Science of the Total Environment 560–561 (2016) 150–159

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Real-time sensors for indoor air monitoring and challenges ahead in deploying them to urban buildings

Prashant Kumar [a,b,*], Andreas N. Skouloudis [c], Margaret Bell [d], Mar Viana [e], M. Cristina Carotta [f], George Biskos [g,h], Lidia Morawska [i]

[a] Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences (FEPS), University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom
[b] Environmental Flow Research Centre, FEPS, University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom
[c] Joint Research Centre, European Commission, Institute for Environment and Sustainability TP263, via E Fermi 2749, Ispra, VA I-20127, Italy
[d] Transport Operations Research Group, School of Civil Engineering and Geosciences, Newcastle University, Claremont Road, Newcastle upon Tyne, NE17RU, United Kingdom
[e] Institute of Environmental Assessment and Water Research, IDAEA-CSIC, Jordi Girona 18, 08034 Barcelona, Spain
[f] IMAMOTER - C.N.R. Sensors and Nanomaterials Laboratory, via Canal Bianco 28, 44124 Ferrara, Italy
[g] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2628 CN, The Netherlands
[h] Energy Environment and Water Research Center, The Cyprus Institute, Nicosia 2121, Cyprus
[i] International Laboratory for Air Quality and Health, Queensland University of Technology, 2 George Street, Brisbane, Qld 4001, Australia

HIGHLIGHTS

- State of the art on air pollution sensing in indoor environments is reviewed.
- Technology for indoor air sensing has notably progressed, albeit challenges remain.
- Awareness of, and regulation for, IAQ are lagging behind the technology.
- Therefore, the emerging IAQ sensing technologies appear ahead of their time.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 17 February 2016
Received in revised form 25 March 2016
Accepted 6 April 2016
Available online xxxx

Editor: D. Barcelo

ABSTRACT

Household air pollution is ranked the 9[th] largest Global Burden of Disease risk (Forouzanfar et al., The Lancet 2015). People, particularly urban dwellers, typically spend over 90% of their daily time indoors, where levels of air pollution often surpass those of outdoor environments. Indoor air quality (IAQ) standards and approaches for assessment and control of indoor air require measurements of pollutant concentrations and thermal comfort using conventional instruments. However, the outcomes of such measurements are usually averages over long integrated time periods, which become available after the exposure has already occurred. Moreover, conventional monitoring is generally incapable of addressing temporal and spatial heterogeneity of indoor air pollution, or providing information on peak exposures that occur when specific indoor sources are in operation. This article provides a review of new air pollution sensing methods to determine IAQ and discusses how real-time sensing

* Corresponding author at: Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom.
E-mail addresses: P.Kumar@surrey.ac.uk, prashant.kumar@cantab.net (P. Kumar).

http://dx.doi.org/10.1016/j.scitotenv.2016.04.032

Keywords:
Indoor air quality
Air quality sensing
Gas sensors
Urban buildings
Human exposure
Low cost instrument

could bring a paradigm shift in controlling the concentration of key air pollutants in billions of urban houses worldwide. We also show that besides the opportunities, challenges still remain in terms of maturing technologies, or data mining and their interpretation. Moreover, we discuss further research and essential development needed to close gaps between what is available today and needed tomorrow. In particular, we demonstrate that awareness of IAQ risks and availability of appropriate regulation are lagging behind the technologies.

Contents

1. Introduction . . . 151
2. Key issues for IAQ monitoring . . . 152
3. State of the art in IAQ sensing . . . 152
 3.1. Gas sensors . . . 153
 3.2. Particle sensors . . . 153
 3.3. Packages of sensors . . . 154
4. The challenges: Monitoring design and data utilisation . . . 154
5. Potential benefits of IAQ sensing compared with traditional monitoring . . . 155
6. Regulations and awareness . . . 156
7. Conclusions and future outlook . . . 157
Conflict of interest . . . 157
Acknowledgements . . . 157
References . . . 157

1. Introduction

Indoor air quality (IAQ) is a growing concern in both the developing and developed world. The World Health Organisation linked 4.3 million deaths globally in 2012 to household cooking using coal, wood and biomass stoves, compared with 3.7 million deaths for outdoor air pollution. Most recent assessments have placed indoor air pollution as the 9th largest Global Burden of Disease risk (Forouzanfar et al., 2015). IAQ is affected by household-generated emissions of gaseous species, including volatile organic compounds (VOCs), particle matter (PM) of diverse size ranges (Heal et al., 2012) and microbial contaminants including bacteria, viruses and fungi. These pollutants deteriorate IAQ and have subsequent effects on human health. Another factor of significance to human wellbeing in indoor environments is thermal comfort; temperature and indoor air pollution are often interrelated and governed by ventilation. Mounting evidence links poor IAQ and thermal comfort with reduced human productivity and dissatisfaction in adults (Wyon, 2014), adverse impacts on the learning ability of school children (Wargocki and Wyon, 2013), and the growth of bacterial and fungal staining (blackening) on the building's interior walls and roofs (Kumar and Imam, 2013). Infiltration of outdoor air to indoor environment is another key factor affecting IAQ. This infiltration depends on the type and operation of the building ventilation system (natural or mechanical), as well as outdoor concentrations of the pollutants, which vary, and display heterogeneity and intra-city differences in pollutant concentrations (Kumar et al., 2013a; Zhou et al., 2013). Consequently indoor concentrations of both gases and PM, in the absence of indoor sources often show similar trends to outdoor environments, particularly in naturally ventilated buildings, and therefore can be estimated from the outdoor concentrations (Jones et al., 2000; Kumar and Morawska, 2013).

The primary methods to improve IAQ levels in most buildings are to control the indoor sources and building ventilation to dilute or remove indoor generated pollutants (Kumar et al., 2016). However, such methods are not aimed to apportion contributions from the individual indoor sources, or characterize peak concentrations. A number of conventional instruments are available for monitoring PM and gaseous pollutants to determine the IAQ but most of them have practical and technical limitations preventing them from being deployed in sufficiently large numbers in different parts of a house. These instruments also are expensive and incapable of providing high resolution spatio-temporal data, which is important for quantifying the peak exposure levels and identifying the key sources responsible for indoor air pollution, in order to design and implement mitigation strategies. In this context, a need for real-time gas and PM sensors for assessing IAQ is recognised, and their availability could potentially change the ways IAQ is managed. However, it is important to understand how indoor sensing differs from outdoor and what the unique challenges indoor environments present for IAQ sensing.

The first key feature required of IAQ sensing is low unit cost of sensor kits or systems (i.e., a network of sensor kits). This is often the case for both indoor and outdoor sensing technologies (Kumar et al., 2016; Kumar et al., 2015), however, the requirement that IAQ sensors are capable of detecting sufficiently low concentration levels of pollutants is more challenging. When these sensors are operated with batteries, they should be long-lived so that there is no need for their frequent replacement or to connect them to multiple power points within a building. Size is another factor, and ideally they should be miniaturized so that they can be distributed across the building discreetly without taking up too much space or disturbing people in residential and public buildings. And finally, they should be silent, in order to be accepted by the building occupants.

A further question is how realistic is it to deploy sensors for IAQ assessments. Many types of sensors have been used to measure air pollutants concentrations (Kumar et al., 2015), particularly for industrial applications and for vehicle emission monitoring, however, in both these cases the concentrations are high in the order of ppm compared to those found in indoor environments (IAQ EU Directives, 1989; WHO, 2010a, 2010b). As a result, the first challenge is to make these sensors more sensitive to low concentration levels. In doing so, however, we would run into problems of selectivity (i.e., there are many compounds in the air at low concentrations, which the sensors would detect, and give the similar response as to the compound we want to measure).

A number of review articles focuses on IAQ (Morawska et al., 2013; Luengas et al., 2015), outdoor air pollution sensing (Castell et al., 2014; Kumar et al., 2015), gaseous sensors (Xin et al., 2015) or health effects (Lim et al., 2012; Smith et al., 2000). However, none of them have