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Development of an Optical Real-Time Measurement System for Air Change Rates in Indoor Environments

Rebekka Grüttner[1], *Christian Friebe*[1]
[1] Institut für Luft- und Kältetechnik gemeinnützige Gesellschaft mbH, 01309 Dresden, Germany
rebekka.gruettner@ilkdresden.de

Summary:
This article presents a novel measurement system and method for determining air change rates in real-time using an optical principle. It measures the attenuation of light intensity through fog aerosols in an indoor volume, employing a light source (laser) and a detector to capture transmitted intensity, allowing measurements across distances of 1 to 50 m. Results were validated against conventional methods, such as the SF_6 tracer gas decay method and volumetric air change measurement. Disturbances like temperature variations and external light were successfully mitigated.

Keywords: real-time air change measurement, optical measurement, local air change rate, indoor air quality, energy efficiency

Background

Nowadays, people spend most of their time indoors, making healthy air quality essential for their well-being and performance. The air change rate (ACR), measured in h^{-1}, is a key parameter for assessing air quality, indicating how often indoor air is replaced. By measuring the ACR, the effectiveness of ventilation systems can be evaluated and improved as necessary. However, measured ACR values may, for practical reasons, deviate from the intended design values [1]. ACR measurement is typically performed by analyzing tracer gas concentrations at defined points within a room [2-5]. The commonly used tracer gas, SF_6, has the highest global warming potential. Real-time measurements require relatively high tracer gas concentrations, while lower concentrations require sampling in containers and time-consuming laboratory analysis, leading to delays and potential uncertainties in measurement quality. Various methods are used for ACR measurement, with the constant decay method using SF_6 considered especially accurate according to Weis et al., and thus widely applied [2-6]. Nevertheless, uncertainties for this method range from 10 % to 80 %, depending on the distribution of concentration and the measurement location, while device uncertainty itself ranges from only 1.5 % to 5 %.

A new optical measurement system for measuring ACR has been developed, tested, and validated. It provides real-time air change rates, is climate-friendly, and is significantly more cost-effective, achieving accuracy levels comparable to those of traditional measurement methods.

Measuring Method and Basics

The measuring system is based on the attenuation of light as the beam passes through an aerosol-air mixture. Depending on the aerosol particle concentration (aerosol used DEHS), the continuous-wave laser beam (laser class 2M) is attenuated as it traverses the measuring area, with only a portion of the light directed to the detector (CMOS sensor), see Figure 1.

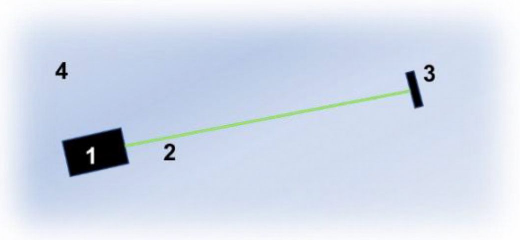

Fig. 1. Function principle: 1 laser, 2 Laser beam through measuring area, 3 Detector, 4 air-aerosol mixture

The measurement is conducted optically by analyzing the recorded brightness curve. The measurement process is shown in Figure 2 and is divided into four distinct phases. Initially, the baseline brightness without aerosol is measured, followed by the introduction and uniform distribution of the aerosol. After a brief settling period, the recording of the decay curve begins. Based on the formula principles for the ACR from concentrations according to the tracer gas decay method and the Beer-Lambert law, the ACR can be calculated according to eq. (1) using two defined points in time t_1 and t_2 and the corresponding brightness values. The brightness I_1 is lower than I_2 due to the higher aerosol concentration.

I_0 represents the initial brightness, measured without the introduction of aerosol particles. Additionally, the natural decay rate (NDR), which accounts for processes such as particle adhesion and evaporation, must be subtracted. This value is either known or measured in advance under the given ambient conditions. The result represents an average ACR between two timesteps.

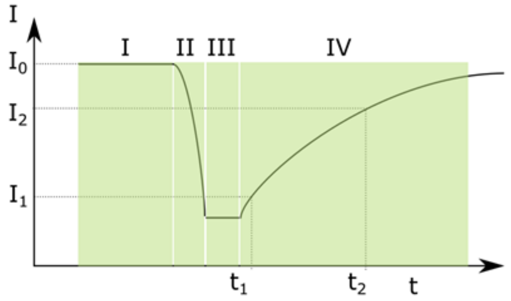

Fig. 2. Measurement phases' light intensity: I: baseline without aerosol concentration; II: aerosol introduction; III: uniform aerosol distribution; IV: aerosol dilution by ventilation

$$ACR = \frac{1}{t_2 - t_1} ln\left(\frac{ln\frac{I_0}{I_1}}{ln\frac{I_0}{I_2}}\right) - NDR \quad (1)$$

The ACR is also obtained from the exponent of the exponential regression fit according to eq. (2) and (3), which takes into account the entire curve.

$$\log\left(\frac{I_0}{I(t)}\right) = I_0 \cdot e^{-N\,t} \quad (2)$$

$$ACR \;=\; N - NDR \quad (3)$$

Description and Results

The measurement requires a constant laser intensity. Temperature-related fluctuations are compensated by using a reference beam measurement, while the influence of ambient light is minimized with the help of a bandpass filter and a stray light trap (baffle). Since the sensor records brightness values between 0 and 255, the radiation intensity is adjusted before measurement using a polarisation filter. CFD simulations of room airflow showed that local ACR measurements at a single point can deviate by up to 20% from the room's average ACR. The new measurement system is suitable for areas between 1 and 50 metres, allowing determination of both local ACR for specific areas and average ACR for the entire room. The brightness curve is analysed in real time using software. Validation measurements showed a maximum deviation of ACR of 6 % compared to volumetric ACR measurements and a maximum deviation of 6 % compared to SF6 tracer gas decay measurements. For the first time, the new measurement system enables precise ACR determination in real time without climate-damaging tracer gases. By using comparatively simple and harmless components, a time- and cost-efficient measurement system was developed that, in addition to determining average and local air change rates, can also measure the cleaning efficiency of filter-based devices in relation to aerosols.

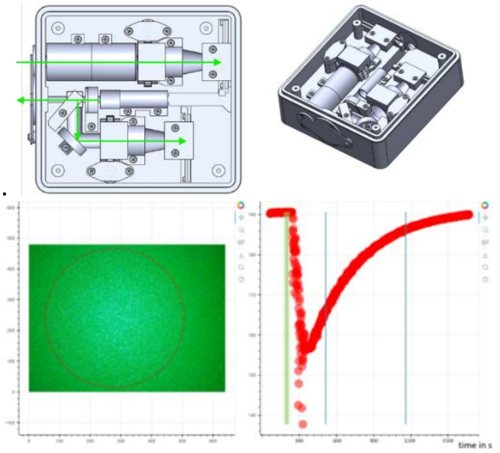

Fig. 3. Set-up of the measuring device (top); measuring software with signal and its progression (bottom)

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