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Kalyanova, Olena; Jensen, Rasmus Lund; Heiselberg, Per

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Data Set for Empirical Validation of Double Skin Facade Model

Olena Kalyanova, Ph.D-student,
Aalborg University;
ok@civil.aau.dk

Rasmus Lund Jensen, Research Assistant,
Aalborg University;
rlj@civil.aau.dk

Per Heiselberg, Professor,
Aalborg University;
ph@civil.aau.dk

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SUMMARY:
During recent years, attention to the double skin facade (DSF) concept has greatly increased. Nevertheless, the application of the concept depends on whether a reliable model for simulation of the DSF performance will be developed or pointed out. This is, however, not possible to do, until the model is empirically validated and its' limitations for the DSF modeling are identified. Correspondingly, the existence and availability of the experimental data is very essential.

Two sets of accurate empirical data for validation of DSF modeling with building simulation software were produced within the International Energy Agency (IEA) Task 34 Annex 43. This paper describes the full-scale outdoor experimental test facility 'the Cube', where the experiments were conducted, the experimental set-up and the measurements procedure for the data sets. The empirical data is composed for the key-functioning modes of a double skin facade: 1. External air curtain mode, it is the naturally ventilated DSF cavity with the top and bottom openings open to the outdoor; 2. Thermal insulation mode, when all of the DSF openings are closed.

Available data sets consist of two groups of parameters, which were measured simultaneously. These are the parameters of boundary conditions and the parameters that reflect the DSF performance. The boundary conditions include the climate data, e.g. wind profile, outdoor temperature etc. Parameters of the DSF performance discussed in the paper are: temperature gradients in the DSF cavity, mass flow rate in the naturally ventilated cavity, surface temperatures, etc.

1. Introduction

The DSF concept is relatively young and belongs to the dynamic building systems, which act in unison with weather variation, taking the benefits from the outdoor climatic conditions. The DSF concept carries the notion of transparency, openness and intelligence, which are highly appreciated together with the concept's advantages, if well designed, in improving the acoustics, providing daylight and being energy efficient.

The design, dimensioning and application of DSF must be carried out meticulous, as insufficiencies will lead to an increased energy use (mainly for cooling) and inferior indoor climate. However, standard tools for designing conventional buildings are not sufficient enough when designing a DSF, as it requires results from detailed dynamic simulations.

In the literature one of the main problems reported regarding DSF modeling and simulations are the absence of experimental data (Gertis 1999, Saelens 2002). Most of the mathematical models have not been validated against empirical data and require an expert knowledge in the physics of DSF to perform the simulations. Consequently, the degree of confidence in the simulated results is rather low. There is a lack of systematic literature or guidelines on how to model DSF and what are the most suitable tools to use, most of this is caused by the lack of empirical validations.

Still, DSF solutions are being proposed in the building design and erected, resulting in poor indoor climate and unnecessary energy use. It is therefore critical to expand knowledge about dimensioning of DSF buildings, to obtain some tools, which can help to optimize the performance of DSF systems.

To address the problem of lacking experimental data a wide range of measurements has been carried out in an outdoor, double-skin façade full-scale test facility 'the Cube'. This work has been conducted in the framework of IEA SHC Task 34 /ECBCS Annex 43 "Testing and Validation of Building Energy Simulation Tools".

2. Ventilation modes

According to the literature, there are many classification schemas exist for describing the DSF performance (Poirazis 2004, Loncour et al., 2004). However, focusing on the energy performance and flow path in the double skin façade, the DSF classification according to the ventilation principle is being used, as in Loncour et al., (2004):

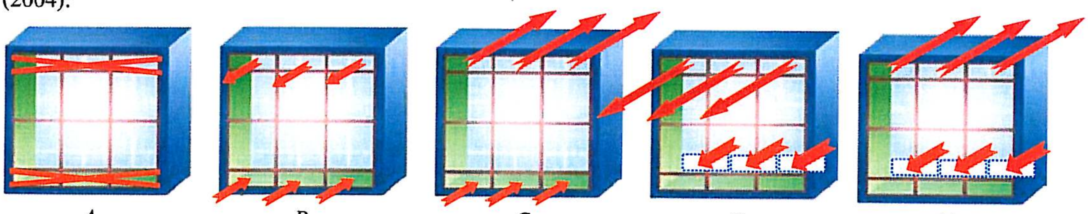


Figure 1. Classification of DSF according to ventilation principle. A- thermal insulation, B-external air curtain, C- preheating mode, D- exhaust mode, E-internal air curtain.

Due to the extremely time consuming and complex procedure involved in operating and data processing, only two ventilation modes were tested:

- External air curtain; (01.10.2006 – 15.10.2006)
- Transparent insulation mode/thermal buffer. (19.10.2006 - 06.11.2006)

MODE 1: External air curtain mode. The external operable windows at the top and bottom of the cavity were open, the air entered the DSF at the bottom of the cavity, it was heated while passing through the DSF cavity and then, released to the external environment, carrying away some amount of the solar heat gains. The flow motion in the cavity was naturally driven.

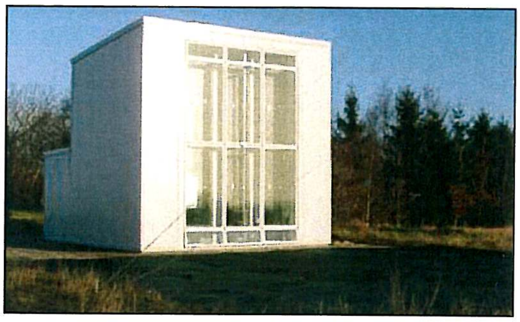
MODE 2: Transparent insulation mode. All the openings were closed. The principle of this mode is the same as of the conventional window. Air in the DSF cavity is heated to the temperature higher than the outside temperature, this decreases the radiant heat exchange between the internal window surface and the adjacent room.

3. Experimental test facility

'The Cube' is an outdoor test facility located at the main campus of Aalborg University. It has been built in the fall of 2005 with the purpose of detailed investigations of the DSF performance, development of the empirical test cases for validation and further improvements of various building simulation software for the modeling of buildings with double skin facades in the frame of IEA ECBCS ANNEX 43/SHC Task 34, Subtask E- Double Skin Facade.

The test facility is designed to be flexible for a choice of the DSF operational modes, natural or mechanical flow conditions, different types of shading devices etc. Moreover, the superior control of the thermal conditions in the room adjacent to the DSF and the opening control allow to investigate the DSF both as a part of a complete ventilation system and as a separate element of building construction.

The accuracy of these measurements is justified by the quality of the facility construction: 'the Cube' is very well insulated and tight.



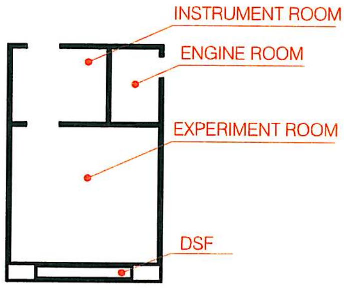


Figure 2. 'The Cube' (left). Plan of 'the Cube' (right).

'The Cube' consists of four domains, which are named as: Double Skin Façade, Experiment room, Instrument room and Engine room.

All openings of the double skin façade are controlled and can be operated separately. The combination of open openings defines the operative strategy of the DSF, see Figure 1. Depending on the mode of DSF performance, it can function as a barrier for the solar heat gains, as an additional insulation, can preheat the air coming into the occupied zone, etc. In any of the above cases, the DSF affects the thermal conditions in the experiment room.

The temperature in the experiment room can be kept constant, as there is a cooling unit installed in the engine room and a ventilation system with the heating and cooling unit installed in the experiment room, Figure 3. In order to avoid temperature gradients in the experiment room, a recirculating piston flow with an air speed of approximately 0.2 m/s is used. This resulted in typical temperature gradient of approximately 0.02°C/m and maximum of 0.1°C/m. The air intake for recirculation is at the top of the room, after the intake the air passes through the preconditioning units of the ventilation system and then it is exhausted at the bottom of the room through the fabric ke-low impulse ducts. Maximum power on cooling and heating unit is 10 kW and 2 kW respectively.

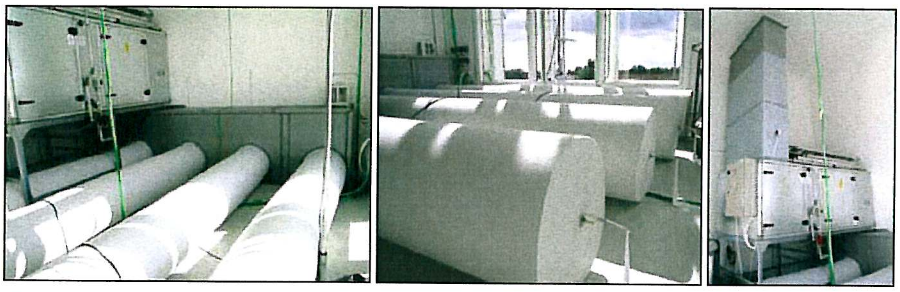


Figure 3. KE-low impulse fabric ducts in the experiment room (left, centre), Ventilation system in the experiment room (right).

Knowledge of solar radiation is crucial for the task of these experiments. However, in non-laboratory conditions the ground reflected solar radiation depends on the surrounding of the test facility and therefore it can vary a lot. For this reason, a large carpet was fixed on the ground from the side of the southern façade of 'the Cube' to achieve uniform reflection from the ground. The size of the carpet ensures a view factor between the DSF and the ground of approximately 0.5. Achieving of a reasonably higher view factor would require to double-up the carpet size.

The fabric of the carpet was chosen so that it does not change reflectance property when it is wet due to its permeability and have reflectance property of apx. 0.1, close to the generally assumed reflectance property of the ground. The carpet is also seen in the Figure 2.

Absorption, reflection and transmission properties of all the surfaces in the DSF, experiment room and windows were tested at the EMPA Materials Science & Technology Laboratory. This was also the case for the ground carpet. The information about the optical properties of the surfaces is available as a function of the wavelength, in the wave length interval 250-2500nm.

4. Preliminary tests

A number of preliminary experiments were completed before the final experimental set-up. Preliminary experiments were focused on improvements and "calibration" of the test facility, improvements of measurement techniques and on best suitable positioning of equipment.

The air tightness of 'the Cube' was measured during construction, insulation and air tightening of the test facility, before and after installation of the experimental setup to ensure the tightness. The final infiltration rate was 0.3 h^{-1} at 100 Pa. Transmission heat losses were estimated for two set points, when the difference between the air temperature in the test room and outdoors was 16°C and 21°C resulting in a heatloss of 0.26 W/(m^{2o}C). These tests have confirmed that 'the Cube' is extremely tight and well insulated.

5. Experimental data sets

5.1 Measurement conditions

Duration of each experiment was approximately 2 weeks and started in fall 2006. Since the autumn/spring season represents the most complete spectrum of the DSF performance, the experiments were carried out in autumn. Contrary to summer, climatic conditions in early autumn (or late spring) are more inconsistent, there are many periods with large cloud cover of the sky, while the solar radiation intensity with the clear sky can still be relatively strong, the temperature variation between day and night time is more considerable and, consequently the day time periods may lead to significant solar heat gains, while the night time periods may lead to significant heat losses if the DSF performance has not been optimized.

The air temperature, air flow rate in the cavity and, correspondingly, the amount of surplus heat gains removed with the cavity air are the main measures of the double skin façade performance, and also it can be used as a measure for validation of a building simulation tool for modeling of a DSF performance. The air temperature in the experiment room of 'the Cube' was kept uniform and constant at approximately 22°C to minimize the influence of the interior environment on DSF performance.

Both, the interior and exterior environment define the boundary conditions for the DSF, and the detailed knowledge of those was essential for further application of the experimental results and evaluation of the DSF performance.

The surplus solar gains into the experiment room were measured indirectly, by assessment of the total cooling power delivered to the experiment room in order to keep the air temperature constant. All of the equipment in the experiment room, which function as a heat source, was connected to the wattmeter to keep track of all loads and losses in the room.

5.2 Boundary conditions

5.2.1 Wind speed, wind direction and mean wind speed profile

The natural wind speed varies in time and space, the character of its variation is highly random and the wind flow is highly turbulent. At the same time, the wind speed is one of the main contributors to the natural ventilation flow.

The change of the mean wind velocity depending on height and intervening terrain is expressed through the mean wind speed profile. Once the mean wind speed profile is identified based on a wide spectrum of wind velocities and wind directions with a substantial number of measurement points, then the wind profile turns to be one of the characteristics of the test facility.

Experimental data for the vertical wind speed profile covers a measurement period from 1st of June 2006 until 1st of January 2007. This period includes various wind directions and wind speeds. Wind velocity and wind direction was measured in six points above the ground in order to build a vertical wind profile. Both 2D and 3D ultrasonic anemometers were placed on the mast in the centre line of the building, 12m away from its South façade (Figure 4). The sampling rate was 5 Hz.

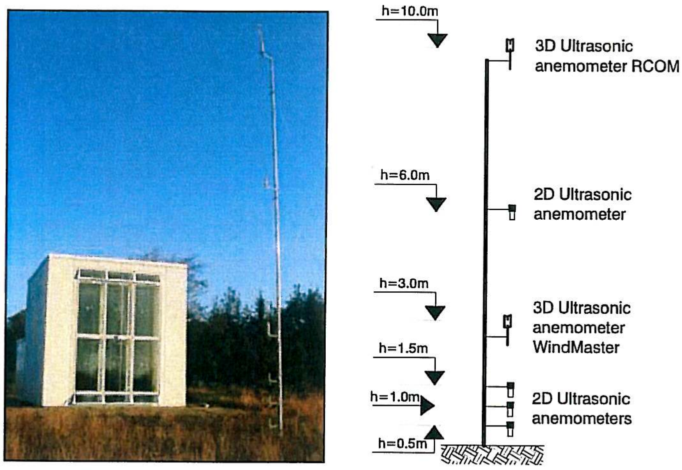


Figure 4. Wind mast in front of 'the Cube' (left). Positioning of equipment on the mast (right).

5.2.2 Outdoor air temperature, air humidity and solar radiation

Outdoor air temperature was measured using two thermocouples type K at the height of 2 m above ground. Air humidity of the outside air was measured continuously for completing the list of required climate data parameters for building simulation tools. Outside air humidity was measured every 10 minutes.

For purpose of weather data assembling two pyranometers were placed horizontally on the roof of 'the Cube'. BF3 pyranometer measures Global and Diffuse solar irradiation on the horizontal surface. Another pyranometer, Wilhelm Lambrecht, measures only Global solar irradiation on the horizontal surface and was placed on the roof for control of BF3-readings. In the Table 1, the weather boundary conditions are divided into two groups, corresponding to each test mode.

Table 1. Weather conditions during the experiments.

MODE	Mean outdoor air temperature	Mean wind speed	Mean diffuse solar irradiation on horizontal	Mean total solar irradiation on horizontal
	°C	m/s	W/m^2	W/m^2
1	12.5	3.6	91*	175*
2	9.6	5.2	58*	89*

* Mean for solar irradiation is given only for the periods with sun.

5.2.3 Air temperature and vertical temperature gradient in the DSF cavity

Direct solar radiation is an essential element for the façade operation, but it can heavily affect measurements of air temperature and may lead to errors of high magnitude using bare thermocouples. A number of tests were carried out preliminary to the experiments, where various techniques were investigated on their ability to shield thermocouples from direct irradiance, in order to achieve an accurate and reliable way to measure the air temperature reducing the error caused by radiation (Kalyanova et al., 2007). As an outcome of these tests, all of the thermocouples placed free in the DSF cavity were protected: thermocouples were coated with silver, shielded from direct solar radiation by a silver-coated tube, which was continuously ventilated by a minifan, see Figure 5. The air temperature in the DSF cavity was measured at six different heights in the centre line of the cavity. The measurements were carried out with the sampling frequency 5Hz and averaged for every 10 minutes.

The dimensionless air temperature was used to investigate the vertical temperature gradients in the DSF cavity, the definition of it is given in equation 1.

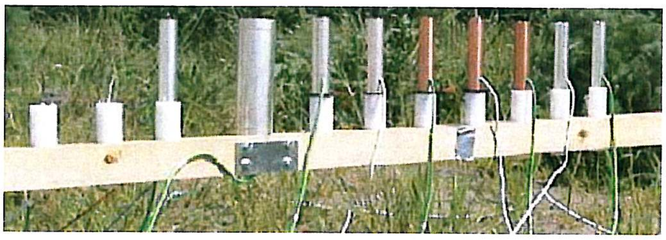


Figure 5. Experimental setup: testing of shielding techniques for air temperature measurements under direct solar access.

$$t_{\dim} = \frac{t_h - t_o}{t_i - t_o} \qquad (1)$$

t_h - temperature in the DSF cavity at the height h, °C
t_o - outdoor air temperature, °C
t_i - indoor air temperature (in the experiment room), °C

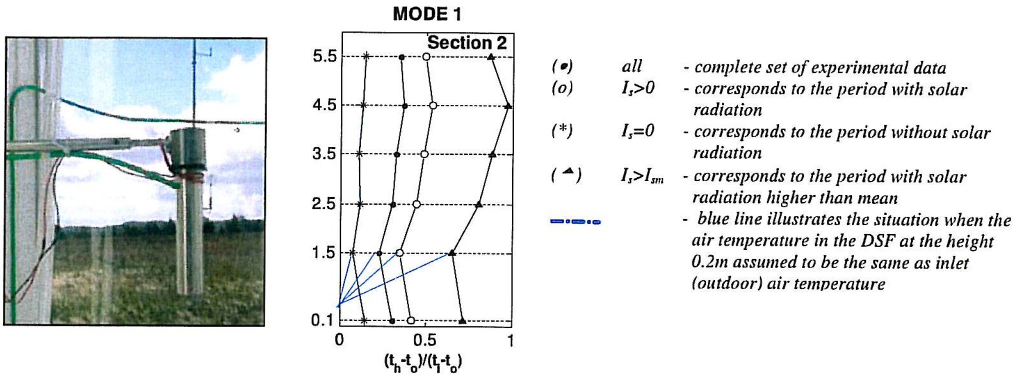


Figure 6. Silver coated ventilated tube for shielding a thermocouple from solar radiation (left). Dimensionless temperature gradient in the DSF cavity in the MODE1 (right).

For all sections the measurements at the bottom of the cavity were at the height of 0.1m above the floor. Looking upon the dimensionless profiles (Figure 6) it is possible to observe that the air temperature measured at the bottom of the DSF is relatively high. This is likely to be an experimental error. If the inlet air temperature is assumed to be the same as the outdoor air temperature, then it is reasonable to approximate the dimensionless air temperature in the centre of the inlet opening to zero (at the height 0.2m), which is illustrated with a *blue line.*

5.2.4 Surface temperature of the glazing

Measurement of glazing surface temperature was performed in the centre of a glazing pane for each large window section. The temperature was measured at: the internal surface of the inner window (ii), the external surface of the inner window (ei), the internal surface of the outer windowpane (ie).

This measurement was conducted with sensors shaded from direct solar access. Continuous shading of the thermocouple sensor at the inner pane (ie) was ensured by a thin aluminium foil fixed around the sensor at the external surface. As a result, the foil shaded both a sensor at the external (ie) and internal (ii) surfaces. The thermocouple at the internal surface of the outer pane (ei) was shaded in a similar way by a piece of aluminium sticky tape on the external surface of the outer pain.

5.2.5 Mass flow rate in the DSF cavity

Assessment of the air change rate is crucial for the evaluation of indoor climate and the performance of a double skin façade. As a result, the air change rate repeatedly becomes a target for measurement, prediction and simulation. In the meantime, the air flow occurred in the naturally ventilated spaces is very intricate and extremely difficult to measure. The stochastic nature of wind and as a consequence non-uniform and dynamic flow conditions in combination with the assisting or opposing buoyancy force cause the main difficulties. There were three techniques used for the air flow measurements, but only two of them were successful:

Velocity profile method. This method requires a set of anemometers to measure a velocity profile in the opening, and then the shape of the determined velocity profile depends on amount of anemometers installed. Instead of placing equipment directly in the opening in the case of the double skin façade, it can be placed in the DSF cavity, where the velocity profile can be measured in a few levels instead for one.

Tracer gas method. This method requires the minimum amount of measurements and equipment, but it is characterized with frequent difficulties to obtain uniform concentration of the tracer gas, disturbances from the wind washout effects and finally with the time delay of signal caused by the time constant of gas analyzer. The constant injection method (Etheridge, 1996) was used in the experiments.

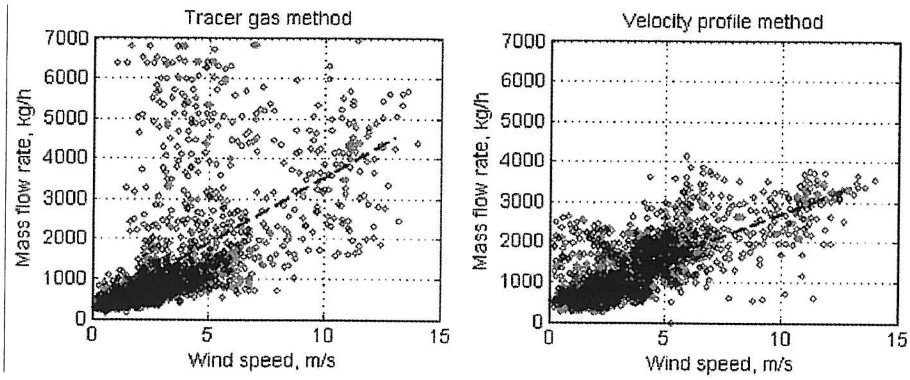


Figure 7. Mass flow rate measured in the DSF cavity with the tracer gas method (left), velocity profile method (right) and illustrated as a function of the wind speed. MODE 1.

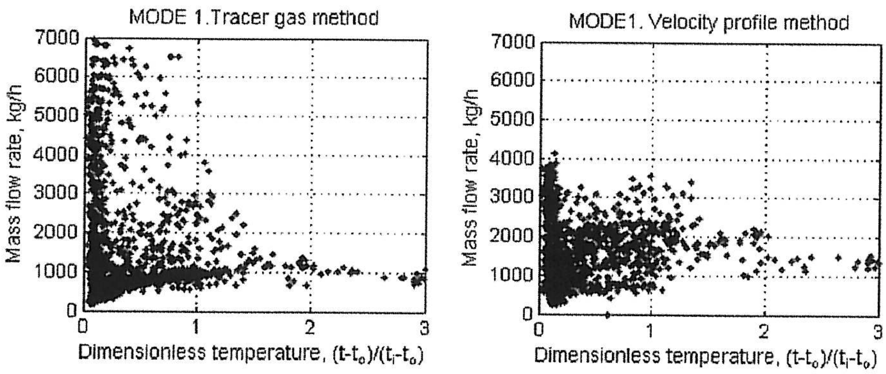


Figure 8. Mass flow rate measured in the DSF cavity with the tracer gas method (left), velocity profile method (right) and illustrated as a function of dimensionless temperature in the cavity. MODE 1.

In the Figure 7 and Figure 8, it is illustrated that the major part of experimental data is available for the wind dominated driving forces, although it is common to assume that the mass flow rate in a double-skin façade cavity is buoyancy driven. The wind impact is present even for the periods with relatively strong solar radiation.

Both of the measurement methods have sources of errors and comparing their outputs have some level of disagreement. However, the natural air flow phenomena is very complex and this results is the best approximation to the long time monitoring of natural air flow phenomena and can be used for experimental validation of numerical models of natural ventilation air flow, for more information see Kalyanova (2007).

5.2.6 Power loads in the experiment room

One of the main targets of this experimental work was to accurately estimate solar gains and heat losses by the room adjacent to the double skin façade, as these parameters independently reflect the performance of the DSF cavity. Their independence is assured by the minimized influence of the experiment room on the DSF performance, as the thermal conditions in the room were kept constant, no regulation of the window openings used and no shading devices installed, building is very well insulated and air tight, the air tightness of the building, the transmission heat losses are known and all influencing climate parameters were measured.

Water was used in the cooling unit of the ventilation system. With the purpose to avoid the condensation on the surface of the surface of the cooling unit, the minimum water temperature was set to 12°C. The difference between the supply and return water temperature from the cooling unit in the experiment room was measured using one thermocouple type K with a maximum uncertainty of 0.1°C. The mass flow of the water supplied to the cooling unit was measured with a water flow meter MULTICAL from Kamstrup, which measures in a range from 0 to 1 kg/s and calibrated to an uncertainty of ±0.1% of the reading. Both the temperature difference and the water mass flow were collected by Helios data logger at a frequency 0.1 Hz.

The heating unit in the ventilation system was rarely activated, as in most cases, the additional heating load from the fan of the ventilation system in the experiment room ensured a sufficient cooling load. To keep a track on all loads to the experiment room, including the heating unit, all equipment in the room was connected to a wattmeter. The accuracy of the device was 0.1% of the reading (2.6 kW).

6. Summary

The details about the experimental test facility and experimental set-up, described in this paper, provide a good foundation for empirical validation of thermal building simulation tools for modeling double-skin façade buildings. In this work, extensive studies of the mass flow rate and air temperatures in the cavity and adjacent zone are supported with detailed information on the input parameters for a building thermal simulation tool. The generally rare experimental data for the DSF-buildings, containing results of the mass flow rate measured in a naturally ventilated are especially unique.

The experimental methods used for measurements do have sources of errors; the experimental results are limited in time and available only for certain boundary conditions. Nevertheless, the availability of these results are very important for further research within the DSF concept. Also, the results are usefull for further improvement of building simulation tools and models when predict the performance if the double-skin façade.

7. Anknowledgement

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