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A method to determine heating power and heat up time for intermittent heating of churches

Magnus Wessberg[a]*, Tor Broström[b], Tomas Vyhlidal[a]

[a]Dept. of Instrumentation and Control Eng., Faculty of Mechanical Eng., Czech Technical University in Prague, Technicka 4, Prague 6, 166 07, Czech Republic
[b]Uppsala University Cramergatan 3 62157 Visby Sweden

Abstract

Intermittent heating, common in churches, requires higher heating power than steady state heating. With respect to energy use and preservation aspects, the heat up time should be short. Systems for intermittent heating are often designed using rule of thumb estimates or inadequate steady state calculations. This paper presents a method to relate heating power and heat up time for a specific building where thermal characteristics of a building are determined using a step response test.

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Keywords: intermittent heating;

1. Introduction

Many churches in Sweden are unheated during the periods when they are not used. Diminishing populations in the countryside is gradually forcing congregations to join together resulting in fewer services at each church [1]. Further, small congregations have often limited resources with the result that climate control for conservation must be minimized to save booth energy and costs [2]. Traditionally most churches are heated intermittently [3] which requires much higher heating power than steady state heating. In todays practice, intermittent heating systems are designed using rule of thumb estimates or, in the worst case, steady state calculations. This paper presents a method to determine heating power and heat up time for a specific building.

When a church is heated intermittently, a major part of the energy is used to heat up the walls. This means that conventional methods for calculating the heating load at steady state conditions are not applicable. The underlying theory was developed already in the 19th century and results in a simple and manageable model that describes the relation between heating power and heat up time for a given building. However, difficulties in determining the thermal properties of a historic masonry construction have been a barrier for the application. Furthermore, the simplified model was not validated against actual data.

In buildings with heavy stone walls it is generally most energy efficient to use heating systems with as high power as possible and thereby let the heating period be as short as possible. Long heating periods do not only lead to higher energy cost but also an increased risk for damage on the artefacts due to drying. In Scandinavia recommendations of 6-12 hours are common. A drawback is that this course of action requires high heating power resulting in high costs due to investments or electrical tariffs. From the

* Corresponding author. Tel.: +46-73-072 55 20; fax: +0-000-000-0000 .
E-mail address: magnus.wessberg@konstvet.uu.se

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energy efficiency point of view it is important to minimize energy consumption by turning on the heat at the right time before service. When the heating system is controlled manually, this is often based on either practical aspects such as working hours etc. or in some cases the experience of the staff [4]. There are “intelligent” control systems that aim to predict heat up time but they are based on insufficient physical models.

The present paper presents a method where the thermal characteristics of a building are determined using a step response test. The building is heated with constant power input while air and wall temperatures are measured. This allows for a parameter study in the design phase, relating heating power and heat up time for that particular building.

2. Theoretical model for intermittent heating

Intermittent heating in historic buildings has been studied since the 19th century when heating systems started to be installed in churches. In 1922 the Swedish state-owned energy company Vattenfall financed theoretical and practical studies to facilitate the introduction of electric heating in churches [5]. In 1930 Krischer presented a study that was in line with the results from Vattenfall [6]. They both concluded that a simplified mathematical model could be derived from the heat transfer equation solved for the case of a semi-infinite slab heated with constant heat flux. This solution is now common knowledge and can be found in texts on heat conduction or building physics e.g. [7].

According to the simplified model, the increase in temperature during a heating occasion with constant heat flux is proportional to the square root of time. The solution is based on the following conditions:

- In the beginning of the heating occasion the temperature distribution in the wall is constant and equal to the indoor air temperature
- The heating occasion is so short that only a part of the wall is affected by the heat wave
- The heat flux into the wall is constant
- The area of windows, doors etc. is small compared with the wall area.
- The infiltration rate is small.

The two last points imply that the loss due to infiltration and conduction, P_l, is small compared to the heat flux into the wall P_w. It is assumed that the loss factor $F = P_w / P_s$ is constant where P_w and P_s is the heat flow into the wall respectively the heat supplied, see figure 1a.

The temperature increase at the wall surface, $\Delta\vartheta_w$, during a heating occasion is determined by

$$\Delta\vartheta_w(0,t) = \vartheta_w(0,t) - \vartheta_w(0,0) = \frac{P_w}{A} \cdot u \cdot \sqrt{t} \tag{1}$$

where $u = \frac{2}{\sqrt{\pi}} \cdot \frac{1}{\sqrt{\lambda_w c_w \rho_w}}$ (2)

and $\sqrt{\lambda_w c_w \rho_w}$ is the thermal effusivity of the wall (W/(m^2 K s^{½})

The air temperature can be expressed as

$$\Delta\vartheta_i = \frac{P_w}{A} \cdot u \cdot \sqrt{t} + \frac{P_w}{A} \cdot \frac{1}{\alpha_w} \tag{3}$$

where α is the heat-transfer coefficient between air and wall (W/(m^2 °C)).

Under the assumption that α is constant we have a linear relation for both the wall temperature and the air temperature, see figure 1b.

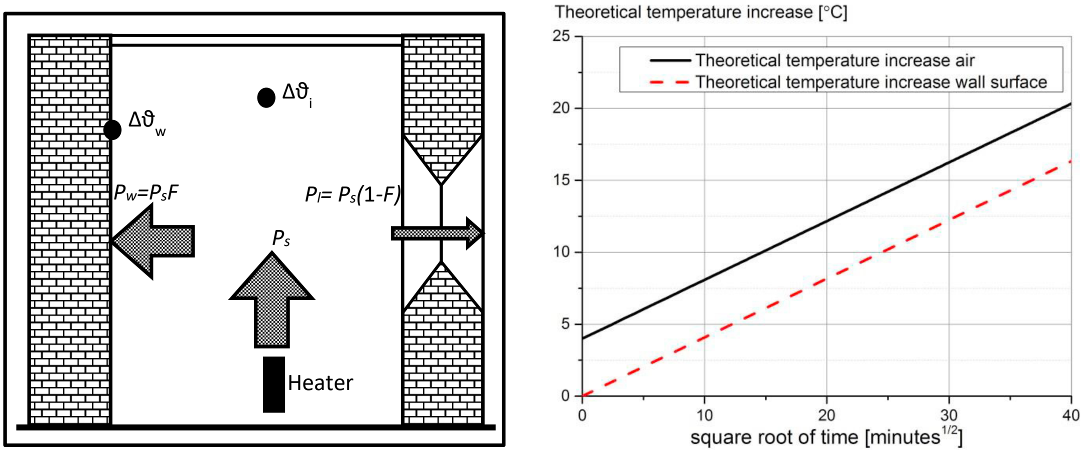

Fig. 1. (a) Heat flux at intermittently heating; (b) Theoretical temperature increase according to eq. (1) and eq.(3).

3. Method to determine thermal characteristics in of the building

Equations (1) and (3) can be used to calculate the heating power as a function of heat up time, or vice versa, for a given building. Based only on the physical characteristics of a given historic masonry wall, it is difficult to determine the buildings material parameter, u. Broström developed a method to determine the parameters u/A and $1/\alpha A$ from measurements of temperature during a step response test, i.e. a heating occasion with constant heating power [8].

As the increase of temperature in the air and on the surface of the wall, according to eq. (1) and (3), are linear functions of square root of time the following reasoning must apply. If eq. (3) is compared with a standard linear equation

$$y = kx + m \tag{4}$$

Where y is the increase of temperature, $\Delta\vartheta$, during a heating occasion and $x = \sqrt{t}$, it is easy to identify the slope of the line as

$$k = \frac{P_w}{A} u \tag{5}$$

and the intercept as

$$m = P_w \frac{1}{\alpha A} = \Delta\vartheta_i - \Delta\vartheta_w \tag{6}$$

which is the difference between air and wall surface temperature. Knowing the supplied power P_s, the building characteristics u/A and $1/(\alpha A)$ can thus be determined from measured data during the step response test at a heating occasion.

A large number of step response tests were carried out in medieval stone churches to validate eq.(1) and eq.(3). Two of the tests are shown in figure 2. Every test follows the same pattern. In the beginning it takes some time to heat up the interior air but after some time, depending of the church's characteristics, the temperature increases according to the model as described by eq. (1) and eq. (3).

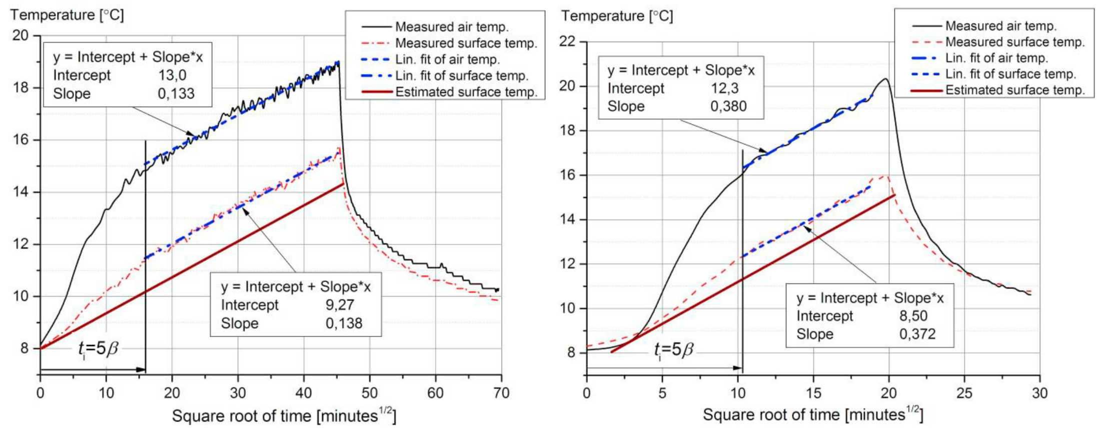

Fig. 2. (a) A heating occasion in Väskinde church Gotland Sweden; (b) A heating occasion in Tingstäde church Gotland Sweden

Some observations from the step response tests need to be commented. In the beginning of the heating occasion it takes some time before the wall heat flux reaches its maximum value due to the thermal inertia of indoor air and interiors. The heat accumulation in air and interiors can be modelled using time constant β [9]

$$P_w = P_s F\left(1 - e^{-\frac{1}{\beta}t}\right) \tag{7}$$

As shown in fig 2, after an initial time period of approximately, 5β, the data follow the theoretical model

The intercept of the straight lines in Fig 2 are 1-3 degrees higher than ϑ_{w0} i.e. the initial wall temperature. According to equation (3) the intercept should theoretically be the same as $\vartheta_{w0.}$ In reality it will be a little bit lower than ϑ_{w0} due to the thermal inertia of air. The difference can to some extent be explained by a measurement error of the wall surface temperature ϑ_e [8]. The temperature sensors were applied on the wall surface and the measured value is therefore a weighted average of the wall surface temperature and the air temperature. The absolute size of the error is thus dependent of the difference between wall and air temperature. The measured value, ϑ_{wm}, at the wall surface can be estimated by

$$\vartheta_{wm} = v_w\,\vartheta_w + v_i\,\vartheta_i \tag{8}$$

where v_w and v_i are weighting factors. It is suggested that $v_w = 2/3$ and $v_i = 1/3$ are reasonable estimations of the weighting factors [8]. The measurement error, ϑ_e , will thus be

$$\vartheta_e = \vartheta_{wm} - \vartheta_w = (\vartheta_i - \vartheta_{wm})/2 \tag{9}$$

The parameters u/A, $1/\alpha A$ and F also need to be commented. u/A is a material specific constant but can change during the year depending on the degree of moisture in the wall. The heat transfer coefficient α is temperature dependent and the energy loss factor F is dependent on booth indoor and outdoor temperature difference and wind conditions. However all step response tests, which was carried out under different seasons, showed that the variations in all these above mentioned factors are small and is not much influenced by seasonal climate changes.

3.1. Method to determine thermal characteristics

To determine the thermal characteristics u/A and $1/\alpha A$ of a building during a heating occasion, a step response test can be carried out as follows:

1. Set the heating system to constant (maximal) power P_{s0}
2. Log wall temperature, ϑ_{wm}, and air temperature, ϑ_{im}
3. Determine t_i, defined as the time when the temperature difference between air and wall surface has become constant indicating that the initial time period has passed. See figure 2.
4. From data measured after t_i, calculate the measurement error, ϑ_e , at an arbitrary time and perform numerical linear regression on with
   $\vartheta_i = a_0 + a_1 x$
   for indoor air temperature and

$\vartheta_w + \vartheta_e = b_0 + b_1 x$
for wall temperature
$x = \sqrt{t}$ for both ϑ_i and ϑ_w,

5. The thermal parameters can then be determined by $u/A = a_1/P_{s0}$ and $1/\alpha A = (a_0 - b_0 + \vartheta_e)/P_{s0}$.

The increase of air temperature as a function of time can be described as:

$$\Delta\vartheta_i = \vartheta_i - \vartheta_{i0} = P\frac{a_1}{P_{s0}}\sqrt{t} + P\frac{a_0 - b_0 + \vartheta_e}{P_{s0}} \tag{8}$$

3.2. Calculate heat up time with a given heating power

The model can be used to calculate the heat up time by using eq. (8), and set $P = P_s$ i.e. the same power as used at the step response test

$$t_s = \left(\frac{\vartheta_{iset} - \vartheta_{i0} - a_1 + b_0 + \vartheta_e}{a_1}\right)^2 \tag{9}$$

where
t_s is time to reach desired set point temperature ϑ_{iset}
ϑ_{iset} is the desired set point temperature
ϑ_{i0} is initial air temperature
a_0, b_0 and a_1 are parameters from the regression analysis made at the step response test.

3.3. Calculate heating power needed for a given heat up time

The model, eq. (8), can also be used to determine the required power to heat up the building within a certain time

$$P = P_{s0}\frac{(\vartheta_{i0} - \vartheta_{iset})}{a_0 - b_0 + \vartheta_e + a_1\sqrt{t}} \tag{10}$$

where
t is time to reach set point temperature ϑ_{iset}
ϑ_{iset} is the set point temperature.
ϑ_{i0} is initial air temperature.
a_0, b_0 and a_1 are parameters from the regression analysis made at the step response test.
P_{s0} is the power used at the step response test.

3.4. Economic optimisation of heating power

For design purposes, it is possible to determine the optimal heat up time which results in the lowest overall cost. Higher heating power results in shorter heat up time and lower energy cost but tariffs and the installation costs increase. Lower heating power, on the other hand, will lead to longer heat up time with the opposite effects on costs. The total annual heating cost depends thus on the installed heating power and the energy use.

$$C_{tot} = PC_i + PtC_e + C_f \tag{11}$$

Where
- C_i Cost for installation and tariff per heating occasion and kW(cost/kW)
- C_e Energy cost per heating occasion (cost/kWh)
- C_f Fixed cost, independent of energy consumption and installed power
- P Required installed power according to eq. (10)

Fig 3 shows, in principal, how the different power cost, energy cost and total cost depend on heat up time. Short heat up time reduces energy cost but requires higher power cost. The cost optimal heat up time is when the total cost curve is at its lowest.

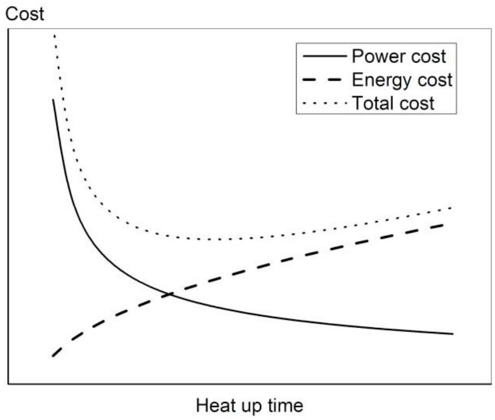

Fig. 3. Cost for intermittent heating as a function of heat up time.

4. Conclusions

This paper shows that with a relatively simple method it is possible to determine the thermal properties of a historic stone building where both construction and materials in the masonry walls are unknown. By performing a step response test the thermal properties can be derived which in turn can be used to calculate heat up time before service.

This allows for a model based control of the intermittent heating where selecting the right heat up time will minimise both energy use and the negative effects on sensitive interiors of the building. In an iterative process, the model parameters can be adjusted each time the building is heated.

Furthermore the proposed method can be used to for designing new heating systems. In that case a step response can be carried out with the old heating system or with portable heaters to derive the parameters which then can be used to determine the appropriate heating power with respect to the required heating time and the properties of the building.

Finally method can be used before the installation of a new heating system when it comes to optimize the economic trade-off between the fixed cost for the installed heaters and variable cost for energy used at every heat up time.

Even though the theoretical model is based on a number of simplifications, it still improves accuracy, in comparison to common practice, in both design and control of systems for intermittent heating.

In the next stage this method will be applied in a control unit that automatically updates the thermal parameters every time the church is heated and calculates the heat up time for next service.

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