International Communications in Heat and Mass Transfer 78 (2016) 214–223

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Experimental investigation of the influence of convective and radiative heat transfers on thermal transmittance measurements☆

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ARTICLE INFO

Available online 30 September 2016

Keywords:
Thermal transmittance
Heat flow meter
Convective coefficient
Radiative coefficient

ABSTRACT

Walls thermal transmittance value (U-value) is essential to identify the performance of a wall and it is used for the energy labeling procedure. If on one hand the heat-flow meter can measure heat fluxes across its plate giving back the wall's U-value, on the other hand, if air temperatures and wall's inner surface temperatures are measured, it is necessary to set the total heat transfer coefficient value in order to calculate the heat fluxes. Many correlations were developed in scientific literature to quantify the convective heat transfer coefficient and it is possible to distinguish similarity based and experimentally ones.

In this paper, the actual total heat transfer coefficients in different case studies were obtained by measuring the physical parameters that are needed to define them. Convective and radiative contributions were separately evaluated and, finally, actual convective heat transfer coefficients were compared with the same coefficients obtained by applying the correlations available in literature and with the constant value suggested by the Standard.

The aim of this study is to analyze the differences between the various coefficients values and their influence on the thermal transmittance evaluation, in order to better understand the existing correlations and the UNI EN ISO 6946 applicability. This is an initial part of a research which aims to provide an overall more accurate representation of the building behavior, forthcoming developments will deal with the analysis of heat transfer on the outer side of walls.

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1. Introduction

It is well known that the behavior of walls highly influences annual energy needs. Many findings in literature demonstrate how the effect of dispersions through opaque surfaces affects the annual energy consumption of buildings [1–4]. Wall performances are calculated through the thermal properties of each layer; when it is not possible to obtain information about materials thermal properties, the Standards provides thermal conductivity and conductance values [5,6]. Low thermal conductivity values allow achieving high thermal resistance values. For this reason, a good performance is influenced by material type, thickness and mass density of each layer. Regarding stationary conditions, an electro-thermal analogy is generally used to calculate heat flows across walls, which can be modeled as a series of resistors crossed by the heat flow [7]. On the other hand, taking into account existing buildings characterized by unknown stratigraphies, it is possible to investigate walls performances by using proper measurement techniques.

Currently, two techniques can be used to determine the thermal resistance value in existing buildings: the *in-situ* heat-flux measurement, which is a non-destructive method [8,9], or the direct inspection of the building envelope layers through direct measurement of their thickness (destructive method). The non-destructive method involves the employment of a heat-flow meter, which has to be used in compliance with the standard ISO 9869 [10].

The aim of this study is to evaluate the influence of different convective heat transfer coefficient expressions on thermal transmittance evaluation and to assess the impact of these differences on measured U-values, highlighting the resulting dissimilarities. Starting from the many correlations found in literature (they are also very different considering the way they were obtained) and the need to assume a convective heat transfer coefficient in order to evaluate the U-value (*i.e.* when only air temperature and surface temperature probes are used to measure the thermal transmittance of a wall), the influence of the *h* coefficient on the thermal transmittance final value was investigated. The convective heat transfer coefficients were calculated by using both similarity-based and experimentally-based correlations.

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.09.008
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Nomenclature

Ar	Archimedes number
g	Gravity acceleration [m/s^2]
Gr	Grashof number
h	Total convective heat transfer coefficient [W/m^{2}K]
h_{avg}	Average total convective heat transfer coefficient
h_{conv}	Convective heat transfer coefficient [W/m^{2}K]
h_{rad}	Radiative heat transfer coefficient [W/m^{2}K]
H	Height of the vertical surface [m]
L_c	Characteristic length [m]
Nu	Nusselt number
Pr	Prandtl number
q	Heat flux [W]
Ra	Rayleigh number
Re	Reynolds number
R_i	i-th layer thermal resistance [m^{2}K/W]
R_{se}	External surface resistance [m^{2}K/W]
R_{si}	Internal surface resistance [m^{2}K/W]
R_{tot}	Wall total thermal resistance [m^{2}K/W]
T_{air}	indoor air temperature [°C]
T_e	External air temperature [°C]
T_i	Internal air temperature [°C]
T_m	Average thermodynamic temperature
T_{si}	Internal surface temperature [°C]
ΔT	Temperature difference between surface and air [°C]
T_{sup}	Surface temperature [°C]
u	Inside air velocity near the wall [m/s]
U_{avg}	Thermal transmittance average value [W/m^{2}K]
U-value	Thermal transmittance value [W/m^{2}K]
v	Wind velocity [m/s]
β	Cubic expansion coefficient [1/K]
ε	Emissivity
λ	Thermal conductivity [W/mK]
ν	kinematic viscosity [m^2/s]
$\boldsymbol{\sigma}$	Stefan-Boltzmann constant [W/m^{2}K^4]

2. State of the art

2.1. U-value measurement

While U-values measurements in lab conditions are reliable and controlled [11,12], the accuracy of *in situ* U-value measurements are affected by many factors, such as the heat flow meter location. On this basis, Meng et al. [13] conducted a study on the influence of the thermocouple location, the pasting location, pasting angle, shape and size of the heat flow meter on the *in situ* measurement accuracy of the U-value. The authors proposed an optimized choice of the various parameters, in order to improve the *in situ* measurement accuracy of the heat flow meter method. In their study, Desogus et al. [14] made a comparison of different measuring methods of buildings fabric thermal resistance, applying invasive and non-invasive methods, measuring the test wall physical characteristics, employing the heat-flux meter method and the destructive sampling one. Thermal resistance measurements could be affected by structural abnormalities, if they are detected in the measuring region. Due to this, a preliminary thermographic analysis is essential: this technique allows identifying heat losses paths, such as those due to cold bridges and missing or bad walls insulation [15,16].

Asdrubali et al. [17] showed the outcomes of a measurement campaign conducted to investigate the *in situ* thermal transmittance of several green buildings; differences ranging from −14 to +43% were found between calculated and measured U-values. The authors employed the instruments following the instructions contained in the reference Standards [10]. In [18] *in situ* U-value measurements by means of a few commercial heat flow meters under different measuring conditions and envelope components were performed. The authors showed the results of an experimental campaign finalized to assess the metrological performance of the heat flow meters and to evaluate the influence of environmental conditions. Moreover, *in situ* measured U-values were compared with the estimated ones from design data and field analyses. The results indicated a good behavior of the heat flow meter when tests are conducted according to ISO 9869. Wang et al. [19] proposed a method aimed to the dynamic analysis of *in situ* data taking into account wind velocity, in order to assess the wall thermal resistance by measuring the interior and the exterior heat fluxes and temperatures. A heat flow meter experiment platform considering wind velocity was built, on which the proposed method, the mean method and the dynamic analysis method suggested by the international Standard ISO 9869 were applied to the test wall under different wind velocities. In [20] Peng and Wu performed *in situ* measurements of the thermo-physical characteristics of a room using the heat-flow meter method according to the ISO 9869; three different methods were used to estimate the thermal insulation of a test chamber.

2.2. Convective coefficients

As mentioned, the U-value can be calculated by means of the electrothermal analogy, according to the UNI EN ISO 6946 [21]. This Standard shows the procedure and suggests outside and inside surface resistances values for different heat flow directions. These resistances are function of radiative and convective heat transfer mechanisms. Many studies were conducted in order to identify correlations able to describe convective heat transfer coefficients. There are many similarity-based and experimental expressions of these coefficients calculated for different boundary conditions. Most of the convective coefficients were derived starting from a flat plate configuration and from tests in monitored rooms. The common correlations suggested by ASHRAE [22] are founded on the statement that the surface convective heat transfer phenomenon of the external wall of a building is comparable to the one that occurs along a flat slab. Natural convection was analyzed by Churchill and Chu [23] and Churchill and Usagi [24] taking into account uniformly heated and cooled vertical plates and suggesting a generalized correlation effective over the full range of Rayleigh and Prandtl numbers. Alamdari and Hammond [25] applied a similar method in order to achieve correlations for buoyancy-driven convective heat flow in buildings characterized by natural ventilation, under laminar and turbulent flows. Aiming to make their correlations simpler, they stated that Rayleigh number can be substituted with an expression depending on the difference between film temperature and surface temperature, making negligible the characteristic length effect for turbulent flow. They found that this approach involves a small error over the temperature values verified in building simulation. Fohanno and Polidori [26] focused on correlations for homogeneously heated (vertical) surfaces in building, characterized by laminar or turbulent flows. In order to obtain their expressions, they assumed heat flows and temperature values equal to the average ones. All these correlations are widely described in literature, for instance in critical reviews [27].

Furthermore, many researchers provided convective heat transfer correlations derived by experiments in indoor spaces equipped with particular air-conditioning systems [27]. Min et al. [28] published measurements outcomes regarding indoor convective heat transfer, by means of a full-scale room. Awbi and Hatton [29] studied natural convective phenomena from heated surfaces in test rooms with different sizes. Khalifa and Marshall [30] analyzed an extended range of relevant heating cases for buildings, also considering homogeneously heated surfaces. They employed a full-scale room in order to define convective heat transfer coefficients for all surfaces. These convective coefficient expressions are written in the standard form $h = C(\Delta T)^n$, where C and n have different values in each expression. Only the expressions in

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