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A simulation study on the performance of double skin façade through experimental design methods and analysis of variance

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Abstract. Systematic studies of the thermal fluid dynamic behaviour of building envelope systems through experiment analyses is limited by the relevant amount of time and high costs necessary to carry out a relevant number of tests covering all the possible configurations. Building simulation can be used as a tool to support the design of the experiments, i.e. to test, in a parametric way, different configurations to highlight the main trends, and therefore select the most relevant cases to be tested experimentally. Such a preliminary activity to maximize the effectiveness of the experiments may relates to both parametric analysis of indoor/outdoor boundary conditions, as well as parametric analysis of building envelope configurations. In the framework of a research project on double skin facade (DSF) systems where experiments are planned on a full-scale prototype, a model of a DSF is realized in a whole building energy software tool, and used to carry out a preliminary sensitivity analysis, by means of orthogonal array method and analysis of variance. Simulations were carried out in EnergyPlus, using the Airflow window module, and under steady-state conditions, a series of variables (cavity depth, venetian blinds tilt angle, airflow rate) have been investigated to assess their impact on the heat extract through the ventilation air and the total heat transmission between the outdoor and indoor environment. The results show that the main driver in the performance of DSF considering net heat rate transfer is the irradiation impinging on the façade in terms of boundary conditions, and coherently, the shading device is the feature that most affects the performance of the system among the characteristics of a DSF.

1. Introduction

Double skin facade (DSF) systems have become an interesting and important architectural element in buildings in the last few decades because of their transparency look and potentials for reduction of energy demand compared to conventional, single skin facades [1]. However, to really achieve a good energy performance, double skin facades need to be properly designed, and because of their intrinsic complexity, such a task is not trivial. This means that a designer needs to rely on numerical tools that can replicate the fluid mechanic and thermal phenomena occurring in the DSF and, therefore, that such physical processes are well understood - as well as properly modelled in simulation tools. The behaviour of a DSF can be highly dynamic and the interaction between multiple domains is affected by several variables, such as the geometric features, the thermo-physical, optical, and aerodynamic characteristics of the different DSF elements [2].

In the frameworks of the research project project REsponsive, INtegrated, and VENTilated – REINVENT – Windows [3], experimental analyses on a ventilated DSF are planned to be used to increase the understanding of the phenomena occurring in a DSF. Experimental analyses are aimed at both assessing the energy performance and investigating the complex interrelation of thermophysical phenomena occurring in the systems (thermophysical behaviour of DSFs in relation to cavity features, shadings, and airflows). These activities will be based on tests carried out on a full-scale prototype/test-bed, installed in a climate simulator located in the laboratories of NTNU and SINTEF.

Relatively few full-scale experimental studies are available in literature, and this is probably due to the high costs associated to such activities, since the experimental rig and setup is complex, and the analyses to carry out may be unlimited, due to the high number of variables that can be investigated. Because of the general limitations in time and resources, it is crucial to understand what is the minimum number of experimental runs that can provide a general picture of the interaction between different variables (cavity depth, airflow rate, shading position, boundary conditions) and the performance of DSF systems. In this context, a proper design of an experiment is therefore at the basis of a successful experimental activity and building simulation tools can be a suitable strategy to support the design of the experiments.

In order to prepare the plan for the experiments under the research project REINVENT Windows, a DSF system has been modelled in a whole building energy software tool to carry out a global sensitivity analysis on the important parameters and configurations that might be tested. The numerical analysis was carried out in EnergyPlus, using the Airflow window module [4], under different steady state conditions, and a series of variables (cavity depth, venetian blinds tilt angle, airflow rate) have been parametrically investigated to assess their impact on the net heat transfer between the outdoor and indoor environment. The aim of this activity, whose results are reported in this paper, is therefore to draw some preliminary conclusions on the overall behaviour of DSFs so that the numbers of test to be carried out can be minimised while still investigating the most relevant aspects of the problem.

2. Methodology

2.1. Numerical model and simulation settings

The model of DSF simulated in EnergyPlus follows the real, full-scale test bed to be tested in the laboratory. The transparent part of the DSF has dimension of approx. 1.4 m (W) x 2.8 m (H), and a cavity that can be varied in the range 20 to 60 cm. White aluminium venetian blinds 50 mm wide are positioned in between the inner and outer glazing. The inner and outer glazing of the DSF is made of a two low-E glass planes with thickness 4 mm and with gap thick 16 mm between planes (4-16-4 mm). Gap is filled with a mixture of air and 90% Argon. Overall optical and thermal properties of inner and outer glazing are calculated according Window software developed by Lawrence Berkeley National Laboratory. The DSF is modelled through the in-built module called “Aiflow-window”, directly available in EnergyPlus [4].

Because the focus of the research is placed on the façade component alone, the DSF is modelled in a virtual cubicle, and it is the only surface exposed to the outdoor conditions, while all the other surfaces were set as adiabatic and a fix temperature value (equal to the indoor air temperature setpoint) is imposed. Wind effect was eliminated from study, as well as naturally induced flow by temperature differences in the cavity, as the Airflow window module in EnergyPlus only allows mechanically ventilated cavities to be simulated [5]. In this first part of the research, the performance of the DSF is analyzed under steady state conditions, and this means that some settings have been implemented in EnergyPlus (and in the weather data file used) to assure constant outdoor temperature values and irradiation levels on the façade

2.2. Selection of simulation runs

Because of the high number of combinations to be simulated to carry out a global sensitivity analysis, the full factorial design (i.e. the analysis where all the values of the independent variables are combined) would have resulted in many simulations. It was therefore decided to make use of the so-called “Taguchi method” of design of experiments. This technique provides a systematic approach that allows one to find the minimal number of experiments using orthogonal arrays. The minimum number of experiments required by the Taguchi method can be determined based on the number of factors and the corresponding levels and is based on orthogonal arrays [6]. Number of experiments can be reduced by following two properties of orthogonal array:

- *Balancing property***.** The vertical column for each independent variable has a special combination of level settings, and all the level settings need to appear an equal number of times.
- *Mutual orthogonality*. The array for each factor (i.e. the proposed combination of factor’s levels in column) needs to be mutually orthogonal to any other column of level values, which means that the inner product of vectors corresponding to weights is zero.

With the selected variables and levels, the full factorial design of experiment for the DSF with open cavity would result in $5^6 = 15625$ combinations and for the case with closed cavity in $5^4 = 625$ – hence a total of more than 16000 simulations. Through the application of the Taguchi method, a L25 orthogonal array for both cases is chosen, being the orthogonal array, among all the possible ones, that leads to the minimum amount of simulations to be carried out – 2 x 25 combinations (simulations).

In this study, five levels for each of the six control factors are used (Table 1). Five levels can be assigned to airflow path (*inside → inside, inside → outside, outside → outside, outside → inside* and closed configuration). For the last level of airflow path, air is trapped inside closed cavity and mechanically induced airflow rate should be equal to zero. Since one of the prerequisites of Taguchi method is that factors should be mutually independent, closed cavity should be analysed separately as it is dependent on airflow rate (values different from zero cannot be assigned to that level of airflow path). Therefore, for the design of experiment, different configurations of open cavity of DSF were analysed separately from closed configuration. For the case of the open cavity, dummy treatment was used for airflow path, where *inside → inside* level was repeated twice to be able to exclude the closed configuration from this array. For the closed cavity case, four factors with five different levels were analysed (Table 1). The results of the simulations carried out for both ventilated cavity and closed cavity are shown in Table 2.

2.3. *Data post-processing and performance metrics*

The Taguchi method allows the influence of different levels of factor on one or more performance indicators to be assessed and allows on understanding how the variations of a factor affects the variations of performance indicator [7]. In this way, it is possible to find the contribution of each individual factor, but it is not directly possible to conclude whether the estimated contribution is significant or not. To overcome this limitation, the analysis of variance (ANOVA) is coupled to the performed the global sensitivity analysis, where an additional statistical tool (F-test) is used to understand the relevance of the contribution [8]. The criteria for accepting or rejecting the significance of a factor is based on the comparison between the ratio of mean sum of square of a variable and the mean sum of square of the error to calculated F-value.

Table 1. Factors and their corresponding levels for two analyzed cases.

	Level 1	*Level 2*	*Level 3*	*Level 4*	*Level 5*
					OPEN CAVITY
Temperature difference [^{0}C]	-25	-15	-5	5	15
Incident solar radiation [Wm^{-2}]	0	200	400	600	800
Airflow rate [m^{3}s^{-1}m^{-1}]	0	0.002	0.004	0.006	0.008
Slat angle [^{0}]	Open	4	45	65	90
Cavity depth [cm]	20	30	40	50	60
Airflow path []	I→I	O→O	I→O	O→I	I→I
					CLOSED CAVITY
Temperature difference [^{0}C]	-25	-15	-5	5	15
Incident solar radiation [Wm^{-2}]	0	200	400	600	800
Slat angle [^{0}]	Open	4	45	65	90
Cavity depth [cm]	20	30	40	50	60

Table 2. Orthogonal array of Taguchi and corresponding values of performance indicator.

Experiment #	***Temperature difference [^{0}C]***	***Solar radiation [Wm^{-2}]***	***Airflow rate [m^{3}s^{-1}m^{-1}]***	***Slat angle [^{0}]***	***Cavity depth [cm]***	***Airflow path []***	***Specific net heat flux [Wm^{-2}]***	***Temperature difference [^{0}C]***	***Solar radiation [Wm^{-2}]***	***Slat angle [^{0}]***	***Cavity depth [cm]***	***Specific net heat flux [Wm^{-2}]***
	OPEN CAVITY							***CLOSED CAVITY***				
1	-25	0	0	Open	20	I-I	-11.1	-25	0	Open	20	-11.1
2	-25	200	0.002	4	30	O-O	-8.6	-25	200	4	30	36.9
3	-25	400	0.004	45	40	I-O	106.3	-25	400	45	40	111.8
4	-25	600	0.006	65	50	O-I	-214.5	-25	600	65	50	265.8
5	-25	800	0.008	90	60	I-I	260.7	-25	800	90	60	319.4
6	-15	0	0.002	45	50	I-I	-11.6	-15	0	45	50	-7.3
7	-15	200	0.004	65	60	I-I	101.0	-15	200	65	60	78.3
8	-15	400	0.006	90	20	O-O	75.1	-15	400	90	20	177.0
9	-15	600	0.008	Open	30	I-O	312.6	-15	600	Open	30	269.8
10	-15	800	0	4	40	O-I	186.4	-15	800	4	40	447.6
11	-5	0	0.004	90	30	O-I	-76.8	-5	0	90	30	-4.0
12	-5	200	0.006	Open	40	I-I	113.0	-5	200	Open	40	88.1
13	-5	400	0.008	4	50	I-I	146.7	-5	400	4	50	161.2
14	-5	600	0	45	60	O-O	255.4	-5	600	45	60	337.3
15	-5	800	0.002	65	20	I-O	255.4	-5	800	65	20	291.2
16	5	0	0.006	4	60	I-O	0.0	5	0	4	60	-0.5
17	5	200	0.008	45	20	O-I	91.7	5	200	45	20	81.9
18	5	400	0	65	30	I-I	184.6	5	400	65	30	226.8
19	5	600	0.002	90	40	I-I	326.0	5	600	90	40	145.2
20	5	800	0.004	Open	50	O-O	424.3	5	800	Open	50	346.1
21	15	0	0.008	65	40	O-O	12.1	15	0	65	40	3.0
22	15	200	0	90	50	I-O	85.4	15	200	90	50	116.5
23	15	400	0.002	Open	60	O-I	355.3	15	400	Open	60	100.1
24	15	600	0.004	4	20	I-I	236.6	15	600	4	20	263.2
25	15	800	0.006	45	30	I-I	448.2	15	800	45	30	374.4

In this investigation, the performance indicator selected to study the dependence and contribution of various design (control) factors as well as boundary conditions (noise) factors on the DSF behaviour was the specific net heat transfer rate [W/m^2]. This is the net heat transfer rate through the glazing normalized over the glazed area [4], and is equal to the balance of the following quantities:

- the directly transmitted solar radiation rate;
- the convective heat flux exchanged at the indoor surface of the DSF; and
- the net infrared heat flux exchanged between the DSF's indoor surface and the room's surfaces.

It is important to stress that for all the cases where there is mass exchange between the ventilated cavity of the DSF and the indoor/outdoor environment, the convective gain/loss through the ventilation air is not accounted in the performance metric described above.

3. Results

3.1. Simulation results

The average specific net heat flux is 146.2 W and 168.8 W for the open cavity and the closed, respectively (25 plus 25 experiments runs). The average value is shown with the dashed grey line in the figures 1a and 1b. For every level of every factor mean value is visible on graph which is denoted with blue point. For example, average value for level 1 (-25 ^{0}C) of temperature difference (outdoor minus indoor temperature) is 26.6 Wm^{-2} (Figure 1a) for open cavity case. This value is obtained as arithmetic mean of specific net heat transfer of the first five experiments (Table 2). Similar analysis is done for the other levels of temperature difference and the other factors. The greater the vertical range of the factor on the figures below (Figure 1a and 1b), the greater the impact on the performance indicator – e.g. solar radiation is the variable that affects the most the net heat transfer, while airflow rate the least, for open cavity case. Difference between highest (level 5, 800 Wm^{-2}) and the lowest mean value for levels (level 1, 0) is 332.5 Wm^{-2} for incident solar radiation, while for airflow rate is only 98.9 Wm^{-2} (Figure 1a and Table 3).

3.2. *Analysis of variance ANOVA*

The influence of the factors on the performance indicator (specific net heat transfer) can be quantified in the form of percentage when the squared deviation for each level of a variable are summed and then divided by the total sum of squared deviation for all variables. [9]. As shown in Table 3, for the open cavity case, the highest percentage contribution to the net heat transfer rate comes from incident solar radiation (49.44 %), while the temperature difference and the slat angle of venetian blind are also important (19.58 % and 11.37 %, respectively) to a certain extent. The contribution of other four factors expressed in percentage is much lower than for these factors and it goes in the following descending order: airflow path, cavity depth and airflow rate. For the case of closed cavity, incident solar radiation is by far the one that contributes the most to net heat transfer, while the other three factors have significantly lower percentage contribution, with the blind slat angle being the only other with some significance.

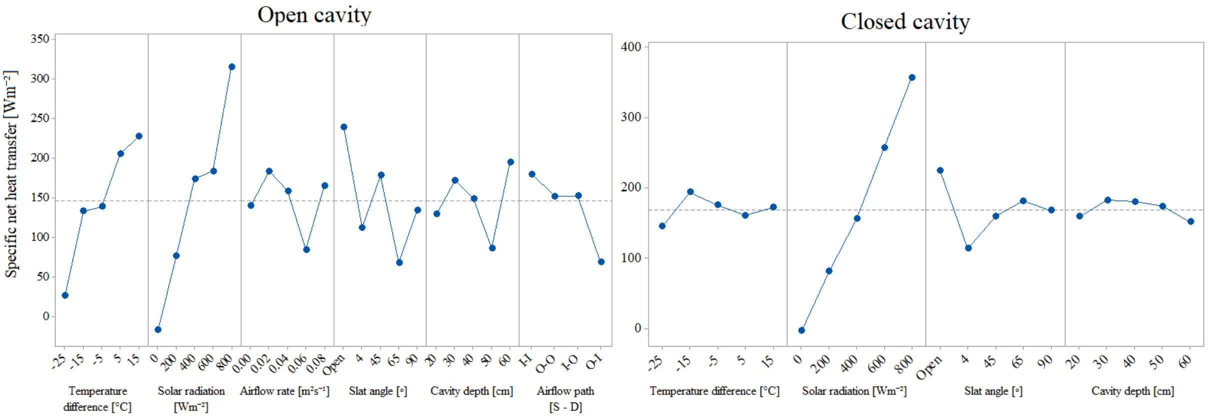

Figure 1a and 1b – Effect of different level values on specific net heat transfer rate

Table 3. Contribution rate and results of ANOVA test

	Degree of freedom	*Delta [Wm^{-2}]*	*Contribution [%]*	*Rank*	*F-value*	*F (3/4,25,0.95)*	*Significance*
OPEN CAVITY							
Incident solar radiation	4	332.5	49.4%	1	15.04	2.87	YES
Temperature difference	4	201.0	19.6%	2	5.96	2.87	YES
Blind Slat angle	4	171.1	13.5%	3	4.12	2.87	YES
Airflow path	3	111.0	6.6%	4	2.68	3.10	NO
Cavity depth	4	108.4	5.5%	5	1.67	2.87	NO
Airflow rate	4	98.9	4.6%	6	1.38	2.87	NO
CLOSED CAVITY							
Incident solar radiation	4	359.7	89.4%	1	138.51	2.87	YES
Blind Slat angle	4	110.2	7.0%	2	10.88	2.87	YES
Temperature difference	4	48.5	1.4%	3	2.23	2.87	NO
Cavity depth	4	30.9	0.8%	4	1.25	2.87	NO

The significance of the contribution of each factor is assessed through the F-test and the analysis of variance (ANOVA) [8]. The critical F value that determines the significance of some variable is taken from F-distribution tables at 95 % confidence level [9]. The number of levels (L-1) and number of simulations/experiments (N-L) determines this critical value, which is equal to 2.87/3.10 (Table 3). The ANOVA test conducted at 95% confidence level accepts the significance of incident solar radiation, temperature difference and slat angle, while rejects significance of other factors for open cavity case. For closed cavity case, the ANOVA test accepts significance of incident solar radiation and slat angle of venetian blinds, while rejects significance of temperature difference and cavity depth.

4. Discussion and conclusions

The outcomes of this study show that the impinging irradiance level is the leading factor (in this case, a boundary condition), when the focus is placed on the net energy transfer through a DSF. This is true regardless the DSF is ventilated or operated in buffer mode. When it comes to variables that are related to the technology and configuration of the façade, the analysis highlight that the slat angle of the venetian blind is the most relevant parameter. These results are in line, as they show that solar irradiance and its control factor is the variable affecting the most the DSF's behaviour.

Even if this analysis has been conducted only on a mechanically ventilated DSF, it is reasonable to assume that a similar trend would be also seen in naturally ventilated facades. This is because the airflow rate in the latter case depends heavily on the stack effect realised in the DSF's cavity, which is itself largely due, again, on the impinging irradiance, and the shading system used to control it.

The study has focused on the influence of different parameters on the specific net heat transfer through the DSF surface, without considering the convective gain or loss due to the ventilation air that flows in the cavity, when this interacts with the indoor air (for example, in the exhaust air curtain mode, or supply air mode). This led to the conclusion that the airflow path is not an important variable, as well as the airflow rate. However, if the focus had been placed on the total energy transferred between the inside and the outside (i.e. including also the convective gain or loss through the ventilation flow), results would have been probably different. In the next steps of this activity, more performance metrics will be used to assess the influence of the variables on a larger domain.

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