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Non-residential water demand model validated with extensive measurements

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Abstract

Existing guidelines related to the water demand of non-residential buildings are outdated and do not cover hot water demand for the appropriate selection of hot water devices. Moreover, they generally overestimate peak demand values required for the design of an efficient and reliable water system. Recently, a procedure was developed based on the end-use model SIMDEUM® to derive design rules for peak demand values of both cold and hot water during various time steps for several types and sizes of non-residential buildings, i.e. offices, hotels and nursing homes. In this paper, the design rules are validated with measurements of cold and hot water patterns on a per second base. The good correlation between the simulated patterns and the measured patterns indicates that the basis of the design rules, the SIMDEUM simulated standardised buildings, is solid. Moreover, the SIMDEUM based rules give a better prediction of the measured peak values for cold water flow than the existing guidelines. Furthermore, the new design rules can predict hot water use well. In this paper it is illustrated that the new design rules lead to reliable and improved designs of building installations and water heater capacity, resulting in more hygienic and economical installations.

1 Introduction

Non-residential users have a significant impact on drinking water demand and exhibit a diurnal pattern which is completely different from residential users (Loureiro et al., 2010; Blokker et al., 2011). In the Netherlands, non-residential water demand amounts to approximately 28 % of the total distributed water. Small-scale business users, defined as buildings using less than 10 000 $m^3 yr^{-1}$, use 12 % of the total distributed water. Small-scale users include shops, hotels, restaurants, schools, offices, health care institutions, and campsites. Large-scale business users are defined as customers that use more than 10 000 $m^3 yr^{-1}$ and are mainly concerned with industrial activities (Baggelaar and Geudens, 2008). Despite the significant impact of non-residential users, limited information relating to their expected water demand exists.

This lack of information creates problems during the design of water infrastructure and in the management of water demand (Ilemobade et al., 2010). To guarantee a high expected water demand, pipe diameters in distribution networks are generally oversized. However, it is understood that this overcapacity causes water quality problems, especially discolouration (Vreeburg, 2007). This lack of information also complicates the design of drinking water installations inside buildings as well as the optimal selection of the type and capacity of heating systems. Badly designed systems can cause stagnant water with hygienic consequences, and are less energy efficient and therefore more expensive to operate. The occurrence of *Legionella* in non-residential buildings is an internationally recognised problem (van der Kooij et al., 2005).

For the design of the drinking water distribution system outside as well as inside buildings, understanding the peak value of the total water demand, maximum momentary flow ($\mathrm{MMF}_{\mathrm{cold}}$), is essential (Loureiro et al., 2010; Blokker and van der Schee, 2006). In the Netherlands, guidelines exist that provide the $\mathrm{MMF}_{\mathrm{cold}}$ for non-residential buildings of various types and sizes (Table 1). These guidelines are based on limited measurements carried out between 1976 and 1980 (Scheffer, 1994). Presumably, they are no longer suitable for modern utility buildings. The outlined problems, caused by overcapacity, and new developments in *Legionella* control, suggest that the existing guidelines do not give an accurate insight into peak water demand.

Understanding hot water demand is required to select the correct type of water heater as well as the design capacity of the hot water device. In addition to the peak demand of hot water, i.e. maximum momentary flow ($\mathrm{MMF}_{\mathrm{hot}}$), the hot water use (HWU) in different time periods is required for the choice and design of hot water devices. The desired time period depends on the type of selected water heater system (Scheffer, 1994). For the characteristic values of hot water demand ($\mathrm{MMF}_{\mathrm{hot}}$ and HWU) no (inter)national guidelines exist, similar to those for cold demand (Table 1).

To provide the desired insight into the water demand of non-residential buildings, in 2010 a procedure was developed to derive design rules for the peak demand values of both cold and hot water for various types of non-residential buildings, i.e. offices, hotels and nursing homes (Pieterse-Quirijns et al., 2010). The design rules consider for example the difference between business and tourist hotels, or nursing homes with care and those with self-contained apartments. The design rules are based on water demand patterns simulated by SIMDEUM$^{®}$, an end-use model which simulates residential and non-residential water demand patterns (Blokker et al., 2011). In the procedure, SIMDEUM simulates diurnal water demand patterns, for a specific value of a dominant variable. This dominant variable characterises the size of a building, such as the number of employees in an office or the number of beds in a nursing home. A crucial part of the procedure is the standardisation of each type of building, meaning that for a specific value of the dominant variable, a building is constructed with the corresponding number of toilets, showers, kitchen personnel, visitors, etc.

Before the SIMDEUM based design rules can be applied in practice and replace existing guidelines, they need to be validated. For the validation, measurements of cold and hot water diurnal demand patterns are required on a per second base for various buildings, to ensure an accurate determination of peak demands. This is the first time that water demand patterns (especially hot water demand) will be measured on such a small timescale in the Netherlands. The validation procedure consists of two steps. In the first step, the standardised buildings, on which the design rules are based, are validated with the measurements and surveys. The simulated patterns of the standardised buildings are compared with the measured daily patterns of cold and hot water demand. An example is given in Fig. 1 for a nursing home. The correlation between the simulated patterns and the measured patterns shows that the basis of the design rules, the SIMDEUM simulated standardised buildings, is solid. The surveys will show whether the construction of the standardised buildings based on the dominant variable corresponds with practice. Since the survey component of this validation step is still in process, its full outcome will be presented in future papers.

The second validation step forms the core of this paper. In this step, the outcome of the design rules are compared with the measured peak demand values of cold and hot water and with the existing design guidelines. The design rules are evaluated and the consequences for design of distribution systems and heating systems are illustrated.

2 Methodology

2.1 Methodology to derive design rules for non-residential buildings based on SIMDEUM

The procedure to derive the design rules for the peak demand values of cold and hot water for non-residential buildings is extensively described in Pieterse-Quirijns et al. (2010). The aim of the design rules is to predict the peak demand values (MMF_{cold}, MMF_{hot} and HWU in different time periods) for various types of offices, hotels and nursing homes of arbitrary size. The new design rules predict the peak demand values as a function of a (dominant) variable. The dominant variable for offices is the number of employees, for hotels the number of rooms and for nursing homes the number of beds. For a specific value of the dominant variable, a standard building is constructed, i.e. each functional room is equipped with appliances and users. For this purpose, the number of appliances and users is established as a function of the dominant variable for each type of non-residential building. For this value of the dominant variable, x, 100 diurnal water demand patterns are simulated with SIMDEUM. From these demand patterns, the peak demand values are derived, i.e. maximum momentary flow (MMF) for total and hot water (MMF_{cold} and MMF_{hot}) and the maximum hot water use (HWU) during various time periods of 10 min (HWU_{10}), of 1 h (HWU_{60}), of 2 h (HWU_{120}) and of 1 day (HWU_{day}). The resulting design parameters are defined as the 99-percentile of the 100 values of the different peak demand values. The design rules for each peak demand value can be described as simple linear relationships of the dominant variable for each type of non-residential building.

2.2 Methodology to measure cold and hot water demand of non-residential buildings

For the measurement of cold and hot water demand an ultrasonic flow meter is used, the Proline Prosonic Flow meter. It is a clamp-on meter that can be installed without disturbing the water supply. To ensure an accurate measurement of peak demand, the logging frequency was set to 1 s. The logging precision was 0.5 %. The water demand was measured during minimal 20 weekdays for hotels and nursing homes and 30 working days for offices.

In each category of non-residential users, two buildings were selected with different values of the dominant variable. It appeared to be very difficult to find suitable buildings for the measurements. Narrow installation environments, the presence of buffers in the hot water circulation system, not enough straight pipes to install the flow sensor with desired distance from fittings, such as valves, T-pieces, elbows, etc. were the most encountered problems. Moreover, it appeared that Dutch offices are seldom equipped with a collective hot water system. Therefore, the measurement of hot water was not possible, and the developed design rules for offices can only be validated on cold water use. Since the hot water use in offices is very small, this is not a problem. The selected buildings are given in Table 2. During the measurements, full occupation was aimed for. However, this was difficult to achieve for the two hotels. The occupation varied between 4–100 % during weekdays.

2.3 Methodology to validate design rules for non-residential buildings based on SIMDEUM

For the validation of the design rules, the following methodology is applied:

1. Compare MMF and HWU from design rules with measured peak demand values:
   (a) MMF and HWU from SIMDEUM based design rules for the selected buildings (Table 2);
   (b) $\mathrm{MMF}_{\mathrm{cold}}$ from existing guidelines (Table 1) for the selected buildings (Table 2);

(c) measured MMF and HWU as $\overline{x} + 3 \cdot \sigma$, where $\overline{x}$ is the average value of the peak demand values from approx. 20–30 measured diurnal patterns and σ is the corresponding standard deviation. The resulting MMF and HWU represent the 99.7-percentile. For hotels, it was not possible to apply this calculation method due to the highly variable occupation. The peak demand values for hotels are considered to be the maximum measured peak demand or the average of the measured peak demands on the days with full occupation.

2. Compare designs based on MMF and HWU with designs in practice:
   the design of distribution systems is based on MMF; the maximum velocity (v_{max}) of flowing water in pipes, determines the selected diameter; the internal diameter of pipes is related to MMF and v_{max} by

$$d_{\text{in}} = \sqrt{\frac{\text{MMF}/1000}{0.25 \cdot \pi \cdot v_{\text{max}}}} \cdot 1000 \text{ [mm]} \tag{1}$$

where v_{max} is the maximal allowed design velocity set at $2\,\text{m}\,\text{s}^{-1}$, d_{in} is the internal pipe diameter in mm. The calculated internal diameter is compared with a limited number of existing copper pipe diameters, applied in drinking water installations. The smallest copper pipe fulfilling the calculated internal diameter is selected in design.

Moreover, the outcome of the design rules for MMF_{hot}, HWU_{10}, HWU_{60} and HWU_{120} are compared with company guidelines of a Dutch supplier of heating systems. The design of the heating system is based on all four peak demand values.

3 Results and discussion

3.1 Comparison of measured and predicted peak demand values for cold and hot water

The measured peak demand values for all non-residential buildings are presented in Table 3. This table also includes the predicted peak demand values by the newly developed design rules, based on SIMDEUM and the existing guidelines for cold water. For offices of different sizes, the SIMDEUM based design rules predict the $\mathrm{MMF}_{\mathrm{cold}}$ well. They slightly underestimate the $\mathrm{MMF}_{\mathrm{cold}}$ with 10 %. The design rules show an improved prediction compared to the existing Dutch guidelines, which overestimate $\mathrm{MMF}_{\mathrm{cold}}$ with 30–80 %.

For hotels, the derivation of peak demand values from the measured water demand patterns is difficult, due to the varying occupation. 30 measuring days appears to be too short to achieve a statistically sound procedure because of the additional variation due to variable occupation. The maximum value of the parameters (MMF and HWU) do not always coincide with the days with full occupation nor do they occur on the same day, e.g. $\mathrm{MMF}_{\mathrm{cold}}$ and HWU_{10} take place at different days and even on days with low occupation. Therefore, the outcomes of the design rules are compared with the maximum value of each peak demand characteristic and with the average of the measured peak demand on the days with full occupation. For statistically sound conclusions for hotels with varying occupations a longer measuring period is recommended. Careful comparison shows that the deviation between measured peak demand and the outcome of the design rules varies from an underestimation of maximal 30 % to an overestimation of maximal 15 %. The $\mathrm{MMF}_{\mathrm{cold}}$ can be predicted fairly well, while the hot water demand appears to be (slightly) underestimated. For hotels, the new design rules show an improved prediction, as the existing guidelines overestimate $\mathrm{MMF}_{\mathrm{cold}}$ with 70–170 %.

The new design rules predict both cold and hot water demand of the nursing home very well. All predicted peak demand values overestimate the measured data with less than 17 %. This is better than the existing guideline that overestimates $\mathrm{MMF}_{\mathrm{cold}}$ with

75 %. At the moment, an additional nursing home is searched for to measure the water demand to substantiate this conclusion.

3.2 Consequences for design of distribution systems and heating system

The design of the outside and inside distribution system is based on the maximum momentary flows (MMF_{cold} and MMF_{hot}) for pipes distributing the total amount of water and the hot water pipes respectively. In Table 3, the resulting pipe diameters are shown, based on the measured and the predicted peak demand values. The table shows that the newly developed design rules result in the same design as the measurements would. This indicates that the deviation between the design rules and the measurements falls within the design accuracy, given by the limited number of existing pipe diameters. Moreover, the design rules result in smaller diameters, than applied in practice and predicted by the old guidelines. With the supply of the same amount of water, this will result in better water quality with respect to both discolouration and hygiene, due to higher velocities and less stagnancy.

No publicly available rules exist for the choice of the type of heater and its capacity. In general, the design of the heating system is based on four peak demand values, i.e. the maximum momentary flow MMF_{hot} and the hot water demand in the time periods HWU_{10}, HWU_{60} and HWU_{120}. Since the new design rules always predict one or two of these peak demand values with a deviation less than 10 % from the measurements, the design rules lead to the same choice of heating system as the measured peak demand values would. Although no public rules exist, each company producing and selling heating systems will have some guidelines. The guidelines of a specific Dutch supplier result in a large overestimation of the four mentioned peak demand values. The resulting MMF_{hot} and HWU_{10} are approx. 5 times higher than the measured ones and HWU_{60} and HWU_{120} are approx. 3 times higher, which would result in too large selected capacity. This clearly shows that with the newly developed design rules an enormous energy gain will be achieved. Moreover, less hygienic problems will be encountered.

4 Conclusions

Recently, new SIMDEUM® based design rules were developed for cold and hot water demand of non-residential buildings. In this paper, these design rules are validated with measurements of both cold and hot water on a per second basis for different buildings. The validation shows that the design rules predict the cold and hot water demand peak values reasonable to good. The deviation of the predicted demand values from the measured ones is mostly less than 15 %. Sometimes a higher deviation is found, but less than 30 %. These deviations are much smaller than the deviations of existing guidelines for $\mathrm{MMF}_{\mathrm{cold}}$ which overestimate by 30–170 %. Moreover, the new design rules give insight into hot water use, where no existing public guidelines are available.

The new design rules improve the design of the building installation, expressed as the selected pipe diameters, and of the heating system. First of all, the design rules lead to the same pipe diameter and the same heating system as based on the measured peak values. This means that the design based on the new rules is reliable. Secondly, the selected pipe diameters are smaller than the ones used in practice and the ones predicted by the existing guidelines. This indicates that the common practice leads to oversized systems, with corresponding potential quality problems. Also the heater capacity can be reduced based on the outcome of the design rules. The guidelines of a heater supplier estimates a 3–5 times higher value for the peak demand values of hot water. Thus, the improved insight of the new design rules will lead to an energy efficient choice of the hot water systems. An enormous energy-saving is gained here. Moreover, the smaller design of the heating system reduces the stagnancy of water, leading to less hygienic problems.

The new SIMDEUM based design rules lead to more hygienic, economic and energy-saving designs of the distribution networks and indoor installations. These designs diverge from the common practice in the Netherlands. In this paper it is shown that the common practice leads to oversized systems. In other countries the same tendency is expected, although international guidelines do not exist in the public domain. Therefore, it is recommended to apply the SIMDEUM based procedure to develop design rules for peak demand values for various building types in specific countries to improve the designs. Due to the physical basis of SIMDEUM, the presented procedure is easily transferable to other countries when specific information on users and appliances is available. An additional advantage is that the water demand patterns, on which the design rules are based, will also improve demand allocation in hydraulic network models.

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Table 1. Current guidelines for maximum momentary flow of cold water in various non-residential buildings (Scheffer, 1994).

Type of non-residential building	Relation for peak demand $\mathrm{MMF}_{\mathrm{cold}}$ $(\mathrm{l\,s^{-1}})$
Office-toilets with cistern	$1.464 + 0.0019 \cdot$ (number of employees)
Office-toilets with flushing valve	$2.603 + 0.0031 \cdot$ (number of employees)
Hotel business	$q\sqrt{n} + 40\,\%^{*}$
Hotel tourist	$q\sqrt{n} + 70\,\%$
Retirement home	$1.177 + 0.0092 \cdot$ (number of beds)
Nursing home	$2.257 + 0.0130 \cdot$ (number of beds)

*q$\sqrt{}$n-method; $q\sqrt{n} = 0.083 \cdot \sqrt{\Sigma \mathrm{LU}}$, LU is number of loading-units.

Table 2. Selected buildings for measurement of cold and hot water demand, to validate the developed design rules for offices, hotels and nursing homes.

category offices	number of employees (x)	category hotels	number of hotel rooms (x)	category nursing homes	number of beds (x)
office I	255	business hotel I	80	nursing home (care needed residents)	260 212 (hot)
office II	2000	business hotel II	192		

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Table 3. Comparison of the measured peak demand values for cold and hot water with the outcome of the SIMDEUM based design rules (“new”) and existing guidelines for cold water (“old”) for non-residential buildings (offices, hotels and nursing homes) and the resulting pipe diameters compared with diameters used in practice (d_{pract}) and diameters selected based on measured peak demand (d_{meas}).

Building	Peak demand parameter	measured	Peak demand value SIMDEUM based design rules		existing guidelines		Consequences for selection diameter of pipes [mm]			
							d_{pract}	d_{meas}	d_{new}	d_{old}
offices										
office I	$\mathrm{MMF}_{\mathrm{cold}}$ [l s^{-1}]	1.09	1.0	(−11 %)	1.9	(+79 %)	54	35	35	42
office II	$\mathrm{MMF}_{\mathrm{cold}}$ [l s^{-1}]	3.97	3.7	(−8 %)	5.3	(+32 %)	54	54	54	64
hotels based on maximal measured values (not on the same day)										
business hotel I	$\mathrm{MMF}_{\mathrm{cold}}$ [l s^{-1}]	1.85	1.3	(−27 %)	3.1	(+69 %)	76	42	35	54
	$\mathrm{MMF}_{\mathrm{hot}}$ [l s^{-1}]	0.84	0.8	(−10 %)		–	54	28	28	–
	HWU_{10} [l]	338.83	292.7	(−14 %)		–				
	HWU_{60} [l]	986.66	851.0	(−14 %)		–				
	HWU_{120} [l]	1500.00	1359.9	(−9 %)		–				
	$\mathrm{HWU}_{\mathrm{day}}$ [l]	5560.00	4998.4	(−10 %)		–				
based on average measured values during full occupation										
business hotel I	$\mathrm{MMF}_{\mathrm{cold}}$ [l s^{-1}]	1.50	1.3	(−11 %)	3.1	(+107 %)	76	35	35	54
	$\mathrm{MMF}_{\mathrm{hot}}$ [l s^{-1}]	0.69	0.8	(+11 %)		–	54	28	28	–
	HWU_{10} [l]	255.10	292.7	(+15 %)		–				
	HWU_{60} [l]	844.49	851.0	(+1 %)		–				
	HWU_{120} [l]	1288.00	1359.9	(+6 %)		–				
	$\mathrm{HWU}_{\mathrm{day}}$ [l]	5143.73	4998.4	(−3 %)		–				
based on maximal measured values (not on the same day)										
business hotel II	$\mathrm{MMF}_{\mathrm{cold}}$ [l s^{-1}]	2.02	2.1	(+2 %)	4.8	(+139 %)	67	42	42	64
	$\mathrm{MMF}_{\mathrm{hot}}$ [l s^{-1}]	1.31	1.1	(−18 %)		–	54	35	35	–
	HWU_{10} [l]	493.65	455.3	(−8 %)		–				
	HWU_{60} [l]	2224.88	1594.4	(−28 %)		–				

Table 3. Continued.

Building	Peak demand parameter	measured	Peak demand value SIMDEUM based design rules		existing guidelines		Consequences for selection diameter of pipes [mm]			
							d_{pract}	d_{meas}	d_{new}	d_{old}
based on maximal measured values (not on the same day)										
	HWU$_{120}$ [l]	3881.99	2666.5	(−31 %)		–				
	HWU$_{\mathrm{day}}$ [l]	9731.56	10573.8	(+9 %)		–				
based on average measured values during full occupation										
business hotel II	MMF$_{\mathrm{cold}}$ [l s^{-1}]	1.8	2.1	(+15 %)	4.8	(+170 %)	67	42	42	64
	MMF$_{\mathrm{hot}}$ [l s^{-1}]	1.2	1.1	(−10 %)		–	54	35	35	–
	HWU$_{10}$ [l]	473.9	455.3	(−4 %)		–				
	HWU$_{60}$ [l]	1994.3	1594.4	(−20 %)		–				
	HWU$_{120}$ [l]	3456.8	2666.5	(−23 %)		–				
	HWU$_{\mathrm{day}}$ [l]	9662.3	10573.8	(+9 %)		–				
nursing homes										
nursing home (260 beds cold) (212 beds hot)	MMF$_{\mathrm{cold}}$ [l s^{-1}]	3.22	3.7	(+15 %)	5.6	(+75 %)	54&35	54	54	76
	MMF$_{\mathrm{hot}}$ [l s^{-1}]	1.91	2.2	(+17 %)		–	54	42	42	–
	HWU$_{10}$ [l]	380.90	395.9	(+4 %)		–				
	HWU$_{60}$ [l]	1432.27	1531.0	(+7 %)		–				
	HWU$_{120}$ [l]	2353.93	2559.7	(+9 %)		–				
	HWU$_{\mathrm{day}}$ [l]	7197.96	7803.0	(+8 %)		–				

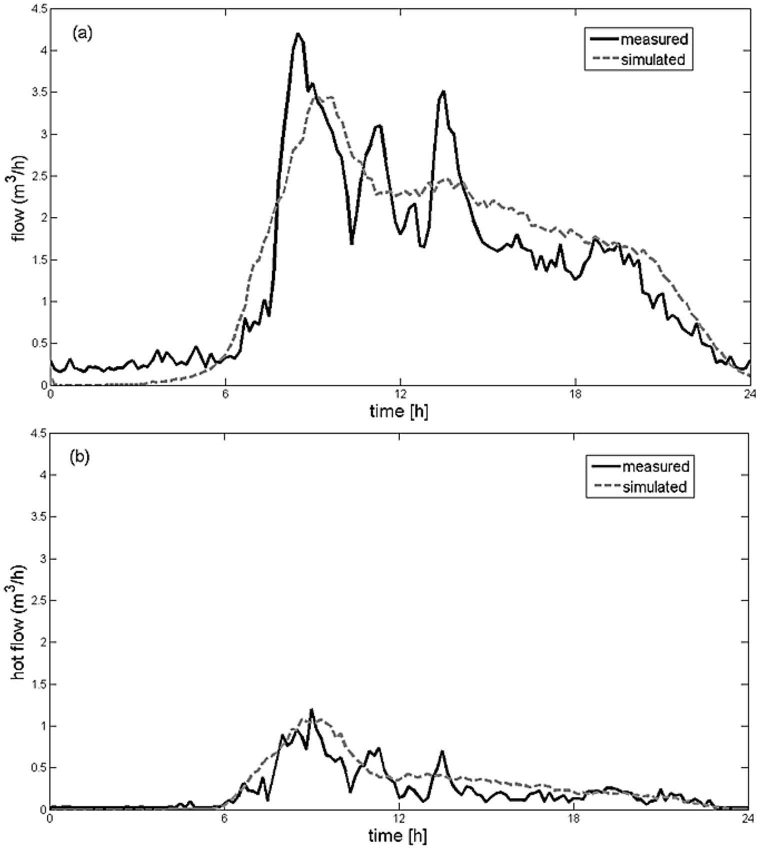

Fig. 1. An example of measured diurnal demand pattern of cold water **(a)** and hot water **(b)** for a nursing home and the simulated demand of the corresponding standardised building.