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THE FEASIBILITY OF OFF-HOUR ACCELERATED VENTILATION AS PASSIVE COOLING IN COMMERCIAL BUILDINGS USING THE INTEGRATED TRNSYS/CONTAM MODEL

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ABSTRACT

Throughout the night, the outdoor air temperature often drops below the comfort temperature, even during summer, and is considered as a cooling source. This low outside temperature can be used to reduce the energy consumption of cooling processes in commercial buildings. They are ventilated with large volumes utilizing 100 % outdoor air either at night or during the off-hours. This study first involved the evaluation of an integrated multi-room airflow model, CONTAM, with the multi-room thermal model Type 56 from TRNSYS. The results from the thermal and airflow studies show that a coupled airflow/ thermal model must be considered. Additionally, a simulation study was undertaken to investigate the feasibility of off-hour accelerated ventilation in a real 9 floor commercial office building in reducing the air conditioning energy consumption while maintaining acceptable indoor environmental conditions. The mechanical system is designed to be employed in either normal or accelerated ventilation (free-cooling) mode.

Keywords: Off-hour ventilation, saving energy, accelerated ventilation, commercial buildings, infiltration and inter-zonal airflow

INTRODUCTION

Several studies have been conducted to improve the use of night accelerated ventilation, which reduces the air conditioning system use and consequently, cooling energy consumption. Recent works were concerned with determining the different conditions which would benefit from night accelerated ventilation and in providing practical advice for the designers to take advantage of this free cooling approach (Nyman, 1992), (Stephan et al., 1990), (Bajwa, 1992), (Evans, 1992), (Evans, 1993), (Van Der Maas et al, 1991), (Yang et al., 1990). In particular, Blondeau et al. (1995), represented night accelerated ventilation through the thermal multi-room model Type56 from TRNSYS. This thermal model assumes that the infiltration airflow is constant for each zone and rejects inter-zonal airflow. However, recent study (McDowell, 2003) demonstrates that airflow in each zone varies largely according to the weather conditions (wind velocity and direction and the outdoor temperature), inside temperature, pressure coefficient value and the operation of the ventilation system present. Further, when using accelerated ventilation the interaction between zones is higher, creating large inter-zonal airflow. Also, the airflow components are larger, to support this increased airflow.

To examine off-hour accelerated ventilation technique, an integrated thermal / airflow model has been used in which the multi-room thermal model Type 56 of TRNSYS is integrated with the multi-room CONTAM model (McDowell, 2003). The heat transfer in multi-room buildings depends greatly on interior/exterior and inter-zonal airflows. A large existing multi-zone office building equipped with both ventilation systems and flow controllers was employed for this study. The ventilation network (fan, duct, flow controllers) was designed to be employed in either normal or accelerated ventilation modes.

This paper reports the results of a feasibility study concerning the replacement of an air conditioning system with a pure ventilation system in a multi-zone commercial building during the spring mid-season; ideally with the goal of system substitution, or at the minimum, a realization of energy savings due to a decrease in air conditioning operating times. To determine the influence of natural ventilation (wind and/or stack effects), the gain obtained using accelerated ventilation was determined in order to show the energy saving aspect of this technique.

AIRFLOW, THERMAL AND INTEGRATED MODELS

Several strategies exist for solving the airflow/thermal equations applied to building physics (Hensen, 1996), (Megri et al., 1996). The integration of the airflow model COMVEN into the TRNSYS software has been accomplished by Dorer and Weber (1994) and Megri (Megri et al., 1995). In order to study a large variety of buildings in the USA, a new integration of CONTAM into TRNSYS was proposed (McDowell et al., 2003).

TRNSYS is a transient system simulation program with a modular structure that was designed in the 1970's by the Solar Energy Laboratory at the University of Wisconsin (Klein, 1976, 2000). By breaking problems down into a series of smaller components, TRNSYS is able to solve complex energy system problems. The TRNSYS multi-room building model is Type 56 (Klein, 1976, 1983, 2000a, 2000b). Type 56 allows a different approach to calculate the energy usage of buildings by using the energy rate control method without specifying the HVAC system type. This method assumes that the HVAC equipment is adequately sized to meet the load at all times (McDowell et al., 2003). When the internal loads and other gains and losses are calculated, Type 56 then checks if the zone set-point has been maintained. If it has not, then the amount of energy required to maintain the set-point independent of the HVAC system efficiencies and operating characteristics, is determined. This method allows the latent loads to be determined by maintaining a relative humidity set-point, if there is a corresponding sensible cooling load. Consequently, the TRNSYS loads are represented as the idealized energy required to maintain the set-point. Component loads, however, can be very different from the energy required to meet these loads because they can include system issues.

CONTAM (Walton, 1997), (Haghighat et Megri, 1996) is a multi-room airflow and contaminant dispersal program containing an updated version of the AIRNET model (Walton, 1988, 1989) and a graphical interface (Dols, et al., 2002) for data input and display. The latest version of CONTAM is CONTAMW 2.4b (Walton et al., 2005). Although CONTAM considers both "the imaginary zones" as well as the inter-zonal airflow, it is still not able to determine the distribution of airflow and temperature within the same room (Megri et al., 2005), (Megri, 2007).

A de-coupled "ping-pong" approach in which the thermal and airflow models run in sequence (i.e., each model uses the results of the other model in the previous time step) has been used. The airflow calculations use air temperatures computed in the previous time step. In the ping-pong approach, each model uses the input values computed by the other model at the previous time step. For example, to compute the airflows at hour "t + Δt", the airflow model uses zone temperatures computed by the thermal model at hour t.

Examples of integrated programs using the ping-pong technique are: EnergyPlus/ COMIS, EnergyPlus/ Airnet, Type 56 of TRNSYS /COMIS and Type 56 of TRNSYS / CONTAM. In the case of the integration with TRNSYS, a solution is iteratively determined at each time step of the simulation. In each iteration loop, the room air temperature values are passed from the thermal building model Type 56 to the COMIS or CONTAM Type, which returns the respective airflow rates to Type 56. The predicted airflow rates per room are assigned to inter-zonal, infiltration or ventilation, which all are required by Type 56.

CASE STUDY

This study considers a large, existing multi-zone office building equipped with both ventilation systems and flow controllers. A complete description of the building, including geometry, orientation, occupation schedules, wall composition and energy loads during normal conditions is provided. The building possesses a ground floor and 8 additional stories, including one upper floor beneath the roof. To simplify the study, only one representative floor was modeled. Each floor is comprised of a large number of zones, such as offices, meeting rooms, hall, and toilets. Eight representative zones were created out of the 67 existing elementary ones. Each of the zones is composed of elementary zones with the same orientation and similar operation (Figure 1). Eight zones can be studied in more detail than 67. It was assumed that the adjacent floors (top and bottom) were at the same thermal condition as the floor being modeled, simplifying the modeling simulation. Simulations were carried out using the weather data of Chicago, Illinois (USA) and were performed over a 3 day period (2-4 May).

The integrated airflow/thermal model CONTAM/TRNSYS has been tested and evaluated for different configurations, but has not yet been documented, whereas the CONTAM/TRNSYS and COMIS/TRNSYS comparison shows that both software packages yield the same results as long as the input data are the same. However, CONTAM is more user-friendly, unlike the COMIS program. Regarding the couple CONTAM/TRNSYS, a complete investigation is required to understand this integration. TRNSYS is not able to read the ventilation values calculated within CONTAM directly, and the only way that these values can be introduced is through the TRNBID interface program used by Type 56 of TRNSYS. The infiltration from both CONTAM and COMIS can be read by Type 56 of TRNSYS.

Table 1. Description of the 8 principal zones of the floor modeled

Zone	1	2	3	4	5	6	7	8
Room Type	Office	Office	Office	Office	Office	Meeting Room	Toilets	Hall
Number of elementary zones	15	8	10	6	19			
Position	NW	SE	NE	NE	SW	-	-	-
Glass m^2/orient.	53/NW 3.5/SW	28/SE	35/NE	21/NE 3.5/SE	67/SW 3.5/SE	-	-	
			Surface Area m^2					
Floor or Roof	197	107	133.5	113	267	50.5	168	273
Exterior wall	79-NW 14.3-SW	39-SE	47-NE 15-SE	36.5-NE 14.5-	98-SW 12-SE	3.8-NE	-	4-NE 9-SE

Zone	1	2	3	4	5	6	7	8
				SE				
Wall in contact with the other zones	121/Zo8 15/Zo5	99/Zo8	98/Zo8	58/Zo8 18/Zo6	165/Zo8 15/Zo1	84.5/Zo8 18/Zo4	138/Zo8	121/Zo1 99/Zo2 98/Zo3 58/Zo4 165/Zo5 84.5/Zo6 138/Zo7
Internal Walls	208.5	105	136	109.5	287	26	-	-
Air Volume (m^3)	603	328	408	345	816	155	514	835
				Inside loads				
Occupants Nb	30	16	20	14	40	25	-	-
100 W/occ.[total (W)]	3000	1600	2000	1400	4000	2500	-	-
Lighting [W/m^2]	10	10	10	10	10	6	6	6
[total(W)]	1970	1071	1334	1127	2668	304	1008	1637
Machinery Nb.	15	8	10	7	20	-	-	-
250W/mac. [total(W)]	3750	2000	2500	1750	5000	-	-	-

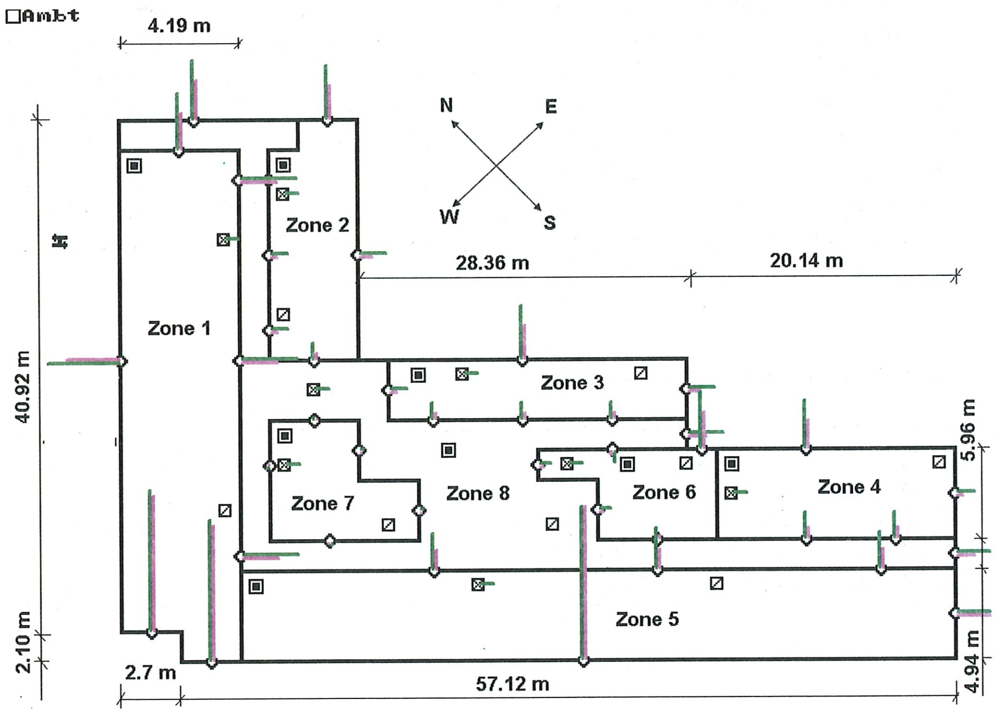

Figure 1. Building Layout and snapshot airflow distribution (CONTAM software)

Because of the large airflow to be exhausted (or supplied), we consider separate ductwork and fans for each zone (7 fans and 7 networks), except for the hall (zone 8) from which air is exhausted via the bathroom exhaust. The ducts are designed for an exchange rate of 5 ACH, and the flow controllers are designed for an exchange rate of 10 ACH. The air inlets are located at the facades of the perimeter offices. Every office has a crack in the external and internal walls, characterized by the power law ($K = 0.08\ m^3/(s.Pa^n)$, $n = 0.65$). Building airflow distribution changes significantly according to the weather conditions, leakage characteristics of the walls, and the operation of the ventilation system, and is especially true when accelerated ventilation is employed in a large building. Here the interaction between zones is high because of the large inter-zonal airflow.

The comparison of the temperature predicted by the integrated model (Type 56 of TRNSYS/ CONTAM) and the thermal model (Type 56 from TRNSYS alone) reveals large differences between these models (the maximum difference observed in zone 1 is about 8°C). These differences are due to various reasons, including the fact that thermal models do not consider the wind effect and the infiltration values are considered to be constant. Furthermore, the inter-zonal airflows are considered negligible. In our case, the external walls were exposed to different wind velocities and directions that varied according to time. The variation of the infiltration levels and also inter-zonal airflow are very significant. These observations have been also confirmed by (McDowell et al., 2003). The thermal coefficients, such as, the U-Value, solar factor of glass (SF) for different orientations, thickness of the floor and exterior wall are given in Tables 2 and 3. This study considered the thermal inertia of the floor, ceiling, and all internal walls of each zone. The occupation rate scenario for each zone and the schedule of the machinery and lighting are given in Table 4.

Table 2. Wall characteristics

U or SF	**Value**
U coefficient “exterior opaque wall”	$0.7\ W.m^{-2}.K^{-1}$
U coefficient “glass”	$3.3\ W.m^{-2}.K^{-1}$
SF of glass “orientation NW and SW”	0.57
SF of glass “orientation NE and SE”	0.40

Table 3. Wall composition

Walls	Characteristics
Floor (or roof)	20 cm of concrete
Internal Wall	10 cm of terracotta bricks +1 cm of plaster on each side
Exterior Wall	1.5 cm mortar + 33.5 cm of concrete + 4 cm of polystyrene + 4cm of polystyrene + 1 cm of plaster

Table 4. Scenario and rate occupation of different zones, machinery, and lighting

Hour	5	6	7	8	9	10	11	12	13	14	15	16	17	18
RATE Occp.	0	0.25	1	1	0.5	0.5	1	1	1	0.5	0.4	0.1	0	0
Rate Fonc.	0	0.4	1	1	1	0.6	0.6	1	1	1	0.7	0.6	0.5	0

The temperature control was realized for every zone independently of other zones. The first simulation, extended over a one year period, revealed the air conditioning requirements to be much greater than the heating requirements. Therefore, the use of night accelerated ventilation has a good chance of being favorable. Simulations for this building showed the maximum infiltration reached was 8.876 ACH. For all these reasons, the coupled airflow / thermal model must be used to study the feasibility of off-hour ventilation. The evaluation of weather conditions, demonstrates that, at times, the indoor temperature is less than the outdoor temperature, demonstrating that the effects of the internal loads and the solar radiation are significant.

Figures 2 and 3 demonstrate the variation of temperatures using several different approaches. The set point temperature is T_s = 23°C. curves 2 and 3 are determined using the integrated model, with an increase of ventilation airflow from 1 ACH (curve 1) to 5 ACH (curve 2) and to 10 ACH (curve 3), while curves 4, 5 and 6 are determined using the thermal model alone, and considering as infiltration input the maximum and minimum values predicted by the airflow model. The ventilation airflow used with the thermal model are 1 and 10 ACH. The thermal model may over estimate, or even sometimes underestimate, the indoor temperature because of the simplification related to this category of models, including the fact that the thermal models do not perform airflow conservation.

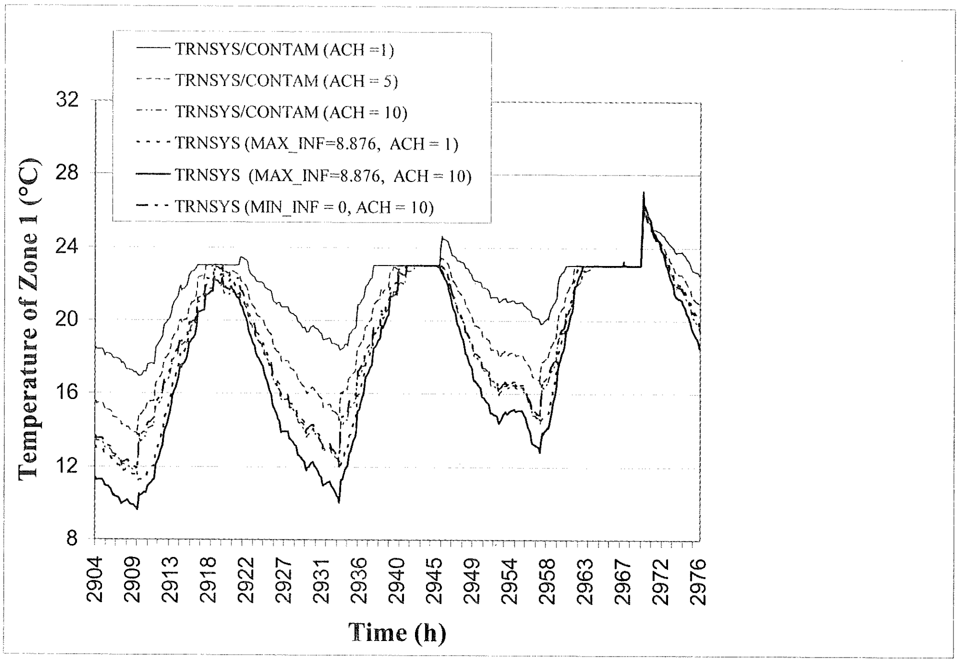

Figure 2. Temperature of Zone 1, using different level of modeling approach

The energy savings realized using the off-hour ventilation technique is shown in Figures 4 and 5. To determine the energy performance, air conditioning/cooling energy P1 was computed, considering the set point temperature of T_s = 23°C during the occupied period (5 AM -5 PM). After 5 PM a free evolution (cooling power = 0) with a minimum ventilation rate of 1 ACH, representing normal ventilation was considered. P2 is the air conditioning cooling energy with set point T_s = 23°C and 1 ACH from 5 AM until 5 PM. Between 5 PM and 5 AM, the accelerated ventilation of 10 ACH was used. The difference (P1-P2) is the cooling energy saved by accelerated ventilation. Figures 4 and 5 represent the energy savings over a three day period during the spring midseason (2-4 May) in the city of Chicago. We conclude that the benefit from off-hour accelerated ventilation is related to many factors and, most importantly, weather conditions. The off-hour accelerated ventilation can be profitable during certain periods and not economically justifiable during other periods.

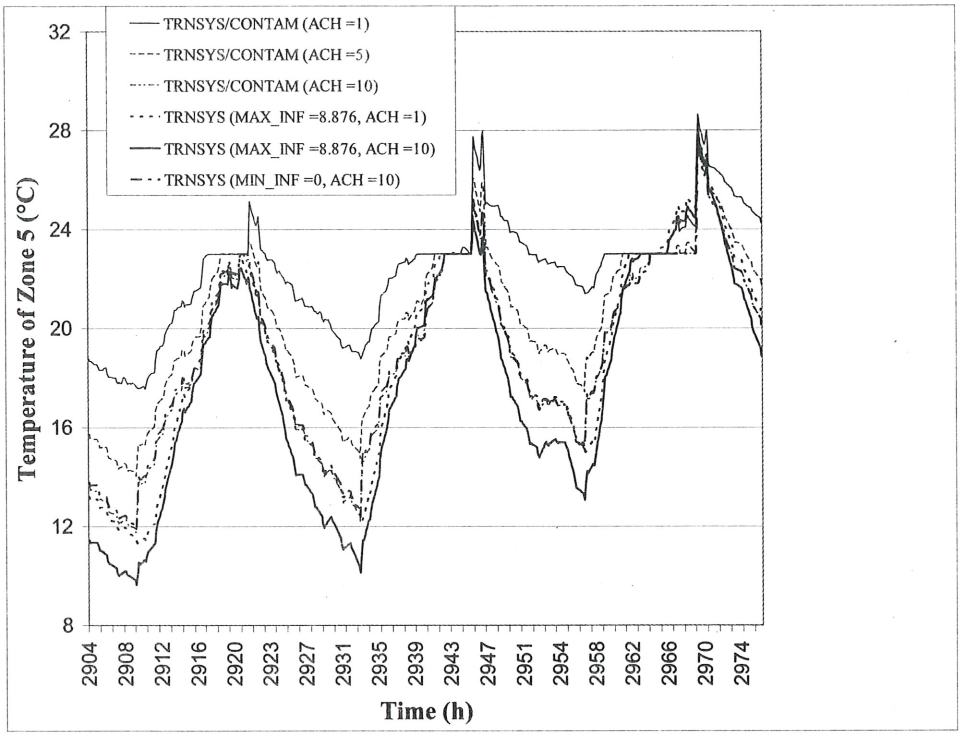

Figure 3. Temperature of Zone 5, using different level of modeling approach

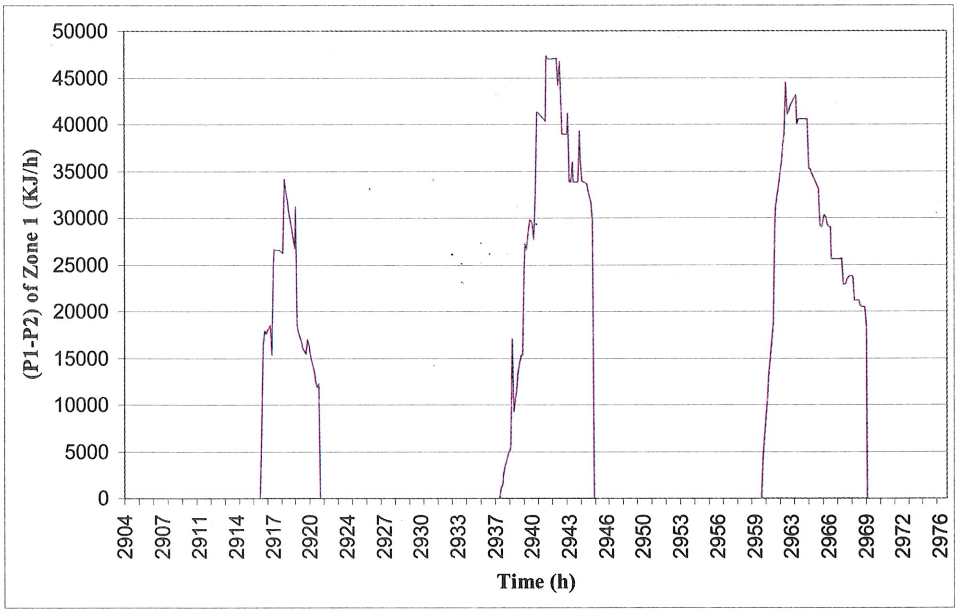

Figure 4. Cooling energy saving from off-hour accelerated ventilation for Zone 1

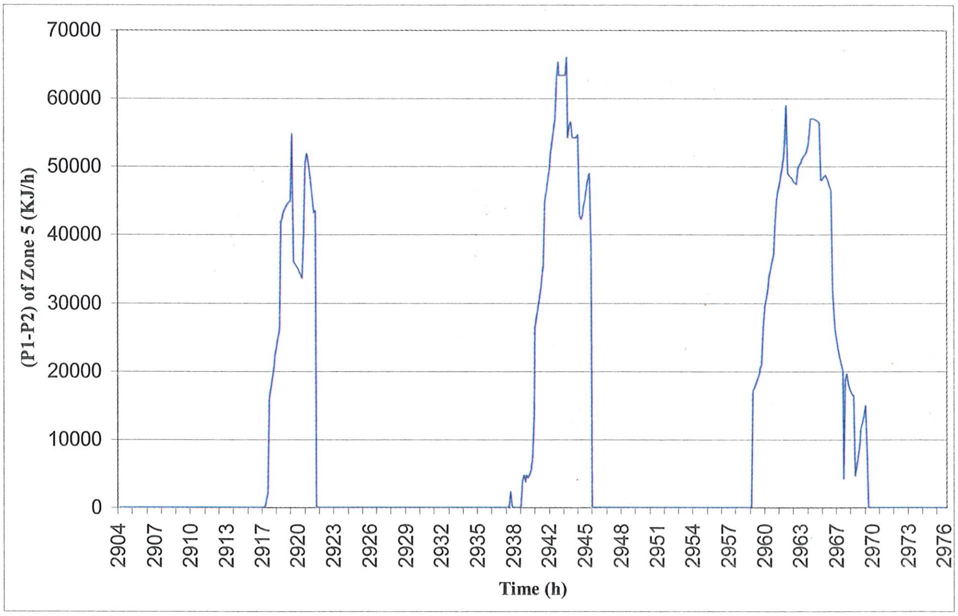

Figure 5. Cooling energy saving from off-hour accelerated ventilation for Zone 5

CONCLUSIONS

The integration of the airflow model CONTAM into the TRNSYS software evaluated. We realized that the ventilation can only be introduced within the TRNSYS environment. Ventilation introduced within CONTAM, can only be used with the airflow simulation. This issue has been resolved using COMVEN/TRNSYS. In order to satisfy the CONTAM requirements, thermal modeling of the ventilation system must be taken into account. A more detailed study will be conducted to estimate the savings in electricity consumption when the off-hour and day accelerated ventilation technique replaces the air conditioning system, while still respecting physical constrains, such as spatial geometry and thermal comfort.

This study is the first step in providing a methodical approach in adapting the ventilation system (fan, duct, flow controllers) for either night or day ventilation during a long period of time. A complete study is required, taking into account “all costs” (investment, maintenance, and operating costs) in order to determine the exact benefits of using off-hour and day accelerated ventilation in a specific situation and during a long period of time.

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