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Frequency response limitation of heat flux meters

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ABSTRACT

Heat flux meters are used for measuring the heat flux densities going through walls, usually at quasi-steady state. The limitations of heat flux meters under dynamic conditions are well documented in the literature; nonetheless there is a theoretical limitation which is mostly not considered and should be also taken into account. Since heat transfer is a dissipative process, it would be expected to obtain transfer functions which act as low pass filters. Nonetheless, this paper shows that the transfer functions modeling heat flow rate may become high pass filters, which is against the physical evidence. In order to show this theoretical limitation of the heat flux meters, the heat equation is transformed in different classes of models, from partial differential equations to transfer functions related to surface temperatures and heat flux density going through a wall.

1. Introduction

Energy efficiency of buildings has an increased interest due to the necessity of tackling primary energy consumption in modern societies as well as societies in development [1]. The evaluation of energy efficiency of buildings requires the measurement of their thermal performance, and particularly, thermal performance of walls which are usually studied assuming the classical heat transport theory [2]. There are significant discrepancies between predicted and measured thermal performances of buildings and building components [3]. The reason of such discrepancies may be diverse:workmanship, making tests at stationary state or at dynamic conditions, etc. [4,5]. A gap may exist between predicted and measured thermal performances, but it should be quantifiable. Therefore, efforts need to be focused on defining experimental techniques in-situ to be used so that predicted and measured thermal performances to be in agreement.

As noted, the guideline for the assessment of wall thermal performances is the classical theory of heat transfer [2]. One usual estimation method is the heat flux meter method [6–13], which gives a measure of the heat flux density going through a wall assuming that the heat flux meters have negligible thermal resistance in comparison with the wall thermal resistance; then, heat flux through a heat flux meter is assumed equal to heat flux through the wall on which it is plastered [14,15]. Heat flux meters are useful for measuring heat flux through surfaces of homogeneous walls at steady state or quasi-steady state conditions. However, among other practical problems, heat flux through non-homogenous walls and/or under dynamic conditions is not well captured by the heat flux meters [14,10]. Anyway, in-situ measurements may be used for solving parameter identification problems, i.e. for estimating thermal resistances and capacitances of walls in order to obtain wall thermal performances of building component [16]. For this, solar irradiance, ambient and surface temperatures are usually considered independent variables or inputs (driving functions) and heat flux density is considered a dependent variable or output (response function). It is assumed that heat flux density going through the heat flux meters, $q_{hfm}(\mathrm{W/m^2})$, which is due to the difference of heat flux meter surface temperatures, T_{hfm1} and $T_{hfm2}(^\circ C)$, equals the heat flux density going across the outdoor/indoor surface of the wall. A heat flux meter gives estimations of heat flux densities by using its surface temperatures and its known thermal resistance, $R_{hfm}(\mathrm{K/W})$, Fig. 1.

Due to experimental limitations of heat flux meters, it is recommended the use of thermal cameras for choosing a representative area of the wall where placing sensors and it is noted that sensors should not be exposed to direct solar irradiance or only night time data may be included in the analysis [14]. Different in-situ studies avoid such limitations by measuring heat flux across the outdoor/indoor surfaces locating heat flux meters indoors instead of outdoors [4,17–19]. Nonetheless, the identification

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Nomenclature

b_i	temperature source on branch i, $^\circ C$ or K
C_i	thermal or heat capacity in node i, J K^{-1}
C_{wall}	thermal capacity of the wall, J K^{-1}
c	specific heat capacity, J kg^{-1} K^{-1}
e_i	temperature difference over the thermal resistance R_i, $^\circ C$ or K
f_i	heat rate source in node i, W
I_s	solar irradiance, W m^{-2}
N	number of nodes
p	heat sources, W m^{-3}
q_i	heat rate on the branch i, W
Q_i	heat flux density inside the wall, W m^{-2}
R_i	thermal resistance on the branch i of the thermal network, K W^{-1}
R_{wall}	thermal resistance of the wall, KW^{-1}
R_{si}	indoor surface heat transfer resistance, KW^{-1}
R_{so}	outdoor surface heat transfer resistance, KW^{-1}
s	complex variable
S	wall surface area, m^2
T_o, T_i	outdoor, indoor air temperature, $^\circ C$ or K

Greek letters

α	wall absorptivity
κ	thermal conductivity, W $m^{-1}K^{-1}$
θ	spatial temperature distribution, $^\circ C$ or K
θ_i	temperature of node i, $^\circ C$ or K
θ_{so}, θ_{si}	surface temperatures outside, inside, $^\circ C$ or K
ρ	density, kg m^{-3}
$\partial/\partial t$	differential operator in time
$\nabla\cdot$	divergence operator
∇	gradient operator

Vectors and matrices

$\mathbf{A}$	incidence matrix of the thermal network
$\mathbf{A}^T$	transpose of the incidence matrix
$\mathbf{A}_d$	state matrix in the state-space model (discrete time)
$\mathbf{A}_S$	state matrix in the state-space model (continuous time)
$\mathbf{B}_d$	input matrix in the state-space model (discrete time)
$\mathbf{B}_S$	input matrix in the state-space model (continuous time)
$\mathbf{b}$	vector of temperature sources on the branches
$\mathbf{C}$	diagonal matrix of thermal capacities
$\mathbf{C}_S$	output matrix in the state-space model
$\mathbf{D}_S$	feed through matrix in the state-space model
$\mathbf{f}$	vector of heat rate sources
$\mathbf{f}_C$	vector of heat rate sources connected to nodes with a thermal capacity
$\mathbf{f}_0$	vector of heat rate sources connected to nodes without a thermal capacity
$\mathbf{G}$	diagonal matrix of thermal conductances
$\mathbf{H}_S$	transfer matrix
H_{ij}	output i regarding to input j component of transfer matrix
$\mathbf{H}_d$	discrete transfer matrix
H_{dij}	output i regarding to input j component of discrete transfer matrix
$\mathbf{I}$	identity matrix
$\mathbf{u}$	input vector in the state-space model

Vector in Greek letters

$\boldsymbol{\theta}$	vector of temperatures
$\boldsymbol{\theta}_C$	vector of temperatures in nodes with a thermal capacity
$\boldsymbol{\theta}_0$	vector of temperatures in nodes without a thermal capacity

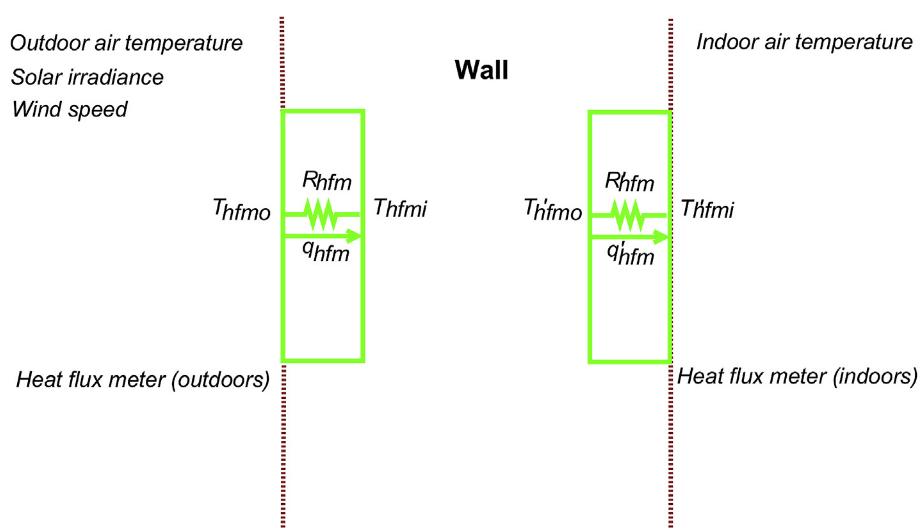

Fig. 1. Heat flux meters located on the outside and inside faces of a wall.

problem could be solved by considering solar irradiance, ambient and surface temperatures only. In this sense, wall surface temperatures would be assumed as dependent variables or outputs.

This paper aims to overview well-known experimental problems related to the use of heat flux meters and to highlight a theoretical problem which appears in the use of heat flux meters, that is, transfer functions related to heat transfer may become high pass filters against physical evidence [20]. Section 2 introduces heat