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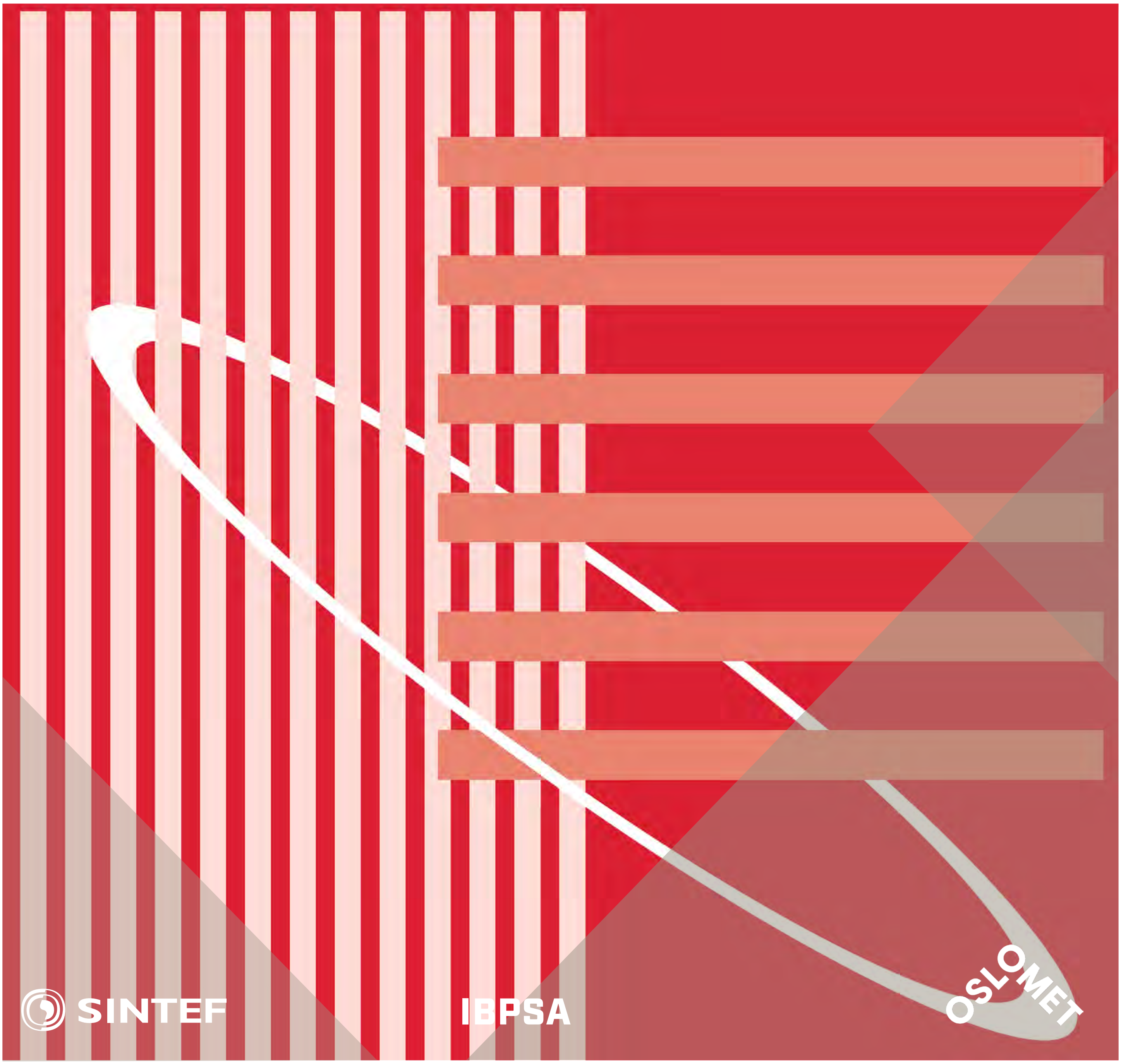

SINTEF Proceedings

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The Potential of the Multi-Angled Facade System in Improving Natural Ventilation

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Abstract

This paper is part of a research study focusing on highlighting the potential of using Multi-Angled Facade systems in improving natural ventilation inside an office room. The multi-angled façade is a three-dimensional façade with two different window orientations. The design of the intake and outtake depends on formulae from SBi Directive 202. The calculations of the consumed energy and the evaluation of indoor climate are made using the software packages IDA ICE and Autodesk CFD. The results show that the two oriented facade parts will help to improve air penetration, with heat removal upto 31% higher than for a flat façade, thus leading to a better indoor climate in the office room.

Introduction

The research study focuses on the potentials of the Multi-Angled facade in improving natural ventilation inside the office room and providing an acceptable indoor climate.

The design concept of the Multi-Angled facade is a three-dimensional façade that extends outwards from, and is connected at its sides to, the original building flat façade. The design concept targets the use of two different orientations of windows in each façade (see Figure 1) to optimize the use of solar radiation and daylight through the façades, depending on the appropriate window properties and the solar shading control system (Hannoudi et al., 2016b) A considerable advantage would be that, while having the solar shading shut on one part of the room façade due to direct solar radiation, another part of the façade may have no shading, thus continuing to provide daylight and views to the outside on sunny days.

Global climate change is posing increasingly severe threats to ecosystems, human health, and the economy. Climate change is caused by the release of large amounts of greenhouse gases into the atmosphere as a result of human activities worldwide, especially the burning of fossil fuels for electricity generation, heating, and transport (The European Environment Agency (EEA), 2020). Buildings account for approximately 40% of energy consumption and 36% of CO2 emissions in the EU. Buildings are therefore the single largest energy consumer in Europe (European Commission, 2020).

The aim of this research is therefore to minimize these negative environmental impacts, by integrating a natural ventilation system into the design of buildings. Many office and commercial buildings worldwide have implemented this strategy such as Red Kite House and Bloomberg European HQ in Great Britain and Industriens Hus in Denmark. The previously mentioned building has used a double-skin facade with natural ventilation, while this research presents the potential of the Multi-angled facade System as a new facade concept that is not used or researched before to improve natural ventilation inside the building.

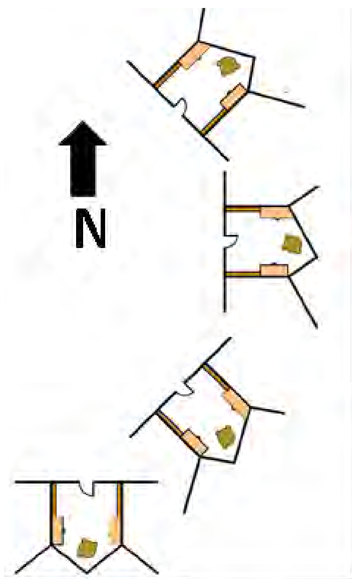

Figure 1 Different orientations for an office room that show the use of two different orientations of windows in each room façade, where the large part is oriented more to the North and the small part is more to the South (Hannoudi et al., 2017b)

Background

All buildings need a ventilation system (mechanical, hybrid, or natural) to achieve an acceptable indoor climate and good air quality. In winter, the ventilation system maintains good air quality and removes CO_2 when it exceeds the acceptable limit, whereas in summer it maintains an acceptable thermal indoor climate.

The air that penetrates through room openings depends on two main factors: the thermal driving force and wind pressure. The thermal driving force depends on thermal buoyancy and the temperature difference between the inside and outside of the building. Usually, the difference between indoor and outdoor temperatures during the summer season in Denmark, as an example case study used in this research is between 3 °C and 4 °C (State Building Research Institute, 2000).

Natural ventilation depends also on the wind pressure. For example, in Denmark the annual mean wind speed is approx. 4 m /s inland and approx. 5.5 m /s to the coast. Generally, the prevailing wind direction is from the west–southwest; on warm summer days and from the east–southeast. On some winter days, the wind direction is from the north (Technical University of Denmark, 2009).

Using the information above regarding wind speed and temperature difference between inside and outside will help carrying out calculations for the natural ventilation design. There are several natural ventilation principles that can be implemented in the design of an office building, such as one-side ventilation, cross ventilation, and thermal buoyancy ventilation. Many office rooms in Europe, specifically Denmark, are single rooms with a door that opens to the corridor. Thus, one-side ventilation can be adopted when designing natural ventilation inside a room. This research will concentrate on natural ventilation in offices by implementing the first principle, i.e. one-side ventilation. Since the office room is a part of a building, there are some periods when the door is opened, which might create a kind of cross ventilation. But the assumed scenario in this research is while the door of the room is closed, which most often happens.

A healthy and accepted indoor climate can be ensured in the office rooms by implementing an automatic control of the opening of façade windows. The size of the window openings and the frequency of opening are based on the pre-defined values of the operating parameters for temperature, CO_2 level and humidity, both for the indoor and the outdoor climate. These values are pre-defined in a control system made by the producing company

Methods

This study starts with a literature review on the potential of natural ventilation in buildings, including the principles, design methods, and control systems of natural ventilation. The review was combined with communications with some experts in this field, such as consultants from Window Master International A/S, as the best company in Denmark for the design of natural ventilation and one of the providers of natural ventilation solutions in northern Europe.

The method for investigating the potential of the multi-angled facade system in improving natural ventilation consists of three main steps:

1. The intake and outtake areas are designed depending on formulae from the (SBi) directive 202 (State Building Research Institute, 2002).
2. The results of number of overheating hours, relative humidity (RH), CO2 evaluations, and energy consumption are calculated by the software IDA ICE (IDA Indoor Climate and Energy, 2019).
3. The simulations of airflow through the office room facade (both the flat and Multi-angled façade) and inside it, along with the room temperature and air velocity are conducted by the Autodesk software CFD 2019

Input data for the calculations and simulations

Calculations for the window opening area

The window opening areas that allow sufficient natural ventilation were calculated for different outdoor climate parameters, as listed in Table 1 and in Table 2 that completes Table 1. This is in accordance with the procedure in SBi directive 202, which is based on differences in solar radiation, external and internal operative temperature in different periods of the year to calculate the necessary opening area for natural ventilation. The typical values for outdoor temp. and solar radiations in the Danish climate are represented by middle values (average values) and critical values are represented by maximum values. The values are either hourly-based values or whole day values. (State Building Research Institute, 2002). The input data for the main parameters for the calculations are presented in the next section.

Table 1 The parameters used for the calculations of window opening areas based on the temperature and solar radiations intensity.

The Season	The month	The period	Temperature °C	Solar radiation
Winter	January	middle day	middle	middle
Summer	July & August	middle day	middle	middle
		maximum day	middle	middle
		maximum hour	maximum temperature	maximum hour value
Autumn & Spring	April October	middle day	middle	middle
		maximum day	middle	middle

Table 2 The parameters used for the calculations of window opening areas, which are based, in addition to the above parameters, on wind velocity, and wind direction. 1.for day with t_{max}>20 °C. 2. for day with t_{max} >25 °C. 3. for hours with t>25 °C. 4. For the whole year

The Season	The month	Wind velocity	Wind direction
Winter	January	no wind	
Summer	July & August	25%-quantile[1]	south east
		25%-quantile[2]	south east
		25%-quantile[3]	south east
Autumn & Spring	April October	25%-quantile[4]	south west
		25%-quantile[4]	south west

The calculations were divided into six scenarios for an office room with a flat façade. The calculations for the scenario with the most critical climate data were made for an office room with a flat facade in addition to a room with a Multi-Angled façade where the demand for natural ventilation is highest in both facade types and the calculated opening area is the largest compared to the other scenarios. The six scenarios represented the best possibilities in defining the necessary climate data for the different seasons of the year. In the winter situation, the wind speed is low when the outdoor temperature is below 0°C. Therefore, calculations were based on thermal buoyancy of the air inside the room. One scenario is made for this season due to the lower demand for natural ventilation compared to the other seasons. In the summer situation, calculations were carried out for the middle and maximum temperature respectively in the summer months where the heat load is greatest (July and August). In the spring and Autumn situation, calculations were carried out for the middle and maximum temperature respectively in the April and October. The input data for the main parameters for the calculations are shown below.

Scenario 1: Ventilation based on heat removal

- July and August
- Time period (middle day)
- Middle temperature 16 °C
- middle solar radiation 2850 Wh/m² day
- Wind from south east 1 m/s

Scenario 2: Ventilation based on heat removal

- July and August
- Time period (Maximum day)
- Middle temperature 21°C
- middle solar radiation 4404 Wh/m² day
- Wind from south east 1,3 m/s

Scenario 3: Ventilation based on heat removal

- July and August
- Time period (Maximum hour)
- Maximum temperature 29 °C
- Solar radiation maximun hour 7236 Wh/m² day
- Wind from south east 4,6 m/s

Scenario 3-1 (Multi-angled facade): Ventilation based on heat removal

- July and August
- Time period (Maximum hour)
- Maximum temperature 29 °C
- Solar radiation maximun hour 7020 & 5130 Wh/m² day
- Wind from south east 4,6 m/s

Scenario 4: Ventilation based on CO_2 removal

- January
- Time perio(Middle day)
- Middle temperature -1°C
- Middle solar radiation 372 Wh/m² day
- No wind

Scenario 5: Ventilation based on CO_2 removal

- April or October
- Time period (middle day)
- Middle temperature 7,4 °C
- middle solar radiation 1674 Wh/m² day
- Wind from south west 1 m/s

Scenario 6: Ventilation based on CO_2 removal

- April or October
- Time period (Maximum day)
- Middle temperature 12,45 °C
- middle solar radiation 3270 Wh/m² day
- Wind from south west 1 m/s

The window opening areas for both facade types were calculated through the following steps:

1. Defining the placement of the intake and outtake points. The greater the distance between them the better, as this increases the stack effect, where the air moves into and out of the room resulting from air buoyancy. Buoyancy occurs due to a difference in air density resulting from temperature. There are multiple ways to achieve this. One solution is to have an opening close to the floor level, and another higher up at the ceiling level (Roth, 2020). This solution will be used in the calculations, and the distance between the centre of intake and outtake is 2.4 m (Figure 2). This is by assuming that the height of the openings (both intake and outtake) is 0.2 m and the intake is 0.3 m higher than the floor The only disadvantage of this solution is that the lower opening (intake) can be affected by snow, leaves, etc. Because of the near distance to the ground.

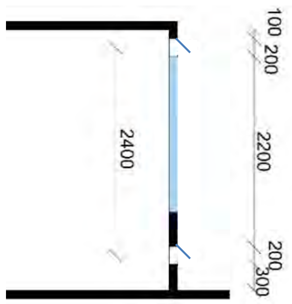

Figure 2 The placement and the distance between the intake and outtake in the room facade

2. The calculation of the required opening areas for heat removal by natural ventilation starts by calculating the required air change for heat removal from solar radiation and the internal heat gain inside the office room. This calculation also considers the specific heat loss transmission through the external facade envelope, and the specific ventilation heat loss. The next step is to calculate the pressure difference between the inside and outside, where thermal buoyancy and wind work. Finally, the required area of the opening is calculated according to the pressure difference in the opening and the necessary air change for heat removal.

3. The calculation of the required opening area for CO_2 removal by natural ventilation is divided into two types: with wind pressure on the façade and without wind pressure. For the first type of calculation, the first step is calculating the required air change for CO_2 removal inside the room. The next step is calculating the pressure difference between the inside and outside, which takes into consideration the internal pressure inside the room and the wind pressure. The internal pressure calculation depends on the wind pressure coefficient and the opening area in addition to the room volume and the air density. The pressure difference depends on the difference between the pressure caused by the wind and stack effect in the room on one hand and the internal pressure on the other hand. Finally, the required opening area is calculated according to the pressure difference in the opening and the necessary air change for CO_2 removal inside the room. For the second type of calculation, the first step is calculating the required air change for CO_2 removal inside the room which takes into consideration the CO_2 concentration outside and inside the room in addition to the emission of CO_2 per person. Then, the required area of the opening is calculated according to the pressure difference in the opening due to temperature difference, and the necessary air change for CO_2 removal inside the room.

<u>Simulation in IDA ICE</u>

The input data for the simulations in IDA ICE were based on Danish Building Regulations, Danish and European standards, site visits and interviews. The input data are:

- A model for a room with inner dimensions 5 x 4.5 x 3 m (L x W x H) . These dimensions were based on site-visits and a case study for a large number of office buildings in Copenhagen. The model of the room had adjacent rooms above, below and on each side. The model of the room is simulated with two types of external facades, a flat facade and a multi-angled façade, where the large part is oriented more to the North and the small part is more to the South.as per Figure 3. The optimized dimensions and the angles of this facade are the results of a number of simulations carried on this facade concept. The room external facade is directed toward the west, where the optimal usage of this facade concept is either towards the West or the East.
- The building is located in Copenhagen, Denmark: Latitude 55.633 N, Longitude 12.667 E.
- It is assumed that two occupants are working in the room (activity level 1.2 met (European Committee for Standardization, 2006). An average occupancy of 80% is expected for the two occupants with two computers (40 W/PC) .
- The electrical lighting is in use during the occupancy hours and is assumed to be energy efficient lighting

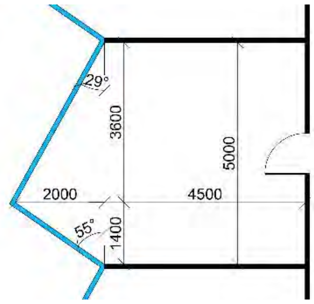

Figure 3 A plan for an office room with a multi-angled façade system

that provides 500 Lux for the working area of the office room (European Committee for Standardization, 2006) (which is assumed to be 2/3 of the room area). The electrical lighting has a total lighting power of 110 W with luminous efficacy of 80 lm/W. Energy-efficient fluorescent lighting is used as the source of electrical lighting.
- For the naturally ventilated office room, the opening's area is calculated according to the scenario for the period "Maximum hour," both for the flat façade and the Multi-Angled Façade. This scenario is with the most critical climate data that provides the data for window maximum openings area. The size of the opening's area is adjusted and optimized in the flat façade to improve the indoor climate in the office room. This optimized opening area is divided into two parts and used on the two sides of the Multi-Angled Façade. The window starts to open in the following two cases:
  1. The operative temperature doesn't fulfil the criteria in summer for building category (B) 24.5+-1.5 °C (European Committee for Standardization, 2006). Category (B) is used because it is a normal office building and
  2. CO_2 concentration doesn't fulfil the criteria for building category (B) 500 PPM above the outdoor level (European Committee for Standardization, 2006) so the concentration is between (min. 700 PPM. and max. 1100 PPM). relative humidity is kept between 30% and 70% (European Committee for Standardization, 2001)
- For the office room mechanically ventilated, the mechanical ventilation system is Variable Air Volume VAV during working hours (08:00–17:00). The control of the ventilation system depends on room temperature and CO_2 concentration. The heat exchanger efficiency is 80%. Fan efficiency (electricity to air) is 0.8. The ventilation system have a normal pressure drop of about 800 Pa. The SFP of the ventilation system is 1000 J/m^3 (Hvlid, 2014).
- It is assumed that the heating system consists of water-based radiators. Heating set point is 21°C during working hours (07:00–17:00) (European Committee for Standardization, 2006) and 16°C outside working hours. It is assumed that the energy source for heating

the building and for the domestic hot water is district heating.

- The parapet under the window consists of a concrete panel (thickness is 0.1 m) and insulation from the outer side (thickness is 0.245 m) with facade covering materials of wood. U-value for the parapets is 0.125 W/m^2K, which is accepted in the Building Regulation 2015.
- External shading devices are used with a shading factor of 0.2. For the office room with multi-angled facade, the shading system of the small window more towards the south depends on the operative temperature (closes at 24°C). The shading system of the large window more towards the north depends on solar radiation intensity (closes at 250 W/m^2 (solar radiation intensity measured externally)), which is recommended in Denmark.
- The air change through leaks in the building envelope does not exceed 1.00 l/s per m² heated floor area by pressure test with 50 Pa" according to BR15 (Building and housing agency, 2019).
- The window of the flat facade is a three-layer glass window (U_g is 0.53 W/m^2 K, LT_g 0.72, g_g 0.5, U_f 1.56 W/m^2K) (Secretariat of the energy labeling scheme for vertical windows, 2020). This window is also used for the large part of the multi-angled facade, while the smaller part has the window (U_g is 0.62 W/m^2 K, LT_g 0.74, g_g 0.63, U_f 1.56 W/m^2K) (Secretariat of the energy labeling scheme for vertical windows, 2020). The lower window frame is at a height of 0.9m from the floor and the upper window frame is at a height of 2.85m from the floor for the flat facade and 3m for the multi-angled facade. The window area below 0.9m doesn't provide daylight to the working area inside the room and it increases the heat loss at the same time.The ratio between the glass area to the window area is almost 0.82.

Simulation in Autodesk CFD

The input data for the simulations in Autodesk CFD are as follows:

- The input data for the model of the office rooms are the same as those used in the IDA ICE simulations (explained subsequently) in terms of the dimensions, internal heat gain, and material properties.
- The input data for the solar radiation on the room's external facade and the airflow through the intake and outtake of the rooms were taken from the results of the simulations with IDA ICE mentioned in the last section. The solar radiation values were the average values in July.
- The external and internal operative temperatures were assumed to be 20 °C and 25 °C, respectively, which are average values in the summer in Denmark.

Three main horizontal levels for the results 0.1m, 1.1m, 1.7m (ankle, head of a sitting person, head of a standing person), will be focused on in addition to a vertical plane through the openings.

Results

Calculations for the window opening area

The results of the calculations for the window opening areas in the six scenarios are summarized in Table 3.

The maximum intake and outtake areas in Table 3 can be used for the design and dimensioning the window while the other areas in Table 3 represent the opening area for this window in different periods through the year. The penetration length is the depth that the air penetrating through the opening area inside the room, reaches.

Table 3 The result of the calculations for the window opening areas in the six scenarios according to the parameters mentioned in table 1and 2

Scenario nr.	Intake (m^2)	outtake (m^2)	penetration length (m)
1	0.010	0.010	2.450
2	0.025	0.025	3.210
3	0.078	0.078	3.980
3-1	0.107	0.107	3.640
4	0.004	0.004	2.460
5	0.006	0.006	2.340
6	0.007	0.007	1.970

IDA ICE simulation results

The results of the simulations of the energy consumed inside the office room with a flat façade and multi-angled façade, for both mechanical and natural ventilation scenarios, in addition to the results of the simulation of the indoor climate are listed in Table 4 and 5 (these results will be discussed in detail subsequently).

Table 4 The results of the simulation of primary energy consumption for lighting, HVAC Aux, heating, and the total primary energy consumption for the flat and multi-angled façade, for both mechanical ventilation (MV) and natural ventilation (NV) scenarios, according to BR15

	Flat facade		Multi-angled facade	
	MV.	NV.	MV.	NV.
The room area (m^2)	22.5	22.5	27.5	27.5
Lighting ($kWh/(m^2\cdot year)$)	5.7	5.7	4.3	4
HVAC Aux (fans & pumps). ($kWh/(m^2\cdot year)$)	13.5	0	10.5	0
Heating ($kWh/(m^2\cdot year)$)	26.9	32.1	25.0	29.6
Total ($kWh/(m^2\cdot year)$)	46.0	37.9	39.8	33.6

Table 5 The results of the simulation of the indoor climate of office rooms with the flat and multi-angled façade (MAF) (both naturally ventilated)

		Flat facade (nr. of hours)	MAF (nr. of hours)
Overheating hours	above 26°C	88	38
	above 27°C	24	6
CO_2 level (ppm)	1100 - 700	1720	1410
	700 - 400	890	1200
Relative humidity (%)	70%- 80%	11	7
	lower than 20%	28	46

To compare the amount of heat removed by natural ventilation through the outtakes of both rooms with a flat facade and multi-angled facade, Table 6 lists the average values of heat removed by natural ventilation in Watt through the outtake in the flat facade **FF**, and the outtake in both parts of the multi-angled facade **MAF1**. The table also presents the results of two other simulations of heat removal by natural ventilation through the multi-angled façade. In the simulation of **MAF2**, there was an intake in one part of the multi-angled façade that was double in size, while the intake on the other part was removed. In the simulation of **MAF3** there were two intakes in one part of the multi-angled façade, while the intake on the other part was removed.

Table 6 The average amount of heat removed by natural ventilation in Watt through the outtakes of both rooms with a flat facade (FF) and multi-angled facade (MAF)

	FF (W)	MAF 1 (W)		MAF 2 (W)	MAF 3 (W)	
Intake		P1	P2	P1	P1.1	P1.2
Area (m^2)	0.2	0.1	0.1	0.2	0.1	0.1
Jan	58	14	33	49	24	25
Apr	98	66	90	79	38	39
Jul	230	165	135	225	107	110
Oct	60	35	50	41	19	21

The results of Table 6 will be discussed in detail subsequently

Results for Simulation in Autodesk CFD

The results of the simulations with Autodesk CFD for the temperature distribution in naturally ventilated office rooms with a flat facade and multi-angled facade at three levels are shown in Figures 4-6. The three levels from the ground (0.1 m, 1.1 m, 1.7 m) (ankle, head of a sitting person, head of a standing person. The results of the simulations with CFD software for the air velocity in the naturally ventilated office rooms with a flat facade and multi-angled facade at horizontal and vertical planes are shown in Figures 7-10. The results in the Figures 4-10 will be discussed in detail subsequently.

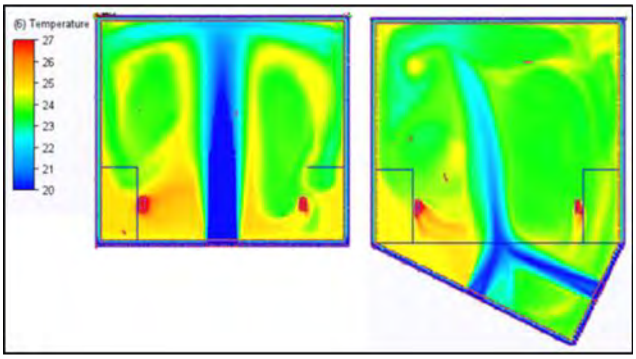

Figure 4 Temperature distribution (°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with 0.1 m from the ground.

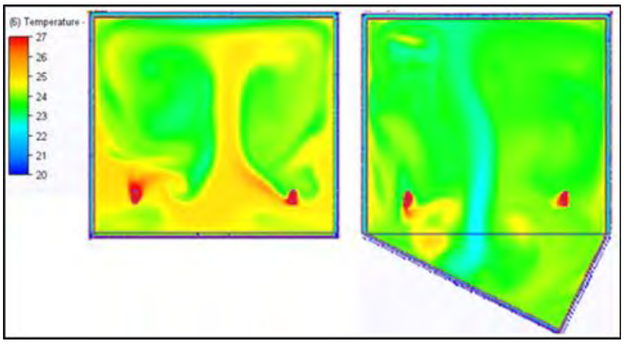

Figure 5 Temperature distribution (°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane 1.1m from the ground.

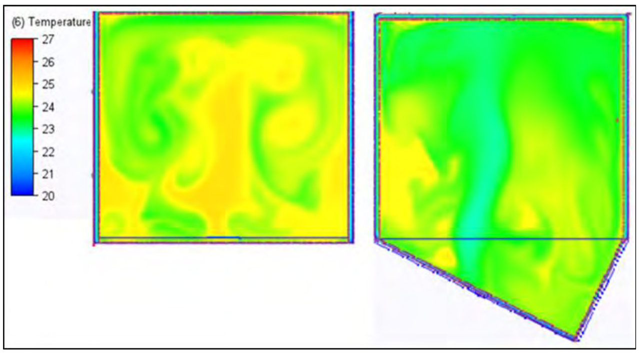

Figure 6 Temperature distribution(°C) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane 1.7 m from the ground.

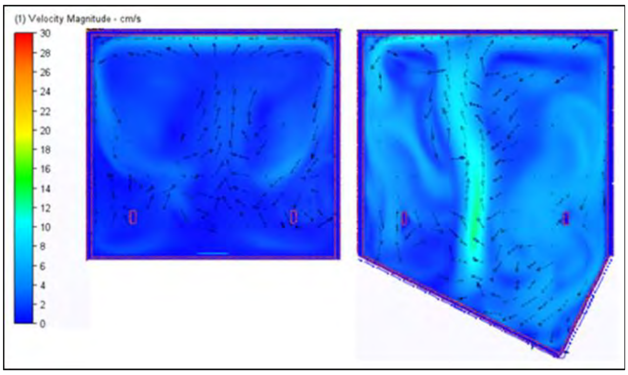

Figure 7 Air velocity (cm/s) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with a height of 1.1 m from the ground.

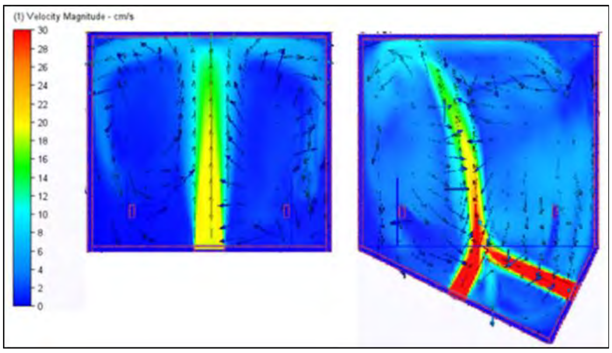

Figure 8 Air velocity (cm/s) in the naturally ventilated office rooms with a flat and a multi-angled facade at a horizontal plane with a height of 0.1 m from the ground

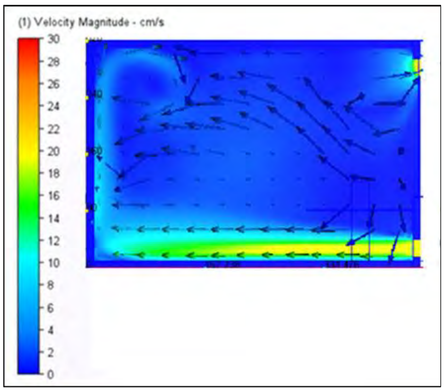

Figure 9 Air velocity in the naturally ventilated office rooms at a vertical plane with a distance of 2.5 m from the sidewall and through the ventilation opening.

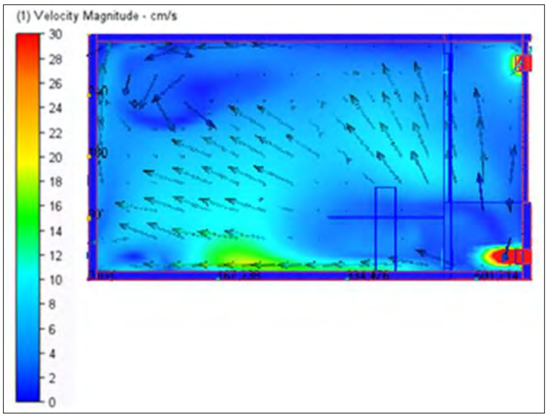

Figure 10 Air velocity in the naturally ventilated office rooms with a multi-angled facade at a vertical plane with a distance of 2.0 m from the sidewall where it comes through the ventilation opening.

Discussion

Natural ventilation is one of several solutions that can be implemented in buildings to reduce the total energy consumption by saving the energy required for mechanical ventilation. The area-weighted primary energy consumption (energy consumption/room area) for mechanical ventilation of the office room, as simulated and presented in this research, is about 25% of the total area-weighted primary energy consumption, and this saving is economically significant in the long term.

The calculations for the intake and outtake areas were based on several equations from SBi Directive 202. In general, the calculation results are very close to similar results for a number of models presented in the SBi Directive 202, Which gives them credibility. The results of the calculations made by these equations for the opening areas were used in the simulations in the IDA ICE software and the opening area chosen was from the third scenario (Maximum hour), which is the largest opening area due to the high solar radiation intensity on the facade. There was a need to adjust the size of the openings taken from Table 3 for the simulations in IDA ICE to achieve an acceptable indoor climate. This was due to the difference between the results of calculations based on fixed values in Table 3 and those from dynamic simulations by IDA ICE.

The simulations in IDA ICE provided results in three main areas: the energy consumption, indoor climate, and amount of heat removed by the air. Regarding the first type of results for a room with a Multi-angled facade, there is a saving of about 16% of the total area-weighted consumed energy, when it is naturally ventilated, as shown in Table 4. Using the design concept of multi-angled façade also has its impact on the consumed energy when it is naturally ventilated, compared to a naturally ventilated flat facade room. A naturally ventilated multi-angled façade room saves about 12% of the total area-weighted consumed energy compared with a naturally ventilated flat façade room, as shown in Table 4. There is an increase in the energy consumed for heating for a naturally ventilated multi-angled facade room of about 18% compared to the energy consumed for heating a mechanically ventilated multi-angled facade room, as shown in Table 4. This is because of the impact of eliminating the heat exchanger that was used in mechanical ventilation. The design concept of a Multi-Angled Façade also has an impact on the indoor climate, which is much better for a naturally ventilated Multi-Angled Facade room compared with a naturally ventilated flat façade room. The number of overheating hours above 26°C and 27°C are much lower for a naturally ventilated multi-angled facade room compared to a flat façade room, as shown in Table 5. The same is true for the CO_2 concentration, which is lower for the naturally ventilated Multi-Angled Façade room, as shown in Table 5.

The multi-angled facade design concept affects the amount of heat removed under natural ventilation. In July, the average amount of heat removed inside a multi-angled facade room by natural ventilation is approximately 31% higher than the heat removed by natural ventilation inside a flat facade room, as shown in Table 6. The ventilation openings with two different orientations in a multi-angled façade improves the natural ventilation and increases heat removal. This can be attributed to the different wind directions on the two sides of the multi-angled façade, which can drive the natural ventilation inside the room. The average amount of heat removed by natural ventilation in July inside a Multi-Angled Façade room with two openings, each on one section of the two multi-angled facade parts, is about 39% higher than the heat removed by natural ventilation inside a Multi-Angled Façade room with two openings on only one part of the multi-angled facade, and about 34% higher than the heat removed by natural ventilation inside a multi-angled facade room with one double-sized opening on only one part of the Multi-Angled Façade, as shown in Table 6. This demonstrates the positive impact of having two differently oriented openings on the natural ventilation inside the room.

The simulations with the CFD software yielded two types of results: the room temperature and air velocity. The room temperature was higher in the naturally ventilated flat façade room compared with the multi-angled façade room. The average temperature at three levels from the ground (0.1 m, 1.1 m, 1.7 m) (ankle, head of a sitting person, head of a standing person) ranged between 23.5 °C and 25 °C in the flat facade room, and between 23 °C and 24 °C in the multi-angled façade room. The temperature was more uniformly distributed at the three levels in the multi-angled facade room than in the flat façade room, as shown in Figures 4-6.

The air velocity was higher in the naturally ventilated room with multi-angled facade than with the flat facade. At the level 0.1 m from the ground, the average velocity was 10 cm/s in the multi-angled façade room, and approximately 4 cm/s in the flat façade room. These values cover most of the areas at this level except the path of the air draught from the openings, where the air velocity was approximately 22 cm/s and 30 cm/s in the flat facade and multi-angled façade room, respectively. At higher levels (1.1 m and 1.7 m), the average velocity ranged between 12 cm/s and 8 cm/s in the multi-angled façade room, and between 4 cm/s and 8 cm/s in the flat façade room, shown in Figures 7-10. In general, the air velocity at the three levels, except for the lowest level in the path of the air draught, was within the permissible mean velocity of category A according to the CEN report (Ventilation for buildings - Design criteria for the indoor environment) (CR 1752).

Conclusion

The results of the study show that the multi-angle design concept has the potential of improving natural ventilation inside an office room compared with a flat facade. Furthermore, the average amount of heat removed by natural ventilation inside the multi-angled facade room was approximately 31% higher than the heat removed by natural ventilation inside the flat facade room. There were also reductions in the total energy consumed by the building owing to savings in the consumed energy for mechanical ventilation. There is a saving of about 16% of the total area-weighted consumed energy, when a room with a Multi-angled facade is naturally ventilated. The naturally ventilated office rooms with multi-angled facade can provide an acceptable indoor climate in terms of room temperature, where the number of overheating hours above 26 °C and 27 °C were much lower compared with a naturally ventilated flat façade room. Moreover, the CO_2 level was acceptable and there were no draught problems in the working area inside naturally ventilated office rooms with multi-angled façade.

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