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Measurement of air flow rates in evacuation stairwells of high-rise buildings by tracer gas methods

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Abstract
Pressurized evacuation stairwells provide safe escape routes to occupants and access to rescue crews in case of fire in a high-rise building. The air overpressure prevents smoke from entering the rescue staircase and firefighter elevator shafts. Pressure losses were measured in four stairwells to better understand aerodynamic flow resistance. Flow resistance was then determined from the measured pressure loss and air volume flow. The present paper reports a method to measure volume flow by the tracer gas method. We determined flow rates in the four staircases with high accuracy and certainty by using the tracer gas sulfur hexafluoride (SF_6) combined with rapid infrared spectroscopy. We demonstrated that the constant-emission and pulsed-emission tracer gas methods are well suited for flow rate measurements under difficult flow conditions. The pulsed injection of tracer gas into the ventilation system requires an accurate mass flow controller. Uniform mixing of the tracer gas upstream of the measuring section is a key condition for reliable measuring results.

Keywords - Pressurized stairwells, air flow rate, tracer gas methods, measurement uncertainty

1. Introduction

High-rise buildings are required to have emergency exits on each floor to smoke-free escape staircases. These pressurized evacuation stairwells provide safe escape routes to occupants and access to rescue crews in case of fire. The air overpressure prevents smoke from entering the rescue staircase and firefighter elevator shafts [1]. Airflow resistance along the shaft and air resistance at doors and other openings are not well known due to large differences in stairwell types. Different sources report wide variations of values of resistance coefficients. Detailed knowledge of aerodynamics is required to properly design a pressurized ventilation system that guaranties safe pressure differentials across open escape doors without exceeding a limit of the force required to open the door from the low-pressure side.

Engineers at Aicher, De Martin, Zweng AG have initiated a Bachelor-of-Science project [2] at the Lucerne University of Applied Sciences and Arts (HSLU), Switzerland. Pressure losses were measured in four stairwells to better understand aerodynamic flow resistance (Fig. 1 and 2). Flow resistance can be determined from the measured pressure loss and air flow rate. The present paper reports a procedure to measure mass (and volume) flow by the tracer gas method.

Fig. 1 Building 1, at left (Allmend Hoch2, Lucerne) and building 2 (staff accomodation building of Lucerne Hospital)

Fig. 2 Building 3, at left (Building CHN of the ETH Zurich) and building 4 (Zurich Airport ZRH OPC4, Kloten)

2. Methods

The measurement of air volume flow in pressurized evacuation stairwells is difficult because of geometrical constraints and aerodynamic complexities of the ventilation system. Flow rates in the four staircases could be determined with high accuracy and certainty by using the tracer gas sulfur hexafluoride (SF_6) combined with rapid infrared spectroscopy. We used constant-emission and pulsed-emission tracer gas methods (see Etheridge and Sandberg [3]).

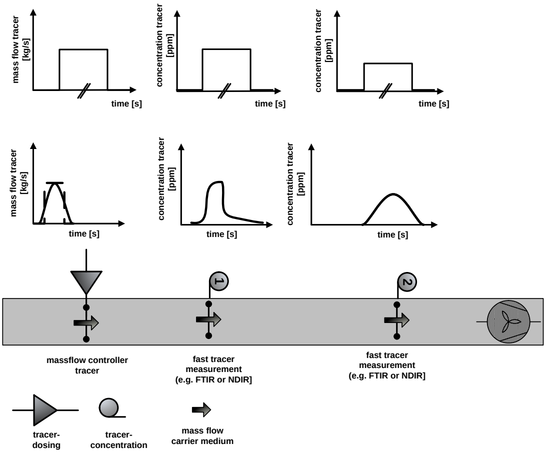

Fig. 3 Experimental setup of the constant- and pulsed-emission tracer gas method (e.g. in exhaust ducts of road tunnels)

Constant-emission tracer gas method

The constant emission tracer method has been used by the authors since 2002 to determine volume flow and leakage in exhaust ducts of 25 road tunnels in Switzerland, Germany, and Slovakia. Tracer methods are completely independent of flow profile disturbances and are regarded by Bettelini [4] as benchmark methods compared to flow rate calculations based on multipoint velocity measurements. Tracer gas, usually sulphur hexafluoride (SF_6) or nitrous oxide (N_2O), is injected into the carrier medium through mass flow meters, dispersed by turbulent flow and measured downstream at different locations through single- or multipoint-sampling. Due to leakages of the duct the measured tracer gas concentration is different at point 2 compared to point 1 (Fig. 3).

Equation (1), formulated by Frei [5], allows to calculate the volume flow of air, $q_{V\ Air}$, at the measuring point from the measured concentration of tracer gas and its mass flow at the dosing point.

$$q_{V\,Air} = 10^6\,ppm \cdot \frac{1}{\rho_{Air}} \cdot \frac{R_{Tracer}}{R_{Air}} \cdot \frac{q_{m\,Tracer}}{c_V} \qquad \left[m^3/s\right] \tag{1}$$

$q_{m\ Tracer}$	mass flow of tracer at the dosing point	[kg/s]
R_{Tracer}	specific gas constant of the tracer	[J/(kg K)]
R_{Air}	specific gas constant of the air in the exhaust duct	[J/(kg K)]
c_V	volumetric tracer gas concentration at the measuring point	[ppm]
ρ_{Air}	density of the moist air at the measuring point	[kg/m³]

Pulsed-emission tracer method

The pulsed-emission method (PEM) is not a new idea. Earlier applications of PEM were hindered by two important problems: Accurate tracer gas dosing and sufficiently fast concentration measurements were nearly impossible due to technical limitations. Today, accurate dosing through mass flow controllers/meters and fast tracer measurements by Fourier Transformation Infrared Spectroscopy (FTIR) and/or Non Dispersive Infrared Spectroscopy (NDIR) are both possible. The PEM basically applies two numerical integrations: At the dosing point, the tracer mass flow over time, and downstream, at stations 1 and 2, the tracer gas concentration over time (see Figure 3).

A tracer gas pulse with a mass flow rate of $q_{mTracer}(t)$ is injected upstream and the time-varying tracer gas concentration c(t) is measured downstream at positions 1 and 2. It is essential that the tracer gas is well mixed with the air. Furthermore, the whole amount of tracer gas must have left the duct at the time t_2. If that is the case the following integral mass balance, Equation (2), reported by Persily [6], is applicable.

$$\int_{t1}^{t2} q_m(t) \cdot c(t) \cdot dt = \int_{t1}^{t2} q_{m\,Tracer}(t) \cdot dt\,; \qquad q_m(t) \geq 0 \tag{2}$$

Assuming a constant air mass flow, q_m, during the observed time interval, and assuming that the mass flow of the tracer gas is negligible compared to the air mass flow, the mass flow of air can be calculated according to Equation (3):

$$\bar{q}_m(\xi) = \frac{\int_{t1}^{t2} q_{m\,Tracer}(t) \cdot dt}{\int_{t1}^{t2} c(t) \cdot dt}\,; \qquad t_1 \leq \xi \leq t_2 \tag{3}$$

Considering the volumetric concentration rather than the mass concentration of the tracer gas in the air, Equation (3) is transformed to the following:

$$\bar{q}_{m\ Air} = 10^6\ ppm\ \frac{R_{Tracer}}{R_{Air}} \cdot \frac{\int_{t1}^{t2} q_{m\ Tracer}(t) \cdot dt}{\int_{t1}^{t2} c_V(t) \cdot dt} \qquad [kg/s] \tag{4}$$

$c_V(t)$:	measured volumetric tracer gas concentration at time t	[ppm]
$q_{m\ Tracer}(t)$:	mass flow rate of tracer gas at time t	[kg/s]

Equation (4) is equivalent to Equation (1) with the difference that the mass flow of the tracer gas at the dosing point as well as the measured concentration are no longer constant and have to be integrated over time.

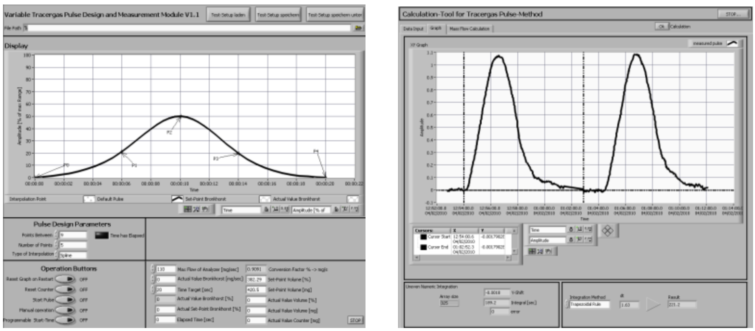

Fig. 4 Design and numerical integration tools for individual pulse generation (upstream) and analysis (downstream)

Once the concentration data are entered, the start point and the end point of the time interval t_1 to t_2 are set by two cursor clicks, Fig. 4. If there is a background concentration, the offset can also be corrected with the cursor. A further advantage of this tool is its flexibility with regard to the tracer gas used.

Experimental procedure

The authors have applied both methods successfully in earlier experiments to measure the extract airflow rates of road and railway tunnels. For the investigation in four staircases in high-rise buildings with much smaller dimensions, the equipment and gas injection system had to be downscaled. Good measuring conditions were obtained by multipoint injection upstream, and multipoint gas sampling downstream of the fan for both methods and on all sites. A typical measurement scheme is shown on Figure 5 for building 2, a 10-story staff accomodation building of Lucerne Hospital. Figures 6 to 9 show photos of the dosing, injection, sampling, and data acquisition systems.

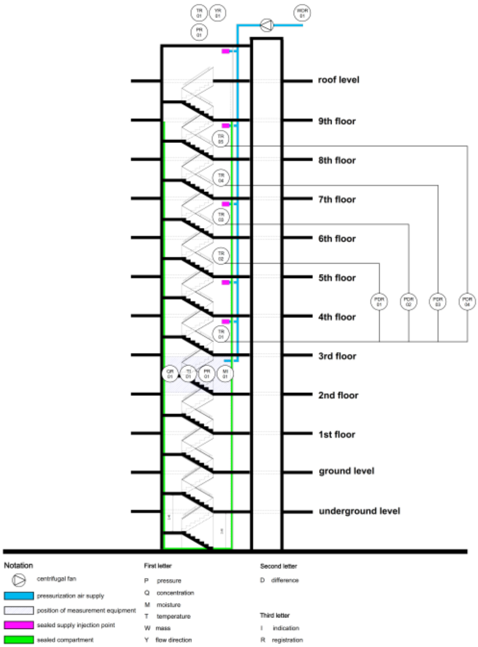

Fig. 5 Measurement scheme of building 2 (staff accomodation building of Lucerne Hospital)

Fig. 6 Dosing equipment with massflow controller and tracer gas bottle (right)

Fig. 7 Multipoint tracer injection upstream on the roof level of building 2

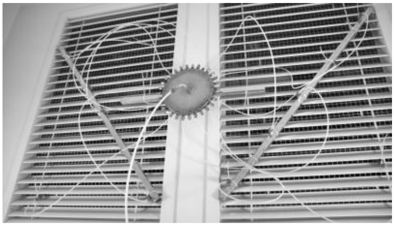

Fig. 8 Multipoint tracer sampling downstream inside building 2

Fig. 9 Infrared-spectroscopy concentration measurement in the pressurized escape stairwell

Measured tracer concentration responses to tracer injections by the constant- and pulsed-emission methods are shown in Fig. 10.

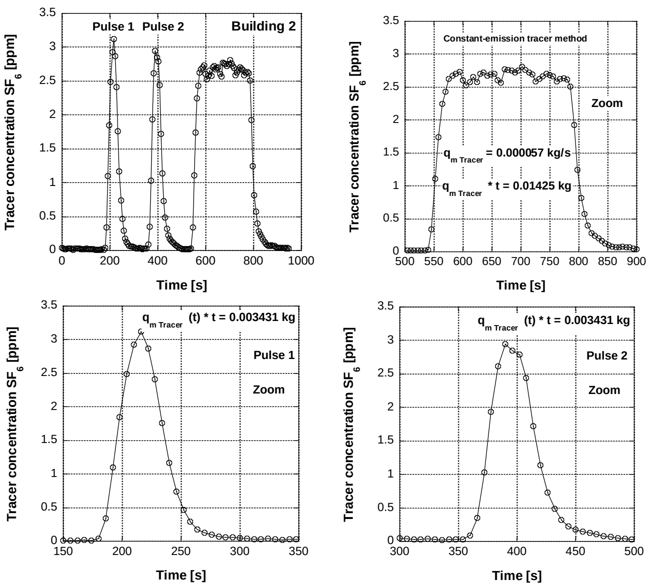

Fig. 10 Measurements of tracer concentration SF_6 in the pressurized escape stairwell

3. Results and discussion

The results of the two measurement methods differ by less than 6% (Table 1). This difference is caused by operating points that have not completely settled to stable equilibrium when the two tracer gas methods have been applied sequentially.

Table 1. Comparison of experimental results

Mass flow rate [kg/h]	**Pulsed-emission method**	**Constant-emission method**	**Deviation [%]**
Building 1	21584	20409	5.8
	18548	17807	4.2
	11385	10786	5.6
Building 2	18168	18080	0.5
	17737	17622	0.7
GUM	**18590**	**18500**	**0.5**
	19012	18500	2.8
	19274	17330	(11.2)
	12553	14972	(16.2)
Building 3	28943	29194	0.9
	29243	28394	3.0
	25763	24641	4.6
Building 4	20848	19914	4.7
	20964	19914	5.3
	19292	19914	3.1
	17893	17333	3.2
	18733	17333	(8.1)

An alternative method to determine flow rates in these four buildings by measuring air velocities in the duct cross section (grid method) would have involved excessive measurement uncertainty [7]. In addition, the installation of the necessary equipment would have been more expensive. The authors have prepared uncertainty budgets (see Frei et al. [8]) according to the ISO "Guide to the expression of uncertainty in measurement," GUM [9], for both tracer gas methods.

Experimental results of measurement campaigns in three Swiss road tunnels showed comparable deviations between pulsed- and constant-emission tracer methods. Furthermore there was validation work done by comparing single-point and multi-point tracer gas extraction for concentration measurements (see Frei et al. [8]).

Measurement uncertainty budgets for the used pulsed- and constant-emission tracer methods show expanded uncertainties (confidence interval 95%) between 4 to 4.6% for mass flow rates (Fig. 11 and 12).

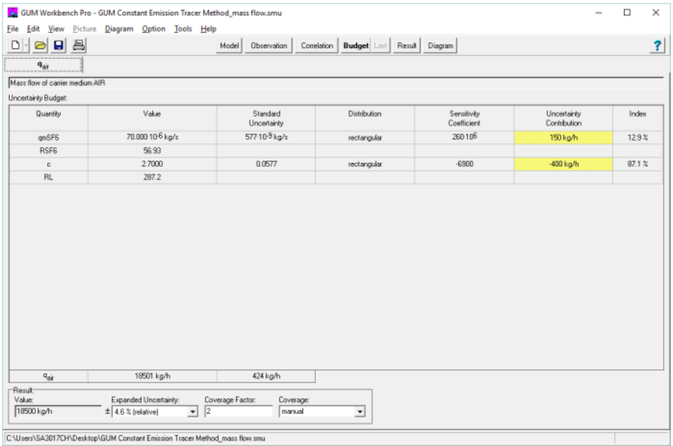

Fig. 11 Measurement uncertainty budget for constant-emission tracer method

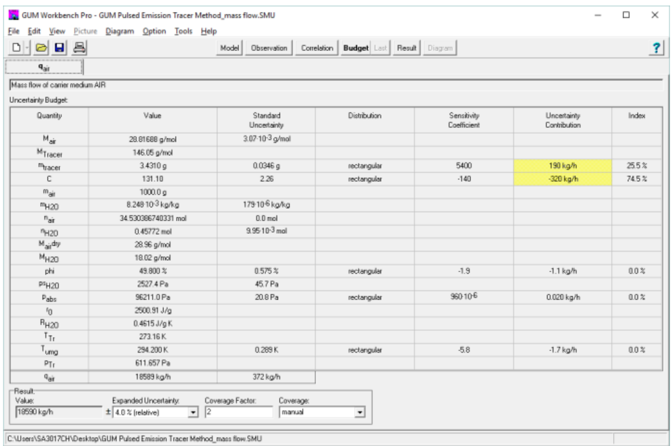

Fig. 12 Measurement uncertainty budget for pulsed-emission tracer method

4. Conclusions

We demonstrated that the constant-emission and pulsed-emission tracer gas methods are well suited for flow rate measurements under difficult flow conditions. The downscaling of pulse generation was successfully accomplished. The pulsed injection of tracer gas into the ventilation system requires an accurate mass flow controller and a LabVIEW®software application. Uniform mixing of the tracer gas upstream of the measuring section is a key condition for reliable measuring results. For future projects, the authors intend to replace sulfur hexafluoride (SF_6) by nitrous oxide, commonly known as laughing gas (N_2O), or by 1,1-difluoroethane (DFE, $C_2H_4F_2$).

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