CHALLENGE JOURNAL OF STRUCTURAL MECHANICS 3 (1) (2017) 38–46

HVAC systems: measurements of airflows in small duct length

Clito Félix Alves Afonso *

Department of Mechanical Engineering, Engineering Faculty, Porto University, 4200-465 Porto, Portugal

ABSTRACT

One of the most feasible ways to measure duct airflows is by tracer gas techniques, especially for complex situations when the duct lengths are short as well as their access, which makes extremely difficult or impossible other methods to be implemented. One problem associated with the implementation of tracer gas technique when the ducts lengths are short is due to the impossibility of achieving complete mixing of the tracer with airflow and its sampling. In this work, the development of a new device for the injection of tracer gas in ducts is discussed as well as a new tracer-sampling device. The developed injection device has a compact tubular shape, with magnetic fixation to be easy to apply in duct walls. An array of sonic micro jets in counter current direction, with the possibility of angular movement according to its main axle ensures a complete mixing of the tracer in very short distances. The tracer-sampling device, with a very effective integration function, feeds the sampling system for analysis. Both devices were tested in a wind tunnel of approximately 21m total length. The tests distances between injection and integration device considered were: $X/Dh = 22$; $X/Dh = 4$; $X/Dh = 2$; and $X/Dh = 1$. For very short distances of $X/Dh = 2$ and $X/Dh = 1$, semi empirical expressions were needed. A good reproducibility of airflow rate values was obtained. These preliminary tests showed that the practical implementation of tracer gas techniques in HVAC systems for measuring airflow rates with a very short mixing distance is possible with the devices developed.

ARTICLE INFO

Article history:
Received 9 September 2016
Accepted 6 November 2016

Keywords:
Tracer gas
Airflow
Constant emission
Injection device
Sampling device
Sonic micro jet

1. Introduction

Tracer gas techniques in the measurement of airflows have innumerable advantages when compared with other more conventional methods, as explained by Rifat (1990), namely its high precision, independence of the flow complexity, almost no flow disturbance, and good flow asymmetry tolerance. Airflows can be calculated with a very high precision in a range from very small airflows to high airflows. Important research work has been done by Cheong and Rifat (1992), Cheong (1994, 1996, 2001), Cheong and Chong (2000), Rifat and Lee (1990), Rifat and Cheong (1993) with the aim of application of tracer gas measurement in ducts, using 8mm tubular injection probe with a row of 3mm holes. Results were presented until a minimum distance between the tracer injection and sampling of $X/Dh = 7$. In countries like Sweden the method of duct airflow calculation by tracer gases is wide spread as per Dantec (2001), and has been implemented with simple multi tube tracer injection, for distances between de injection and sampling point great than $X/Dh = 10$. Carter (1998) obtained an important conclusion in his work: short period time sampling can give reliable airflow measurement.

Nomenclature

Dh	hydraulic diameter [m]
X	distance [m]
s	mean distance between jets orifices [m]
Q_{xDh}	airflow for distance $X/Dh =$ x [m^3/s]
$Corr_{xDh}$	airflow correction for distance $X/Dh =$ x [m^3/s]
$Q_{xDhcorr}$	corrected airflow for distance $X/Dh =$ x [m^3/s]

---

* *Corresponding author.* Tel.: +35-196-7619530 ; Fax: +35-122-5081440 ; E-mail address: clito@fe.up.pt (C. F. A. Afonso)

ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2016.11.027

So to say in almost all work carried out in duct airflow measurements by tracer gas technique the plans of injection and sampling are located far way, ISO 4053/I (2003) and Grieve (1989). However, in situations of real application, the distances between those plans can be very close. Therefore, it is of great importance the development of new techniques studying the dispersion of tracer gas for short distances, even though values of $X/Dh = 1$.

The tracer gas technique had not been much spread, mainly because of the complexity and price of the equipment, mainly the analyzer. This fact restricts this technique to some research work in laboratory, and is not so practical for field measurements. However, in the last years, with the evolution of microelectronics, it become possible to construct portable equipment, with very high sensitivity, been light, compact and at relatively low price. Manly for the above reasons, and in the opinion of others authors CEDR (2003), this technique has the potential to become the standard method of duct airflow measurements, in a next future. This global context gives the motivation for the present work.

2. Injection Device Development

2.1. Initial conditions

The main objective of the present work is the development of a practical field deployable device, for tracer gas airflow measurement. This fact puts some initial conditions regarding the type and shape of the devices. The injection and sampling devices need to be simple to be implemented in ducts. The simplest way of carrying out this desiderate is making appeal to tubular configurations. So, with only two duct orifices with the same diameter, the injection and sampling probes can be easily applied to duct walls. For commodity, the present devices have the possibility of magnetic fixation to common steel ducts. Concluding, the injection must be carried out through only one inlet and not in a series of inlets, to have success in its practical application.

2.2. Injection device design

The present work tries to solve the major difficulty for tracer gas injection devices for duct airflow measurements: the capacity of gas dispersion in extremely short distances $(X/Dh = 1)$. This need, and the initial condition of a unique tracer gas inlet, poses a great design challenge. The present solution consists of a 300mm nominal length probe, Fig. 1, with an array of 200-micron diameter micro sonic jets feed by four distribution chambers.

The probe diameter is 12.5 mm. Four miniaturized hydraulic equilibrated circuits, with only one common inlet, feed these chambers. This number four comes from analyses of the geometry of all the circuit. Fig. 2 represents the ratio of velocities versus the number of distribution chambers. One immediate conclusion from this figure is the benefice of the distribution chambers, to minimize velocities gradients, and consequently minimized pressures gradients. The array of sonic jets (15 in each chamber) is then feed by near equal pressures. The injection orifices are all equal in diameter, made by high precision technique, and operating in sonic regime. So, the tracer gas flow obtained with this arrangement is almost equal for all the jets of the array and the tracer gas injection along the body of the probe is well balanced. The sampling device works exactly same principle but in vacuum.

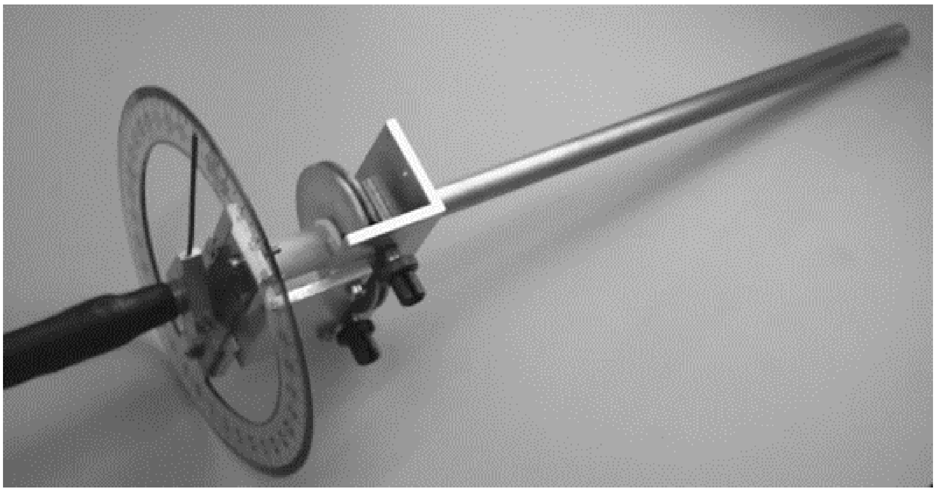

Fig. 1. Prototype of the tracer gas injection device.

The array of sampling points along the device collects the sample, carrying out in this way a very effective integration of the tracer gas concentration. Fig. 3 shows the relative position of the two developed probes in the duct, rotated ninety degrees relative to each other for more effective integration. Additionally, the injection probe has the possibility of scanning angular movement. In this system the adjustment of the scanning angle has a maximum regulation of 45º for each one of the sides (left/right). In this probe it was adopted a system with a regulated alternative movement. The cope for this feature is an improvement in the tracer gas dispersion for low duct air velocities. A sensor was installed for the measurement of the scanning frequency. For better adjustment of the scanning angle a goniometer with a pointer, was also installed.

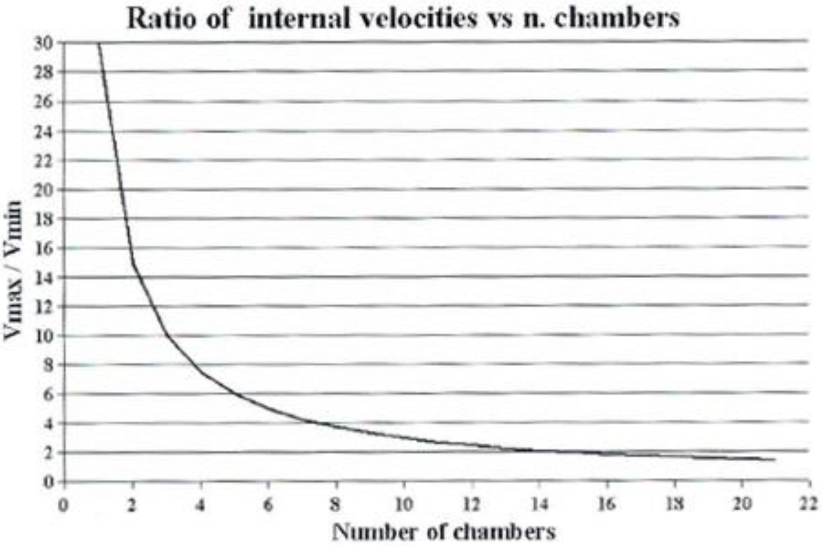

Fig. 2. Ratio of velocities versus the number of distribution chambers.

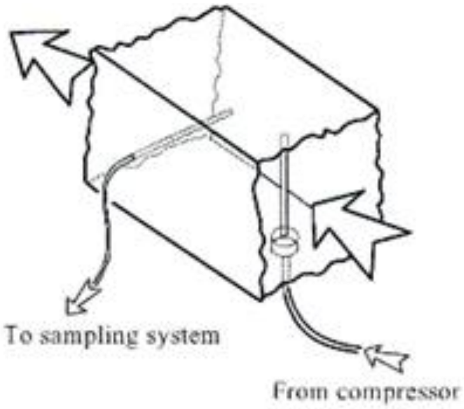

Fig. 3. Relative position of the two developed probes in the duct.

2.3. Experimental setup

The test facility consists basically in a calibrated wind tunnel allowing different airflow rates. The air movement is obtained with an axial fan with ten composite blades of adjustable pitch. The total length of the wind tunnel is 21m with a working section of 0.3m x 0.3m and a length work of 15m. The injection device was placed at the center of the 15m length work section. The calibration of the wind tunnel was carried out with a Pitot tube, scanning the working section area with a six by six matrix for various flow rate values and using the log Tchebycheff method ISO (2000) ANSI/ASHRAE Standard 111-118 (1998). Fig. 4 represents the wind tunnel layout with its main dimensions. The tracer gas concentration was measured by using a photoacoustic multi-gas analyzer, model 1312, manufactured by INNOVA (Grieve PW, 1998). Fig. 5 shows the complete injection circuit. Tracer gas flows from the pressurized bottle to the tracer dozer trough a very sensitive low pressure regulator. One metering valve controls the mixture of the tracer with exterior carrier air. This mixture flows to the inlet of a compressor, which pressurizes the mixture to the injection probe. Sulphur hexafluoride, SF6, was the only tracer gas used in the tests. The sampling integration device was placed in different locations, from $X/Dh = 22$ to $X/Dh = 1$, in a horizontal position (90º relatively to the injection device).

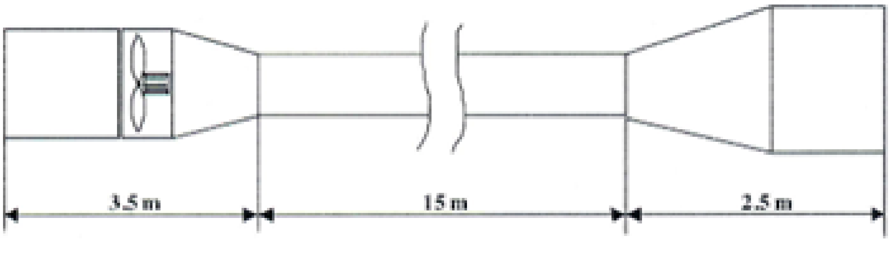

Fig. 4. Wind tunnel layout with its main dimensions.

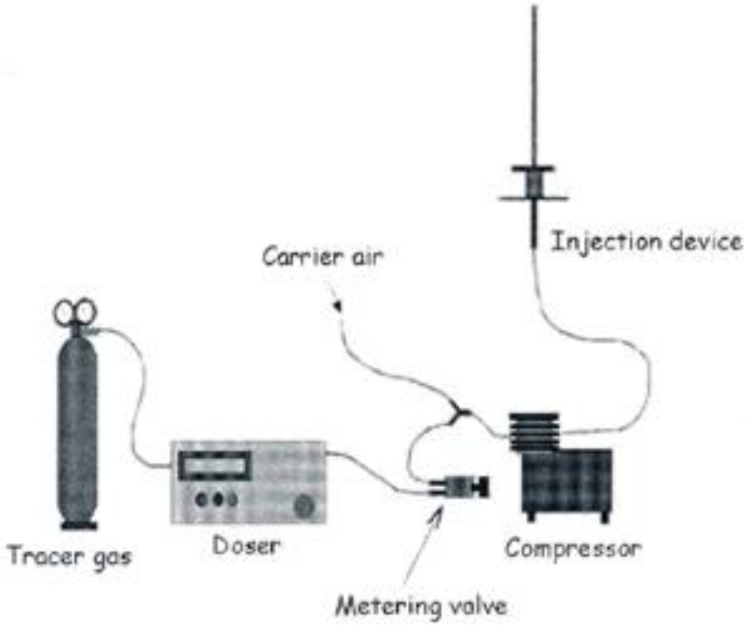

Fig. 5. Complete injection circuit.

3. Initial Tests and Results

For the evaluation of the effectiveness of the prototypes developed, some initial tests and experiments were performed by Silva (2002). The tests can be classified in three categories: measurement of airflow for different distances between in injection and sampling probes; evaluation of tracer gas concentration gradients in the wind tunnel and tests for effective contribution of the angular movement of the injection probe.

3.1. Measurement of airflow rates for different duct distances

The injection probe was placed half way of the working length of the wind tunnel (15 m as already mentioned). The objective of this initial duct length is to guarantee that the airflow is not yet completely developed (the worst conditions).

The sampling probe was placed in different positions downstream, remaining the injection probe in the central position for all the tests. Only for easy access the injection probe was mounted in vertical position and the sampling device in horizontal position for all the tests carried out. In real applications the relative position between the sampling and injection devices of ninety degrees is the unique condition. The sampling time was of 18s for all the tests and was imposed by the characteristics of the tracer gas analyzer. The multiplexed sampling system did not impose any restriction in these times and was synchronized by computer control. The test duration has the typical value of 30min. For numerical processing of the results a real time analysis of the data was carried out in order to verify the necessary conditions of permanent regime (sampling gas concentration with stabilized values).

Initially, the distance between the sampling and injection devices was of $X/Dh = 22$ following $X/Dh = 4$, $X/Dh = 2$ and $X/Dh = 1$. For each X/Dh several tests were carried out with different airflow rates. For the duct length tests of $X/Dh = 22$, a total of five tests were done for rotation speeds between 300 and 1200rpm, corresponding respectively to airflows of 0.288 m^3/s up to 1.308 m^3/s and average air velocities of 3.20m/s up to 14.53 m/s. The results are shown in Table 1 and in Fig. 6.

Table 1. Table for device at distance $X/Dh = 22$.

Airflow w/Pitot Tube	Device $X/Dh = 22$	Difference (%)
0.288	0.300	4.10
0.399	0.421	6.98
0.508	0.538	5.92
0.619	0.634	2.44
1.308	1.288	1.53

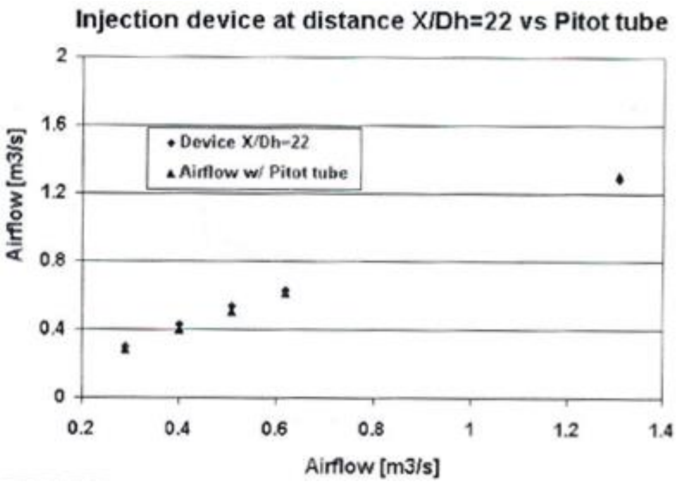

Fig. 6. Device at distance $X/Dh = 22$.

For the duct length of $X/Dh = 4$ and $X/Dh = 2$, a total of ten tests for each one were done again in the same range of fun rotation speeds of the previous tests. The results are shown in Table 2 and Fig. 7 for the first situation and in Table 3 and Fig. 8 for the second situation.

Table 2. Table for device at distance $X/Dh = 4$.

Airflow w/Pitot Tube	Device $X/Dh = 4$	Difference (%)
0.288	0.378	31.17
0.399	0.470	17.75
0.508	0.546	7.50
0.619	0.650	5.03
0.733	0.755	3.04
0.849	0.856	0.85
0.962	0.940	2.32
1.080	1.072	0.76
1.195	1.185	0.80
1.308	1.310	0.15

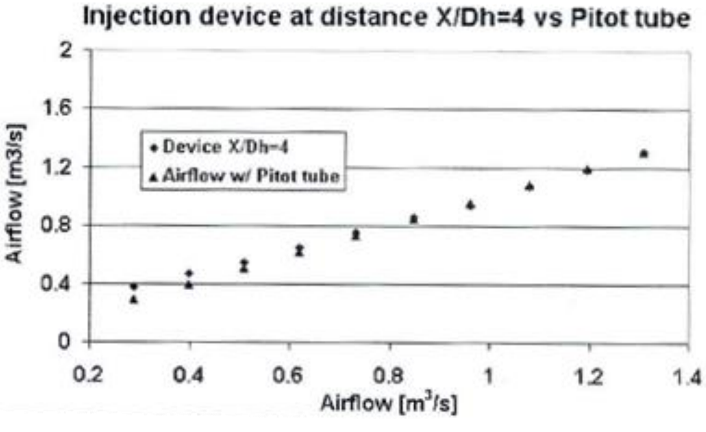

Fig. 7. Device at distance $X/Dh = 4$.

Table 3. Table for device at distance $X/Dh = 2$.

Airflow w/Pitot Tube	Device $X/Dh = 2$	Device $X/Dh = 2$ correction	Prevision	Difference (%)
0.288	0.342	0.288	0.281	0.15
0.399	0.465	0.391	0.391	1.98
0.508	0.581	0.488	0.510	3.86
0.619	0.727	0.615	0.623	0.57
0.733	0.879	0.748	0.738	2.06
0.849	t.026	0.876	0.851	3.20
0.962	1. 145	0.976	0.964	1.42
1.080	1.289	1.101	1.080	1.88
1.195	1.367	1.160	1.192	2.93
1.308	1.526	1.300	1.305	0.64

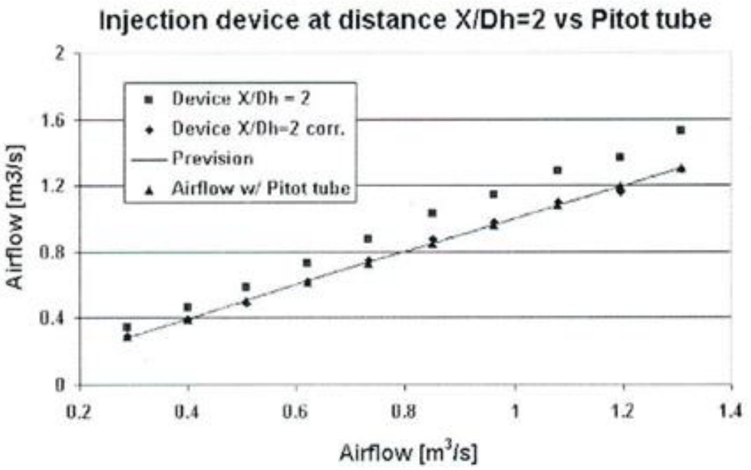

Fig. 8. Device at distance $X/Dh = 2$.

The third column of Table 3 represents the airflow rates calculated with the tracer gas technique and corrected through the expression presented by Eq. (1).

$$Q_{xDhcorr} = Q_{xDh} - Corr_{xDh}\ . \tag{1}$$

Finally, the $X/Dh = 1$ tests have been carried through a total of ten tests, for the same range of fan rotation speeds. The results are shown in Table 4 and in Fig. 9. As in Table 3, the third column of Table 4 represents the airflow rates calculated with the tracer gas technique and corrected through the expression presented by Eq. (1).

The tracer gas duct dispersion for very short distances is particularly difficult. The tests for distances $X/Dh = 2$ and $X/Dh = 1$ had the aim to evaluate the behavior of the injector device in this extreme conditions. In real practical situations of airflow measurement in HVAC systems, with much frequency, these short distances are the only hypothesis to measure. So, it is of great interest to have correlations or semi-empiric relations to apply to the measured values for this particular measurement situation. For these shortest distances, an effect of bypass is clear patent in the results. As can be seen mainly in Figs. 8 and 9 the airflow calculated with the tracer gas technique and with the Pitot tube (the reference) diverges with the airflow increase. This effect is due to the incomplete mixture of the tracer gas with the airflow for very small distances. Despite this, the obtained airflow rates with this new injection device are smooth, representing a potential for posterior use of some form of correlation.

It is now necessary to carry out more tests and deep statistical analyses in order to obtain a semi-empirical expression that can correlate the measured values with the real ones. To overcome the effect of bypass due to the incomplete tracer dilution, it was considered in the present work a simplified method of correction, for duct distances of $X/Dh = 1$ and $X/Dh = 2$. These corrections had been done taking as reference the airflow rates measured with Pitot tube. The expression proposed for calculation of the correction, has the form of a function of the airflow, with the generic form already shown in Eq. (1).

Table 4. Table for device at distance $X/Dh = 1$.

Airflow w/Pitot Tube	Device $X/Dh = 1$	Device $X/Dh = 1$ correction	Prevision	Difference (%)
0.288	0.311	0.303	0.281	5.00
0.399	0.471	0.413	0.397	3.52
0.508	0.592	0.486	0.510	4.26
0.619	0.735	0.581	0.623	6.07
0.733	0.945	0.742	0.739	1.25
0.849	1.104	0.853	0.851	0.49
0.962	1.286	0.987	0.964	2.57
1.080	1.441	1.093	1.080	1.16
1.195	1.574	1.178	1.192	1.41
1.308	1.752	1.308	1.305	0.01

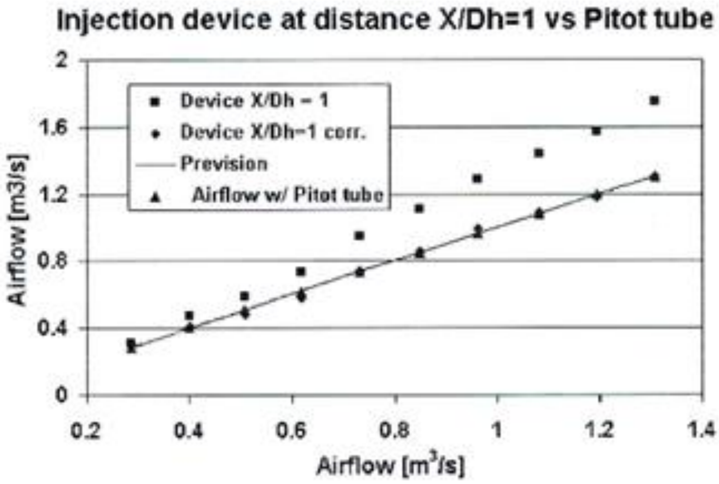

Fig. 9. Device at distance $X/Dh = 1$.

The correction for $X/Dh=Z$, $Corr_{2Dh}$, have the following form, Eq. (2):

$$Corr_{2Dh} = 1.44^{-1} \cdot Q_{2Dh} + 5.93^{-3} . \quad (2)$$

For the duct length of $X/Dh = 1$, $Corr_{1Dh}$ can be expressed as, Eq. (3):

$$Corr_{1Dh} = 2.998^{-1} \cdot Q_{1Dh} + 7.82^{-2} . \quad (3)$$

The standard deviation for the corrected airflow values, are 1.8% for $X/Dh = 2$, and 2.57% for $X/Dh = 1$. These standard deviations are acceptable, taking in account the difficulty in tracer gas dispersion for so short duct distances. For $X/Dh = 4$ tests it can be seen that there is a good agreement between the Pitot tube and tracer measurements except for low airflow rates. This may be due to the fact that at low airflow rates the turbulence is not still high enough which turns difficult the tracer mixing process. The turbulence phenomenon is characterized by transversal air a movement that enables the dispersion of the tracer gas. So, the observed deviation of the experimental curve is due to a lower turbulence in lower speeds and consequently a more difficult mixing process. Comparing these results with the work of other authors, it was reported that the minimum distance obtained for a good tracer mixture is of $X/Dh = 7$ (Cheong, 1994). This distance is almost double of the distance $X/Dh = 4$ obtained with this new injection device being able to conclude that the results for $X/Dh = 4$ are acceptable in spite of the standard deviation of 6.94% for all the airflow range studied. In the tests for distance $X/Dh = 22$ the standard deviation found for all the range of airflows was 4.19%. This value is similar to the one found for $X/Dh = 4$ being then possible to conclude then that are not significant improvements in tracer gas dispersion for $X/Dh > 4$. This distance in measurements of HVAC systems have a great importance. Usually in real systems the available duct lengths for measurement are very short.

3.2. Tests for evaluation of the injector angular movement

The evaluation tests of gradients of concentration and the effect of the rotation of the injection probe (movement of angular scanning) had been carried through the distance $X/Dh = 3$. This distance was selected because it was intended to evaluate the gradients in the initial tracer gas dispersion phase concluding then on the potential of tracer gas dispersion in very short duct lengths. The existence of orifices in the duct wall for measured distances of $X/Dh = 4$ and $X/Dh = 2$ used in the previous tests for the measurements of airflow explains the choice of the distance $X/Dh = 3$. The aim was to measure the profiles of concentration and the effect of the rotation of the injection device (scanning movement), simultaneously. Three very narrow aperture sampling probes had been installed in the upper face of the duct with similar vertical position of the injector device. These special probes have a similar Pitot tube shape, with 4 mm diameter, working in depression (air sample).

One of the sampling probes was installed in the axle of the duct, another one 50 mm away of the wall duct, and the remaining one at half these two distances. The depth of the three probes was exactly the mean section of the duct. To be able to evaluate the effect of the rotation of the injection device (movement of angular scanning) two different airflows had been compared. For high airflows, the penetration of the sonic jets is less effective. Consequently, the movement of angular scanning is not so effective too. So, this is the worst condition and then the necessity to study this condition. Conditioned by the total monitoring time of the tracer gas analyzer, only one half of the duct was monitored in the tests. In Figs. 10 and 11 that represents respectively the concentration profiles for an airflow of 0.619 m^3/s and of 0.962m^3/s, the remaining section is represented by symmetry for better understanding. The scanning frequency has a value of 10Hz (10 scanning/s) and was constant for the tests. The graph compares two distinct situations: the injector device with an angular scanning movement of approximately 90º aperture (45º for the left and 45º for the right against the flow) and a static injection in counter current (0º).

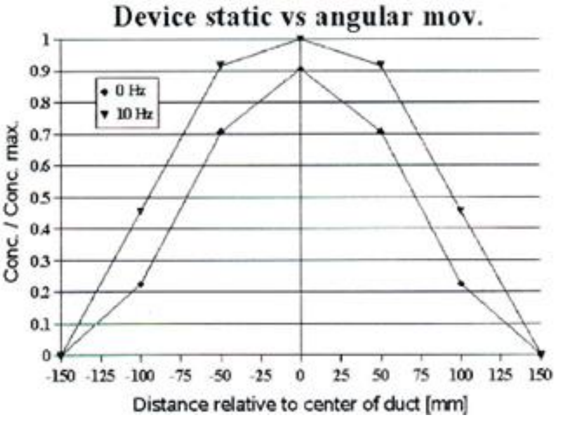

Fig. 10. Concentration profiles for an airflow 0.619 m^3/s.

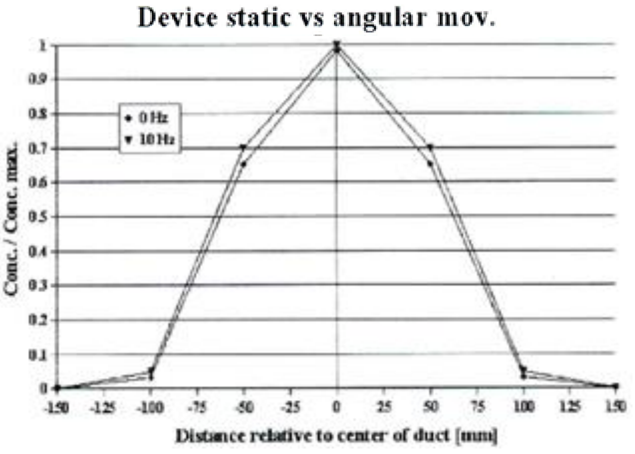

Fig. 11. Concentration profiles for an airflow 0.962 m^3/s.

Each value represented in the graphs is the average of a series of values obtained from the tracer gas concentration monitoring. The number of measurements varies slightly with the duration of each test but was never lower than twenty measurements. One conclusion that can be withdrawn from these graphs is that the effect of the rotation movement is less noticed for higher airflows as already mentioned. Regarding these results, it is than possible to conclude, that there is no advantage in the movement of scanning for higher airflows. In the situation of application of this technique to the measurement of airflows in HVAC systems where the air speed usually does not exceed the 10m/s, the possibility of scanning movement has some future potential interest.

4. Smoke Tests

The smoke tests were carried out through a transparent section of the wind tunnel. A smoke generator made by Günther Schaidt Safex Chemie, model FlowMarker (2001) was used. The smoke used has a density close to the air, Fig. 12 represents a photograph of a group of parallel free jets, produced by this new injection device (12.5 mm diameter). The outlet of the smoke generator is behind the body of the injection device. The smoke is sucked by the low pressure created near the base of the jets (zone of strong depression), and the smoke is accelerated by the high speed of the jets. The diffuse aspect of the smoke is due to high velocity of it. The special flash used with the camera, with a high illumination speed, was not capable of freezing the smoke movement.

Fig. 13 represent the flow visualization at a main flow velocity of 3.2 m/s seen from an upper position. The dispersion effect of the counter current jets is patent in this figure. Viegas (1981), studied the parallel air jets interaction and concluded that for $X/s > 50$ there is an interaction of the jets and they behave like they were emitted from only a single source. In the present work $s = 2.5$ mm resulting in a distance of $X = 125$ mm, for the above condition. This distance is lower than $X/Dh = 1$ (300 mm), condition that in theory satisfies the main objective of tracer gas dispersion in very short distances.

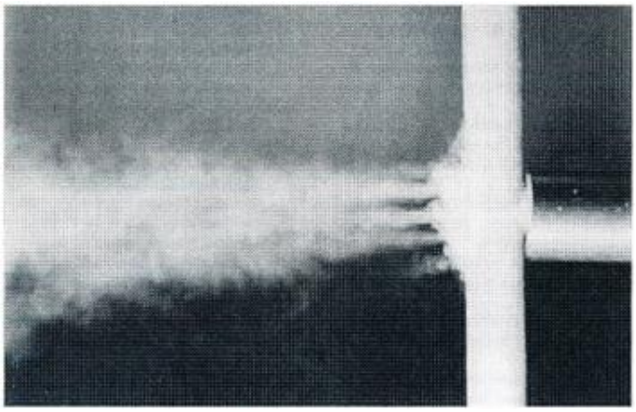

Fig. 12. Photograph of a group of parallel free jets.

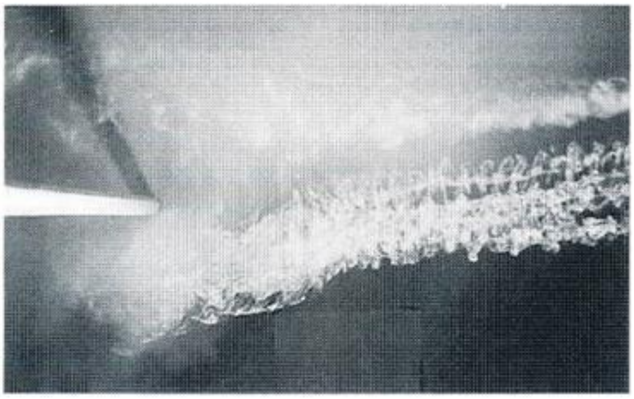

Fig. 13. Flow visualization - main flow velocity of 3.2 m/s seen from an upper position.

5. Conclusions

In this work, it is presented a new prototype device for injection and sampling of tracer gas for measurement of duct airflows. The devices after tests carried out in a wind tunnel showed that they are able to measure accurately airflows for very small distances between the injection and sampling of tracer gas. In this study, four different distances were considered with practical interest in applications of HVAC systems. The airflows measured with the tracer gas technique using those new devices showed a good correlation with the ones obtained with a reference Pitot tube. For very short distances of $X/Dh = 1$ and $X/Dh = 2$, simplified correction expressions are necessary. These devices are easy to apply in field measurements, producing accurate airflow values.

REFERENCES

ANSY/ASHRAE Standard 111-118 (1988). Practices for measurement, testing, adjusting and ba1ancing of building heating, ventilation, air conditioning and refrigeration systems, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.

Carter G (1998). Tracer Gas Air Flow Rate Measurement as an Alternative to Pitot Tube Traverse in Commercial Building Ventilation Systems, *M.Sc. thesis*, UC Berkeley, Berkeley.

Center for Environmental Design Research (2003). College of Environmental Design, UC Berkeley, Berkeley.

Cheong K (1994). The Application of Tracer-Gas Techniques for Measuring Airflow in HVAC Systems. *PhD thesis*, School of the Built Environment, University of Nottingham, Nottingham, UK.

Cheong KW (1996). Tracer gas technology for airflow measurements in HVAC systems. *International Journal of Energy Research,* 20(12), 1081-1094.

Cheong KW (2001). Airflow measurements for balancing of air distribution system-tracer-gas technique as an alternative. *Building and Environment*, 36.

Cheong KW, Chong KY (2000). Development and application of an indoor air quality audit to air-conditioned building in Singapore. *Building and Environment*.

Cheong KW, Rifat SB (1992). Application of tracer-gas techniques for measurement of friction-factors of rectangular ducts. *Air Infiltration Review*, 13.

FlowMarker lnstructions Manual (2001). Günther Schaidt Safex Chemie.

Grieve PW (1989). Measuring Ventilation Using Tracer-gases, Brüel and Kjaer.

Indoor Climate and Ventilation (2001). Measurement of main air flows using tracer gases. *Dantec Dynamics Application Note*.

INNOVA Air Tech Instruments (1998). Monitor Multigaz Type l3l2 Instructions.

International Standard ISO 3966. Mesure du Débit des Fluides dans les Conduites Fermées-Méthode d' Exploration du Champs des Vitesses au moyen de Tubes de Pitot Doubles", International Standards Organisation, Genève.

International Standard ISO 4053/I-1977 (F). Mesurage de Débits de Gaz dans les Conduites - Méthodes par.

McWilliams (2003). Review of airflow measurement techniques, energy performance of buildings group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley.

Rifat SB (1990). Comparison of tracer gas techniques for measuring airflow in ducts. *Journal of the Institute of Energy,* 63.

Rifat SB, Cheong KW (1993). Tracer-gas techniques for design and commissioning of HVAC system. *Proceedings of First International Conference on Environmental Engineering*, Leicester, UK.

Rifat SB, Lee SF (1990). Turbulent flow in duct: Measurement by a tracer gas technique. *Building Services Engineering Research and Technology,* 11.

Silva AR (2002). Medição de Caudais de Ar pelo Método de Emissão Constante com Desenvolvimento de Sonda para Gás Traçador. *Ph.D. Thesis*, INETI, Lisboa.

Traceurs-Partie I: Généralités, International Standards Organisation, Genève.

Viegas DX (1981). Uma Técnica de Erosão Aplicada ao Estudo da Interação de Jatos Turbulentos com uma Superfície Plana. *Ph.D. Thesis*. Faculdade de Ciências e Tecnologia da Universidade de Coimbra, Portugal.