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# A test bed for thermal fluid dynamic analysis of double skin facade systems

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**Abstract.** The experimental analysis of the thermal fluid dynamic behavior of double skin facade (DSF) requires full scale prototypes or actual facade systems. Because of the crucial interaction with the solar irradiation, tests are usually carried out on facades that are outdoor exposed. However, such an approach has limitation when it comes to a systematic and parametric analysis of the performance of these technologies, as the (outdoor) boundary conditions can hardly be controlled. To overcome this limitation, a new test bed has been conceived and constructed to allow carrying out systematic and parametric analysis on DSF systems. The test bed is a full scale DSF, with the possibility to vary the cavity depths from a minimum value of 200 mm to a maximum value of 600 mm. The total height of the DSF sample is ca 3.6 m, with a transparent window area of approx. 1.4 m (W) x 2.8 m (H). The test bed is installed in a steel frame and is tested through a Climate Simulator facility (a hot-box like facility, with the possibility to irradiate the outside surface of the test sample through a solar simulator). In the paper, the concept of the test bed, the construction features, and its sensor/control set-up are presented, together with an overview of its potentials (and limitations) to carry out experimental analysis on the thermal fluid dynamic behavior of DSF systems.

## 1. Introduction

A double skin façade (DSF) is composed of a multi layered façade envelope, which has an external and internal glazed layer with a buffer space in between, used for ventilation and solar control – when equipped with internal shading devices [1]. DSF have become increasingly popular in last two decades because their high degree of transparency, they can provide higher level of occupant's comfort than conventional single-skin facades, and at the same time they have the potentials of providing highly efficient energy and visual performance [2]. However, a DSF usually has a greater complexity compared to single skin facades, both in terms of construction and of thermal and fluid mechanical phenomena. This means that the optimal performance of DSFs may depend to a greater extend on its correct design and management while in operation. [3]. Good design and management means finding the optimal configuration and the best operational mode in response to external conditions and occupant's requirements.

In order to design and control DSF, the physical processes occurring in DSF must be understood well. These processes include transport of mass and energy in highly non-linear and interactive systems [4]. Even if DSFs have been studied since a relatively long time, there is a long series of open questions concerning the phenomena involved, and especially the way these are modelled and simulated with sufficient degree of accuracy and a within a suitable computational time.

Experimental analyses are therefore still necessary to investigate and better understand these complex phenomena and to optimize DSF performance.

Experimental studies are done with different level of complexity, some of them include tests in real conditions (transient state) during longer periods, while other include shorter periods of observation in



controlled environment and with steady state conditions. Experiments in controlled environment enable a much more detailed examination of the cause-and-the-effect relationships in observed processes, as opposed to experiments in real conditions. This type of test is directly manipulated by a scientist, where variables can be controlled and held at constant level to minimize or stabilize their effects on subject. When it comes to testing of DSF facades, control experiments are possible only in climate simulators (climate chambers), where exterior and interior conditions can be simulated, including the effect of solar irradiation. Usually, experiments are performed in steady state conditions where some performance indicator/variable are examined in response to constant level combination of controllable factors (simulated weather conditions and DSF configuration). This type of studies is quite rare due a very high demands in terms of economic costs, but no other type of experimental test provides such a detailed approach to the problem. In the framework of the research project called REINVENT (REsponsive, INtegrated, VENTilated - REINVENT – windows), experimental tests in controlled environment on full-scale DSF prototype with controllable cavity features will be performed for the better understanding of the thermal and fluid dynamic behavior of DSF systems.

The aim of this paper is to present the experimental set-up, consisting of both the façade mock-up and the test facility, as well as the experimental design to plan tests with this system.

## 2. Experimental set-up

The analysis of the thermal and fluid dynamic behaviour of double skin facade systems is carried out through a series of experiments on a double skin façade test bed, developed on-purpose for the research project. The test bed is installed in a climate simulator test ring. In the following section, characteristics of test ring and bed will be presented, along with the measurement equipment intended for monitoring of physical processes.

### 2.1. Climate simulator test facility

The Large-Scale Vertical Building Envelope Climate Simulator (Climate Simulator, Figure 1A) is an experimental facility designed to test full-scale building envelope components (opaque and transparent), under simulated, controlled (outdoor and indoor) boundary conditions, in terms of air temperature, air humidity, and solar irradiation. This system has been originally developed for testing of exterior walls and elements (with a height of up to 3.9 m), including testing of walls and facades with integrated, technologies, but can also be used for testing indoor partition systems and for accelerated ageing tests.

The Climate Simulator is composed of two coupled test cells, independently accessible, and the test wall/façade sample, positioned between the two chambers. The total dimensions of the test system are (W x D x H): 7.0 m x 4.4 m x 3.9 m, while each chamber has the following internal dimensions (W x D x H): 3.7 m x 1.5 m x 3.3 m. The walls, ceiling and floor of each test cell are made of vapor tight prefabricated panels with high density polyurethane foam injection and stainless-steel structure/interior 120 mm thick. The wall/façade sample under test can measure up to 3.9 m in height and 3.6 m in width, and have a thickness of up to 0.8 m. The sample under test is installed in a steel or wood frame, which is placed/removed from the measuring position by means of a bridge crane.

The climatization of each chamber is assured by a full recirculating air system equipped with heating and cooling coils, which controls the temperature and relative humidity of each chamber and assures a good uniformity of the quantities through an air circulation that goes from the ceiling to the floor. The heating and cooling units of each test cell are designed to maintain the air temperature in the range -28 °C to +80 °C (outdoor cell), and +5 °C to +50 °C (indoor cell) with an accuracy of  $\pm 0.3$  °C. The relative humidity can also be controlled in the range 20 % to 95 %, with an accuracy of  $\pm 3$  %.



**Figure 1a and 1b.** Climate simulator and double skin facade

The test cell that functions as the outdoor environment is equipped with a solar simulator, a matrix of 9 metal-halide lamps (0.4 m x 0.4 m each) for a total size of 2.4 m x 2.4 m. This system can deliver an irradiance of  $1000 \text{ Wm}^{-2}$  at 0.8 m distance from the lamps plane, with a spectrum that replicates (as much as possible) solar at the Earth surface. The solar simulator can be dimmed in the range 40 % to 100 % and draws up to approximately 44 KVA. Air temperature, relative humidity, and irradiation level setpoints can be variable during the test, so that dynamic profiles of air temperature, relative humidity, and irradiation can be realized.

The integrated monitoring and control system of the test facility allows a real-time control of the digital and analogue signals (both input and output) and for the correct programming of the test bed activity, including dynamic profiles for all the main physical quantities. The monitoring and control system of the test bed makes use of capacity probes with accuracy of  $\pm 1 \%$  and Class A (accuracy  $\pm 0.1 \text{ }^\circ\text{C}$ ), 3-wire PT100 probe, for relative humidity and air temperature measurements, respectively. Additional sensors can be installed to monitor physical quantities on the sample under tests. These sensors can be either digital or analogue, connected either to the controller of the Climate Simulator or to an independent controller/data acquisition device.

## 2.2. Double skin facade test bed

The DSF test bed is made of a double skin system realized with commercially available aluminium frame with thermal brake (Figure 1B). The transparent glazing area has following dimensions: 1.4 m (W) x 2.8 m (H), where both the inner and outer glazing of DSF are made of a double clear glass plane (4 mm thick) with low emissivity coating, facing a 15 mm space in between filled with mixture of air and 90 % Argon.

The cavity depth can be changed, thanks to dedicated hardware components and system design made of supporting scissors, in order to test different cavity depth values and, consequently, cavity ratio. The cavity depth can be arranged from 200 mm to 600 mm and it contains a white aluminium (RAL 9006) venetian blinds, with 50 mm blades. The angle of the venetian blinds can be adjusted through the electric motor between  $0^\circ$  (corresponds to horizontally placed blinds) and nearly  $90^\circ$  (corresponds to completely closed sun-shading device, or vertically placed blinds). The position of blinds in the cavity cannot be changed directly, but the position of glazing can be changed relative to the position of blinds. This feature allows the influence of blinds-to-glass distance on heat transfer and fluid dynamics in cavity to be tested.

The DSF has four openings, two inlets and two outlets, which cover whole width of double skin façade. Simply by closing two out of four these openings, various airflow paths (ventilation modes) can be tested. The test bed is equipped with a dedicated section for calibration of airflow monitoring in the cavity. Calibration of the airflow measurement in the cavity will be carried out through a series of off-line tests where different measurement techniques will be adopted in parallel to assess the mass-flow. Airflow profile reconstruction through hot-wire anemometers readings and pressure-drop method [5]

will be used during the tests in the climate simulator. However, additional measurements with calibrated orifice plates, gas tracer techniques (with CO<sub>2</sub> as marker), and ultrasound sensors will be carried out to calibrate the readings of the first two techniques prior to the test runs in the climate simulator.

### 2.3. Measurement devices and monitoring system set-up


Several types of sensors are intended for monitoring physical quantities inside DSF cavity, on the surface of glazing and in climate chamber and air supply system. Depending on the type, sensor's output is given with analogue signal of voltage and current or digital signal (RS485). More information on the types of sensors along with their uncertainties is given in Table 1. The given accuracy is the uncertainty of sensor for the most appropriate range.

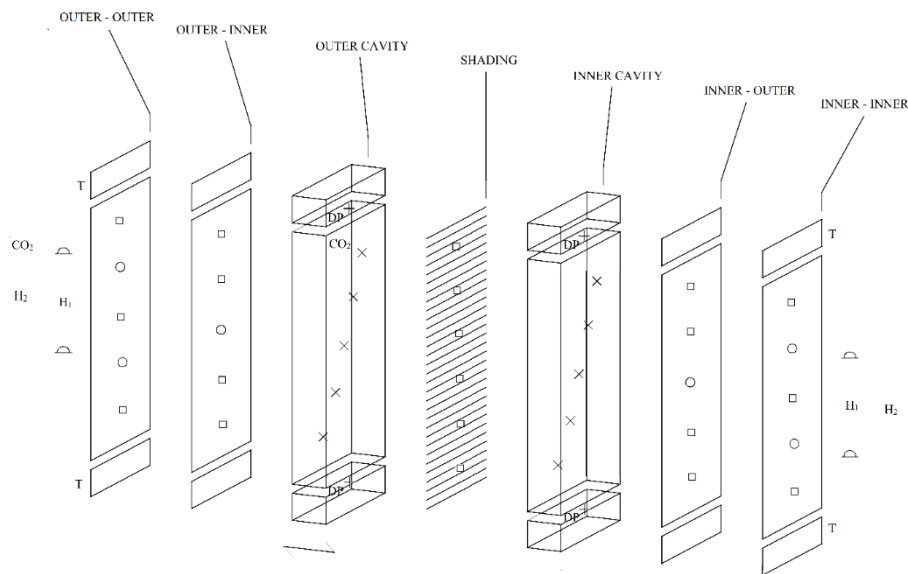
Pyranometer is intended to measure incident solar radiation on outer surface of glazing, as well as one transmitted through the DSF. Several type of temperature sensors is planned to be mounted so they can measure temperature of air in the cavity, inlets, outlets and in the inner and outer part of climate chamber. Up to twenty-five resistance thermometers will be placed on the inner and the outer glazing of double skin façade, as well as on the venetian blinds for monitoring of surface temperatures (Figure 1).

The proper placement of air velocity transducers will minimize disturbance on the airflow, which is crucial for assessing fluid dynamics and velocity profile inside cavity of DSF. Air velocity sensors (hot-wire anemometers) are installed on five heights in the cavity, with the possibility to arrange the position of the transducers in the cavity orthogonally to the airflow. The rate of heat transfer per unit surface area is measured with heat flux meters attached to the glazing.

Sensors for measuring intensity of solar radiation, CO<sub>2</sub> concentration temperature and relative humidity will be located in the inner and outer part of climate chamber. All sensors are connected to multiplexing station composed of several acquisition cards, where multiple analogue and digital signals are combined into one digital signal. Monitoring and recording of the data are done through a National Instruments single board unit and LabVIEW software, with continuous acquisition with time-step of 5 s.

**Table 1.** Sensor characteristics

<i>Sensor type</i>	<i>Signal</i>	<i>Amount</i>	<i>Symbol</i>	<i>Accuracy</i>
<i>Pyranometer</i>	4 ...20 mA	5		Achievable uncertainty: 20 % (hourly) and 10 % (daily)
<i>Air temperature and relative humidity</i>	Digital (RS485)	2	H <sub>1</sub>	± 1.5 %RH for ranges (0...90 % RH) and (15...35 °C) and ± 0.3 °C for range (0...70 °C)
<i>Air temperature and relative humidity</i>	Digital (RS485)	2	H <sub>2</sub>	± 1.5 %RH for ranges (0...90 % RH), ± 0.3 °C for range (0...70 °C)
<i>Air temperature</i>	Digital (RS485)	4	T	± 0.3 °C for range (0...70 °C)
<i>Air speed and temperature</i>	4 ...20 mA	12	×	± (0.15 m/s + 3 % of measurement) for range 0...2 m/s and ±0.3 °C
<i>Air temperature</i>	4 ...20 mA	8	+	± 0.3 °C for range (0...70 °C)
<i>Differential pressure</i>	4 ...20 mA and 0 ...10V	4	DP	±3%
<i>CO<sub>2</sub> concentration</i>	4 ...20 mA	2	CO <sub>2</sub>	for 2000 ppm ± (50 ppm + 3% of measurement) at 20 °C, 50 % RH
<i>Surface temperature</i>	3 wire PT100	24	□	from ±0.37 °C at -10 °C to ±0.70 °C at 80 °C
<i>Heat flux density</i>	2 wire mV	8	○	± 3 %
<i>Airflow and temperature</i>	Digital (RS485)	2		±5 % or from Dim. 100 = ±1.00 l/s to Dim. 630 = ±6.30 l/s



**Figure 2.** Scheme of sensor layout

### 3. Design of the experiment and planned tests

Conducting the experiment in a climate chamber under steady state conditions requires time to assure constant boundary conditions and heat/fluid flow. Up to two or even three days might be needed to achieve thermally and dynamically steady state situation in the system and only after accomplishing this, measurements can be taken [6]. To test all the different configurations of DSF in response to all the combinations of artificially created boundary conditions (solar radiation and temperature) would require a time in the range of years. Instead of covering all the possible configuration of DSFs and boundary conditions, a systematic approach for finding the minimal number of experiments using orthogonal arrays was adopted.

The so-called Taguchi method [7] is employed in this research to narrow down the total number of experiments assuring at the same time the full representativeness of the experimental runs. This method has been chosen due its straightforwardness and simplicity.

**Table 2.** Factors and corresponding levels for three different experimental designs

	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>	<i>Level 4</i>
<b>MECHANICAL VENTILATION</b>				
<i>Temperature difference [°C]</i>	-25	-10	0	15
<i>Incident solar radiation [Wm<sup>-2</sup>]</i>	400	600	800	1000
<i>Airflow rate [m<sup>3</sup>s<sup>-1</sup>m<sup>-2</sup>]</i>	0.002	0.004	0.006	0.008
<i>Slat angle [°]</i>	Without	45	90	Closed
<i>Cavity depth [cm]</i>	20	35	45	60
<i>Airflow path [I]</i>	I→I	O→O		
<b>CLOSED CAVITY</b>				
<i>Temperature difference [°C]</i>	-25	-10	0	15
<i>Incident solar radiation [Wm<sup>-2</sup>]</i>	400	600	800	1000
<i>Slat angle [°]</i>	Without	45	90	Closed
<i>Cavity depth [cm]</i>	20	35	45	60
<b>NATURAL VENTILATION</b>				
<i>Temperature difference [°C]</i>	-25	-10	0	15
<i>Incident solar radiation [Wm<sup>-2</sup>]</i>	400	600	800	1000
<i>Slat angle [°]</i>	Without	45	90	Closed
<i>Cavity depth [cm]</i>	20	35	45	60
<i>Airflow path [I]</i>	I→I	O→O		

Three different main cases are planned for the DSF operational mode: closed configuration of DSF, mechanically ventilated DSF and naturally ventilated DSF. Only two configuration of airflow paths

(inside → inside and outside → outside) will be investigated due to limited time resources, while still considering that the conditions at the outlet are independent on the outlet opening direction itself (i.e. whether the outlet is open towards the inside or the outside).

For the naturally and mechanically ventilated cavity, a mixed level design of four to five factors with four levels and one factor with two levels is chosen, which results in L32 orthogonal array for each of the cases. For the closed cavity configuration case, due to lowest number of examined factors (four factors with four levels), a L16 orthogonal array is obtained. With the selected variables and levels, the full factorial design of experiment for the DSF with all considered configurations would result in 4352 experiments (2048+256+2048). The Taguchi method reduces this number of experiments to just 80 experiments. After the experimental tests are concluded, a parametric analysis of the dependence and contribution of various control factors (DSF configuration) as well as noise factors (temperature difference and solar radiation) on the DSF behaviour will be carried out. This is performed through the analysis of variance (ANOVA) and F-test control to understand the contribution and significance of each individual factor on some defined performance indicators.

#### 4. Conclusion

This paper reports the design of a new test bed for the full-scale characterisation of the thermal and fluid mechanical behaviour of double skin facade systems. The test bed is planned to be operated in conjunction with a large-scale climate simulator, which will allow the boundary conditions around the DSF system to be controlled, including the level of irradiation on the facade plan provided by a solar simulator. The facade test bed is flexible in terms of airflow path and cavity ratio, since the opening towards the inside or the outside of the DSF can be alternatively operated, and the cavity depth varied.

Through this combined test rig, equipped with a relatively large number of sensors and an integrated control-monitoring system, it will be therefore possible to experimentally study infinite combinations of boundary conditions and facade operation modes. Orthogonal array design of experiments and analysis of variance are the approach and tools planned to be adopted to reduce the numbers of experiments to a minimum number that is still representative of the entire domain of exploration, and to assess the influence of different factors on the DSF's performance.

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