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PITOT-STATIC TUBE OR PITOT TUBE FOR MEASURING FLOW RATES ?

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Abstract – Where volume flow rates in ventilation applications are to be measured common practise is to integrate the velocity profile over the entire cross-section. One of the instruments used to carry out the flow velocity traverse is the Pitot-static tube. The paper examines, on an experimental basis, whether the readings of both total and static pressure by a Pitot-static tube could not validly be carried out by a combination of a Pitot tube that measures the total pressure and tappings at the wall of the duct where the static pressure is picked up. The advantage becomes particularly interesting for applications where the flow rate may change in time.

Keywords: flow rate, Pitot tube, Pitot-static tube.

1. INTRODUCTION

A lot of ventilation applications entail substantial energy costs. Fact is that many of these applications do not require continuously the full ventilation capacity for which the fan system has been designed. Many of these ventilation systems would be more economically operated if the fan performance were to match more closely the real but minimum volume or pressure requirements. Different volume flow rates can be supplied either by a fan with variable rotational speed or variable blade angle setting or by a multiple fan system where fans are operating in parallel.

Equipping these fans with a regulator is not a major technical challenge. But, the real difficulty is the correct measurement of the control variable that is the actual flow output.

If the ventilation circuit or network connected to a single fan is fully passive, i.e. the overall hydraulic resistance of the circuit is constant and well known, the volume flow rate produced by the fan can be reasonably well determined by measuring either its rotational speed or its blade angle setting. In this particular case an appropriate calibration suffices to determine the relationship that exists between volume flow rate and rotational speed or blade angle setting.

But, for multiple fan systems and/or ventilation circuits that have regulators, the aforementioned relationship can no longer be determined. Indeed, the duty point of any fan in a network may move along its characteristic curve, and thus entail a different value of the flow rate, even though its rotational speed or pitch angle did not change, and vice versa. Here one needs to measure directly the real volume flow produced by the fan. This measurement can only be achieved if there is an appropriate airway section available upstream or downstream of the fan where the flow pattern is supposed to be steady and fully developed. Optimal would be, of course, an airway with a standardised section. Unfortunately, industrial site installations have their own constraints and often it is unlikely that such a standardised section is available or could be built in.

Because the velocity varies from point to point over the cross-section of the airway, integral methods using orifice plates or gas tracing should be preferred. But, gas tracing is a one-off and delicate method to operate while the use of an orifice plate is costly in energy consumption and, therefore, often not taken into consideration.

The only practical solution available is to determine the flow rate from an unbiased averaged air velocity value. Enough readings of the velocity component and its direction need then to be recorded. With this velocity profile pattern and an adequate integration technique, one may be able to determine the fluid volume flow rate with an acceptable accuracy. Obviously, the number of measurement points has to be all the more important that the velocity profile is distorted. The integration calculation is largely simplified if the distribution of the measurement points in the concerned cross-section follows certain rules.

As long as the flow pattern stays steady, these measurement points may be sequentially accessed with only one instrument that follows a predefined traversing path [1]. Usually the measurements are carried out either with a Pitot-static tube or with an anemometer.

But, in changeable flow conditions all the points should ideally be measured simultaneously, or at least, within a time span that is much shorter than the time between two changes of the duty point of the fan. Moreover, most site applications do probably not provide an easy access to the measurement section that has been chosen for this purpose. Convenient would then be to install permanently a certain number n of instruments in parallel.

If these instruments are Pitot-static tubes, their entire set up would be expensive. Replacing them by a bunch of tubes, fashioned as Pitot tubes would be a more economical solution, provided that the static pressure could be measured elsewhere. If the static pressure were uniformly distributed over the entire cross-section, a straightforward solution would be to pick it up at the wall of the duct. This solution, if only to simplify the entire set up, would also reduce the number of hoses that transmit the pressure information to a local manometer, n+1 instead of 2n. If n is large, the gain is worthwhile.

The approach of substituting the static pressure of the Pitot-static tube by the static pressure measured at the wall, has been discussed in literature [2] and corrections are given for fully developed flows in pipes. But there seems to be no experimental evidence of whether this method could be applied or need to be encouraged in practical cases. The following question is certainly not without interest : what would be the loss or maybe the gain in accuracy on the ultimate value of the flow rate if this new approach were to replace the recommended method with the Pitot-static tube?

2. PROBLEM STATEMENT

In turbulent flow the time-averaged static pressure varies with the distance from the wall of the pipe. According to Goldstein, the radial variation of the static pressure is given by the equation :

$$p_{stat} = p_w - \rho\, v'^2 - \int_r^R \rho \frac{w'^2 - v'^2}{r} dr\,, \qquad (1)$$

where u', v' and w' are the r.m.s. values of the velocity fluctuations in the axial, radial and tangential directions respectively, p_w the static pressure recorded by the hole in the wall, ρ the fluid density and R the pipe radius.

Starting from this datum, it is obvious that the static pressure is not uniform across the entire cross-section and must be maximum at the wall since v' and w' are zero. It is less obvious how this static pressure is sensed by the traversing Pitot-static tube.

Studies focussed on this particular aspect [2] propose corrections to be applied to the reading of the total-pressure sensed by the Pitot-static tube. But, because the turbulence intensity is mostly unknown, it seems useful from a practical point of view to evaluate experimentally the margin of error that may exist on the ultimate result of the flow rate.

3. OBJECTIVE OF THE WORK

The objective of this experimental work is not to confirm the theory, but to examine in how far this approach is applicable for measuring the flow rate in most industrial ventilation systems and particularly for the ones where volume flows are due to change.

At this point it should be noted that the study does not replace a multiple point method such as the log-Tchebycheff by a new one. It aims only to simplify the instrumentation.

Surprisingly, this approach seems never to have been taken into consideration in ISO-norm context.

4. FACILITY SET-UP

A schematic top-view of the test facility is given in figure 1. A series of ducts with diameter of .8 m forms an open loop circuit with a bell-mouth shape piece at its inlet side. Variable volume flows are produced by adjusting the rotational speed of the ducted centrifugal fan that is driven by a voltage controlled DC motor.

The test section is located at the inlet side of the fan, approximately at 3D from the circuit entry. An orifice plate has been installed in the fan downstream section at approximately 5.5D from the outlet of the duct, so ensuring an airway that meets the ISO standards of length of more than 20D [3].

5. INSTRUMENTATION

The measurement instrumentation is basically made up by a movable Pitot-static tube, a differential pressure transducer in the range up to 3 kPa and a digital data acquisition system and a processing unit.

A multiplexing system set up by eight electronic valves mounted in parallel allows the experimenter to connect the first portal of the pressure transducer to either one out of eight possible input pressure signals. The second portal picks up the ambient pressure so that all the measured pressures are in fact differential values with respect to the same reference value.

The calibrated electrical output signal of the transducer is directly displayed on an voltmeter and is at the same time recorded on a PC equipped with a data acquisition board.

Appropriate A/D conversions and data filtering are achieved by LABVIEW software so to output measured values at a rate of ten per second.

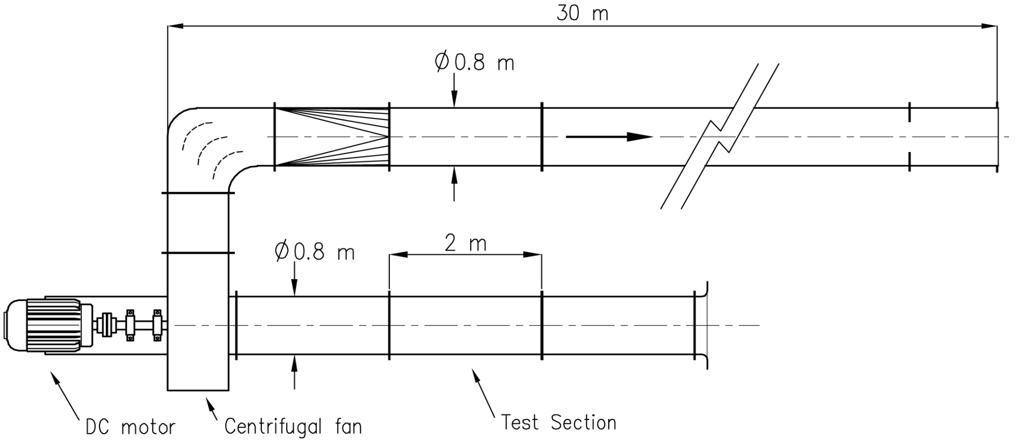

Figure1. Test facility

6. METHODOLOGY

The experimental work is seen to be carried out in two major steps.

During the first time, the experimenters aim only at observing how the static pressure measured by a Pitot-static tube would behave versus the one measured at the wall. Of interest here are not only the results in cases of well developed flow patterns, but also those where the flow pattern is or has been distorted. It should be clear that in this context there is no need to carry out a velocity traverse according to a log-Tchebycheff scheme, nor is there any care about measuring the air volume rate. Therefore, this kind of investigation needs only the Pitot-static tube to be moved equidistantly along, for example, two diagonals.

The second step involves the tests that focus mainly on the flow rate determination. In this case, obviously, the Pitot and wall measurements are taken at best in the inlet duct of the fan i.e. where the flow is most likely to be steady and reasonably well developed. Nevertheless, for the sake of having a so-called reference value of the flow rate, a standardised orifice plate is additionally installed in the test circuit. Now, the locations to which the Pitot-static tube is moved matter and, therefore, follow the recommendations of the ISO standard according to a log-Tchebycheff scheme [4].

Various air flow rates are explored by changing the rotational fan speed.

7. EXPERIMENTS AND RESULTS

For all concerned tests, eight measured pressure signals are sequentially recorded : four independent gauge pressures at four wall tappings, one static and one total pressure picked up by the Pitot-static tube and two averaged pressure related to the orifice plate.

Where the comparison between the two independently measured values of the static pressure is concerned, one may observe that virtually all twenty-one tests show similar results, i.e. the static pressure picked up by the Pitot-static tube shows a slightly lower value than the one measured at the wall of the duct. For tests where the flow conditions are virtually not disturbed, the difference between the two averaged values stays generally below 5 %. For slightly disturbed flows this difference may go up to 10 %.

Where the proper flow rate measurements are concerned, a cross-section close to the inlet of the fan is investigated (see figure 1). The measurement programme is achieved according the following scheme : the Pitot-static tube is moved manually along one diameter of the cross-section to each of the seven predefined *r/R* locations. At each of these locations the data acquisition system reads the two Pitot values, the four independent static pressure values at the wall and the two averaged pressure values related to the orifice plate. This measurement procedure is then repeated for a second traverse along a new diagonal that is perpendicular to the first one.

Although it should be discouraged, a few limited tests are nevertheless carried out at a cross-section downstream of the fan. In this case, despite the installation of an "etoile" flow straightener at 2D upstream, the velocity profile stayed disturbed as can be seen on figure 2 where the profile is pictured by the total pressure curve. This figure displays in fact three sets of dots that are respectively the total and static pressure, both measured by the Pitot-static tube and the static pressure at the wall. All dots are plotted versus the

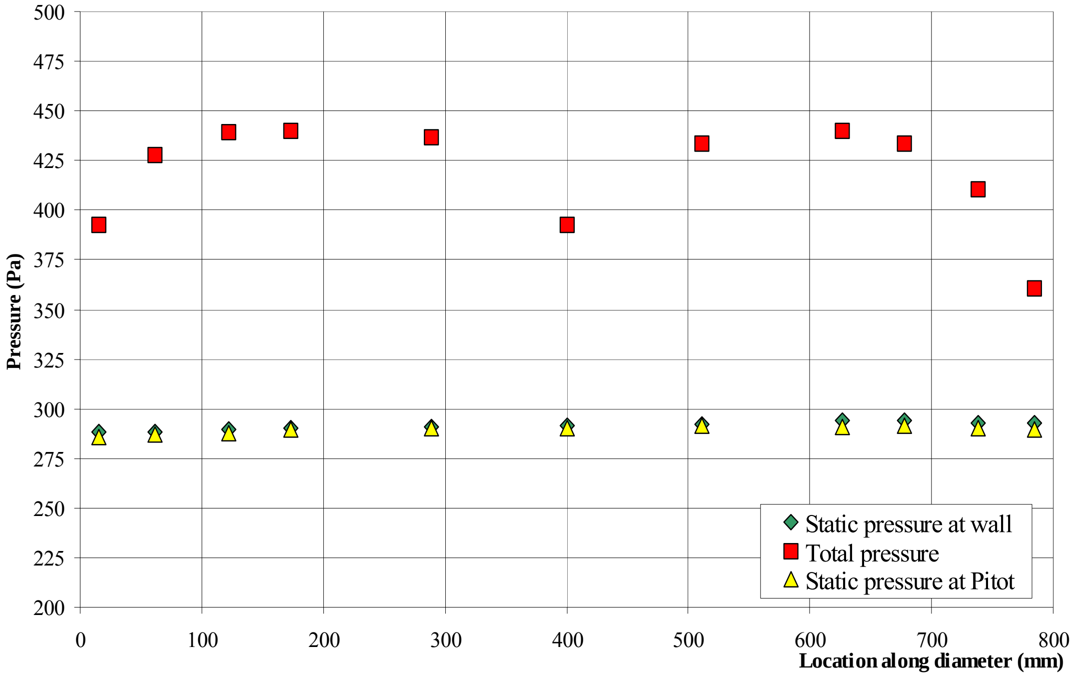

Figure 2. Pressure profiles downstream of "etoile" flow straightener

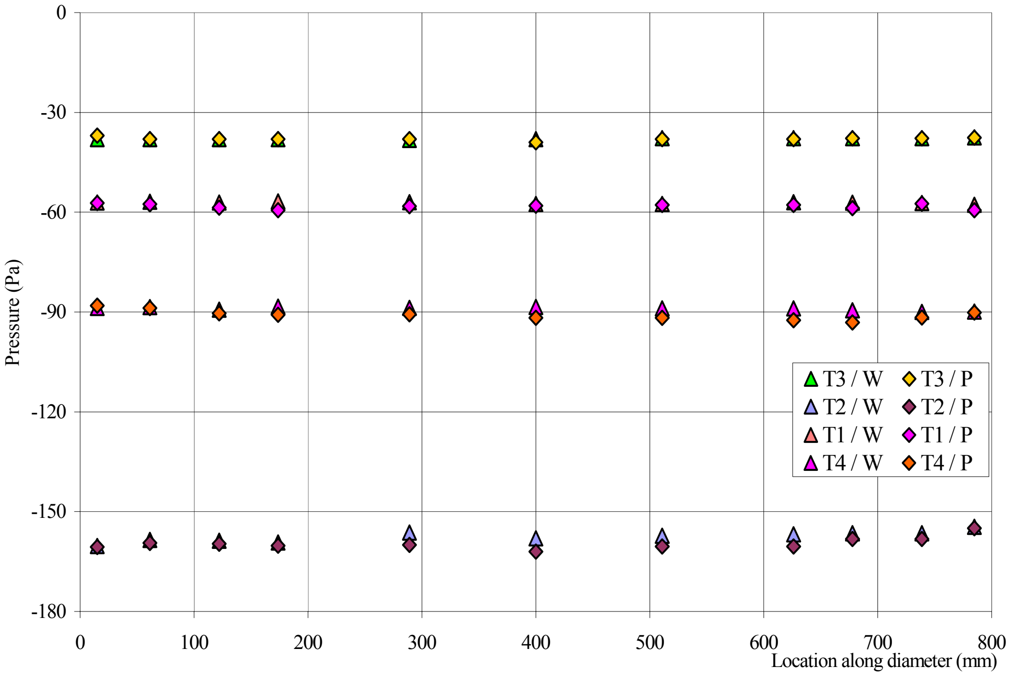

Figure 3. Pressure values for Tests 1, 2 , 3 & 4 along Diameter 1

locations of the Pitot-static tube. The test conditions in this case are characterised by a Reynolds number of around 808,000 that corresponds to a volume flow of 7.5 m^3/s. After testing a second and smaller flow rate (5 m^3/s), there is no point in going on with measurements in this downstream cross-section because the velocity profile does not match the normal profile for which a Tchebycheff traversing method may be applied. Let it be noted in passing that all four tests show similar results where the difference between Pitot and wall static pressure is concerned: the difference, rather small (.6% in case of figure 2), tends to stay constant over the cross-section.

At the upstream side of the fan, four different volume flow rates are explored.

Figure 3 plots the two average static pressure values for the four flow volumes as a function of the location of the Pitot-static tube. The double set of dots for D1 and D2 in figure 4 may give an idea of the corresponding velocity profiles during tests T1, T2, T3 and T4.

The entire set of experimental results enables one to

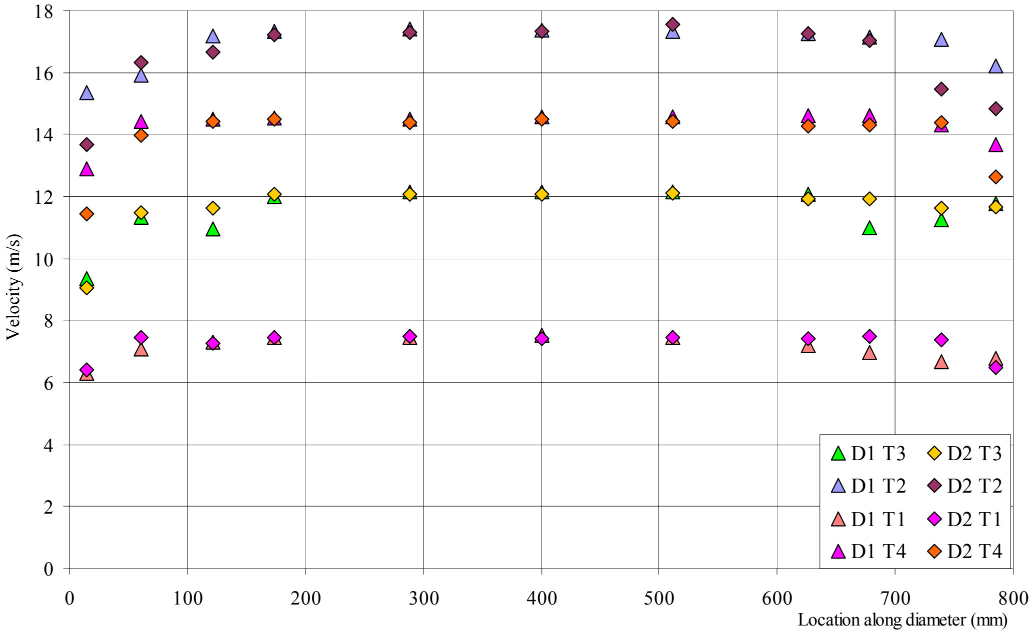

Figure 4. Velocity profiles : Tests 1, 2 , 3 & 4 (D1& D2)

observe that :

- the static pressure at the wall stays very stable. The average value of the standard deviation of all measurements at the wall is around 1.2 Pa, ranging between .4 and 2.1 Pa ;
- the static pressure picked up by the Pitot-static tube has also an almost constant value and the measurement scatter has a slightly lower but similar standard deviation, i.e. 1.1 Pa, ranging between .5 and 2.0 Pa ;
- as expected, none of the static pressure at the wall shows a lower value than the one measured by the Pitot-static tube.

From these results we may draw a first conclusion, i.e. a measurement of the static pressure at the wall provides a valid alternative value for the one obtained by the Pitot-static tube if the flow is reasonably steady. This observation is all the more useful that the volume flow is proportional to the square of the pressure difference, so reducing the error by half.

Where the final aim of these investigations are concerned, i.e. determination of the volume flow, table 1 shows interesting results.

TABLE I. Volume flow calculations and mutual differences

Test #	(1) O.pl. m^3/s	(2) Pitot m^3/s	(3) Wall m^3/s	(1-2) %	(1-3) %	(2-3) %
T1	3.48	3.59	3.58	3.2	2.9	.3
T2	8.07	8.32	8.26	3.0	2.4	.7
T3	5.64	5.77	5.73	2.2	1.6	.6
T4	6.88	7.07	7.03	2.7	2.1	.6

The column marked (1) records the calculated volume flow rates by using the data related to the orifice plate according to the ISO formulas [3]. As previously mentioned, these results are considered here as a sort of reference values. The next column (2) corresponds to the flow rates calculated according to the Tchebycheff method ; all data involved are exclusively produced by the Pitot-static tube. The column (3) represents the results calculated in a similar manner as the second one, however the static "Pitot-pressure" values being substituted by the ones of the static "wall-pressure". Columns five, six and seven show the mutual differences in percentage between the calculated flow rates for the tests listed in column one.

Remarkable are that :

- the Tchebycheff traversing method yields flow rate values that are systematically higher than the ones obtained by the orifice plate. Nevertheless, these results may be considered as being satisfactory since the expected error of an orifice plate method is already around 1.5 to 2 % ;
- substituting the static Pitot pressure by the one measured at the wall seems to reduce the error of overestimating the flow rate ;
- the differences between the two columns related to the Tchebycheff method are less than .8 % and, therefore, not to be considered as being significant.

8. CONCLUSION

The experimental results show that the difference between the static pressure picked up by the Pitot-static tube and the static pressure measured at the wall is sufficiently small in order to allow one to have confidence in the calculated flow rates.

This finding may open the way to a simplification of a standardised flow rate measurement method that is based on a velocity traverse with Pitot-static tubes.

Likely it may also provide a solution to the difficult and not yet satisfactory solved problem of measuring flow rates in industrial ventilation applications where the duty points of one or more fans are due to change in time. Indeed, one could build a rather low cost equipment that is an assembly of ordinary Pitot tubes. This assembly being permanently installed in a well chosen section of the circuit, would yield the advantage of having an almost simultaneous measurement of the total pressure values at all predefined locations within one plane. The static pressure being measured at the wall would allow the velocity profile to be determined and hence, the volume flow rate to be calculated.

From a theoretical point of view, the observed difference between both static pressure values is certainly an interesting aspect that needs further and thoroughly investigation.

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