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Verification and application of continuous surface temperature monitoring technique for investigation of nocturnal sensible heat release characteristics by building fabrics

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ABSTRACT

This study verified and applied a novel technique, continuous surface temperature monitoring (CSTM), developed by the authors to investigate the nocturnal sensible heat release characteristics by building fabrics. The CSTM technique uses infrared technology to estimate the nocturnal sensible heat (SH) transfer between building finishes materials and the surrounding environment without knowing the physical and thermal properties of the tested materials. Forty-seven repeated indoor test were carried out for verification with the traditional internal energy equation (IE method), i.e. the product of mass, heat capacity and temperature change. The results were delightfully satisfactory with only 1.8–5.2% of average discrepancy. The R^2 value of 0.972 between the two methods suggested that the developed CSTM technique statistically fits well with sensible heat release calculated by IE method. This means that the CSTM technique can be used to estimate sensible heat release from an object with insignificant error. CSTM technique was then applied for investigating 13 building surfaces in Central, Hong Kong. The findings proved that CSTM technique can be applied on number of buildings simultaneously to investigate the sensible heat release characteristics of different types of building fabrics. The results showed that granite walls release more sensible heat than ceramic walls.

1. Introduction

During the past several decades, urban heating has started causing increased formation of harmful smog, resulting in human discomfort and health problems due to intensification of heat waves over cities and in increased demand for electricity [1–4]. The urban heat island (UHI) phenomenon and its characteristics were first studied by Howard [5]. UHI means the urban air temperature is higher than the rural air temperature, from sunset to sunrise. This has been extensively studied by different researchers around the world [2,6–9]. It has been proposed by Oke [9] that in many cases, the heat island is basically a nocturnal phenomenon attributable to differences in urban and rural cooling during the period around sunset. The primary cause of UHI is the growing use of high thermal mass materials such as concrete and asphalt for urban development [9]. Heat gets stored in higher thermal mass building materials and is re-radiated to the surrounding environment at night. The secondary contributor is anthropogenic heat release caused by energy usage, e.g., space cooling, industrial plants and vehicle exhausts. Effects of urban canyon situations worsen the case [10]. Hence, UHI is considered as a by-product of urbanization of human civilization [6,11,12] which creates highly unsustainable environment. It is considered as one of the major problems in the 21st century.

However, there are limited research works in extant literature that have studied direct measurement of heat flux on building fabrics at a particular period of time, e.g. morning, noon and at night [13–17]. As mentioned by Christen [18], due to the complicated configuration of surface materials, it is almost impossible to have direct measurement of storage heat flux in an urbanized area. Besides, it has been mentioned by Oke [9] that although in many instances it may be easy to identify an urban surface (e.g., a street 'canyon' which includes the street and its flanking walls), it becomes very difficult to define the urban surface for larger areas, up to and including the whole city. Therefore, in the early 1990s, many studies were based on the surface energy balance (SEB) model [3,9,19,20]. The heat released by building materials are mainly referred to as residual of the SEB equation [6] or derived by simulation programs, e.g., TAS and Envi-met [21,22].

Therefore, this study is motivated by the importance of studying energy released by building fabrics and the lack of research and methods for direct measurement of energy released by building fabrics. Instead of solely measuring the surface temperature of building structures, the proposed continuous surface temperature measurement (CSTM) technique measures the actual energy

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released from building fabrics to the outdoor environment during the cooling period. Thus, studying energy release characteristics of different building fabrics is possible, using the proposed CSTM technique. The energy release characteristics provide information for architects and engineers to choose suitable building materials and finishes fixing systems for lowering UHI effects.

2. Background and assessment methods for UHI study

First study of the heat island effect was conducted in London by Howard [5]. It is a major phenomenon observed in large cities. The increase in urban temperature is the most obvious consequence of urbanization [6,12], as it affects human comfort, health and economic growth [23]. Usually, methods for assessment of UHI effect can be classified into two approaches: urban heat island intensity (UHII) and SEB. The former is temperature based and the latter is energy based. UHII is used as an indicator of urban heating, calculated as the difference between spatially-averaged surface temperature [24,25] or air temperature [12,26–29] of urban and rural areas. It has been widely used in UHI researches. SEB is an energy based approach that includes measurement of different types of energy. It is a more complete and comprehensive set for measuring UHI. However, it requires data measurement by different instruments, such as radiometer, anemometer, thermometers and heat flux plates, etc. Because of the complexity of the measurement, many studies have derived SEB by numerical simulation [3,30–32]. This is also the reason why for field studies, researchers prefer to apply UHII, instead of SEB, as an indicator of UHI.

An energy based UHI indicator for field test was developed by Hoyano [14]. It is called the heat island potential (HIP), which is based on measuring sensible heat flux from building fabric [14,16,17,33]. HIP, instead of determining surface/air temperature difference between urban and rural areas, calculates the heat flux transferred by building materials to the surrounding environment [17]. Unlike comprehensive SEB, HIP is more convenient as it derives heat flux from building surfaces from surface temperature, neglecting the anthropogenic heat and focusing on sensible heat. The CSTM technique proposed in this study is quite similar to the HIP. It is also a tool to evaluate effects of different building materials in terms of UHI. Yet, radiative effects and convective energy transferred (J/m^2), instead of heat flux (W/m^2), are derived by CSTM. Unlike the previous studies on SEB or even HIP, CSTM takes into account the variable time, i.e. time for cooling. For identifying effects of different building materials on UHI, HIP is not enough to identify "hot" or "cool" materials since heat flux and surface temperature keep changing during the heat transfer period. A particular material can be hotter than another at one moment but cooler at another moment if the two have different cooling rates. Therefore, measurement over a period of time is proposed, instead of a specific time [34,35], to calculate energy heat release from building materials during the entire cooling period. Details of development of the CSTM technique are discussed in this study.

3. Methodology

The proposed CSTM technique is the only simple method for direct in situ measurement of energy release by building fabrics. The overall CSTM technique starts with formulation of the energy transfer equation by considering the surface temperature change. The basic principle of CSTM technique is that the total energy change of an object is closely correlated to the surface temperature change. The quantum of sensible heat transfer, mainly by convection and radiation, from building finishing materials to the environment, is reflected in its surface temperature change. Therefore, the total nocturnal sensible heat transfer can be estimated by integrating the total surface convective and radiative heat flux curves respective to the total cooling time after sunset (e.g., 4:00 p.m. to 6:00 a.m.). The "sensible heat transfer" is named as "sensible heat release" by building fabrics throughout this study for easy understanding, i.e. stored heat released out to the outdoor environment. On the other hand, by referring to the first law of thermodynamics, i.e. the rule of energy conservation, the internal energy change is equal to the energy transferred to the surroundings. Therefore, another simple method to estimate sensible heat transfer by an object is to calculate the total internal energy change of an object, namely, the internal energy (IE) method. The, IE method is applied to verify the effectiveness of CSTM technique.

CSTM calculates sensible heat transfer from building materials while IE equation calculates the total internal energy change of the building's materials. By the rule of energy conservation, after completion of the cooling process, the two variables should be equal to or proportional to each other (in case of heat loss by other means). In order to validate the proposed CSTM technique, verification tests are carried out in the laboratory on common building finish materials: concrete, marble, ceramic; and then field tests in Central, Hong Kong is carried out.

4. Formulation of CSTM equations

Development of the CSTM technique started with the fundamental equation of energy exchange of an object during a change of temperature. Sensible heat is the heat energy transferred from a surface to the surrounding air when there is temperature difference [36–39]. It can be estimated by calculating the change of IE. The magnitude of it is the product of the object's mass, m, its specific heat, c, and its temperature change, ΔT. According to [36], when the volume of the object is essentially constant for the heat transfer, and the whole object is having a uniform temperature, then sensible heat ΔSH [J] can be written as Eq. (1). According to the *first law of thermodynamics*, the principle of energy conservation means heat transferred outward is the total change of internal energy [40]. Hence, the following Eq. (1) is also named as IE equation in the rest of this study:

$$\Delta \text{IE} = \Delta \text{SH} = mc_p\Delta T = \rho V c_p \Delta T \quad (1)$$

where m refers to the mass of the object in [kg], c_p is the specific heat capacity in [J/kg °C], ΔT refers to the surface temperature change [°C], ρ [kg/m^3] is the density and V is the volume [m^3]. This equation enables us to calculate energy release by an object during the cooling period, provided thermal properties of materials and temperature differences are known. The CSTM technique tries to obtain ΔSH from another point of view, i.e. by integration of different forms of heat transfer to the surrounding environment. It is based on the first law of thermodynamics, energy conservation, i.e. change in internal energy is equal to the total heat gain or loss [40]. The merit of calculating heat release by different forms of heat transfer is that it does not require details of thermal properties of the tested materials. Instead, it requires measurement of surface temperature change of the object. The following sections show construction of equations used to calculate ΔSH by CSTM technique.

4.1. Construction of sensible heat equation for CSTM

As mentioned before, this study developed a novel technique to quantify the total sensible heat release by a material to the surrounding environment without knowing its thermal properties. According to Hoyano [17,33,41] and Berdahl [42], calculation of sensible heat does not include the effect of local heat conductivity of individual building materials. Therefore, the basic assumption of the CSTM technique is that the total sensible heat release (ΔSH)