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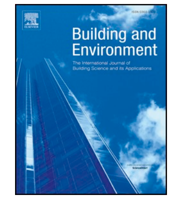

Development of a dynamic external CFD and BES coupling framework for application of urban neighbourhoods energy modelling

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ABSTRACT

Current building energy models are weak at representing the interactions between neighbourhoods of buildings in cities. The effect of a neighbourhood on the local microclimate is complex, varying from one building to another, meaning that neighbourhood effects on the airflow around a particular building. A failure to account for this may lead to the miss-calculation of heat transfer and energy demand. Current building energy simulation (BES) tools apply convective heat transfer coefficient (CHTC) correlations, which were developed by using a simplified model of wind flow that neglects neighbourhood effects. Computational Fluid Dynamics (CFD) techniques are able to model these neighbourhood effects and can be used to improve CHTC correlations.

This work aims to develop a framework that couples CFD and BES tools to enhance the modelling of outdoor convective heat transfer in different urban neighbourhoods. A dynamic external coupling method was used to combine the benefits from both domains. Firstly, a microclimate CFD model was validated before the coupling stage using wind tunnel data. Secondly, the framework was tested using a benchmark model of a building block. Fully converged values of the surface temperature and CHTC were achieved at each time-step by the BES and CFD domains. The results highlight the importance of neighbourhood effect while the prediction of the hourly averaged external convection using coupling method can amend the simulation by up to 64% comparing to the standalone conventional BES models with DOE-2 CHTC approach.

Nomenclature

h_c	W/m^{2}K	convective heat transfer coefficient	T_s	°C	building surface temperature
q_c''	W/m^2	convective heat flux	U	m/s	flow velocity
δ	m	site boundary layer thickness	z	m	altitude, height from ground
α		exponent of wind speed profile	T_a	°C	air temperature
T_b	°C	air temperature at ground level	L_a	K/m	air temperature gradient within troposphere
E_r	m	radius of the Earth	H_b	m	additional height to the troposphere
I		turbulence intensity	u'_z	m/s	rms velocity fluctuation
k	J/kg	turbulence kinetic energy	ε	m^2/s^3	turbulent dissipation rate
C_μ		k–ε model constant	h^*	W/m^{2}K	virtual h_c for ENERGYPLUS
T_g	°C	ground temperature	P	Pa	pressure
ρ	kg/m^3	density	u		fluctuating component of velocity vector
μ	kg/ms	molecular viscosity	μ_t	kg/ms	eddy viscosity
H	m	height of target building (prototype)	E_1		simulation error
q_{hr}		hit rate	N		number of observations

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$FAC2$		fraction of predictions within a factor of two of observations	i, j, k		3 dimensional component as subscript
o		observed value	p		predicted value
$D_{q_{hr}}$		relative deviation of q_{hr}	$W_{q_{hr}}$		absolute deviation of q_{hr}
U_c	m/s	computed time averaged velocity vector	U^*	m/s	time averaged instantaneous scalar velocity
L	m	length of target building (prototype)	W	m	width of target building (prototype)

1. Introduction

The building sector consumes about 21% of world's delivered energy [1]. Its share is around 40% in many developed countries, such as the U.S., the UK and in most EU countries [2,3]. The growth of energy demand of the built environment is expected to occur in countries with an emerging market economy [1] attributable to rapid and continuous urbanization projected up to 2030 [4]. Urbanization is accompanied by an increase in urban density, and changes to district planning and regional microclimates. With populations shifting from rural to urban locations, more attention should be placed on reducing the energy demand of buildings, especially in the urban context. In particular, a better understanding and assessment of building energy demands in cities can help decision makers to propose appropriate regulations for indoor and outdoor environments and aid urban planners in the design and modification of cities. However, they are hampered by a lack of comprehensive modelling tools capable of considering the complexity of urban morphologies and dynamic neighbourhood environments, known as the *neighbourhood effect*.

There are many simulation packages capable of modelling building energy demands, such as ENERGYPLUS, REVIT, DOE-2, and EQUEST. They calculate heating/cooling loads by simultaneously solving mass and energy conservation equations for a finite number of zones [5]. Convection is an important mechanism of heat transfer at a building's exterior whose effect can be two to three times larger than the radiant transfer [6–8]. Simplified outdoor airflow models have reported errors of 20–40% when predicting total building energy demand [9]. Predictive errors in the calculation of convective heat transfer are related to the improper capture of local dynamic wind gradients. Current building energy simulation (BES) tools use an empirical convective heat transfer coefficient (CHTC), which is often not accurate enough for a specific case, especially in complex urban contexts where the neighbourhood effect shapes the microclimate around a building. Instead, the algorithms embedded within them treat building clusters the same way as an isolated building. This is because they were developed through specific in-situ measurements [10] and so they are unable to increase account for variations in urban morphologies.

Computational fluid dynamics (CFD) techniques can solve the conservation laws at various scales and are known for their strength in modelling airflows. CFD has been widely applied to environmental studies of different scales, from indoor climates to district and city communities [11–18]. However, CFD does not include the dynamic response of the buildings into the microclimate. The coupling, or integration, of CFD and BES techniques can compensate for their individual limitations and offer a more accurate assessment of the built environment. In such scenarios, CFD is used to discretise the fluid domain and BES to discretise the building energy load calculation [19].

In general, there are two methods of coupling CFD and BES tools, known as *internal* and *external* coupling. The internal approach is used to expand the capability of existing programs by developing new code. However, application of this method is very limited [20] due to its high computational expense, convergence concerns and high cost for development [21]. Conversely, external coupling is a more widely used method, perhaps because BES and CFD techniques are each well developed, albeit separately. More accurate predictions of building energy demand can be obtained by using the advantages of each tool. Fig. 1 shows different types of BES-CFD coupling. Among all the coupling methods, fully dynamic coupling provides the most accurate results as iterative calculation of each time step is guaranteed with converged results between two programs.

Previous applications of the external coupling of CFD and BES tools have mostly focused on the prediction of CHTC for interior surfaces [5,21,23,24]. Building energy demand assessment can be enhanced by using a coupling technique to take account of the effects on the microclimate of a single building of its surrounding neighbourhood. Existing studies that use outdoor coupling are very limited [25–29]; for example, Mochida et al. [25] and Allegrini et al. [27] used the cross-ventilation rate, estimated by site-scale CFD simulation, as the input for the BES analysis. Although their CFD domain covered the outdoor environment, the main change in BES occurred inside the room due to the updated ventilation rate, but there was no significant improvement of the exterior CHTC. Nikkho et al. [29] proposed wind factors to modify the wind profiles in the BES domain. The factors were dependent on the local terrain and urban morphologies, but they did not differentiate between surfaces or buildings because the weather data was applied uniformly to each object in the BES domain. Yi and Feng [26] and Malys et al. [28] used CFD to improve surface CHTC for BES. Some of these studies were designed for specific cases, and so do not generally reflect miscellaneous and random urban morphologies [25,28,29]. Also, most of the executed couplings [25–27,29] between tools lack an iterative process that improves predictive accuracy, and so the dynamic coupling approach is recommended.

This study aims to develop a practical and general framework for the coupling of CFD and BES tools, to improve the prediction of CHTC values, and to improve the prediction of the energy demands of buildings located in urban neighbourhoods. Section 2 outlines an appropriate coupling approach, communications between BES and CFD tools, and the CFD microclimate modelling method. Section 3 validates the CFD microclimate model using empirical measurements made in a wind tunnel so that can be used to investigate the energy demand of a case-study building. A case-study building, which is a simple city block located in Los Angeles as an example of an extreme climate, is introduced. In this section, four scenarios are explored, where the location of the case-study building is varied inside its neighbourhood to demonstrate the impact of surrounding buildings. A comparison of the external façade CHTC for each location is used to show the importance of the neighbourhood effect.

2. Methodology

2.1. A general approach to couple CFD and BES tools

The external method is adopted for the integration of BES and CFD. Mutually-consistent geometrical models are created in the BES and CFD domains with coherence in the boundary name. Buildings are tested using a fully dynamic approach to ensure that convergence is guaranteed for each time-step; see Fig. 1. Here, convergence is a unique solution shared by both domains. For this study, both domains achieve the same (or with only a slight difference) convective heat flux (q_c'') for outdoor surfaces at every time-step before moving to the next one.

A schematic of the coupling process for the building energy assessment is presented in Fig. 2. The goal of this framework is to improve the assessment of the energy demand of any building or community. Information required by the framework includes site data, building designs and operation conditions. Bespoke code is used to transfer customized inputs and meteorological data to the two domains. The