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Sensitivity analysis of predicted night cooling performance to internal convective heat transfer modelling

Kim Goethals [a,*], Hilde Breesch [b], Arnold Janssens [a]

[a] Research Group of Building Physics, Construction and Services, Department of Architecture and Urban Planning, Faculty of Engineering, Ghent University, J. Plateaustraat 22, B-9000 Ghent, Belgium

[b] Sustainable Building Research Group, Department of Construction, Catholic University College Ghent, Gebroeders Desmetstraat 1, B-9000 Ghent, Belgium

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ABSTRACT

The potential of night cooling, a passive cooling technique of growing interest, is typically investigated by numerical means. In particular multi-zone energy simulation is currently appraised for building design. Unfortunately, in addition to the inaccurate approximation of an ideally mixed room, the implemented empirical convective heat transfer coefficients (CHTCs) only apply to specific flow regimes – forcing to use arbitrary correlations and, thus, possibly limiting the usefulness of the simulation results. Therefore, the authors of this paper investigate the sensitivity of the night cooling performance to convection algorithms. First, the authors examine the applicability of convection correlations for real building enclosures, extracted from literature. Subsequently, simulations of a night cooled office room during summertime of a moderate climate (Belgium) are carried out in TRNSYS, using different convection correlations in addition to varying design parameters. The results show that the choice of the convection algorithm strongly affects the energy and thermal comfort predictions. More importantly, the convection algorithm is of the same importance as the design parameters – making an exact definition of the CHTC crucial. Therefore, additional research by experiments or airflow codes, based on fluid dynamics, is regarded necessary.

1. Introduction

Developments in information technology, since the mid-1960s, have led to opportunities to study thermal processes in buildings dynamically. Until then only simple hand calculation methods were available. Today, multi-zone energy simulation (BES) software coupled with airflow codes, based on fluid dynamics, can provide information on all locations in and outside a building of any desired variable. However, high computational costs of computational fluid dynamics (CFD) limit its usability to the domain of academics or specialists. Moreover, competency in handling complex airflow codes brings about a steep learning curve for practicing engineers. Therefore, stand-alone BES is currently appraised for building design. Alongside the implementation of more advanced heat transfer models such as ray-tracing for view factor calculation together with radiosity models, the radius of BES has widened substantially, integrating not strictly thermal physical processes, but also e.g. illumination [1] or moisture transport in fabric [2]. Unfortunately, the prediction of the interior convective heat transfer still remains ill-defined. Some BES programs, such as DOE-2 and SUNREL, combine convection with inter-surface radiation by modelling the two processes with a combined transfer coefficient. More recently (re)developed dynamic whole-building simulation programs – e.g. ESP-r, EnergyPlus, TRNSYS – model radiation and convection separately, increasing the adaptability and, thus, their accuracy. These programs employ the so-called well-mixed assumption. This treats the room air as uniform and characterizes the surface convective heat transfer by a convective heat transfer coefficient (CHTC) and by the temperature difference between the room air and the internal surface.

Predominantly, these convection coefficients rely on correlations derived from experimental data. However, the convective heat transfer algorithms can also be based on boundary layer theory, admitting a pure theoretical development [3]. More recently, first cautious steps are taken towards modelling the convective heat transfer by CFD – as performed by, amongst others, Awbi and Salmerón et al. [4]. Anyhow, comparison of convection correlations reveals strongly differing convective heat transfer predictions. Alongside the investigated flow regime and the mechanism of fluid flow, the dimensionality of the experimental/simulation model itself plays an important part in deriving convection correlations. For example, the majority of the correlations recommended by CEN [6] are derived from data mainly based on experiments with isolated horizontal and vertical surfaces. Although these studies treat an important class of problems with many practical engineer-

* Corresponding author. Tel.: +32 9 264 78 61; fax: +32 9 264 41 85.
E-mail address: kim.goethals@ugent.be (K. Goethals).

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Nomenclature

A	area (m^2)
a_{front}	solar absorptance at the inside of the wall
Ar	Archimedes number ($\beta \cdot g \cdot L \cdot (T_{exh} - T_{sup}) \cdot v^{-2}$)
C, C_1, C_2, n, n_1, n_2	correlation constants
D_h	hydraulic diameter ($4 \cdot A \cdot P^{-1}$) (m)
g	gravitational acceleration ($m\,s^{-2}$)
H	characteristic height (m)
h_c	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$h_{c,for}$	convective heat transfer coefficient in case of forced convection ($W\,m^{-2}\,K^{-1}$)
$h_{c,mix}$	convective heat transfer coefficient in case of mixed convection ($W\,m^{-2}\,K^{-1}$)
$h_{c,nat}$	convective heat transfer coefficient in case of natural convection ($W\,m^{-2}\,K^{-1}$)
J	jet momentum number ($n \cdot v_{sup} \cdot g^{-1}$)
L	characteristic length (m)
n	air change rate (ach)
q_{conv}	convective heat flux ($W\,m^{-2}$)
Q_{conv}	convective heat transfer rate (W)
P	perimeter (m)
R	thermal resistance ($m^2\,K\,W^{-1}$)
$T_{a,l}$	local air temperature (°C)
$T_{a,r}$	room air temperature (°C)
T_{exh}	exhaust temperature (°C)
$T_{a,e}$	outside air temperature (°C)
T_{ORMT}	outdoor running mean temperature (°C)
T_s	surface temperature (°C)
T_{sup}	supply temperature (°C)
TE	temperature excess hours (h)
v	fluid velocity ($m\,s^{-1}$)
v_{sup}	supply temperature ($m\,s^{-1}$)
W	width of the nozzle (m)
β	volumetric thermal expansion coefficient (K^{-1})
ΔT	difference between surface and reference temperature (°C)

ing applications, the suitability of these coefficients for building energy analysis is at best questionable. By neglecting the inherent three-dimensionality, complexities in real building enclosures, which significantly affect the flow pattern and the heat transfer, are not taken into consideration – as shown by Clarke [7]. Bearing this in mind, numerous researchers have shown the sensitivity of thermal predictions to the modelling of internal convection. The worthy effort of the IEA [8], solely focusing on heating and free-floating conditions, acknowledged the dominant role of convective heat transfer in the building's energy balance, next to more detached attempts [9–21]. Moreover, the importance is believed to significantly increase in case of high ventilation rates, such as night cooling – as explored in e.g. Artmann et al. [11]. Unfortunately, before-mentioned authors based their investigation on arbitrary values of the CHTC – i.e. independent of the interior and ventilation system design, limiting their authority. Note that this last-mentioned passive cooling technique constitutes a valuable alternative to energy-wasting mechanical cooling using an air conditioning system – as experimentally shown by, amongst others, Blondeau et al. [12] and Høseggen [13]. In fact, at night – when the outdoor air temperature is usually lower than the building temperature, natural or mechanical ventilation cools down the building fabric. The following day, the thermal mass absorbs the heat by solar and infrared radiation and room air convection, affecting the internal conditions by day as follows: reducing peak air temperatures and the operative temperature while creating a time lag between the occurrence of external and internal maximum temperatures [14,15]. As a result, building users enjoy an improved thermal comfort while clients can possibly build smaller mechanical cooling plants – or even leave out – and operate their buildings more efficiently. Finally, reduction of the peak cooling demand would be of great interest to the power generating industries. Thus, as the design and performance analysis of this passive cooling technique of growing interest is typically based on numerical modelling, the authors of underlying paper believe that further analysis of the CHTC is crucial.

Therefore, the authors of this paper assess the impact of empirically derived convection algorithms on the night cooling performance, relative to the most meaningful design parameters. First, based on an extensive literature review, this paper reports on the applicability of convection correlations for BES. Extending the work of Khalifa [16] and Beausoleil-Morrison [10], this study focuses on algorithms derived for real building enclosures. Subsequently, numerical simulations of a night cooled office during summertime of a moderate climate (Belgium) are carried out in TRNSYS. In this, the authors implement different convection correlations – which are not necessarily apt for the flow regime at hand – to assess the impact on the predicted night performance. Finally, this sensitivity analysis also varies the design parameters to investigate the relative importance of the choice of convection algorithms.

2. Applicability of CHTC correlations in full-size enclosures: literature review

2.1. Fundamental considerations

Newton introduced the concept of CHTCs stating his 'Law of Cooling':

$$\frac{Q_{conv}}{A} = h_c \cdot \Delta T \quad (1)$$

The heat flux, $Q_{conv} \cdot A^{-1}$, occurs by virtue of a temperature difference between the surface and the surrounding fluid ΔT. This simple equation is the defining relation for the convection coefficient h_c. However, a substantial portion of work involves the determination of the CHTC as it is related to the mechanism of fluid flow – natural, forced or mixed, the flow regime – laminar or turbulent, the properties of the fluid and the geometry of the specific system of interest. Furthermore, the choice of a reference temperature proves delicate for indoor air in buildings. In particular, defining a characteristic dimension and choosing a reference temperature leaves room for interpretation and limits the applicability of the CHTCs for use in BES – as shown in the following sections.

2.1.1. Characteristic dimension

To account for the scale of the system, convective heat transfer correlations preferably include a characteristic dimension or length scale. Unfortunately, the works of e.g. Khalifa [17] and Khalifa and Marshall [18] go on a single size configuration. As a consequence, their correlations apply only to geometries similar to the experiment setup. When a length scale is actually part of the convection correlation, its definition depends primarily on the mechanism of fluid flow. Alamdari and Hammond [19] and Awbi and Hatton [20] link the natural convection heat transfer coefficient to the height or the hydraulic diameter of the considered surface. After all, the density differences causing fluid to flow come from the temperature difference between the surface and the surrounding air. On the other hand, as forced convection correlations relate, amongst others, to the velocity, some authors take into account a characteristic dimension of the external agent – e.g. the nozzle width of the fan [21]. Meanwhile, Spitler et al. [22,23] and Fisher et al. [24,25] rely on the room volume, given one specific inlet. In conclusion, next to