AIRFLOW PATTERNS IN SCHÖNBRUNN PALACE

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ABSTRACT

The purpose of this study is to find more information of the complicated air flow pattern in the Schönbrunn palace. The aim is to improve the control of the air infiltration. We have used a passive tracer gas technique, a special case of the constant injection technique, called the homogeneous emission technique. The results gives Air Change Rate's (ACH) of 0,7 to 1,7 in different rooms and parts of the palace. Wind driven ventilation dominates stack driven ventilation. We found a considerable air flow between floors. Simple one zone calculations of air leakage over windows partly confirmes the ACH measured. The palace management will use the results of the investigation in the ongoing planning process to improve the indoor climate and abating the indoor deterioration.

KEYWORDS

Air flow pattern, Air exchange efficiency, Air tightness, Tracer gas, Large premises.

INTRODUCTION

In year 1569 Emperor Maximilian II acquired hunting grounds outside the old city of Vienna, along the river with the name Wien. A large hunting lodge on the grounds, named Katterburg, was used by the imperial family as a country residence. Kattenburg was destroyed twice, by the Hungarians in 1605 and by the Turks in 1683 . A beautiful spring was found on the grounds in the early days, a „Schöner Brunnen", which gave the name of the future palace, built by the Habsburg family.

Schönbrunn Palace, now on the World Heritage List, was transformed into its present shape by Empress Maria Theresia and architect Nicolaus Pacassi in the middle of the 18th century. From then on the palace became the favourite summer residence of the imperial family. The palace and its original decorations have been preserved to a high degree. The palace grounds are very large and house in a number of buildings more than 2000 rooms. On the first floor of the main building there are some 40 state rooms, open to the public.

In 1997 the palace was visited by some 1,4 million people. The running and caretaking of the palace is now handled by a limited company. The management ensures that this cultural heritage is preserved by operating a conservation plan. One part of the plan is to understand better and to control the indoor climate as well as the penetration of contaminated outdoor air and the airflow within the building.

The indoor climate is mainly controlled by unwanted and wanted cross-ventilation (open windows) and air infiltration as well as by a modern heating and ventilation system supplying part of the ground floor in the east wing (the public entrance area). The plan is to install a similar system in the west wing and to use existing chimneys for exhaust air and to balance the air-flows to fight air infiltration. Having in mind the temporary very strong winds sweeping down the Donau valley, air infiltration cannot be avoided by mechanical systems only.

Better understanding of the air exchange in the east wing will benefit the planning of the ventilation system for the west wing. With a better understanding of the over all air movements in the palace, the running the mechanical ventilation system in a smart way as well as passive actions like closing/opening doors and having windows under control, will contribute to slow down the indoor detereoriation. And, very important, we need a better understanding of possible smoke circulation patterns in the case of fire.

This paper deals with the measurement campaign in the east wing of the palace and measurements in the Rösselzimmer and the Vieux-Laque Zimmer during the 1997/98 winter season and the conclusions to be drawn.

METHODS

Background

To understand the air flow in the Schönbrunn palace we need to know the air change rate. One reliable way to determine the air exchange rate is to measure it. Several tracer gas measurement procedures exist. ASHRAE Fundamentals Handbook (1989), Etheridge and Sandberg (1996), Liddament (1996), Stymne and Boman (1996), Dietz et al (1986).

Tracer gas is released into the building in a specified manner, and the gas concentration is monitored and related to the building's air exchange rate. All tracer gas measurement techniques are based on a mass balance of the tracer gas within the building. If we assume that the outdoor concentration is zero, and that the tracer is perfectly mixed within the building, then the mass balance takes the form:

$$V\frac{dC}{dt} + QC = F \qquad (1)$$

where V = Building volume in m^3
C = Concentration of tracer gas
Q = Air flow rate in m^3/s;
F = Tracer gas injection rate in m^3/s
t = time in s

The simplest tracer gas measurement technique is the decay method, which is a standardized procedure (ASTM 1983). If a fixed quantity of tracer gas is uniformly distributed, the concentration will reach a peak level, $C_{(0)}$. The concentration rate will then gradually decay. After distribution of the tracer, the injection rate F becomes zero. F can be eliminated. Integration of the two first terms yield:

$$C_{(t)} = C_{(0)} e^{-\frac{Q_t}{V}} \qquad (2)$$

where $C_{(0)}$ = tracer gas consentration at start of measurement
$C_{(t)}$ = tracer gas concentration at time t

The air change rate (Q_t/V), is given by the logarithmic gradient of the tracer gas concentration curve. We have used this method at Schönbrunn Palace by plotting the CO_2 gas concentration decay over time in the Viux-Laque room on logarithmic paper.

In the constant concentration technique, the tracer gas injection rate is continously adjusted so that the concentration of tracer gas remains constant, then the first term is eliminated. The air flow rate is then:

$$Q = \frac{F}{C} \qquad (3)$$

In the constant injection technique, the tracer gas is injected at a constant rate and all terms in equation (1) remain and the integration yields:

$$C_t = \frac{F}{Q} + \left[C_0 - \frac{F}{Q}\right] e^{-\frac{Q_t}{V}} \qquad (4)$$

The constant injection technique can also be applied to the calculation of average inverse air change rate After sufficient time, the transient term is reduced to zero, the concentration attains equilibrium and equation (1) is reduced to:

$$\left[\frac{V}{Q}\frac{dC}{dt}\right] + (C) = \left[\frac{F}{Q}\right] \qquad (5)$$

$$\left[\frac{V}{Q}\frac{dC}{dt}\right] \to 0 \quad (Q) = \frac{F}{(C)} \qquad (6)$$

This assumption is only valid if the average air change rate is constant over the measurement time. The method provides insufficient weighting to peaks in air change rate that may result from cross-ventilation or airing by windows.

Dietz et al (1986) introduced a special case of the constant injection technique. This technique uses permeation tubes as a tracer gas source. The tubes release gas at an ideally constant rate into the building being tested. Sampling tubes packed with an adsorbent collect the tracer from the interior air by diffusion. One of the authors used this technique to investigate the air change rate in the the Swedish Museum of Natural History in Stockholm, Holmberg (1990)

Stymne et al (1992) have introduced a homogeneous emission technique, another special case of the constant injection technique. The technique charts local mean age of air in larger premises. The local mean age of air (τ_p) is a quantity. It tells us the average time the air in a specific point in a room has been in a building.

The basis of the technique is to inject tracer gas at a constant rate in all the zones of a zone divided building. The gas injection rate in each zone has to be proportional to the volume of the zone. The local steady state concentration (C_p) will be equal to the tracer injection rate per volume (S/V) multiplied with the local mean age of air ($\bar{\tau}_p$). The local mean age of air will thus be obtained from a measured local tracer concentration:

$$\bar{\tau}_p = \frac{C_p}{(S/V)} \tag{7}$$

The homogeneous emission technique has been proposed as a NORDTEST method by Stymne (1995). At Schönbrunn palace we used the method for the measurement campaign during the winter season 1997/98.

Measurement technique

We refer to the references. Stymne, H. and Boman, C.A. (1996), Etheridge, D. and Sandberg, M. (1996), Dietz, R.N., Goodrich, R.W., Cote, E.A. and Wieser, R.F. (1986).

Measurements in Rösselzimmer

Rösselzimmer is a dining room on the first floor in the east wing. It is a „grand room“, much decorated and with a floor area of 90 m^2 and a height of 6 m. There are four windows and doors at each end. It connects with the Oval-Chines Zimmer but is closed from the rest of the east wing by glassdoors. We used 10 gas emitters and four air samplers (adsorption tubes). Temperature and relative humidity were recorded during the 14 day long measurement campaign (961031-961114). It was a one-zone test with hexaflourobensen as tracer.

Measurements in east wing

We divided the east wing in two zones, ground floor and first floor. The ground floor air was seeded by 33 gas emitters (zone A) and the first floor by 38 gas emitters (zone B). The ground floor zone is mainly one large entrance hall for the public. It has mechanical ventilation. The first floor is diveded into 20 rooms which are part of the state apartments. We used hexaflourobensen as tracer in zone A and octafluortoulen in zone B. On the ground floor we had 18 air samplers and in the first floor 25. Temperature and relative humidity were recorded during the 14 day long measurement campaign (971027-971111). We had considerable problems with uncontrolled windows and doors during the test because there were many wisitors to the palace at the time, and building work was ongoing in the west wing.

Remeasurements in east wing

Part of the east wing was retested in the beginning of 1998. We chose to measure a row of rooms on the first floor in the east wing, i e the Vieux-Laque Zimmer, the Blauer Chines Salon and the Napoleonzimmer. This investigation was a two-zone measurement campaign, again over 14 days. The file of rooms was seeded with hexaflourobensen and the large room at the end of the file, the Zeremonien-saal, was seeded with octafluortoulen. We used the gas emitters from the large 1997 campaign already present in the east wing, and moved 5 B-type gas emitters to the Zeremoniensaal. Further more we used electronic samplers in the Vieux-Laque Zimmer to register the difference betwen day and night adsorption. Temperature and relative humidity were recorded during the campaign (980119-980203).

Decay measurements of CO_2 in Vieux-Laque Zimmer

In this room, as part of the EU 1383 PREVENT-project, we have an extensive climate measurement system, based on the Landis & Gyr BMS system vith Visonik software. CO_2 is measured in the room and a decay profile is registered every day. The room has a floor area of 63,5 m^2 and a volume of 365 m^3. As we consider the air in the room relatively well mixed and the forces driving the ventilation process constant, the decay in tracer gas concentration is logarithmic, with the air change rate being directly related to the decay gradient.

Air Infiltration Measurement System (AIMS) measurements in 1990

We have compared the measurement results from Schönbrunn Palace with the results from measurements at the Swedish Museum of Natural History. In that case we used 28 gas-emitters (PFT's) and 106 adsorbers (CATS) and we divided the building into 5 zones. All AIMS laboratory work was carried out by the Brookhaven Laboratory in Upton, New York. The measured room volume was 13200 m^3.

It was a 2 day test carried out twice (900326-900327 and 900328-900329)

RESULTS

Results of measurements in Rösselzimmer

point no	local mean age of air [h]	room specific flow rate [h^{-1}]	ACH	temp [°C]	relativ hum. [%RH]
P1	0,58	1,71	±0,16	18,2	
P2	0,58	1,71	±0,16	18,2	47
P3	0,65	1,53	±0,14	18,2	
P4	0,54	1,86	±0,17	18,2	
total ventilation flow rate, [m^3/h]		339	±10		
mean age of air		0,59			
specific air flow rate (ACH), [h^{-1}]		**1,70**	**±3%**		
average air temperature, [°C]		18,2			
relative air humidity, [%RH]		47			

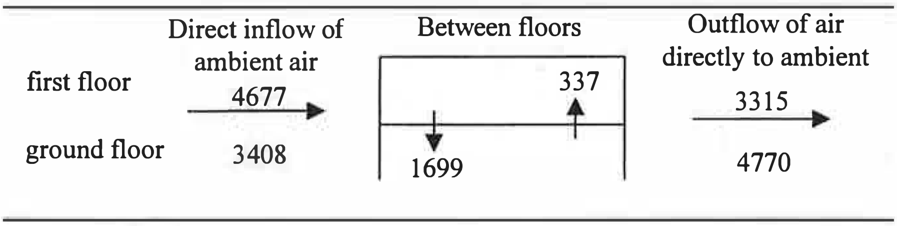
Results of measurements in the east wing

Schönbrunn Ost. Entrance building, Ground floor

no	room total vol.=5960m^3	vol. m^3	local mean age of air [h]	room specific flow rate [h^{-1}]	ACH	temp [°C]	relativ air humidity [%RH]
101	Mariannenhof		0,96	1,08	±0,10		
102	Gardeobe		1,21	0,87	±0,08		
103	Kapellenhof		1,20	0,90	±0,08		
104	Information		1,23	0,89	±0,11	18,7	41
105	Eingang		1,58	0,67	±0,06		
total ventilation flow rate, [m^3/h]				5152	±121		
mean age of air				1,20			
specific air flow rate (ACH), [h^{-1}]				**0,83**	**±2%**		
average air temperature, [°C]				19,1			
relative air humidity, [%RH]				41			

Schönbrunn Ost. Entrance building, 1st floor

no	room total vol.=4370m³	vol. m³	local mean age of air [h]	room specific flow rate [h⁻¹], ACH		temp [°C]	relativ air humidity, [%RH]
1	Durchgang	180	0,92	1,08	±0,10		
2	Salon Franz- Karl	427	1,14	0,87	±0,08		
3	Schreibzimmer F-K	280	1,11	0,90	±0,08		
4	Geburtszimmer F-J	410	1,12	0,89	±0,11	18,7	41
5	Doktorzimmer 5	250	1,50	0,67	±0,06		
6	Doktorzimmer 6	150					
7	Terassenzimmer	140	1,23	0,81	±0,06		
8	Rotes Zimmer	290	1,34	0,75	±0,07		
9	Frühstückzimmer	210	0,98	1,03	±0,09	17,2	44
10	Gobelin Salon	490	1,20	0,84	±0,07		
11	Millionenzimmer	200	1,16	0,86	±0,08		
12	Kabinett	55					
13	Porzellanzimmer	110					
14	Napoleonzimmer	235	1,07	0,93	±0,12		
15	Viux- Laque Zimmer	365	1,05	0,96	±0,08	15,8	46
16	Blauer Chines Salon	580	0,88	1,13	±0,10		
total ventilation flow rate, [m³/h]				4973	±66		
mean age of air				1,12			
specific air flow rate (ACH), [h⁻¹]				**0,90**	**±1%**		
average air temperature, [°C]				17,2			
relative air humidity, [%RH]				44			



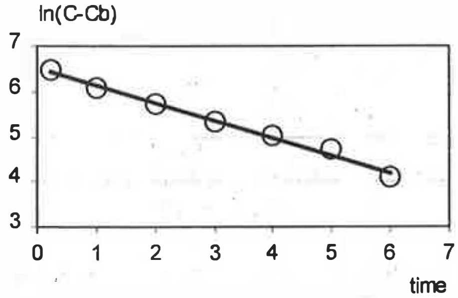
Results of remeasuring in the east wing

Entrance building, 1st floor, measurement no 2

no	room al vol.=5960m³ tot	vol. m³	local mean age of air [h]	room specific flow rate [h⁻¹], ACH		temp [°C]	relativ air humidity [%RH]
14	Naopoleon Zimmer		1,02	0,98	±0,06		
15	Viux- Laque Zimmer		0,84	1,19	±0,23	13,3	35
16	Blaues Chin. Salon		0,93	1,07	±0,07		
17	Küche+ Gang		1,12	0,89	±0,08		
24	Maschinenraum		0,88	1,14			
25	Zeremoniensaal		0,97	1,04	±0,01		
total ventilation flow rate, [m³/h]				6614	±114		
mean age of air				0,98			
specific air flow rate (ACH), [h⁻¹]				**1,02**	**±2%**		
average air temperature, [°C]				13,3			
relative air humidity, [%RH]				35			

The two zone measurement failed due to a misplacement of sources.

Results of CO_2 decay measurements



$$\ln(C - C_b) = -0{,}39t + 6{,}53 \quad \rightarrow \quad n = 0{,}39\left[h^{-1}\right]$$

The decay measurements in the Vieux-Laque Zimmer give an ACH of 0.4 on an afternoon with „no“ wind and over 1,0 on windy afternoons with more than 4 m/s wind speed. The average wind speed during the measurement period in 1997 was around 5 m/s.

Results of the 1990 measurements at the Swedish Museum of Natural History

The ACH for the five zones measured 0,34; 0,95; 6,25; 1,33 and 1,09 respectively. Zone 3 is a stairwell. The mean value for the other four zones taking the different room volumes into consideration was 0,93. The building is a heavy brick building built in year 1905, and the windows are weatherstipped. The prevailing wind in Stockholm is West and 2 m/s and in Vienna West and 7 m/s, winter values.

DISCUSSION

We divide air exchange between indoors and outdoors into ventilation (intentional and ideally controlled) and infiltration (unintentional and uncontrolled). Ventilation can be natural or forced. Natural ventilation is unpowered airflow through open windows and doors. Forced ventilation is intentional air exchange, powered by a fan. Infiltration is uncontrolled airflow through cracks and interstices. Infiltration, exfiltration and natural ventilation airflows are caused by pressure differences due to wind, outdoor-indoor temperature differences and appliance operation.

Air exchange rates need to be known to ensure control of indoor climate and contaminant levels. In large buildings such as the Schönbrunn palace, the effect of infiltration and ventilation on distribution and interzone airflow patterns, including smoke circulation patterns in the case of fire, has to be determined.

If we study a typical window on the east facade in the first floor, the ACH values measured correspond relatively well with calculated airflow values. Data from Liddament (1996) Table A12 Leakage Characteristics-Windows give an air flow over one window of ca 150 m^3/h at 4 Pa. If we compare with the CIBSE Applications Manual AM10:1997 the Explicit method under para 5.4.1 give ca 200 m^3/h at 3 m/s wind. We have estimated the total leakage area for one window, not weather stripped, sidehung, two single pains of glass („Kastenfenster“) and with caulked frames in a brickwall in the first floor to 150 cm^2. If we look into the ASHRAE Handbook 1993, chapter 23, we can estimate an effective leakage area at 4 Pa of 105 cm^2 for the typical window.

Uncertain air speed measurements over the slots around glass doors to the Rösselzimmer gives at v = 0,6 m/s ca 850 m^3/h. There are four windows in the room but the adjoining oval room has some impact on the ACH.

Assuming that the average air leakage through windows in the east wing is around 150 m^3/h per window at 4 Pa, then the 40 windows per floor could well let in the about 4000 m^3/h per floor that we have measured during the ACH-test. A NW or a SE wind attack on the east wing facades (Cv = 0,25, perpendicular winds) give an airflow caused by wind of ca 5000 m^3/h per floor.

The open stairwells as well as the very large front doors have a definite impact on air flow patterns. As seen under 3.2, a large quantity of air is circulated between the floors. This result is a disturbing fact for the palace management. It indicates that doors to stairwells are left wide open, and it gives a warning signal that escapeways would very soon be contaminated with smoke in the case of fire. The palace has some 4000 visitors a day (yearly average) so we can expext more than 400 people per hour on the first floor at the same time.

The ground floor is partly heated (ventilation on 100% recirculation wintertime) and the first floor is unheated (except for the shopping area) The temperature difference is 2 to 5 K between floors. During a cold winter month it will be around 10 K difference We have observed the downflow of air in stairwells by using detecting smoke. The airflows between the floors could probably be stabilised if the ventilation unit supplying the entrance area were operated with max outdoor air.

The air infiltration in the east wing is large enough to cope with 400 persons per hour and to keep the CO_2 level under 1000 ppm. In a few smaller rooms such as the Vieux-Laque Zimmer we measured higher values for short times.

Comparing windward and leeward windows on the first floor facades with detecting smoke confirms that wind driven ventilation dominates stackdriven ventilation.

The cold air entering the the first floor rooms between brick wall and the wooden panels around the windows was found to be convection streams of indoor air and not penetrating outdoor air as presumed.

Simple structures can be examined analytically with data from handbooks. Larger and more complicated structures require more systematic investigations with powerful tools such as the tracer gas homogeneous emission technique or a multi zone infiltration model. We have decided to take a further step by modelling air flows in the Schönbrunn palace with NMF and IDA. Bring and Sahlin (1993). NMF stands for the Neutral Model Format, it is a suggested standard for model expression. IDA stands for a simulation environment, a model family has been developed for studies of coupled air flows in multi zone buildings.

We are not convinced that we today fully understand the complex interaction between building characteristics and driving forces in the Schönbrunn palace.

We would like to convey the opinions of Stymne and Boman (1996) on uncertanties of the homogeneous emission tracer gas technique. Uncertainties are : repeatability 8%; emission rate 5%; sampling rate 5%; analysis 3%; precision including repeatability and reproducibility 10%; accuracy – systematic errors 5%. As usual, uncertainty figures can always be disputed, but in the case of the Schönbrunn measuring campaign we have accepted them as relevant.

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