CLIMA 2000, Brussels 1997

Topic 5: Energy and environment

Heating systems and their influence on the energy demand of buildings

Michael Bauer, University of Stuttgart, Lehrstuhl für Heiz- und Raumlufttechnik

Abstract

For new design approaches the engineers of HVAC systems need tools for estimating energy requirements of different heating systems in advance. The heat losses of buildings can be classified into three fields. These are at first the losses through transmission and ventilation. Further on there are the losses which occur during heat generation (e.g. boiler heat losses). The third field contains the losses occurring at the heat distribution (e.g. pipe heat losses). The results presented in this paper will show that the ability of a heating system to follow the needed heating load in rooms have great influence on the energy demand.

This paper describes the results of various HVAC simulations. It shows the range of energy saving potentials for different heating systems. The paper also gives answers on how generalizations can be made and how the calculation of the energy saving potential can be performed without simulation. Further on functions and parameters are explained which help to calculate the actual heating energy demand. These functions and parameters are based on the ideal energy demand of a building. They consider the behaviour of the real heating system as well.

1. Introduction

Reducing energy consumption is one of the most important global goals now and in future. The major share of energy consumption is caused by heating and cooling buildings in order to provide comfortable and clean living and working conditions. New energy saving acts are often dealing with better thermal insulation of buildings. As a consequence of this the boundary conditions are changing for HVAC hardware and software as well as for the design procedures.

The design of energy efficient heating systems needs to consider the possible utilization of available energy saving potentials in buildings. Energy saving potentials can always be found in places where energy or heat losses occur. The heat losses in buildings can be classified into three fields. These are at first the losses through transmission and ventilation. Further on there are the losses which occur during heat generation (e.g. boiler heat losses). The third field contains the losses occurring at the heat distribution (e.g. pipe heat losses). Nowadays the utilization of energy saving potentials is only done by optimization of these fields individually. Integrated system concepts are hardly carried out. The proposal will show that today with the prevailing boundary conditions the mentioned classification is not enough to classify energy efficient heating systems. Therefore the thermal behaviour of buildings and different heating systems is calculated by using dynamic simulation programs /1/ and validated simulation models of heating components /2/. The results show that the ability of the heating system to follow the needed heating load in rooms also has great influence on the energy demand.

2. Energy Expenditure is determined by the benefits delivery

2.1 Objectives

In the last few years the heat losses in all three mentioned fields, building, heat generation and heat distribution, were specified clearly. This has led /3,4/ to national and European energy saving acts in order to improve thermal insulation of buildings. Also the pipes of heating systems are better insulated nowadays compared to former times. In the same way the boiler constructions were improved so that the heat generation has become more efficient today. Also the performance of the boilers has been improved by using suitable controlling systems which make it possible that the efficiency in partial load operation is almost equal than in full load operation. Nowadays the heat losses at the heat distribution and at the heat generation are less than ten percent. Further optimization in these individual sections will only be possible in a magnitude of 1 – 3 percent points.

In the field of building physics energy saving acts which require raised thermal insulation for buildings come into effect. Because of this the energy demand of new buildings has been lowered to approximately 80 kWh/m^2a. With this positive development the passive solar energy in buildings has become more important. However the use of passive solar energy use does not depend on the building itself but on the ability of the heating system to react to changing heating loads. I.e. passive solar energy gains can only be utilized for heating purposes if the heating system is able to follow fast changes of the heating load in the room. This is for example the case if intense solar radiation occurs. Otherwise more energy than required is provided to the room. Therefore the ability of heating systems to use solar and internal loads has to be evaluated in addition to the heat losses by transmission, ventilation, heat distribution and heat generation.

2.2 The methodology to visiualize the benefits delivery

Heating systems are evaluated by comparing benefit and expenditure as it is done in other technical systems. The benefit or the task of a heating system is to maintain comfortable thermal conditions in the rooms for the occupants. The requirements of the occupants to their thermal environment are independent from the heating system. Mostly they specify their demands with nominal temperatures for the room air and for the inside surface temperatures of the walls. This temperatures depend on activity and clothing. A further task of a heating system is to warm up the outside air flow, which is necessary because of hygienic and building physical reasons to room air temperature. The delivery of the benefit by the heating system is called by Ast /5/ “benefits delivery”. The planning tasks for good benefits delivery consist of suitable selection, dimensioning and arrangement of the room heating systems /6,7/.

It is possible to determine the heat load which must be provided to a room in order to supply exactly the existing demand – the heating load. The time dependent integral over the heating loads – the ideal minimal energy demand $Q_{0,N}$ – is an energetic figure of comparison for subsequent processes which satisfy the demands (benefit delivery, heat distribution, heat generation). Figure 1 shows the way of the demand development in a building. Starting from the building itself, its planned usage and the climatic influences it is going over benefits delivery and heat distribution to the heat generation system. Since each of these subsections – benefit delivery, distribution and generation – cannot be implemented in an ideal way, an additional energy demand is caused. If this additional energy demand is brought into relation with the ideal minimized energy demand $Q_{0,N}$, which is typical for a building and its use, an expenditure value e_i can be defined. This expenditure value will be used as an energetic evaluation figure for the individual subsections. Therefore the ideal minimal energy demand $Q_{0,N}$ multiplied with the expenditure value e_i of the individual subsections gives the yearly energy demand which is needed by the heat generation system.

According to these considerations the energy demand of heated buildings depends on the building physics, on the orientation of the building, on the climatic conditions but mainly on the use and the benefits delivery system. In the last years, the thermal insulation of buildings could be improved by energy saving acts. Therefore the value of the nominal heat load in relation to the room area was lowered to 30 – 40W/m^2. Because of this lower heat load the influences of the benefits delivery system – and depending on that the influence of user behaviour – have a greater impact on the energy demand. Despite of this the most energy saving acts are still restricted to the terms of the thermal behaviour of buildings. The effectiveness of heating systems is not considered. The energy demand of heated buildings decreased from about 250 kWh/m^{2}a to approximately 80 kWh/m^{2}a for new buildings within the last 10 years as shown in figure 2. On the other hand the internal gains like gains through persons and gains by computers and lighting accessories remained unchanged, if they were not even equal or growing. Also the solar heat gains grew because of larger window constructions in rooms oriented to the south. As a consequence of this the share of internal and external heat gains on the whole yearly energy demand is increasing.

As shown in figure 3 nowadays the share of the solar and internal heat gains on the energy demand in residential buildings is about 30%. With future energy saving acts this value will increase to approximately 40% until the year 2000. In office buildings with significantly higher internal heat gains this share is already between 40 and 80%.

Because of the relative rise of internal and external heat gains heat loads take effect faster and stronger than previously. With these boundary conditions heating systems can only work energy efficient if they are able to use internal and external heat gains for heating purposes. If the heating system cannot follow varying heating load profiles, the room will be warmed up to much by the heating system. This will lead to an inevitable increase of the energy demand. Thus the aim for energy efficient designed heating systems must be the ability to deliver the heat within a given time and exactly at the location where it is needed. Rietschel /8/ has already referred about this context and concluded in 1902: "*The perfect heating system would be that one, which would be able to deliver in every place of a heat loss a heat substitute of the exactly the same amount.*"

2.3 Influence of the benefits delivery on the energy demand

With simulation programs /1,2/ the influence of the benefits delivery on the energy demand can be determined. Therefore an example room has to be defined. The example room is displayed in figure 4. It has an floor area of 5 m x 5m and a height of 3 m. The thermal insulation of the building meets the standards of the German energy saving act of 1995. The room has a nominal heating load of *900 W*. There is one external wall which is oriented to the south. Therein a window with a k-Value $k_f = 1{,}5\ W/m^2K$ is integrated. The climate boundary conditions for the simulations are given by the test reference year /9/. The room is used as an office room with an internal load of *600 W* from 7:00 a.m. to 5:00 p.m..

To show the difference between the energy delivery of a real heating system and the actual heating demand of the example room first a cold winter day with no solar gains is considered. So, for this first example consideration the outside temperature is assumed to be constant at $'_{AU} = -12°C$.

Figure 5 shows the profile of the required heating load depending on the time. With the occurrence of internal heat gains at 7.00 a.m. the heating load is reduced by the amount of the heat gains. In this case the internal heat gains are utilized for heating purposes. A real heating system (e.g. a traditional radiator heating system controlled with thermostatic valves designed with a water inlet temperature of $'_v = 90°C$ and a difference between water inlet and outlet temperature of σ = 20 K) is not able to follow the required heating load profile. Figure 5 indeed shows only an insignificant reaction of thermostatic valve and the water mass flow. Therefore much more energy than needed is provided to the room. Because of that the room temperature increases by 1 – 2 K. A temperature rise of this magnitude is usually not noticed by the user. However the additional energy demand is considerable. The shaded part of the diagram shows the additional needed energy demand compared to the actual required heating load. In this example the expenditure value e_1 is about 1,1 – 1,15. Usually the outside temperatures are higher than *-12°C* and the sun is shining as well. So the unneeded additional energy demand will be even more which can be seen for an other example in figure 6. During days with higher outside temperatures and with solar heat gains the discrepancy between required heating energy demand and the heating energy demand which is delivered by a real heating system becomes even more evident. Similar big differences between required energy demand and real delivered energy demand are caused by operation strategies which include night set back or morning warmup after a night set back, if they are used without any interaction with the room. Therefore a night set back controlled by a parallel set point translation of the water inlet temperature during night times, is only leading to an opening of the thermostatic valve in the room, i.e. the thermostatic valve is reacting to the decreasing room temperature. This means the energy saving strategy does not working. Therefore it is not possible to confirm energy savings which are computed theoretically for a night back in practice.

With a variety of different simulations the thermal behaviour of heating systems and the difference between the actual required energy demand and the delivered energy demand can be calculated. With the results of the simulations the expenditure values, which are characteristic for a heating system, can be defined. The results show, that the dependency of the expenditure value e_1 on occurring internal and external heat gains as well as on the heat load (heating operation strategies) can be described with the relative heating load β_Q /10/. The relative heating load is defined as the quotient between the actual heating load and the nominal heating load. With increasing internal and external heat gains the actual heating load at a time is getting lower and the relative heating load varies much more within a given time. In an annual consideration this influence can be described by the annual mean of the relative heating load:

$$\beta_Q = \frac{\frac{1}{t_{Jahr}} \int \dot{Q} dt}{\dot{Q}_N} = \frac{Q_{0,N}}{t_{Year} \dot{Q}_N}$$

Figure 7 shows the principal correlation between the expentidure value e_1 of the benefits delivery and the relative heating load. The lower curve in figure 7 represents a fast, PID controlled heating system. The upper one shows a standard heating system equipped with a thermostatic valve. Depending on the thermal insulation standard and the utilization of the building the expentidure value will be between 1,05 and 3,0. This means the larger the load variations during heating are, the larger is the difference between the delivered energy demand of the real heating system and the actual required demand. In extreme situations these deviations are that high that up to three times as much energy is provided to the room than it is required. In comparison to this the expentidure value of 1,01 to 1,04 for heating distribution and 1,05 to 1,1 for heating generation are clearly smaller.

The transfer behaviour of the heating controller has the greatest influence on benefits delivery. Therefore thermostatic valves with proportional behavior work not as good as continuous or uncontinuous PID controller. The ability to follow the required profile differs significantly for these controllers.

The second influencing factor is the type of the heating system. Here it is important whether the heating system is able to deliver exactly the amount of heat which is required at a given time and at a given location. Fast reacting heating systems with a lot of possibilities for application have to be evaluated better than slow reacting, heavy heating systems which cannot balance comfort deficits within a given time and a given location. Bach /11/ describes this dependence with the time constant T_{HK} of the room heating system

$$T_{HK} = \frac{C_{HK}}{(kA)_n}$$

In equation (2) C_{HK} is the entire heat capacity of the heating system of the room. $(kA)_n$ is the so

$$(kA)_n = \frac{\dot{Q}_n}{\Delta \vartheta_n}$$

called capacity of the heating system under nominal conditions. It is defined as
Thus the ability of the heating system to react fast its mass and water contents has to be small and its nominal heat emission has to be as high as possible. The time constant is a significant number for the qualities of a heating system. It is not related to the design of the heating system like for example the choice of the inlet and outlet water temperature. This is given by a second evaluation figure - the transfer coefficient K_Q. The following formula can be derived for K_Q

$$K_Q = \frac{\dot{Q} - \dot{Q}_0}{\dot{Q}_0} = 1 - \left(\frac{1}{\Phi_0} - 1\right) \ln \frac{1}{1 - \Phi_0}$$

At this Q_0 is the heat emission in the initial situation. Q is the resulting heat emission after an

$$\Phi_0 = \frac{\sigma_0}{\Delta \vartheta_{V,0}}$$

abrupt change finally. Φ_0 is the effectiveness of the radiator at the starting point
σ_0 is the temperature difference between water inlet and outlet temperature in this connection. $\Delta'_{V,0}$ is defined as the temperature difference between water inlet temperature and room air temperature. The equation for the transmission coefficient is identically to the derivation of the

characteristic equation of the heating system, which is identical the gradient profile of the heat emission over the mass flow. Figure 8 shows this correlation. The curvature of the characteristic curve of the heat emission is decreasing with an increasing effectiveness Φ_0. This means the transfer behaviour is becoming less dependent on the operating point with increasing effectiveness.

The steady and dynamic behavior of a heating system can only be evaluated in connection with the corresponding control system. Real automatic controllers react more or less imperfectly to the operating-point-dependent transfer behaviour. Thus large transfer coefficients and therewith great effectiveness should be aspired in regard to the control characteristic. This means that low water inlet temperatures and large temperature differences between inlet and outlet temperatures

$$\frac{(kA)_n}{\dot{m}_0 \ c_W} = \ln \frac{1}{1 - \Phi_0}$$

are needed! For the effectiveness a further informative correlation can be given
According to this the room heating system has to be designed for a capacity (high nominal heat emission) which is as high as possible and a water mass flow rate which is as small as possible.

In figure 9 the influence of the design inlet and outlet temperatures of the water is shown for the example of a radiator heating system with a thermostatic valve. For a design inlet temperature of 90°C and an outlet temperature of 70°C a expenditure value of 1,2 to 1,25 can be obtained. For lower design water inlet temperatures (e.g. 50°C) and water outlet temperatures (e.g. 30°C) the expenditure value can be lowered to approx. 1,1. This would mean that only by lowering the design temperatures an energy saving potential of about 10 to 15% is given.

In figure 10 the influences of heating systems and controllers on the expenditure value e_1 are represented. There are no influences due to the design temperatures of the heating system if an ideal PID controller is used. Only the time constant of the heating system is determining here. Therefore heating systems with small time constants, i.e. with small mass and small water contents, are to be evaluated better than heavy heating systems with large water contents.

3. Conclusion

In very good insulated buildings the energy demand for heating mainly depends on the benefits delivery system in the rooms. The better thermal insulation is leading on one hand to an increased energy demand. On the other hand the share of internal and external gains is decreasing. Thus their influence on the thermal behavior of the building and depending on that the influence on the benefits delivery of the heating system is decreasing as well. Therefore heating system can only work efficiently if they are able to use internal and external heat gains for heating purposes. It is shown, that in this aspect standard heating systems often deliver 40 – 50 % more energy than required to the room. With the presented results it is possible to estimate how effective heating systems will deliver the required energy demand to the room. This gives the possibility to design energy efficient heating systems, which are able to deliver the benefit, e.g. heat demand, exactly as temporally and locally required.

This concept will be brought into the VDI-Guideline 2067 for the calculation of the energy demand and the economic efficiency of building installations /12/. The guideline will no longer be based on measured energy consumption. The idea of the new concept is, that the energy demand will be divided into the following parts:

- energy demand depending on the building physics and the utilization of the building
- energy demand depending on the ability of the HVAC system to deliver heating cooling and fresh air as required
- energy requirement depending on the way of energy distribution
- energy requirement depending on the way of energy generation

The work has been started in 1995. It is expected that the main parts of the new guideline will be published in the end of 1997.

4. References

/1/ TRNSYS: A Transient System Simulation Program. Solar Energy Laboratory, University of Wisconsin, Madison, USA 1994.

/2/ Lebrun, J.: IEA-ANNEX 17: Building Energy Management Systems, Evaluation and Emulation Techniques, Synthesis Report. University Liege, March 1993.

/3/Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden, Wärmeschutzverordnung – WSVO), 01.Januar 1995

/4/ Verordnung über energiesparende Anfordnungen an heizungstechnische Anlagen und Brauchwasseranlagen (Heizanlagen-Verordnung-HeizAnlV), 01.Juni 1994.

/5/ Ast, H.: Energetische Beurteilung von Warmwasserheizanlagen durch rechnerische Betriebssimulation. Universität Stuttgart, Dissertation 1989.

/6/ Bach H.; Bauer M.: Heizflächen richtig auslegen. SBZ 10/1995

/7/ Bach, H; Bauer, M.; Reichert, E.: Heizkörper – eine architektonische Aufgabe. Deutsches Architektenblatt DAB 10/1996.

/8/ TRY: Testreferenzjahre - Meteorologische Grundlagen für technische Simulation von Heiz- und Raumlufttechnische Anlagen. BINE Informationsdienst, Fachinformationszentrum Karlsruhe, Oktober 1991.

/9/ Rietschel, H.: Leitfaden zum Berechnen und Entwerfen von Lüftungs- und Heizungs-Anlagen,Verlag von Julius Springer, Berlin 1902.

/10/ Bauer M.: Energiegerechte Planung von Heizanlagen. Vortrag XXIV Internationalen TGA-Kongress, Hannover 1996.

/11/ Bach H.: Die Nutzenübergabe bestimmt den Aufwand – ein neuer Denkansatz in der Heiztechnik. Vortrag XXIV Internationalen TGA-Kongress, Hannover 1996.

/12/ Bach, H; Bauer, M.; Diehl, J.: Anmerkungen zur künftigen VDI 2067 – Wirtschaftlichkeit von gebäudetechnischen Anlagen. Bundesbaublatt BBauBl, März 1995.

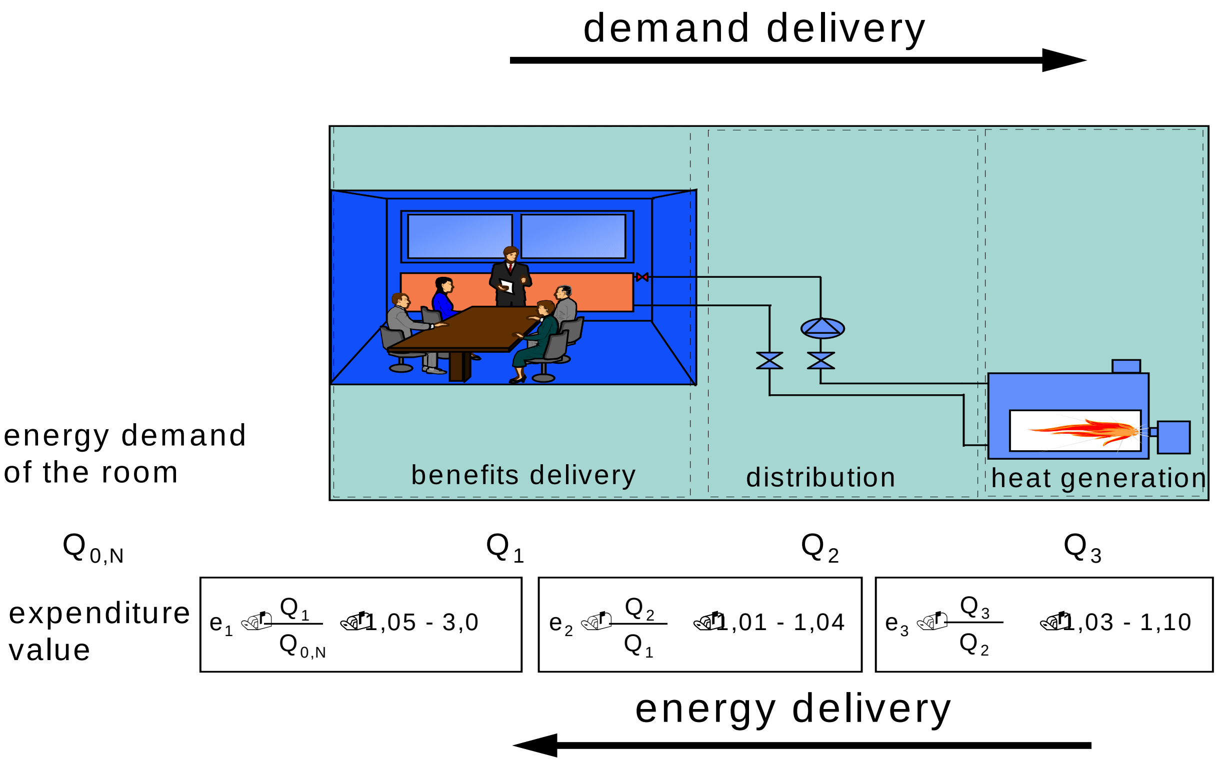

Figure 1: Demand and energy delivery

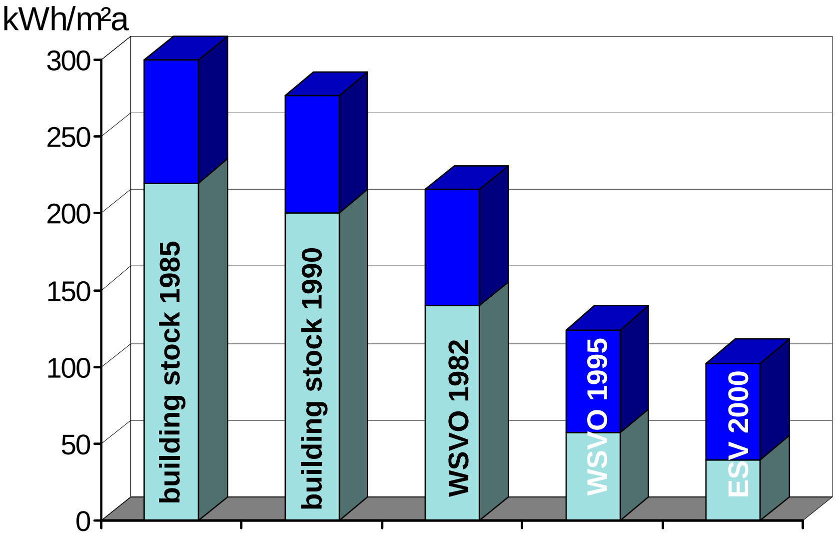

Figure 2: Energy demand of buildings

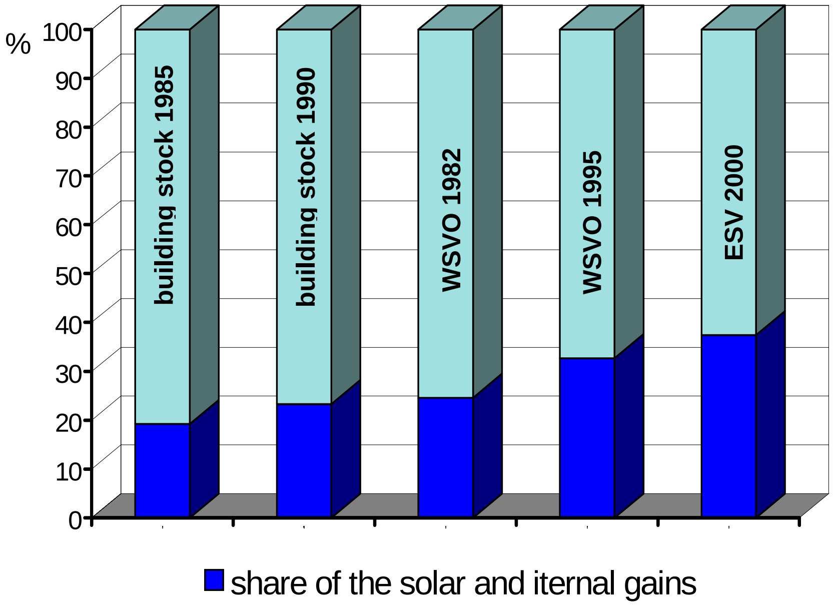

Figure 3: Share of the solar and iternal heat gains on the energy demand

nominal heating load 900 W
occupancy from 7-17 o'clock with
600 W iternal gains

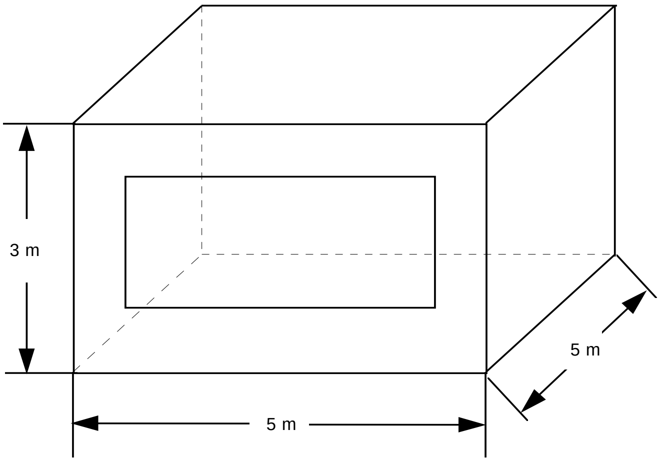

Figure 4: Room, orientation south

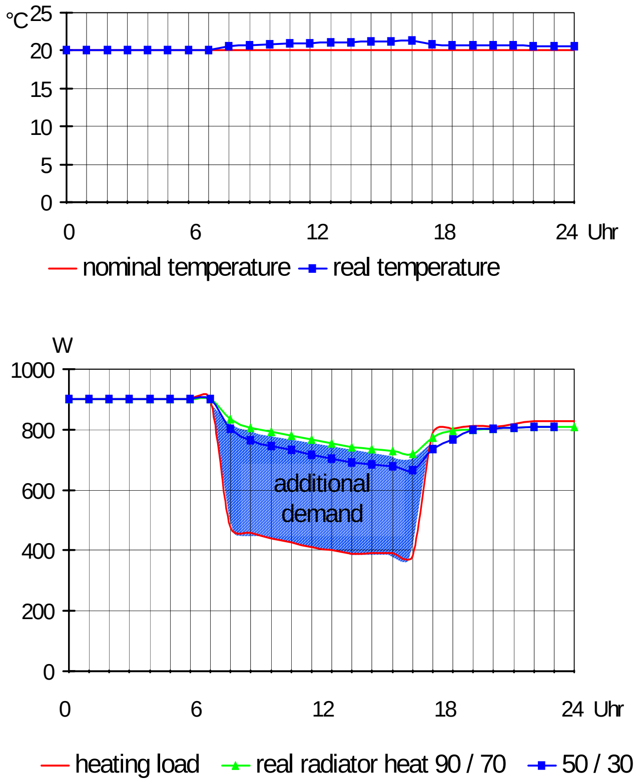

Figure 5: Room temperature and heat load

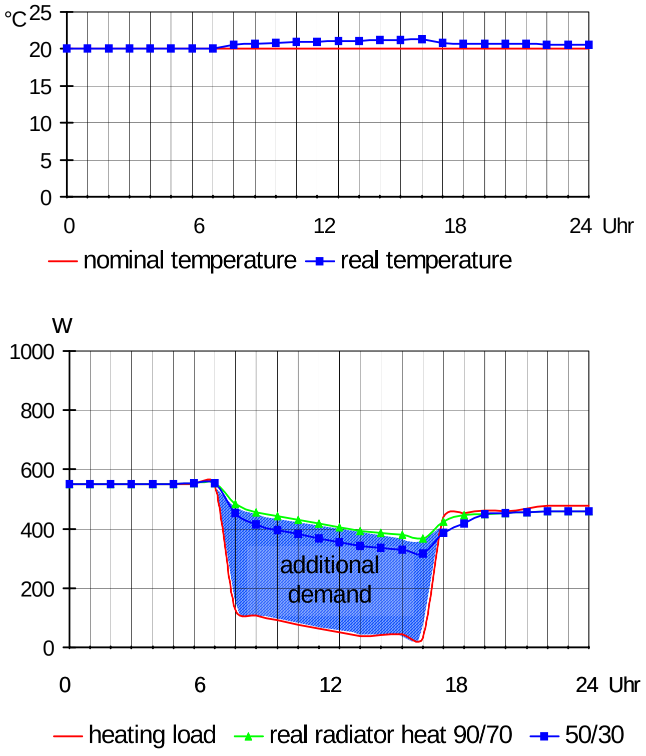

Figure 6: Room temperature and heat load

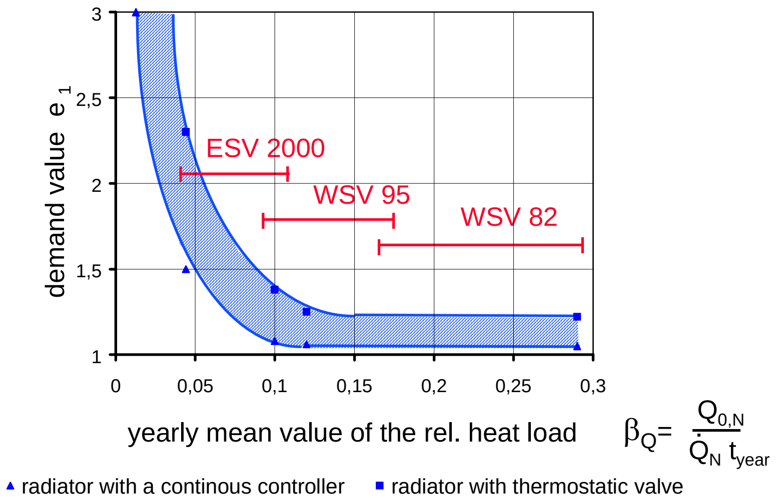

Figure 7: Expenditure value / rel. heat load

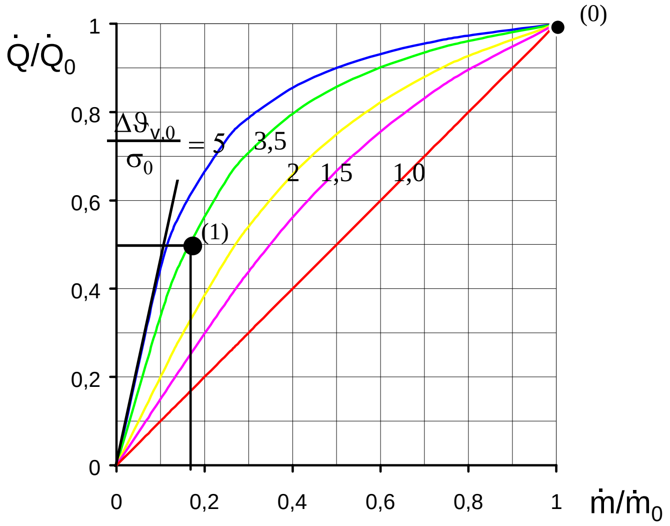

Figure 8: Heat emission / water mass flow

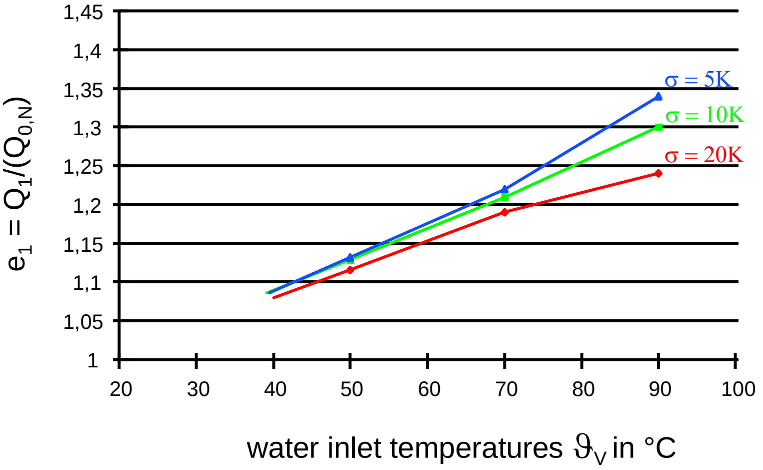

Figure 9: Expenditure value by different design water inlet temperatures

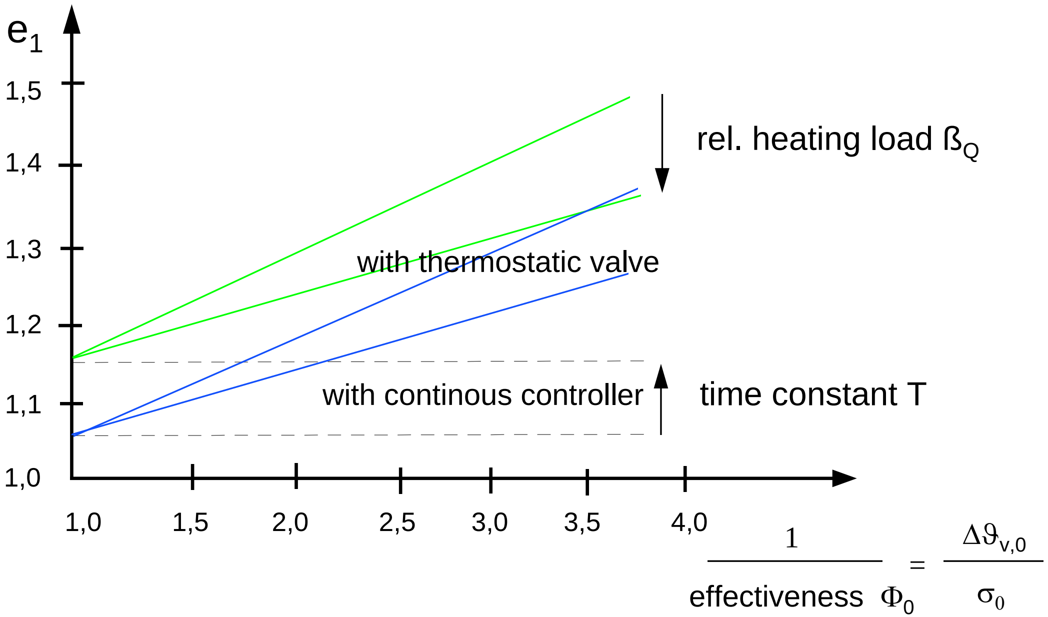

Figure 10: Expenditure value of benefits delivery