OPTIMIZATION OF NIGHTTIME VENTILATION PARAMETERS TO REDUCE BUILDING ENERGY CONSUMPTION BY INTEGRATING DOE2 AND MATLAB

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ABSTRACT

The nighttime ventilation strategy uses the outdoor cold air during the night to cool the building mass. The cooled building mass then is used as a heat sink during the next hot day. Mechanical nighttime ventilation requires a fan for the outside air ventilation. The energy use by the fan reduces the potential cooling energy savings. Higher nighttime ventilation flow rate and its duration decrease required cooling energy during next hot day in the building, also they increase fan energy consumption. In an optimal nighttime ventilation operation, these parameters need to be optimized based on each day outdoor temperature variation.

We have developed an algorithm to optimize fan flow rate by integrating DOE2 (building energy simulation software) with MATLAB's genetic algorithm (GA). In our developed algorithm MATLAB can send desired values of optimization variable for different hours to DOE2 to simulate building energy use, also MATLAB can receive building energy consumption and other data from DOE2 for the optimization. This online connection between DOE2 and MATLAB create powerful building optimization tool. This optimization tool can be used for finding optimal solution of nighttime ventilation fan flow rates and maximizing energy savings. Also, by using this tool nighttime optimization can be easily applied to different buildings and systems. Nighttime ventilation can be investigated in DOE2 by considering effective parameters such as: 1) nighttime ventilation duration, 2) nighttime ventilation fan flow rate, 3) outdoor temperature set-point, and 4) temperature difference between outdoor and indoor. Optimization results show outdoor temperature between 10 to 18 °C and temperature difference more than 8 °C are appropriate for nighttime ventilation.

Keywords

Nighttime ventilation, building energy, optimization, integration

1 INTRODUCTION

Nighttime ventilation is a strategy used for reducing cooling energy consumption in buildings. Many studies have investigated the effect of nighttime ventilation in different climates [1-4]. The nighttime ventilation strategy uses the nighttime outdoor cold air to cool the thermal mass of the building. During the next day, the cooled thermal mass is used as a heat sink. For mechanical nighttime ventilation a fan is needed to bring in outdoor air during the night that allows control of outside air ventilation. The energy use by the fan, in turn, reduces the potential cooling energy savings.

Parameters that specify nighttime ventilation effectiveness are classified into three main categories [5-7]: building parameters (thermal mass), technical parameters (outdoor air flow rate, nighttime ventilation duration), and climatic parameters (outside temperature, humidity, and solar radiation).

Higher nighttime ventilation flow rates and duration can decrease building cooling energy consumption, also they increase fan energy consumption. In an optimal control operation, these parameters need to be optimized. For nighttime ventilation to be effective, building thermal mass is a necessary requirement, therefore, in buildings with low thermal mass nighttime ventilation is not efficient.

Various studies have evaluated the effect of different parameters such as climate, air flow rate, and thermal mass, on effectiveness of nighttime ventilation and occupant comfort [8-11]. However, fewer studies considered duration of nighttime ventilation [15, 16]. Most studies have used simplified method of building model or optimization. Developing an accurate method of optimization that can be applied in all types of buildings still needs more investigation.

To study the potential of nighttime ventilation, Wang et al. [18] evaluated the important factors influencing nighttime ventilation performance such as ventilation rate and duration, building mass and climatic conditions. They used EnergyPlus to simulate the indoor thermal environment and energy consumption in typical office buildings with mechanical nighttime ventilation in three cities in northern China. They results show that with night ventilation rate of 10 ach, the mean radiant temperature of the indoor surface decreased by up to 3.9 °C and longer duration of operation, the more efficient the night ventilation strategy becomes A variety of optimization methods have been applied in building control problems such as, linear and non-linear optimization (LP & NLP) [12,13], genetic algorithm optimization technique [14, 15, 16], and dynamic programming (DP) [17]. The most common method used in building optimization is genetic algorithm (GA) that is a search technique used in computing to find solutions to optimization problems.

Congradac and Kulic [19] discussed IAQ and energy savings potential of the HVAC system through the application of the GA. Their results showed up to 20% energy savings for chiller. They applied results from optimization problem with Matlab to EnergyPlus model of the building and introduce this model as a reliable model for optimization.

The objective of this paper is to assess the performance of mechanical nighttime ventilation cooling and optimize nighttime fan flow rate in typical conditioned office buildings. An hourly building energy simulation model, DOE2.1E [20, 21], was used to calculate building energy consumtion. In addition, the MATLAB software was integrated with DOE2 for optimization of outdoor fan flow rate during the night. Genetic algorithm was used in MATLAB as the optimization method. The effects of various parameters such as outdoor temperature, indoor-outdoor temperature difference and nighttime ventilation duration were studied to evaluate the effectiveness of nighttime ventilation.

2 METHODOLOGY

Nighttime ventilation is optimized by integrating MATLAB as an optimization software and DOE2 as building energy calculation software. Genetic algorithm (GA) was chosen for optimization method since it is a stochastic method and does not require an exact equation of objective function. In this integration GA method generate a set of flow rates for different hours during the night and sends them to DOE2. DOE2 calculates building energy consumption for the entire day base on the specified nighttime fan flow rates and returns the results to GA. This process is continued until GA reaches to its maximum iteration and GA introduces final set of nighttime fan flow rates that optimized building energy consumption.

The results of this optimization were used to investigate the effect influencing parameters such as ioutdoor temperature, indoor-outdoor temperature difference, and nighttime ventilation duration.

2.1 **Building model**

The selected prototype building is a one-story office building with 5 zones and a plenum. The total floor area is 464.5 m^2 (5000 ft^2) with a height of 2.4 m (8 ft). There is no shade from other nearby facilities. The building is built with medium weight construction. Interior loads are surface mounted fluorescent lighting at 16 W/m^2, equipment at 10.8 W/m^2, and peak occupancy of 9.3 m^2 (100 ft^2) per person. Infiltration is 0.25 air changes per hour (ACH). Design temperatures for cooling and heating are set at 25.5°C (78 °F), and 21°C (70 °F), respectively. A single variable air volume system serves the entire building. The system has a variable speed fan motor, and VAV boxes with a minimum stop of 30%. The cooling and heating system operate from 8am to 6pm weekdays and is off during nights and weekends. HVAC plant works with gas fired hot water generator and reciprocating air cooled chiller. Detail of building construction and systems are shown in Table 1.

Table 1: Detail of building description

Parameters	**Description**
Floor area [m^2] (ft^2)	464.5 (5000)
Wall construction	Wood shingles, plywood, R-11 fiber insulation, gypsum board
Roof construction	Roof gravel, built-up roofing, R-3 to R-30 mineral board insulation, wood sheathing ceiling
Window glass	0.6 cm plate double pane
Door glass	1.3 cm plate single pane
Interior loads	Lighting=16 W/m^2, equipment = 10.8 W/m^2, people = 9.3 m^2 (100 ft^2) per person
Interior partitions [W/m^2K] (BTU/hr ft^2 F)	U-value = 8.5 (1.5)
Infiltration	0.25 ACH
Chiller	Reciprocating air cooled chiller (COP=3.65)
Boiler	Gas fired hot water boiler (Eff = 85%)

2.2 **External temperature conditions:**

Outdoor temperature has a strong effect on the effectiveness of ventilation. During the air conditioning period, from June 1 to August 31, the maximum, minimum and average outside air temperatures are shown in Table 2 for Montreal. In this paper optimization is applied on weekdays of July.

Table 2: The maximum, minimum and average outside air temperatures for investigated cities

City	**Jun**			**Jul**			**Aug**		
	Max T [°C] (°F)	**Min T [°C] (°F)**	**Ave T [°C] (°F)**	**Max T [°C] (°F)**	**Min T [°C] (°F)**	**Ave T [°C] (°F)**	**Max T [°C] (°F)**	**Min T [°C] (°F)**	**Ave T [°C] (°F)**
Montreal	30 (86)	7.2 (45)	18.5 (65.4)	31.6 (89)	8.3 (47)	20.7 (69.2)	28.9 (84)	7.7 (46)	19.5 (67.2)

2.3 **Optimization method (Genetic algorithm)**

Genetic Algorithms (GA) are stochastic search algorithms that borrow some concepts from nature. At the start of the algorithm, an initial population is generated, either randomly or according to some rules. The reproduction operator selects population members (set of optimization variables) from the previous population to be parents for new members. This parenthood selection can range from a totally random process to one that is based by the member's fitness value (value of objective function for each member).

Each new generation are formed by the action of genetic operators on the older population. Finally, the members of the population pool are compared via their fitness value to choose optimal solution. A GA is left to progress through generations, until certain criteria (such as a fixed number of generations, or a time limit) are met [22].

2.4 Integrating DOE2 and MATLAB

Building energy use and cost analysis tool (DOE2.1E) was used for building simulation. DOE2 is a widely used, validated and accepted freeware building energy analysis program. It can calculate the energy use and cost for all types of buildings; it has a complete library and weather data; and most importantly it has available source code with possibility to add functions. For MATLAB and DOE2 integrating, first, GA generates chromosomes that are matrices of nighttime fan flow rates. These matrices include fan flow rates from one hour before working hours (7am) to five hour before working hours (3am). Each of these chromosomes has five elements that fill with a number between zero and one. These numbers show the fraction of that hour fan flow rate to maximum possible fan flow rate. After that MATLAB calls AWK (a text-processing programme) and create an input file of DOE2 base on each of these chromosomes. Finally DOE2 is run and building energy consumption is return to MATLAB for that chromosome as a fitness value. Figure 1 shows optimization process.

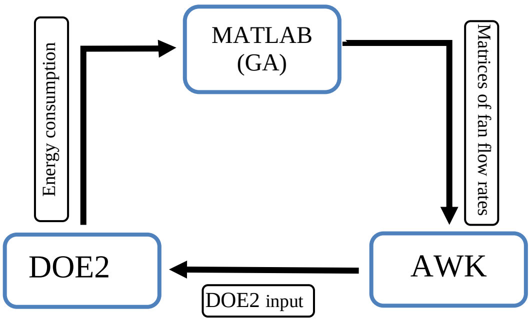


Figure 1: Optimization process

Result and Discussion

Nighttime fan flow rates optimization was applied for five hours before working hours during the summer (Jun, July and August) at Montreal. The results for days with energy savings during summer are listed in Table 3. These results show total energy savings up to 8% and cooling energy saving up to 23%. These savings happened in a day with high diurnal temperature range and average temperature near 17 ˚C.

The results for total-building and cooling-energy consumption with and without nighttime ventilation during some days of summer are shown in Figures 2 and 3.

Table 3: Daily weather conditions and optimization results during summer in Montreal

Day No.	Date	Diurnal ave temp.	Diurnal temp. range	Night ave temp.	Ave fan flow rate fraction	Energy savings (kWh)	Cooling savings (kWh)	% Energy savings	% Cooling savings
1	8-Jun	20.2	13.9	14.0	0.4	2.1	6.7	2.0	9.7
2	10-Jun	23.4	14.4	17.4	0.3	0.8	4.5	0.5	4.2
3	13-Jun	13.6	8.9	10.0	0.3	1.2	1.1	1.9	6.2
4	14-Jun	17.1	16.1	10.2	0.6	7.8	13.6	8.1	23.0
5	15-Jun	19.9	15.0	13.3	0.7	5.5	13.8	4.3	16.6
6	16-Jun	20.0	8.3	16.6	0.4	1.9	7.3	1.6	10.1
7	17-Jun	22.1	11.7	17.1	0.4	0.1	5.3	0.1	5.8
8	22-Jun	19.4	11.1	14.8	0.4	1.4	5.8	1.4	9.0
9	23-Jun	20.1	12.8	14.1	0.5	4.5	10.6	3.9	14.2
10	24-Jun	22.5	15.6	15.7	0.5	2.4	10.0	1.7	10.5
11	28-Jun	16.6	15.0	10.0	0.1	1.1	2.4	1.7	6.3
12	29-Jun	16.7	9.4	13.6	0.5	3.7	8.7	4.9	22.1
13	6-Jul	17.4	8.9	14.0	0.3	1.2	4.3	1.1	6.7
14	7-Jul	19.3	11.1	14.7	0.5	2.8	8.3	2.2	10.8
15	8-Jul	20.1	10.6	15.7	0.4	1.9	6.4	1.4	7.2
16	14-Jul	20.6	11.1	16.7	0.5	1.3	7.6	1.1	10.2
17	22-Jul	15.7	9.4	13.0	0.2	0.4	2.3	0.5	6.2
18	27-Jul	17.2	13.9	10.8	0.4	1.6	6.2	2.1	14.2
19	28-Jul	20.0	12.2	14.7	0.5	1.7	7.9	1.5	10.8
20	29-Jul	21.3	8.9	17.3	0.4	1.7	6.2	1.3	7.4
21	5-Aug	19.9	12.2	14.3	0.4	2.5	7.3	2.2	10.4
22	11-Aug	20.4	12.8	14.3	0.5	4.4	11.3	3.2	12.8
23	12-Aug	20.0	11.1	16.2	0.5	2.5	9.1	1.9	10.9
24	18-Aug	18.8	10.6	15.1	0.2	0.6	3.1	0.7	5.4
25	19-Aug	22.2	12.2	16.4	0.4	0.6	5.9	0.4	6.5
26	22-Aug	19.9	12.2	14.7	0.9	7.3	15.5	4.4	15.4
27	23-Aug	18.8	8.3	16.7	0.4	0.6	6.4	0.5	8.9
28	25-Aug	15.2	11.7	9.8	0.1	0.8	1.6	1.7	5.9
29	26-Aug	15.9	12.8	11.9	0.4	1.3	6.5	2.1	19.7
30	30-Aug	18.5	11.1	13.8	0.4	1.1	6.2	1.4	12.8

Figure 4 shows total energy savings percentage verses outdoor average and diurnal temperature range. Base on the results at constant outdoor average temperature, energy savings increase when there is a higher temperature range. Also the results show that higher energy savings happened at outdoor average temperature between 15 ˚C and 22 ˚C and energy savings decrease when outdoor average temperature is out of this range.

Figures 5 and 6 show results for fan flow rates during the night between hour 7 (7am) and hour 3 (3 am) verses outdoor temperature at that specific hour and temperature difference between indoor and outdoor. The results show that minimum suitable temperature difference between outdoor and indoor to apply nighttime ventilation is 8 ˚C. Using the outdoor air with temperature difference less than 8 ˚C cannot reduce building energy consumption. Also, outdoor temperature between 10 ˚C and 18˚C are appropriate for nighttime ventilation and energy savings of nighttime ventilation reduce significantly when outdoor temperature is out of this range.

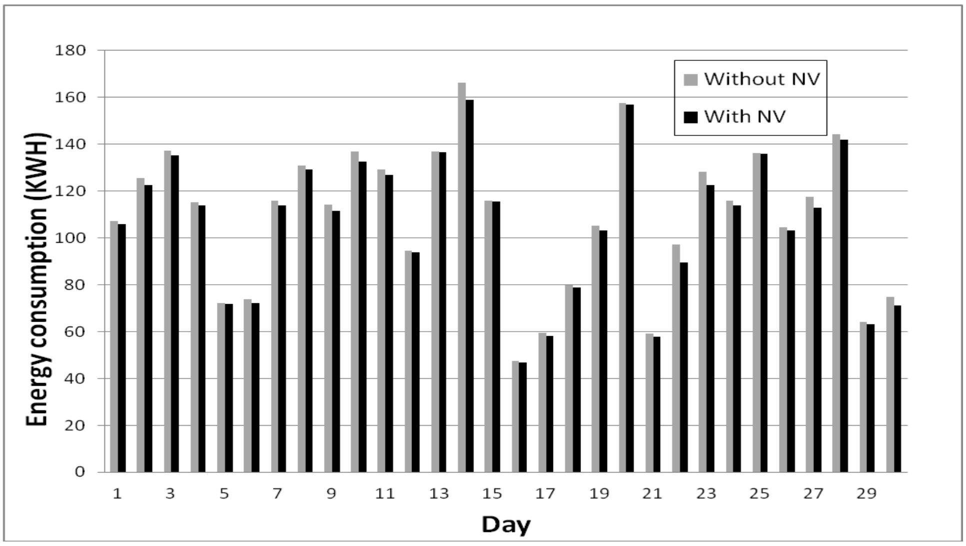


Figure 2: Building total energy consumption with and without nighttime ventilation during summer in Montreal

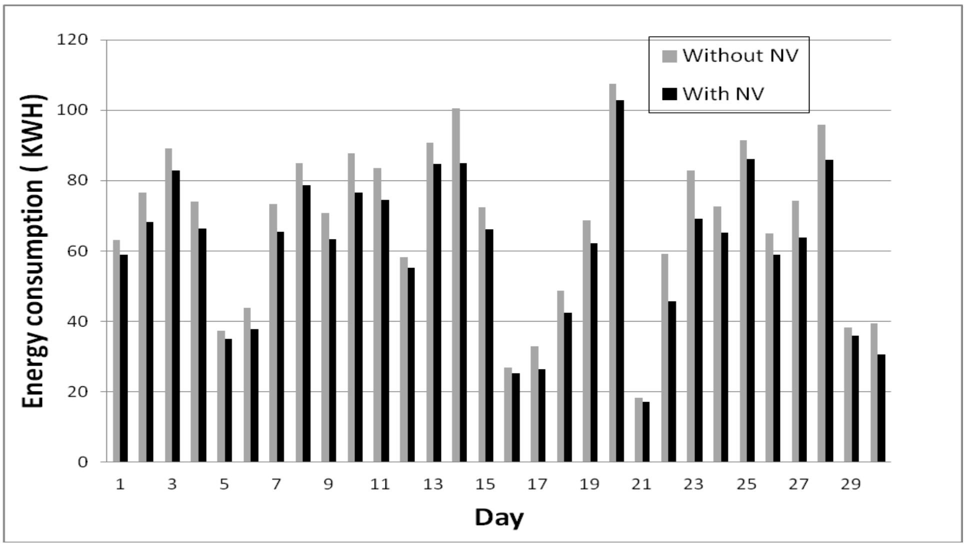


Figure 3: Building cooling energy consumption with and without nighttime ventilation during the summer in Montreal

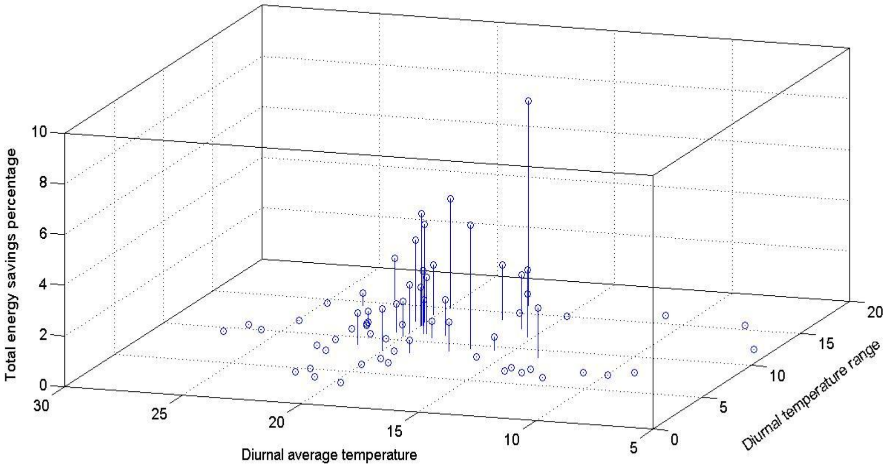


Figure 4: total energy saving percentage verses diurnal outdoor average temperature and diurnal temperature range.

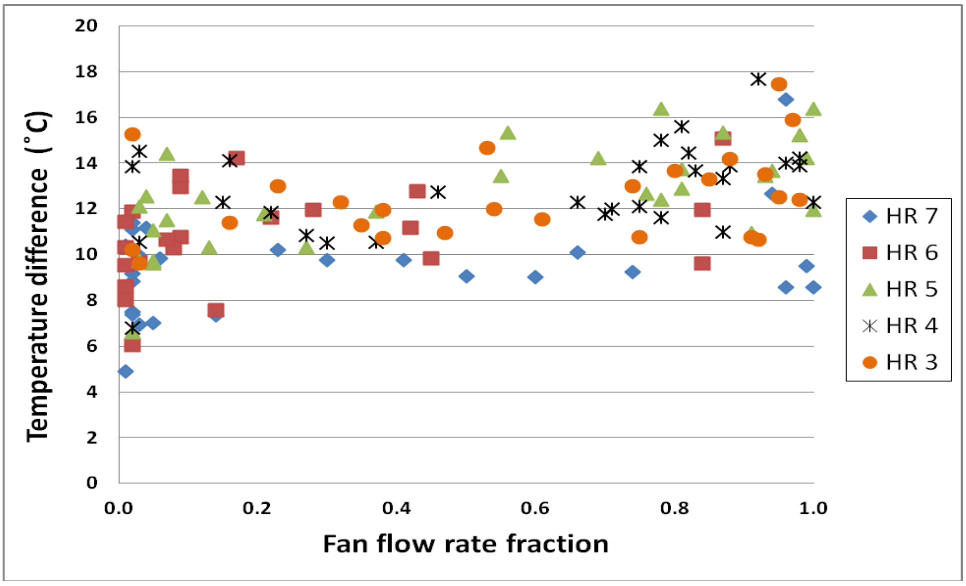


Figure 5: Nighttime fan flow rate fraction versus temperature difference between outdoor and indoor temperature for 5 hours before working hour during summer in Montreal

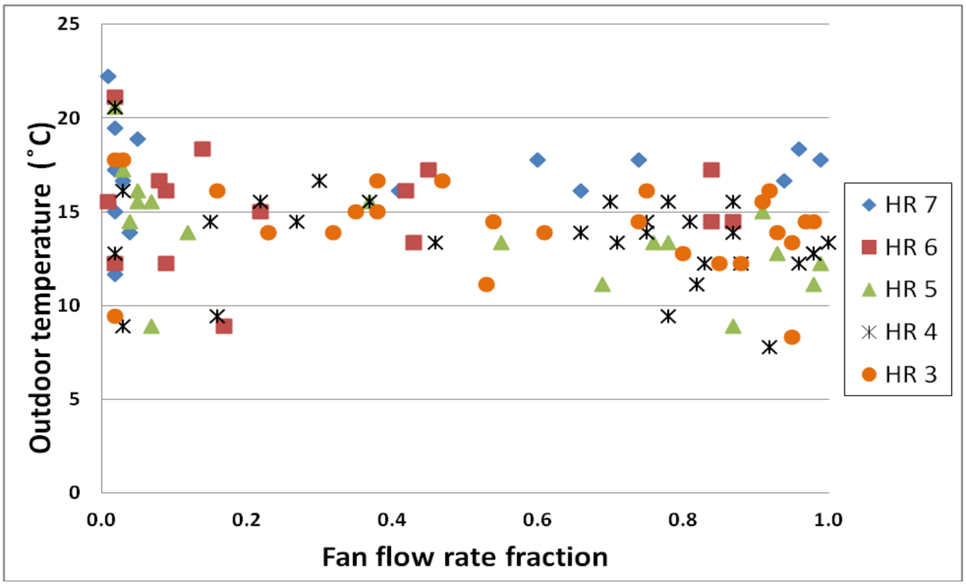


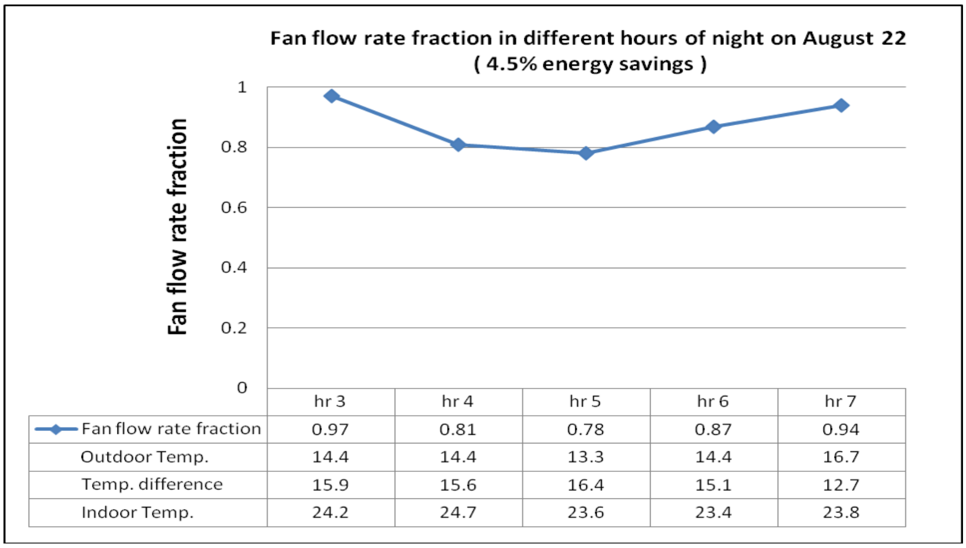
Figure 6: Nighttime fan flow rate fraction versus temperature difference between outdoor and indoor temperature for 5 hours before working hour during summer in Montreal

To better understand of nighttime ventilation optimization, the hourly results for fan flow rates for some days with higher energy savings potential are shown in Figures (7-10). The results show that optimization is converging towards an indoor temperature of about 23 ˚C at the beginning of the day. To reach this goal, optimization uses higher fan flow rates during hours with lower outdoor air temperatures and higher temperature differences between outdoor and indoor.

3 CONCLUSIONS

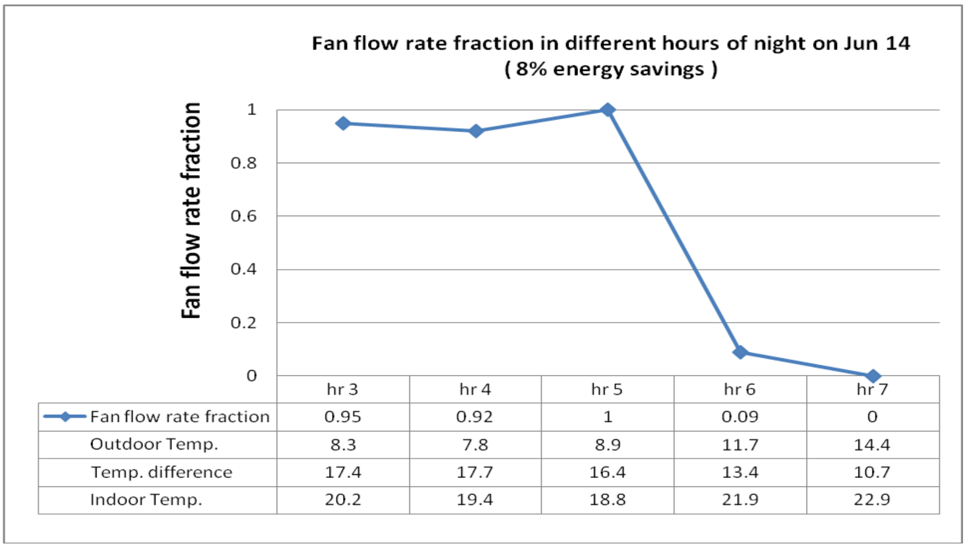
We have integrated DOE2 and MATLAB to optimize building energy use and nighttime fan flow rates. The results of this optimization were used to investigate the effect of outdoor temperature, indoor-outdoor temperature difference and nighttime ventilation duration.

Nighttime fan flow rates optimization was applied for five hours before working hours during the summer (June, July and August) in an office building in Montreal. The results show that nighttime ventilation decrease total energy consumption up to 8% and cooling energy consumption up to 23%. These savings occurred in days with high diurnal temperature range and average temperature near 17 ˚C. Higher energy savings are calculated for days with an outdoor average temperature between 15 ˚C and 22 ˚C.



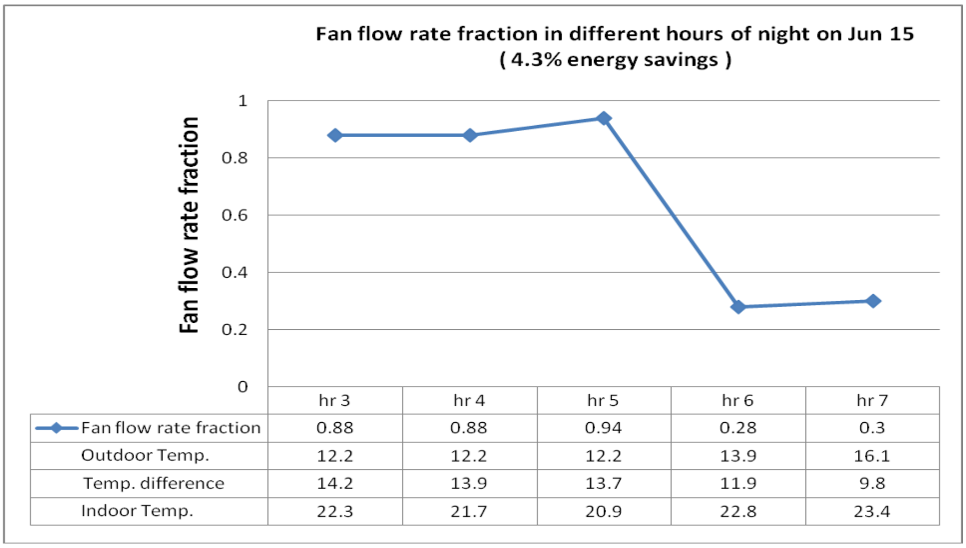
	hr 3	hr 4	hr 5	hr 6	hr 7
Fan flow rate fraction	0.97	0.81	0.78	0.87	0.94
Outdoor Temp.	14.4	14.4	13.3	14.4	16.7
Temp. difference	15.9	15.6	16.4	15.1	12.7
Indoor Temp.	24.2	24.7	23.6	23.4	23.8

Figure 7: Hourly fan flow rate fraction and temperatures from 3am to 7am for August 22 in Montreal



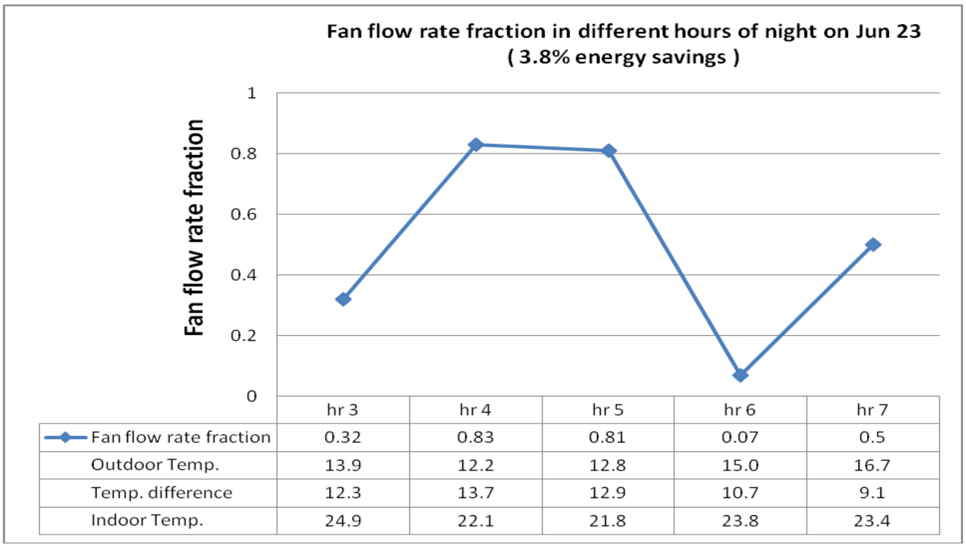
	hr 3	hr 4	hr 5	hr 6	hr 7
Fan flow rate fraction	0.95	0.92	1	0.09	0
Outdoor Temp.	8.3	7.8	8.9	11.7	14.4
Temp. difference	17.4	17.7	16.4	13.4	10.7
Indoor Temp.	20.2	19.4	18.8	21.9	22.9

Figure 8: Hourly fan flow rate fraction and temperatures from 3am to 7am for Jun 14 in Montreal



	hr 3	hr 4	hr 5	hr 6	hr 7
Fan flow rate fraction	0.88	0.88	0.94	0.28	0.3
Outdoor Temp.	12.2	12.2	12.2	13.9	16.1
Temp. difference	14.2	13.9	13.7	11.9	9.8
Indoor Temp.	22.3	21.7	20.9	22.8	23.4

Figure 9: Hourly fan flow rate fraction and temperatures from 3am to 7am for Jun 15 in Montreal



	hr 3	hr 4	hr 5	hr 6	hr 7
Fan flow rate fraction	0.32	0.83	0.81	0.07	0.5
Outdoor Temp.	13.9	12.2	12.8	15.0	16.7
Temp. difference	12.3	13.7	12.9	10.7	9.1
Indoor Temp.	24.9	22.1	21.8	23.8	23.4

Figure 10: Hourly fan flow rate fraction and temperatures from 3am to 7am for Jun 23 in Montreal

4 ACKNOWLEDGEMENTS

This work was in part supported by an internal grant from the Faculty of Engineering and Computer Science at Concordia University, Montreal, Canada and by a Discovery Grant from Natural Sciences and Engineering Research Council of Canada (NSERC).

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