System Simulation Report

System: PCM storage to reduce cycling rates for boilers

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PCM storage to reduce cycling rates for boilers

by

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A technical report of Subtask C

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1 Introduction

At the Institute of Thermal Engineering, Graz University of Technology, the possibility to reduce the start-stop cycles of boilers by coupling the boiler with a storage tank was investigated within a national project (Heinz et al. 2006). A more detailed description of this work, including an analysis of the annual emissions caused by the start-stop operation can be found in (Heinz, 2007).

In single family houses boilers are the main source of energy used for the purpose of space heating and for the preparation of domestic hot water (DHW) in Austria. The power, that a boiler has to supply, varies with the current heat demand of the heating system. Nowadays most of the commercially available boilers can modulate their power between their nominal load and a minimum continuous load, which is typically 30-50 % of the nominal load. If there is a heat demand, that is lower than this minimum continuous load, the boiler will be operating in the so-called start-stop or cycling operation. In this mode the burner is switched on and off in order to achieve an average load that is smaller than the minimum continuous load.

The dimensioning of boilers is done according to the heating load of a building at the design ambient temperature, which occurs only for some days or even hours of the year. Additionally the nominal load of the boiler is often chosen too high for “safety” reasons, or there is no boiler available with a suitable nominal load. This especially applies to single family low energy buildings, as the smallest boilers available on the Austrian market have a nominal power of 10 kW, whereas the heating load of such buildings is typically much lower. In these cases the heat demand is lower than the minimum continuous load of the boiler most of the time and the boiler is operating in start-stop operation for a great part of the year.

The start-stop operation can cause significant emission peaks of CO, HC, NO_x and particles in every start- and stop-phase. Figure 1.1 shows a typical evolution of the CO and HC emissions of a boiler during a start-stop cycle (qualitative).

The emissions of the start-stop operation can cause a significant increase of the total annual emissions of a boiler compared to the emissions of the continuous operation. According to measurements carried out within a national research project (Heinz et al., 2006) the amount of additional emissions due to the start-stop operation is supposed to be directly dependent on the number of start-stop cycles. A possibility to reduce the number of cycles is to couple the boiler with a storage tank. This tank should have a small volume and therefore a small space requirement in order to increase the acceptance of the user. PCMs offer the possibility to decrease the tank volume in comparison to water tanks with the same storage capacity.

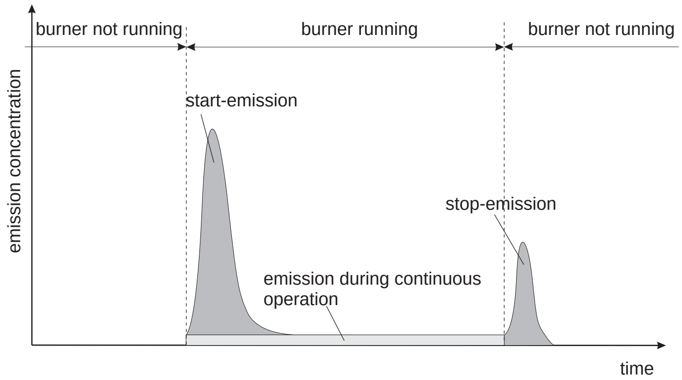


Figure 1.1: Typical evolution of the emissions of a boiler during a start-stop cycle (qualitative)

In order to enable an evaluation of different systems concerning the additional emissions of boilers due to start-stop operation, the knowledge of the number of start-stop cycles that occur per year is necessary. The operation of boilers and especially the frequency of start-stop cycles is influenced by many parameters. The operation is not only affected by the characteristics of the boiler itself and its control, but also by the attached heating system and its interaction with the building. In order to be able to consider all these parameters, the whole system consisting of the boiler, the heating system and the building is integrated into a transient simulation in the simulation environment TRNSYS 16 (2005). Different possibilities of the hydraulic integration of the boiler are investigated, with a focus on the comparison between systems with and without storage tank. The emphasis of the system simulations is on the performance of the system and on the effects of the storage on the whole system rather than on the performance of the storage itself.

2 Basic conditions for the simulations

Each simulation study is based on certain conditions and assumptions that have to be defined preliminarily. In this work reference systems have been defined, which shall be shortly described in this chapter. A more detailed description can be found in (Heinz, 2007). In order to analyse the influence of different parameters on the results, a parameter study was performed, using values different from those used in the reference systems.

2.1 Building

During the start-stop operation of the boiler the transient behaviour of the system can be subject to very fast changes, especially if the boiler has a small thermal capacitance. In this case it is necessary to use quite small simulation time steps of only a few seconds in order to achieve realistic results. On the other hand the detailed thermal simulation of buildings is typically done with simulation time steps of 30 to 60 minutes, as the dynamics of the system are much lower. Because of the high requirements for the size of the time step no detailed building simulation is performed in this work, as this would cause very long simulation times. Instead a simplified building model is used (Thornton, 2004). This component takes thermal loads (like the transmission losses and ventilation losses of the building, heat input from the heating system etc.) and converts them to temperatures by imposing the loads on a simple building model. The user provides the loads as well as an estimate of the thermal capacitance of the building. This approach allows the consideration of the thermal interaction between the building and the heating system without a detailed simulation of the building.

Table 2.1 shows the properties of the used reference building. The thermal capacitance of the building was chosen as a "medium heavy" construction according to ÖNORM EN 15203 (2006) and OIB Leitfaden (2006).

Table 2.1: Properties of the used reference building

useful floor area [m²]		150
space heating demand [kWh/m².a]		75
heat load (transmission + ventilation)* [kW]		6.32
thermal mass [kJ/K]		43000
window area [m²] / window area ratio [%]	south	12 / 24
	east	4 / 9.9
	west	4 / 9.9
	north	3 / 6

* at the design ambient temperature

In the following a description of the thermal loads, which are imposed on the building, is given. The evolution of the loads with time was partially (solar gains, internal gains, [redacted] of a detailed building simulation and saved into a [redacted] mposed on the simplified building model in the simulations of the start-stop behaviour of boilers. Figure 2.1 shows the evolution of the [redacted] er the year. The energy balance of the building [redacted] .2.

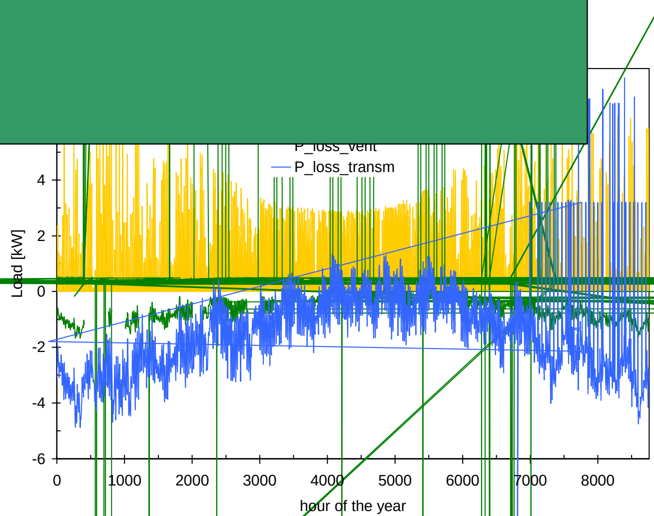


Figure 2.1: Solar gains $P_{gain,sol}$, internal gains $P_{gain,int}$, ventilation losses $P_{loss,vent}$, and transmission losses $P_{loss,transm}$ in the course of the year

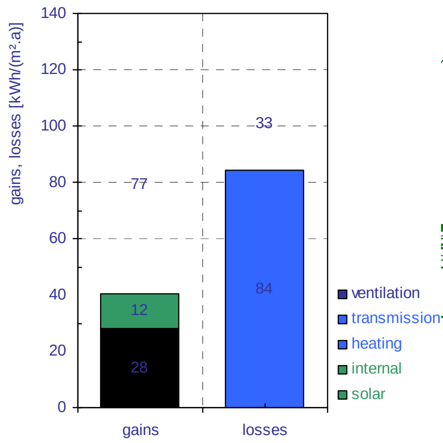


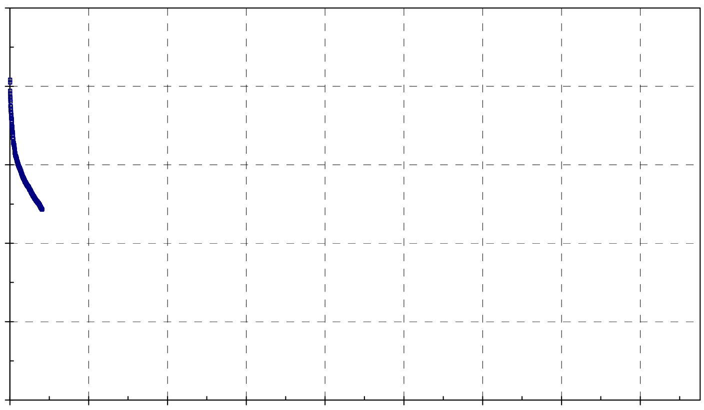
Figure 2.2: Energy balance of the building over the heating season

The heating energy demand of the reference building in an average climate of Graz is approximately 77 kWh/(m².a). This is a bit lower than the minimum requirement for newly built residential buildings according to OIB Richtlinie 6 (2006) (78 kWh/(m².a)). In the parameter study (see chapter 3.1.1) buildings with different heating energy demands are considered in order to evaluate the influence on the resulting number of start-stop cycles.

Resulting annual duration curve of the heat load

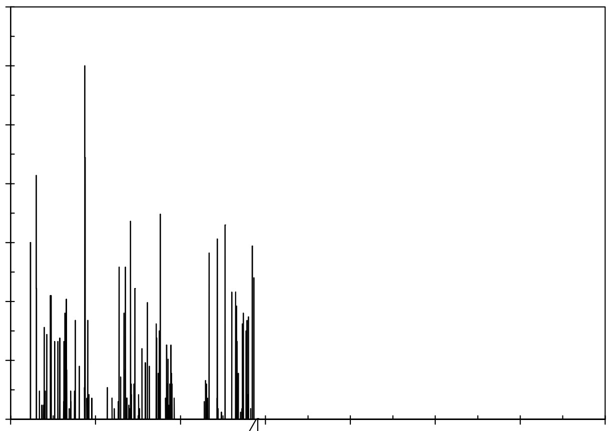
The heat load that is needed to keep the building at a certain room temperature is a result of the sum of all loads that are imposed onto the building and their interaction with the thermal capacitance of the building, which causes a dampening and a time shift of this heat load. Basically the heat load is dependent on the ambient temperature and therefore on time.

If the heat load is plotted as a function of the duration of the exceedance of the respective values per year, the result is a so-called annual duration curve. In the heating system used in the simulations a radiator is used to keep the building at a constant room temperature of about 20°C. Thus the power released by the radiator is a measure for the effective heat load of the building at the respective time. By using the simulated average powers of the radiator in every hour of the year, the annual duration curve of the heat load shown in Figure 2.3 was generated. The integral of the duration curve over the year is the annual space heating demand of the building (approximately 11250 kWh/a).



in which a DHW flow rate is assigned to each time step (step size one minute) of the simulated year.

A DHW demand of 200 l/d (4 persons with 50 l/(d.person)) with a DHW temperature of 45°C is used in the simulations. As an example Figure 2.4 shows the DHW demand for one week of the generated DHW profile.



The hysteresis for switching off the burner is the temperature difference, by which the set temperature T_{set} of the boiler is allowed to be exceeded. The burner is switched off, if the boiler temperature reaches $T_{set} + \Delta T_{hyst}$.

The minimum stop time prevents the burner to re-start too fast after it has switched off. This measure is used to reduce the number of start-stop cycles of boilers with a very low water content.

In the simulations it was tried to consider the parameters shown above in a realistic way by choosing a suitable boiler model. After an investigation of the functionality of different models available for TRNSYS, Type 869 (Haller, 2006) - developed at SPF Rapperswil in Switzerland - was chosen. This model fulfils all basic requirements such as the possibility of simulating start-stop operation, the consideration of the thermal capacitance of the boiler and the possibility of simulating different types of boilers and different fuel types.

Table 2.2 shows the main properties of the two boilers used in the simulations. Most of the data is chosen according to the two boilers that were investigated in a national project (Heinz et al., 2006). In the simulations both boilers are supposed to be able to continuously modulate their heating power between the nominal and the smallest continuous load. In the parameter study the effects of different water contents and minimum stop times are investigated.

Table 2.2: Properties of the simulated boilers in the reference system

		gas boiler	**pellet boiler**
nominal load	[kW]	12	12
smallest continuous load	[kW]	4	4
heated water content*	[l]	7	70
internal thermal mass*	[kJ/K]	6	55
condensing	[-]	yes	no
heat loss rate to environment	[W/K]	7	7
ΔT_{hyst}	[K]	5	5
min. stop time	[min]	5	5

* the sum of the heated water content and the internal thermal mass is the thermal capacitance of the boiler

2.3 Hydraulics and heating system

The frequency of start-stop cycles is not only influenced by the boiler and its control but also by the connected heating system and its interaction with the building. Different possibilities of the hydraulic integration of the boiler into the heating system are considered.

2.3.1 Basic Parameters

Space heating system

In the simulations radiators with a design flow/return temperature of 50/30°C are used as the space heating system. The flow temperature is adapted to the ambient temperature according to a heating curve with a radiator exponent of 1.3 (see Figure 2.5). At an ambient temperature of above 15°C the heat supply is stopped. The thermal capacitance of the radiators is chosen according to (Recknagel et al., 1997) with 350 kJ/K, which corresponds to a water content of about 83 litres.

The design flow rate through the heating system is 500 kg/h. The radiators are equipped with thermostatic valves that control the mass flow through the radiator depending on the current room temperature.

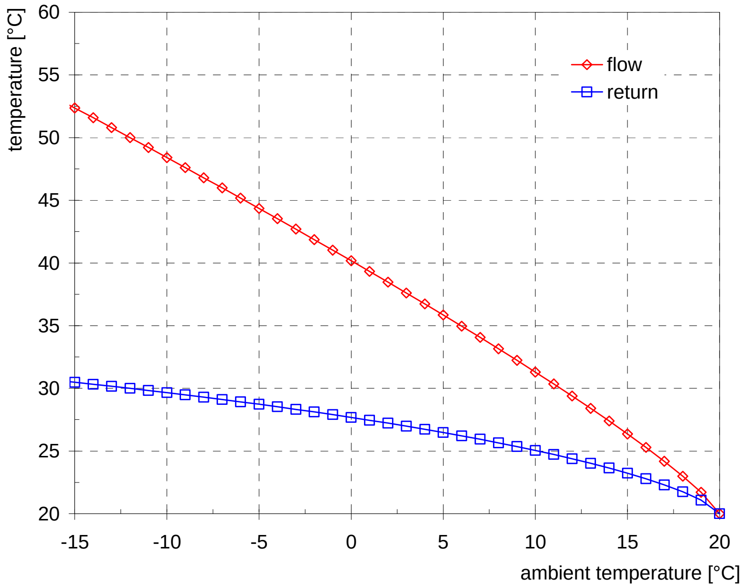


Figure 2.5: Heating curve: flow and return temperature as a function of the ambient temperature

Heat distribution system

The piping of the heat distribution system is assumed to consist of copper pipes with a diameter of 22 mm, a total length of 50 m and an insulation thickness of 20 mm (λ=0.04 W/(m.K)). The piping between the boiler and the DHW tank in the system categories 1 and 2 (see Table 2.3) is done with the same pipe dimension and insulation and a total length of 20 m. The piping between the buffer store and the plate heat exchanger in system category 3 (see Table 2.3) also has a total length of 20 m, again with the same pipe dimensions and insulation.

The thermal capacitance and the losses of the pipes are considered by the used TRNSYS model Type 709.

Preparation of domestic hot water

The cold water and DHW temperature are assumed with 12 and 45°C. For the preparation of the DHW the possibilities of a DHW tank and direct instantaneous preparation are considered.

In the system categories 1 and 2 a DHW tank with a volume of 300 litres is used, which is charged by the boiler via an internal heat exchanger every night from 3:00 to 4:30 am. During this time the space heating system is deactivated.

In the system category 3 an instantaneous preparation of DHW without DHW tank is done. This means that the water is heated via a flat plate heat exchanger, exactly ca0.98 176.93716 666.33847

Table 2.3: Summary of all simulated system concepts

system	type of boiler	type of buffer storage	type of DHW preparation	hydraulic integration and control of the boiler
System Category 1: no buffer storage, DHW tank				
G1a	gas	no storage	DHW tank	boiler temperature controlled as a function of the ambient temperature, throttle control
G1b	gas	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve
G1c	gas	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, hydraulic switch
P1	pellets	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, hydraulic switch, return temperature control
System Category 2: buffer storage, DHW tank				
G2a	gas	water storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage
G2b	gas	water storage + PCM modules	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage
P2a	pellets	water storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage, return temperature control
P2b	pellets	water storage + PCM modules	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage, return temperature control
System Category 3: buffer storage, instantaneous preparation of DHW				
G3a	gas	water storage	instantaneous preparation of DHW	constant boiler temp., flow temperature control via mixing valve, buffer storage
G3b	gas	bulk PCM tank	instantaneous preparation of DHW	constant boiler temp., flow temperature control via mixing valve, buffer storage

System category 1: systems without buffer storage

In these systems no buffer storage tank is used. The thermal capacitance of the heating system includes the boiler, the piping and the radiators. In the systems G1c and P1 there is an additional hydraulic switch with a volume of 2 litres.

In these systems the boiler is controlled in the following way concerning the start-stop operation:

If the power on the demand side decreases, then, depending on the hydraulic integration of the boiler, either the return temperature to the boiler increases or the flow rate through the boiler decreases. If the demand side load decreases below the smallest continuous load, the outlet temperature of the boiler will increase and exceed the set temperature. At the time when the boiler temperature reaches $T_{set}+\Delta T_{hyst}$ the control switches off the burner. The flow through the boiler and the heating system is maintained. The burner is switched on again, when the outlet temperature of the boiler falls below the set temperature. If the burner has a minimum stop-time, it will not switch on before the end of this time, even if the outlet temperature falls below the set temperature.

System G1a: Gas boiler, throttle control

In this system the boiler's set temperature is changed as a function of the ambient temperature according to the heating curve (see Figure 2.5). The heating power of the radiator is additionally controlled via a thermostatic valve that changes the flow rate through the radiator depending on the room temperature. A hydraulic scheme of the system is depicted in Figure 2.6.

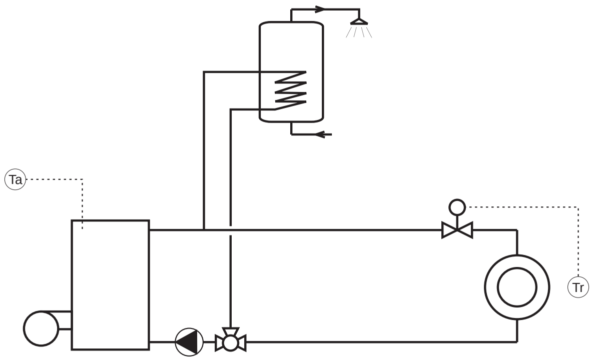


Figure 2.6: Hydraulic scheme of system G1a – system with throttle control

System G1b: Gas boiler, mixture control

The boiler is operated with a constant set temperature of 50°C. The flow temperature entering the radiator is controlled as a function of the ambient temperature according to the heating curve. The respective flow temperature is created by mixing a part of the cold return water to the hot flow water in a mixing valve (see Figure 2.7). The heating power of the radiator is additionally controlled via a thermostatic valve that changes the flow rate through the radiator depending on the room temperature. In Austria this is the most commonly used system.

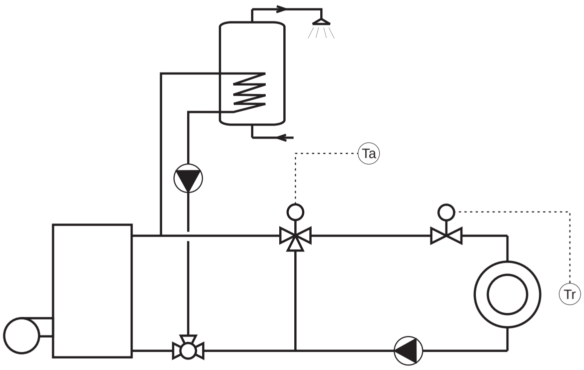


Figure 2.7: Hydraulic scheme of system G1b – system with mixture control

System G1c: Gas boiler, mixture control, hydraulic switch

The only difference to system G1b is that the boiler is hydraulically decoupled from the space heating system via a hydraulic switch, as shown in Figure 2.8. The volume of the hydraulic switch is 2 litres. The flow rate in the boiler cycle is constant.

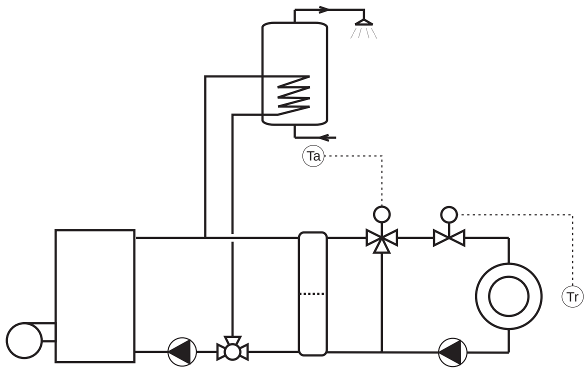


Figure 2.8: Hydraulic scheme of system G1c – system with mixture control and hydraulic switch

System P1: Pellet boiler, mixture control, hydraulic switch, return temperature control

This kind of system is used with the pellet boiler. In principal it is similar to system G1c, with the difference that the return temperature to the pellet boiler is kept above 50°C via a temperature-controlled mixing valve. This is a measure that is necessary for pellet boilers in order to prevent the condensing of flue gas. The boiler is operated with a constant set temperature of 70°C. A schematic of the system is shown in Figure 2.9.

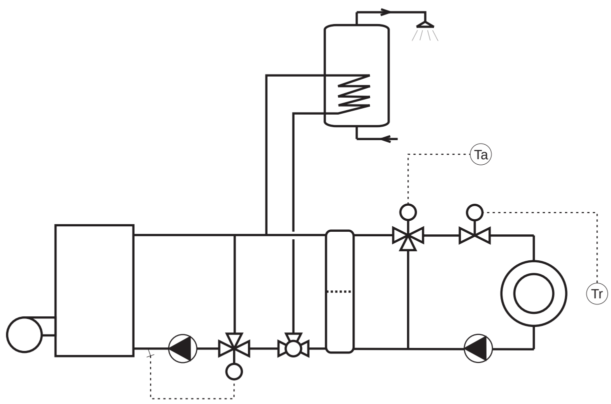


Figure 2.9: Hydraulic scheme of system P1 – system with mixture control, hydraulic switch, return temperature control

System category 2: Systems with buffer storage tank and DHW tank

In these systems the boiler charges a buffer storage tank, which is used to decouple the heat production from the heat consumption, both hydraulically and temporally. This shall result in a reduction of the start-stop frequency of the boiler in times with low heat consumption. The simulation of the storage tank is performed with the storage model Type 840 (Schranzhofer et al., 2006).

The DHW preparation is again done using a separate DHW tank with a volume of 300 litres. In principal also an instantaneous preparation of DHW out of the buffer storage is possible (compare system category 3), which would save additional space. However, this system category shall consider existing systems with a DHW tank, into which an additional buffer storage is integrated in order to reduce the start-stop operation.

The control of the boiler concerning the start-stop operation is slightly different from the systems without buffer storage:

Like in the systems without storage the burner stops when the boiler's temperature exceeds $T_{set}+\Delta T_{hyst}$. The pump in the boiler cycle stops with the burner in order not to influence the temperature stratification in the tank. The buffer storage is now discharged by the heating system. The burner is switched back on, when the temperature at a certain position in the storage tank (sensor positioned at 85 % of the height of the tank) falls below 50°C.

System G2a: Gas boiler, water tank

A schematic of the system G2a is shown in Figure 2.10. The gas boiler charges a water tank, out of which the heating system is supplied. The simulations are performed for the storage volumes listed in Table 2.4.

Concerning the comparability with the systems without storage tank (systems G1a,b,c) and the system with PCM modules in the tank (system G2b) the following problem arises:

The boiler set temperature in the systems without storage tank is 50°C. In the system G2b the PCM Sodium Acetate Trihydrate (with graphite) with a melting temperature of 58°C is used. To make use of the PCM and to provide a sufficient temperature difference for charging, the boiler's set temperature is therefore increased to 65°C. Because of the higher boiler temperature a higher temperature range is utilized, resulting in an advantage compared to the systems without storage. In order to enable a comparison both to systems with no storage tank and to the system with a tank with integrated PCM modules, this system is simulated both with a set temperature of 50°C and 65°C.

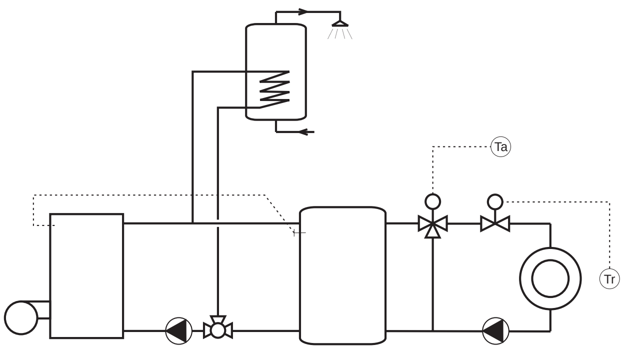


Figure 2.10: Hydraulic scheme of system G2a – gas boiler, water tank

System P2a: Pellet boiler, water tank

This system is similar to System G2a but uses a pellet boiler and a return temperature control (like in system P1). As in the system without buffer storage (system P1) the pellet boiler is operated with a set temperature of 70°C.

System G2b: Gas boiler, water tank with integrated PCM modules

In this system cylindrical PCM modules filled with Sodium Acetate Trihydrate + Graphite are integrated into the water storage tank in order to increase the storage capacity. The length of the modules matches the height of the tank. The same storage tank volumes as in the systems without PCM modules are used (see Table 2.4). Concerning the volume fraction of PCM two different values (50 and 75 %) are used. Table 2.5 shows the properties that are assumed for the PCM modules. The simulation of the storage tank is performed with the storage model Type 840 (Schranzhofer et al., 2006) using material data that was measured at the Institute of Thermal Engineering (Heinz, 2007) and considering the subcooling and hysteresis of the PCM material.

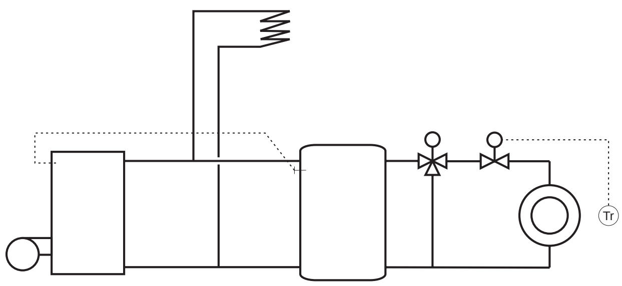
Table 2.4: Properties of the different buffer storage tanks used in the systems G2a,b and P2a,b

storage tank				number of PCM modules**	
volume	diameter	height	insulation* thickness	PCM fraction ~ 50 %	PCM fraction ~ 75 %
[l]	[cm]	[cm]	[cm]	[-]	[-]
25	23.4	58.4	5.0	10	16
50	29.4	73.6	5.0	17	25
100	37.1	92.7	5.0	27	41
200	46.7	116.8	5.0	43	65
300	53.5	133.7	5.0	57	85
500	63.4	158.5	5.0	80	120

*$\lambda_{insulation}$=0.04 W/(m.K) ** systems G2b and P2b

Table 2.5: Properties of the PCM modules used in the systems G2b and P2b

PCM material module material	Sodium Acetate Trihydrate + Graphite stainless steel
outer diameter modules	50 mm
inner diameter modules	47 mm
thermal conductivity PCM	4.5 W/(m.K)



System category 3: Systems with buffer storage tank and instantaneous DHW preparation

In these systems the boiler charges a buffer storage, which is used to decouple the heat production from the heat consumption. This shall result in a reduction of the start-stop frequency of the boiler in times with low heat consumption. Additionally the buffer storage also supplies a flat plate heat exchanger for the instantaneous preparation of DHW. As there is no separate DHW tank, this is the system category with the lowest space requirements.

In order to ensure that hot water is available shortly after opening the tap, the piping between the plate heat exchanger and the buffer storage (length 10 m in one direction) has to be kept at a temperature above 45°C. Therefore a small flow rate of warm water (3 l/h) is always allowed to flow through the piping.

The boiler is operated with a set temperature of 65°C. This is necessary in order to enable a proper charging of the PCM in the system G3b. In the system with the water tank the boiler could be operated with a lower temperature. However, in order to have the same useable temperature difference (storage capacity) in both systems, the same temperature is used. The boiler is controlled in the following way concerning the start-stop operation:

Like in the systems without storage tank the burner stops when the boiler's temperature exceeds $T_{set}+\Delta T_{hyst}$. The pump in the boiler cycle stops with the burner in order not to influence the temperature stratification in the tank. The buffer storage is now discharged by the heating system or the DHW preparation system. The burner is switched on again when the temperature at a certain position in the storage tank (the sensor position is given in the system descriptions) falls below 50°C.

System G3a: Gas boiler, water tank, instantaneous preparation of DHW

In this system a water tank is used as the buffer storage. The boiler cycle, the space heating system and the DHW preparation are connected to the tank via separate double ports, as shown in Figure 2.12. The simulation of the storage tank is performed with the storage model Type 840 (Schranzhofer et al., 2006).

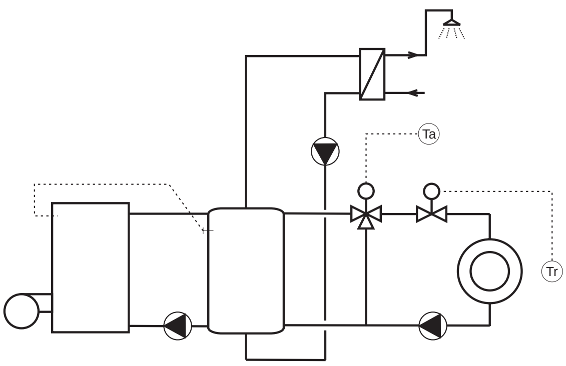


Figure 2.12: Hydraulic scheme of system G3a – gas boiler, water tank, instantaneous DHW preparation

The buffer storage has a volume of 45 litres, which is the same volume that is used for the PCM tank in system G3b. The sensor for the boiler control is located at 85 % of the height of the tank.

System G3b: Gas boiler, bulk PCM tank, instantaneous preparation of DHW

In this system a bulk PCM tank is used as the buffer storage. The higher storage capacity compared to a water tank shall result in a lower number of start-stop cycles and a better coverage of the DHW demand. The hydraulic integration of the storage tank cannot be done as easily as in system G1a, as the PCM tank has to be charged and discharged via one single internal heat exchanger.

The hydraulic integration used in the simulation, which allows both charging and discharging of the PCM storage, is shown in Figure 2.13 and Figure 2.14. If the mass flow in the heat generation cycle is higher than in the heat consumption cycle, the tank is charged. If the mass flow in the heat consumption cycle is higher, the tank is discharged.

The simulation of the storage tank is performed with the model Type 841 (Heinz, 2007). The PCM tank has a volume of 45 litres and has the same properties as the tank used in the experimental work performed at the Institute of Thermal Engineering (Heinz, 2007). The sensor for the boiler control is located at approximately 33 % of the length of the heat exchanger tube (see Figure 2.14).

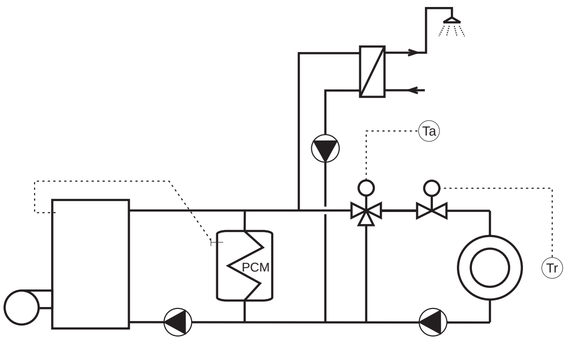


Figure 2.13: Hydraulic scheme of system G3b – gas boiler, bulk PCM tank, instantaneous DHW preparation

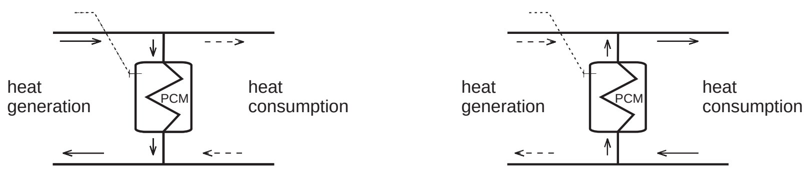


Figure 2.14: Left: charging of the PCM tank; right: discharging of the PCM tank

3 Simulation Results

The results of the simulations are analysed concerning different aspects. The main result is the annual number of start-stop cycles of the boiler, which was later used for the calculation of the annual emissions of CO and HC (Heinz, 2007). In addition the annual efficiency of the boiler and the annual efficiency of the system are analysed according to equation (0.1) and (0.2). The annual efficiency of the boiler is calculated out of the useful energy that is transferred from the boiler to the heating water Q_{useful} and the fuel energy Q_{fuel} used by the boiler over the year.

$$h_{boiler,a} = \frac{Q_{useful}}{Q_{fuel}} \tag{0.1}$$

The annual efficiency of the system is a function of the total useful energy used in the system and the fuel energy used by the boiler. The useful energy is the sum of the space heating energy transferred to the room Q_{SH} (energy emitted by the radiator plus energy lost from the pipes to the room) and the energy of the consumed domestic hot water Q_{DHW}. In this definition of the efficiency all heat losses of the heat distribution system and all storage losses are included. The losses because of the distribution of DHW from the DHW tank or the flat plate heat exchanger (in systems with an instantaneous preparation of DHW) to the tap are not included, as they are assumed to be the same for all systems.

$$h_{system,a} = \frac{Q_{SH} + Q_{DHW}}{Q_{fuel}} \tag{0.2}$$

The electric power consumption of the pumps, the boiler and other components is also not considered.

3.1 System category 1: systems without buffer storage

Figure 3.1 shows the results of the annual number of start-stop cycles and the annual efficiencies of the different systems without buffer storage. The systems with gas boiler show a high number of start-stop cycles, which is due to the low water content of the boiler. The differences between the different hydraulic systems used for the gas boiler are not very high. As the pellet boiler has a much higher water content (see Table 2.2), system P1 shows a much lower number of cycles.

The annual efficiencies of the system are about 10-12 % lower than the annual efficiencies of the boiler in all systems. The systems using a gas boiler show higher efficiencies than the system with the pellet boiler because the gas boiler is condensing. The slightly lower values of system G1c are due to the hydraulic switch, which causes higher return temperatures to the boiler (constant flow rate in the boiler cycle, variable flow rate in the space heating cycle).

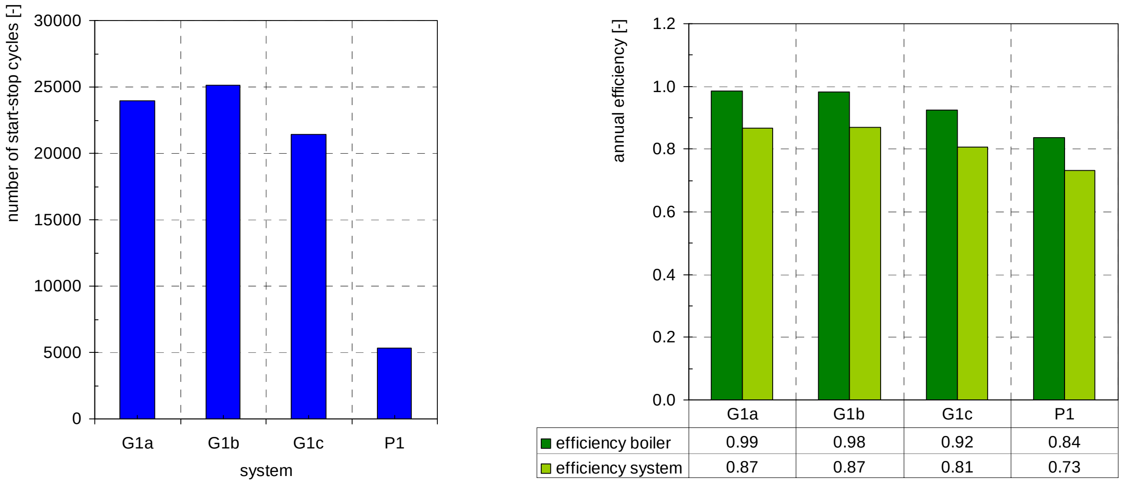


Figure 3.1: Annual number of start-stop cycles (left) and annual efficiency (right) of the systems without buffer storage

Figure 3.2 shows the average daily load of the boiler and the number of start-stop cycles per day in the course of the year for system G1a. The number of cycles is much higher in times of low heat demand. During summer the boiler is only operated once a day when it is charging the DHW tank.

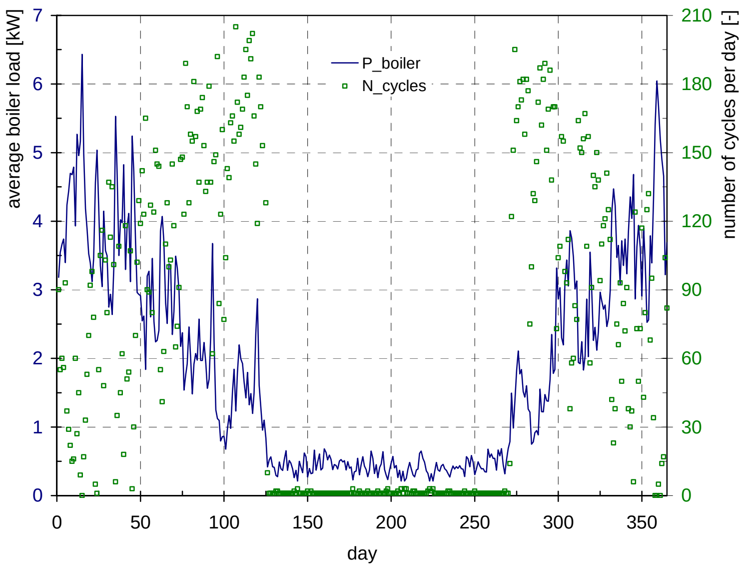


Figure 3.2: Average daily boiler load and nr. of start-stop cycles per day in the course of the year for system G1a

In Figure 3.3 a plot of the number of start-stop cycles per hour as a function of the average hourly boiler load is shown for system G1a. At loads lower than the smallest continuous load of the boiler (4 kW) the number of cycles shows a strong, almost linear increase.

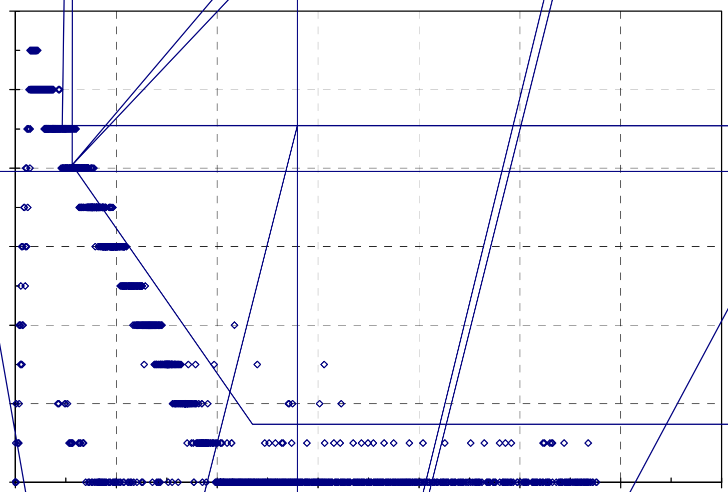


Figure 3.4 shows the annual duration curve of the heat load for the three different space heating demands. It can be seen in the figure that the time in which the boiler has to be operated in start-stop operation is increasing with decreasing space heating demands. Thus the annual number of cycles increases with decreasing space heating demand (see Figure 3.5). As the system losses stay approximately constant with different space heating demands, the annual efficiency of the system decreases with decreasing heat demands (higher fraction of the losses).

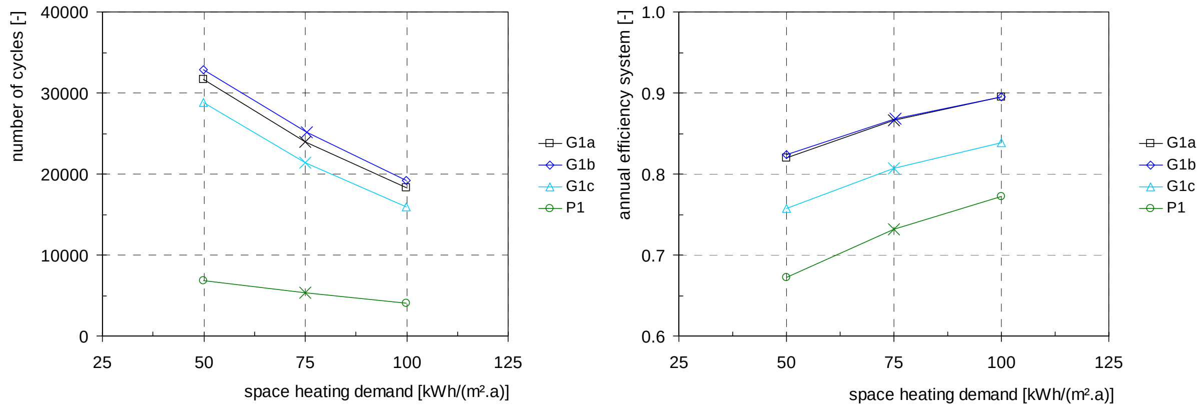


Figure 3.5: Annual number of start-stop cycles (left) and annual efficiency of the system (right) for different space heating demands

Water content of the boiler

The influence of the water content of the boiler on the annual number of cycles and the annual efficiency of the system is shown in Figure 3.6. The results show that an enlargement of the water content of the boiler results in a decreasing number of cycles. In the systems with the gas boiler the effect of different water contents is depending on the used hydraulic system. In system G1b (mixture control) the reduction of the number of cycles is lower than in the other systems, which is due to the lower mass flow rates in the boiler cycle.

If the same hydraulic system (G1c and P1c) and the same water content are used, the results with the gas and the pellet boiler are quite similar.

The annual efficiency of the system is decreasing with an increasing water content of the boiler, which is due to higher standby losses.

The pellet boiler was not simulated with a water content of only 7 litres, as such boilers are not manufactured in practise.

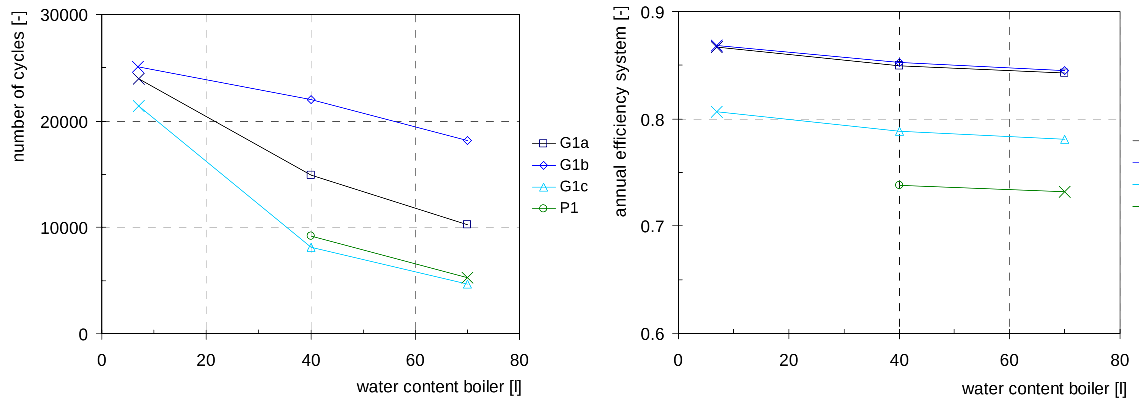


Figure 3.6: Annual number of start-stop cycles (left) and annual efficiency of the system (right) as a function of the water content of the boiler

Minimum stop time of the burner

The use of a minimum stop time of the burner is a measure to reduce the number of start-stop cycles of boilers with a low water content. As shown in Figure 3.7 the influence on the number of start-stop cycles is quite high for the systems with the gas boiler.

In system P1 (pellet boiler) there is no effect, which shows that a minimum stop time is not required for boilers with a high thermal capacity.

The annual efficiency of the system is hardly influenced by the minimum stop time of the boiler.

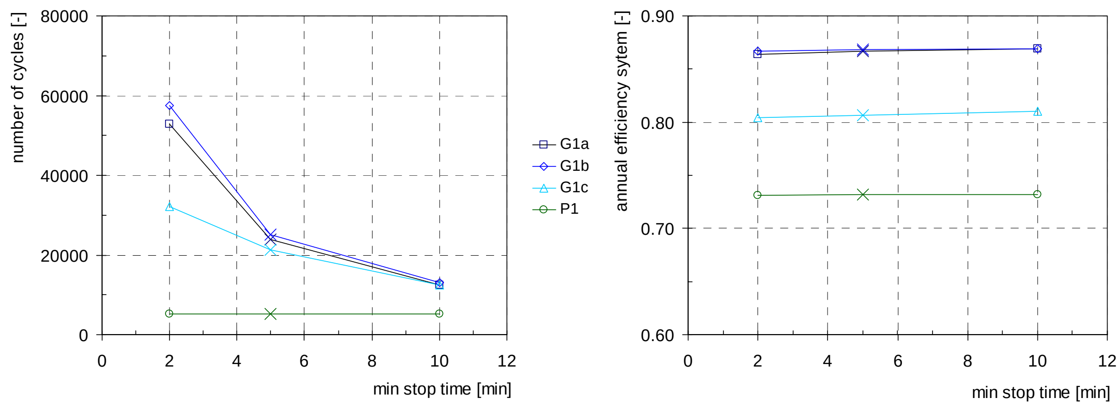


Figure 3.7: Annual number of start-stop cycles (left) and annual efficiency of the system (right) as a function of the minimum stop time of the boiler

3.2 System category 2: systems with buffer storage and DHW tank

3.2.1 System G2a,b (Gas boiler)

The results for the system with a water storage (G2a) and for systems with a water storage with integrated PCM modules (G2b) are shown in Figure 3.8 for different storage volumes (compare Table 2.4). As explained in chapter 2.3.2, the simulations of the system with water storages were performed with different boiler set temperatures, to enable a comparison both to systems without storage (set temperature 50°C) and to systems with a storage with PCM modules (set temperature 65°C).

In comparison to the systems without buffer storage the number of start-stop cycles is reduced strongly. Even with the smallest volume of only 25 litres a reduction of about 70 % (set temp. 50°C) or 90 % (set temp. 65°C) can be achieved. With increasing storage volumes the number of cycles decreases, whereby the potential for a further reduction is low for volumes above 200 litres. Because of the lower utilized temperature difference the number of cycles is higher with a boiler temperature of 50°C in comparison to 65°C. On the other hand the higher temperatures decrease the annual efficiencies of the condensing boiler by 2-3 %.

The integration of PCM modules allows an enhancement of the storage capacity, resulting in a further decrease of the number of start-stop cycles especially with small storage volumes. There are only minor differences between the PCM volume fractions of 50 and 75 %. The integration of PCM modules hardly influences the annual efficiencies of the boiler and the system.

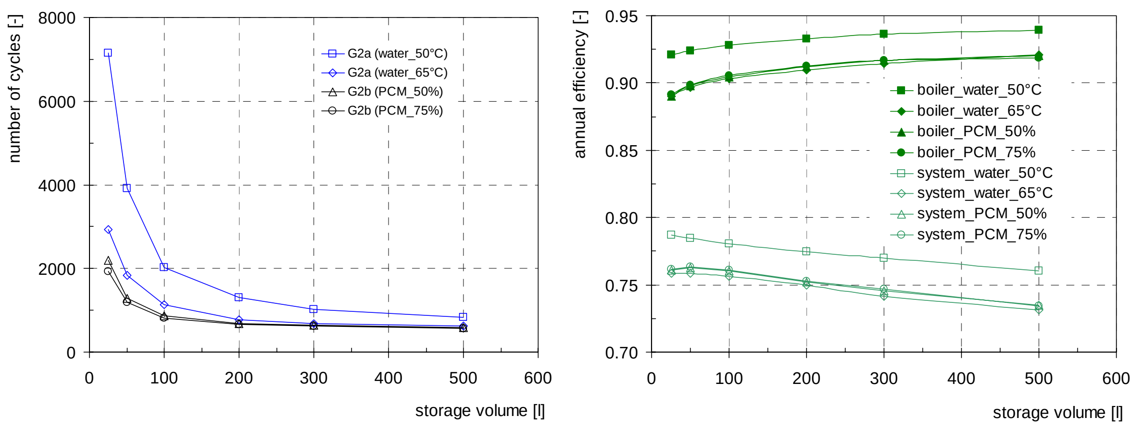


Figure 3.8: Gas boiler: annual number of start-stop cycles (left) and annual efficiencies (right) for different storage volumes for systems with water storage (G2a) and for systems with water storage with integrated PCM modules (G2b)

The annual efficiency of the boiler increases with increasing storage volumes, as the boiler is more operated in continuous operation and with higher loads. On the other hand the annual system efficiency decreases with increasing volume, which is due to higher storage losses, as all storage volumes are assumed to have the same insulation thickness of 5 cm. Thus the system efficiency of larger volumes could be increased by using a better insulation of the storage.

3.2.2 System P2a,b (Pellet boiler)

The results for the system with water storage (P2a) and for systems with water storage with integrated PCM modules (P2b) are shown in Figure 3.9 for different storage volumes (compare Table 2.4). The number of cycles of systems with different storage volumes is quite similar to the systems with the gas boiler. The reduction of the number of cycles (about 50 % with the smallest storage volume) compared to the system without buffer storage (P1) is lower than in the systems with the gas boiler. This is due to the much larger water content of the pellet boiler, which causes a relatively low amount of cycles even if no storage is used.

The annual efficiencies show a similar trend as in the systems with the gas boiler concerning their dependency on the storage volume.

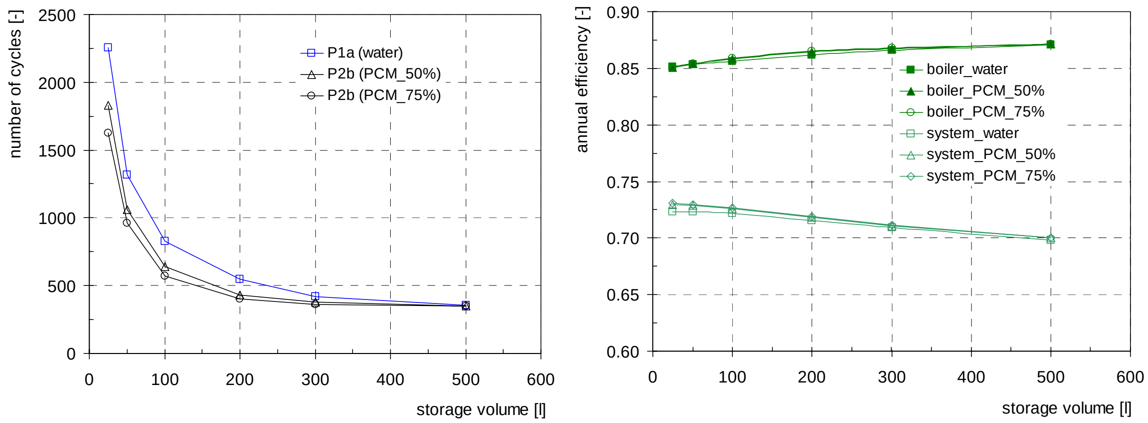


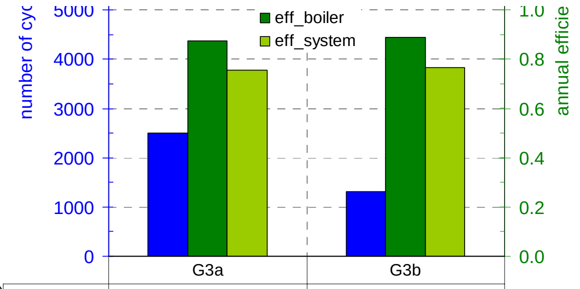
Figure 3.9: Pellet boiler: annual number of start-stop cycles (left) and annual efficiencies (right) for different storage volumes for systems with water storage (P2a) and for systems with water storage with integrated PCM modules (P2b)

3.3 System category 3: systems with buffer storage and instantaneous DHW preparation

As explained in chapter 2.3.2 this system category works with an instantaneous DHW preparation via a plate heat exchanger, which is supplied by the buffer storage (volume 45 l). Thus the buffer storage is (at least partly) discharged every time the tap is opened and DHW is withdrawn. As the used buffer storage tanks have a relatively small volume, the stored energy content is probably not high enough to provide the required DHW temperature of 45°C until the end of large DHW draw-offs. Therefore the amount of DHW which is provided with temperatures lower than 45°C was determined as an additional result.

Figure 3.10 shows the number of start-stop cycles and the annual efficiencies for the system G3a (water storage) and the system G3b (bulk PCM storage). Due to the higher storage capacity of the PCM storage in system G3b the number of cycles can be reduced by 50 % compared to system G3a. The annual efficiency of the boiler is also slightly higher, which is a result of the lower amount of heat produced in start-stop operation due to the higher storage capacity.

The annual losses caused by the instantaneous preparation of DHW (circulation pipe from the tank to the plate heat exchanger) are in the same order of magnitude as the losses of the DHW tank used in the other system categories. That's why the annual system efficiencies are quite similar to the systems G2a and G2b with the same buffer storage volume (compare Figure 3.10 and Figure 3.8).



	G3a	G3b
n_cycles	2503	1307
Reihe4		
Reihe3		
Reihe5		
eff_boiler	0.87	0.89
eff_system	0.76	0.77

Figure 3.10: Annual number of start-stop cycles and annual efficiency for the systems G3a (water storage) and G3b (bulk PCM storage)

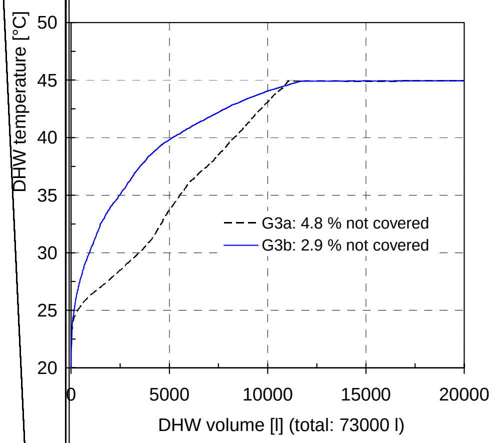


Figure 3.11: DHW volume which is provided with a temperature below the required temperature (45°C); percentage of the energy required for the preparation of DHW that is not covered by the system

As shown in Figure 3.11 both systems are able to cover the DHW demand almost completely, although the storage volume is only 45 litres in both cases. The figure shows the DHW volume per year, which is provided with a lower temperature than the temperature on the y-axis. The fraction of the DHW energy demand not covered is slightly lower in the system with the PCM storage (2.9 %) than in the system with the water storage (4.8 %). The used DHW demand profile is supposed to pose quite high requirements on the DHW preparation, due to some large draw-offs with high water flow rates (> 1000 l/h). However, the fraction of these draw-offs on the total DHW energy demand is quite low (see Figure 3.12). In order to be able to cover the total demand including large draw-offs, the volume of the storage tank would have to be increased.

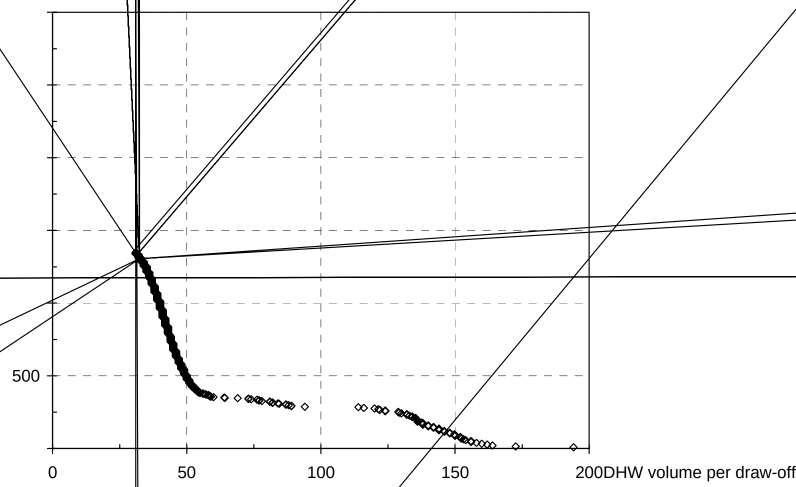


Figure 3.12: DHW volume in the individual draw-offs (DHW temperature 45°C) and cumulated DHW energy demand

Among all simulated systems this system cat

4 Summary and conclusions

The performed work shows that the frequency of start-stop cycles of a boiler is strongly dependent on several parameters concerning both the boiler itself, the heating system to which it is coupled and the building. Parameter variations that were performed in this study include the boiler water content, the minimum stop time of the burner and the annual space heating demand of the building. The effect of the number of start-stop cycles on the annual emissions of carbon monoxide and hydrocarbons was analysed in detail in (Heinz et al. 2006) and (Heinz, 2007).

For the systems investigated in this work it was found that the number of start-stop cycles can be strongly reduced by coupling the boiler with a storage tank. This is especially true for boilers with a very small water content, where the number of cycles can be reduced to about 20% compared to a system without storage, assuming a tank with a volume of only 50 litres.

The use of PCM storage tanks for reducing the start-stop cycles of boilers results in a lower number of cycles compared to water tanks. However, due to the following reasons it will be difficult to present PCMs as a competitive alternative to water for this application:

- The main benefit of the storage tank is a reduction of emissions. Mostly emissions are not considered to be a strong argument for making additional investments in the heating system. Therefore the cost for a storage unit will be a decisive factor. Although the costs of PCM storage units have not been investigated in this study, it is for sure that a PCM storage will be much more expensive than a water storage, which is unbeaten in terms of simplicity and cost of the storage material.
- Because of the relatively high temperature differences that are used in heating systems with domestic hot water production the reduction of cycles compared to a water storage with the same volume is limited. The resulting reduction of the total emissions is relatively low, especially if it is seen in comparison to the reduction that is achieved by the introduction of a storage into a system without storage.

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