Measurement of the Impact of Buildings on Meteorological Variables

Dasaraden Mauree – Ecole Polytechnique Fédérale de Lausanne – dasaraden.mauree@epfl.ch
Laurent Deschamps – Ecole Polytechnique Fédérale de Lausanne – laurent.deschamps@epfl.ch
Paul Bequelin – Laboratory, Ecole Polytechnique Fédérale de Lausanne – paul.becquelin@epfl.ch
Pierre Loesch – Ecole Polytechnique Fédérale de Lausanne – pierre.loesch@epfl.ch
Jean-Louis Scartezzini – Ecole Polytechnique Fédérale de Lausanne – jean-louis.scartezzini@epfl.ch

Abstract

A meteorological tower was installed on the EPFL campus in a semi-urban environment for the high frequency monitoring of the microclimate. This project was done in the larger framework of the measurement of the meteorological profiles, and also for a quantification of the energy consumption and the outdoor human comfort. A long-term monitoring of various meteorological variables like wind speed, air temperature, turbulence, humidity is realized by the use of 3D sonic anemometers, surface temperature sensor, and a meteorological station so as to analyse the micro-climate in an urban context.
The preliminary results from the experimental setup confirm that the wind speed is considerably modified in the urban canopy. We show that the decrease in the wind speed will have a significant effect on the heat convection coefficient. Furthermore, we demonstrate that it is possible to reconstruct the air temperature along the vertical axis with a correction using the data from the meteorological station. In the near future, a net radiometer will be installed to analyse the influence of the incoming and outgoing radiation in the urban setup on the energy balance of the district.

1. Introduction

The Fifth Assessment Report (AR5) issued by the IPCC (Intergovernmental Panel on Climate Change) in 2013, stated that there is clear evidence that the current global warming is being caused by human activities. There is compelling proof this is due to the release of greenhouse gases (GHG) such as carbon dioxide (CO2) from the combustion of fossil fuels to produce energy (IPCC, 2013). A large proportion of global energy demand has been related to buildings that are therefore, one of the main sources of air pollution. Approximately half of the primary energy use in Switzerland occurs in buildings. Of this energy, about 30 % is consumed by space heating, cooling, and water heating; 14 % by electricity use, and 6 % by construction and maintenance (SFOE, 2011). In addition, the building sector accounts for more than half of the CO2 emissions in Switzerland, which shows that it is among the most significant contributors to carbon emissions. This implies also that the building sector provides a real opportunity for a large improvement with regards to energy efficiency and reduction of CO2 emission. The efficient planning of future buildings and districts will only be possible if urban planners have the appropriate tools and information at their disposal. For example, the future development of the EPFL campus shows the need to densify the existing building stock (Coccolo et al., 2015), but the question still remains on its design in order to reduce energy consumption while at the same time increase the liveability of the outdoor environment.
It is now well known that the urban climate depends on a series of processes taking place at different spatial (from global to local) and temporal scales (Oke, 1982); building energy demand and urban climate are also closely related and interdependent (Ashie et al., 1999; Salamanca et al., 2011; Mauree et al., 2015). It is thus essential to have access to tools, which can evaluate - with precision - the interactions that exist between buildings, their energy use, as well as the local climate. Several models have been developed in the recent years to better represent the various phenomena that influence the energy use and the urban climate (Krpo et al., 2010; Mauree et al., 2017; Mauree et al., 2017a). One of the major drawbacks of these models

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is the lack of data to validate and to further understand the various processes taking place in the urban areas.

The monitoring of high resolution vertical meteorological profiles is essential to determine the impact of urban areas / buildings on these variables: it is necessary to represent these effects when evaluating building energy use, air pollutant dispersion, and renewable energy potential in urban planning scenarios. Monitored meteorological data are scarcely available with high vertical resolution. Campaigns such as the BUBBLE (Rotach et al., 2005) observation period provide useful information and data to develop and generalize new parameterization schemes. However, there is a strong need for such data and in multiple configurations in order to develop new tools and methodologies which can then be used in the evaluation of building energy use. The vertical profiles of variables such as wind speed and direction, and the air temperature in the vicinity of buildings are crucial in the determination of the momentum and heat fluxes.

In the current study, we first give an overview of the experimental setup, the type of instruments that have been installed, and details related to their configuration. We then give the preliminary results from the setup and provide a sensitivity analysis of the heat convection coefficient. Finally, we conclude and give a few perspectives for the current study.

2. Experimental Setup

This experiment was set up in the framework of the MoTUS (Measurement of Turbulence in an Urban Setup) project (motus.epfl.ch). In the following sections we describe the setup, instruments, and calculations done for the various instruments.

2.1 Mast

For this purpose of the study, a 27 m mast was installed on the EPFL campus in Lausanne, Switzerland, to measure various meteorological parameters (see Fig. 1). The average building height in this district is around 10 m.

Fig. 1 – Location of the setup on the campus (indicated with the red cross). This image is taken from Open Street Map whose copyright notices can be found here: https://www.openstreetmap.org/copyright (CC-BY-SA-2.0).

2.2 Instruments

Table 1 lists the various instruments installed on the mast. Seven 3D sonic anemometers have been placed along the vertical axis every 4 m. A meteorological station was set at the bottom of the installation (1.5 m above ground level) to measure the relative humidity and the atmospheric pressure. Both of these variables will then be used to correct the sonic temperature measurement from the anemometers to calculate the air temperature. A surface temperature sensor was also installed at 1.5 m to measure the ground temperature. At the top of the tower two AXIS-cameras have been installed; one looking at the sky and the other one at the campus. The objective of these cameras is, for example, to provide useful information on cloud coverage. Data from the instruments are collected with a frequency of 1Hz based on the recommendations by Kaimal and Finnigan (1994) and stored in a database at EPFL.

Table 1 – List of instruments

Instrument	Brand	Type
3D sonic anemometers	Gill	WindMaster
Meteorological station	Gill	GMX 300
Surface temperature sensor	Optris	OPTCSLT15K

The sonic anemometers as well as the weather stations work with a frequency of 1 Hz. Fig. 2 gives an illustration of the experimental setup of the meteorological tower.

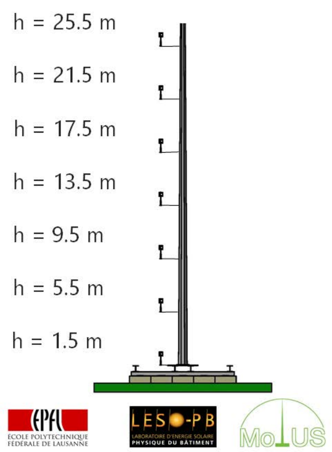

Fig. 2 – Experimental setup

A complete schematic of the setup as well as the communication protocols used can be found in Fig. 3.

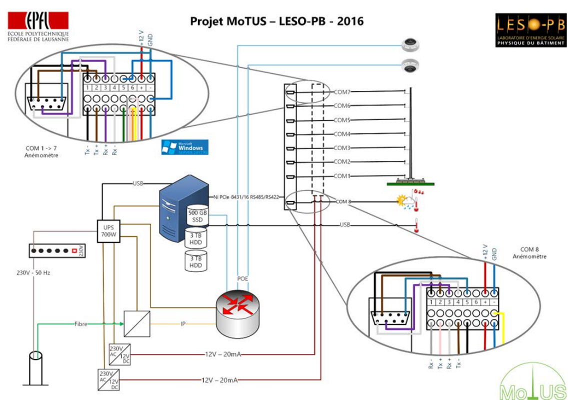

Fig. 3 – MoTUS schematic and protocols

2.3 Air Temperature Calculation

The sonic anemometers measure the sonic temperature. As these values do not correspond to the air temperature, we use a formula developed by Cassardo et al. (1995) to correct the sonic temperatures in order to determine the air temperature. To do this we needed the vapour pressure as well as the air pressure for every time step. These values were obtained from the Maximet weather station. The air temperature can be calculated as follows:

$$\theta_a = \frac{\theta_s}{1 + 0.32\left(\frac{e}{P}\right)} \tag{1}$$

where θ_a is the corrected air temperature in Kelvin, θ_s is the sonic temperature (K), P is the air pressure (Pa), and e is the vapour pressure (Pa) that is calculated using:

$$e = RH * 100 * \left(6.11 * 10^{\left(\frac{7.5\theta_m}{237.3+\theta_m}\right)}\right) \tag{2}$$

where RH is the relative humidity and θ_m is the air temperature measured using the Maximet weather station. Note that here we assume that the relative humidity is constant along the vertical axis and that hence the vapour pressure is as well.

2.4 Convection Coefficient

The convective heat flux can be calculated as a product of the heat convection coefficient and the difference in the surface and air temperature. A detailed review of the more commonly used formulations can be found in Mirsadeghi et al. (2013). For the purpose of the study we evaluate the impact of using localized wind speed on two formulations of the McAdams heat transfer coefficients, and analyse their sensibility to local wind speed. Firstly, in its original form, the coefficient is given by:

$$h_c = 5.678\left[m + n\left(\frac{U}{0.3048}\right)\right] \tag{3}$$

where h_c is the convective heat transfer coefficient (in $W/m^2.K$), ***m* and *n*** are constants with a value of 0.99 and 0.21, U is the wind speed (in m/s) calculated on the wind attack angle on a particular surface in the windward or leeward-direction. For the purpose of this study we will simply assume U to be the horizontal wind speed. Note that this is the formulation used for $U < 4.88$ ms^{-1}.

Secondly, we choose the linearized form as commonly used in software such as CitySim (Robinson, 2012) for example:

$$h_c = 2.8 + 3U. \quad (4)$$

3. Results Analysis and Discussion

3.1 Wind Speed

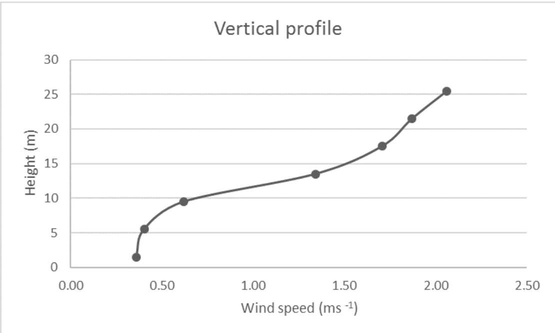

Fig. 4– Vertical profile of the horizontal wind speed (m s^{-1}) for the night of 01/09/2016 measured from the sonic anemometer

As can be expected in an urban context, the wind profile is highly impacted by the presence of buildings. It can be noted from Fig. 4, that the characteristic logarithmic profile is present above the building roof, and that below in the canopy layer, there is low horizontal wind speed. This corresponds to results and findings previously reported (Rotach et al., 2005; Santiago and Martilli, 2010; Mauree et al., 2017).

3.2 Air Temperature

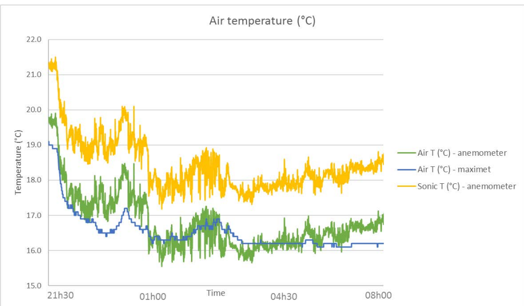

Fig. 5 – Air temperature (°C) for the night of 04/09/2016 measured from the sonic anemometer, the weather station and the corrected air temperature

We can see from Fig.s 5 and 6, that the calculated air temperature from the sonic anemometers corrected by the sonic temperature has a very good agreement (correlation coefficient is equal to 0.81) with the values from the Maximet weather station.

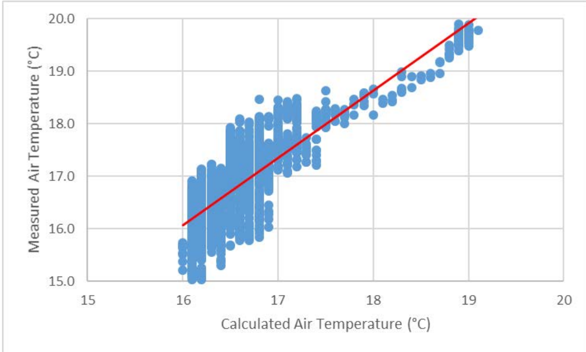

Fig. 6 – Measured and corrected air temperature (°C)

We can highlight that there seems to be an overestimation of the temperature (σ=0.44 °C).

3.3 Heat Convection Coefficient

A sensitivity analysis is done using the wind speed usually taken at the standard meteorological height (10m), and the wind actually measured using the anemometers that corresponds to each floor of the LESO-PB building.

Table 2 – Convection coefficient at each floor using Equation 3

Floor	h_c ($W/m^2.K$)	Relative difference
1st	7.0	35 %
2nd	7.2	34 %
3rd	8.1	26 %

Table 3 – Convection coefficient at each floor using Equation 4

Floor	h_c ($W/m^2.K$)	Relative difference
1st	3.9	43 %
2nd	4.0	41 %
3rd	4.7	32 %

As can be seen from Tables 2 and 3, there is a significant difference between the convection coefficient calculated using the localized wind speed and the one typically taken at 10 m. The difference can go up to 43 % if we consider the 1st floor. Although the original formulation of McAdams seems to present slightly better results, it should be highlighted that this formulation is recommended when wind speed is measured far enough from the surface, without any disturbance. In addition to the fact that building energy software generally uses data from meteorological stations that are not taking into account the urban microclimate, it is also demonstrated that the use of local meteorological data will have a significant impact, according to which formulation of the convection coefficient is adopted. We additionally compared the coefficient from CIBS and they showed results (not shown here) close to the original formulation by McAdams.

4. Conclusions and Perspectives

This paper presents an experimental setup used for the high frequency and long-term measurement meteorological variables in an urban setup. Seven 3D sonic anemometers have been installed along a vertical axis to provide high frequency measurements of the wind speed and air temperature. A meteorological station installed at the bottom of the mast provides local weather conditions such as the relative humidity, and the air temperature and pressure.

It was shown that the wind speed is highly impacted in an urban setup and that this considerably influences the calculation of the heat convection coefficient. Differences of up to 43 % were noted for the LESO case. An analysis of the sensitivity of two heat convection coefficients was performed. It was established that the use of local climatic data does not have the same effect on their calculation. This can have significant influence when evaluating strategies such as natural ventilation or when conceiving high-energy efficiency building.

The current study will in the near future be expanded to include an analysis of the temperature difference along the vertical axis on the calculation of the convective heat flux, and how this impacts the building energy consumption simulation. Furthermore, high frequency monitoring will be used to calculate turbulent fluxes (momentum and heat) in an urban context, and to develop new parameterization for the Canopy Interface Model (Mauree et al., 2017). Additionally, a net radiometer will be installed at the beginning of 2017 to complete the setup.

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Nomenclature

Symbols

RH	Relative humidity (-)
θ	Air temperature (K)
e	Vapour pressure (Pa)
P	Air pressure (Pa)
U	Horizontal wind speed (ms^{-1})
m, n	Constants
h_c	Convective heat transfer coefficient ($W/m^2.K$)

Subscripts/Superscripts

m	Maximet weather station
s	Sonic measurement
a	Corrected air temperature

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