International Flame Research Foundation
***The Finnish and Swedish National Committees***
***Finnish – Swedish Flame Days 2013***

# ON THE DESIGN OF BIOMASS-FIRED HEAT-STORING STOVES FOR THE HEATING OF BUILDINGS

Tuomas Paloposki

Aalto University
Department of Energy Technology
tuomas.paloposki@aalto.fi

## ABSTRACT

The analysis of the performance of heat-storing stoves is discussed. A significant part of the work is the application of methodology and results from the field of fire safety engineering. Some simple models and results obtained with them are presented. Areas where further research is needed are suggested.

*Keywords: Wood burning; heat release rate; heat storage*

## 1 Introduction

### 1.1 Background

In Nordic countries, firewood has traditionally been the energy source for the heating of buildings. Since very early days, various technologies have been developed to improve the comfort and energy efficiency of wood firing. This paper presents a discussion of the design principles of heat-storing stoves; such stoves provide an elegant solution to the problem of matching the heat demand of the building with the heat supply from the burning of firewood. Here we need to match two processes with remarkably different time scales. The heat demand of modern, well-insulated buildings tends to be fairly low and uniform; there are, of course, seasonal and diurnal variations, but it is nevertheless sufficient for the purposes of this paper to consider the heat demand to be roughly constant within a time scale of 24 hours. On the other hand, the burning of firewood is a rapid, intense process, and it is quite possible to organize the firing procedure in such a way that within a few hours a sufficient quantity of heat is released to keep the building warm for one or even several days. It is the task of the heat-storing stove to absorb the heat from the burning of the firewood, to store it temporarily, and to finally release it for heating of the building.

Stoves which are capable of producing maximal thermal comfort with high efficiency and low emissions are needed for environmental reasons. Thus, stove design, fuel preparation and firing practices all need to be studied and improved. The trend towards better thermal insulation in new buildings means that the heat demand of the buildings will generally decrease and overheating may become a problem unless stoves with a sufficiently low thermal output can be developed.

In an earlier paper (Saastamoinen et al. 2005), the thermal behavior of heat-storing stoves was discussed from the point of view of finding analytical solutions for the transient heat conduction equation. The results were presented in the form of infinite series solutions; while this is fully in accordance with the tradition of transient heat conduction studies, such solutions are not always easy to use and it was now felt worthwhile to investigate whether something simpler but still useful could be developed. In another paper (Paloposki et al., in press), the heat release rate from firewood burning inside the stove was determined from experimental data using techniques developed for fire safety studies. Some results and ideas from the earlier work can now be employed in the present study.

## 1.2 Objectives

The objectives of this paper are: (1) to try to develop simple mathematical models for the behavior of heat-storing stoves, and (2) to see if the methodology developed in the field of fire safety engineering can be applied to the analysis of heat-storing stoves.

The focus is mainly on system-level analysis, e.g., in how to design the stove to achieve good energy efficiency and good match between the stove and the building. Emissions of harmful compounds from wood firing and methods of reducing those emissions are a complex problem and are not addressed here.

It must be noted that this paper is not really a report of completed work but more like a description of a research plan. It is anticipated that more results will follow in the future.

# 2 Case description

To make it easier to put things in perspective, a hypothetical case is outlined in this section. The accuracy which is being aimed at is really of the order-of-magnitude type; nevertheless, two or more significant digits are sometimes used to ensure that the results will not be excessively distorted due to round-off errors.

The stove is assumed to have a width of 0.8 m, a depth of 0.5 m and a height of 2 m. The total volume of the stove is therefore 0.8 $m^3$. Assuming that the stove is made of stone material with a density of 2000 $kg/m^3$ and that the “void fraction” of the stove is 0.2, the mass of the stove becomes 1300 kg (the “void fraction” is the fraction of the internal volume occupied by fire chamber, flue gas channels, etc.). The total surface area of the front wall, the two side walls and the top is 4 $m^2$.

The stove specified here is somewhat similar to the stove shown in Figure 1, although the calculations presented here are based on a simplified geometry of a rectangular block with no indentations etc.

Assume that the surface of the stove is at a uniform temperature of 50 °C (this is normally considered to be an appropriate value regarding thermal comfort) and that the heat transfer coefficient between the stove and the room is 10 $W/m^2K$ (this covers both natural convection and radiation). Thus, the heat flux from the stove to the room is approximately 300 $W/m^2$ and the total heat flow is 1.2 kW. During 24 hours, the total amount of energy provided by the stove is roughly 30 kWh.

The first point worth mentioning is that the internal heat transfer processes inside the stove structure must be quite important; otherwise the stove performance cannot be tuned to be acceptable. For the sake of argument, let us assume that the temperature distribution within the stove is totally uniform at any given time but that the temperature of the whole stove first increases during the firing period and then slowly decreases with time (this is the the lumped-capacity assumption). In this case, the temperature of the stove would have to increase fairly rapidly by approximately 90 K during the firing period and then the stove would slowly cool down back to the original value during the following 24 h (in this calculation, it was assumed that the stove material has a specific heat capacity of 900 kJ/kgK). Thus, at the end of the firing period, the temperature of the stove would need to be above 100 °C, but having such a high surface temperature would be both dangerous and inconvenient for the occupants. In addition to that, the heat flow to the room would initially be much higher than what is needed but would then decrease quite rapidly and finally be below what is needed. All of this would be against our objectives. Thus, the heat must initially be stored in the interior structure of the stove and then slowly transferred to the outer surface of the stove in such a way that the surface temperature of the stove remains at a desired level. Consequently, considerable temperature gradients must exist within the stove structure. This issue will be further discussed in Section 5.

**Figure 1. A stove in "Ivars", which was originally a parsonage in the Ostrobothnia region in Finland and is now located in the Seurasaari Open Air Museum in Helsinki. The building was constructed in 1760, but the age of the stove is unknown.**

Assuming that the efficiency of the stove is 75 %, the total chemical energy in the firewood burned in the stove must be 40 kWh. For firewood with a heating value of 4 kWh/kg (14.4 MJ/kg), the quantity of firewood is thus 10 kg. Assuming that the logs are rectangular blocks of wood (10 cm x 10 cm x 30 cm, density 500 kg/m$^3$), the number of logs is 7 and the total surface area of the firewood is 1 m$^2$.

If the burning is assumed to take place within one hour, then the heat release rate needs to be 40 kW. For a firewood configuration described above, the specific heat release rate (heat release rate divided by the surface area of the fuel) should be 40 kW/m$^2$.

## 3 Wood burning analysis in fire safety engineering

Wood is an important building material; considerable effort has therefore been invested in determining the burning rate of wood at different conditions pertaining to, e.g., the burning of floor, wall and ceiling linings. Such studies have typically concentrated on the behavior of a planar surface of wood exposed to thermal radiation from a fire. Quantitative experimental data have been obtained with several different techniques, including the cone calorimeter and the Ohio State University apparatus. The general consensus seems to be that the burning rate of wood is linearly proportional to the incident radiant flux (Drysdale 1998 pp. 188–189). A very rough calculation based on the information presented by Drysdale suggests that a burning rate of approximately 2 mm/min is obtained when the incident radiant flux is 100 kW/m$^2$ (corresponding to black-body radiation at 900 °C). For wood with a density of 500 kg/m$^3$ and a heating value of 14.4 MJ/kg, such a burning rate means that the specific heat release rate from the burning surface exceeds 200 kW/m$^2$. Translating this result into our case study, it would seem that if the combustion temperature is assumed to be approximately 900 °C (which would not seem to be an unrealistic value), the firewood batch would be completely burned within 10 minutes. This result is quite against everyday experience and we need to look at what kind of limiting factors might exist that would slow down the combustion process so that the burning times would become reasonable. This is where the burning of wood cribs needs to be considered.

A wood crib is a pile of wood composed of crosswise layers of wooden sticks with a specified geometry. Wood cribs were originally developed to serve as ignition sources for various fire experiments. Such experiments include both standard testing of the fire performance of building products and the more varied studies which have been carried out with mainly scientific objectives. Photographs of such a crib before and after a fire experiment are shown in Figure 2.

As it has been important to ensure that ignition sources with well-known and repeatable heat release characteristics are available, considerable attention has been paid to the burning of wood cribs. A typical feature of the burning of a wood crib is that a large fraction of the total surface of the wood sticks is facing the interior of the crib and is well shielded from thermal radiation by the other sticks and relatively inaccessible to oxygen due to the narrow flow paths provided by the spacings between the sticks. Thus, depending on the crib geometry, the burning rate of the wood may be much less than that of planar wooden surfaces, as was illustrated by the results of Gross (1962). In those experiments, different types of wood cribs were placed on a balance and burned. The cribs were composed of rectangular sticks with a square cross-section and a length of ten times the thickness. The experiments were coded as X-Y-Z, where X was the thickness of the sticks in cm, Y was the number of sticks in each layer, and Z was the number of layers.

Gross found that the burning rate typically increased in the beginning, remained relatively steady for a while, and finally decreased as the cribs collapsed into a heap of glowing embers. Plots of the maximum heat release rate and the maximum specific heat release rate are shown in Figure 3. It can be seen that the highest values of specific heat release rate were around 100 kW/m$^2$ and thus comparable to the values observed for planar surfaces exposed to thermal radiation. For cribs with high packing density, lower values of specific heat release rate were observed. In particular, the results from the series X-7-10 seem to have been close to what would be desirable in our case.

**Figure 2. A wood crib before a fire experiment (left) and after the fire the experiment (right). The fire was extinguished with water before the crib had been completely consumed. The wood sticks had a cross-section of 40 mm x 40 mm and a length of 305 mm.**

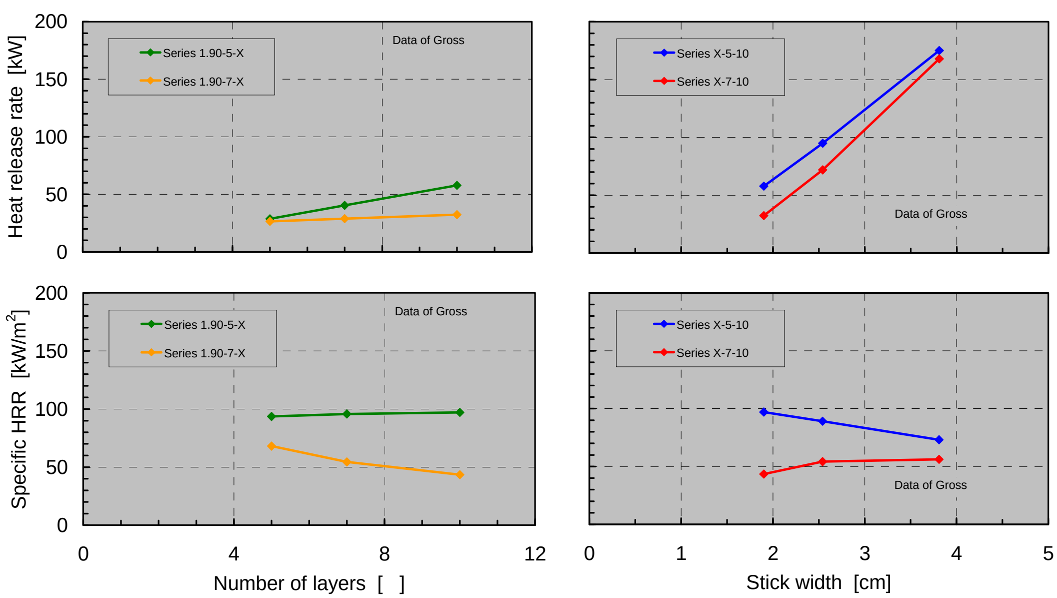


**Figure 3. The maximum values of heat release rate and specific heat release rate in the experiments of Gross (1962). For the loosely packed cribs (series 1.90-5-X and X-5-10), higher values of heat release rate and specific heat release rate are observed than for the densely packed cribs (series 1.90-7-X and X-7-10). The sticks appear to shield each other from thermal radiation and to obstruct the flow of air to the surface of the sticks, thus retarding the combustion. The magnitude of the effect depends on the configuration of the crib, but seems to follow the intuition that the effect should be stronger for densely packed cribs.**

In the X-7-10 configuration, there were 10 layers of sticks on top of each other and the horizontal spacing between the sticks was roughly half of the stick thickness. In addition to the experiments shown in Figure 3, Block actually carried out an additional experiment where the crib geometry was kept similar but the sticks had a thickness of 9.15 cm; the same value for the specific heat release was observed even in that experiment (this result is not included in the figure since it would have required a different scale on the horizontal axis). It is too early, however, to declare the X-7-10 configuration to be optimal for wood firing, but the observation seems to be in agreement with the common wisdom that to achieve clean burning with low emissions, the firewood should not be packed too loosely in the fire chamber (Hyytiäinen 2000 pp. 56–58).

Finally it may be noted that the international standards related to the analysis of load-bearing capability of timber structures during a post-flashover fire (e.g. EN-1995-1-2) use values in the range of 0.5…0.8 mm/min for the burning rate of wood surface. These values are much lower than the 2 mm/min estimated above. Furthermore, using the information presented by Drysdale one can calculate that the corresponding radiant fluxes will be in the range 23…36 kW/m$^2$ which correspond to black-body radiation at 520…620 °C. Such temperatures are quite low considering what should be expected to occur in post-flashover fires; the explanation for such discrepancy is not known.

## 4 Heat release rate modeling

In fire safety studies, the progress of a fire is often divided into three distinct phases. They are:

1. The growth phase. This phase begins at ignition and is associated with a rapidly increasing heat release rate. The growth phase is often also called $t^2$-fire, since a relatively simple way to describe the fire development with time is to assume that the heat release rate is proportional to the square of time from ignition.
2. The fully developed fire phase. The fire has reached a quasi-steady state where some mechanism prevents its further growth. Thus, the heat release rate remains constant. The limiting factor could be e.g., the availability of oxygen.
3. The decay phase. A significant fraction of the fuel has already been burned out and scarcity of fuel starts to limit the heat release rate. Often the decay phase is associated with the collapse of the fuel structure into a heap of glowing embers. The heat release rate is often assumed to be an decaying exponential function of time.

Figure 1 shows results from one stove experiment, in which three batches of firewood were burned in a stove. Details of the experiment and the calculation method are given by Paloposki et al. (in press.). For each batch, we can clearly see the three phases described above (growth, fully developed burning, decay). In this particular experiment, the heat release rate during each of the three fully developed phases seems to have been around 30 kW, which is in fact quite close to what would be needed in the case study presented in this paper.

It remains to be seen, however, whether such analyses can help us in establishing improved practices for fuel preparation and firing patterns.

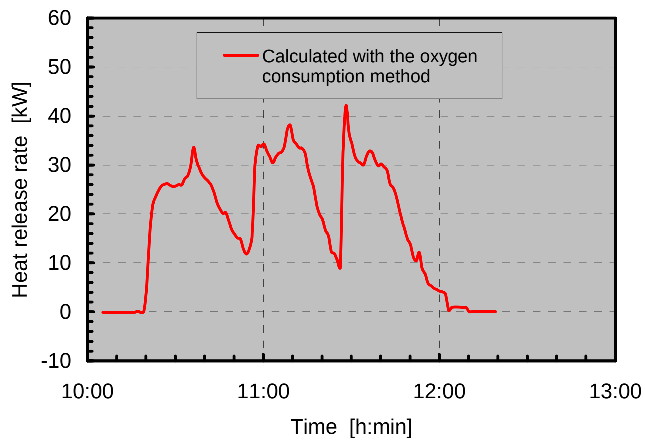


**Figure 4. Heat release rate from burning firewood during a stove experiment. The heat release rate was computed from experimental data by using the oxygen consumption method. Three batches of firewood were burned in this particular experiment, and the combustion behavior of each batch exhibits the three different phases of fire development (growth phase, fully developed phase, decay phase). Details of the experiment and the calculation method are given by Paloposki et al. (in press).**

# 5 Heat transfer within the stove

In this section, the heat transfer within the stove structure is discussed. The situation is depicted in Figure 5. The stove wall is assumed to consist either of a single layer (with a thickness $L$) or of two layers (each with a thickness $L/2$). Heat from the fire is transferred to the left-hand side surface of the stove wall at $x = 0$ and will be conducted through the wall to the right-hand side surface, from where it will be transferred to the room by conduction and radiation.

In the two-layer case, the layers may be separated by thermal insulation material or by an air gap or both. Thermal insulation material has traditionally been employed as an expansion joint which allows for the differential thermal expansion between the inner and outer layers (Hyytiäinen 2000 pp. 72–73, Siikala et al. 2003 p. 72), but it would seem to be advantageous to use the thermal insulation also to achieve desired heat transfer characteristics. The air gap could simply be a concealed cavity, the purpose of which would be to achieve optimal heat transfer characteristics for the wall. The effect of such an air gap within the wall structure was studied by Buchner and Hofbauer (2003). Another explanation for an air gap is related to the use of side channels. Ever since the development work described by Cronstedt (1775), many stoves have been equipped with side channels in which the hot flue gases are directed downwards near the outer walls of the stove before exiting to the chimney. After the firing period has ended, the chimney damper is closed and the flow of flue gas ceases; from this point on, the side channels can be assumed to act as passive gaps within the wall structure.

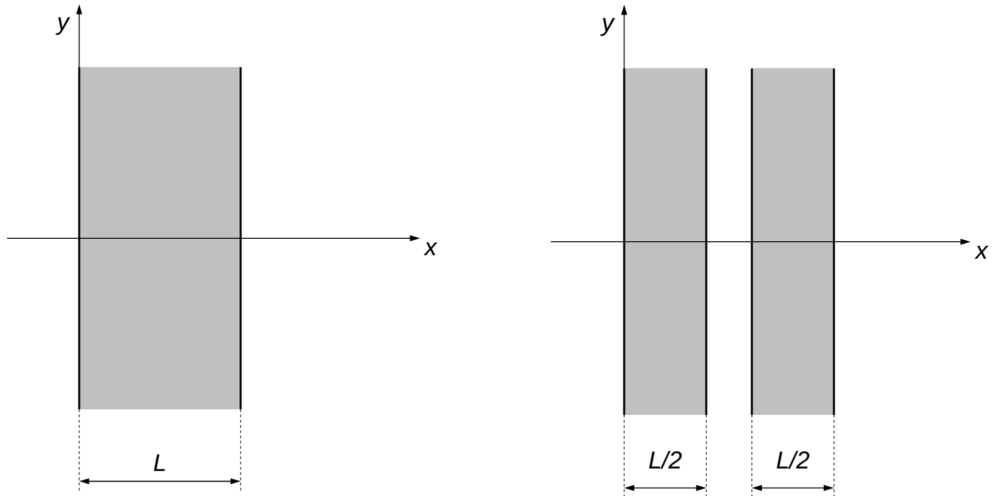


**Figure 5. Two examples of simplified stove wall geometry for heat transfer calculations. Heat from the fire is transferred to the left-hand surface at *x* = 0 and propagates through the wall to the right-hand surface, from where it is transferred to the room by convection and radiation.**

In the case outlined in Section 2, our aim was to achieve a constant heat flux of 300 $W/m^2$ at the right-hand side surface. Let us assume that the stove is fired once each day for a period of one hour. Thus, the heat flux at the left-hand side surface should obey a step function with a constant value of 7.2 $kW/m^2$ for one hour and zero for the following 23 hours. After that, the firing cycle repeats itself.

It should be noted that while a heat flux of 7.2 $kW/m^2$ will satisfy the energy balance, it appears to be quite low when compared with heat fluxes normally expected to occur in combustion equipment (cf. the rough estimates presented in Section 3). One possible explanation is that the one-dimensional geometry considered in this paper might not be realistic enough; often the fire chamber is relatively small when compared with the outer dimensions of the stove, and if one does not want to go dirctly into a full 3-D analysis, then it might be a good idea to set up the equations assuming cylindrical symmetry.

Three different sets of calculations were carried out to get some idea of the heat transfer process. It was assumed that the stove wall consists either of one layer with a thickness of 16 cm or of two layers, each with a thickness of 8 cm. Setting the total thickness of the wall at 16 cm will yield a volume of 0.64 $m^3$ for a wall area of 4 $m^2$ in agreement with the case defined in Section 2. The thermal conductivity of the wall material was assumed to be 1.2 W/(m·K).

The first set were calculated with a computer program which was based on the numerical solution of the one-dimensional heat conduction equation (Program IGN). This program had been developed for the EU-funded research project Fire Star and had originally been intended for analyzing the effect of wildfire on buildings. Program IGN has a second-order discretization in space and a first-order Euler implicit discretization in time and computes the evolution of the temperature profile within an one-layer wall.

The second set were calculated by using a lumped-capacity model for an one-layer wall. The results of such calculations were expected not to be realistic, but it was felt interesting to see how much the results would differ from the results of Program IGN.

The third set were calculated by using a separate lumped-capacity model for each of the two layers in a two-layer wall. The heat transfer coefficient between the layers was assumed to be 15 W/m$^2$K (as a coarse imitation of the heat conduction process within an one-layer wall).

Some results from simple calculations are shown in Figure 6. The non-uniformity of the temperature distribution inside the wall can be clearly seen. However, it is noteworthy that at least for this case, the two-layer model seems to be quite good in predicting the temperature of the outer surface.

In the future, the models should be refined to take into account more complex stove geometries and the temperature dependence of the heat transfer processes occurring inside the stove material and at its surfaces. The use of commercial software for heat transfer modeling will also be considered.

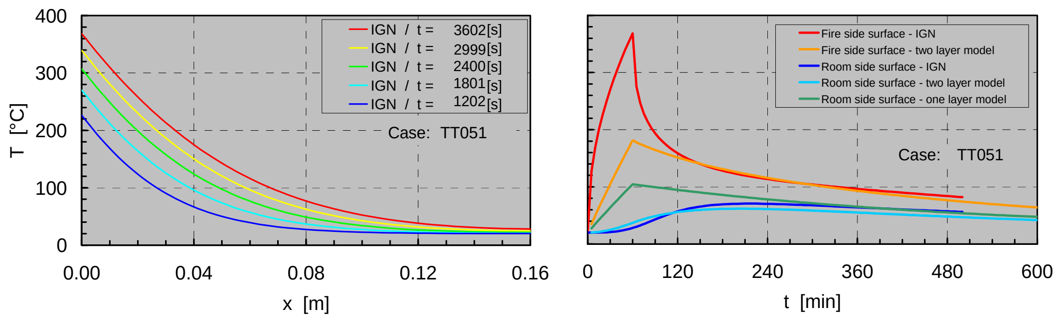


**Figure 6. Results from heat transfer calculations. Left-hand side: evolution of temperature distribution inside an one-layer wall. As the firing period ends after one hour, the temperature distribution is notably non-uniform, indicating that the lumped-capacity model is inappropriate. Right-hand side: evolution of surface temperatures of the wall. For the analysis of heat transfer from the stove to the room, it is important to be able to predict the temperature of the room side surface accurately; at least for this case, surprisingly good results are obtained with the two-layer model where each of the layers is analyzed using the lumped-capacity assumption.**

## 6 Conclusions

Theoretical analyses of the design and operation of heat-storing stoves are needed to satisfy the ever higher requirements on thermal efficiency and comfort. At the same time, the emissions of harmful compounds should be reduced. In this paper, some of the techniques of fire safety engineering were briefly described and their application to the analysis of wood firing in stoves was discussed. While the techniques seem to show some promise, much work still lies ahead of us.

## 7 Acknowledgements

The computer program IGN used in this work was created as part of the EU funded research project Fire Star.

## REFERENCES

Buchner, K: & Hofbauer, H. 2003. Optimisation of ceramic heat storage of stoves. E*nergy and Buildings* **35** pp. 1121–1128. doi:10.1016/j.enbuild.2003.09.010.

Cronstedt, C. J. 1775. *Beskrifning på ny inrätning af kakelugnar til weds besparing*. Sederholm, Stockholm.

Drysdale, D. 1998. *An introduction to fire dynamics, 2nd ed*. John Wiley & Sons, Chichester.

Gross, D. 1962. Experiments on the burning of cross piles of wood. *Journal of Research of the National Bureau of Standards–C. Engineering and Instrumentation.* **66C** pp. 99–105.

EN 1995-1-2:2004 (E). Eurocode 5 – Design of timber structures. Part 1–2: General – Structural fire design. European Committee for Standardisation (CEN), 2004.

Hyytiäinen, H. 2000. *Pientalon tulisijat*. Rakennustieto, Helsinki.

Paloposki, T., Saastamoinen, J., Klobut, K & Tuomaala, P. (in press) Analysis of wood firing in stoves by the oxygen consumption method and the carbon dioxide generation method. *Biomass and Bioenergy*, article in press. doi:10.1016/j.biombioe.2011.12.041.

Saastamoinen, J., Klobut, K, Paloposki, T. & Tuomaala, P. (2005). Simplified dynamic model for heat input and output of heat storing stoves. *Applied Thermal Engineering* **25** pp. 2878–2890. doi:10.1016/j.applthermaleng.2005.02.009.

Siikala, A.-M., Väisänen, P. & Huttunen, R. 2003. *Tiili. Perustietoa arkkitehti-opiskelijalle*. Helsinki University of Technology, Department of Architecture, Espoo. Available online: http://arkkitehtuuri.tkk.fi/oppituolit/ro/julkaisut/tiili.pdf