

A METHODOLOGY TO COMPARE COLLECTIVE HEATING SYSTEMS WITH INDIVIDUAL HEATING SYSTEMS IN BUILDINGS.

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ABSTRACT

To compare energy performance of collective heating systems with individual heating systems within apartment buildings, an assessment methodology was developed and implemented in Matlab. As start-up losses and part load are considered to have an influence on the efficiency of heat generation, this is incorporated in the production model. Next, a branched pipe model is used to simulate the time delay and heat transfer to the environment in the distribution network. Finally, reproducible and statistic representative domestic hot water (DHW) tap patterns, based on a survey in 600 households and verified with in situ measurements, are used as input for the simulations.

The simulation based methodology is illustrated with a case study. Simulations are executed for a building with 6 apartments. Starting from the same building parameters, occupancy rate, DHW demand profile and a similar comfort level for space heating, the collective 2-pipe system and an individual heating system per apartment were compared on primary energy use. For the collective system, the effect of insulation thickness of the pipes and the concept of piping shaft on energy consumption has been evaluated.

KEY WORDS: building simulations, collective heating systems

1. INTRODUCTION

Collective heating systems reappear more frequently in residential buildings, more precisely the central heating systems with one primary distribution circuit and substations in each apartment, because of the fact that collective systems make the integration of renewable energy much easier. Moreover, collective systems permit to reduce the installed power for domestic hot water (DHW). Thanks to an increased rate of insulation, peak demand for space heating (SH) is becoming significantly lower than peak demand for domestic hot water (DHW) generation. This leads to the fact that individual heating production, with combined production of SH and DHW, will be oversized for SH.

To enable a comparison of the energy performance, the specific energy losses related to each system need to be quantified. On one hand, oversizing of individual systems implies a large number of start-stops, resulting in additional energy losses and poor part load efficiency. On the other hand collective systems imply increasing distribution losses, which are shown to be overestimated in the simplified calculations in the European Performance of Building standards in Europe by Himpe et al. [1]. An evaluation based on measurements was made by Cholewa et al. [2]. This paper aims to enable an objective comparison by keeping both building and occupant parameters identical. Therefore a model-based approach is set up. The assessment is illustrated on a case study, namely an apartment building with 6 apartments.

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2. METHODOLOGY

2.1 General methodology A simulation environment is developed where collective and individual heating systems for space heating and domestic hot water (DHW) are implemented in a pre-defined building with imposed occupancy rate and behaviour. The occupant behaviour is simulated with the ‘Profile generator’ ([3]), and beside statistical ‘presence’ and ‘internal gain’- profiles, it consists of randomly generated DHW-profiles for each individual tapping point which are based on a survey in 600 households and verified with in situ measurements.

The simulation environment is developed to fit his purpose, it is comparing energy performance and comfort level of individual and collective systems. Therefore part load behaviour and the impact on the boiler efficiency are included in the assessment.

2.2 Simulation method The model consists of a number of sub-models, implemented as Matlab-functions with flow and temperature input and outputs passed between them. The component models are discussed in the next chapter. To simulate the dynamic behaviour a step by step approach is used. The timestep Δt is variable between 60 sec or 1 sec during periods with DHW-demand. During 1 timestep, inputs of the Matlab functions are considered to be constant.

In each timestep the primary mass flow is calculated proportional to the deviation of the zone-temperature from the set point. When there is a DHW-demand, the primary mass flow is calculated that would lead to the imposed temperature T_{mix} coming out of the valve at the conditions of that timestep. The mass flow that is calculated directly in the hydronic sub-models is imposed as such in the installation for the next timestep. So it is assumed a perfectly controlled installation, although with a time-delay of one timestep. This means that the influence of pressure variation in the circuit by pumps, friction, control valves,... is not taken into account. This simplification of the hydronic behaviour assumes therefore a well-designed good working installation. The impact of this simplification will be investigated in further research.

In some specific sub-models, the output temperatures are the result of differential equations that can be written as

$$dy/dt = -a * y(t) + b \quad (1)$$

Eq (2) is a non-homogeneous linear ordinary differential equation (ODE) with constant coefficients a and b . Its solution for $t=\Delta t$ with initial condition $y(0)$, for a different from zero, is

$$y(\Delta t) = y(0) * \exp(-a * \Delta t) + b/a * (1 - \exp(-a * \Delta t)) \quad (2)$$

So, in contrast of the inputs, some outputs vary during a timestep. Therefore, instead of the end value of Eq(2) a mean value of the temperature is passed to the other sub-models, calculated as

$$y_{mean} = \frac{b}{a} + \frac{y(0)-y(\Delta t)}{a\Delta t} \quad (3)$$

Energy balances performed on the pipe model, the substation model and the boiler model show relative errors of about 0.01% or less.

2.3 Component models

Boiler model. The boiler model simulates a boiler without heat exchanger or storage tank and with a temperature setpoint. The required power is calculated to obtain the setpoint temperature $T_{setpoint}$ with

respect to the thermal capacity of the boiler C_{boiler} [J/K], the skin losses of the boiler to the environment UA_{boiler} [W/K], the incoming mass flow in the boiler \dot{m}_{boiler} [kg/s] at temperature T_{in} , and limited to the minimum and maximum admitted power of the boiler P_{min} [W] and P_{max} [W]. The boiler behaviour is described by equation (1), with $y=T_{boiler}$, and a and b equal to

$$a = (UA_{boiler} + \dot{m}_{boiler} \cdot c) / C_{boiler} \quad (4)$$

$$b = (P + UA_{boiler} T_{env} + \dot{m}_{boiler} c T_{in}) / C_{boiler} \quad (5)$$

It is possible to define a minimum on time $t_{on,min}$ and off time $t_{off,min}$ and a waiting time until the boiler starts at minimal ($t_{startup1}$) and at full demanded power ($t_{startup2}$). Start-up losses are represented by a negative power. This results in the following relationship between the on (positive value) or off (negative value) time of the boiler, the required power to obtain $T_{setpoint}$ and the supplied power:

Table 1 Relation between time, required boiler power and supplied boiler power

	← toff,min →	← 0 →	← tstartup1 →	← tstartup2 →	← ton,min →	← 0 →
Preq	<Pmin	any value	>0	>0	any value	>0
Psup	0	0	-0.01Pmax	Pmin	max(Preq,Pmin)	max(Preq,Pmin)

A maximum boiler temperature and temperature increase of the incoming water can be imposed, which if exceeded causes a shutdown of the boiler. A minimum water flow rate is required to let the boiler start.

The boiler model returns the power supplied by the boiler, without taking the gas side efficiency into account. The fuel consumption can be calculated in post processing phase as a result of the partial load ratio PLR, the water flow and the incoming temperature T_{in} , as described in [4].

Pipe model. The distribution system is simulated using the plug-flow method (TRNSYS type 31 [5]). This pipe model is limited to the thermal losses and the transport delay in the distribution network. As described in §2.2, the hydraulic behaviour is not included in the models.

Thermostatic control valves. Thermostatic valves with proportional control are assumed at the end of each riser pipe. The proportional band is between 45°C and 50°C. As described in §2.2, there is a direct relationship between the opening of the valve and the water flow. Below 45°C, when the valve is 100% open, a water flow of 0.1l/s is imposed in the installation.

Mixing valve model. The valve model simulates an idealized thermal valve. The mixing temperature T_{mix} is the result of a heat and mass balance. In the following equations subscripts c and h refer to cold and hot water and \dot{m} is a mass flow.

$$T_{mix} = (T_c \cdot (\dot{m}_{mix} - \dot{m}_h) + T_h \cdot \dot{m}_h) / \dot{m}_{mix} \quad (6)$$

The hot water flow is calculated to force the mixed temperature to equal a pre-set mixed temperature. Hence, it is assumed that the valve can adjust the mixing perfectly, with however a delay of the simulation step.

$$\dot{m}_{h,i+1} = \dot{m}_{mix,i} \cdot (T_{mix,sp,i} - T_c) / (T_{h,i} - T_c) \quad (7)$$

A tapping is considered as a total heat load that must be supplied. As long as the mixed temperature T_{mix} is lower than a predefined useful temperature T_{useful} , the mixed water doesn't contribute to the demanded heat load. Consequently the DHW demand will be extended in time until the total provided DHW heat reaches

the total demanded DHW heat. This is schematically represented in Fig. 1. Although, if the useful temperature can't be reached during a continuous period of predefined length and the real tapping is over, the tapping is stopped even if a heat lack exists.

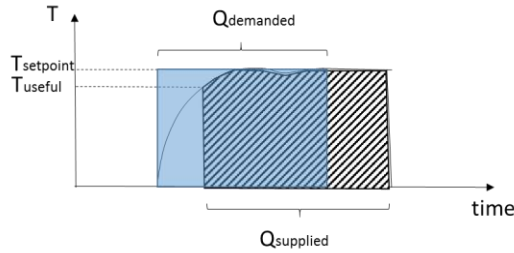


Fig.1 Workings of the mixing valve, with demanded and supplied total heat load.

Substation model. A model without storage is used. If there is a DHW demand, flow for space heating is blocked and a constant primary flow passes at the primary side of the heat exchanger HX. The substations are modelled using the effectiveness-NTU approach for a counter-flow heat exchanger and the UA-value of the HX is assumed to be flow dependent. The dependency is defined by a coefficient (C) which is determined using catalogue data. The heat flow \dot{Q} for a satellite unit with constant C, with flow \dot{m}_{prim} and incoming temperature T_{sup} at the primary side, and with flow \dot{m}_{sec} and incoming temperature T_c at the secondary side, is

$$UA = C / (1/\dot{m}_{prim} + 1/\dot{m}_{sec}) \quad (8)$$

$$\dot{C}_h = 4187 * \dot{m}_{prim}, \dot{C}_c = 4187 * \dot{m}_{sec}, C_{hat} = \min(\dot{C}_h, \dot{C}_c) / \max(\dot{C}_h, \dot{C}_c) \quad (9)$$

$$Ntu = UA / \min(\dot{C}_h, \dot{C}_c) \quad (10)$$

$$\xi = \frac{1 - \exp(-Ntu * (1 - C_{hat}))}{1 - C_{hat} * \exp(-Ntu * (1 - C_{hat}))} \quad (11)$$

$$\dot{Q} = \xi * \min(\dot{C}_h, \dot{C}_c) * (T_{sup} - T_c) \quad (12)$$

An extra water volume is added at the entrance of the HX, to represent the thermal mass of the satellite unit. The thermal capacity is determined to fit measurements of the outgoing hot water temperature TDHW performed on a cold satellite unit. Heat losses to the environment are taken into account.

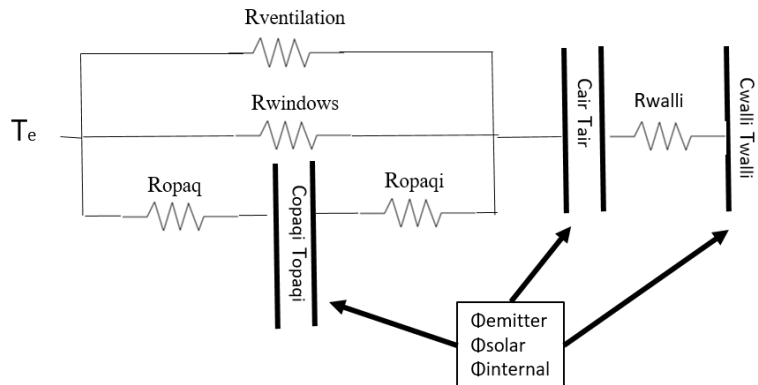


Fig.2 Zone model with 3 capacitances, heat losses and heat gains.

Zone model. The zone model simulates the thermal behaviour of one heating zone in a building. Air and internal and external walls are modelled as 3 lumped capacitances which can be described by equations like Eq 1. They are connected by resistances as in Fig. 2. Ventilation losses and losses through windows are modelled as parallel resistances between air and exterior. Heat from the emitter and internal and solar gains are mainly assigned to the air capacitance, and partly to the walls. Internal gains from occupants and from

the DHW installation (satellite units, riser pipes, tapping ducts for collective systems and boiler, tapping ducts for individual systems) are considered.

The zone contains 1 radiator, with radiator constants C and n, incoming temperature $T_{emitter,in}$ and outgoing temperature $T_{emitter,out}$. It is modelled as a lumped capacitance $C_{emitter}$ with incoming and outgoing power $P_{emitter,in}$ and $P_{emitter}$ leading to a temperature change $\Delta T_{emitter}$,

$$P_{emitter\ in} = \dot{m}_{emitter} * ((T_{emitter,in} - T_{emitter,out,i-1}) \quad (13)$$

$$P_{emitter} = C * (T_{em,i-1} - T_{room})^n \quad (14)$$

$$\Delta T_{em} = (P_{emitter\ in} - P_{emitter}) * timestep / C_{emitter} \quad (15)$$

and a new outgoing temperature according to

$$T_{emitter} = T_{room} + \frac{T_{emitter,in} - T_{emitter,out}}{\log_{\frac{T_{emitter,in} - T_{room}}{T_{emitter,out} - T_{room}}}} \quad (16)$$

The mass flow rate is controlled by a proportional control with TTRV as input, and imposed as such on the installation (as described in §2.2). The flow through the emitter $\dot{m}_{emitter}$ is a fraction of the nominal flow.

$$\dot{m}_{emitter} = \max(0, \min(1, ((T_{TRV} - T_{setpoint})) * 2)) * \dot{m}_{emitter,nom} \quad (17)$$

3. CASE DESCRIPTION

An apartment block with 3 floors and 6 dwellings was considered as a case. The characteristics of the building and installation are summarised in Tabel 2 to 4. The symbols refer to the model description in §2.3.

The length of the riser-pipe going to zones 2,4 and 6 and starting at the boiler is 17m, the riser-pipe to zones 1,3 and 5 is 27m. The branches to the zones are located at the end of the riser-pipes and at 3m from each other. Inner diameters vary between 42mm and 28mm. They're basically isolated with 3cm isolation with $\lambda=0.05\text{W/mK}$.

The set-point temperature of an apartment was set to 21°C during occupancy, with a preheating time of 30 minutes, and with night setback to 15°C. The design power, temperatures and flow of the radiators are 3300W, 65/30 °C, 0.023l/s.

The behaviour of the occupants was simulated using the Profile Generator as described in §2.1.

Table 2 Building parameters

	app11	app12	app21	app22	app31	app32
mean U-value (W/m ² K) (*)	0.67	0.67	0.67	0.67	0.31	0.25
enclosing surface (m ²)	46	30	46	30	134	134
protected volume (m ³)	264	312	264	312	264	312
air tightness n50 (1/h)	4	4	4	4	4	4
ventilation ratio (1/h)	0.29	0.33	0.29	0.33	0.29	0.33

(*) 8cm wall isolation ($\lambda 0.021\text{W/mK}$), 15cm roof isolation ($\lambda 0.021\text{W/mK}$), windows $U=1.5\text{W/m}^2\text{K}$

Table 3 Boiler parameters.

	Pmax (kW)	Pmin (kW)	Cboiler (kJ/K)	Tsetpoint (°C)	UA (kW/K)	Tmax (°C)	ΔT_{max} (°C)	trun,min (s)	toff,min (s)	mmin (s)
collective	60	15	360	70	0.006	95	50	300	0	0.0001
individual	30	7.5	20	70	0.004	95	50	300	0	0.0001

Table 4 Parameters satellite unit and mixing valve

m_{prum} (kg/s)	HE (J/kgK)	Csatunit (J/K)	UAe (W/K)	Tuseful (°C)
0.28	20 000	3000	0.3	35

4. RESULTS

The case with 6 dwellings is simulated during the months January and July with a collective (CHS) and individual heating system (IHS). Results are presented in table 5.

In the following tables 5,6,7 Q_{fuel} is the total fuel consumption for the 6 dwellings, Q_{cv} and Q_{DHW} the total net energy consumption for space heating and domestic hot water for the 6 dwellings, Q_{distr} are the distribution losses in the collective pipe network, η_{boiler} the mean boiler efficiency and η_{start} the number of boiler starts/day. Discomfort for space heating (in Kh) is defined as $\int_{t_1}^{t_2} (T_{sp} - T_{op}) dt$ for $T_{op} < 19^\circ\text{C}$. Discomfort DHW gives the time it takes to reach $T_{sp, mixing} - 1^\circ\text{C}$.

Table 5 energy consumption and discomfort for collective and individual installation (winter and summer)

	Units	collective (January)	individual (January)	collective (July)	individual (July)
Energy					
Q_{fuel}	kWh	3441	3102	1964	1280
Q_{cv}	kWh	1437	1491	0	0
Q_{DHW}	kWh	903	914	904	944
Q_{distr}	kWh	560	-	635	-
η_{boiler}	-	0.85	0.77	0.79	0.74
η_{start}	starts/day	61	32 (* ¹)	36	4 (* ¹)
Discomfort (* ²)	Kh	31 (18,42)	33 (20,46)	-	-
Discomfort DHW(* ²)	s	8 (1,14)	14 (1,77)	9 (1,15)	30 (1,80)

(*¹) mean value for 6 boilers, (*²) mean value for 6 zones (min, max)

Discomfort for DHW increases with an IHS. During periods without space heating, the boiler start-up delay is part of the time delay at the tapping points. This leads to a mean time delay in July of 30 s, relative to 9 s for the CHS, and a maximum time delay up to 77 s in January and 80 s in July.

Fuel consumption is lower for the IHS. Improved part load behavior and decreasing relative amount of skin losses result in a better efficiency of the collective boiler. Beside it can be seen that the collective boiler has still many starts/day. Simulations with thermal control valves closed at night, between 0h and 5h, show no significant improvement. Indeed, the power of 60kW is still large compared to the space heating demand. The boiler efficiency, particularly in the CHS, decreases in periods with lower space heating demand, which can be explained by the working of the thermal control valves. Despite of the improved boiler efficiency, the distribution losses in the CHS result in a fuel consumption that is 35% higher in July and only 10% higher in January. The difference between both months can be explained by the increasing relative amount of distribution losses in July and the recuperation of distribution losses for space heating in January. It should be noted that the skin losses of the boiler which are contributed to the apartment only in the IHS, also lower the energy consumption for space heating.

More simulations were performed to clarify the impact of the distribution losses in the CHS. The distribution efficiency can be defined as the proportion of the outgoing energy to the incoming energy in the pipe network. This definition is only appropriate if the 'distribution losses' are really lost, as with a ventilated shaft, but probably not in case they are regained as heat gains in the apartments. Hence a case with infinite pipe isolation is simulated to investigate the impact on energy consumption of the pipe network. Further a

worst-case scenario with 0cm pipe insulation and a case with ventilated shaft are simulated. Results are presented in table 6 and 7.

Table 6 energy consumption and discomfort for variants on collective installation (January)

	Units	3cm isol shaft is part of protected volume	infinite isol	0cm isol	3cm isol ventilated shaft(* ¹)	0cm isol
Energy						
Q _{fuel}	kWh	3441	3305	4169	4078	6370
Q _{cv}	kWh	1437	1867	368	1836	1856
Q _{DHW}	kWh	903	904	903	903	902
Q _{distr}	kWh	560	-	2296	733	2865
η _{boiler}	-	0.85	0.85	0.86	0.86	0.89
η _{start}	starts/day	61	56	81	74	122
Discomfort (* ²)	Kh	31 (18,42)	47 (30,59)	4 (1,10)	53 (33,67)	65(44,97)
Discomfort DHW(* ²)	s	8 (1,14)	8 (1,14)	10 (1,18)	8 (1,14)	9(1,17)

(*¹) temperature of shaft set at 10°C, (*²) mean value for 6 zones (min, max)

With infinite pipe insulation, the fuel consumption is 4% lower than for the reference case with 3cm isolation. 19% of the incoming energy in the pipe network, is lost to the environment, but it is regained in the zones as internal gains and causes a 29% lower consumption for space heating. If the pipes have no insulation, not all the distribution losses are useful gains, and the fuel consumption increases with 20%. In the worst-case scenario with no pipe insulation and a ventilated shaft, fuel consumption increases with 83% relative to the reference case.

Table 7 energy consumption and discomfort for variants on collective installation (July)

	Units	3cm isol	infinite isol	0cm isol	3cm isol, ventilated shaft (*)
Energy					
Q _{fuel}	kWh	1964	1276	3828	1964
Q _{cv}	kWh	0	0	0	0
Q _{DHW}	kWh	904	905	904	904
Q _{distr}	kWh	635	4	2357	635
η _{boiler}	-	0.79	0.73	0.86	0.79
η _{start}	starts/day	36	20	73	36
Discomfort (* ²)	Kh	-	-	-	-
Discomfort DHW (* ²)	s	9 (1,15)	8 (1,14)	10 (1,23)	9 (1,15)

(*¹) temperature of shaft set at 20°C

In July a comparison between the simulation with 3cm and with infinite pipe insulation shows an impact of the distribution losses on fuel consumption of 35%. Energy losses in the distribution network appear even higher during summer. Indeed, the thermal control valves work more frequently which results in higher return temperatures in the pipe network compared with space heating. It was verified that simulations without thermal valves give lower energy losses in the distribution network during summer. Obviously the concept of the piping shaft has no influence on the fuel consumption, but it affects discomfort during summer. The summer discomfort, defined as $\int_{t_1}^{t_2} (T_{op} - 23) dt$ for $T_{op} > 23^\circ\text{C}$, goes from 1728Kh for the reference case to 29Kh for case with the ventilated shaft.

If the shaft is part of the protected volume and the distribution losses can be usefully regained in the apartments, the impact of the pipe network is very low (+4% fuel consumption in January). In a well-insulated building, attention must be paid to limit the extra gains coming from the distribution network: a minimum pipe insulation is necessary. In summer time, where additional gains coming from the distribution

network cause rather discomfort, the impact of the pipe network on both energy performance and comfort level is more important (+35% fuel consumption in July).

5. CONCLUSIONS

A simulation environment was developed in Matlab, enabling a comparison between collective and individual heating systems. In this paper the comparison was performed for a well-insulated dwelling with 6 apartments, based on a real case with respect to the building and most of the installation characteristics. The occupant behaviour was simulated with statistic representative occupancy profiles and domestic hot water (DHW) tap patterns. Simulations were performed for January and for July.

Overall the energy performance of the individual installation in the case study appears better, but in some specific conditions the performance of the collective installation approximates that of the individual system. It was shown that during the heating season, with a minimum of pipe insulation (3cm) and the pipe shaft part of the protected volume, fuel consumption of both systems are similar. But outside the heating season, there is still an important difference in favour of the individual system. As a remark the number of apartments seems not enough to improve the part load efficiency and number of start-stops of the collective system significantly. Concerning discomfort, the time delay for DHW tapping can be significantly longer with an individual boiler, depending on the start-up delay of the boiler. On the other hand, the solution for collective systems with a shaft in the protected volume can cause problems with discomfort in summer. In future work the simplification of the hydronic behaviour will be evaluated. Simulations will be performed on buildings with more apartments where the efficiency of the collective boiler is expected to increase. Sensitivity analyses will be performed on building insulation and different type of families.

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