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## [T09-43] Measurement and Modelling of Air Flow Rate in a Naturally Ventilated Double Skin Façade

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### SUMMARY

Air flow rate in a naturally ventilated double skin façade (DSF) is extremely difficult to measure due to the stochastic nature of wind, and as a consequence non-uniform and dynamic flow conditions. This paper describes the results of two different methods to measure the air flow in a full-scale outdoor test facility with a naturally ventilated double skin façade. Although both methods are difficult to use under such dynamic air flow conditions, they show reasonable agreement and can be used for experimental validation of numerical models of natural ventilation air flow in DSF.

Simulations by the thermal simulation program, BSim, based on measured weather boundary conditions are compared to the measured air temperature, temperature gradient and mass flow rate in the DSF cavity. The results show that it is possible to predict the temperature distribution and airflow in the DSF although some discrepancies were found.

### INTRODUCTION

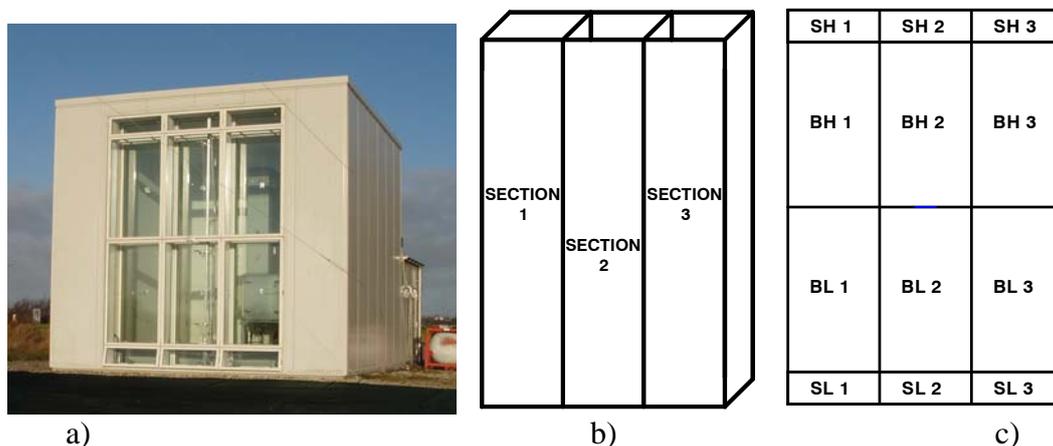
The use of Double Skin Façades (DSF) has increased during the last decade. There are many reasons for this including e.g. aesthetics, sound insulation, improved indoor environment and energy savings. In a DSF-building a great part of the energy flow happens through the DSF construction and, for that reason, it is extremely important to be able to predict its performance. As pointed out by H. Manz and Th. Frank: “...*the thermal design of buildings with the DSF type of envelope remains a challenging task. As, yet, no single software tool can accommodate all of the following three modeling levels: optics of layer sequence, thermodynamics and fluid dynamics of DSF and building energy system*” (Manz and Frank, 2005). DSF-buildings are extremely dynamic, especially, if the cavity is naturally ventilated, and needs continuously to adjust its performance not only to the solar irradiation, but also to the highly fluctuating natural driving forces. Due to the extreme dynamics of the system, the changes happen very rapidly and they can rarely be smoothed in time. Consequently, any shortcomings in the design might result in increased energy use and increased temperature fluctuations in the occupied zone.

Assessment of the air change rate is crucial for the evaluation of the performance of a double skin façade. However, the air flow in a naturally ventilated double skin facade is very intricate and extremely difficult to measure because of the stochastic nature of wind and as a consequence the non-uniform and dynamic flow conditions. Depending on the external conditions and the double skin façade functioning mode, (Loncour et. al. 2004), the air flow rate in a ventilated cavity can vary significantly in magnitude and direction.

In the literature, there are different methods used for estimation of the air change rate in a naturally ventilated space. These are based on the tracer gas methods or measurement of velocity profiles in the opening or the air gap (Larsen 2006, Hitchin and Wilson 1967). This paper describes two different methods used to measure the air flow in a full-scale outdoor test facility with a naturally ventilated double skin façade. The paper also describes the empirical validation process of the Danish building simulation tool, BSim, where a model of a DSF-building is built up to simulate the outdoor DSF test facility, ‘the Cube’ and especially the temperature and air flow rate in the naturally ventilated cavity.

## EXPERIMENTAL SETUP

In this work, the full-scale experiments are conducted in the experimental test facility the ‘Cube’, which is described in detail in (Kalyanova and Heiselberg 2006). The ‘Cube’ is located in an open flat country with the DSF openings facing south. There are two experimental zones: the double skin façade cavity and the test room behind the DSF. The building has a shape of a cube with the dimensions 6x6x6 m. Window partitions of the façade visually subdivide the DSF into three sections, see Figure 6. Internal dimensions of the double façade cavity are following, height – 5.5 m, width - 3.6 m, depth – 0.58 m.



Transcription: 1<sup>st</sup> letter stands for “B” – big and “S” – small; 2<sup>nd</sup> letter stands for “H” –high and “L” – low; Number stands for “1”, “2”, “3” – number of DSF section.  
 Figure 6. a) The 'Cube'. b) Section of the DSF cavity. c) DSF openings.

Experiments in the naturally ventilated cavity were completed for an external air curtain mode with openings in the external façade at both the bottom (SL1-3) and the top (SH1-3). In this mode, the external operable windows at the top and bottom of the cavity are open to the outside, the air enters the DSF at the bottom of the cavity, heats up when passing through the DSF cavity and then released through the top openings to the external environment, carrying away some amount of the solar heat gains. The flow motion in the cavity is naturally driven. The air flow rate depends only on wind and buoyancy and is limited by the opening size. The external air curtain mode is a frequently used solution in summer to prevent surplus solar gains into the room and to improve the efficiency of the solar shading by limiting the air temperature in the cavity by external air flow to minimize/avoid increased heat transmission/radiation to the room. Thus the opening degree of the windows was adjusted to the mean air temperature in the double façade cavity was 5-10 degrees above the outdoor temperature, in order to avoid too high cavity temperatures in the external air curtain mode.

### The 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 wash-out 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. Carbon dioxide ( $\text{CO}_2$ ) was used as tracer gas and was released in the lower part of the double skin façade cavity, just above the SL openings. Even distribution of the tracer gas along the DSF cavity was ensured by delivery through a perforated tube of internal diameter 3.5 mm, perforation distance 4mm and 0.5mm diameter of perforations. Samples of the tracer gas dilution were taken in 12 points,

Figure 7a (4 samples per section) at the top of the DSF cavity, but below the SH- openings. All the samples were mixed in a collector,

Figure 7b, and then the average concentration was measured by a gas analyzer BINOS. Outdoor  $\text{CO}_2$  concentration was measured continuously by a gas analyzer URAS. Both devices were preliminary calibrated to an accuracy of 10ppm. A Helios data logger collected data from the gas analyzers with a frequency of 0.1 Hz.

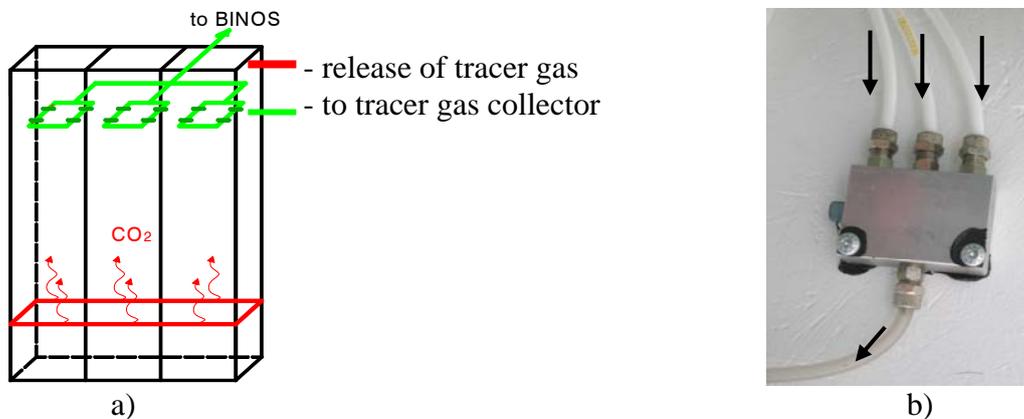


Figure 7. a) Experimental setup for the tracer gas method. b) Collector of the samples.

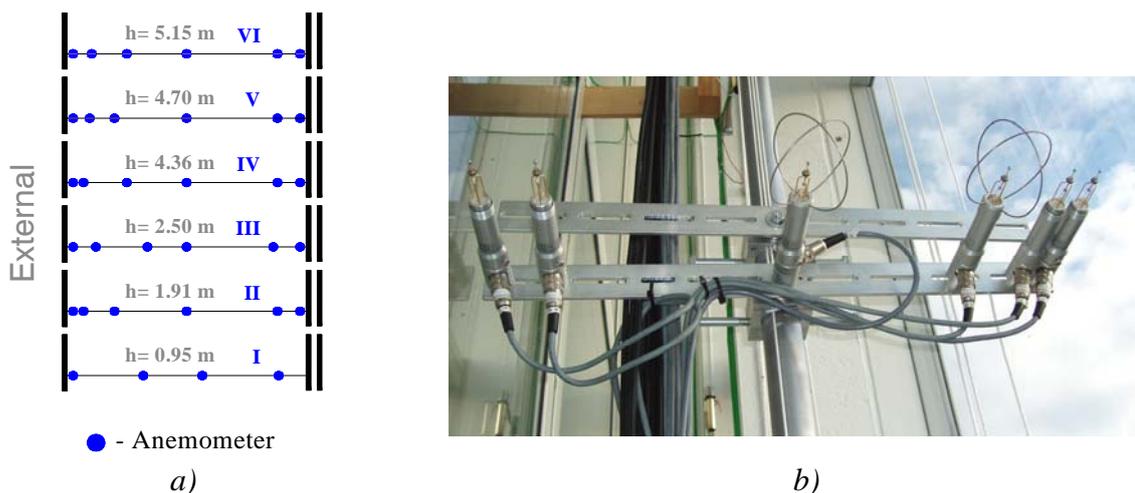


Figure 8. a) and b) Positioning of anemometers in the DSF cavity.

### The velocity profile method

This method requires anemometers to be placed in the DSF cavity to measure velocity profiles in the DSF cavity. The velocity profile was measured in a few different heights for better accuracy. During the experiments the velocity profiles were measured in section 2, see Figure 6, in 6 heights, see Figure 8, at a frequency of 10Hz for a 10 min averaging period. Hot

sphere anemometers are temperature compensated and to ensure accurate measurements under the direct solar radiation they were preliminary tested and calibrated under artificial sun conditions, in the wind tunnel. The velocity profiles were measured only in the mid section of the cavity, and equal flow conditions was assumed in all three sections of the DSF cavity for the air flow estimation.

### BSim

BSim is an ISO STEP based, integrated building design tool, (Wittchen et al. 2005). The core of the design tool is a common building data model shared by the different design tools, and a common database with typical building materials, constructions, windows and doors.

Figure 9 illustrates the user interface of BSim. In BSim the direct solar radiation is calculated every  $\frac{1}{2}$  hour based on the actual position of the sun. The surfaces where the ray of sunshine hits is also the surfaces that receive the energy and it is possible to have light passing through a room without affecting the heat balance. The diffuse radiation from the sky entering a zone is distributed according to a chosen weight factor. Calculation of heat flow from a surface is based on dynamic calculations of both the convective heat transfer coefficient and long wave heat exchange. The convective heat transfer coefficients are calculated based on empirical correlations, mainly using dimensionless numbers.

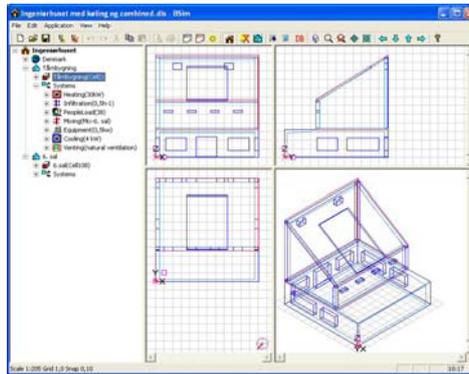


Figure 9. SimView, the user interface of BSim for editing and viewing the layout of the building

The model was constructed according to the documented geometry and thermal properties of the constructions in ‘the Cube’, (Kalyanova and Heiselberg 2006). It consists of four thermal zones, the double-skin façade (DSF), the experiment room, the instrument room and the engine room. The main thermal characteristics of the building and model are available in Simulation period was set according to the length of the weather file for the external air curtain mode (01.10.2006 – 15.10.2006), using the weather data file to define the outdoor thermal conditions, (Kalyanova et. al. 2008). No shading devices were included in the model. Modeling of the natural ventilation mass flow rate in the DSF cavity is based on the “loop equation” as described by Axley 2001 and is defined via the area, the heights and the discharge coefficients of the openings and the surface pressure coefficients. The discharge coefficient of the top and bottom opening was measured prior to the experiments in a wind tunnel. In BSim, surface average pressure coefficients are used. Therefore the calculated airflow in the DSF is mainly dependent on the calculated thermal driving force.

Table 6. Simulation period was set according to the length of the weather file for the external air curtain mode (01.10.2006 – 15.10.2006), using the weather data file to define the outdoor thermal conditions, (Kalyanova et. al. 2008). No shading devices were included in the model.

Modeling of the natural ventilation mass flow rate in the DSF cavity is based on the “loop equation” as described by Axley 2001 and is defined via the area, the heights and the discharge coefficients of the openings and the surface pressure coefficients. The discharge coefficient of the top and bottom opening was measured prior to the experiments in a wind tunnel. In BSim, surface average pressure coefficients are used. Therefore the calculated airflow in the DSF is mainly dependent on the calculated thermal driving force.

*Table 6. Thermal characteristics of 'the Cube'.*

|   |                               |
|---|-------------------------------|
| Terrain type                            | Scattered windbreaks          |
| Longitude                               | 9°59'44.44"E                  |
| Latitude                                | 57°0'41.30"N                  |
| Total area of windows (visible glazing) | 6.3.229(2.693) m <sup>2</sup> |
| Total area of top openings open         | 0.32 m <sup>2</sup>           |
| Total area of bottom openings open      | 0.39 m <sup>2</sup>           |
| External windows of DSF                 | Clear glass                   |
| Internal windows of DSF                 | 4-Ar16-4                      |
| U-value of external windows             | 5.33 W/m <sup>2</sup> K       |
| U-value of internal window              | 1.39 W/m <sup>2</sup> K       |
| U-value of external walls               | 0.08 W/m <sup>2</sup> K       |
| U-value of the floor construction       | 0.15 W/m <sup>2</sup> K       |
| g-value of external window              | 0.8                           |
| g-value of internal window              | 0.63                          |
| Net volume of DSF                       | 11.24 m <sup>3</sup>          |
| Net volume of exp.room                  | 143.11 m <sup>3</sup>         |

*Table 7. Weather conditions during the experiments.*

| Mean outdoor air temperature<br>°C | Mean wind speed<br>m/s | Mean diffuse solar irradiation<br>W/m <sup>2</sup> | Mean total solar irradiation on horizontal<br>W/m <sup>2</sup> |
|------------------------------------|------------------------|--|--|
| 12.5                               | 3.6                    | 91*  | 175*   |

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

## MEASUREMENT RESULTS

The empirical data set is available for a 2 weeks period, from 1<sup>st</sup> of October until 15<sup>th</sup> of October, and includes all necessary weather data, such as wind speed, wind direction, outdoor air temperature and humidity, total and diffuse solar irradiation on a horizontal surface, ground temperature under the foundation and atmospheric pressure. It includes a wide spectrum of various thermal conditions: periods with high direct solar radiation, with high diffuse solar radiation and of cool and warm outdoor air temperature. The air temperature in the DSF cavity, vertical temperature gradient in the cavity, surface temperatures of the glazing, mass flow rate in the DSF are available in the empirical data set. During the experiments, the air temperature in the room adjacent to the DSF cavity was kept constant at 22°C. The cooling/heating power load to the room was measured and included into the empirical data set as a parameter that reflects the performance of the DSF.

Measurement results obtained with the velocity profile and the tracer gas method show reasonable agreements, see Figure 5. Air flow rate measured with the tracer gas technique contains periods with high dilution of the tracer gas leading to serious uncertainties in the

accuracy expressed by overestimation of the air flow rate. For example in the period October 6-9, measured air flow corresponds to 300-600 ACH in the DSF cavity. Because of the high wind speed (11 m/s) and wind direction directly into the DSF openings, occurred high air flow is likely as well as the occurrence of the wash-out effect.

For the air flow measurements in the double façade cavity with the velocity profile method Figure 6 shows a repeatedly changing shape of the velocity profile. The hot-sphere anemometers do not determine the flow direction and the estimation of the air flow rate in the cavity is suitable only if there are no changes in flow direction within the profile, as appearance of the reverse flow. However, this is very difficult to determine, and is damaging for the accuracy of the estimated airflow in the DSF cavity. Moreover, the number of measurement points within the velocity profile and the measurement frequency are very essential for accuracy.

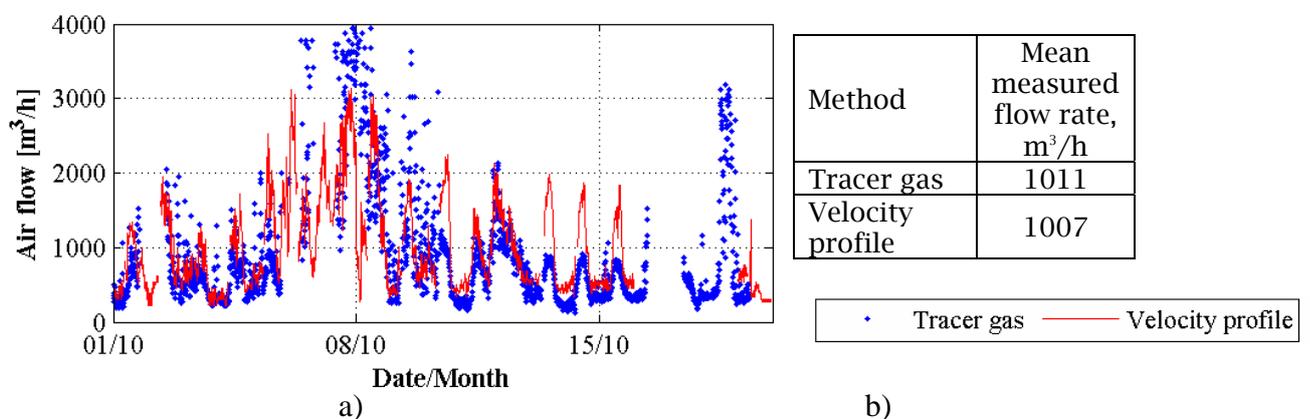


Figure 5. a) Measured air flow rate in the DSF cavity by tracer gas and velocity profile technique. b) Average measured air flow rate.

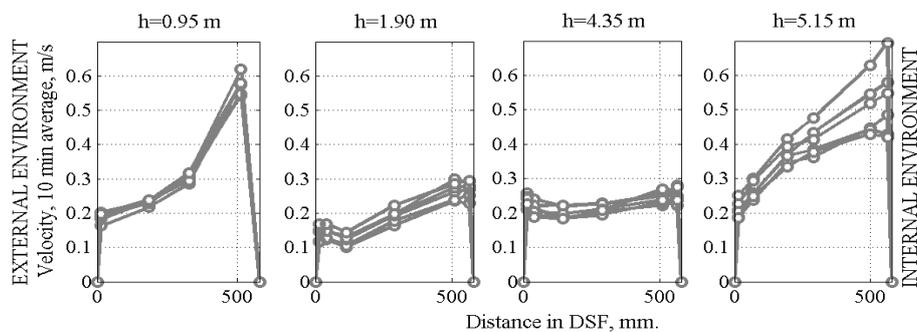


Figure 6. Example of the velocity profile deformation within the DSF cavity.

Both described measurement methods have sources of error and compared to laboratory conditions have relatively large uncertainties. Although the methods provide results with reasonable correspondence, there is a large potential for further research to improve accuracy when measuring air flow in naturally ventilated cavities.

### Comparative and empirical validation

Only simulation results for the global parameters are reported here. These are the air temperature and the mass flow rate in the DSF cavity. The air flow rate in a double skin facade cavity is rather high compared to the temperature difference between the air in the cavity and outdoor therefore it is essential to perform the empirical validation of the air temperature predictions in the models via 'the temperature raise in the DSF' to track the

amount of energy transported by the air flow. Due to the magnitude of mass flow rate, an error in prediction of the air temperature in the range of 1°C can mean hundreds of watts of error in energy balance.

Figure 7 illustrates the temperature raise in the DSF cavity above the outdoor air temperature for two days with the principally different boundary conditions: 10<sup>th</sup> of October – a day with high direct solar radiation and 11<sup>th</sup> of October – a day with mainly diffuse solar radiation. It is obvious that the simulation results are also different for these two days: for days with a large amount of direct radiation, the air temperature in the DSF cavity is underestimated, while good agreement is achieved for a cloudy day. The same observations were valid for most of the simulated results (2 weeks period).

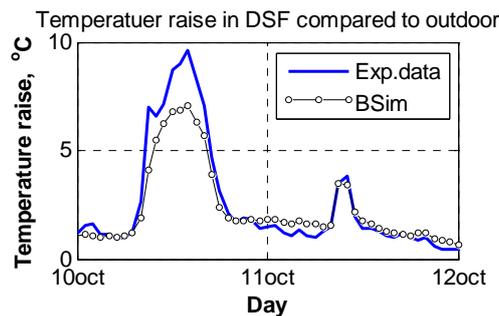


Figure 7. Measured and simulated temperature raise in the DSF cavity compared to outdoor air temperature.

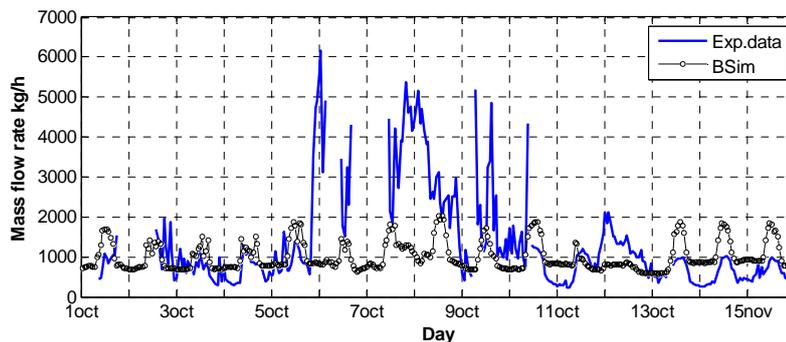


Figure 8. Mass flow rate in the DSF cavity measured with the tracer gas method and simulated in BSim.

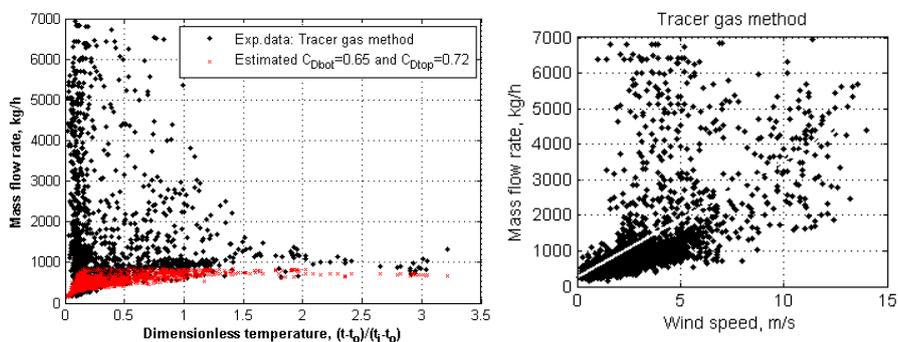


Figure 9. Illustration of the estimated mass flow rate in the DSF cavity for pure buoyancy natural ventilation (left). Mass flow rate as a function of the wind speed- experimental data (right).

Calculation of natural ventilation is particularly interesting as the natural mass flow rate is exceptionally difficult to simulate, yet, it is one of the key actors in DSF performance. In Figure 8 it is shown that prediction of the mass flow rate in the DSF cavity is not very accurate. The reason for this is that BSim uses an empirical expression for single-sided natural ventilation and the impact of wind pressure in the model is almost negligible. This is in large contrast to the experimental data, as the mass flow rate in the DSF cavity was driven by both buoyancy *and* wind, see Figure 9. In Figure 9 it is seen that the major part of experimental data is available for the wind-dominated or assisted driving forces, although it is common to assume that the mass flow rate in a double-skin façade cavity is buoyancy-driven. In Figure 9 (left) it is also illustrated what was the expected mass flow rate in the cavity if the wind force is neglected.

## CONCLUSION

The air flow rate in a naturally ventilated double-skin facade is very intricate and extremely difficult to measure because of the stochastic nature of wind and as a consequence the non-uniform and dynamic flow conditions. Although measurement results show reasonable agreements both the described measurement methods have sources of error and compared to laboratory conditions have relatively large uncertainties and there is a large potential for further research to improve accuracy when measuring air flow in naturally ventilated cavities.

## ACKNOWLEDGEMENT

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