2011 International Conference on Environment Science and Engineering
IPCBEE vol.8 (2011) © (2011) IACSIT Press, Singapore

A New Technique for Quantifying Sensible Heat Loss by Building Finishes

Janet F. C. Sham[1], Tommy Y. Lo[2]
Building and Construction Department[1,2]
City University of Hong Kong
Hong Kong, HKSAR
e-mail: fcsham@student.cityu.edu.hk[1]
e-mail: bctommyl@cityu.edu.hk[2]

Abstract— **This paper proposes a novel technique, continuous surface temperature monitoring (CSTM), that uses infrared technology to estimate the sensible heat (SH) transfer between building finishes materials and the surrounding environment *without* knowing the physical and thermal properties of the tested materials.**

Keywords-component; continuous temperature measurement, sensible heat, infrared technology

I. INTRODUCTION

During the past several decades, the urban heating causes the increase formation of harmful smog, causing human thermal discomfort, health problem due to the intensifying heat waves over cities and also increases the demand of electricity [1] [2] [3] [4]. Therefore, urban heat island (UHI) phenomenon and its characteristics have been extensively studied [3]. It has been proposed by Oke T., 1982 that in many cases, the heat island is basically a nocturnal phenomenon attributable to urban/rural cooling differences in the period around sunset [5].Researches on UHI problem have been carried out in many developing or developed countries such as USA, Korea, Vietnam, China, Tokyo, Thailand, Italy etc [6] [7] [8] [9].

Many studies show that the street canyon geometry on radiation and thermal properties of the building fabric is the primary causes on UHI [3] [10]. Solar energy absorbed by building surfaces and paved surfaces in daytime will be released at night. Hence, the urban heating is induced by the complexity of urban-structures design which has higher thermal admittance that can capture, store and release large quantities of heat energy [11] [12]. This causes the overall ambient temperature of urban areas higher than the surrounding rural areas. Therefore, study on the impact of building materials to UHI becomes essential. There are different approaches used for UHI study, most of them are done by numerical simulation modeling [13] [14] [15] [16] [17] [9] [6], satellite data for capturing horizontal surface temperatures, e.g. roofs and pavements [6] [18] [7], and weather station data [19] [11] [20]. Only limited study involves capturing data by field tests [21] [22] [23] [18] [24]. Some of them used infrared technique to capture the vertical surface temperatures [18] [22] [24] [23].

Usually, urban heat island intensity (UHII) is used as an indicator of urban heating. It is calculated as the difference between spatially-averaged surface or air temperature of urban and surrounding rural areas [19] [25] [11]. Besides UHII, there is a relatively new index called the heat island potential (HIP) which is based on sensible heat flux [26] [23].The authors also agreed that sensible heat flux should be a more suitable parameter for estimating thermal effects on the atmosphere from building fabrics [26]. However, instead of studying heat flux which reflects the heat flow per unit area *per unit time* (W/m^2); this study investigates the total amount of heat flow per unit area *over a period of time* (J/m^2), say at night. Therefore, a continuous surface temperature monitoring (CSTM) technique is developed to investigate the total (convective and radiative) heat flow from the building to the surrounding air. The study mainly focused on nocturnal period (cooling period) because the heat stored at building fabric will be released at night when the air temperature is lower than the fabric temperature.

II. THEORY

A. Sensible Heat Equation (SH): $mc\Delta T$

Heat transfer is usually in three modes: conduction, convection, and radiant emission. Sensible heat is heat energy transferred from a surface to the surrounding air when there is temperature difference. The magnitude of it is the product of object's mass, *m*, its specific heat, *c,* and its temperature change, ΔT. Assuming that the volume of the object is essentially constant for the heat transfer, and the whole object as having a uniform temperature, then sensible heat , ΔSH [J] can be written as (1):

$$\Delta SH = mc\Delta T = \rho vc\Delta T \qquad (1)$$

where, *m* refers to the mass of the object in (kg), *c* is the specific heat capacity in ($J/kg\cdot{}^{o}C$), $\Delta \boldsymbol{T}$ refers to the (surface) temperature change (${}^{o}C$), ρ (kg/m^3) is the density and $\boldsymbol{V}$ is the volume (m^3).

This equation enables us to calculate the energy loss by an object within a specific period of time, e.g., at night, provided that the thermal properties and temperature differences are known.

B. Development of CSTM Technique

This study developed a simple technique for estimating the total sensible heat loss of a material to the surrounding environment without knowing its thermal properties. The energy loss by conduction is assumed to be negligible. The basic assumption of the CSTM technique is that the total sensible energy change per unit area [J/m^2] of the object is equal to the total convective and radiative heat flux from the object to the surrounding environment over a period of time. The total heat flux q_w, by the combined mechanism of convection and radiant emission, can be expressed in (2) [27]. It is a function of time of cooling as shown below:

$$q_w = h_c\left[T_w(t) - T_{air}(t)\right] + h_r\left[T_w(t) - T_{radsurface}(t)\right] \quad (2)$$

where q_w [W/m^2] is the heat flux of surface w, i.e. heat energy transferred per second per unit area of the surface w, T_w [^{o}C] is the surface temperature of the object. It is measured by the infrared camera. T_{air} [^{o}C] is the ambient temperature which is measured by the thermometer. $T_{rad.\ surface}$ [^{o}C] is the radiative surface temperature, i.e. the surrounding surface temperature which causes radiative heat transfer. In this study, since the surrounding environment is in a steady state, it is assumed that the surrounding radiative surfaces are at the equilibrium temperature of the ambient temperature; therefore, the surrounding radiative surface temperature, $T_{rad.\ surface}$ is assumed to be equal to the ambient temperature. It is t [s] is the time for cooling. h_c [J/s·m^2·^{o}C] and h_r [J/s·m^2·^{o}C] are the convective and radiative heat transfer coefficients, respectively.

It is assumed that the magnitude of wind velocity is constant over the cooling area; therefore, according to the ASHRAE Handbook [28], the equations for estimating the convective heat transfer coefficient h_c, under free convection with wind velocity set to zero and without considering its spatial distribution, are as follows (Eq. 3):

$$\text{If} \quad L^3\Delta T<1, \quad h_c = 1.42(\Delta T / L)^{0.25}$$

$$\text{If} \quad L^3\Delta T>1, \quad h_c = 1.31(\Delta T / L)^{\frac{1}{3}} \quad (3)$$

where L [m] is the characteristic length of the sample.

In addition, the radiation heat transfer coefficient h_r can be defined as [27,29]:

$$h_r = 4(\varepsilon\sigma)(T_{air})^3 \quad (4)$$

where ε is the emissivity and σ is the Stefan-Boltzmann constant, $\sigma = 5.6697\text{x}10^{-8}$(W/m^2·^{o}C^4).

Eq. (2) assumes that the heat transfer of an object is dominated by convection and radiation, where conduction is neglected. The total energy released can be found by integrating the convective and radiative heat flux over a period of time as shown below:

$$\Delta SH/A = \int_0^t q_w dt$$

$$(\rho Vc\Delta T)/A = \int_0^t h_c\left[T_w(t) - T_{air}(t)\right] + h_r\left[T_w(t) - T_{radsurface}(t)\right]dt \quad (5)$$

where A (m^2) is the convective and radiative area of the object.

By referring to (5), the integration of the time behavior of heat flux is equal to the total heat energy transferred per unit area of the object by convection and radiant emission. It is also equivalent to the total sensible heat loss from the object to the surrounding environment. The parameters required to calculate the heat flux, q_w include an object's surface temperature, $T_{w,}$ air temperature, T_{air}, and convective and radiative heat transfer coefficients (h_c +h_r). Hence, no information on thermal properties such as mass and specific heat capacity are needed to calculate the total convective and radiative/sensible heat loss as required in (1). The foregoing calculus assumes that the change in surface temperature of the object is mainly contributed by convection and radiant emission. Therefore, the sensible heat (SH) mentioned in the following sections all refer to the convective and radiative heat transfer from the tested object to the surrounding environment.

III. Laboratory Validation

A. Experimental Setup

Four test samples, 1) concrete, 2) marble, 3) clay and 4) ceramic were heated under the sun at noon for 3 hours (11 am to 2 pm), and the changes in surface (radiant) temperature were recorded at intervals of 60 and 120 seconds in the laboratory by infrared camera [FLIR type PM 695] with accuracy ±2oC and thermal sensitivity of 0.08oC. The air temperature (hence radiative surface temperature) was measured by electronic thermometer [Digi-Sense Thermocouple Thermometer Dual J-T-E-K] with accuracy ±0.4^{o}C. Since two instruments were being used for measuring the two variables (i.e. surface temperature and air temperature). Therefore, systematic errors do exist in the test. This can be minimized by carrying out calibration of the two instruments.

Besides, errors on surface temperature reading by infrared camera may occur if the setting of emissivity is wrong. Therefore, the samples were sprayed with flat black paint, which optimized the heat energy absorbed by the samples and also enhance the radiation emitted by the samples. The emissivity that refers to the black object was set as 1 in the camera. The samples were arranged as in Fig. 1(a). The infrared camera was placed perpendicular to the sample surface to minimize any error caused by an altered angle of view. Further, insulation (i.e. nylon sheet) was placed between the samples and the table to minimize heat loss to the table (by conduction). Temperature data are recorded at the centre of the sample surfaces as shown in Fig. 1(b): Sp1 (concrete), Sp2 (marble), Sp3 (clay) and Sp4 (ceramic), and the ambient temperature is measured by thermometer. The samples are shown in Fig. 1, and the details of the four building finish samples and the parameter settings for data analysis are listed in Table I.

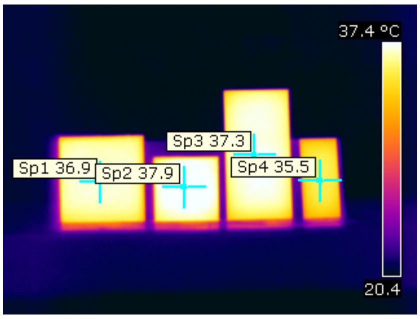


Figure 1. Thermal image of the four common building materials.

TABLE I. PARAMETER SETTINGS AND MATERIALS PROPERTIES OF THE FOUR BUILDINGS FINISHES SAMPLES

PARAMETER SETTINGS				
Recording time (seconds)	7000			
Recording intervals (seconds)	120	60		
MATERIALS PROPERTIES				
	Concrete	Marble	Clay	Ceramic
Density (kg/m^3)	2305	2647	2783.4	2676
Heat capacity (J/(kg·K))	837	808	879	850
Emissivity (black)	1	1	1	1
Volume (m^3)	0.0002	0.0001069	0.000094864	0.0000214
Exposed area (m^2)	0.026	0.0153	0.0268	0.009725
Length (cm)	10	7.5	15.4	9.5

B. Validation Results

In order to testify the applicability of CSTM technique on calculating sensible heat loss of different materials, validation tests were carried out. Six repeated measurements that were taken on different dates within January to May in the laboratory on sensible heat loss; estimated by the CSTM technique and calculated by the formal SH equation ($mc\Delta T$). The cooling curves of different materials are shown as follows (Fig. 2):

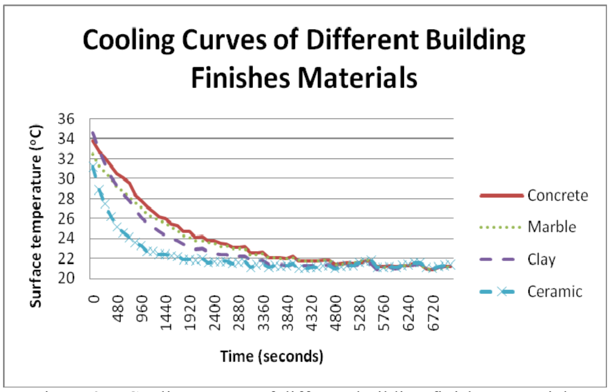


Figure 2. Cooling curves of different building finishes materials

The surface temperature change ($T_w(t)$-$T_{air}(t)$) obtained from the above cooling curves will be put in (5) for calculating the sensible heat loss. The results revealed that using the CSTM technique is quite satisfactory: the average percentage discrepancy $\left(\frac{CSTM - SH}{SH}\right)$ of the six tests on the four different building finishes tile materials is about 11.86% and the standard deviation of the percentage discrepancy is 9.40%. The above results are then processed with paired t-test (with confident level of 95%) in order to check whether there is significant difference between the results obtained by the two methods. The t-test results are listed in the following Table. II:

TABLE II. T-TEST RESULTS OF CSTM AND SH EUQATION

	CSTM	**SH equation**
Mean	120727.5958	121861.6083
Variance	4358678487	4776332422
Observations	24	24
df	23	
t Stat	-0.337520194	
P(T<=t) one-tail	0.369392893	

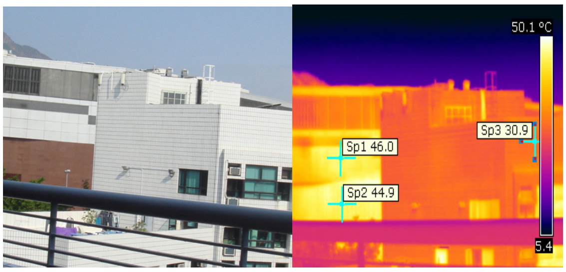
According to the above table, the p-value is 0.37 (p-value > 0.05), that means it can be said that the two sets of sample data has no significant difference with 95% confidence level.

IV. FIELD MEASUREMENT

A. Experimental Setup

Three types of building fabrics: Aluminium panel, granite panel and ceramic tiling are measured in-situ by CSTM. The measurement was taken at the rooftop of the academic building located inside the City University of Hong Kong. Two buildings with three different types of building fabrics were examined. The recording interval is set as 900secs.

The photo and the corresponding thermal image are shown in the following Fig. 3(a) and (b) respectively. Besides, the results are shown in the next section.



(a) (b)

Figure 3. Cooling curves of different building finishes materials

B. *Experiment Results*

The cooling curves of the three wall finishes are shown in the following Fig. 4. It shows that the cooling curve of the building fabric with ceramic tiling is significantly different from the building fabric with aluminium and granite panel. It has lower surface temperature.

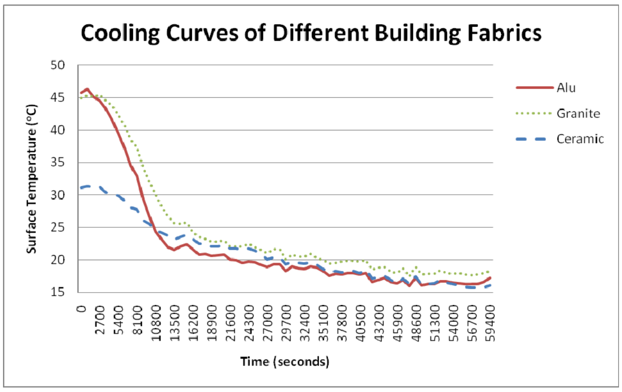


Figure 4. Thermal image of the four common building materials.

The above surface temperature change are then put in (5) and the sensible heat flux curves of the three wall finishes are constructed. As mentioned before, the integration of the sensible heat flux curves with respect to the cooling time. The sensible heat energy released by the three examined wall finishes are derived. The results are listed in the following Table III:

TABLE III. ENERGY RELEASED OF DIFFERENT WALL FINISHES

Material	Energy Released (J/m^2x10^6)
Aluminium wall finishes	3.0
Granite wall finishes	3.5
Ceramic wall finishes	2.2

From the above Table III, it shows that granite wall has the highest amount of energy released per unit area ($3.5J/m^2$),. The lowest is ceramic wall finishes, i.e. 2.2 J/m^2.

V. CONCLUSION

In summary, this preliminary study proposed a new technique, Continuous Surface Temperature Measuring (CSTM) technique for in-situ quantification of energy released by building fabrics. The merit of this method is that physical and thermal properties of the building fabric are not required in the whole process. Besides, the result of the laboratory validation test shows that the average percentage difference of the proposed CSTM and traditional SH equation is only 11.86%. After t-test, the p-value is 0.37 (p-value > 0.05), that means it can be said that the two sets of sample data has no significant difference with 95% confidence level. This method can also be used for calculating different energy releasing level of different building fabrics and their influence on urban heat island effect.

REFERENCES

[1] *Long-term performance of high-albedo roof coatings.* Bretz, Sarah E. and Akbari, Hashem. 1997, Energy and Buildings, Vol. 25, pp. 159-167.

[2] Santamouris, M. *Energy and Climate in the Urban Built Environment.* London : James and James Science Publishers, 2001.

[3] *Simulation of surface urban heat island under "ideal" conditions at night-Part 2: diagnosis and causation.* Oke, T. R., et al. 1991, Boundery Layer Meterology, Vol. 56, pp. 339-358.

[4] Siegel, R. and Howell, J. *Thermal Radiation Heat Transfer.* 4th. New York : Taylor and Francis, 2002.

[5] *The energetic basis of urban heat island.* Oke, T.R. 455, 1982, Journal of the Royal Meteorological Society, Vol. 108, pp. 1-24.

[6] *Urban heat island modeling in conjunction with satellite-derived surface/soil parameters.* Hafner, J. and Kidder, S.Q. 1999, Journal of Applied Meteorology, Vol. 38, pp. 448-465.

[7] *Assessment with satellite data of the urban heat island effects in Asian mega cities.* Hung, T., et al. 1, 2006, International Journal of Applied Earth Observation and Geoinformation, Vol. 8, pp. 34-48.

[8] *Modeling and simulation of the Tokyo urban heat island.* Saitoh, T. S., Shimada, T. and Hoshi, H. 1995, Atmospheric Environment, Vol. 30, pp. 3431-3442.

[9] *A canopy layer model and its application to Rome.* Bonacquisit, V., et al. 2006, Science of the Total Environment, Vol. 364, pp. 1-13.

[10] *Simulation of surface urban heat islands under "ideal" conditions at night Part 1: Theory and Tests Against Field Data.* Johnson, G.T., et al. 1991, Boundary Layer Meteorology, Vol. 56, pp. 275-294.

[11] *An investigation of urban heat island intensity (UHII) as an indicator of urban heating.* Memon, Rizwan Ahmed, Leung, Dennis Y. C. and Liu, C. H. 2009, Atmospheric Research, pp. 491-500.

[12] *Weekly storage of coolness in heavy brick and adobe walls.* Bahadori, Mehdi N. and Haghighat, F. 1985, Energy and Buildings, pp. 259-270.

[13] *Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model.* Bruse, M. and Fleer, H. 1998, Environmental Modelling and Software, Vol. 13, pp. 373-384.

[14] *Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate.* Toudert, F. A. and Mayer, H. 2006, Building and Environment, Vol. 41, pp. 94-108.

[15] *Environmental study of the impact of greenery in an institutional campus in the tropics.* Wong, N.H., et al. 2007, Building and Environment, Vol. 42, pp. 2949-2970.

[16] *An approach for coupled simulation of building thermal effecs and urban climatology.* Tanimoto, J., Hagishima, A. and Chimklai, P. 2004, Energy and Buildings, Vol. 39, pp. 781-793.

[17] *Urban canopy modeling of the New York city* metropolitan area: a comparison and validation of single and *multilayer parameterizations.* Holt, T. and Pullen, J. 2006, Monthly Weather Review, Vol. 135, pp. 1906-1930.

[18] *Linking satellite images and hand-held infrared thermography to observed neighborhood climate conditions.* Hartz, D.A., et al. 2006, Remote Sensing of Environment, Vol. 104, pp. 190-200.

[19] *The urban heat island effect at Fairbanks, Alaska.* Magee, N., Curtis, J. and Wendler, G. 1999, Theoretical and Applied Climatology, Vol. 64, pp. 39-47.

[20] *Spatial and temporal structure of the urban heat island in* Seoul. Kim, Y. and Baik, J. 2005, Journal of Applied Meteorology, Vol. 44, pp. 591-605.

[21] *Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong.* Giridharan, R., Ganesan, S. and Lau, S.S.Y. 2004, Energy and Buildings, Vol. 36, pp. 525-534.

[22] *Experimental study of temperature and airflow distribution inside an urban street canyon during hot summer weather conditions. Part I: Air and surface temperatures.* Niachou, K., Livada, I. and Santamouris, M. 2008, Building and Environment, Vol. 43, pp. 1383-1392.

[23] *Analysis of the sensible heat flux from the exterior surface of buildings using time sequential thermography.* Hoyano, Akira, Kohichi, Asano and Takehisa, Kanamaru. 1999, Atmospheric Environment, Vol. 33, pp. 3491-3951.

[24] *Diurnal thermal behaviour of selected urban objects using remote sensing measurements.* Chudnovsky, A., Ben-Dor, E. and Saaroh, H. 2004, Energy and Buildings, Vol. 36, pp. 1063-1074.

[25] *Spatial and temporal structure of the urban heat island in Seoul.* Kim, Y. and Baik, J. 2005, Journal of Applied Meteorology, Vol. 44, pp. 591-605.

[26] *Development of a method to predict the heat island potential using remote sensing and GIS data.* Iino, Akinaru and Hoyano, Akira. 1996, Energy and Buildings 23, Vol. 23, pp. 199-205.

[27] Ozisik, Necati M. *Heat Transfer: A Basic Approach.* USA : McGraw-Hill, 1985.

[28] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook Fundamentals.* Atlanta : s.n., 2005.

[29] *Preliminary survey of the solar reflectance of cool roofing materials.* Berdahl, P. and Bretz, Sarah E. 1997, Energy and Buildings, Vol. 25, pp. 149-158.