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A Methodology to Design Domestic Hot Water Production Systems Based on Tap Patterns.

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Abstract

Due to an increased insulation rate and more energy efficient ventilation systems, the production of domestic hot water (DHW) is growing in importance in the overall heat demand of residential buildings. The selection of a DHW-system with a high production efficiency is therefore important to reduce primary energy use in buildings. Besides selection also a proper use, including adequate sizing and control strategy, will have a positive effect on overall production efficiency.
In a recently executed research project, funded by the Flanders government (IWT), the selection and sizing instructions for domestic hot water installations are being revised. Hereby, a large attention is paid to the actual hot water demand or DHW tap patterns. These tap patterns are gathered by a large number of detailed measurements and simulations.
To deal with this enormous set of data, a methodology to characterize tap patterns is needed to generalize the results which are achieved in this project. Clearly, this characterization depends on the purpose for which it will be used.
First, a methodology to size production units based on tap patterns is presented and illustrated with a number of measurements and elaborated case studies. The basic idea behind this methodology is that the tap pattern will be characterized by the maximum demand within a time step and this for different step sizes. This approach allows to present an overview of possible topologies, which will all meet the net heat demand of the selected case study at an any time.
Afterwards to present some guidelines towards selection, the influence of tap patterns on different topologies is discussed. This discussion is funded with some lab tests executed according to the recently induced Ecodesign regulations. As a result of these considerations, some guidelines to optimize sensor positioning within storage tanks are presented and an evaluation is made regarding the applicability of the Ecodesign labeling within energy performance calculations for buildings.

Keywords - Domestic hot water; Design optimization; Tap pattern; Energy efficiency; DHW characterization

1. Introduction

Due to an increased insulation rate and due to efficiency gains in the thermal comfort installation, the energy use related to domestic hot water consumption is growing in importance [1-4]. The Energy Performance of Buildings Directive [5] stipulates that by 2020 all new buildings in the European Union should be near zero energy buildings. Reducing the energy use for hot water production, whilst maintaining the desired comfort level for the buildings occupants, will become one of the challenges for the future.

To achieve further primary energy savings in buildings, energy efficient technologies and strategies to heat up and distribute domestic hot water (DHW) are being developed and enhanced.

Next to innovative and efficient production units, it becomes even more important to size the hot water installations properly, as the influence of sizing and control on thermal comfort installations was already shown in [6].

Besides energy efficiency, an optimal design of the drinking water system (hot and cold) is also an even more important necessity in order to guarantee the hygienic quality of the water at the taps. Avoiding Legionella-problems means no stagnation of the water in oversized hot water vessels and no too low velocities due to the oversizing of the piping.

Given the fact that Belgium has no national standard, complementing the simplified pipe sizing method of NBN EN 806-3:20016 [7], foreign methods are commonly used. However these foreign methods tend to have very different results for identical buildings with identical installations. The in Belgium most commonly used methods for sizing hot water distribution systems in apartment buildings rely on consumption data of the eighties [8,9], it is evident that there is an urgent need to obtain current and reliable data on water consumption in buildings. This need led other countries to also review their guidelines to smaller peak flows and thus smaller pipe sizes: Germany in 2012 [10] and The Netherlands in 2013 [11].

2. Scope

In the research project 'TETRA-SWW' started in 2012, design tools are developed to properly select and size hot water installations in the residential area, valid both for single dwellings as for large apartment buildings [12].

In this project, the design specifications for each kind of production and distribution concept are discussed and detailed tap patterns were measured in more than 20 different buildings. Further, stochastic tap patterns were generated based on a statistical survey [12] with more than 700 respondents.

This paper stipulates how the tap patterns can be used in order to design all possible topologies optimally. To conclude a brief discussion on these topologies is added to illustrate further optimization based on the insights provided by this methodology.

3. A Generic Sizing Methodology Based on Tap Patterns

3.1 Tap Pattern Analysis for Design Purposes

As stated in the introduction, to size DHW production units it is necessary to have an idea of the domestic hot water consumption. Therefore, within the project in about 20 buildings of different sizes, flow rate ($\dot{V}$), cold (T_{cold}) and supply (T_{hot}) temperatures were measured to characterize hot water consumption. Next to these measurements, also a number of stochastic simulations were executed to obtain a representative consumption profile for a randomly selected kind of end-user. In both approaches the hot water consumption data were scaled to a supply temperature of 60°C and cold water temperature of 10°C. In this way the obtained tap patterns could later easily be compared and translated to the associated heat demand.

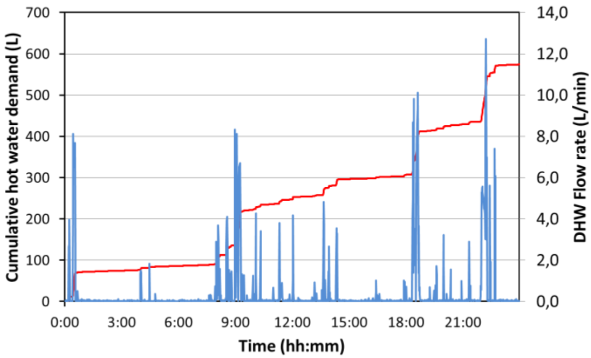

Figure 1: Illustration of a measured tap pattern in a multi-family building, during one day. It can be represented by the cumulative water use (red line, left Y-axis) or by the immediately measured flow rate (blue line, right Y-axis).

In Figure 1, the tap pattern is represented by flow rate, $\dot{V}$ [L/min], and by cumulatively measured water use, V[L]. Both representations have their advantages. The cumulative tap pattern allows the direct interpretation of the total daily consumption, useful to size water tanks. The tap pattern expressed in flow rate allows the direct detection of the peak flow rate, useful to size pipe diameters and instantaneous water heaters (1).

$$\dot{Q}_{DHW}(t) = \rho.\dot{V}(t).c_p.(T_{hot} - T_{cold}) = C_{fix}.\dot{V}(t) \quad (1)$$

$$\text{with } C_{fix} = 3{,}5\ \frac{kW}{l/min})$$

$$V(t) = \int_0^t \dot{V}(t)dt \quad (2)$$

With an indication of the (maximum) daily consumption (L) and the peak flow rate most design issues can be solved. However, regarding production, these two parameters are not sufficient to meet every design option. Moreover, the expected techno-economical optimum cannot be designed, if only these two parameters are specified.

As instantaneous hot water production units are characterized by peak flow rate, they have a high power output. Therefore, in order to meet the requested hot water demand at all time, they are oversized most of the time. For heaters with costs proportional to power (e.g. heat pumps) this is economically inefficient. Further, oversizing has a negative influence on energy efficiency, as shown in system analyses on space heating [6].

An interesting alternative is a hot water production unit with a lower power output, which reduced power is compensated by a storage tank to meet temporarily higher hot water demands. The most extreme example here is the accumulative boiler, which tank size is large enough to meet the daily hot water demand (e.g. an electric boiler, working only on night rate). However, especially for apartment buildings, this leads to large and expensive storage tanks and higher associated heat losses.

A semi-accumulative production unit offers a compromise between these two mentioned approaches, but cannot be designed based on peak flow and daily volume alone. In recently revised standards in Germany and the Netherlands, this aspect is partly met by not only looking at the maximum daily consumption, but also looking at maximum hot water demand during the critical 'bath time' [14] or some intermediate duration time periods [11]. Additional information could be obtained by including also the peak volumes during these intervals. In a more generalized approach it can be said that for design purposes determining the peak demand in every time interval is useful to design every type of production unit.

3.2 Mathematical Analysis of Peak Demand based on Tap Patterns

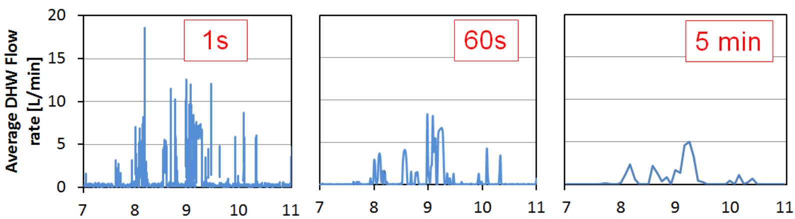

Figure 2: Three representations of a single tap pattern each measured with a different resolution, i.e. 1 second, 1 minute and 5 minutes.

As discussed in [4,13] analyzing tap patterns, shows that the resolution, x[s], has a large influence on the measured or simulated peak flow rate (See Figure 2). It is possible to simulate this influence and present a graph with peak flow rate as a function of the time interval (See Figure 3). To avoid misinterpretation, other symbols are introduced for the peak flow rate, F[L/min]. Figure 3 shows, this can be expressed as a function of the resolution, x[s]. The mathematical link between the two parameters is given by (3) and (2).

$$F(x) = MAX\left(\frac{V(t+x)-V(t)}{x}, \forall t\right) \quad (3)$$

$$C(x) = F(x).x \quad (4)$$

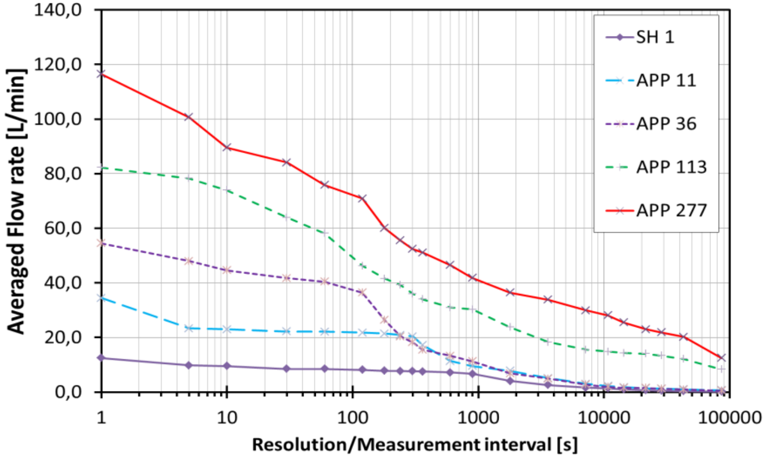

Figure 3: Peak flow rate, F, as a function of resolution, x for 5 different buildings with a centralized hot water installation, i.e. a single home (SH1) and 4 collective buildings with each a different number of flats (APP 11, APP 36, APP 113 and APP 227).

In Figure 3 measurement data for apartment buildings with a different number of apartments are shown. As expected, the peak flow rises with the number of apartments. At large intervals (high x) this augmentation is almost linear. However, at small interval (x is small) this augmentation becomes less pronounced. This is also the case in the different standards [10,11], calculating peak flow rate. Next to this, the duration of this peak interval also grows with the number of apartments. This duration is an indication for the critical bath time, which is used in some standards [10].

To seek for the corresponding bath volume, a ‘volume’ representation of the peak demand is more appropriate, using (4). Figure 4 shows such a graph (blue) in which the maximum hot water demand, C[L], is given as a function of the time interval or resolution, x[s].

3.3 Elaborating a graphical design tool

With regard to its ability to meet the requested hot water demand a DHW-heater can be characterized by its heating power and its ‘active[1]’

[1]The term ‘active’ storage volume refers to the amount of hot water which is reserved as back up, if the thermal power output is temporarily too low to meet the hot water demand, whereas

storage volume. Other parameters or aspects like efficiency, topology, ‘passive’ storage volume, insulation, fuel type will only affect performance (efficiency, legionella risks, …) .

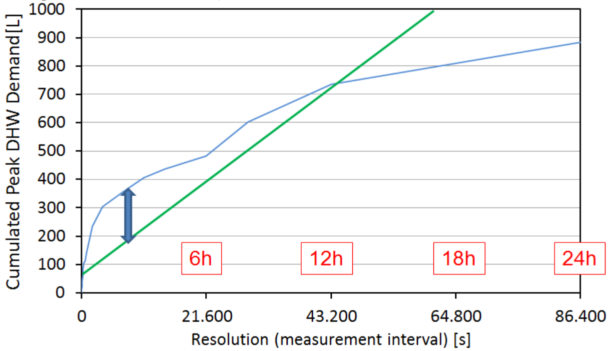

Figure 4: Peak demand, expressed in L, as a function of the duration of the measurement period (blue graph) and an example of the maximum hot water production in L which a boiler with certain power output can provide within a certain interval (green line).

How large this heating and associated active storage volume need to be in order to meet demand at all-time can be derived from Figure 4. As the graph, C(x) represents the maximum hot water demand within a time interval, it is possible to foresee a line representing the possible hot water production over time, H(x). The slope, α of this line is defined by the power output of production, P_Q as this limits flow rate. If there are no restrictions to the time frame in which this production unit can heat up the water, the production can be represented by a straight line through the origin.

$$H(x) = \alpha . x \tag{5}$$

$$\alpha = \frac{P_Q}{c_{fix}.} \tag{6}$$

When the production line exceeds the demand, this means only that for time intervals higher than the x-value, the production unit is able to deliver the requested hot water volume. However, it is possible that temporarily the thermal power of the heater is insufficient and needs to be compensated by hot water stored in a hot water tank.

The next question is therefore how large should this tank be with the corresponding hot water demand. As long as $F(x) < \alpha$, demand is lower than production, which means that the storage tank can be filled. When $F(x) > \alpha$, the storage tank needs to back up the heater in order to meet demand. The volume, V_{tank}, needed to meet this back up period is the largest difference between F(x) and the production line. It can be calculated by the equations in (7).

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the ‘passive’ storage volume can be used to optimize energy efficiency by reducing number of starts (See Section 4).

$$\begin{aligned} V_{tank} &= MAX(C(x) - H(x)) \\ \frac{d}{dx}\big(C(x) - H(x)\big) &= 0 \Rightarrow F(x) = \alpha \end{aligned} \tag{7}$$

If you have a phased production, always start with the lowest power output (e.g. night boiler, where power output shifts between 0 and P_Q or e.g. a building with different decentralized electric boilers who cannot work at the same time, due to electric power restrictions). Also for these cases, it is possible to find the associated 'active' storage volume, V_{tank}[L].

For the common (none time restricted) design, however, it is clear that for every power output a corresponding active storage volume can be found to meet the net heat demand. In the graphical design tool, Figure 5, all these combinations are summarized for different building sizes. It is clear that for solutions above a line for a certain building, the hot water demand for this building is met at any time.

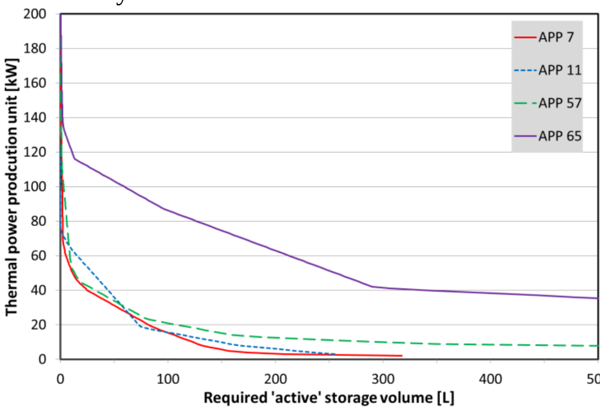

Figure 5: Thermal power of the production as a function of 'active' storage volume for different measured collective buildings, i.e. with 7, 11, 57 and 65 flats. (Graphical design tool)

3.4 Additional Design Considerations

As can be learned from Fig. 5, a storage volume of 100L combined with a gas heater of 28kW is large enough to meet the hot water demand in the measured building with 57 apartments. However, demand will not only depend on number of flats, but also on number of persons and typology of the end-units. Besides this, some additional design considerations ought to be taken into account before using this graph. First, the thermal power output should be augmented with the permanent heat losses, due to distribution (Q_{distr}) and due to storage (Q_{stor}), whereas this last one is proportionally related to the size of the storage tank and its insulation rate.

$$Q_{stor} = \beta . V_{tank} \tag{8}$$

$$P_{Q,practice} = \alpha . C_{fix} + Q_{distr} + Q_{stor} \tag{9}$$

$$V_{tank} = f . V_{tank,practice} \tag{10}$$

Furthermore, the volume of the storage tank cannot be considered entirely, because of non-ideal stratification and sensor positioning. Due to this last, there will be also a passive storage volume. Therefore, a reduction factor (f) needs to be taken into account (10). Supposing a perfect stratification, a comfort control will keep the water above the sensor heated to back up whenever necessary to meet demand. As it is possible the water below this sensor will be cold when the extra hot water is needed, it cannot be taken into account in the design. Next to that, the stratification is never perfect, but will depend on tank design. Table 1 presents an indication of both influences.

Table 1. Example of Commonly Used Values for the Reduction Factor of different types of DHW Tanks[11], combined with the sensor position. (indicative)

Heat exchanger	External	Internal	
Boiler set-up		Vertical	Horizontal
Sensor at bottom	0,9	0,75	0,68
Sensor half way	0,45	0,38	0,34

The values in Table 1 are an indication as these can be defined in more detail, depending on a detailed lay-out and control of the hot water storage tank. Also the position of cold water inlet and hot water outlet will influence this factor.

4. Selection of a Production Unit Based on Tap Patterns

As hot water demand is characterized by high and relatively short peaks and long intervals of no consumption, an efficiency at nominal load is not representative for the actual efficiency. The recently induced Ecodesign regulations aim to offer a more realistic image of the actual production efficiency as the efficiency is measured based on more realistic but standardized tap patterns.

4.1 Test Results of Different Set-ups

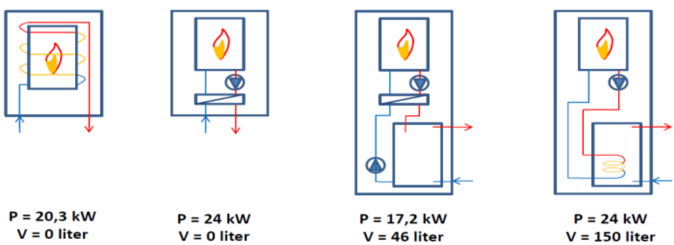

Figure 6: Configuration of tested production units: from left to right a small direct gas heater, a combi-boiler with secondary heat exchanger, a combi-boiler a small storage tank and sensor at the bottom, a heater with a large storage tank and sensor in the middle.

Within the project, the Ecodesign set-up is built and used to test four different topologies namely a small instantaneous gas heater, a combi-boiler with secondary heat exchanger, a combi-boiler with a small storage tank and a heater with a large storage tank (Figure 6). They were tested, if possible, with the S, M and L tap pattern defined in Ecodesign. Table 2 summarizes the results of this evaluation.

Table 2.The measured efficiencies for the 4 topologies based on the S,M and L profile.

	Small direct gas heater	Combi with HE	Combi with tank	Heater plus large tank
S	69%	56%-65%	32%	62%
M	74%	71%-74%	50%	70%
L	/	/	63%	73%

Instantaneous hot water heaters have the best results for small demand, which corresponds with other experimental results found in literature [1].

4.2 Considerations to optimize topology design

The poor results of the storage included topologies are due to the standing losses. With larger profiles the relative importance of these losses drops, explaining the rise in efficiency. Increased insulation rate of the tank will therefore be a first and obvious optimization strategy.

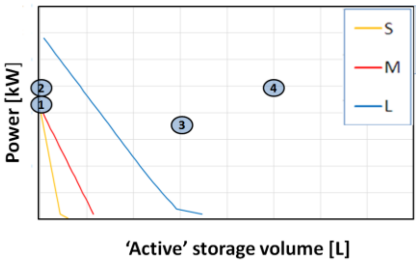

Figure 7: Illustration of the graphical design tool for the Ecodesign tap patterns and compared to the power, active storage volume combinations of the 4 tested set-ups.

Figure 7 summarizes the requested size for every topology for each tap pattern. It is shown that both storage configuration are oversized and it is clear that oversizing has a negative influence, although it cannot explain why the combi-boiler with a small tank is doing worse than the large boiler.

For this, it seems that the sensor position plays it part. Due to the higher position in the large tank there is a large passive volume. Because of this volume the heater does not have to follow the strongly fluctuating hot water demand, as this volume dampens the net demand and reduces the number of starts and stops. The number of start/stops has a negative influence on performance.

Based on this short evaluation, it is already clear that for every hot water demand an ideal sensor position can be found. This position should be that high so the heater and remaining active volume still meet the hot water demand (Figure 7).

5. Conclusion

An elaboration of the tap pattern has led to a graphical design tool, which can be used to size and optimize every combination of storage and heating power. The graph of a pre-defined tap pattern allows to energetically optimize the storage tank by its sensor position.

Further research will aim to predict the tap pattern, which will require a parameterization of the defined graphs. Next to that, a further elaboration of the tap pattern and the influences on efficiency could lead to further optimization. For this a heater model should be evaluated.

Acknowledgment

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