Cost-efficient temperature regulation of an office building utilizing the drop in night temperature

Pål Johan From and Amund J. Føyn

***Abstract*—**This paper proposes a cost efficient approach to lower the temperature in an office building when the expected temperature during the day is higher that desired. The idea is very simple, both in concept and in implementation, and will result in considerable energy savings without the need for large investments.

The concept presented is very simple: First a simple temperature model is used to find a prediction of the expected temperature in each office. Then, if the expected daytime temperature is higher than the desired room temperature we take measures to exploit the cooler night and morning air to cool down the building so that the expected daytime temperature is lowered. This can be done either through the ventilation system, by opening the office window, or by activating a fan. This reduces the need for air-conditioning and is extremely cost-efficient because we exploit the difference in daytime and nighttime temperature.

***Keywords*—** Energy savings, predictive control, temperature control, temperature modeling.

I. Introduction

TEMPERATURE regulation of home and office buildings is extremely energy demanding and represents a large part of the energy consumption in both cold and hot countries. In cold countries heating devices may be required both at day and night and in several hot countries cooling devices are required in the same way. There are, however, several countries where the daytime temperature is uncomfortably high while the nighttime temperature is considerably lower. From an energy efficiency perspective these countries represent a great challenge because heating buildings at night and cooling them during the day represents a substantial energy waste. It is thus desirable to utilize the cool air at night to lower the temperature in the building during the day and vice versa.

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This paper addresses the temperature regulation problem when the temperature at daytime is higher than desired and the temperature at night is considerably lower. We propose to utilize this drop in temperature at night to cool the building mass during the night and morning hours so that the need for cooling during the day is reduced. Because cooling the building by utilizing the cold night air is substantially more cost efficient than air conditioning systems we reduce the total energy usage considerably.

The air conditioning system can account for as much as 40% of the total energy consumption of a building [1]. Intelligent temperature control can therefore potentially result in huge energy savings. To be able to utilize energy control in all kinds of buildings (especially older buildings) there is also a need for low-cost and easy-to-install solutions to solve the temperature regulation problem. This will also allow developing countries to benefit from the technology.

This paper presents a conceptual preliminary study to the topic described above. This includes the following contributions:

- The concept of how to leverage the difference in night and day temperature to reduce the total energy usage is described in detail;
- Preliminary experiments that show that the cool night air can be used as a mean to lower the daytime temperature are presented;
- It is shown that a very simple mathematical model can be used to predict the daytime temperature and is sufficient to reduce the total energy usage in an office building;
- An estimate of the potential energy savings is presented.

This paper does not present detailed experimental results. We leave the validation of the proposed approach based on statistically meaningful experiments (in the sense that a sufficient number of experiments are performed) for future publications. We do, however, present experimental results that show that when the cool night air is let into the office during the night and morning hours, this will reduce the office temperature during the hottest hours of the day.

A. Related Work

The problem of energy-efficient energy control is discussed in several papers, for example in References [1]-[3]. A paper that is relevant to the approach presented in this paper is Reference [1], where a control network that utilizes the off-peak hours to make and store ice for peak hour cooling use is presented. In [2] a model predictive approach to temperature regulation of an air-conditioning system is presented in detail. It is shown that a model predictive control approach will benefit over for example a standard PID controller. A nice introduction to the model predictive control problem can be found in Reference [4].

Furthermore, low-cost temperature control architecture is discussed for agriculture greenhouses in [5]. There are also several advanced temperature control schemes that have been proposed, for example in [6]. Advanced on-off control is described in [7].

II. TEMPERATURE MODELS FOR PREDICTIVE CONTROL

In order to be able to efficiently utilize the outside temperature variations to cool an office building we need to know the outside temperature throughout the night and the expected daytime temperature the following day. The night temperature is not needed in advance, so this can be measured with a simple thermometer. The expected outside temperature during the day is available from the weather forecast and can be continuously downloaded through most meteorology sites on the Internet. At the test site, for example, the expected daytime temperature and weather can be downloaded from the site *http://www.yr.no* free of charge. The main challenge is to find an accurate estimate of the daytime temperature inside the offices based on the (measured) nighttime inside and outside temperature and the expected outside daytime temperature.

A. Predicted Daytime Temperature

The proposed algorithm will continuously evaluate whether an action should be taken in order to decrease the expected daytime office temperature at some time $t = t_d$ the following day. In order to do this we need to have a prediction of the office temperature, say at noon $t_d = 12$, at the decision time $t = t_n$ some time during the night (and hence the subscript n). Here t_n is typically some time during the night or early morning, i.e., $0 < t_d < 8$ (a.m.). We need to predict the daytime office temperature based on the following measurements and predictions:

- measured inside temperature at time t_n, denoted T_n;
- measured outside temperature at time t_n, denoted $T_{n,o}$; and
- the predicted outside temperature at time t_d, denoted $T_{d,o}$.

Note that the “o” (for example in the subscript in $T_{n,o}$) tells us that we are talking about the outdoor temperature; the subscript “n” means the measured night temperature; and the subscript “d” the predicted daytime temperature. From empirical studies and simple curve fitting we have found that the expected inside temperature T_d can be found as a very simple linear model as

$$T = T_n + k_1 (T_{d,o} - T_n) \tag{1}$$

where $0 < k_1 < 1$. In our case we find that $k_1 = 0.8$ gives the best fit for $t_d = 12$, i.e., at noon. This means that the expected outdoor temperature has a larger effect on the office temperature than the measured indoor night temperature at time $t = t_n$.

We can get a slightly more accurate model if we also include the measured outside temperature. We can then write

$$T = T_n + k_2 (T_n - T_{n,o})(T_{d,o} - T_n) \tag{2}$$

where again $0 < k_2 < 1$. In this case we find that $k_2 = 0.1$ gives the best fit for $t_d = 12$.

III. CONTROL

Assume that we have a temperature threshold that the temperature should not arise above. This threshold is given by what the user experiences as comfortable and can be specified either by the individual user of the particular office or as a general requirement for the whole building. We will denote this temperature T_{thr} and is typically around 22^{o}C, which was used in the experiments in this paper. In its simplest form the control problem can then be formulated as an on-off control (switch control) in the following form:

IF
   $T_{thr}<T$ AND $T_{n,o}<T_n$ AND "temperature control is off"
THEN
   "initiate temperature control"
ELSE
   "leave temperature control off"
END

By the term “initiate temperature control" we mean one of the following:

- Open the office window to let cool air enter the office; or
- initiate a fan that actively blows cool air into the office; or
- utilize the ventilation system in the building to cool the air (if all offices are to be cooled).

Because the system is so simple (the actuator only has two states: on or off) the simple control scheme proposed works well with the described system. This control scheme is of course very simple, but it serves the purpose within the settings of this paper, i.e., to develop a low cost and easily implementable system to lower the daytime temperature. We do not find considerable differences between the two temperature models used, which again suggests that a simple temperature model is sufficient to control this system.

IV. Empirical Studies

A set of experimental results were performed in order to prove the viability of the proposed concept. The experimental setup is very simple: we have two offices next to each other with approximately the same temperature profiles. One office is used as a reference and the other office is controlled using the proposed approach. We control the office by opening the window slightly at night if the expected daytime temperature is higher than the desired maximum temperature.

The temperature in the offices has been measured during the morning and day for 13 different days when the window in the controlled office has been opened from approximately 8:30-11:30 every day. We have also measured the temperature in the two offices 11 days where we did not open the office window. When the office window is closed we find no difference (0.02 ^{o}C) between the two offices. We note that there is a constant bias in the temperature between the two offices in that the reference office is always approximately 1.50 ^{o}C colder than the controlled office. This difference has been removed from the results by adding it to the temperature of the reference office.

Table 1 shows the change in the office temperatures at t_d = 10 in the two offices compared to the temperature at 08:00 for the 13 day period. We have chosen days in June when direct sunlight normally causes the office to heat up to uncomfortably high temperatures.

We see that when the window is opened during the morning hours the temperature drop is considerably higher than when it is not opened. In fact, when the window is not opened, the temperature rises, as is expected, during the period from 08:00 to 10:00, while when the window is opened the temperature in the controlled office drops with an average of 1 ^{o}C compared to the reference office. We also note that at only one instant does the temperature in the controlled office rise during this period, and that this is only slightly.

Table 2 shows the change in the office temperatures at noon t_d = 12 in the two offices compared to the temperature at 08:00 for the same 13 day period. We notice that also at noon, which is 0,5-1 hours after the window has been closed, the temperature is still reduced with more than 1 ^{o}C in the controlled office compared to the reference office. This is an important observation as it means that the office temperature is reduced also after the window has been closed, which suggests that the proposed approach may reduce the daytime temperature also when the window is opened during the night.

The average drop in temperature in the controlled office compared to the reference office for the time interval 10:00 to 14:00 is shown in Table 3. This shows that the average reduction in temperature is approximately 1.1 ^{o}C during the hottest period of the day if the office window is left open for about three hours during the morning.

TABLE 1
Change in temperature from 08:00 to 10:00 with and without temperature control.

Controlled office ^{o}C	Reference office ^{o}C
-1,30	-0,10
-1,30	0,00
-0,60	0,10
0,20	0,00
-0,80	0,00
-1,10	0,30
-1,20	0,90
-1,30	-0,30
-2,00	-0,30
-1,40	-0,10
0,00	0,00
-1,10	-0,10
-1,10	-0,10
Average:	**Average:**
-1,00	**0,02**

TABLE 2
Change in temperature from 08:00 to noon with and without temperature control.

Controlled office ^{o}C	Reference office ^{o}C
-0,50	0,30
-0,80	0,10
0,20	0,50
0,40	0,10
-1,30	-0,20
-2,20	0,10
-1,20	2,10
-1,80	-0,40
-1,80	-0,50
-1,80	-0,10
0,30	0,10
-0,70	0,20
-0,70	0,10
Average:	**Average:**
-0,92	0,18

TABLE 3
Average change in temperature during the time period 10:00-14:00 with and without temperature control.

Controlled office ^{o}C	Reference office ^{o}C
-1,023077	**0,08**

A. *Energy Savings*

We can calculate an estimate of how much energy is saved by applying the proposed approach instead of utilizing air conditioning to lower the temperature with 1.1 ^{o}C during the six hottest hours of the day. We have assumed that the implemented system does not use any energy, which is probably not far from the truth.

The total energy saving of a single office is equivalent to a small air condition operating for approximately six hours a day. If we assume that there are 100 days every year where the temperature becomes uncomfortably hot, this is equivalent to approximately 50kWh/month.

In the test building there are approximately 100 offices that all tend to get overheated on sunny summer days. The total energy savings for this building alone if is then 30000kWh. With today's electricity prices at the test site in Norway this is equivalent to about total savings of about US$ 4000 a year.

These results can probably be improved by several factors if more active systems are implemented. By introducing a fan, for example, we can actively blow cold night air into the office during the night using very little energy. This will both allow us to reduce the daytime temperature and will keep the daytime temperature low also during the afternoon as the building mass has been cooled to a lower temperature during the night.

V. Conclusions

We have shown that by implementing a very simple system that consists of a simple controller and a mechanism that opens a window or starts a fan, we can take advantage of the cold night air to decrease the need for air conditioning. The total energy savings for the building used in the test is approximately 30000kWh. This is a considerable amount of energy considering the low implementation costs of the system.

These savings is equivalent to about total savings of about US$ 4000 a year for the test site. More importantly, we are almost able to recover the investments needed to implement the proposed system in a single year.

A. *Future Work*

There are several ways to improve the performance of the system. If the office temperature is to be controlled individually for each office a small energy-efficient fan will probably improve the overall performance of the system compared to opening and closing a window. Even though this would use some energy to drive the fan itself we believe this to be a better solution to the problem. We leave this for future work. If the ventilation system is used to blow cold air into the building, the overall performance can probably be improved even further.

References

[1] H. Cheng, C. ChenC. Cheng, and G Chiu, "An application of distributed air conditioning control network," in American Control Conference, 1998, pp. 3420.

[2] X. Xu, S. Wang, and G Huang, *Robust MPC for temperature control of air conditioning systems concerning on constraints and multitype uncertainties.* in Building Services Engineering Research and Technology, 2020, vol 31, no 1, pp. 39–55.

[3] K. Yonezawa, "Comfort air-conditioning control for energy saving," in Industrial Electronics Society, 2000, pp. 1737–1742.

[4] E. Camacho, and C. B. Alba, "Model predictive control" Springer, 2007.

[5] W. Li, Q. Luo, Z. Li, and Y Li, "The design and implementation of a low cost temperature control system for agriculture greenhouses" in Energy and Environment Technology 2009, pp. 399-401.

[6] K. Katabira, Z. Huijing, Y. Nakagawa, and R. Shibasaki, "Real-time monitoring of people flows and indoor temperature distribution for advanced air-conditioning control", in Intelligent Transportation Systems, 2008, pp. 664-668.

[7] W Jiangjiang, J. Youyin, Z. Chunfa, and S. Guohua, "Control system design in constant-temperature and constant-humidity air-conditioning system," in Chinese Control Conference 2008, pp. 632.

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