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Hourly consumption profiles of domestic hot water for different occupant groups in dwellings

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ABSTRACT

Hourly consumption data of domestic hot water (DHW) is essential to compute the energy demand, and for system sizing. Few on-site measured data and simulation based studies are available to forecast DHW consumption focusing on a daily average, hourly average, appliance consumption, and occupant number. This study derived the hourly DHW profiles for 5 different groups of 1 person, 3 people, 10 people, 31 people and more than 50 people as a function of the number of occupants. Weekday (WD), Weekend (WE) and Total day (TD) consumption variation were analyzed. The study accomplished with on-site hourly DHW consumption measurement from 86 apartments with 191 occupants during one year and findings was also validated against a larger sample from previous study. A specific selection procedure was developed to find out the most representative DHW profile among measured candidates of each group fulfilling the selection criteria. Selected profiles had similar daily consumption (L/per./day) to an average of all profiles and also followed similar consumption pattern during a day. Two sharp peaks with large consumption variance were found in each day and smaller groups had higher consumption during peak hours. Result also found higher evening peak compared to the morning peak and the average consumption of peak hours was 2–4 times higher than non-peaks hours. Morning peaks of WE shifted 2–3 h later from WD's and kept similar position during the evening. Profiles of 5 groups were necessary to normalize with scaling factor to maintain the daily average value. Derived hourly values could be used with monthly factors to deliver hourly profiles of all months and the format of hourly and monthly factors used allows to define DHW consumption in relevant simulation and sizing software.

1. Introduction

Residential building sector has accounted 16–50% of total energy in most of the countries (Saidur et al., 2007) where domestic hot water (DHW) is reported a good percentage of it. In Finnish residential building it requires the second largest of energy demand next to space heating (Hakala, 2014). Dutch residential sector accounted for 72% of total DHW consumption, whereas 12% and 16% had reported for small and large scale of office users (Geudens, 2008). The information of DHW in residential building is very significant because of having a large contribution on overall energy demand.

DHW consumption profile is complicated and strongly fluctuated over time. Graphical location, weather condition, occupant number, occupant behavior toward DHW usages, lifestyle, social and economic condition, etc. were found most significant variables in literature body (Aydinalp et al., 2004; Meyer and Tshimankinda, 1998a; Papakostas et al., 1995; Wolf et al., 1980). Perlman and Mills (Perlman and Mills, 1985) had identified demographics of the location, occupant number, occupant attitude toward usages, ownership, etc. as the most significant factors, whereas Tso (Tso and Yau, 2003) addressed occupant income, ownership of household, housing type, seasonal variation as additional factors. Reference study (Vine et al., 1987) monitored DHW consumption in four apartment buildings in San Francisco for 4–6 months and interviewed the usage pattern of DHW. It reported education, cultural and social norms as significant variables. Abrams and Shedd (Abrams and Shedd, 1996) found a variation of DHW usages from day-to-day and seasonal variation, other studies also marked seasonal variation as a significant factor (Becker and Stogsdill, 1990; Perlman and Mills, 1985). Among all factors Parker (2003) noticed an occupant number as the weightiest factor and occupancy pattern also had a significant impact on domestic energy demand

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Nomenclature

$v_{t,a}$	average consumption of apartment 'a' at hour 't' (Liter)
n	days in a month; n = 1, 2, 3, ..., 31
N	total days in a month (N_{Total} = 30 days, N_{WD} = 20 days, N_{WE} = 10 days for November 2014)
$v_{t,a,o}$	average consumption of each occupant of apartment 'a' at hour 't'
O_a	occupant number at apartment 'a'
v_t	average consumption at hour 't' (L/person)
$v_{t,o}$	occupant 'O' consumption at hour 't' (Liter)
N_i	eliminated total occupant number
$V_{a,m}$	hourly average consumption (L/per./h)
V	annual daily average consumption (L/per./day)
f_m	monthly consumption factor
V_G	daily consumption of given group i.e., sum up consumption of 24 h (L/per./day)
$V_{G,a}$	hourly average consumption of given group (L/per./h)
$S_{m,G}$	scaling factor at 'm' month for given group
$v_{t,G}$	consumption at 't' hour of selected profile for given group (L/person)
$f_{t,G}$	hourly consumption factor at 't' hour of selected profile for given group (L/person)
R_t	consumption ratio at specific hour
DHW_t	hot water consumption at specific hour (L/per./h)
DTW_t	total water consumption at specific hour (Hot + Cold) (L/per./h)
v_m	average hourly consumption at 'm' month (L/per./h)
$v_{t,m,G}$	hourly consumption at 't' hour of 'm' month of year for given group (L/per./h)
$f_{t,G}$	hourly consumption factor

Indices

t	hour in a day; t = 1, 2, 3, ..., 24
a	apartment or dataset; a = 1, 2, 3, ..., 86
i	elinated occupant number (for November i_{TD} = 164, i_{WD} = 164, i_{WE} = 163)
m	month of year
G	group

(Stokes et al., 2004). The study found a higher consumption rate of 3 or less people compare to 4 or higher people occupied Canadian households.

Daily average consumption and hourly profile of DHW are not similar in all countries. The annual average of DHW for Finnish and Swedish people were 43.0 and 33.0 L/per./day (Ahmed et al., 2015b; BBR, 2012). Schipper (1982) found that people of certain developed European countries consumed 7 times less DHW than Americans (Schipper, 1982). In addition, the hourly consumption during a day are also varied along nationwide. German have higher consumption during the morning and low consumption during the evening, whereas Finnish people have a higher consumption during the evening (IEA, 2007). Hourly consumptions were also found diverse along the week (Hidalgo et al., 2012; Papakostas et al., 1995). Papakostas et al. (1995) monitored DHW usages in four apartment buildings in a solar village 3 in Greece and presented the average hourly, daily, yearly DHW usage profiles (Papakostas et al., 1995). The hourly consumption pattern during WD were nearly similar with morning and evening peaks, whereas usage pattern were more uniform during WE. In this study monthly consumption factor in Table 1 are recommended to be used for delivering the hourly profile.

Meyer and Tshimankinda had investigated the DHW consumption in South African traditional houses (Meyer and Tshimankinda, 1996), townhouses (Meyer and Tshimankinda, 1998b) and apartment buildings (Meyer and Tshimankinda, 1998a) over a period of one year. The study reported the consumption in L/per./day as a function of summer WD, summer WE, winter WD and winter WE. Low density traditional houses (Meyer and Tshimankinda, 1996) and townhouses (Meyer and Tshimankinda, 1998b) consumed 30% and 44% more DHW than high density houses and townhouses. Also, 70% of consumption increased from summer to winter for both cases. On the other hand, low density occupied apartments used more than four times hot water than high density apartment buildings and consumption increased by 80% from summer to winter (Meyer and Tshimankinda, 1998a). The daily consumption also varied during WD and WE with two peaks, i.e. morning and evening peaks. In apartments and townhouses, the morning peaks during WD occurred at 6:00 and 8:00 h for high and low density respectively. For evening peaks, it found at 19:00 and 21:00 h, respectively (Meyer and Tshimankinda, 1998a,b). In traditional houses, morning and evening peaks were noticed at 7:00 and 20:00 h in both cases. Though two peaks were available in WD and WE, the WE peaks were shifted 1–2 h later than the WD peaks (Meyer and Tshimankinda, 1998a).

Many researchers also had drawn the DHW consumption pattern based on on-site field measurement since 1970 (Becker and Stogsdill, 1990; Burch and Salasovich, 2002; Perlman and Mills, 1985). The data sets were collected three to four decades ago and might not reflect the current usage pattern. A Danish study found the mean DHW consumption reduction over 200 L/day to about 100 L/day for Danish families during 1989–1996. The reasons were water price, water saving campaign, shorten the family sizes (Knudsen, 2002), energy efficient appliance (Bansal et al., 2011), new regulation and market forces (Koomey et al., 1999) etc.

More review of forecasting method of DHW consumption are well explained in literature body (Aydinalp et al., 2004; Bagge and Johansson, 2011; Blokker et al., 2010; Good et al., 2015; Paatero and Lund, 2006). Blokker et al. (2010) proposed an end use water demand model which could predict the water demand pattern with 1 s resolution. The model based on statistical data of end uses in the household as well as information about occupant number, ages, usage frequency, flow intensity, event duration, volume flow of each usages event, number of occurrences. In this approach end uses and user information required initially. Afterward, information regarding frequency, intensity, and duration of

Table 1
DHW monthly consumption factor for Finnish apartment buildings (Ahmed et al., 2015a,b).

	Annual average specific consumption, L/person/day	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Arithmetic mean (Total)	43	1.105	1.040	1.033	1.005	0.977	0.895	0.880	0.964	0.969	0.980	1.111	1.041
Arithmetic mean (WD)	43	1.119	1.049	1.020	0.999	0.941	0.912	0.892	0.964	0.982	0.987	1.100	1.030
Arithmetic mean (WE)	43	1.067	1.017	1.062	1.023	1.062	0.860	0.845	0.964	0.940	0.961	1.136	1.067