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Dynamic model for measurement of convective heat transfer coefficient at external building surfaces

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ABSTRACT

Uncertainties in current empirical models for the convective heat transfer coefficient (CHTC) have large impact on the accuracy of building energy simulations (BES). These models are often based on measurements of the CHTC, using a heated gradient sensor, where steady-state convective air flow is assumed. If this requirement is not fulfilled there will be a dynamic measurement error. The objectives were to construct a validated dynamic model for the heated gradient sensor, and to use this model to improve accuracy by suggesting changes in sensor design and operating procedure. The linear thermal network model included three state-space variables, selected as the temperatures of the three layers of the heated gradient sensor. Predictions of the major time constant and temperature time evolution were in acceptable agreement with experimental results obtained from step-response experiments. Model simulations and experiments showed that the sensor time constant increases with decreasing CHTC value, which means that the sensor response time is at maximum under free convection conditions. Under free convection, the surface heat transfer resistance is at maximum, which cause enhanced heat loss through the sensor insulation layer. Guidelines are given for selection of sampling frequency, and for evaluation of dynamic measurement errors.

1. Introduction

The convective heat flux q_c (W m^{-2}) from the building above-ground external surface is an important heat transfer process in the simulation of building energy performance. Usually, q_c is expressed as:

$$q_c = h_c (T_s - T_a) \quad (1)$$

where h_c (W m^{-2} K^{-1}) is the CHTC, T_s (K) is the building exterior surface temperature, and T_a (K) is the outdoor air temperature. The h_c coefficient depends on several factors, for examples building geometry, surface roughness, air flow pattern, and wind speed V (ms^{-1}) at some reference position. Many empirical models exist that correlate h_c and V in specific cases, some based on wind tunnel studies of flat plates (see e.g. Jürges [1]), while other models stem from field h_c measurements, using a sensor placed on the building surface [2–6]. There is a high uncertainty in the h_c values predicted by such empirical correlations, and when these values are used as input data to BES programs, this leads to uncertainty in the simulation results [7,8]. Part of the uncertainty in predicted h_c values from empirical models is due to measurement error in h_c.

There exists several methods for measurement of the heat flux and external CHTC (see reviews by [9–11]). Among these methods, the most commonly used within the field of building physics for measurement of CHTC is the heated gradient sensor type, as pioneered by Ito et al. [2]. The heated gradient sensor consists of a gradient heat flux meter (HFM), heated from its back side, using a resistive heater, and equipped with a thermometer for measurement of its front surface temperature T_s (K). The HFM estimates the conductive heat flux q_d (W m^{-2}) through the sensor by measuring the temperature gradient across a slab, using a series of thermocouples. The sensor front surface is in contact with the air boundary layer, whose h_c value is to be measured. The momentary heat balance of the sensor front surface is given by:

$$q_d + I_s/a = q_r + q_c \quad (2)$$

where a is the sensor surface area, I_s (W) is the short-wave solar radiation, and q_r (W m^{-2}) is the net thermal radiation:

$$q_r = \varepsilon_s \sigma \left(T_s^4 - T_r^4 \right) \quad (3)$$

with ε_s = the surface emissivity, σ = the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and T_r (K) = the mean radiant

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temperature. The heat balance of Eq. (2) has been used in various ways for estimation of h_c. In the Ito method [2], for example, two sensors were used simultaneously, which enabled the effects from I_s and q_r to be cancelled out. If a single sensor was used (e.g. [4–6]) then I_s and q_r are first estimated separately, and then h_c is obtained by rearranging Eqs. (1) and (2) into:

$$h_c = \frac{q_c}{T_s - T_a} = \frac{q_d + I_s/a - q_r}{T_s - T_a} \quad (4)$$

Because the heat balance of Eq. (2) does not include heat storage in the sensor body, its application for determination of h_c, by Eq. (4), is valid only when there is no change in stored heat, i.e. when the input quantities of Eq. (4) are at steady-state. Studies where heat storage is taken into account in the heat balance of the heated gradient sensor are rare, and we know only one such work, that of Jayamaha et al. [5], although their sensor was operated with a control system set to keep the rate of heat storage equal to zero. To ensure that steady-state conditions prevail during the measurement of h_c, the sensor response time should be shorter than the time-scale of variations in the environmental parameters involved, e.g. in T_a, T_r, I_s, and in wind speed V.

The objective of the present work was to construct and validate a dynamic model of the heated gradient sensor [2] for measurement of the local CHTC at exterior building surfaces. This model enabled evaluation of effects on measurement accuracy due to limited sensor response time. It also yielded suggestions for improvement of the sensor design, and for selection of sensor operating conditions.

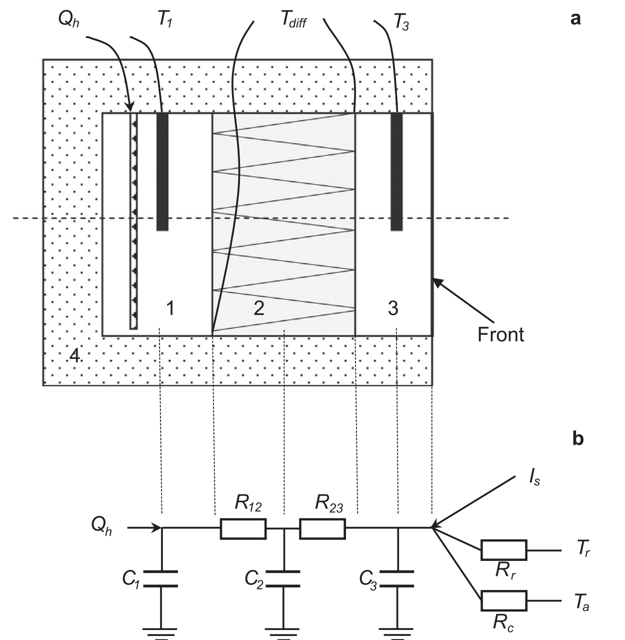

Fig. 1. (a) Schematic cross-sectional drawing of the CHTC sensor, with cylindrical symmetry around the center axis (dashed line). The bottom (1), HFM (2), and top (3) layers, were surrounded by insulation (4), except at the sensor front surface. The electrical heater supplied the heat flux Q_h. The temperatures T_1 and T_3 were measured using PRT probes inserted into the bottom and top layers, respectively. The HFM series of thermocouples measured the temperature difference T_{diff} across the HFM layer. (b) The thermal RC network model.

2. Thermal RC network model

Among the approaches to modelling of thermal dynamic systems, thermal network models are particularly useful, since they incorporate the system behavior into a limited number of state variables, the system temperatures or heat fluxes X_i (K). The time evolution of the system could then be expressed by the time derivative of the vector $\boldsymbol{X}(t)$ as:

$$\dot{\boldsymbol{X}} = f\left(\boldsymbol{X}(t), \boldsymbol{W}(t)\right) \quad (5)$$

where f is a (non-linear) function of the momentary values of $\boldsymbol{X}(t)$ and $\boldsymbol{W}(t)$, and $\boldsymbol{W}(t)$ is the vector of input variables (here, the electrically supplied heat flux, and the environmental parameters). The pseudo-bond graph method (ref. [12], ch.12) was here applied to describe the h_c sensor as a thermal network consisting of resistive (R) and capacitive (C) components, in analogy to electrical RC networks.

Essentially, the h_c sensor, as used by [2–6], consists of a stack of three layers (cf. Fig. 1(a)): (1) the metal bottom layer, which evenly distributes the heat flux Q_h (W), supplied by an electrical heater, over the sensor cross-sectional area a (m^2), (2) the HFM layer, and (3) the metal top layer, which at its front surface emits heats by radiation and convection. Fig. 1(b) shows the thermal RC network, where the bottom and top layers were modelled as pure capacitances, C_1 and C_3 ($J\,K^{-1}$), respectively, since their resistances were negligibly small in comparison to the other thermal resistances of the sensor (cf. Table 1). However, the HFM layer, with its thermal resistance R_2 (KW^{-1}), was modelled using three elements: one center capacitance C_2, and two flanking resistances, R_{12} and R_{23} ($R_2 = R_{12} + R_{23}$). The front surface was thermally connected to its surrounding through radiative and convective thermal resistances, R_r and R_c (KW^{-1}), respectively. The back-side of the sensor, and its side surfaces, faced an insulation layer, which is modelled here as an adiabatic wall, i.e. having an infinite thermal resistance (does not appear in the RC network).

The R and C quantities were estimated from layer thickness H (m), layer thermal conductivity λ ($W\,m^{-1}\,K^{-1}$), density ρ ($kg\,m^{-3}$), and specific heat capacity c_v ($J\,kg^{-1}\,K^{-1}$), as follows:

$$R = \frac{H}{\lambda a} \quad (6)$$

$$C = \rho a H c_v \quad (7)$$

With a sensor radius $r = 40$ mm, we get $a = 5.0 \cdot 10^{-3}\,m^2$. The specification of the HFM (model HFP01, Hukseflux Thermal Sensors, Delft, Netherlands) states that $\lambda_{HFM} = 0.8\,W\,m^{-1}\,K^{-1}$, $H = 0.005$ m, and that its response time is $\pm$ 3 min. Assuming that this response time equals the thermal time constant, we obtained the HFM layer time constant as $\tau_{HFM} = 180s = R_2 C_2$. With $R_2 = 1.25\,KW^{-1}$, estimated based on Eq. (6), we then estimated C_2 to equal 144 $J\,K^{-1}$. We also obtain $\rho c_v = C_2/(aH) = 5.76 \bullet 10^6\ J\,K^{-1}\,m^{-3}$. Table 1 summarizes the parameter estimates of the sensor thermal network model.

The convective heat flux Q_c (W) at the sensor top surface was given as:

$$Q_c = q_c a = \frac{1}{R_c}\left(T_s - T_a\right) \quad (8)$$

where R_c (KW^{-1}) is the convective heat transfer resistance. By comparison with Eq. (1), we obtained $R_c = 1/h_c a$. For the long-wave radiative heat flux Q_r (W) we have:

$$Q_r = q_r a = \varepsilon_s \sigma a \left(T_s^4 - T_r^4\right) \quad (9)$$

Due to moderate temperature differences $\left(T_s - T_r\right)$, Eq. (9) was here linearized into:

$$Q_r = \frac{1}{R_r}\left(T_s - T_r\right) \quad (10)$$