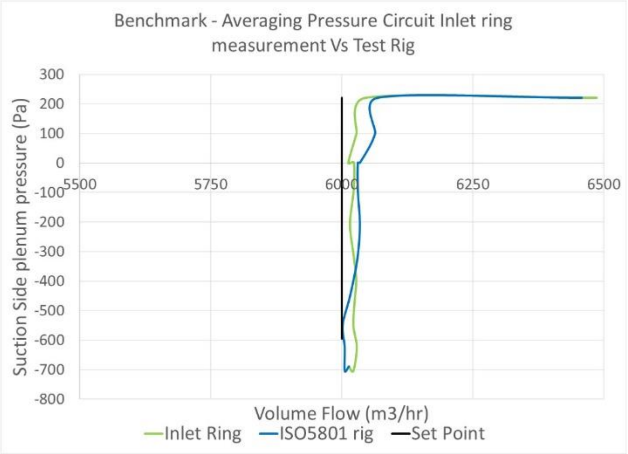

Fig 9 – Pressure circuit flow measurement vs. test rig

Fan Fault – 3 fans operational with faulty fan allowing recirculation

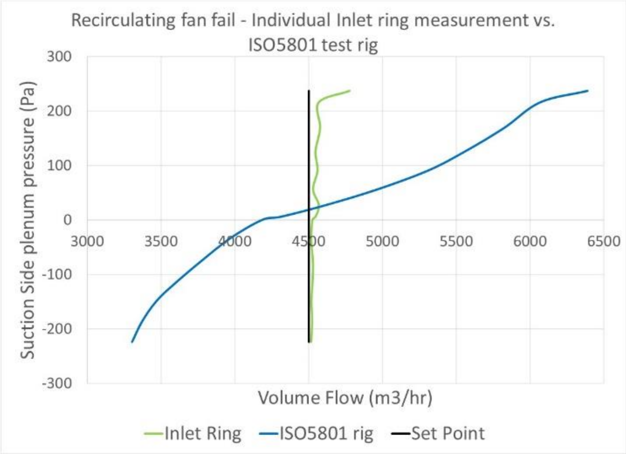

Fig 10 – Individual flow measurement vs test rig

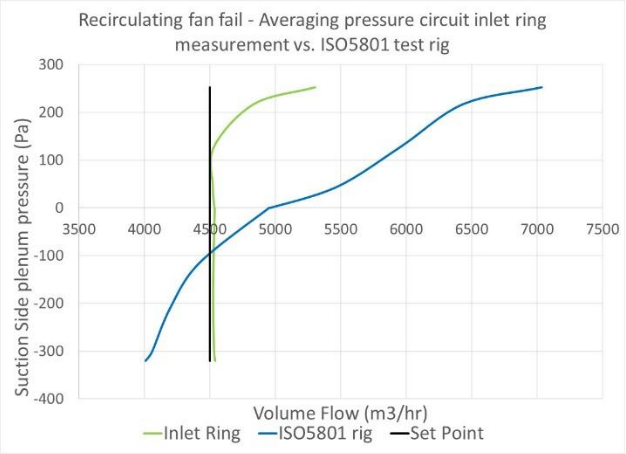

Fig 11 – Pressure circuit flow measurement vs test rig

Fan Fault – 3 fans operational with gravity shutter installed on the faulty fan preventing recirculation

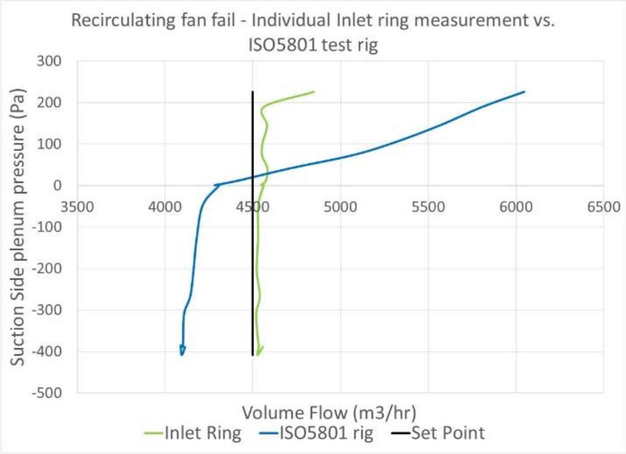

Fig 12 – Individual flow measurement vs test rig

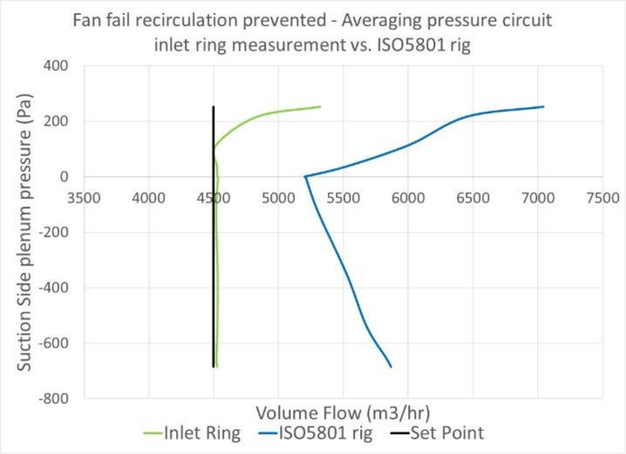

Fig 13 – Pressure circuit flow measurement vs test rig

COMMENTS AND OBSERVATIONS

General measurement detail

Each test measurement was carried out on different days with the measurements taken on the test rig corrected for atmospheric pressure and ambient temperature conditions of the day.

The test piece volume flow rate measurement was carried out using a constant volume controller configured to read pressure differential from each sensor.

- For individual fan flowrate readings, each fan had its own sensor connected to the fan control input and the constant volume controller interrogated the sensor readings via the RS485 Modbus RTU network.
- For the pressure circuit readings, the sensor output was fed direct to the constant volume controller.
- No atmospheric pressure or ambient temperature corrections were applied to the flowrate calculations of the test piece

A further difference between the measurements test results was the type of sensor used.

- For the individual fan pressure measurement readings, a solid-state mass flow sensor was used to determine the pressure drop across the fan
- For the averaging pressure circuit measurements, a diaphragm based inductive transducer pressure differential sensor was used.

Please see 'Further Research' at the end of this paper for comments on the pressure measurement system differences

Benchmark comparison between the Inlet ring volume flow measurement system and the ISO 5801 type A test rig measurement

To compare the accuracy of the inlet ring pressure measurement system with that of an airflow test rig a volume flow rate of 6000 m^3/h was chosen. When shared between the 4 x K3G250 fans used on the test piece, a flow rate of 1500 m^3/h is in the mid-range of the fan characteristic with a potential pressure development of approximately 950 Pa at this flowrate.

Measuring the sum of flow through each fan individually using the solid-state sensors, the test piece measurement system was within a deviation of 7 % of the flow rate measured through the test rig.

When measured using the averaging pressure circuit and diaphragm-based pressure transducer, the test piece measurement system was within a deviation of 3% of the flow rate measured through the test rig.

When considering other forms of manual airflow measurement methods used in site conditions such as rotary vane anemometers, hot wire anemometers, pitot tubes, etc., measuring the flowrate passing through the inlet ring of a backward curved plug fan has a high degree of accuracy.

The effect on measurement accuracy of air recirculation in the event of a fan failure

When one of the fans in the array is switched off to simulate a fan fault, the fan grid controller increases the speed of the other three remaining fans to compensate for the loss of a fan.

When the pressure on the upstream (supply) side of the fan grid is positive, the test piece understates the flowrate passing through it when compared with the flowrate as measured by the test rig. As the pressure increases the error between the test piece and test rig airflow measurement methods becomes significant. This is due to air by-passing the airflow measurement system because the fan in fault is no longer reporting its flowrate to the controller.

When the pressure on the upstream side of the fan grid is negative, the test piece overstates the flowrate passing through it when compared with the flow rate as measured by the test rig. This is due to air recirculating through the fan in fault from the positively pressurized downstream (exhaust) plenum into the negatively pressurized upstream plenum. The recirculated air is bypassing the test piece measurement system.

A further test was conducted to determine what airflow would be registered by the inlet ring flow measurement system with the test rig closed off to prohibit flow onto the test piece. It was found that with no flow passing through the airflow test rig and the three functioning fans running at full speed in an attempt to reach the set point, the test piece was registering a flow rate of 2 655 m^3/h at a suction plenum pressure of –1 149 Pa. At this point the air is only recirculating around the fan grid wall through the non-functioning fan.

There are two noticeable differences in test piece measurement system if the airflow is monitored by each individual fan and when it is measured using a pressure averaging circuit.

When the test piece is operating with no pressure difference across the fan grid wall (free blowing), the individual measurement system overstates the flowrate, and the averaging measurement system understates the flowrate. The individual fan measurement system is changing from bypass to recirculation and the resistance of air passing through the stationary fan and inlet ring accounts for this bias.

The pressure averaging circuit measurement system understates the flow through the test piece at free blowing because a positive pressure is present at the inlet ring pressure tapping of the fan in fault. This causes an error in the averaging circuit which under normal operating conditions a negative pressure would exist at the pressure tapping of all of the fans in the grid.

The effect on measurement accuracy in the event of a fan failure with recirculation prevention

As with the recirculation tests, when one of the fans in the array is switched off to simulate a fan fault, the fan grid controller increases the speed of the other three remaining fans to compensate for the loss of a fan.

When the pressure on the upstream side of the fan grid is positive, the test piece understates the flowrate passing through it when compared with the flowrate as measured by the test rig. As the pressure increases the error between the test piece and test rig airflow measurement methods becomes significant. The type of recirculation prevention product being used is a simple gravity shutter that is being forced open by the positive pressure on the upstream side of the test piece. This is causing air to by-pass the airflow measurement system as seen on the recirculation test.

When the pressure on the upstream side of the fan grid is negative the gravity shutter is functioning as intended, preventing recirculation of air from the downstream side of the test piece recirculating into the upstream side. However, the response of the fan grid control system is different between the individual fan airflow measurement system and the averaging measurement system.

When the flowrate is measured through each fan individually, the accuracy of the airflow system returns back to the benchmark of a deviation of approximately 7 %.

When using a pressure averaging circuit is used, the pressure tapping on the fan in fault is affected by the positive pressure in the downstream plenum of the test piece. The three functioning fans have a negative pressure differential between the suction plenum and the inlet ring tapping, but at the non-functioning fan the pressure at the tapping is higher than the suction side plenum. This pressure ‘leak’ into the averaging pressure measurement circuit induces an error that consistently understates the flow through the test piece.

CONCLUSIONS

The adoption of an array of fans in laid out in a grid pattern has in practice shown benefits in reduced energy consumption, reduced system noise and a level of redundancy should one of the fans in the array fail. This paper explores the system behavior of an array of fans when measuring the flowrate using inlet ring pressure tappings, and the effect on accuracy of the measurement system when one of the fans fail.

- When all fans are functioning as intended, the inlet ring pressure tapping flow measurement system has a relatively high degree of accuracy over other airflow measurement methods.
- In the event of a fan failure, the accuracy of the system deteriorates when recirculation is allowed to happen between the upstream and downstream plenums.
- When recirculation is prevented, the accuracy of measurement system depends on whether the flowrate through the fans is monitored individually or as part of a pressure averaging measurement circuit.
- The choice of recirculation prevention system has an effect whether the air handling system is extracting air from a positively pressurised building (spring loaded mechanised shutters recommended), or from a negatively pressurised building (Gravity shutters adequate)

When one of the fans in an air handling unit array fails, the failure is normally temporary and highly visible where electronically commutated fans are being used. Most electronically commutated fans have either alarm contacts or communication via software that can report on fan operating condition. In the event that a replacement cannot be sourced in a reasonable timeframe, recirculation prevention is recommended to ensure the air handling unit continues to supply or extract a predictable quantity of air to where it is required.

FURTHER RESEARCH

This paper does not explore the event of multiple fan failures or the derivation of a calculation method to predict the level of recirculation in system with no recirculation prevention in place. Similarly the research conducted has not been used in a computational fluid dynamics software to model the behaviour seen in practice, to provide a method to predict the effect of a single or multiple fan failure.

In addition, there were two types of pressure sensor used in the experiments. Up to now, diaphragm-based pressure sensors have been used to calculate the volume flow passing through the fan inlet ring. This type of sensor has some installation considerations specifically relating to its mounting position which requires the sensor to be mounted vertically, and a check on the zero-point output of the sensor which may require regular calibration. The choice of a solid-state sensor removes the requirement for a specific mounting orientation because its mounting position does not affect its accuracy, and the solid-state nature of the measurement system ensures a zero-point accuracy of 0.1 Pa with no drift.

There is a further difference in the range of the pressure sensors with the solid-state sensor having a range of 0–500 Pa and the diaphragm-based sensor having a range of 0-1000Pa. The experiments conducted for this paper explore the behavior of the of a fan array and volume flow monitoring system under the conditions of a fan fault when recirculation is possible and when it is prevented. Further research into the type of sensors used and the effect of their measurement range on the accuracy of the control and monitoring system would augment the conclusions of the work conducted in this paper.